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FUEL RESEARCH INSTITUTE OF SOUTH AFRICA

ONDERWERP:
SUBJECT: REDUCING SMOKE EMISSION BY DIESEL ENGINES

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REDUCING SMOKE EMISSION BY DIESEL ENGINES

SUMMARY

When a diesel engine is operated on diesel oil at a high altitude, as on the Highveld, it is in most cases impossible to obtain the rated output without heavy smoke emission.

If, however, a part of the diesel oil is replaced by a more volatile liquid fuel like petrol or alcohol, mixed with the air aspirated by the engine, full load may be obtained with a clear exhaust.

1. INTRODUCTION

When a diesel engine is loaded beyond a certain capacity, the injected fuel is burnt incompletely and a black smoke, containing carbon particles and other incompletely burnt products, is emitted. The primary cause is that the engine can aspirate no more than a fixed volume of air and consequently only a definite quantity of fuel, of the order of 1/20 to 1/25 (by mass) of the air quantity, can be burnt completely.

It is thus obvious that if the altitude at which the engine operates is increased, the mass of the air induced into the cylinder and consequently also the quantity of fuel which can be burnt, becomes less and the power which can be generated diminishes. The manufacturer's output data generally refer to conditions prevailing at sea level. If the engine has to operate on the Highveld, the rated output cannot be attained without appreciable smoke generation. If this is to be avoided, the engine has to be derated by limiting the maximum quantity of fuel injected into the cylinder at each working stroke. As a result, the maximum power which can be generated is some 15 to 20% below the rated output at sea level. Thus a 45 kW (say, 60 h.p.) engine will only generate 36 to 38 kW in Johannesburg or Pretoria.

Earlier experiments (reported in Technical Memoranda Nos. 24 and 45 of 1972)

indicated/...

indicated that if a portion of the diesel oil is replaced by liquefied petroleum gas (LPG) or methane, the load at which objectionable smoke generation occurs is increased appreciably, and that even on the Highveld the rated output is approached closely with a clean exhaust.

Apart from the fact that in the Republic the use of LPG for this purpose is prohibited now and that methane is not widely available, the use of these fuels is rather cumbersome and also requires fairly expensive additional equipment.

It was therefore investigated whether these gases could be replaced by a more amenable substance, such as a reasonably volatile liquid fuel, likewise admitted at the engine's air intake. Experiments indicated that this was entirely feasible.

2. TECHNICAL CONSIDERATIONS

Earlier experiments had indicated that the test engine could operate smokelessly on diesel fuel when the air/fuel ratio exceeded the stoichiometric value (of approximately 15 : 1) by a factor of the order of 1,35 to 1,4; but that this factor could be reduced to 1,2 when dual-fuel operation (with LPG) was practised. It was anticipated that replacing LPG by petrol would yield comparable results. In this context, reference may be made to figure No. 5*, which shows that in this range the emission of carbon monoxide is low and much less than that of the conventional Otto or spark-ignition engine, which normally operates in the 13 : 1 to 14 : 1 range. The diesel engine, however, emits more nitrogen oxides. This emission could be reduced by operating with leaner mixtures in the range 19 : 1. This, however, would have a slight adverse effect on the efficiency and would increase the emission of hydrocarbons. Apart from their smell, however, this emission is generally considered to be relatively harmless.

In the present experiments, the air/diesel fuel ratio was increased to approximately 25 : 1, at which the engine operates without visible smoke emission, but the output is appreciably reduced. Petrol, or some other

suitable/...

* This diagram appears in a publication by K.C. Salooja in Jnl. of Fuel & Heat Technology, Vol. 19, 2, March 1972.

suitable liquid fuel (like ethyl or methyl alcohol, benzine, paraffin) was then admitted to the air induced into the engine by means of a carburettor-like arrangement mounted on the air-intake port, as illustrated in figure No. 1.

The air/fuel ratio at the intake was generally in the range 60 : 1 to 90 : 1. This mixture is too lean to ignite spontaneously during the subsequent compression in the cylinder. In fact, such an ignition would be most undesirable since the fuels concerned have too low a knock rating to stand the compression ratios commonly prevailing in diesel engines, i.e. 16 : 1 or higher.

Ignition occurs only when the diesel oil is injected, and then proceeds in an orderly manner without knock or detonation, and continues to virtual completion. The result is that notwithstanding the smaller mass of air aspirated by the engine at a high altitude, sufficient fuel can be admitted (and burnt without an objectionable emission of smoke and pollutants) to restore the output almost to the value obtained at sea level.

3. TEST EQUIPMENT

The engine used in the experiments was a Ford "Trader" truck engine of which the relevant particulars are given in Table No. 3.

The apparatus illustrated in figure No. 1 was mounted on the air-intake manifold of the engine. The petrol supply in this case was by gravity from a tank installed at a higher level. Photographs A, B, and C further illustrate the equipment.

4. EXPERIMENTAL PROCEDURE

The engine was installed on a test bed equipped with a dynamometer and the normal equipment for measuring engine speed, torque, and fuel consumption. The smoke density was measured by a Bosch Smoke Meter (cf. Appendix A), and an infra-red analyser was used to monitor the CO concentration in the exhaust gas.

The behaviour of the engine on diesel oil only was studied first. In these test runs, the engine was operated at the maximum power permitted by the excursion of the control rod (constant during each test run) governing the

quantity/...

quantity of oil injected per stroke of the injection pump and the timing of the instant of fuel injection, expressed in degrees before top dead centre (^{o} B.T.D.C.).

Thereafter, the engine was run on the dual-fuel system, again varying the control rod travel and injection timing, and adjusting the petrol flow rate. Although a lead-free petrol was used in these tests, a normal commercial regular-grade petrol will serve equally well.

The main test data are presented in Tables Nos. 1 and 2, and figure No. 2.

5. DISCUSSION OF TEST RESULTS

5.1 OPERATION ON DIESEL OIL ONLY:

Diesel oil only was admitted to the engine in tests A, B, and C (cf. Table No. 2). The rated performance figures for the engine are:

Torque	209 Nm	at	1500 r.p.m.
Output	47 kW	at	2500 r.p.m.

The data for test A show that with the pump stop set at 11,5 mm, which causes unacceptable smoke emission, these figures are not quite approached. In addition, the efficiency was rather low.

Reducing the pump delivery by setting the stop at 8 mm reduced the smoke density to the level of 3 to 3,5, which in practice is not noticeable in the case of a small to medium sized engine; cf. data for tests B, Table No. 2. The output, however, is 20 to 25% less than that obtained in test A, although a good efficiency was achieved.

In the tests C, the pump delivery was further reduced by setting the stop at 7,5 mm. This resulted in a further reduction in the emission of pollutants and of the power. In fact, this mixture is unduly lean, which is reflected by a decrease in the brake efficiency. This adjustment was, however, used for setting the basic oil supply for the dual-fuel tests. Inclusion of the data for this operating condition is consequently expedient.

5.2/...

5.2 DUAL-FUEL OPERATION:

Tests D and E were run under virtually identical conditions, except for the ambient temperature. In test D, this temperature was 21,1^{o}C, a fairly usual figure for Pretoria. In test E, the temperature was 15,8^{o}C, which is rather below the average. In this last test, the volumetric efficiency was consequently somewhat higher than in test D, and the power generated and emission of pollutants were slightly less.

The torque generated at medium speed slightly exceeded the rated level, and the output at approximately 2500 r.p.m. was virtually the same as in test A (i.e. 6% below the rated value at sea level), while smoke emission, of the order of 3,5 to 4,5 on the Bosch scale, is not, or hardly, noticeable.

As the air/fuel ratio during tests D and E was in the range 18 : 1 to 20 : 1, it may be expected that the NO emission was also lower than during test A; cf. Appendix A. The fact that the exhaust temperatures during tests D and E were consistently and appreciably lower than in test A also provides an indication in this direction.

Only in respect of CO emission is dual-fuel operation inferior to that on diesel oil only, but still appreciably better than that of the Otto (spark ignition) engine, where the CO concentration of the exhaust gas is seldom below 2% and frequently exceeds 4%.

With the present arrangements, the quantity of petrol supplied to the engine during the dual-fuel tests was virtually independent of the engine speed; only the quantity of diesel oil was altered. Consequently, the proportion of petrol was highest at low engine speeds, where it was of the order of 35%, and decreased to roughly 20% at the highest speed. The maximum admissible amount of petrol is set by a tendency towards knocking. During the experiments reported here this was not observed, although at lower speeds (near 1000 r.p.m.) knocking appeared to be imminent.

5.3 MODIFICATIONS:

In the lay-out described here, the fuel requirements below a certain load are met by diesel oil only. While this is entirely satisfactory for an engine always operating at, or near, its maximum load, as on the test bed,

this/...

this may not be the case when the engine operates under widely fluctuating conditions. This will be the case when the engine operates a vehicle, tractor or earth-moving equipment.

With the following modification the engine can be supplied with both fuels over a wider range and in more constant proportions:-

The petrol orifice is provided with a tapered metering rod linked to the accelerator, or alternatively, a small butterfly valve, similarly linked, is installed in the inner venturi, as indicated in figure No. 3. A float chamber, as used in the conventional carburettor, could also be installed.

In this manner a roughly constant petrol/diesel oil ratio could be maintained over a wider range of loads and speeds. This ratio would presumably be of the order of 1 : 2, but would depend on the type of engine and its mode of operation and duty cycle. Some experience would obviously have to be gained in tests under actual operating conditions, with the complete system as illustrated in figure No. 4.

5.4 CONCLUSION:

Operating the diesel engine on a dual-fuel system where both diesel oil and lower boiling range fuels are used, achieves the following objectives:

(i) A reduction in the emission of pollutants.

(ii) An increase in the engine output, without smoke generation.

(iii) An extension of the range of fuels upon which the diesel engine can be operated.

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G.A.W. VAN DOORNUM
CHIEF RESEARCH OFFICER.

PRETORIA.
18th June, 1974.

GAWvD/OvR.

TABLE NO. 1 **TEST RESULTS**

Test No.	Fuel	Engine speed r.p.m.	Torque Nm	Output kW	Fuel Cons. g/kWh	A/F ratio	Diesel oil %	CO %	Smoke No.	Brake Efficiency %	Petrol Cons. g/min	Exhaust Temp. °C
A	D	1274	203	27,1	311	15,8	100	0,1	8,9	25,2	-	495
B	D	1247	157	20,5	248	26,7	100	0,08	3,0	31,5	-	350
C	D	1282	139	18,7	260	27,4	100		2,7	30,3	-	330
D	DP	1266	216	28,6	254	18,2	65,3	0,5	4,6	30,7	42	
E	DP	1276	218	29,1	256	18,6	66,1	0,4	3,6	30,4	42	450
A	D	1543	201	32,9	316	15,5	100	0,1	8,5	24,8	-	530
B	D	1527	161	25,7	252	24,8	100	0,1	3,1	31,2	-	385
C	D	1535	149	23,9	251	26,3	100		2,6	31,3	-	390
D	DP	1536	212	34,1	252	18,6	66,5	0,55	4,5	30,9	42	515
E	DP	1524	212	33,3	254	18,9	66,0	0,4	3,8	30,6	42	475
A	D	1804	197	37,2	322	15,4	100	0,1	8,7	24,4	-	580
B	D	1813	156	29,7	264	23,6	100	0,12	3,4	29,7	-	430
C	D	1817	152	28,9	255	24,7	100		2,8	30,8	-	440
D	DP	1802	208	39,3	253	18,3	74,1	0,55	4,8	30,7	43	560
E	DP	1809	201	38,8	258	18,9	74,3	0,5	3,9	30,2	43	550
A	D	2035	184	39,3	396	14,8	100	0,1	9,0	23,9	-	620
B	D	2026	153	32,4	268	23,4	100	0,13	3,4	29,3	-	475
C	D	2030	142	30,2	267	24,9	100		2,5	29,4	-	465
D	DP	2024	199	42,1	255	18,8	76,0	0,5	4,4	30,5	43	590
E	DP	1991	193	40,2	266	19,0	75,8	0,4	3,6	29,4	43	575
A	D	2326	179	43,7	339	15,2	100	0,1	8,3	23,1	-	680
B	D	2223	147	34,2	275	23,3	100	0,15	3,6	28,5	-	495
C	D	2266	134	31,7	284	24,3	100		2,4	27,7	-	495
D	DP	2290	181	43,5	270	19,0	77,6	0,4	4,3	28,8	44	610
E	DP	2293	182	43,6	271	19,7	77,7	0,3	3,3	28,7	44	600
A	D	2536	168	44,6	347	15,9	100	0,1	7,8	22,6	-	750
B	D	2495	136	35,4	293	23,3	100	0,15	3,2	28,5	-	515
C	D	2457	127	32,7	299	24,4	100		2,3	26,3	-	525
D	DP	2525	168	44,5	283	19,5	79,0	0,3	4,0	27,6	44	635
E	DP	2497	168	44,0	288	19,7	78,7	0,3	3,3	27,1	45	625

Remarks: D in Fuel column denotes: diesel oil only used. DP: dual-fuel operation.
Fuel consumption and A/F (Air/Fuel) Ratio refer to total fuel supply, diesel oil + petrol.

TABLE NO. 2

FURTHER DATA PERTAINING TO TESTS

Diesel Oil: Cal.Val. 45,8 MJ/kg Normal Commercial Product

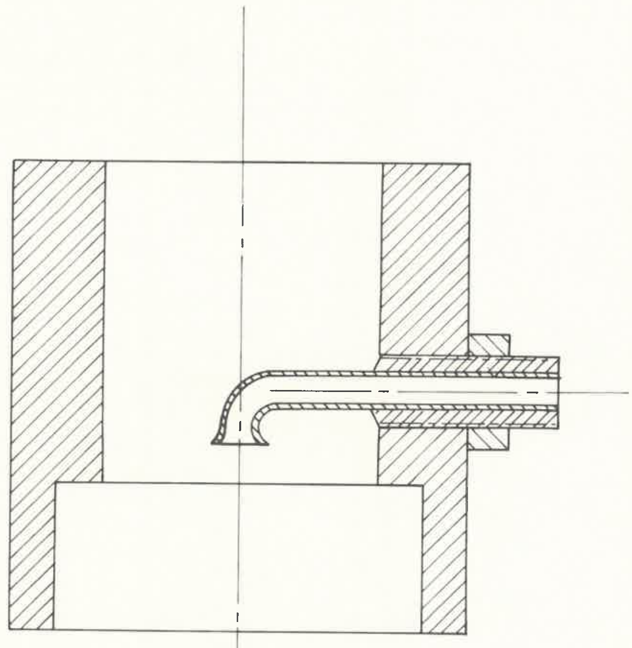
Petrol: Cal.Val. 46,9 MJ/kg lead-free petrol

Test		Inject. Timing °BTDC	Pump Stop mm	Barometer mm Hg	Amb. Temp. °C	Humidity %	Petrol Jet mm
No.	Reference						
A	Ia Rep	23	11,4	651,5	23,0	30	-
B	VI	23	8	654,4	21,6	30	-
C	IVa	23	7,5	654,7	25,8	45	-
D	IV - 13	23	7,5	655,3	21,2	30	0,40
E	IV - 10	23	7,5	655,0	15,8	30	0,40

TABLE NO. 3

SPECIFICATIONS OF TEST ENGINE

Make and type	Ford "Trader"
Engine No.	500 E 38026
No. of cylinders	4
Bore	100 mm
Stroke	115 mm
Engine capacity	3,611 litres
Compression ratio	16 ÷ 1
Rated output	47 kW (64 h.p.) at 2500 r.p.m.
Rated torque	209 N.m (154 ft.lb) at 1500 r.p.m.



PETROL SPRAY NOZZLE
IN AIR INTAKE PIPE

FIGURE 1

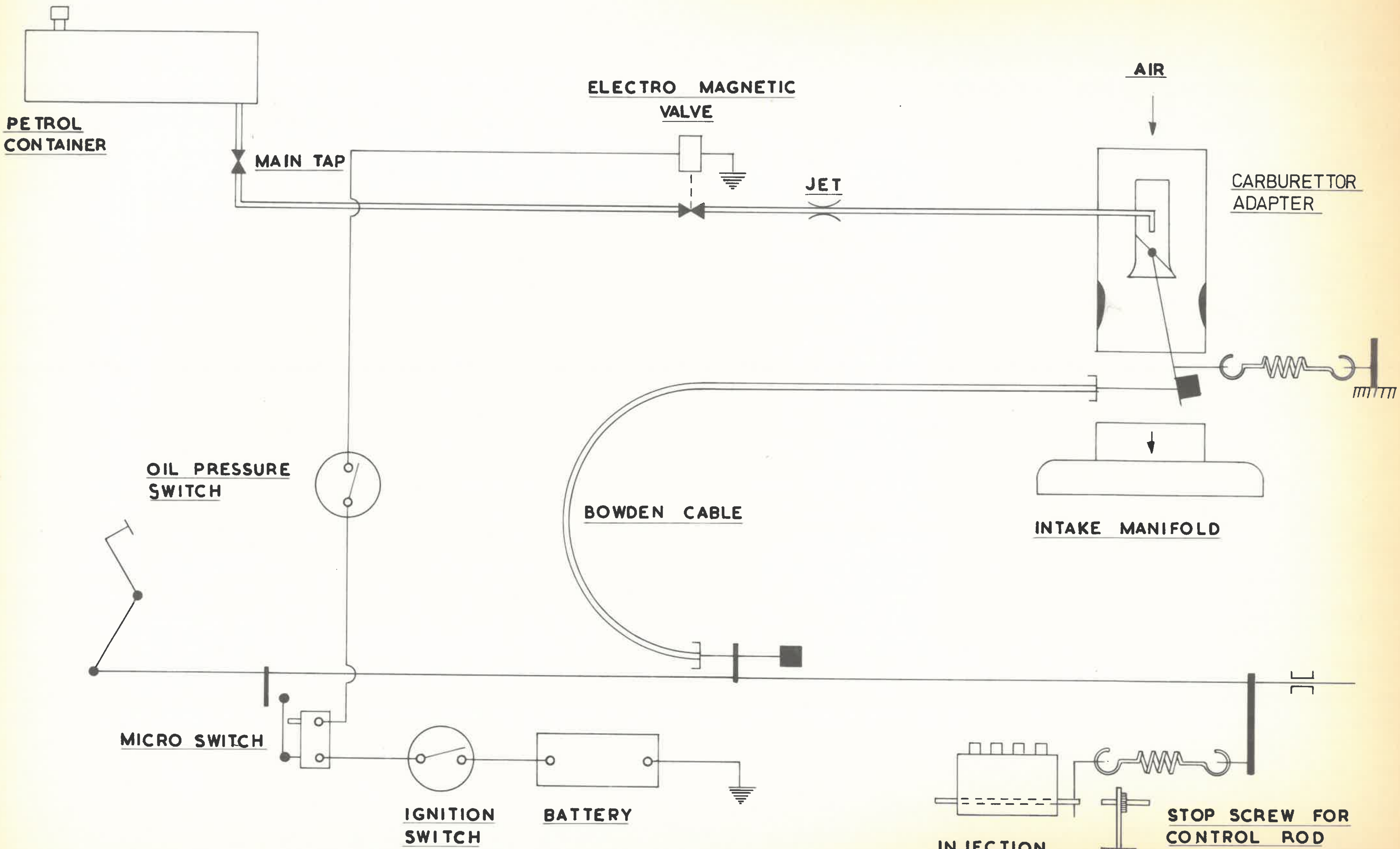

PETROL
CONTAINER
MAIN TAP
ELECTRO MAGNETIC
VALVE
JET
AIR
CARBURETTOR
ADAPTER
OIL PRESSURE
SWITCH
BOWDEN CABLE
INTAKE MANIFOLD
MICRO SWITCH
IGNITION
SWITCH
BATTERY
INJECTION
PUMP
STOP SCREW FOR
CONTROL ROD

FIGURE 3

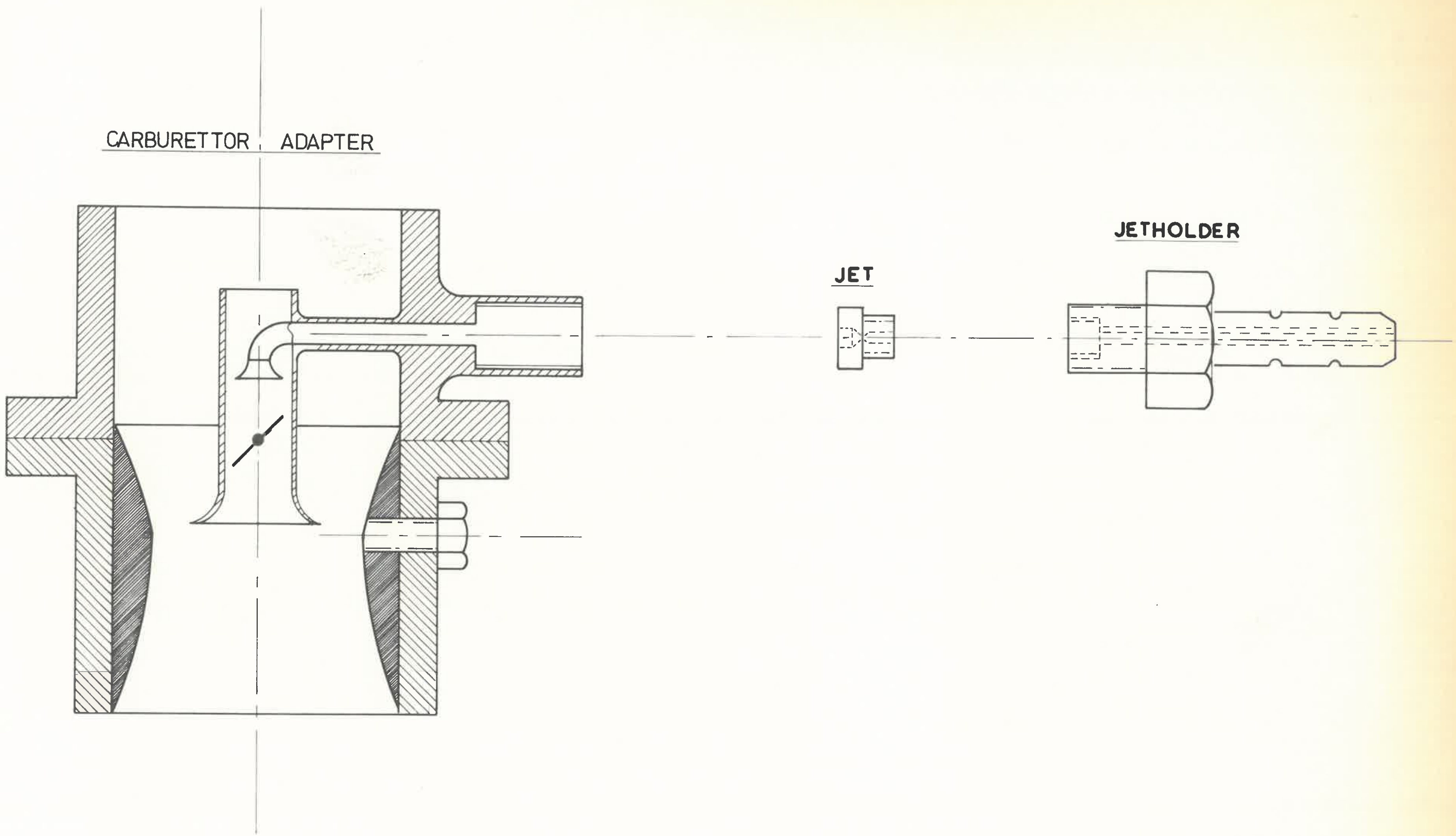
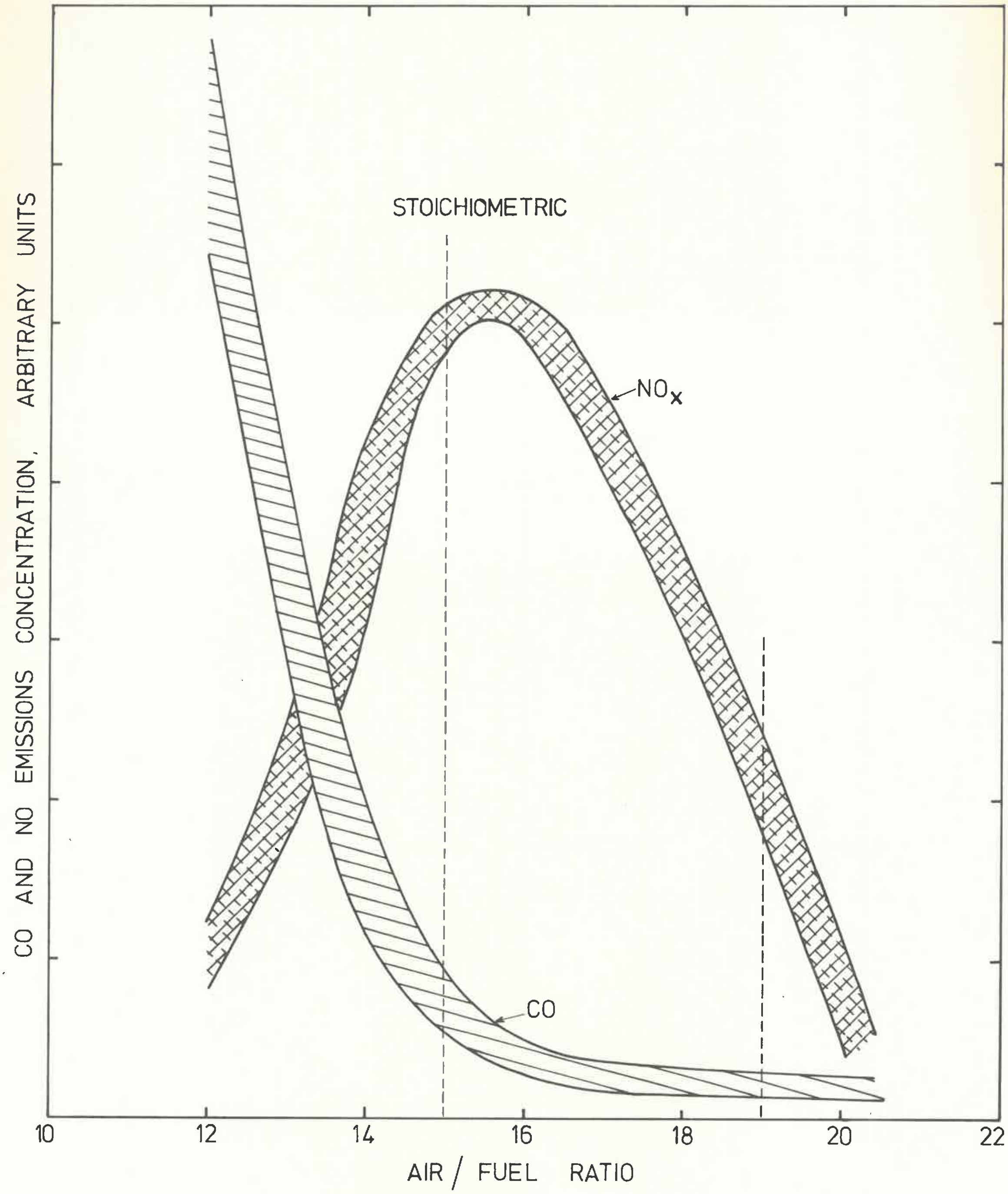


FIGURE 4

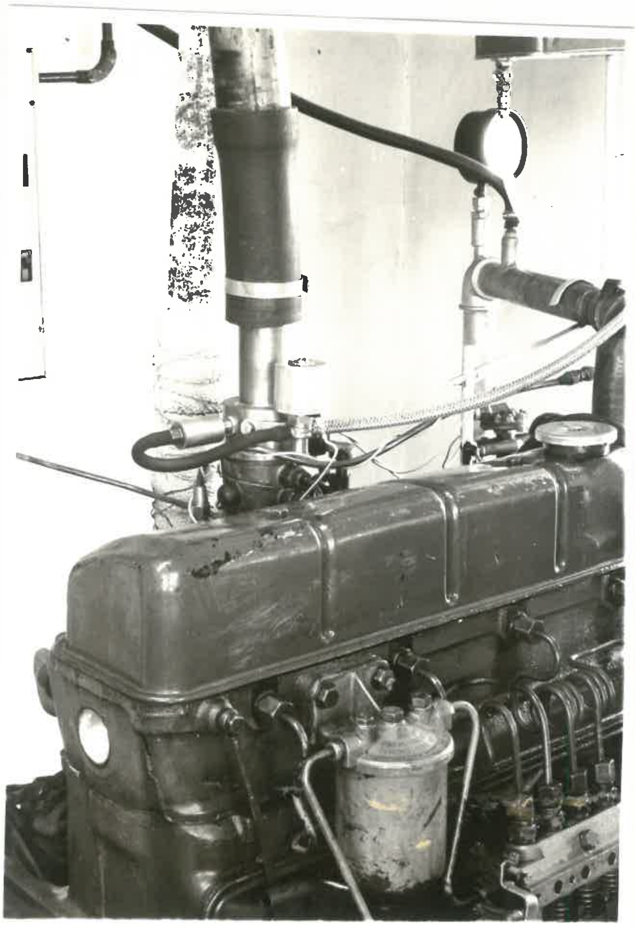


EFFECT OF AIR FUEL RATIO ON EXHAUST EMISSIONS.

(AFTER SALUOJA, JNL. FUEL & HEAT TECHNOLOGY, VOL. 2 , MARCH 1972)

FIGURE 5

A. DETAILS OF EQUIPMENT USED FOR PETROL ADMISSION.



B. EQUIPMENT AS MOUNTED ON DIESEL ENGINE, WITH SOLENOID VALVE.

A P P E N D I X

THE BOSCH SMOKE METER

This instrument was used for the determination of the exhaust smoke density. The operation is as follows:-

A gas sample, always of the same volume, is drawn through a disc of filter paper on which the soot or tarry matter, emitted with the exhaust gas, is then deposited. A grey to black deposit is thus formed on the paper. The shade or density of the deposit is then determined by a photometer supplied with the smoke sampler, and is expressed as a number in the range 0 (clear) to 10 (black).

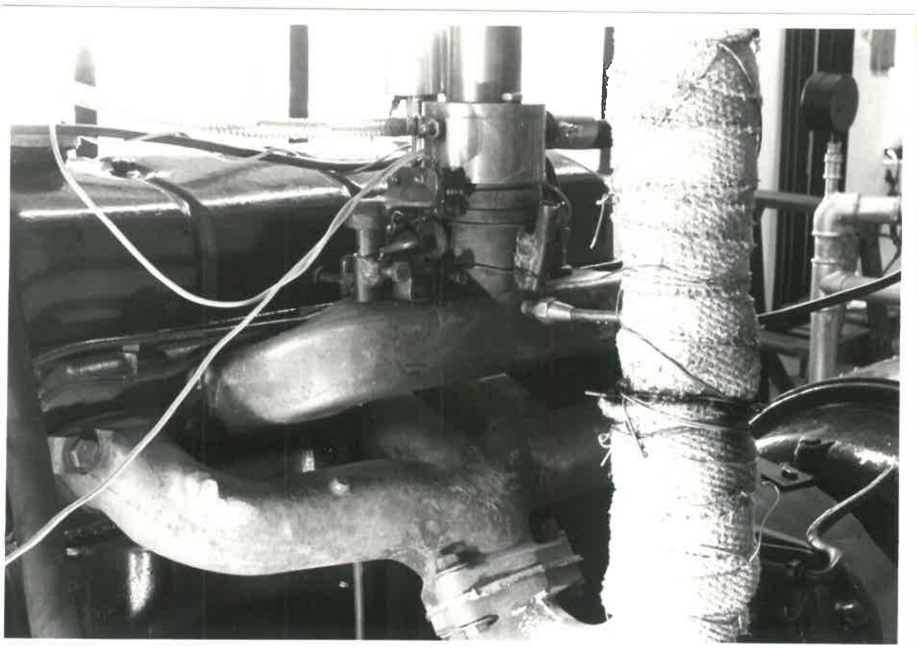
The degree of pollution or nuisance depends, however, not only on the shade but also on the size of the engine; a large engine obviously produces more exhaust gas than a small one. For instance, a smoke-producing deposit of shade 5 would hardly be noticed if emitted by a 2 horsepower engine, but would be clearly visible if generated by a 200 h.p. motor.

Messrs Bosch provide a diagram in which the relation between the shade of the filter paper, engine power (nominal), and the degree of the nuisance or pollution is shown. Figure 6 is a copy of this diagram.

Since the Department of Health has adopted the Hartridge B.P. Smoke Meter as the official test instrument for assessing the density of the smoke emitted by a diesel engine, the correlation of the Bosch and Hartridge scales is presented in figure No. 7.

At present, the maximum permitted density is 70 on the Hartridge scale. This corresponds to a Bosch reading of approximately 5,2.

For details of the test procedure, see the Government Gazette of the 2nd of April, 1971 (No. 3044), page 42.



C. EQUIPMENT AS MOUNTED ON DIESEL ENGINE.

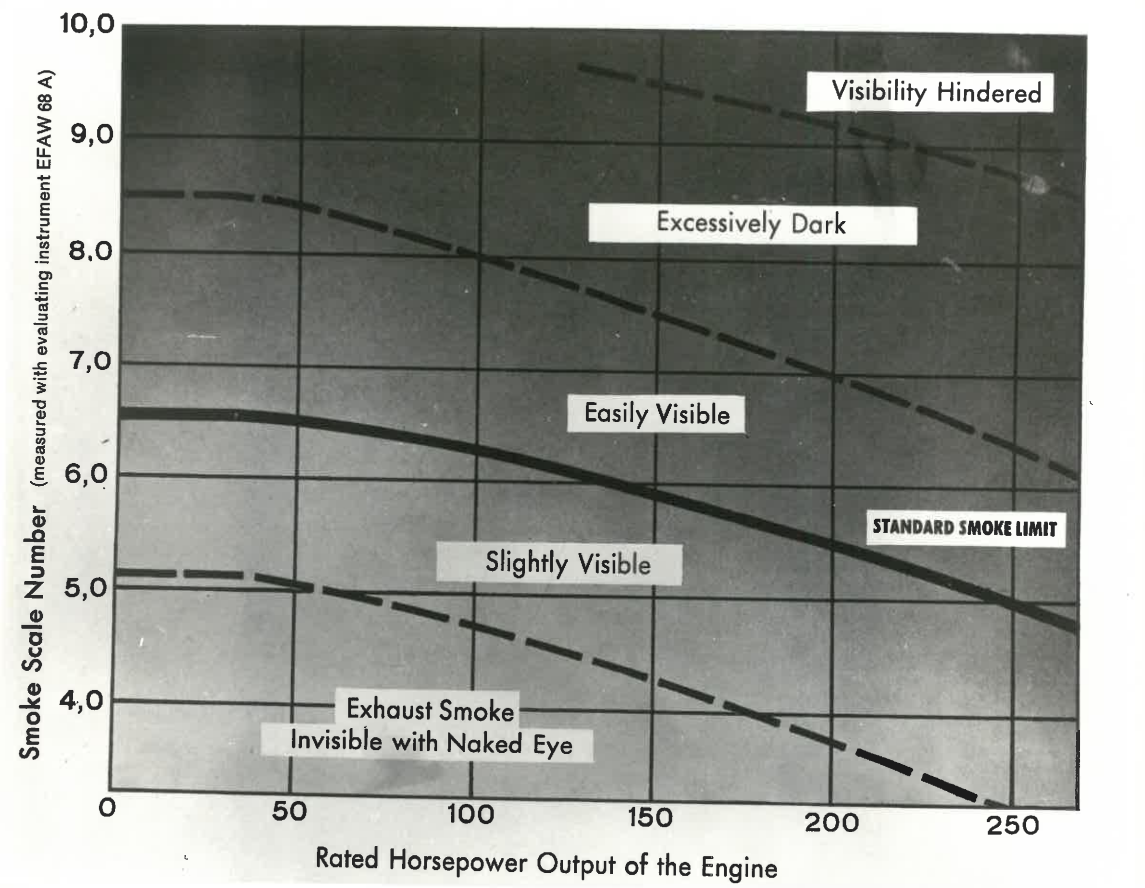


FIG. 6. DIAGRAM ILLUSTRATING THE INTERPRETATION OF THE BOSCH SCALE NUMBERS.

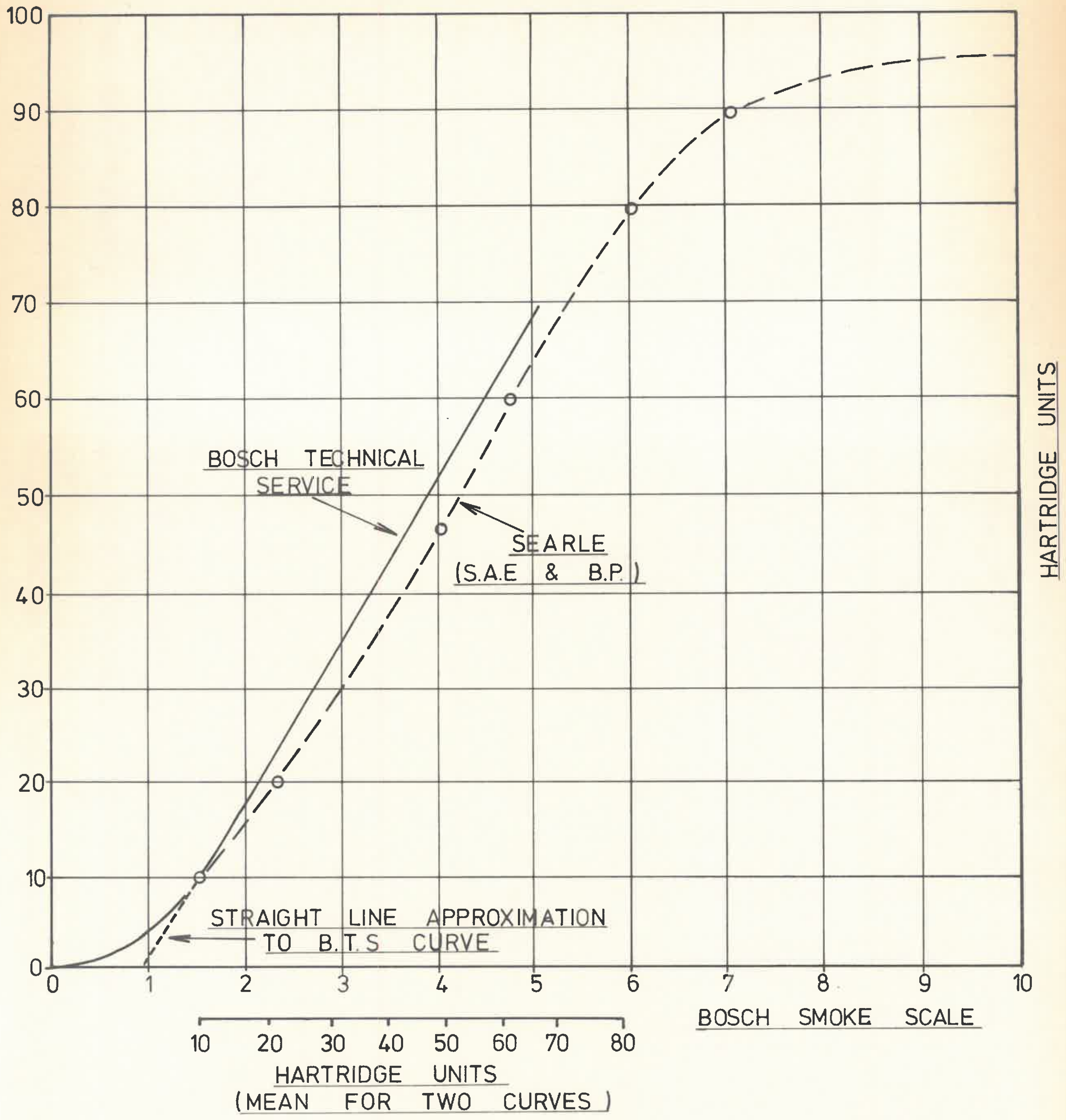


FIGURE 7

AFTER BOSCH

PERFORMANCE OF 3,6 ltr FORD DIESEL ENGINE

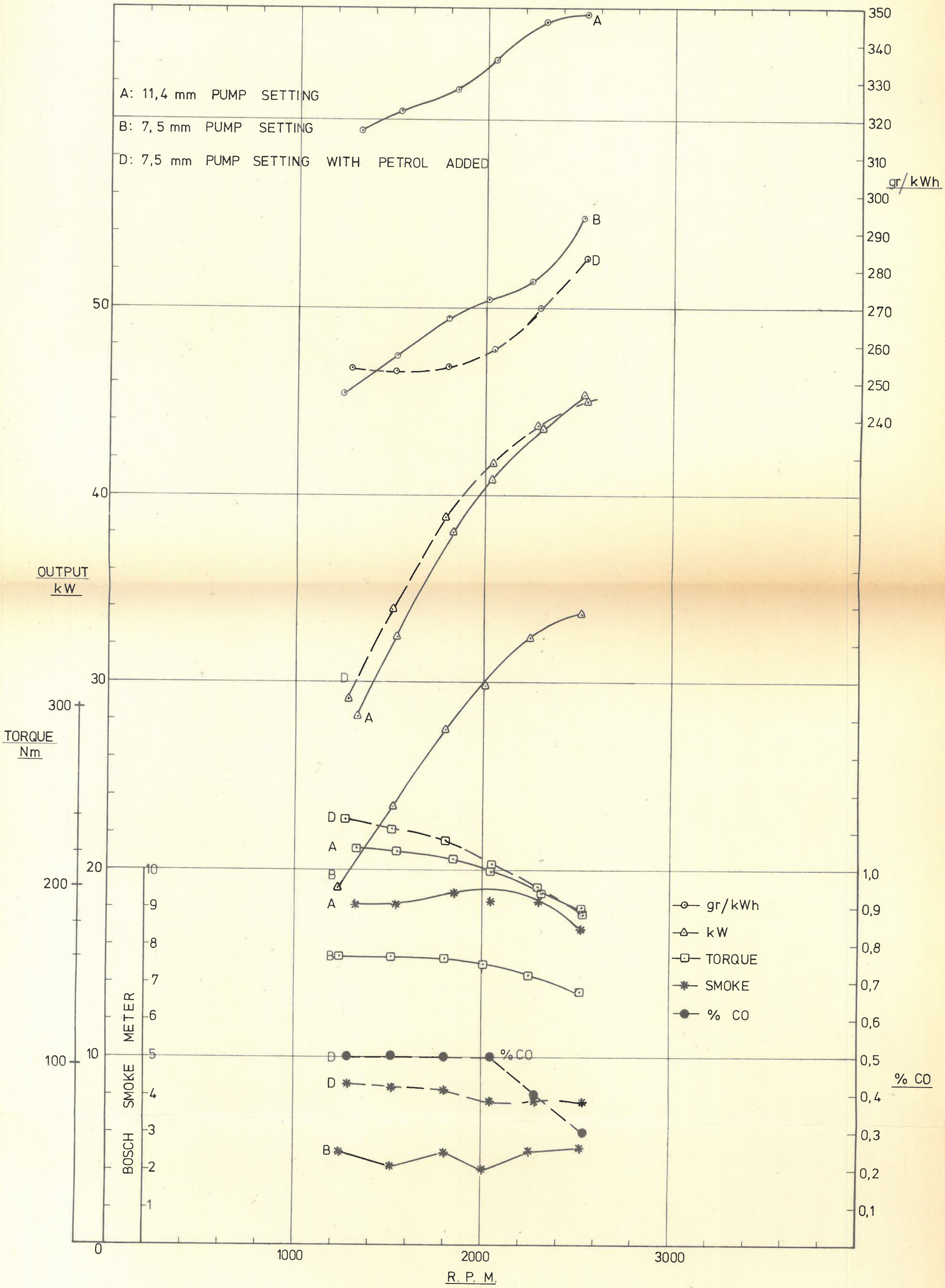


FIGURE 2