PART B.

To study the combustion in commercial Diesel engines with emphasis on the exhaust smoke.

EXHAUST SMOKE DETERMINATION

ON DIESEL ENGINES

There are two reasons why in the last few years the development of a reliable, accurate and convenient diesel exhaust smokemeter has become more urgent: on the one hand the increase in gasoline engine output has led to vigorous efforts to increase diesel engine output correspondingly by going to higher speeds and by operating on a small percentage of excess air at full load. On the other hand, the continuously increasing traffic density has led the medical profession to numerous investigations designed to clarity the influence of the combustion products in the air of the cities on public health.

Diesel exhaust is more readily observed by the general public and therefore causes more complaints than other sources of pollution.

Composition of Diesel Exhaust Smoke.

A diesel engine can show white or black exhaust smoke. White, or rather, bluish smoke is caused by the presence of very small liquid droplets in the exhaust gases. If these droplets do not consist of lubricating oil, as might be the case particularly with two-cycle engines, they are fuel which because of strong turbulence and through contact with hot surfaces has been transformed into fog and which has not burned and at best has oxidized to a very limited degree only. Engines which when warmed up show bluish exhaust smoke will not be found often on the roads because the conditions which cause this smoke also produce a definite drop in engine output, increased fuel and lubricating oil consumption, as well as great susceptibility to breakdown because of lube oil dilution. Such manifestations as so obvious that the owner usually very quickly corrects the conditions which cause bluish smoke. Nowadays bluish smoke caused by low combustion chamber temperatures during idle is encountered very rarely.

Dark, blackish smoke appears when partial oxidation of the fuel molecules takes place, but when insufficient oxygen is available during the course of the combustion to complete the oxidation of the intermediate combustion products extremely rich in carbon. This condition can arise when in the combustion chamber there is locally either a shortage of air or an excess of fuel.

<u>What are the Causes of Black Diesel Smoke?</u>

Defects in the engine, unsuitable fuel properties or defects in the injection equipment can cause excessive smoke. Engine air swirl and turbulence in the combustion chamber have the purpose of providing intimate contact of as much of the air as possible with the injected and evaporated fuel droplets in the brief available time enterval; This much be achieved without serious increase of the engine air consumption or decrease of the mechanical efficiency of the engine. From the design standpoint air motion in the combustion chamber is a major factor in determining maximum engine output and tendency to smoke; From the operational standpoint, any reduction of the volumetric efficiency due to leaking valves or pistons or excessive valve clearance will increase exhaust smoke. Excessively restrictive air filters or exhaust lines can have the same effect. Defects in combustion chamber components such as damaged pre-chamber throats or faulty cylinder head gaskets can also cause excessive smoke. Among the characteristics of a fuel which have an influence on the amount of exhaust smoke are cetane no.,volatility, viscosity, specific gravity, and its tendency to form coke. For fuels having a cetane no.,of less than 40 the long ignition delay must be compensated for by increased air turbulence, higher combustion chamber temperatures of higher compression ratio. Fuels with a cetane no. in excess of 75 require an adjustment of air turbulence and injection characteristics to suit the faster fuel decomposition. High volatility promotes a clean exhaust because of more rapid evaporation of the fuel. Correspondingly, fuels with low volatility show increased tendency to form soot in the exhaust smoke. High fuel viscosity produces poor atomization and by increasing the tendency of the fuel to ashere to the nozzle tip in droplets, it leads to coke deposits near the nozzle exit which in turn produce disturbances of the spray. A pronounced tendency of the fuel to form coke accelerates the accumulation deposits at the nozzle, and such deposits can cause nozzle defects and engine malfunctioning due to deposits in the combustion chamber and on the piston rings.

Although injection pump and nozzles have been very carefully selected during the development process of the engine, quantity and timing in operation and defects can develop at the nozzles, thus causing smoke exhaust. In order to prevent the operator from using during normal operation the excess fuel setting which may be provided for facilitating starting, special control rod stops have been developed which allow the starting fuel quantity to be delivered only at speeds below idle. Poor distribution of the fuel within the combustion chamber can also occur due to coke formation at the nozzle exit because of excessive nozzle temperatures, due to improper functioning of the nozzle valves because of faulty installation of the nozzle in its holder, due to improper filtration or due to low nozzle operating pressures.

Existing Types of Smoke Meters.

Visual elevation of the exhaust smoke density is exceedingly inaccurate even in connection with comparison charts because such factors as illumination, background and memory of the observer play too large a part. Photographic methods are equally unsuitable because, aside from the complexity of the apparatus required, only a very dark exhaust can be made visible in a photograph.

In the region of heavy smoke CO has been observed frequently in the exhaust gases, however, the relationship between CO formation and soot quantity differs for the different combustion systems in use on high-speed Diesel engines and, besides, the various methods for measuring CO content are much too time consuming to be of practical value.

Apparatus

The two Diesel engines tested are described in table 6. each engine was mounted on the chassis of bus body including radiator, fan, clutch, fuel system, and starting mechanism. In the tests, each unit was running on the H.P.A. chassis Dynamometer. (Fig. 17) As the engines were new when received, each was run in for 100 hr. at various speeds and loads before any tests were made. In the tests and engine was operated at the desired speed and load for 1 hr. and the exhaust gases was sampled. The samples were measured or analyzed in the Hartridge B.P. Smokemeter, (Fig.14). Bosch Smokemeter (Fig. 15) and Biard & tatlock Orsat Apparatus (Fig. 16) to determine the percentage of smoke density, carbon dioxide, oxygen, carbon monoxide and Nitrogen. Details of the sampling equipment, methods of analysis, and testing procedure as the following:-

1. HARTRIDGE B.P. SMOKEMETER

At present observers generally assess the density of exhaust smoke visually. This is inaccurate owing to background variations, weather conditions and smoke volume.

Engineer, Therefore, require a reliable scientific instrument for accurately and quickly measuring the density of diesel exhaust smoke and thereby eliminating visual errors. Lesile Hartridge have now perfected and instrument originally developed by the Research Laboratories of the British Petroleum Co. for investigating the causes of visible smoke.

Table 6 Description of Engines Tested

Diesel Engine	A	B
Type	Four-stroke cycle	Two-stroke cycle
Number of cylinders	6	3
Cylinder bore, in mm.	95	110
Piston stroke, in mm.	120	130
Piston displacement, cc.	5,100	3,706
Maximum rated speed, rpm.	3,000	2,200
Maximum rated brake horse-power	120	125
Injection pump	Reformed Bosch	Reformed Bosch
Cooling system	Water cooled	Water cooled
Valve position	Over-head valve	Over-head valve
Compression ratio	19.5	16
Reduction gear	5.72 (40/7)	5.57 (39/7)
No. of wheels	Front-single Rear-dual	Front-single Rear-dual
Tire size	8.25-20	8.25-20

The Smokemeter, which is portable and robust, gives and instantaneous direct reading of smoke density on a 0 -100 scale. It is equally suitable for use by laboratories, factories, garages, service station, Police and Health Authorities. It will also operate on slow and high speed engines of all sizes and can be used at night.

The principle is based on the comparison of the density of a column of smoke with a column of clean air, a Smoke Tube and a clean Air Tube which are optically and dimensionally identical. At one end of the tubes there is a 12 volt, 48 watt Light Source and at the other end a Photo Electric Cell.

These are so mounted on swinging arms that they can both be moved together from the smoke tube to the clean air tube, by the control Lever. The photocell is connected to a microammeter with Smoke Density Scale reading 0 -100 representing percentage light absorbed. A small 12 volt Blower draws in air to the clean air tube which then passes across the surfaces of the light source and photocell. The air flow prevents sooting of these vital surface which if contaminated would give inaccurate reading of smoke density.

A sampling pipe is connected either to a tapping on the exhaust pipe on the diesel engine or to the exhaust outlet in a vehicle. (Fig. 21) The Smokemeter is then switched on and the control lever set to the air tube which is used as the basis for comparing the density of the smoke. The smoke density scale is then set to zero by means of a potentiometer indicating "no smoke". The control lever is then move to the smoke tube

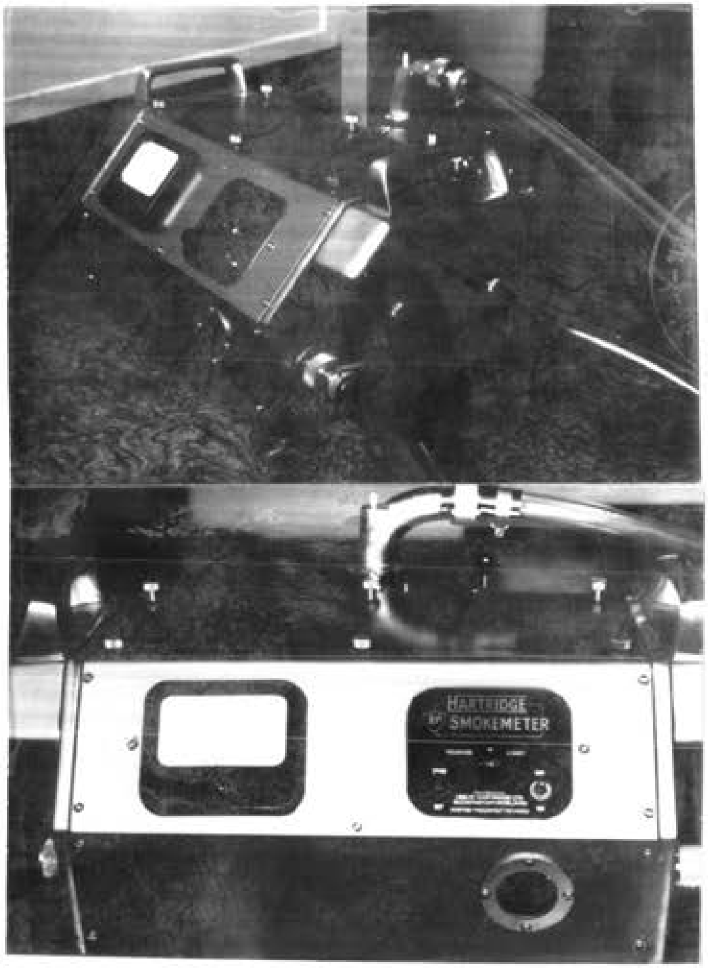

Fig. 14

Hartridge B.P. Smokemeter

and an immediate reading of smoke density is recorded on the scale. (as shown in Fig. 14)

2. BOSCH SMOKEMETER.

A newly developed and accurate testing instrument to measure exhaust smoke of diesel engines.

This smokemeter is suited for measurements on the road, i.e. under all load conditions, as well as on the test stand.

The photo-electric evaluation of the filter paper disk, darkened by the engine exhaust smoke, guarantees on accurate quantitative reading of exhaust soot on the scale of the Evaluating instrument.

On the one hand, highly sooted diesel exhaust gases hinder the visibility of, and cause annoyance to other road-users, while on the other hand the diesel engine shows in the range of incipient smoke a considerable increase in output. This fact is often used by the driver illegally to his advantage. With the aid of the smokemeter the engine adjustment can be tested so that some limit for permissible black smoke can be established and maintained without an excessively conservative limit for maximum engine output.

A sampling pump with gas sampling probe and pneumatic tripping device, a clamp for fastening the sampling pump to the exhaust pipe. The sampling pump which is a suction pump of 330 cu. cm. piston displacement is fitted on one end with a spring-actuated pivoted cover and a retainer for the filter paper disk.

The suction stroke is effected by spring force in order to permit remote operation. It is released pneumatically via a flexible hose 16.5 ft. in length, which can be done from the cabin during road tests. The sampling pump extracts a certain amount of exhaust gas with the aid of the sampling probe inserted into the exhaust line,(Fig. 22) and aspirates it through a filter paper disk, the filter paper disk darkens during this process; this gives the measure of the soot content in the exhaust gases.

The evaluating instrument is of a handy steel box design. It contains a microammeter used as the indicating instrument, a potentiometer for zero adjustment, and adjustment, and a special plug socket to connect the photo-cell probe. (as shown in Fig. 15)

Thereis room for the photo-cell probe and cable, as well as for the installation of a 4.5 V dry-cell battery, in a compartment at the rear of the instrument, closed with a lock-fast cover.

For evaluating the darkened filter paper disk, the probe is placed on the filter paper disk. The light source of the photo-cell probe throws a beam on the disk underneath. The unabsorbed light is then reflected from the darkened disk on to an annular photo-cell, thus generating a photo-cell current corresponding to the degree of darkening. This current is then indicated on the 0-10 scale of the microammeter.

The evaluating intrument does not have to be carried along during the actual test. The darkened filter paper disks can be examined afterwards in the laboratory or the workshop. When using

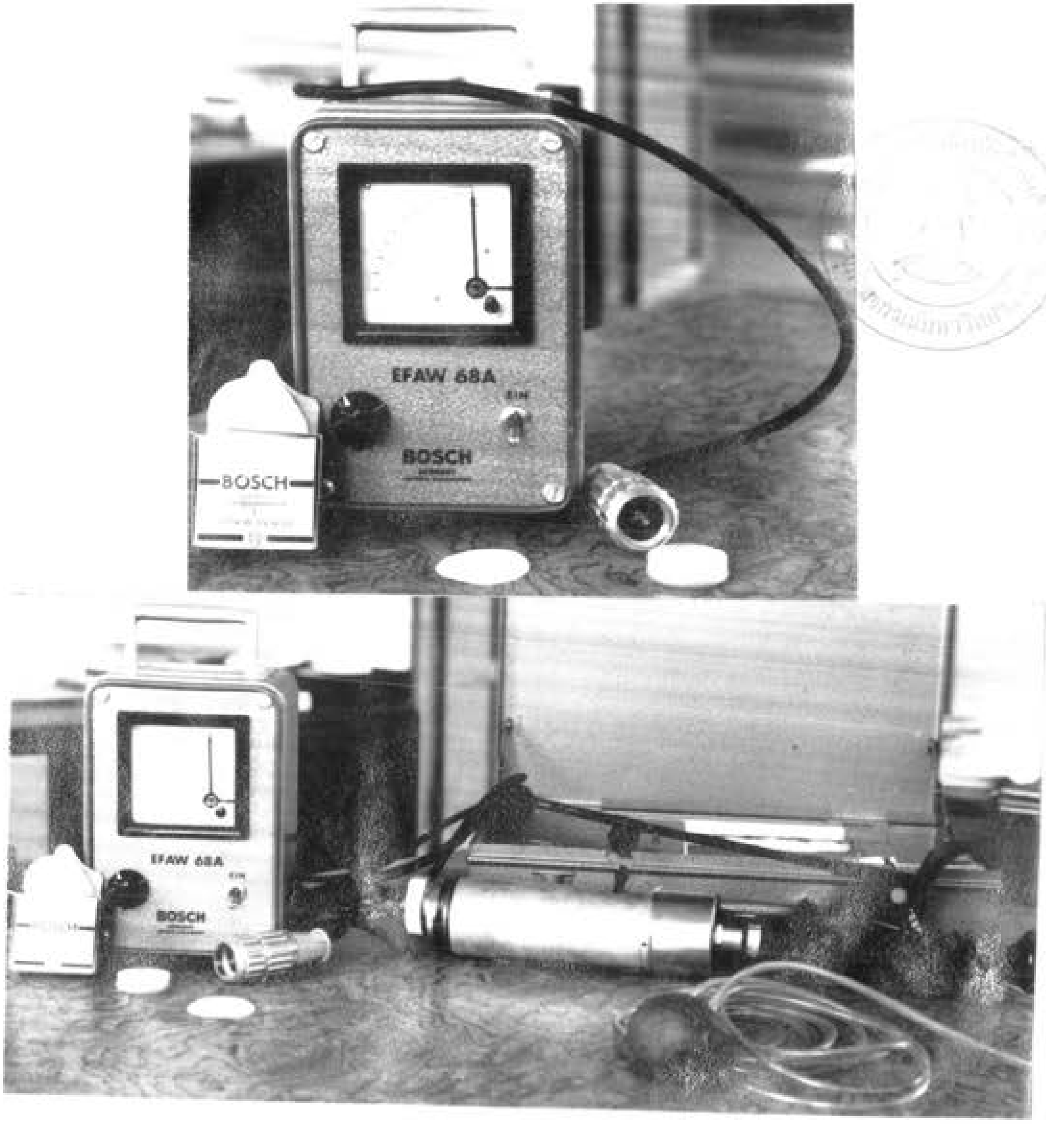

Fig. 15

Bosch Smokemeter

several accessory cases with sampling pump, only one evaluating instrument is required.

3. THE ORSAT ANALYSIS

This experiment covers the technique of the analysis of exhaust of flue gases by the Orsat apparatus and computations of weight of exhaust gased and weight of air supplied.

There are five principal constituents usually found in flue or exhaust gas, viz., carbon dioxide, oxygen, carbon monoxide, nitrogen, and water vapor. Under some conditions hydrogen and hydro-carbons may be present in important quantities, and there may also be traces of sulphur dioxide and trioxide. Usually the five man constituents give a sufficiently accurate indication of combustion conditions. The carbon dioxide Content alone gives a rough approximation of these conditions.

The Orsat is the standard apparatus for the analysis of flue gases from furnaces and of exhaust gases from internal-combustion engines. Recording CO_2 machines and steam-flow air-flow meters may be used, but in setting and calibrating these instruments the engineer again resorts to the Orsat apparatus.(Fig. 16)

The Orsat analysis is made by successively absorbing CO_2, O_2, and CO from the flue-gas sample. The remainder is reported as nitrogen. From this analysis may be calculated the weight of flue gases per pound of carbon burned, and if the fuel analysis and temperature of combustion products are available also, all the gas heat losses may be calculated. These losses include the sensible heat of the dry exhaust gases, the losses due to moisture

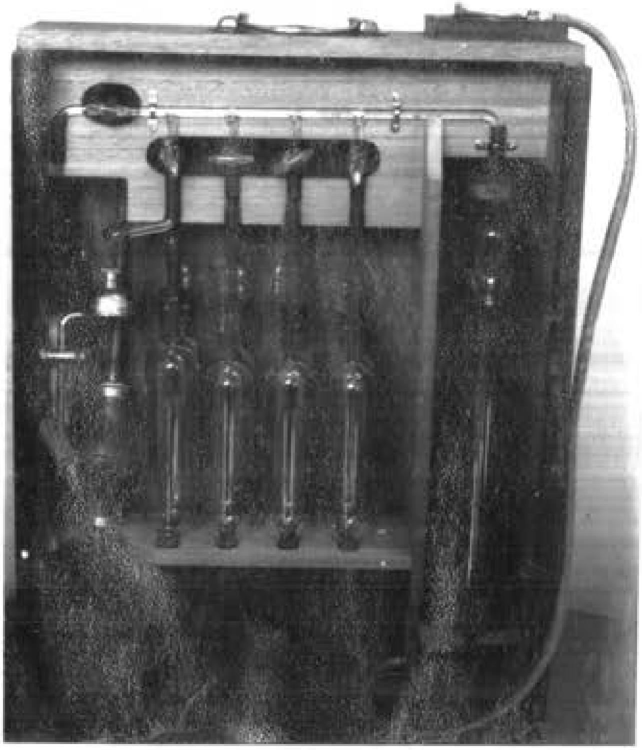

Fig. 16

The Orsat Analysis

in the exhaust gases, and the loss due to unburned carbon monoxide. (In rare cases there may be a loss due to unburned hydrocarbons, and this cannot be determined from the simple Orsat analysis.)

The evaluation of the Bosch and the Hartridge apparatus.

1. That the Bosch apparatus is much cheaper and lighter than the Hartridge.

2. That the Bosch apparatus is much easier to use on the test bed than on the road but that its response in practice is slow.

3. When a comparison is made between the two apparatus used to measure the smoke density of engines running at constant speed; the results given by the Bosch apparatus show variations which are still tolerable even it sometimes troublesome, while the Hartridge apparatus gives results which are reproducible with an accuracy of the order of 2 to 3 per cent for each smoke density level, provided measurements are made on smoke which is really of the same density. (Tests made simultaneously with different apparatus, fed by different probes, placed in the same exhaust system).

4. The Bosch apparatus is not designed to make continuous measurements or measurements at rapidly varying speeds. The Hartridge apparatus allows measurements to be made under widely differing engine conditions and its response is very quick.

5. The Hartridge apparatus as modified allows measurements of exhaust smoke under reduced dynamic pressure.

Correlation of Bosch and Hartridge scales.

Measurement of smoke densities has evolved along different lines in Germany and in Great Britain and it was only to be expected that different scales have been used in these two countries. For mutual understanding it is indispensable to determine what correlation can be found between the two scales.

Comparative tests of various methods.

If is comparatively simple to correlate the readings of different types of smoke-meter but it is a very different matter to establish a relationship between the smoke outputs of an engine working under different sets of conditions.

4. H.P.A. CHASSIS DYNAMOMETER

HPA Chassis Dynamometers can be used for many different purposes. (Fig. 17) Of the large scope of possibilities only a few should be mentioned here: measuring the maximum tractive force, the fuel consumption, as well as the maximum road gradient which the vehicle can surmount. Then, control of the speedometer and the odometer, checking the fuel pump and the lubrication system, as well as mechanical noises and tapping in the engine, gear box, clutch, cardan joint, transmission, etc.; slip of the clutch-examination of automatic gears and different kinds of fuel. Further, vacuometer tests with varying loads.

Through the driving wheels of the vehicle the tractive force is transmitted to a roller set consisting of the measuring roller which is a water-brake and the supporting roller. Both the

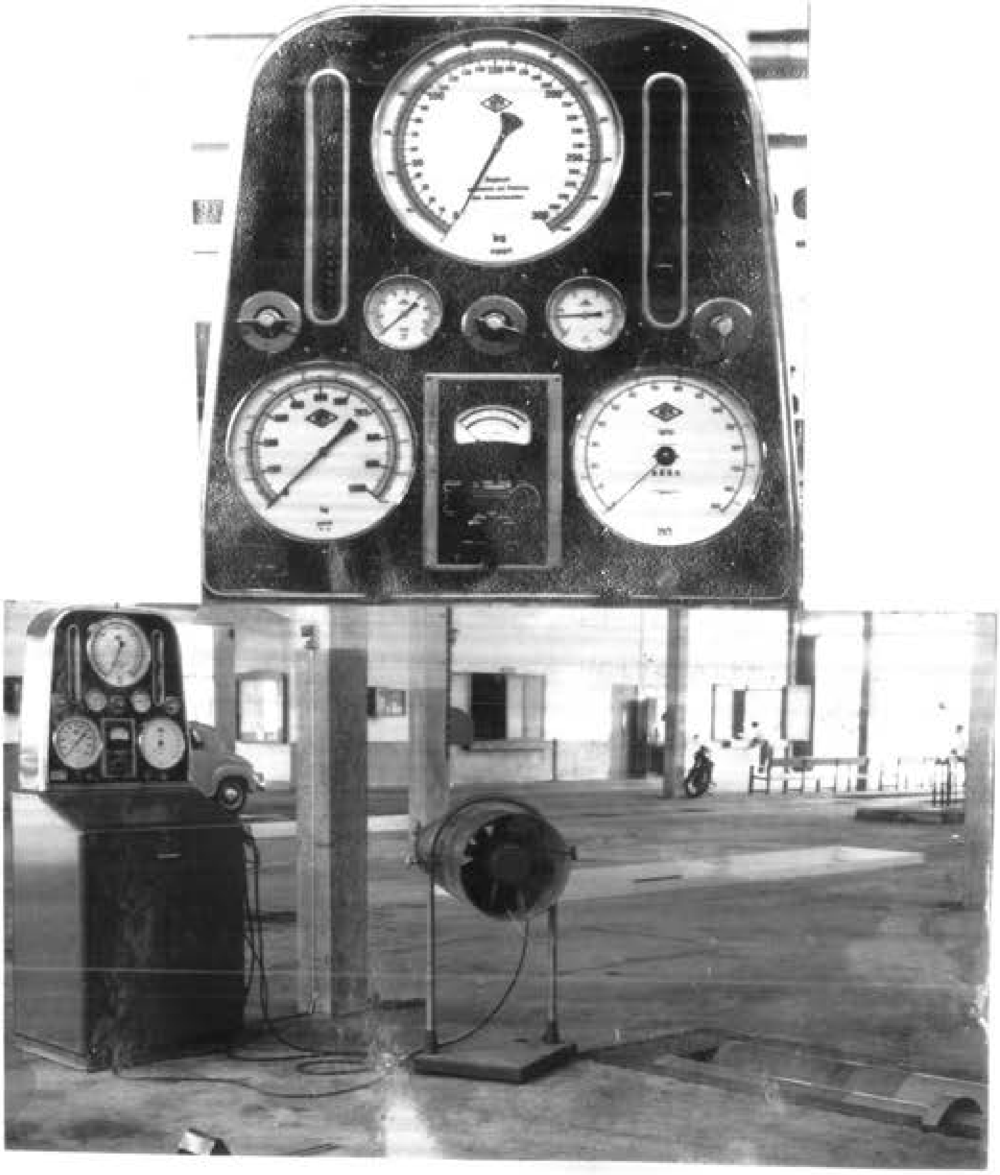

Fig. 17

H.P.A. Chassis Dynamometer

measuring roller and the inside stator are equipped with tightly-spaced shovels which can just pass each other when the roller is rotating. By loading water into the space between rotor and stator a resistance will be built up under rotation. This resistance can be adjusted from Zero to several hundreds of horse powers and consequently any conceivable road condition may be imitated.

The load water is circulating in a so-called closed system, i.e. the water which has been heated in the water-brake circulates throught a radiator placed below the supporting roller from where the cooled water returns to the water-brake.

The hydraulic load is regulated by varying the amount of water in the dynamometer. Two solenoid valves,controlled by push buttons allow water to flow at a constant rate to or from the drums. A steady increase in water flow to the drums uniformly increases the resistance of the drum, and similarly a steady decrease in water from the drums, uniformly decreases the resistance of the drum.

This arrangement enables the driver, who operates the engine throttle, also to operate the change in tractive force at a predetermined rate. Maximum tractive force, at any selected gear ratio, can be determined by loading until tire slip, unsteady conditions and a fall in tractive load occurs. The time to obtain maximum tractive force can be measured. This can be taken as 100 % loading and hence, by timing, 25, 50, 75 % loading can be obtained (Fig.20)

5. Strobotac Electronic Tachometer.

This was used to measure the engine speed. It was placed with the light flashing on the starting handle end of shaft.

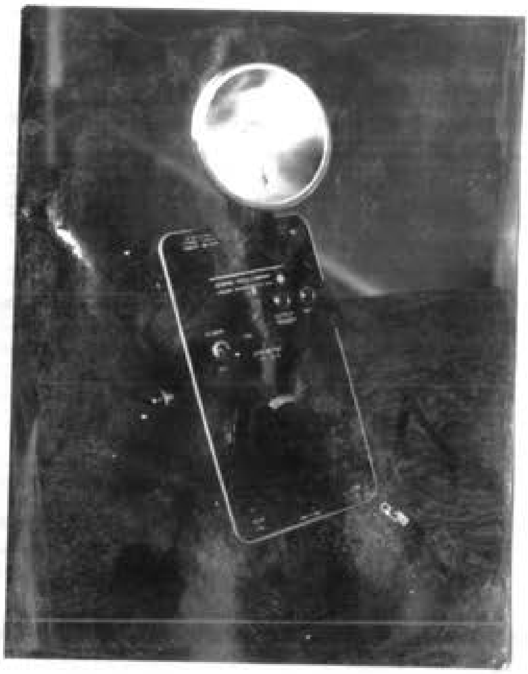

Fig. 18

Strobotac Electronic Tachometer

Fig. 19

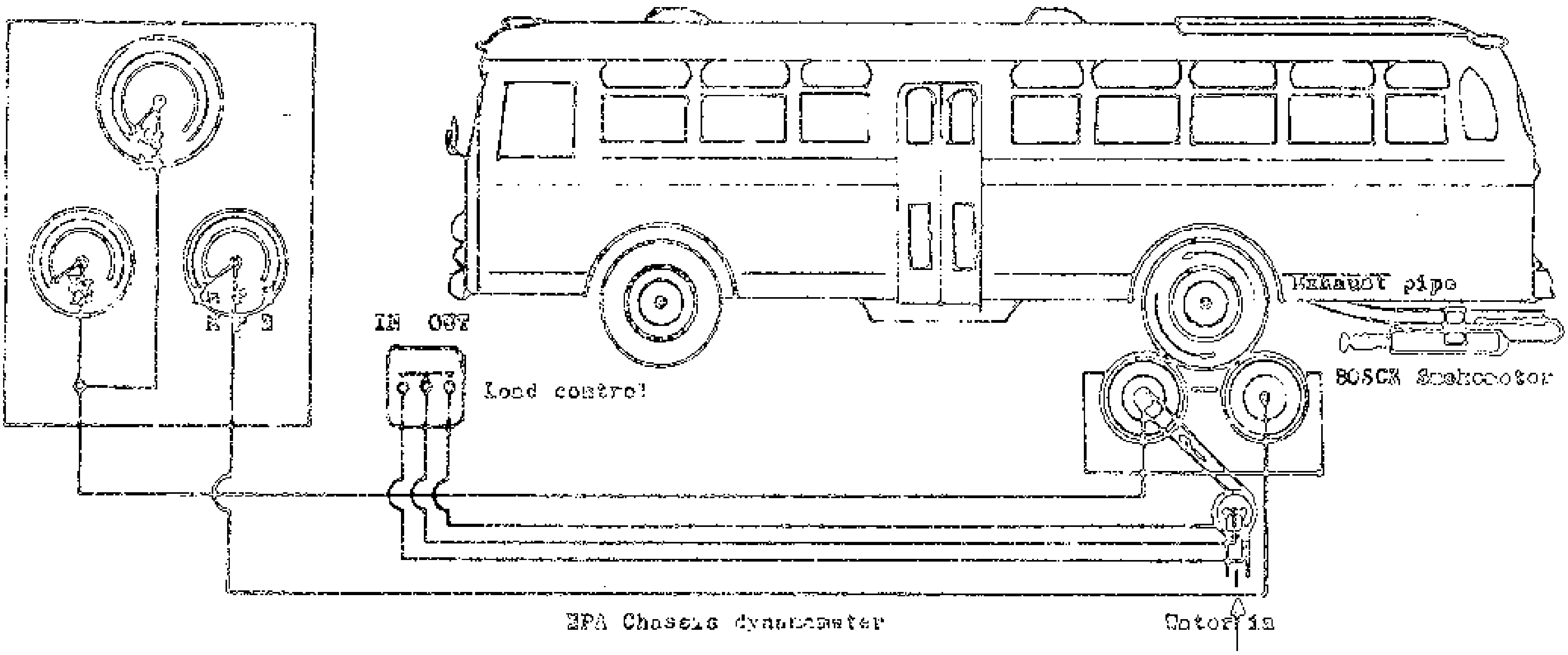

Fig.20 Schematic diagram of experimental apparatus

Experimental Procedure

Choice of test conditions

The aim is to establish the acceptable smoke density and carbon-monoxide content in exhaust gases from a bus engine. By testing new engines at maximum engine speed up to the maximum tractive force, combustion conditions are such as to indicate the greatest smoke density and largest CO content to give an ultimate standard of comparison. Two new buses were selected one with a four stroke engine, the other with a two stroke engine.

Buses that have been in service for a period, and older engines, will have a poorer performance so that, knowing the best that can be obtained from a new engine a value can be assessed that is acceptable for buses in service. Any value below this indicates that service must be carried out. (Fig.28,30)

The sequence of procedure in each experiment (Fig. 19 and 20) was as follows:-

a. The engine is run for a period of time until the water and lubricating oil have been brought to definite operating temperatures.

b. Reading the engine speed from the Strobotac Electronic tachometer by setting the frequency of the internal oscillator. This control is concentric with the range switch mark and is rotated by means of its fluted rim. The dial is calibrated directly in revolutions per minute.

c. Reading on the scales of HPA. Chassis Dynamometer the tractive force in pounds is transmitted to a roller-set consisting of the measuring roller which is a water-brake and the supporting roller. The load is regulated by leading more or less water into the brake system. This is done by means of two solenoid valves controlled by the push buttons IN and OUT of the contact box. Started from zero, 25,50,75,and 100 percent of load in each experiment as shown in data table and the speed of vehicle from speedometer (bottom right) works with great precision in MPH.

d. Reading off the percentage of the Carbondioxide, Oxygen, and carbon monoxide. The percentage in each case is indicated by the difference between the volume of the gas after being pass into the pipette and the volume obtained when making the determination of the gas in the burette from the Orsat apparatus for each load test.

e. Reading of smoke density is recorded on the scale of the Hartridge BP. Smokemeter, and the Evaluating Bosch Smokemeter Instrument for each load test.

Sample of Calculation

The horsepower required to overcome total tractive resistance, being directly proportional to the resistance and the velocity, can be computed from the equation

$$HP. = \frac{lb. \times ft}{33,000} = \frac{R_t \times V}{375}$$

in which R_t = total tractive resistance force in pounds.
and V = the velocity of the vehicle in miles per hour.
at 50 % hydraulic loading, $R_t = 380$ lb. $V = 50$ MPH.

$$\text{HP. at driving wheel} = \frac{380 \times 50}{375} = 50.6$$

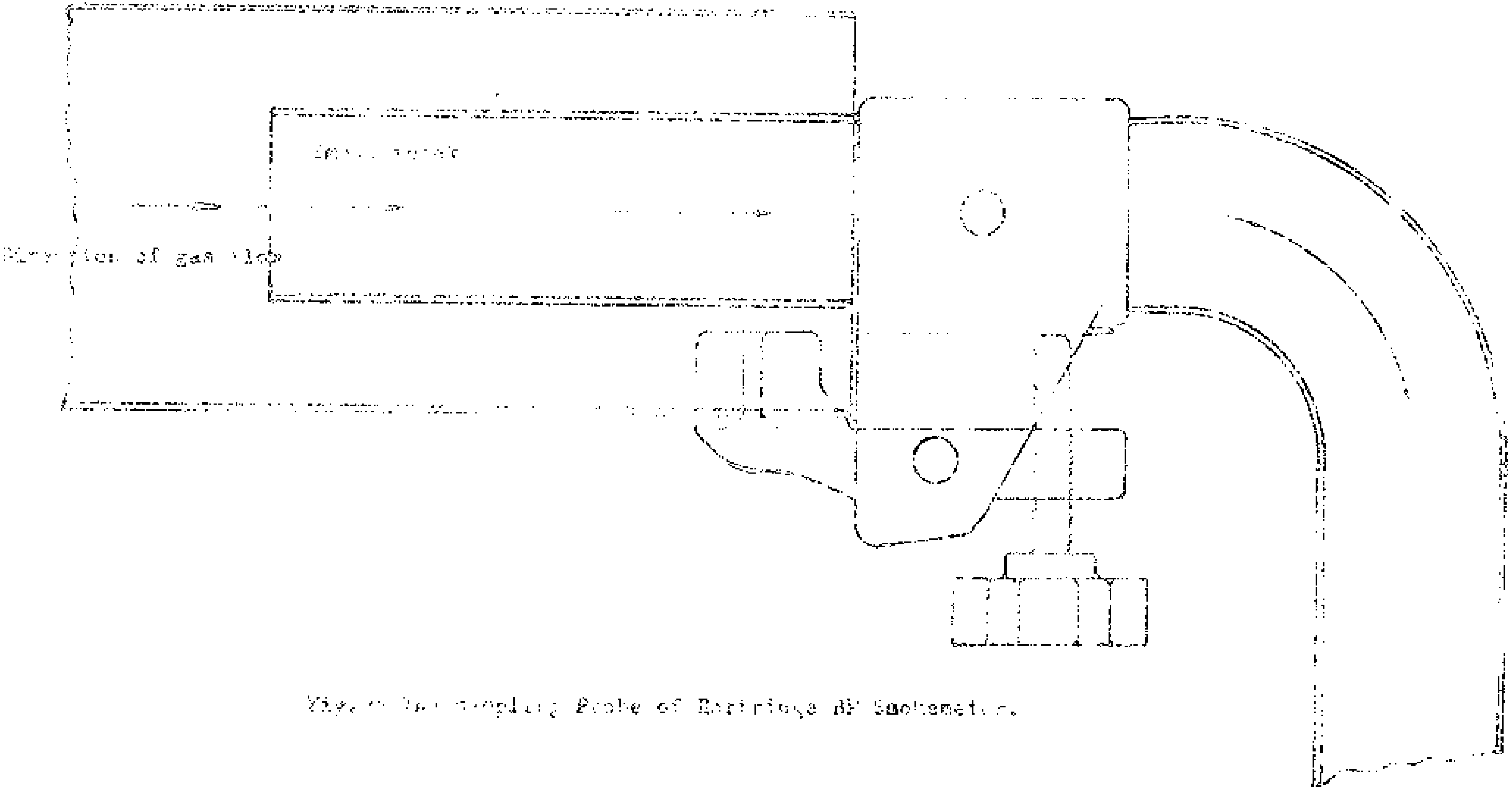

Fig. [illegible] Gas Sampling Probe of Hartridge BP Smokemeter.

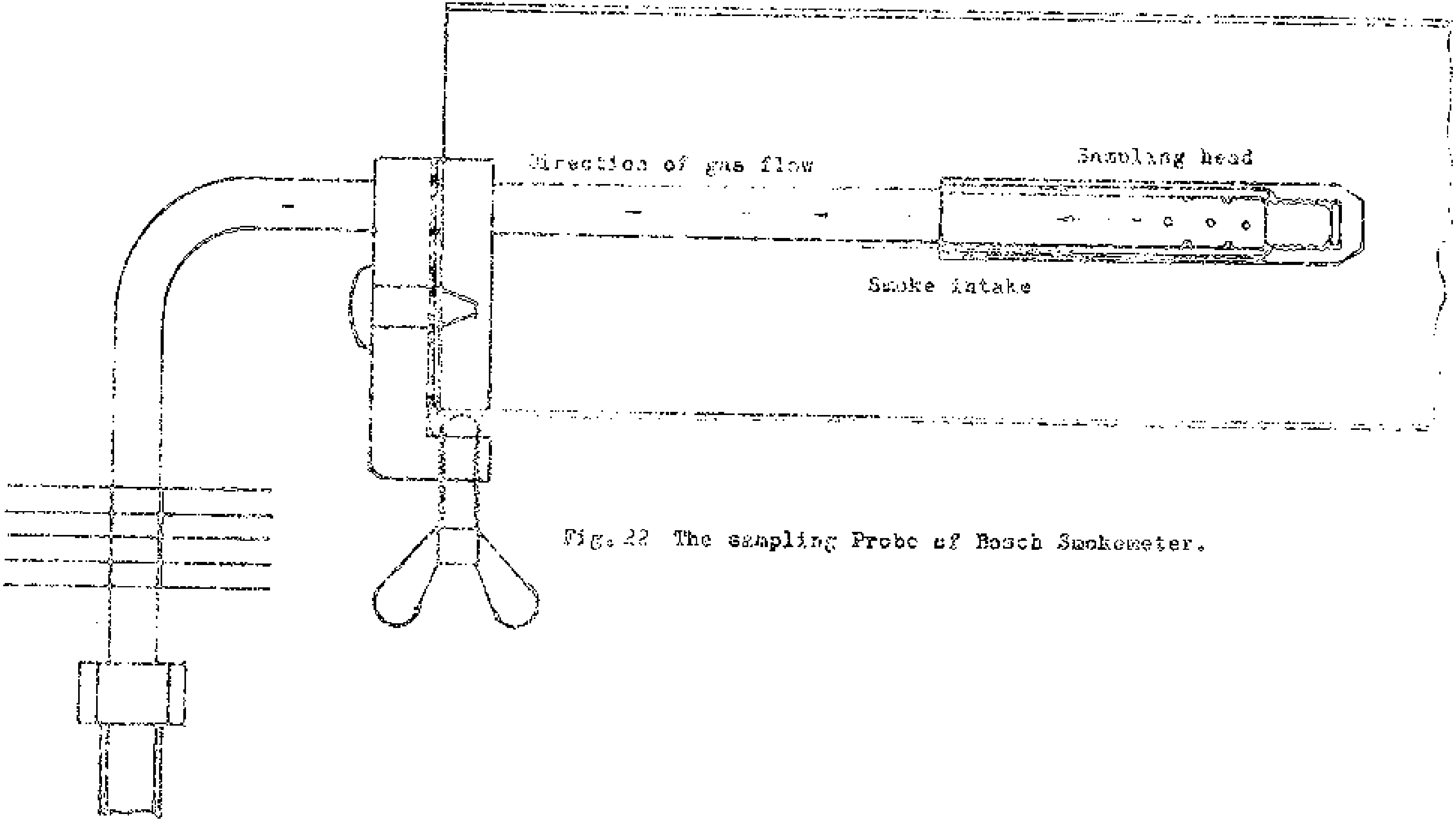

Fig. 22 The sampling Probe of Bosch Smokemeter.

Table 7 Variable Load for 4 Strokes, 6 Cylinders
Water cooled, Diesel engine on 5th Gear

No. of testing	Hydraulic Loading %	Engine speed RPM.	Scale readings		HP.	Gases in %			Smoke density in %	
			Speed MPH.	Tractive Force lb.		CO_2	O_2	CO	Bosch	Hartridge
1	0	2400	50	20	2.6	2.0	16.5	0.2	9	9.1
2	25	2400	50	225	30.0	3.9	16.5	0.5	17	17.2
3	50	2400	50	380	50.6	5.4	16.0	0.7	24	23.9
4	75	2400	50	485	64.6	6.4	15.5	0.8	28	28
5	100	2400	50	525	70.0	6.8	14.0	0.9	30	30.1

Table 8 Variable Load for 2 Strokes, 3 Cylinders
Water cooled, Diesel engine on 5th Gear

No. of testing	Hydraulic Loading %	Engine speed RPM.	Scale readings		HP.	Gases in %			Smoke density in %	
			Speed MPH.	Tractive Force lb.		CO_2	O_2	CO	Bosch	Hartridge
1	0	2400	56	15	2.2	1.5	17.5	0.1	6	6
2	25	2400	56	160	24.0	2.0	16.9	0.4	18	18.1
3	50	2400	56	290	43.2	2.6	16.1	0.7	27	27.2
4	75	2400	56	400	59.6	3.4	14.9	0.9	33	32.9
5	100	2400	56	480	71.6	4.4	13.0	1.0	35	35.2

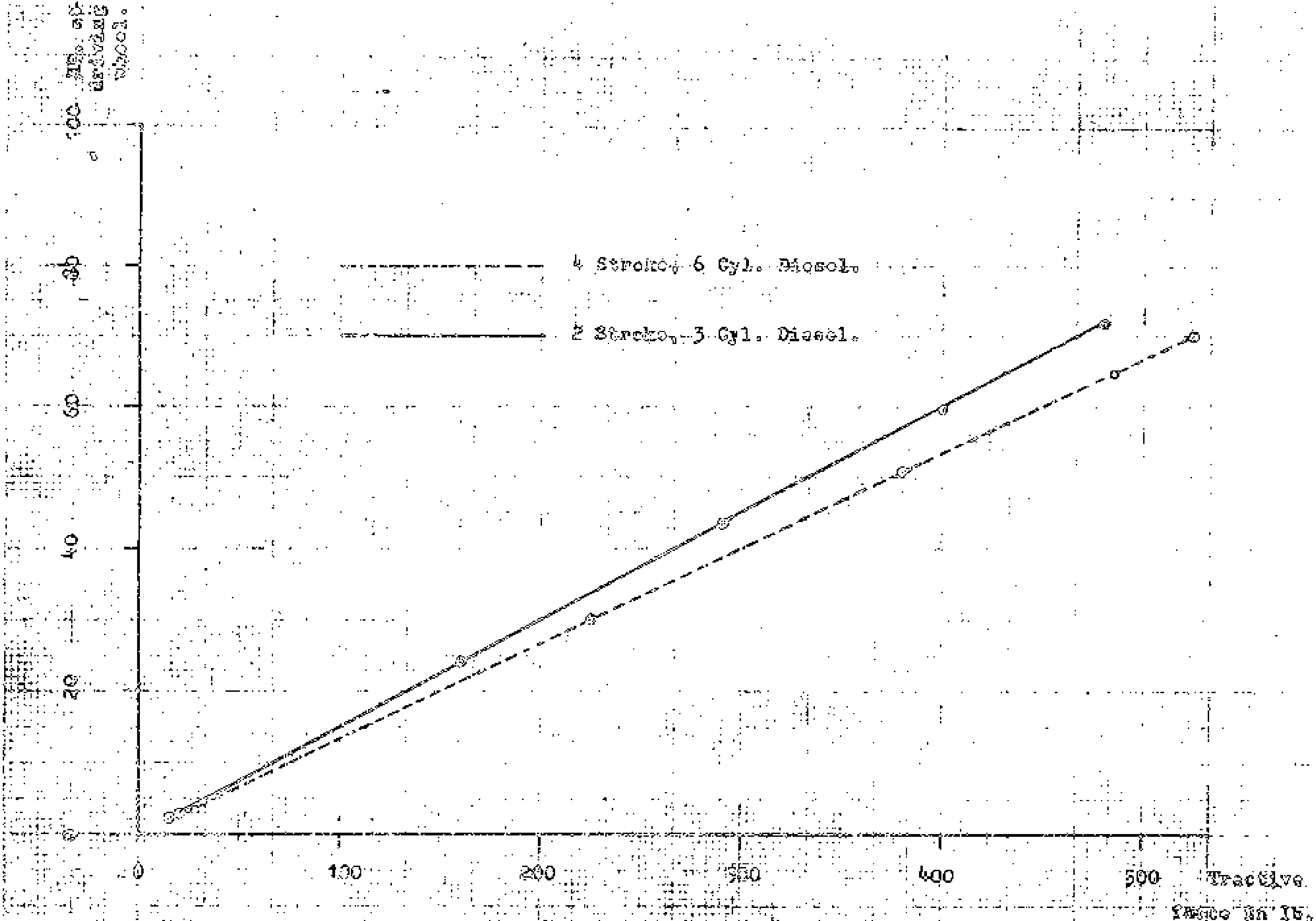
HP. at
driving
wheel.
100
80
60
40
20
0
4 Stroke, 6 Cyl. Diesel.
2 Stroke, 3 Cyl. Diesel.
0
100
200
300
400
500
Tractive
Force in lb.

Fig. 23

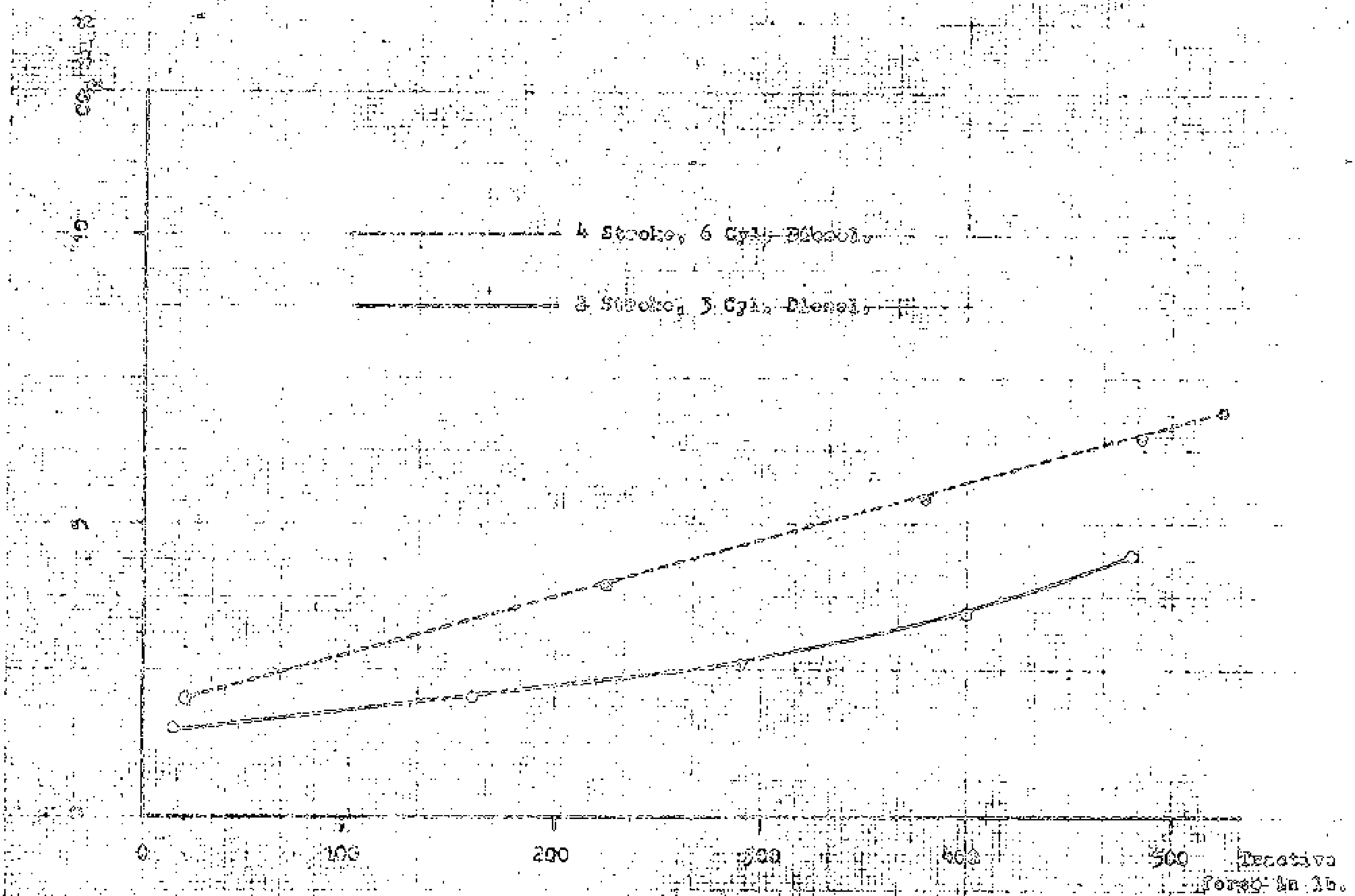
4 Stroke, 6 Cyl. Diesel.
2 Stroke, 3 Cyl. Diesel.
0
100
200
300
400
500
Tractive Force in lb.

Fig. 24

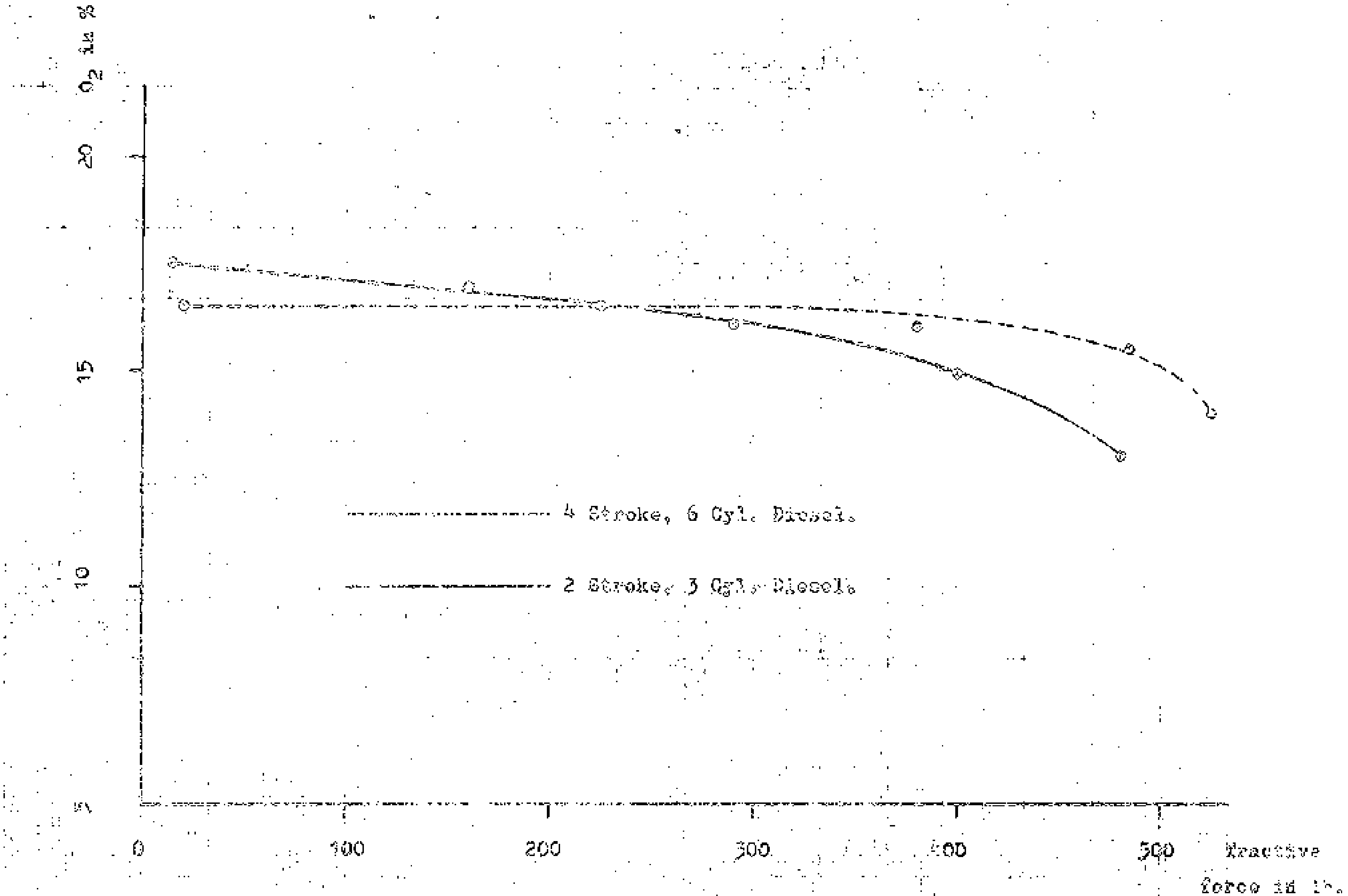
O2 in %
20
15
10
5
0
100
200
300
400
500
Tractive force in lb.
4 Stroke, 6 Cyl. Diesel.
2 Stroke, 3 Cyl. Diesel.

Fig.25

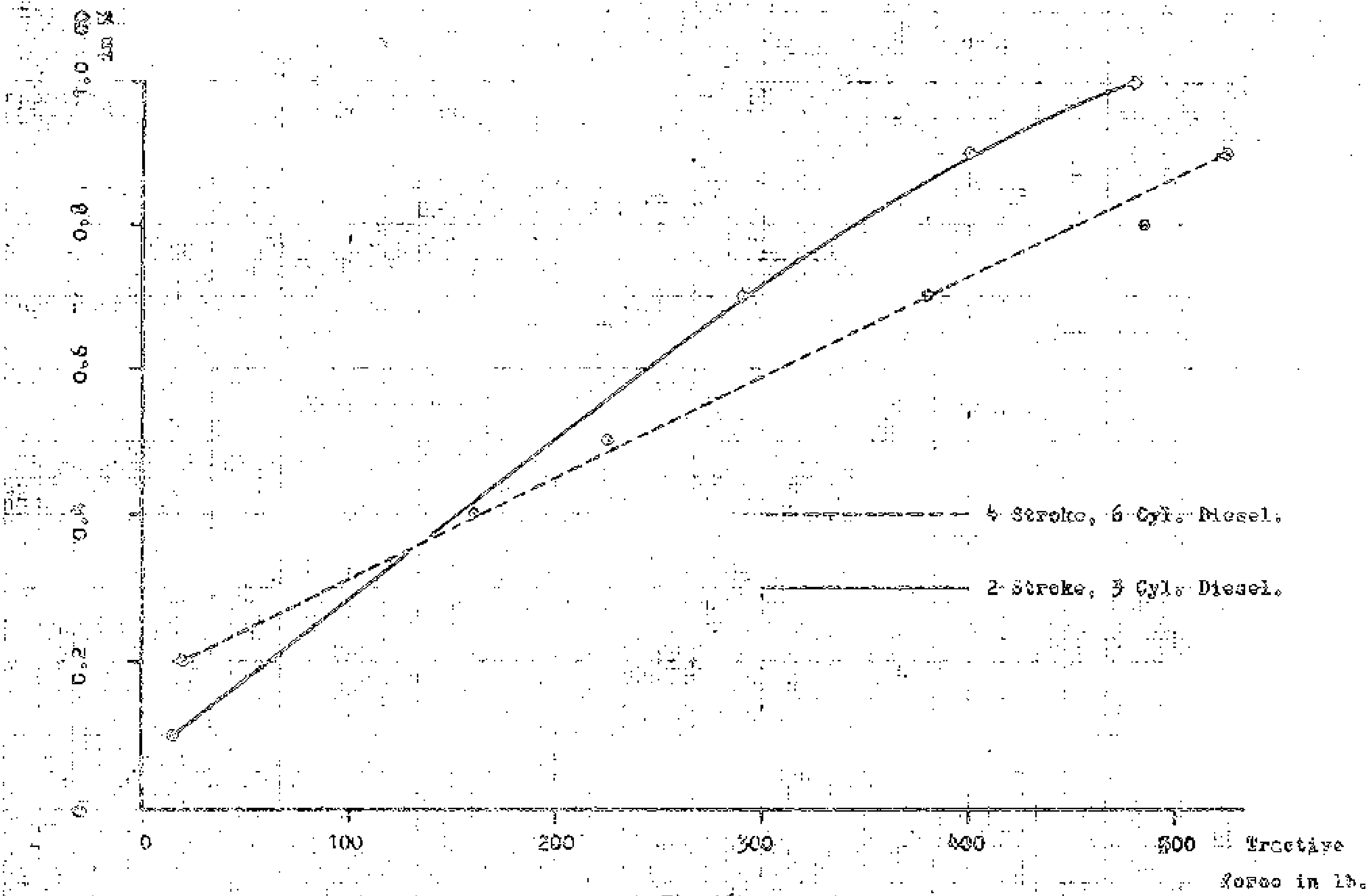
1.0
in %
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
Tractive
force in lb.
4 Stroke, 6 Cyl. Diesel.
2 Stroke, 3 Cyl. Diesel.

Fig.26

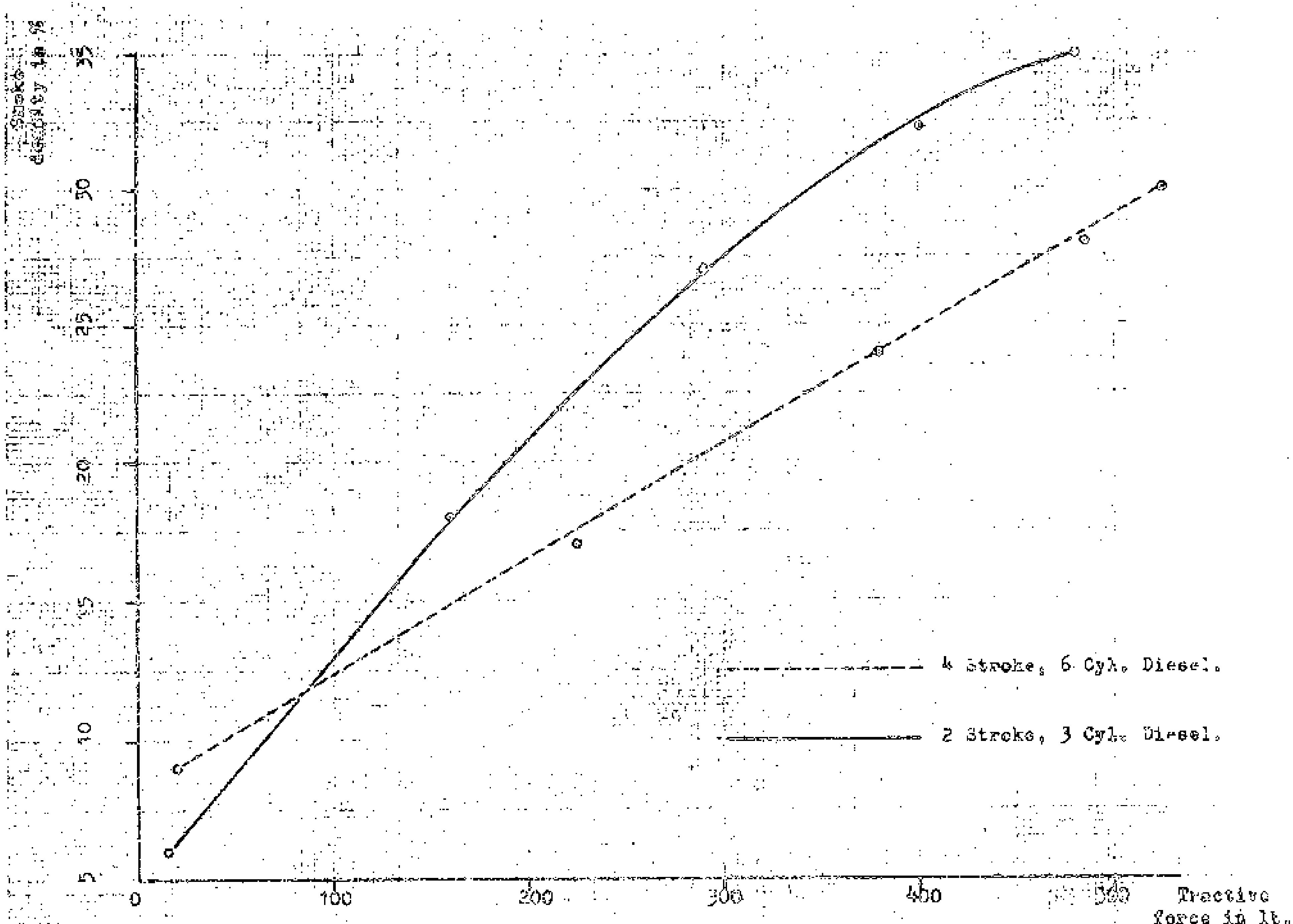
Smoke density in %
35
30
25
20
15
10
5
0
100
200
300
400
500
Tractive force in lb.
4 Stroke, 6 Cyl. Diesel.
2 Stroke, 3 Cyl. Diesel.

Fig.27

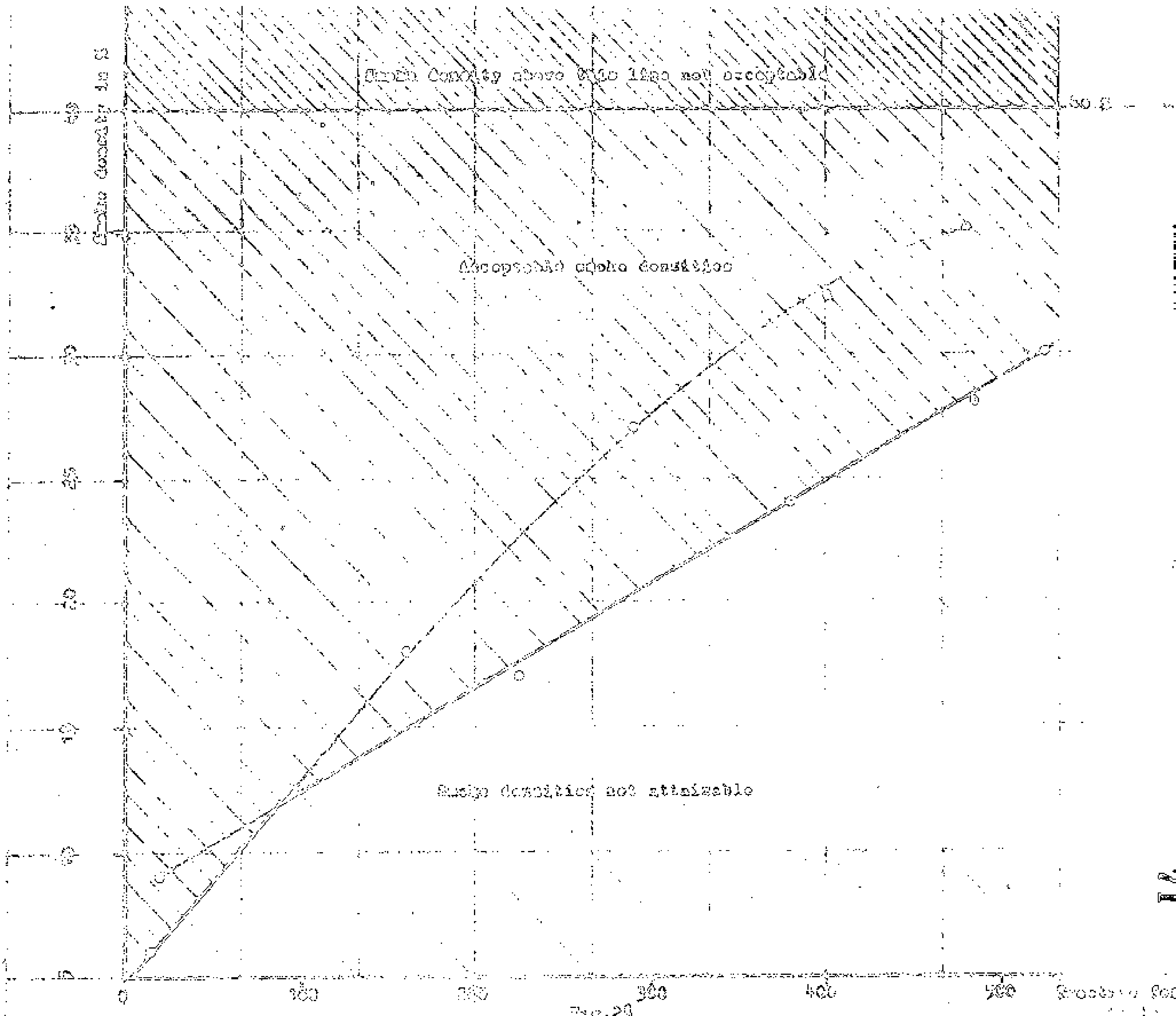Sludge density above this line not acceptable
30 %
Acceptable sludge densities
Sludge densities not attainable
10
0
100
200
300
400
500

Fig.28

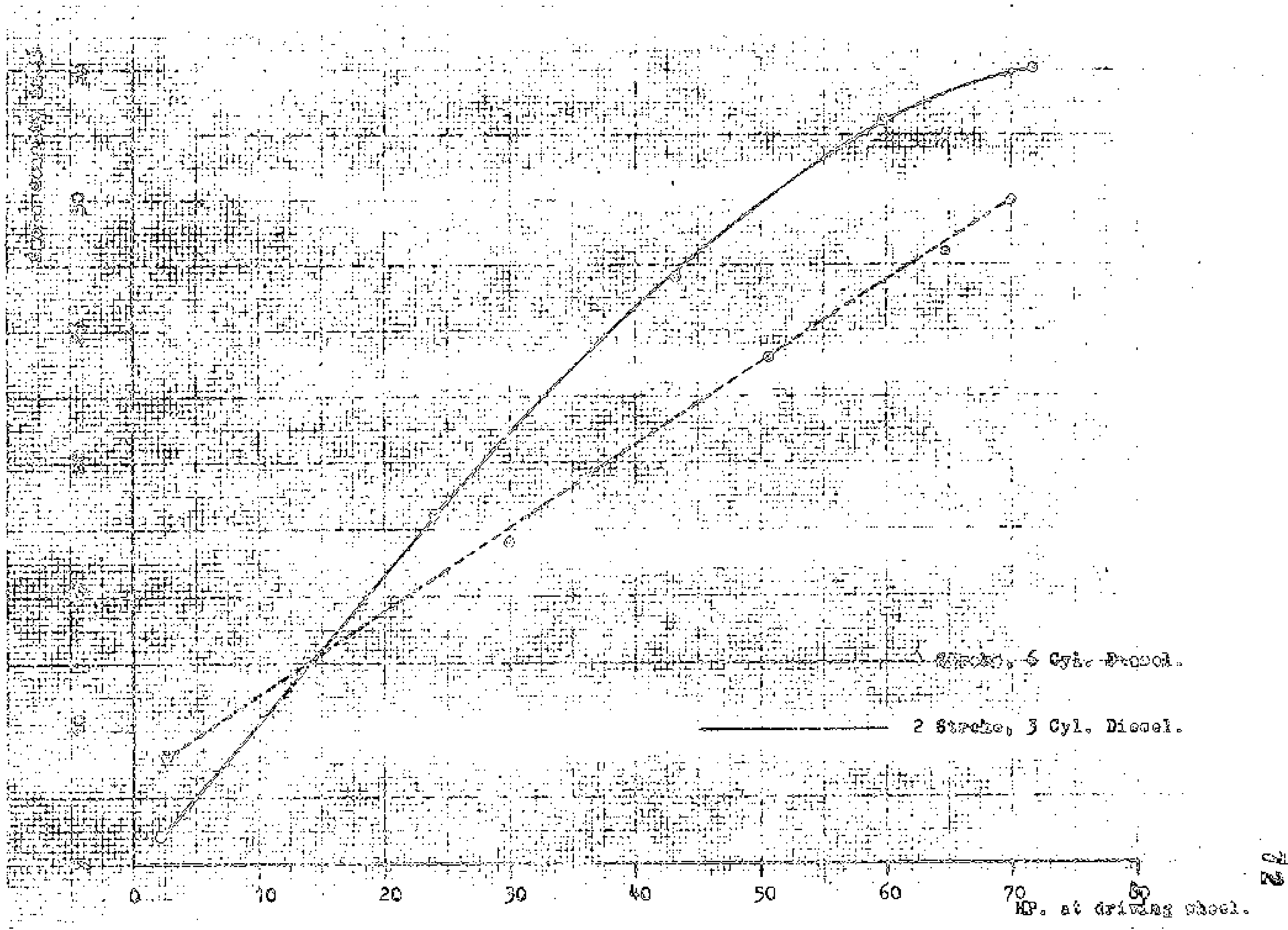
4 Stroke, 6 Cyl. Petrol.
2 Stroke, 3 Cyl. Diesel.
0
10
20
30
40
50
60
70
80
HP. at driving wheel.

Fig. 29

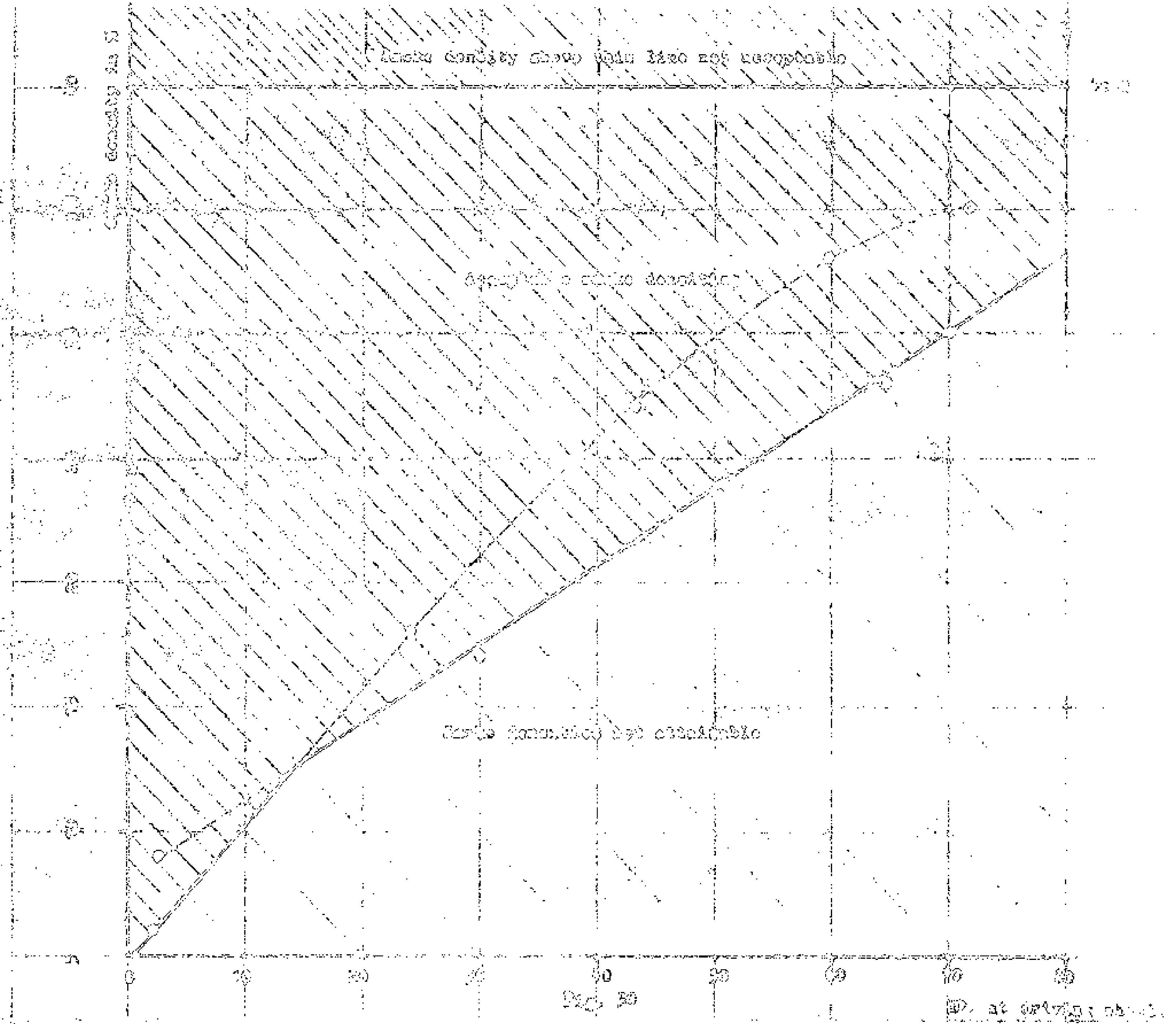
Cable density above this line not acceptable
Cable density in %
Acceptable cable densities
Cable densities not attainable
0
10
20
30
40
50
60
70
80

Fig. 30

CONCLUSIONS.

Despite the favorable conditions for completing combustion in the normal operating range of the Diesel engines tested, products of incomplete combustion were present in the exhaust gases, although the concentration of such products generally was low and could be determined only by sensitive methods of gas analysis. It is important to have a knowledge of the products of incomplete combustion during the combustion process in the Diesel engine. The analysis of the products of incomplete combustion may be a guide toward a better understanding of the Diesel process. From a practical point of view these products are one of the biggest problems in Diesel development.

The products of incomplete combustion observed in the exhaust gases of the two engines and discussed in the following are Smoke density and carbon monoxide.

The concentration of Smoke density was worst in the two stroke engine,and at full load giving meter reading of 35 %. A generally acceptable value of smoke can be taken as 40 %;above this service is required. (Fig.28 and 30)

Despite such low concentrations of carbon monoxide it was observed that the concentration of this gas was affected not only by load but also by engine design.

The control of CO is difficult,but since it increases as the smoke density increases,the control of smoke density will give adequate control of the CO. Concentration can therefore be given solely to smoke density control.

It is unfortunate that the smoke is not readily visitle to the driver and some instrumentation such as a light showing on the instrument panel when 40 % smoke density (Bosch or Hartridge standard) is produced. At the present time regular test services must be carried out in garages. In the case of some older engines the maximum governed speed should be reduced.

Further work must be carried out make the exhaust conditions evident to the driver. He would then know that the vehicle required service.