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SOME NOTES ON OUTBOARD MOTORS

By H. S. RAINBOW

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SOME NOTES ON OUTBOARD MOTORS

By H. S. Rainbow*

The mention of an outboard motor may conjure up for many people an image of a small, noisy, two-stroke engine driving a propeller attached to the end of a long shaft, a particularly noticeable feature being the rather primitive starting means. However, the modern, American style outboard motor, which may have a power rating of up to 100 hp, is a relatively complex, highly developed, means of propulsion. In its present form it is capable of giving a consistent and reliable performance under arduous conditions of operation and exposure.

The outboard motor has not been used so extensively in Europe and in other areas as in the U.S.A. In consequence, the complexity of the product and the problems associated with its manufacture and operation have not been so well understood. It may not be widely known, for example, that the outboard motor, like the refrigerator, motor car and many other products, cannot be produced as a technically and economically competitive article unless it is fully tooled for volume production, with a considerable home and overseas market to support it. It has to satisfy standards of size, shape, weight, finish and cost that make this essential. Against this background very high standards of performance and reliability are demanded which, in terms of specific size, weight and power, must be at least equal to the standards for light aircraft piston engines. To achieve these results a very considerable and sustained engineering effort on design, development and proving, on a world-wide operational basis, is necessary.

Outboard motors are expected to run for long periods under extremes of exposure and climatic and corrosive conditions. The mostly unforeseen and not obvious differences in the behaviour of components and accessories arising from this have led to a very common and widespread under-estimation of the complexity of the problems involved. Materials, components and equipment that will function satisfactorily under chainsaw, lawnmower, motor cycle and automotive conditions are prone to many problems when operated in the damp, humid and corrosive environment normally associated with the operation of an outboard motor.

In the U.S.A. the output of outboard motors represents an annual cash turnover in the region of 160 million dollars. In consequence the industry has been able to support the production of specialized accessories and equipment developed to function satisfactorily under the most adverse operating conditions. By contrast, it has been the tendency in Europe to follow and be influenced by automotive experience and practice, particularly in the choice of materials and design of accessories. Because the actual operating conditions differ so considerably this approach has hindered development and has not produced satisfactory and serviceable answers to many of the problems involved.

Experience has shown that to compete technically and commercially with the volume-produced, highly developed American counterpart the outboard motor must be a sophisticated machine, both in its component features and in its operation and must be produced in large volume by line production techniques.

The author's main object has been to outline some of the more interesting features and to record information on many of the less obvious problems experienced, against the background of the unusual, and sometimes conflicting, operational requirements.

INTRODUCTION

A COMPREHENSIVE KNOWLEDGE and experience of the design, development and volume production of outboard motors has not existed outside the U.S.A. until recent years. There the greater part of the world's production is concentrated, and there the leading technical developments have taken place.

This has been responsible for a widespread under-estimation in Europe of the cost and technical difficulties involved in the manufacture of outboard motors on a volume production basis.

It may not be widely appreciated that the outboard

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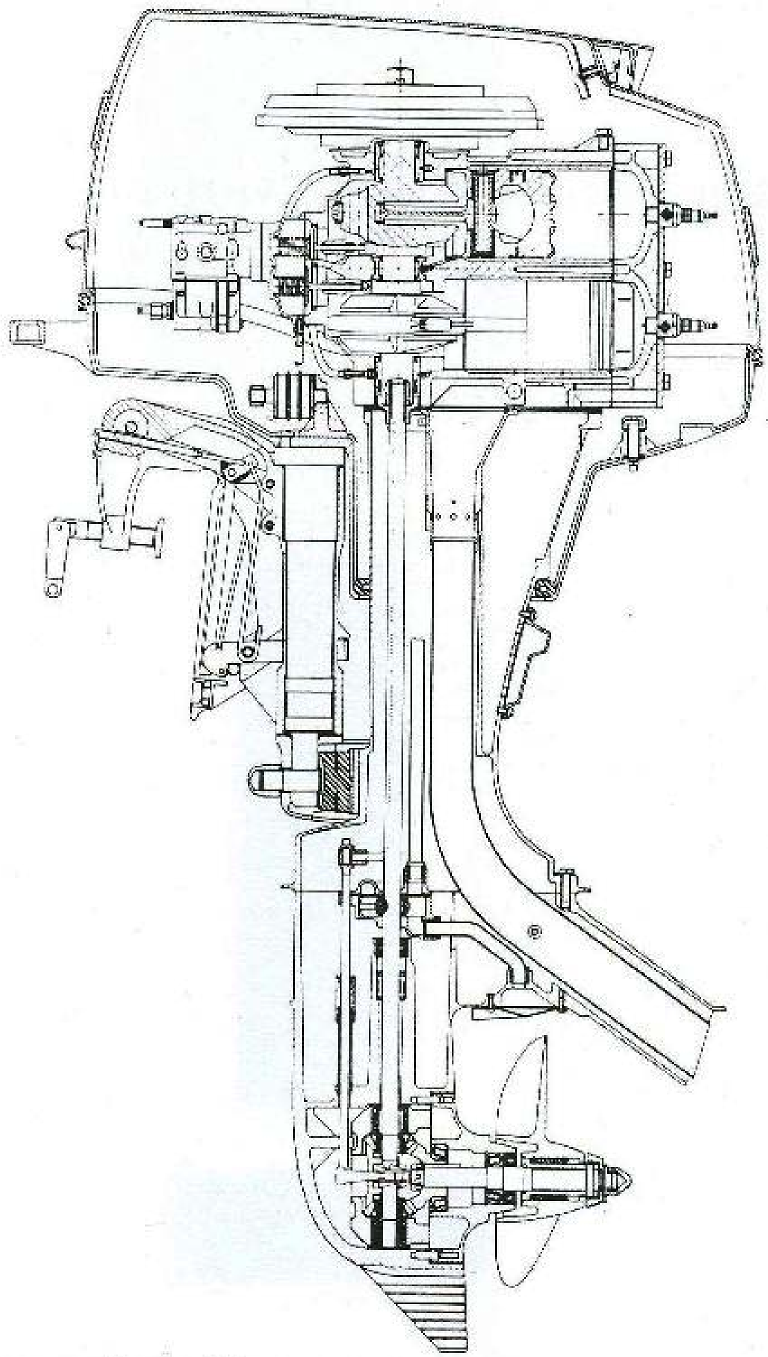


44 in^3 alternate firing, water-cooled, twin cylinder, two-stroke. Powerhead floating on rubber suspension and fully silenced. Electric starting, magneto alternator. Forward, neutral and reverse gears, remote controls.

Fig. 1. 40 hp outboard motor

motor industry is already very firmly established as one of considerable commercial importance. Estimates of world output indicate that over half a million motors are produced annually. This represents a cash turn over at ex-works prices of approximately 160 million dollars. Of this, sales in North America account for 135 million dollars.

With regard to the future of the industry, there are indications of a valuable growth potential as world demand is expected to increase with the general rise in living standards.

THE OUTBOARD MOTOR

The outboard motor is a self-contained power unit designed for mounting on the transom of a boat (Fig. 1). It has a much lower weight per horsepower than an inboard engine and does not require the permanent installation of propeller shafts, gearboxes, stern glands and other features which add greatly to both the weight and the cost.

The motor is arranged to pivot around a vertical kingpin and the full vectored thrust of the propeller is available for steering the craft. This imparts a degree of manoeuvrability that is quite unobtainable with a conventional rudder. It is also free to tilt about a transverse axis which allows navigation, in shoal waters, to a minimum depth at which the craft can float. This facilitates beaching, launching and propeller inspection, and avoids many of the hazards and difficulties associated with inboard installations.

Reliability and flexibility of operation and installation are most important, generators, electric starters, forward, neutral and reverse drives and remote controls being available in a variety of combinations for the convenience of the customer. An interesting safety feature is the throttle starting sequence and gear shift interlock. This makes it impossible to start the motor, or change gear, unless the throttle is closed to the starting and gear shifting position.

The engine, or powerhead as it is sometimes called, is extremely flexible and may be run at trolling speeds, or at maximum or intermediate powers, for as long as may be desired. In fact, the ability of the outboard engine to run at maximum revolutions, hour after hour, throughout its useful life, is one of its most impressive characteristics.

INBOARD OR OUTBOARD?

In this paper we shall say much in favour of the outboard motor. At the same time we must acknowledge the superiority of the inboard installation for many applications.

In the post-war years there has been a phenomenal growth of interest in outboard motor boating and sales of inboard powered craft have increased also. Obviously there is a need, and demand, for both. For certain duties only one, or the other, may be practicable. In other circumstances, either inboard or outboard power may be satisfactory. Choice will then depend on the personal whim of the customer.

In terms of world sales it would seem that because of the lower weight and cost, greater manoeuvrability and convenience, smaller size and better performance, the outboard motor has almost displaced the inboard engine for use with boats under 16 ft. By contrast, for boats of over 22 ft it is usual to find the conventional inboard installation. Between these two sizes the choice will depend very much on the intended use. For a high performance planing hull the outboard motor may be the logical choice, for a displacement cruising hull the inboard engine may be preferred, particularly if extended cruising in off-shore waters is contemplated.

The respective advantages may be summarized as follows:

Outboard power

- Lower cost
- Simple installation
- Reduced fire risk
- Lower weight/hp
- Higher speed/hp
- Superior manoeuvrability
- Less draft giving better shoal water capability
- Easier launching and beaching.

Inboard power

- Greater durability
- Lower fuel consumption
- Lower running costs
- Better boat balance
- Greater seaworthiness
- Better protection for off-shore working.

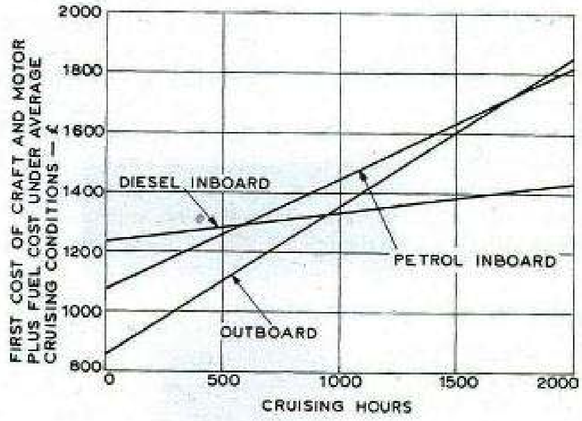
The first cost of an inboard engined craft will normally be considerably higher than that of an outboard craft and a simple comparison based on first cost of craft and engine, plus fuel, does much to explain the growing popularity of the outboard motor (Fig. 2).

THE POWERHEAD

Three basic types of internal combustion engine have been used as powerheads for outboard motors, the two- and four-stroke petrol engine, and the two-stroke diesel engine. Of these only the two-stroke petrol engine has been a commercial success and powerheads of this type are now in common use throughout the world. These engines may be either air or water cooled, or of single- or multi-cylinder design.

It is usual for air cooling to be confined to single cylinder, two-stroke engines, of low power and low first cost, not exceeding 2 to 3 hp. This type of engine can be a very 'temperamental' starter and noise and vibration can often reach unpleasant levels. The most significant disadvantage of the single cylinder motor is that if the plug should 'whisker' the engine will stop. The plug must then be removed and cleaned before the engine can be restarted.

The more popular and sophisticated type of motor employs water cooling and is of multi-cylinder design. This allows a significant reduction to be obtained in both noise and vibration levels. Unlike the single cylinder



Assumptions made

Motor type	Craft length, ft	Maximum speed, knots	Engine power, hp	Engine and gearbox cost, £	Craft cost, £	Fuel consumption cruising, gal/h	Cost of fuel per 1000 hours, £
Diesel inboard .	19	18–20	50	330	900	1·0	100
Petrol inboard .	19	18–20	45	270	800	1·5	375
Outboard . .	19	18–20	40	250	600	2·0	500

Fig. 2. Comparison of first cost plus fuel cost of inboard diesel, inboard petrol and outboard powered craft

model, if a plug should whisker the engine will go on running and frequently the temperature change in the idle cylinder will allow the whisker to fall off. Even if this does not happen the plug can at least be left until the craft has cleared any navigational hazards which may be present.

Power output may be anything from 1 to 100 hp and, at the higher power levels, the motors exhibit quite extraordinary characteristics in terms of specific output, weight and size. This is achieved by employing the two-stroke cycle, relatively high stress levels, high quality steels and by the extensive use of light alloy pressure die-castings.

From time to time, four-stroke cycle engines have been introduced with the object of improving low speed running, eliminating plug fouling and whiskering, and reducing fuel consumption. Unfortunately, these engines have not been able to compete in terms of power output, size and weight. Therefore, and virtually without exception, the multi-cylinder, water cooled, two-stroke engine has proved to be the universal choice for outboard motor powerheads of from 3 to 100 hp.

Up to the 40 hp rating they are usually of the alternate firing twin-cylinder type (Fig. 3). For engines of significantly higher power it is more usual to employ either four or six cylinders in line or the V four arrangement.

At the higher power levels there is a greater challenge to the design and development skills to keep both the size and weight of the engine to acceptable proportions. It follows that it is in the larger engines that the most interesting engineering developments are to be found. During an evolutionary period of over 50 years the outboard motor powerhead has been developed to its present standard by the natural selection of the most fitting designs.

Radial, four-stroke, horizontally opposed, and engines of various other configurations have been tried and have failed commercially because they did not achieve the required standard in terms of size, weight, cost, performance and reliability.

Two-stroke engines, basically, are of two- or three-port design. The three-port arrangement is the most favoured for many applications, because of its greater simplicity and lower cost. It is also perhaps the most well known. For outboard motor powerheads the two-port configuration is generally used, despite its higher cost. The author believes this to be owing, not to its potential for higher specific output, but to its superior low speed characteristics and more constant and easier starting, particularly at the low starting speeds that may be imposed by a hand-starting means.

These two-port engines employ crankcase inlet valves to control induction into the crank chamber. The most common are the automatic reed valve, the crankshaft-driven rotary disc valve and the crankshaft-driven cam-operated poppet valve.

The reed valve (Fig. 4) which may be located in one of several positions between the carburettor and the crank chamber, is used for a number of very good reasons. It is mechanically simple, of relatively low cost, reliable and unlikely to give any trouble in service, wear is negligible

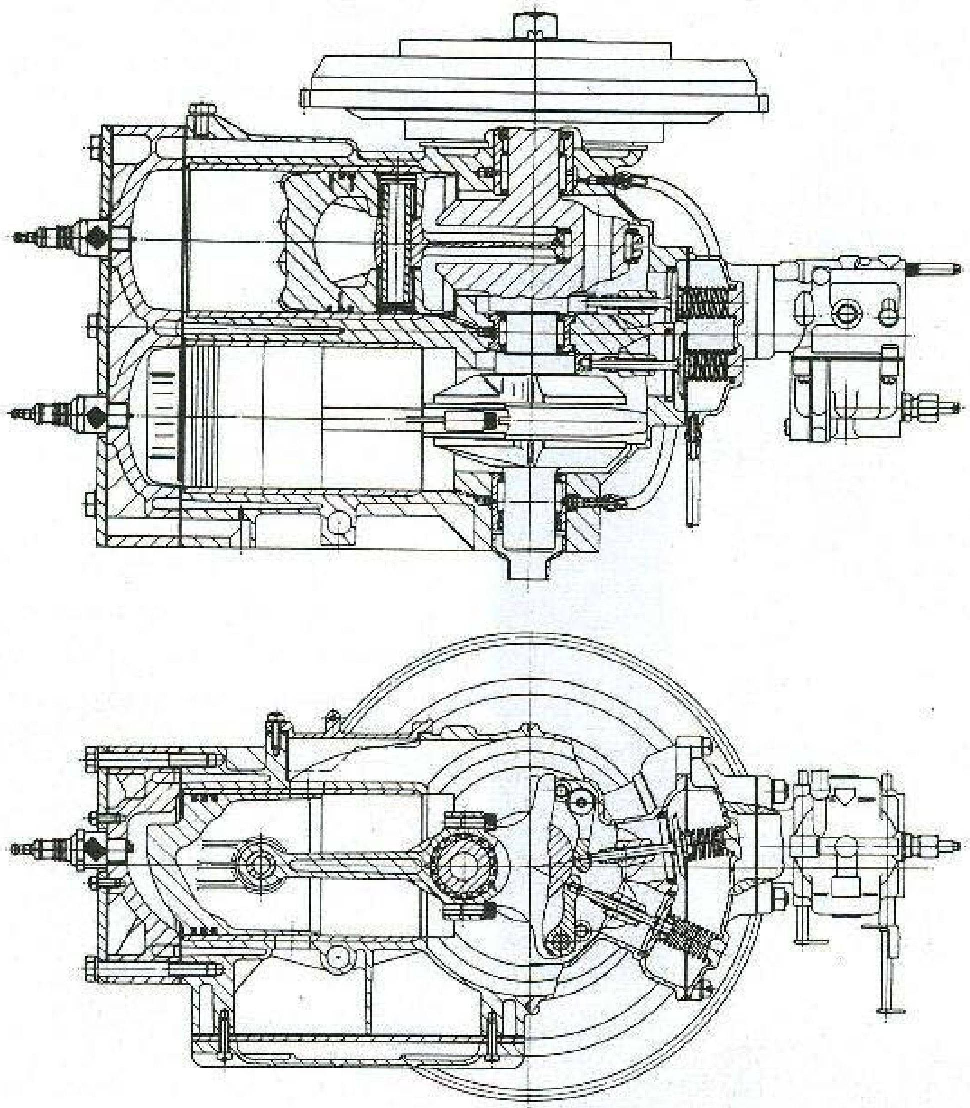


Fig. 3. Powerhead, 40 hp motor

and it requires virtually no maintenance. At certain engine speeds it is inclined to be rather noisy. Should missing or slow burning occur at idling speeds, causing back firing through the transfer port into the crankcase, the reed valves are closed automatically by the internal pressure rise. This prevents the spitting back of fuel and oil through the carburettor which can otherwise cause stalling of the engine at low speeds.

These reed valves are simple sections of spring steel arranged to cover simple intake ports. The reeds are opened by the pressure difference across them during the induction stroke, and closed by the internal pressure during the crankcase compression stroke. One feature of the reed valve that is of interest is that the timing and degree of opening is dependent upon the pressure difference across it. This varies with the speed of the motor, thus at low speeds the valve opens later and less widely, permitting a lesser fuel charge to enter the crankcase. This reduces fuel consumption in the low speed range, and renders it easier to achieve a smooth idling characteristic. Less surplus fuel is likely to accumulate in the crankcase and this is very significant in the low speed control of large two-stroke engines.

The rotary valve, driven by the crankshaft, serves the same purpose as the reed valve. It is sometimes used in special racing engines but is not generally used for production motors. The valve in its simplest form is a hole in the crankshaft. In a more sophisticated form it is a simple ported disc splined to the shaft. In both types ports are arranged to coincide with the intake manifold during the

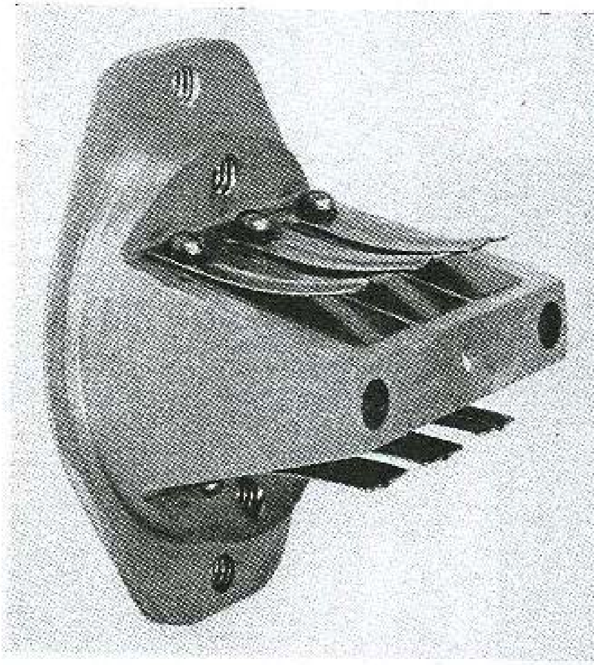


Fig. 4. Reed valve assembly, 18 hp motor

induction phase. At all other phases the ports are sealed and the crankcase pressure assists the sealing during the compression phase. Unlike the reed valve the opening and timing is constant at all engine speeds. This allows a higher volumetric efficiency with the intrinsic advantage of higher specific output, superior acceleration, and greater low speed torque.

The rotary valve engine will inhale substantially the same volume of gas per revolution irrespective of speed.

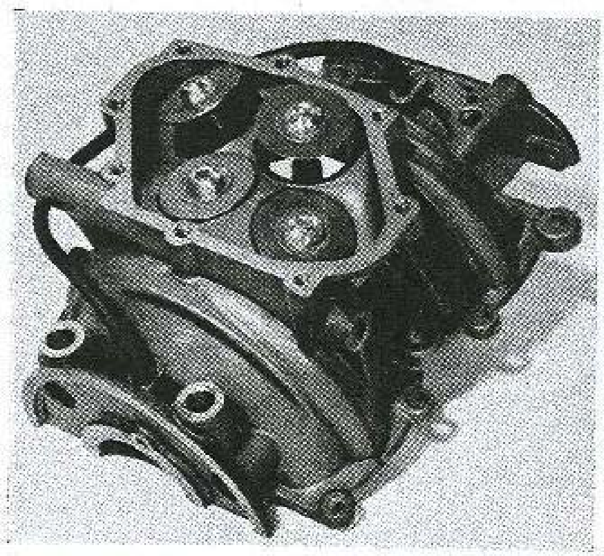
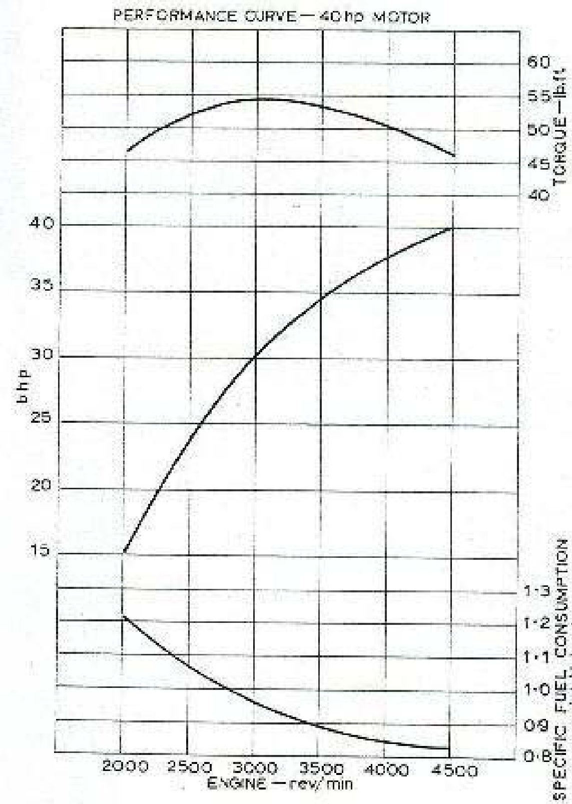


Fig. 5. Poppet valves in crankcase, 40 hp motor

This tends to make the rotary valve type use more fuel at low rev/min when a lesser charge can normally be tolerated for the purpose of matching the engine to the propeller. At low speeds excess fuel is undesirable, as it may cause rough idling and a tendency to stall. However, if carburettor and intake manifold design is good, rotary valve engines can give a good idling performance with the advantage, as previously mentioned, of superior acceleration and as good, or even better, fuel consumption at maximum speeds.

Poppet valve engines exhibit characteristics similar to those already described for rotary valve engines. The Perkins 40 hp engine employs four valves of this type, two for each cylinder (Fig. 5). These are situated between the crank chamber and the induction manifold and are actuated by large diameter cams, in one with the crankshaft, and finger-type followers. The valves are returned by simple helical coil springs to neoprene rubber valve seats which require no maintenance throughout the life of the engine.

The development of this lightweight, engine speed, poppet valve gear has posed many difficult problems



Cubic capacity—44·1 in³ (722 cm³).
bhp outboard crankshaft rating—40 at 4550 rev/min.
Bore and stroke—$3\frac{1}{8} \times 2\frac{7}{8}$ in (79·4 × 73 mm).
Cylinders—two, alternate firing.
Intake valves, cam-operated poppet.
Mean piston speed—2155 ft/min.
Piston acceleration—35 200 ft/sec².
Maximum cylinder pressure at rated power—475 lb/in².

Fig. 6. Performance curve, 40 hp motor

Table 1. Powerhead bearing loads—all models
Main and Big End Bearing Loads
(Nett peak load per unit of projected area)

Model	40	30	18	6·5
Maximum gas pressure, lb/in²	450	369	399	280
Maximum gas load, lb	3470	2730	1962	880
Maximum inertia load, lb	920	865	518	183
Nett load, lb	2550	1865	1444	697
Main bearings				
Top main. Projected area, in²	0·688	0·688	0·688	0·829
Unit load, lb/in²	1855	1355	1060	421
Centre main. Projected area, in²	0·450	0·450	0·500	0·801
Unit load, lb/in²	2835	2070	1445	435
Bottom main. Projected area, in²	0·540	0·540	0·437	0·728
Unit load, lb/in²	2360	1726	1650	479
Big end bearings				
Projected area, in²	0·661	0·661	0·338	0·461
Unit load, lb/in²	3860	2820	4260	1510
Gudgeon pin bearings				
Projected area, in²	0·703	0·703	0·315	0·367
Unit load, lb/in²	3625	2650	4580	1900

associated with wear and lubrication, the choice of materials and surface finishes proving extremely critical. As presently developed the valve gear requires no attention during the normal overhaul life of the engine.

The advantage of this valve gear, and this must be carefully appraised in relation to the extreme simplicity of the reed valve system, is the relatively high torque developed by the engine at low rev/min (Fig. 6). This characteristic is highly desirable for certain sporting activities.

In the construction of outboard motor powerheads it is usual practice to employ light alloy pressure diecast cylinder head, cylinder block and crankcase assemblies, light alloy forged or diecast pistons, forged steel connecting rods and crankshaft, both case hardened all over, and anti-friction ball, roller and needle bearings throughout.

For typical powerhead bearing loads see Table 1.

PRESSURE DIECASTINGS

The extensive use of light alloy pressure diecastings has played an important part in achieving low weight and cost. This technique has been extensively developed by American outboard motor manufacturers and they have established a world lead, producing large four- and six-cylinder in-line, pressure diecast cylinder blocks as a production routine.

The development of the Perkins range of outboard motors at Peterborough has stimulated considerable interest in pressure diecasting, involving the diecasting trade in this country in producing larger and more complex castings than had been attempted before.

Apart from the rotational parts of the engine and transmission system, most outboard motors are built up, almost entirely, from assemblies of light-alloy pressure diecastings. The exception to this may arise when particularly heavy or robust castings are required for commercial or military purposes, and the quantities involved do not justify the cost of producing special dies.

The most interesting casting used in the Perkins engines is the 40 hp cylinder block. This is an aluminium pressure diecasting with cast-in cylinder liners, the water cooling passages and most of the detail work being also cast-in. The weight of the trimmed casting is approximately 19 lb, and as finished it weighs 13½ lb, or complete with crankcase 16 lb. It is produced in a large 1000-ton diecasting press from a highly complex, multiple sliding core die, weighing some 3 tons (Fig. 7).

These finely finished, high strength, low weight, outboard motor components in light alloy, often with the most intricate detail cast in, represent a notable contribution by the diecasting industry to low cost production.

One particularly difficult problem that arises in the application of large pressure diecastings to load, shock or thermally stressed components, is the difficulty of obtaining sample castings for development testing. It is sometimes possible to use sand castings for this work, but these will have strength characteristics entirely different from those obtained from the pressure dies, so this approach is fraught with considerable risk. This means that the design has to be right first time, the expensive production dies being, of necessity, laid down straight from the drawing board. Subsequent modifications are very expensive to embody and severely limited in scope.

It is usual for the trade to supply sample castings in low-melting-point alloy taken from the die before it is hardened. This practice allows tooling, assembly and dimensional accuracy to be checked, but is quite useless for checking the performance of the component under actual operating conditions. For this purpose specimens in the correct material are essential and, although there is a considerable prejudice in the diecasting trade in Great Britain against this, the functional capability of the castings should be fully approved before the dies are hardened for production runs.

FUELS AND LUBRICANTS

In most outboard motor two-stroke engines lubrication is achieved by mixing the oil with the fuel. A proportion of the oil provides for the lubrication of the main and connecting rod bearings and the piston and the cylinder. The rest is burned with the fuel in the combustion chamber. It is known that most two-stroke engines require specially compounded oils to give their best performance, owing to the conditions obtaining inside the engine and the method by which the lubricating oil is supplied. It is also known that two-stroke engines may be sensitive to particular oil and fuel combinations. It is equally true that what is good for one engine may not be good for another, there being a wide difference in the specific output of various engines and in piston, cylinder head and sparking plug temperatures.

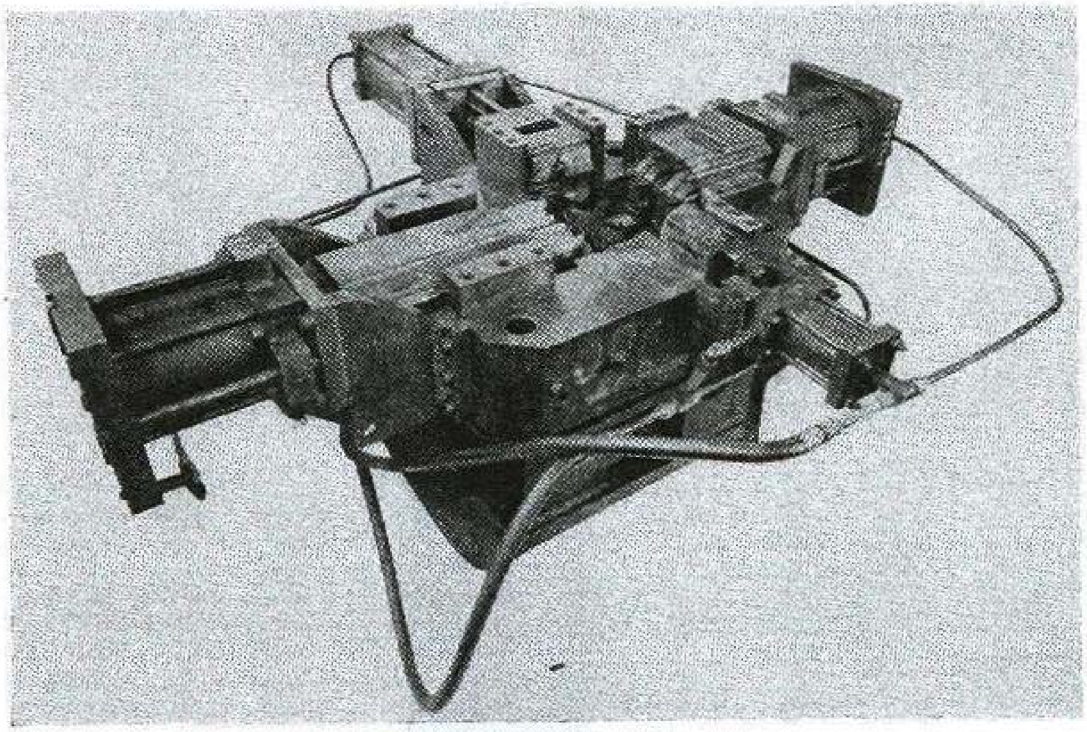


Fig. 7. Cylinder block die, 40 hp motor

The composition of the fuels and lubricants used can influence exhaust smoking and fuming, internal corrosion, bearing life, ring and cylinder bore wear, ring sticking, exhaust and combustion chamber deposits, and, one of the most irritating and difficult problems to solve, plug fouling and whiskering. These problems have all been discussed in many papers relating to two-stroke engines and never before has so much work been done by the chemical industry and the oil industry towards the alleviation of these difficulties (1) (2) (3) (4) (5) (6)*.

Experience has shown that there are good and bad engines irrespective of the fuel and oil that may be used. We know also that some engines will be required to operate in remote regions of the world on fuels and oils that are available locally and for this reason the engine must be one that does not rely on specially formulated oils that may not always be available. That is to say, when an engine is plagued by the more serious problems of plug fouling, whiskering and piston burning, it is necessary to eliminate these problems, as far as possible, by good combustion chamber and piston design.

In our own work at Peterborough, we have found that reducing piston and cylinder head temperatures has been the most profitable way of eliminating these problems. Improved results, in terms of engine cleanliness and spark plug fouling have also been obtained when specially formulated, ashless additive type, outboard motor oils have been used.

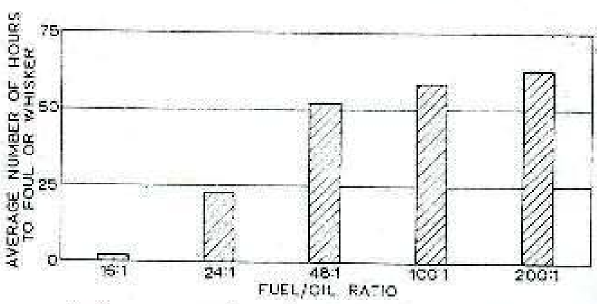
* *References are given in the Appendix.*

On one particular engine that would whisker a plug every 10 hours or so, and would burn out its pistons with disturbing ease, we were able to achieve a plug fouling and whiskering life of 80 to 100 or more hours, and eliminate piston burning completely, by piston and combustion chamber re-design. This is now a consistent average performance for this engine when premium grade fuels and outboard motor oils are used.

When similar engines were run on regular grade leaded fuels and regular grade detergent motor oils, during a tropical testing exercise in Florida, more frequent fouling of the plugs occurred. This plug fouling could be cured by using the detergent motor oil in conjunction with a lead-free gasoline, or by using the leaded fuel in conjunction with an outboard motor oil.

This is mentioned because having produced a good engine, when run on compatible fuel and oil combinations, it was not so good when incompatible fuels and oils were used.

It is our experience, and this is believed to be fairly general, that the mixture ratio has an important influence on the incidence of plug fouling and whiskering (Fig. 8). We have found that as oil content is reduced, so are the plug troubles. Other advantages are: less deposit build up, less ring sticking, less smoking during prolonged idling and trolling and reduced operating costs. Plain bearing engines require more oil than those employing anti-friction bearings throughout. In consequence the latter type are used in all but the very smallest engines.



Engine—two-stroke, twin-cylinder alternate firing.
bhp—4·5 hp at 4000 rev/min.
Bore and stroke—2 × 1·5 in (50·8 × 38·1 mm).
Swept volume—9·42 in³ (154 cm³).
Ignition system—flywheel magneto.
Sparking plug—UJ12 (series Gap).
Trolling speed—1100 rev/min.
Fuel—Shell Premium.
Oil—Shell 2T.

Fig. 8. Influence of fuel–oil ratio on spark plug fouling at trolling speed

Mixture ratios in the region of 20 to 40:1 are fairly common practice. These can be extended to 80, or even 100:1 in some engines (7), by using oils containing specially formulated anti-wear additives. These engines must employ anti-friction bearings throughout and be relatively free from piston and cylinder bore distortion. As the oil content is reduced it is not unusual for the rate of wear to increase in marginal areas. To counteract this specially formulated anti-wear oils can be used. When these special oils are not available the normal mixture ratios must be used.

It would seem that a promising line of development is a separate oil and fuel system on modified four-stroke lines. This would reduce the unnecessary, and wasteful, burning of oil with the fuel, which is responsible for many of the troubles already referred to.

Nevertheless, on a point of principle, we must encourage the lubrication specialists to continue with their work on anti-wear additives as these may prolong the life of our engines irrespective of the eventual method of lubrication employed.

In connection with this the two-stroke engine may possess an inherent advantage. A very low rate of wear has been observed during extensive endurance testing, pistons, rings, cylinder bores, main, big and little end bearings being remarkably free from wear. We have not yet had time to study these observations in detail but wear on the parts mentioned has been consistently negligible after hundreds of hours of endurance running. The author believes this to be partly due to the characteristics of the total loss oil system which ensures that only perfectly clean oil is delivered to the wearing parts. In the future development of the two-stroke engine the advantages arising from this may be of significant importance.

THE IGNITION SYSTEM

It must now be acknowledged that the best work of the engine designer and the lubrication and fuel specialist would be of little practical value were it not for the very considerable contribution made by the ignition system manufacturers, and the excellence of the equipment that they supply. Easy starting, faultless running and long periods of operation without attention, often in damp saline atmospheres, are dependent to a very large degree on the characteristics and quality of the ignition equipment.

In our experience at Peterborough, in the operation of outboard motors under severe climatic conditions in many regions of the world, we have come to believe that a first-class ignition system is absolutely essential to enable an engine to start, and run, satisfactorily at all times.

Our tests on many outboard motor ignition systems have shown a wide variation in standards of performance (Fig. 9). Similarly, tests on a wide range of outboard

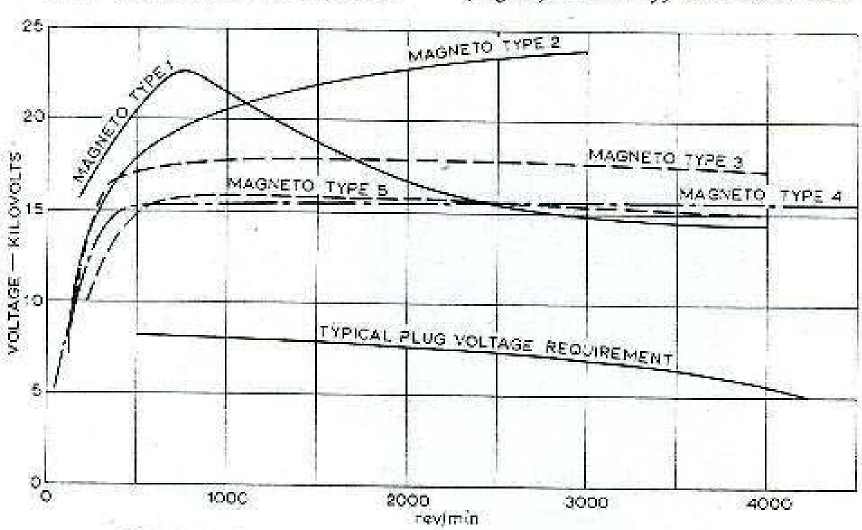


Fig. 9. Typical performance curves, outboard motor magnetos

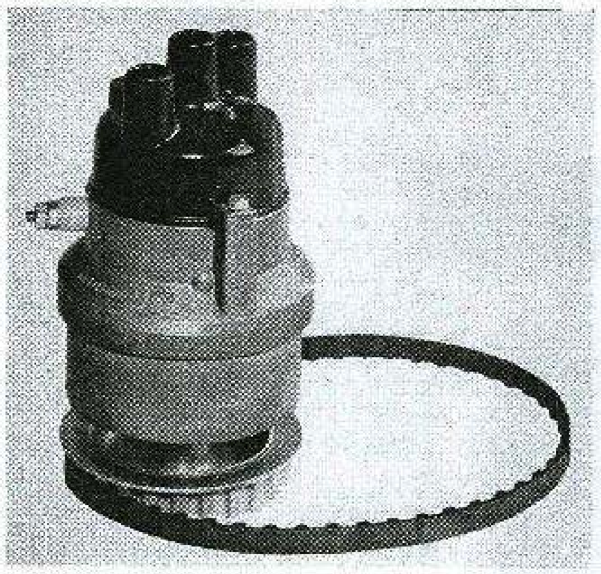


Fig. 10. Belt-driven outboard motor magneto

motors has revealed a wide variation in standards of 'startability' and sensitivity to plug fouling and whiskering.

Bearing in mind the electrical leakage and performance losses that will invariably arise under service conditions, particularly on marine engines operating in damp saline atmospheres, we have found that the best performance in terms of easy starting, low fuel consumption and absence of plug fouling and whiskering is obtained when the ignition reserve is in the region of twice the plug voltage requirement (Fig. 9). This characteristic is particularly important for starting at low cranking speeds, to prevent plug fouling during prolonged idling and trolling, and to extend the life between plug whiskering at full power.

This emphasis on easy starting and trouble-free running for long periods, without attention, has stimulated interest in high-frequency capacitor discharge, surface gap, transistorized and other high energy ignition systems. Whether the practical advantages realized will justify the extra cost that may be involved and whether the customer is prepared to pay for them has yet to be ascertained.

Ignition systems in common use are the simple flywheel magneto, belt-driven miniature magneto and flywheel magneto alternator (Figs 10 and 11). All these are dependent upon the performance of the sparking plug for efficient operation.

In two-stroke engines of high specific output the plug has a particularly difficult duty to perform. This arises from the extremes of combustion chamber temperature encountered and the wide heat range over which the plug is expected to function, horsepower per cubic inch of displacement and operating temperatures being much higher than those normally experienced in four-stroke engines. Whereas porcelain tip temperatures in automotive type, four-stroke engines may not exceed 1000°F to 1200°F, sparking plug thermocouples in two-stroke

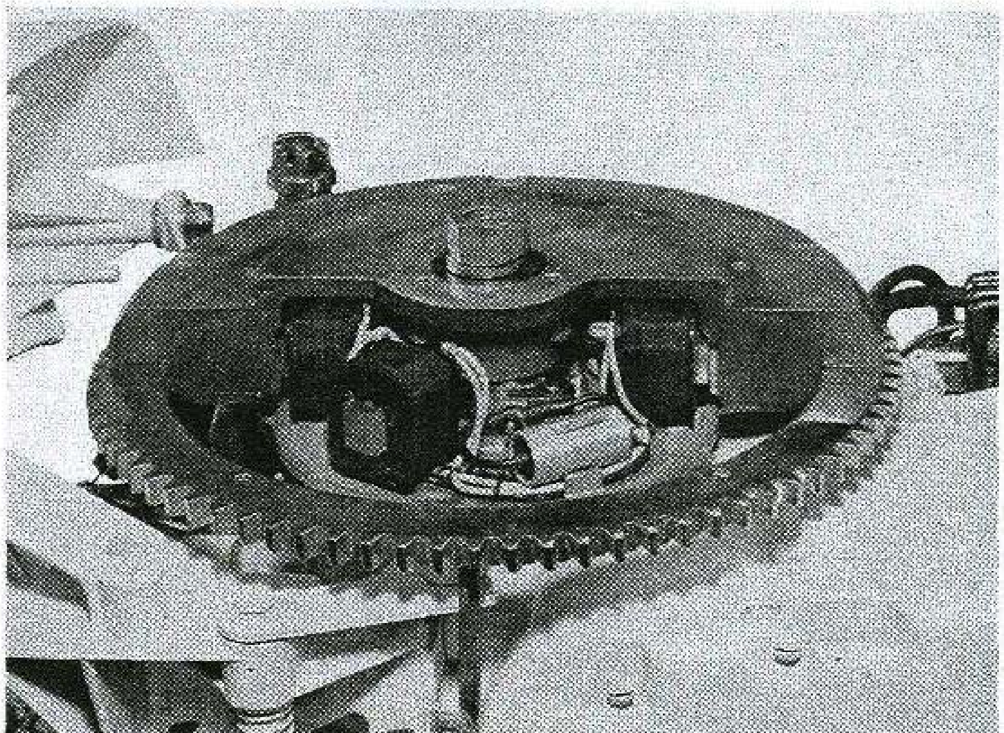


Fig. 11. Flywheel magneto alternator: output 5, 15 or 20 amps a.c.

engines have indicated tip temperatures in the region of 1600°F to 1800°F.

It is expecting a lot of a sparking plug to retain enough heat at extremely low idling speeds, over a sustained period of time, to prevent oil and unburned fuel deposits from accumulating on the porcelain, then a few moments later to reject enough heat, during long periods of running at maximum power, at specific outputs in the region of 1 hp per cubic inch of displacement and porcelain tip temperatures of 1800 degrees Fahrenheit, without running into catastrophic pre-ignition (8) (9). In this connection the important contribution made by our ignition equipment manufacturers to internal combustion engine development is, perhaps, not appreciated as widely as it ought to be.

For seemingly historical reasons the ignition equipment, sparking plugs and radio interference suppressors are developed and supplied by different, and usually independent, manufacturers. Consequently the components are not always properly matched and feature a number of joints and electrical connections which may be very convenient for the manufacturers, but are a source of performance deterioration and unreliability in service.

While assemblies of this kind may be acceptable for motor car engines they are not at all satisfactory for marine work where exposure to saline atmospheres can cause tracking, corrosion and increased resistance at the electrical connections.

A particularly unsatisfactory feature is the radio interference suppressor, particularly the kind with a carbon insert resistance, connected in series with the high-tension lead and the terminal end of the sparking plug. These suppressors can be a source of considerable ignition trouble, particularly if the carbon resistance is not correctly matched to the magneto output, being liable to overheating, intermittent and complete failure. The resistance of these carbon insert suppressors may vary considerably and we have found this to affect ignition reliability, 'startability' and frequency of plug fouling. Almost without exception, when the suppressors have been removed from an engine starting has been improved and plug fouling reduced.

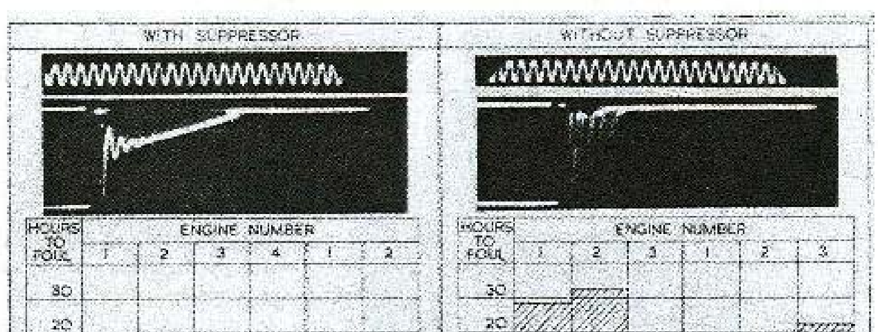
This observation on the adverse affects of suppressors on the running of certain two-stroke engines suggests that a significant change in the characteristics of the spark may occur. The oscilloscope patterns of current wave form (Fig. 12) seem to confirm this. The left-hand pattern shows the firing of a J8J plug, with a 5000 ohm suppressor, at a simulated cylinder pressure of 80 lb/in², and the right-hand pattern shows repeat firing with the suppressor removed.

The affect of this difference on the firing of the charge is not known. The evidence available merely relates an observable and repeatable difference in the oscilloscope pattern of current wave form with a corresponding difference in the engine performance.

The test results (Fig. 12) confirm our earlier observations that the characteristics of an ignition system, modified by a suppressor, can adversely affect plug sensitivity to fouling and whiskering to a marked degree, a condition for which the composition of the fuels and oils and the configuration and operating temperature of the combustion chamber have frequently been blamed.

The author would like to emphasize that a marine engine, and most particularly an outboard motor, requires an ignition system with the minimum number of electrical connections. When connections are essential for assembly reasons they should be totally enclosed and fully waterproofed (Fig. 13).

When suppressors are fitted they should be carefully matched to the ignition characteristics, and preferably employ a wire wound resistance to avoid the inconsistent performance of the carbon insert.



Engine—two-stroke, twin-cylinder, alternate firing.
bhp—6·5 at 4500 rev/min.
Bore and stroke—2 × 1·5 in (50·8 × 38·1 mm).
Swept volume—9·42 in³ (154 cm³).

Ignition system—flywheel magneto.
Sparking plugs—J8J or UJ 12.
Idling speed—900 rev/min.
Fuel-oil ratio—16:1.

Fig. 12. Influence of radio interference suppressors on ignition characteristics and spark plug fouling

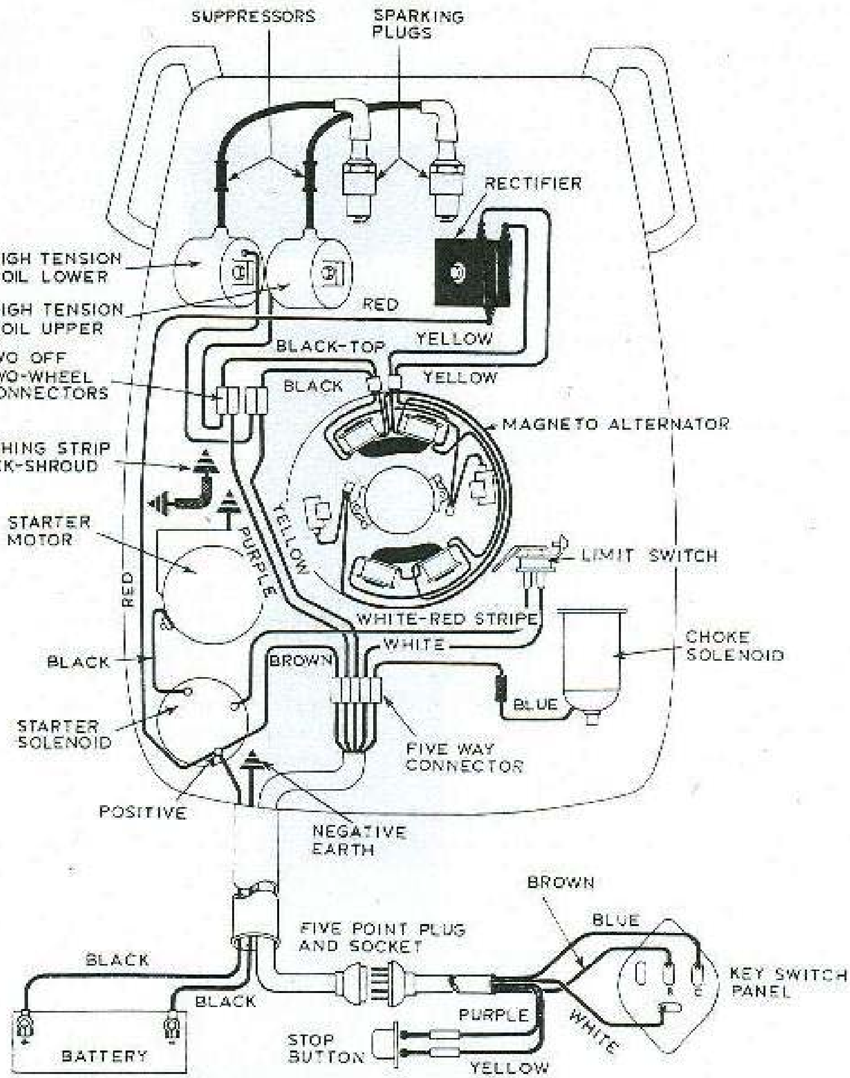


Fig. 13. Electrical equipment and wiring diagram, 40 hp motor

CARBURATION

Most outboard motors employ specially designed carburettors made of corrosion resistant light alloy. These instruments are extremely compact and employ adjustable low speed jets and either adjustable or fixed high speed jets. When the fixed jet is fitted, alternative jets are used to adjust the carburettor to the operating conditions.

This question of jet adjustment is a very controversial one. Technically speaking there is little doubt that the two-stroke engine can be made to perform better when the jets are uniquely adjusted to the operating conditions. There is also little doubt that this adjustment can have a considerable influence on plug fouling and whiskering. Unfortunately, this operation requires a degree of skill that is not always available, and incorrect adjustment can do more harm than good. In consequence, there is a strong trend towards the use of adjustable idling or low speed jets and locked high speed jets, which may be adjusted as a service operation. This would seem to be the most satisfactory answer because there is a considerable change in the functioning of most two-stroke engines after the running-in period. By discreet jet adjustment, after say, 10 hours' running, the performance of the engine can be considerably improved.

A further problem arises in connection with violent boat motion and torsional oscillation of the powerhead at relatively low rev/min. The boat motion makes it difficult to control the effective mixture level and the torsional oscillation can turn the float chamber into a virtual 'cocktail shaker' which produces aeration of the fuel. Both of these variables can cause erratic running.

Concentric bowl type float chambers are sometimes fitted to reduce sensitivity to attitude but this does not solve this problem completely, or that of aeration. For this reason there is a lot to be said in favour of the diaphragm type of carburettor which is not sensitive to either attitude or shaking.

Unfortunately a problem arises with air locking and a bleed valve must be fitted. Our experience with these has shown that the bleed valve, in its present form, introduces an element of instability and uncertainty which makes it not entirely satisfactory in operation.

It is not unusual for outboard motors to be left in position for a whole season. When craft are lying at moorings wide variations in day-to-day and night temperatures and relative humidity may occur. Under these conditions it is possible for water to accumulate in the fuel tank. If this water finds its way into the float chamber it can be very troublesome, causing difficult starting, missing, or complete cutting out of the motor. For this reason the fitting of a water filter in the fuel line will do much to improve the functional reliability of an outboard installation, particularly on craft which spend the season lying at moorings when not in use.

PERFORMANCE AND CONTROL

The performance of the outboard motor is influenced by the matching of the propeller to the boat and by the method of control. For general purposes a propeller is chosen that will give a good average performance, with an average boat, operating under average conditions. In practice there may be a considerable departure from these average conditions and a special propeller may sometimes be required to obtain good performance.

On very small engines a fixed ignition system is employed and the engine is controlled by a simple throttle. For the more sophisticated engines, variable ignition timing, related to full opening and limited closing of the throttle, is used.

This relationship is carefully calibrated to give optimum performance along a relatively wide, propeller law, running line and to provide excess power for acceleration. This allows for the variation in power requirement that arises when the propeller is running with excessive slip during rapid acceleration.

The engine is controlled by advancing or retarding the ignition and varying the throttle by means of an interconnecting cam, the profile of this cam and the variation in angular relationship between the ignition and throttle setting, being uniquely calibrated for each particular engine type. This enables the running to be reasonably well matched to the acceleration and steady state requirements, giving significant improvements in performance and fuel economy (Fig. 14).

The two-stroke powerhead is controlled, for very good reasons, by advancing and retarding the ignition. Reference to Fig. 14 will show that the throttle is never closed. At the higher and lower speed ranges down to idling rev/min, in fact, over as wide a speed range as possible,

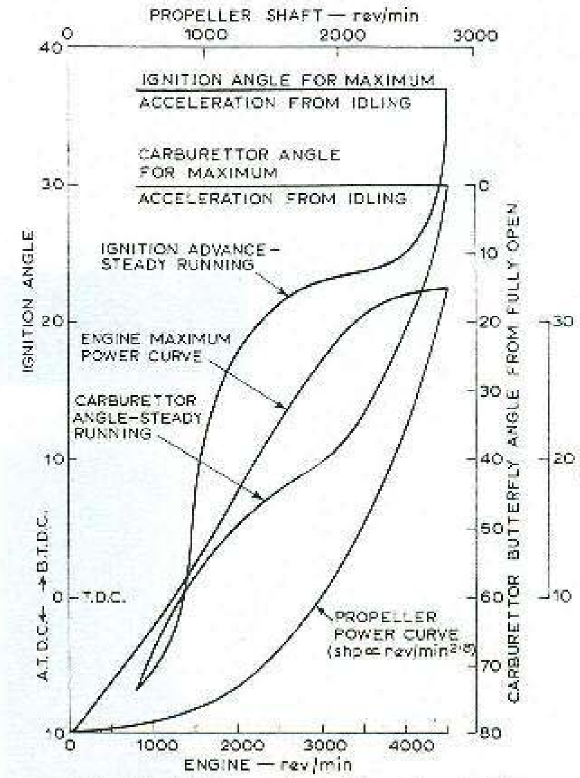


Fig. 14. Relative setting of throttle to ignition

the output of the engine is controlled entirely by varying the ignition timing.

Unlike a four-stroke engine, throttling the intake is not a satisfactory way of controlling a two-stroke engine. The cylinder must always run full and closing the throttle merely prevents the engine inhaling the very air that is so necessary for effective scavenging.

It follows that as the throttle is closed an increasing proportion of the residual exhaust gases are retained in the cylinder to dilute the incoming charge. This dilution so narrows down the range of burning, influenced of course by the degree of stratification that may be present, that the point is reached where the engine can only continue to run by four-stroking. Any further restriction, either at the intake or the exhaust, causes the engine to stop.

This alternate, fire and miss, type of low speed running, associated with a throttle control, has hitherto been acceptable for road vehicle two-stroke engines. These are usually driven on by the over-running of the vehicle when the throttle is closed, and normally are not required to idle smoothly and quietly for many hours at a time. At low vehicle speeds the engine can be kept above the four-stroking limit by engaging a lower gear.

The outboard motor has not this inherent advantage of the road vehicle engine. It cannot change to a lower gear, and has no useful over-run torque to keep it turning over when the throttle is suddenly closed. At this critical stage it may, quite frequently, be subjected to a sudden increase in exhaust back pressure arising from the action of following waves overtaking the craft as it slows down. For some activities the motor may be required to run at idling, or trolling speeds for many hours at a time. Under these circumstances the rough running and torsional vibration associated with four-stroking at low rev/min is not tolerable, for the comfortable operation of the relatively light craft to which most outboard motors are fitted.

On future and more advanced ignition systems it is possible that an improvement in the acceleration characteristics may be obtained by monitoring the ignition advance with a governor, sensitive to speed and manifold depression, the inter-connecting cam being retained for the steady state running. This will avoid excessive ignition advance during rapid accelerations with the consequent advantage of lower maximum cylinder pressures, reduced loads and smoother running.

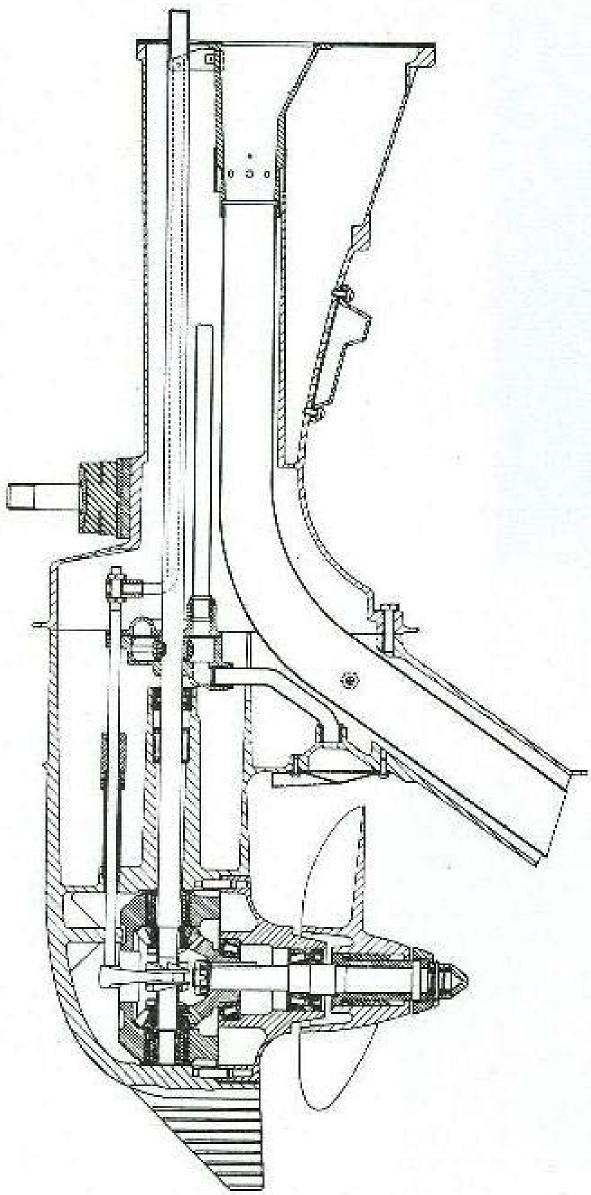


Fig. 15. Underwater unit, 40 hp motor, incorporating transmission, forward, neutral and reverse gears, water pump, exhaust silencer and propeller

THE UNDERWATER UNIT

The apparent simplicity of the underwater unit disguises some very important features and functions that are essential for satisfactory operation (Fig. 15).

The underwater body must be of low drag with profile characteristics that resist fouling up by weed and other forms of marine growth. It must accommodate, in the smallest possible space, the bevel-geared, forward and reverse drives to the propeller shaft.

The lubricating oil for the gearing must be retained without loss through the underwater seals and without risk of contamination by the entry of water into the gear-casing.

It must provide a cooling water inlet to the water pump that is immune from fouling up by weed or silt, and possess anti-cavitation features to assist the proper functioning of the propeller.

Finally, it must give shock-proof protection to the gearbox and propeller, when underwater obstacles are encountered, and provide an underwater outlet for the exhaust gases to be discharged into the propeller slipstream.

Most contemporary underwater units are similar in general principle, but may differ considerably in their detail design and in the means by which the forward and reversing drives are engaged. The simple, three bevel type of forward, neutral and reverse drive, with non-metallic oil and water seals and anti-friction bearings is now generally used. The gear selection is usually made by a rocking fork, or a cam actuated, sliding dog clutch and this has proved to be a simple and entirely satisfactory method of operation.

Our experience has shown that it is not usual for water to be found in the gearbox during a normal season's use. Nevertheless, on some occasions small quantities of water may be found. If correct grades of corrosion-inhibiting outboard motor gear oils have been used this is not usually detrimental.

However, running for long periods, particularly with sea-water in the oil, will, of course, accelerate corrosion and reduce life. It is therefore necessary to drain and refill with clean oil whenever water is found.

PROPELLERS

It is sometimes said that it is difficult to design a bad propeller and there may be some fundamental truth in this. It is not usually the propellers that are either good or bad, but more often the matching of the propeller to a particular engine and boat combination. This, together with the installation of the engine on the transom, is the most critical single factor in obtaining good performance.

Unfortunately, these variables are outside the control of the outboard motor manufacturer, and poor performance, from the use of an incorrect propeller, may sometimes arise.

For the convenience of most customers, and to ensure that a propeller is available wherever a motor may be sold, it is usual for the manufacturer to fit a tolerant, general purpose propeller that will accommodate a degree of mis-matching over a wide range of operating conditions. This allows the motor to be used, as purchased, with the assurance of a satisfactory performance on most types of outboard craft.

When special situations arise that demand a more accurate matching, to give best trolling, working, cruising or top-speed performance, alternative propellers specially designed for these activities may be fitted. The important point is that the engine must be allowed to run at its designed rev/min to avoid either serious overloading or overspeeding of the engine.

For reasons associated with size, weight and portability it has been convenient to run outboard motor propellers at rotational speeds in the region of 2500 to 3000 rev/min. This gives them an inherent disadvantage compared to inboard installations using lower propeller speeds, when relatively high thrust, at low forward speed, is required for moving relatively heavy craft.

It is to be expected, therefore, that with the increasing application of the outboard motor to work boat and commercial duties, alternative gear ratios will be required to allow larger diameter, lower speed propellers to be used.

A further important and somewhat controversial problem arises in connection with the propeller drive. Bearing in mind that the outboard motor is designed to tilt clear of underwater obstructions, it is perhaps natural that outboard motor users are more careless, when navigating shallow waters, than the owners of inboard craft, where a propeller 'foul up' can be an expensive matter to put right.

This has led to the adoption of a shear pin in the outboard motor propeller drive. This is designed to fail under heavy shock loads with the object of protecting both the propeller and the transmission from serious damage. Whereas a safety device of this kind may be quite acceptable when navigating in quiet inland waterways and, in practice, under most operating conditions, the failure of a shear pin in tidal or fast running waters is a more serious matter.

In consequence, although shear pins are still most widely used, there is a rising demand for cushion hub propellers which slip momentarily, upon impact, and thereby avoid the invonvenience and possible danger associated with a failed shear pin (Fig. 16).

NOISE AND VIBRATION

Effective control of noise and vibration, to a degree comparable with automotive practice, is an essential feature, being particularly important in connection with the larger and more expensive engines. In the very small sizes, around 3 hp, the familiar 'phut phut' is still tolerable, but there is a rising demand for low noise levels and in some countries they are enforced by legislation.

The problem of noise and vibration is obviously interrelated and originates from the powerhead. Other sources of noise and vibration exist, but these are not of importance until powerhead noise and vibration has been reduced to a relatively low level.

It is now common practice to reduce noise by total enclosure of the powerhead and to reduce vibration by rubber mounting. In a simple system, as used for the smaller and less expensive motors, a complete assembly,

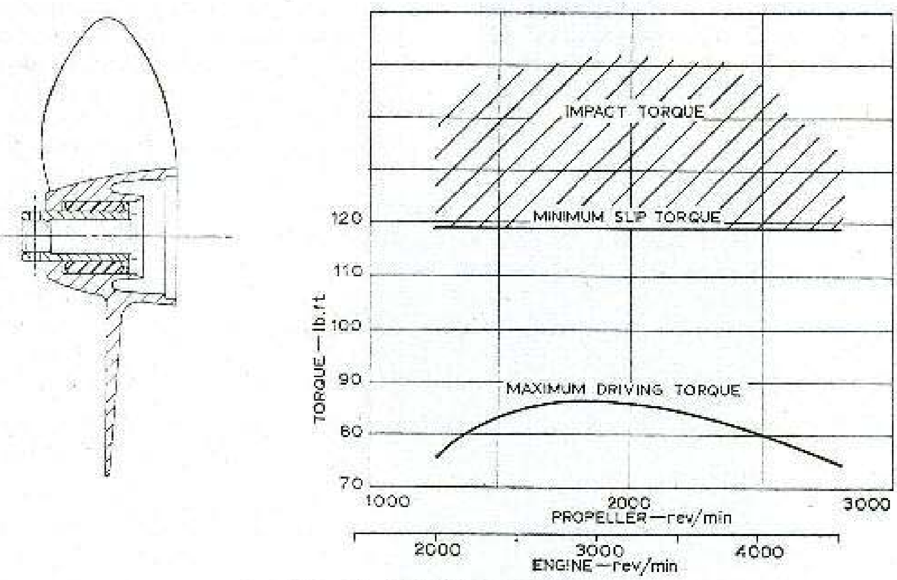


Fig. 16. Slip clutch propeller

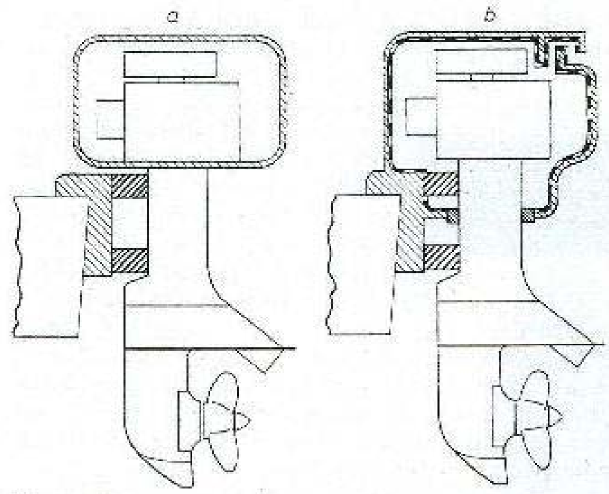


Fig. 17. Motor mounting and enclosure: (a) motor isolated from transom with shrouding attached to powerhead; (b) motor isolated from both transom and shrouding

comprising the shrouding, powerhead, transmission and underwater unit, is attached to the steering, pivot and transom clamping assemblies by rubber mountings (Fig. 17*a*). This system, which insulates the source of vibration and noise from the mounting assembly is simple and effective.

To be more completely effective, there must not be a sound or vibration conducting path between the engine, the shrouding and the boat. If resonance of the shrouding, or of the hull, should occur, and this can sometimes be particularly bad in glass-fibre hulls, this may produce an amplification of the noise or vibration with results that are less tolerable than the noise emitted by the engine itself.

An arrangement sometimes used for the larger and more expensive motors, aims at complete acoustical and vibrational insulation of the powerhead and transmission from the motor mounting and shroud. In this system, the shrouding, powerhead mountings, steering, pivot and clamping assemblies are rigidly attached to the transom, the powerhead and transmission assemblies being completely isolated by rubber mountings (Fig. 17*b*). This has proved to be a highly effective damping means, reducing both noise and vibration to relatively low levels.

A further improvement reduces the radiation of airborne noise from the powerhead by fitting to the shrouding a lining of relatively thick sound-absorbing material. To avoid fumes and fire risk this lining must be impervious to petrol and oil.

Considerable noise can also arise from the air intake and this must be effectively controlled. For the best comfort of the occupants of the boat a rear air intake is preferred. This can take the form of a simple labyrinth sound trap, lined with a sound absorbing material. By this means, the intake air can flow through the labyrinth at relatively low velocity and pressure loss and, at the same time, the outgoing sound wave energy will be drastically reduced by the reflecting surfaces of the absorbent lining (Fig. 18).

So far we have been concerned with noise and vibration as it may affect the occupants of the boat but noise can also be offensive to other users of the waterways and surrounding areas and this must not be overlooked. The engine exhaust is the main cause for concern and this must be reduced to a low 'purr' without excessive loss of power.

It is conventional to use an underwater exhaust discharging into the slip stream of the propeller. By entrainment, the exhaust gases are widely dispersed and adequately silenced. When properly arranged an extractor action can be obtained at high speeds with a significant improvement in the performance of the engine (Fig. 19).

For good starting and idling, the naturally aspirated two-stroke engine requires an unrestricted exhaust to avoid back pressure. This requirement is not met by the underwater exhaust, which may be many inches below the surface of the water at low boat speeds and is exposed

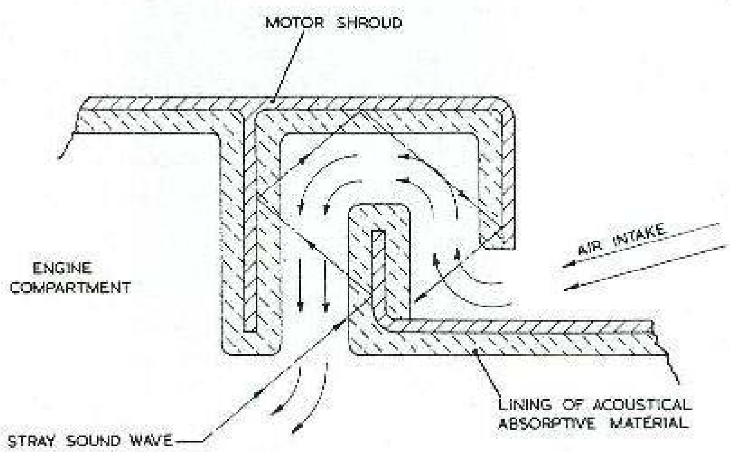


Fig. 18. Labyrinth air intake silencer

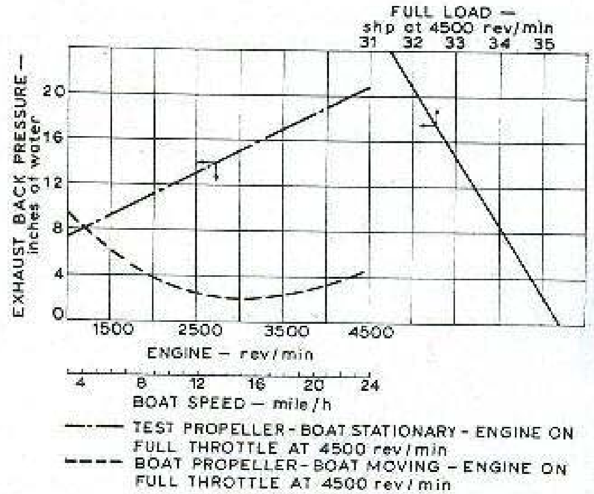


Fig. 19. Effect of exhaust back pressure, 40 hp outboard motor

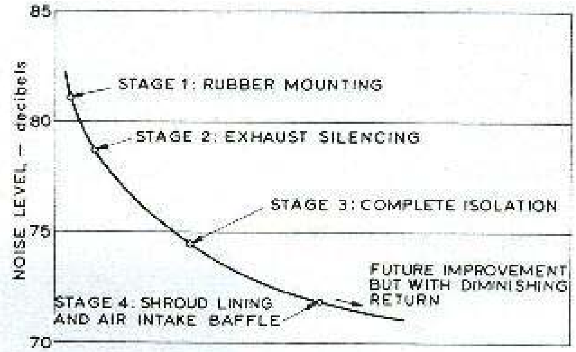


Fig. 20. Reduction in noise level (noise level at 25 metres distance and using 'B' weighting network)

to the dynamic pressure created by the action of following waves. This can create a back pressure in the exhaust pipe of sufficient magnitude to stop the engine, particularly when a fast hull loses speed rapidly after coming off the plane.

To solve this problem, an above-water, auxiliary exhaust system is employed. This permits the free passage of the exhaust gases to the atmosphere, through a simple, low-pressure loss silencer, at starting, idling and trolling speeds.

To prevent the emission of noise as the engine speed is increased, the auxiliary exhaust system is automatically closed by the rising level of the engine cooling water, causing the whole of the exhaust gas to be discharged downstream of the propeller.

To avoid the direct radiation of exhaust noise, from the surface of the transmission casing, a separate internal exhaust duct (Fig. 15) is employed. A proportion of the cooling water is discharged through this duct, to cool and reduce the volume of the exhaust gases, and the other proportion passes to the auxiliary exhaust system as previously described.

Thus there are four stages of modification that we have found necessary to achieve a very low noise level:

(1) Rubber mounting.
(2) Shroud isolation.
(3) Underwater and auxiliary exhaust system silencing.
(4) Air intake silencing and lining of the shroud.

The effect of these modifications on the noise level of a 40 hp motor is shown in Fig. 20.

CORROSION RESISTANCE

Although many outboard motors are used on freshwater lakes and rivers others are operated in estuary and coastal waters, often under tropical conditions of high temperature and humidity and high concentrations of dissolved salts.

In shallow waters highly aerated by incessant motion and in harbours and estuaries, corrosive attack may be aggravated by silt and sand erosion and by the discharge of factory effluent and sewage outfall. The outboard motor operates in a fully exposed position and the presence of these complex corrosive agents can exert a very destructive influence on the functioning, reliability, and life of the component parts.

During extensive testing of motors in many parts of the world, we have known them to be frozen for weeks in ice up to 15 inches thick, submerged in sea-water and washed over by the tide, blistered in the searing heat of the tropics, and left encrusted with salt on exposed moorings for many weeks at a time. After all this they are expected to remain in a perfectly serviceable condition and to give more or less instantaneous starting at the touch of a switch.

From this experience we have observed three quite distinctive problem patterns:

(1) Wet salt corrosion due to high salt concentrations and high humidity.
(2) Dry salt seizure of exposed bearing systems due to high salt concentrations and very dry air.
(3) Wear of exposed rotating parts by the abrasive action of high silt or sand concentrations.

The more serious problems that may arise from these conditions, and which must be prevented by the correct choice of materials and by good design, are:

(1) Corrosion of exposed surfaces causing a rapid deterioration in the appearance, sometimes leading to loss of strength and eventual failure.
(2) Corrosion, or salt or sand, freezing of exposed bearings.
(3) Corrosion freezing of steel bolts, studs or pins in light alloy parts, rendering dismantling very difficult, if not impossible.
(4) Corrosion and wear of those internal parts of the motor exposed to the action of the cooling water flow,

particularly the water pump and rotating or sliding seals.

(5) Corrosion of electrical equipment leading to eventual failure.

Effective resistance to these corrosive attacks has been achieved by the use of corrosion-resistant light alloys. These are given a chemical surface conversion treatment and primed and finished with a very high quality, oven-baked enamel. This enamel has been specially developed to have a high resistance to the action of sea-water and strong sunlight. Wide use is made of stainless steel for exposed shafts, screws and fittings, and less exposed steel parts are heavily cadmium-plated some three or four times thicker than normal commercial practice.

Mating parts are carefully matched, or insulated, to reduce corrosion arising from galvanic action and all screws, assembled in light alloy parts, are coated with a sea-waterproof lubricant to resist corrosion freezing and to facilitate removal.

The electrical equipment is specially designed and waterproofed and contact breaker springs are made from stainless steel to eliminate the risk of corrosive fatigue failure.

Extensive use is made of glass-fibre, plastic and nylon type materials and exposed bearing systems are pre-lubricated and sealed against the elements wherever design and cost considerations will allow.

These features, together with the total enclosure of the powerhead, allow the outboard motor to operate under conditions of severe exposure which are quite unique when compared with more conventional engine installations.

COMPARATIVE DATA

The outboard motor is a self-contained propulsion unit embodying in a common assembly, engine, transmission, gearbox, propeller, powerhead enclosure, mounting and controlling means. Thus it is a unique system not directly comparable with other power plant installations.

In the more powerful motors the two-stroke powerheads are a most interesting development and it is enlightening to compare these with other engine types.

Fortunately, information on the performance, weight, size and cost of conveniently small aircraft and automotive piston engines is available to enable this comparison to be made. Figures prepared from recent information for this purpose show that the outboard powerhead in terms of specific size, output, weight and cost, occupies a rather unique position, combining the high specific power output and low specific weight characteristics of the aircraft engine with the low specific cost of volume-produced automotive engines.

There are, of course, other important considerations which influence this comparison, particularly relative reliability, overhaul life and fuel consumption.

The small aircraft engine, in relatively low volume-production, must achieve standards of safety and reliability much higher than either the outboard motor powerhead or the automotive engine. To ensure this it will require, and receive, meticulous and regular attention on a scheduled inspection and maintenance basis. Because of its influence on range and payload, low fuel consumption will be a particularly important feature. Engines of this type, for obvious reasons, are relatively expensive.

The automotive engine, with the inherent cost advantage of large volume-production, must run for long periods of time without any, or with very little, attention. The risks involved in doing this are relatively slight and a much lower standard of reliability is acceptable. Low first cost is vital and low fuel consumption important in Europe, but not so important in the U.S.A.

The outboard engine production rate will be much higher than that of the small aircraft engine, and much lower than that of the automotive engine. Within these limitations it must achieve the small size, low weight and high specific output of the aircraft engine at the low specific cost of the automotive engine. In service it may be exposed to severe climatic and corrosive conditions and considerable neglect. Fuel consumption will not be a vital consideration owing to a much lower annual utilization, and will be relatively high at 0·8 to 0·9 pints/bhp h. Overhaul life will be in the region of 250 hours for a top overhaul and 500 hours for a complete overhaul. In this connection it is interesting to note that the outboard engine, unlike the automotive engine, may be running at maximum revolutions throughout its operating life.

On the question of reliability and component defect rate the outboard motor must be at least up to automotive engine standards, engine failure being an obvious hazard to safe navigation when operating in coastal or estuarine waters or in fast running streams.

A comparison of costs is given in Fig. 21 and other details are shown in Figs 22, 23, 24 and 25.

CONCLUSIONS

The author has prepared these notes with the object of highlighting some of the problems associated with the

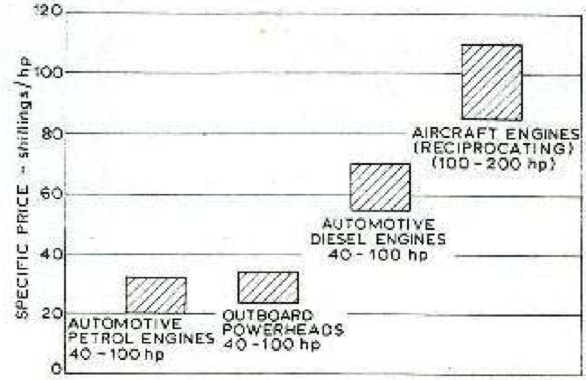


Fig. 21. A comparison of specific cost per hp of reciprocating engines

design, development and production of outboard motors that may not be noticed during a passing association or simple operational experience. He has purposely avoided such controversial issues as 'deflector' versus 'flat top' pistons as they have not been part of the work done. Features of this kind normally reach maturity by selection of the most satisfactory configuration for particular applications, or as a result of development experience and customer preference.

During our work on outboard motors we have had to concentrate on so many new and entirely unsuspected problems that we have not had the time to analyse and

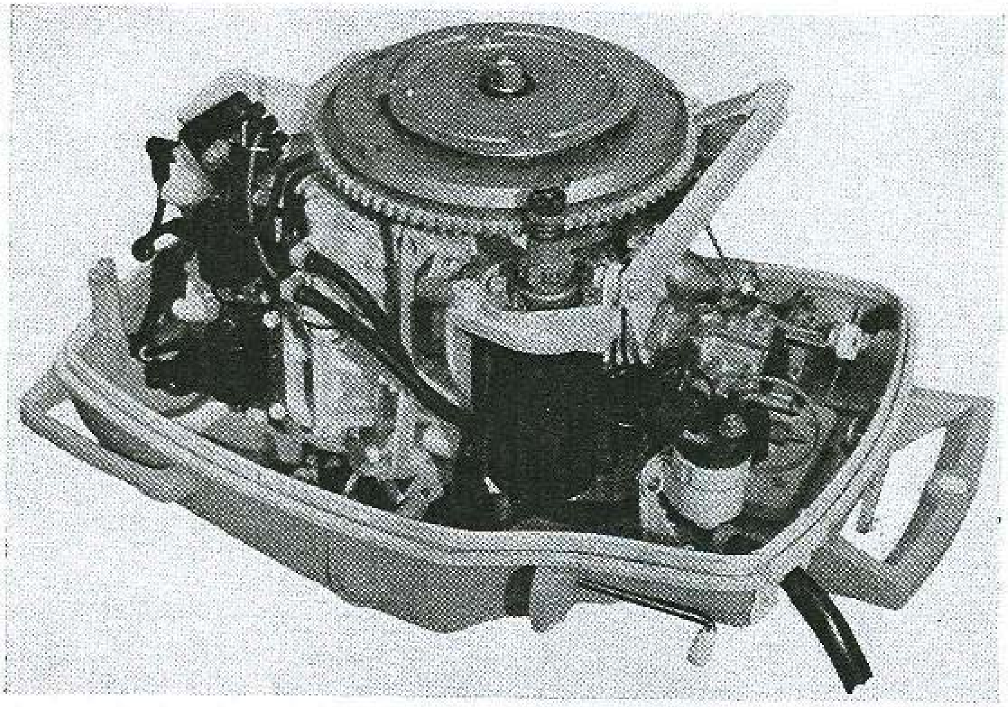


Fig. 22. Powerhead installation, 40 hp motor

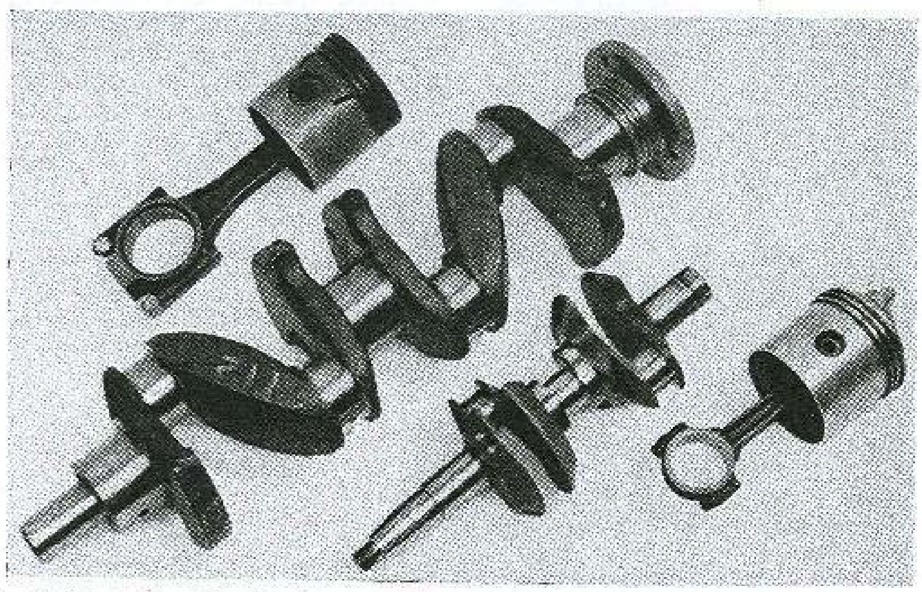


Fig. 23. Comparison of outboard motor and automotive crankshafts, both rated at 20 hp per cylinder

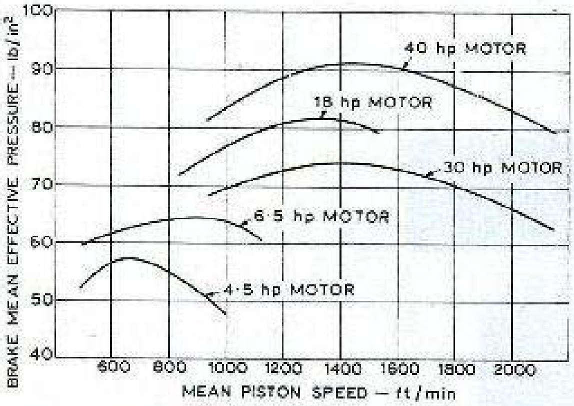
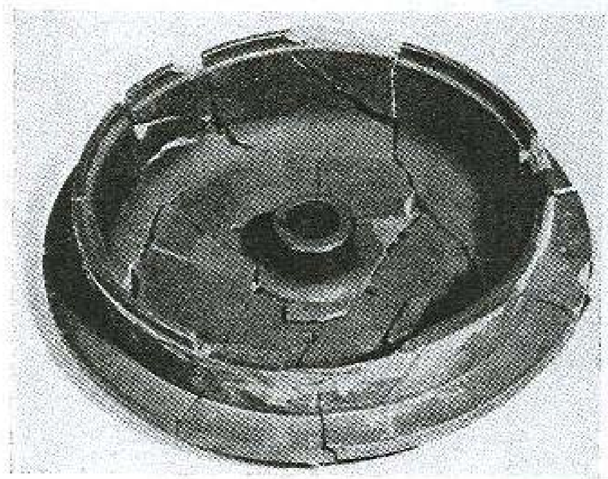


Fig. 24. Brake mean effective pressure against mean piston speed



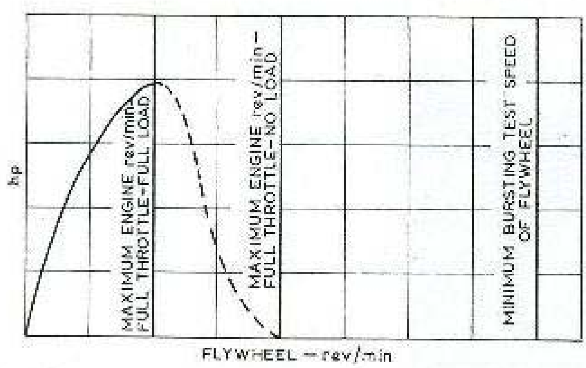


Fig. 25. Design safety factor for outboard motor flywheels

report on the results obtained, or to compare the respective merits of the 'flat top' and 'deflector' configurations. It may be significant that virtually the whole of the world's output of outboard motors is fitted with deflector pistons.

It could be argued with considerable justification that the flat top piston will give better combustion and scavenging, lower fuel consumption, lower piston crown temperatures and less frequent plug fouling and whiskering and better engine balance due to its inherently lower piston weight.

Significant advantages of this kind have been demonstrated on certain small bore motor cycle engines and on certain light car engines. These results are clearly a valuable indication of future possibilities, but it would seem unwise to assume from this that the flat top piston will be equally satisfactory in the big bore engines used for outboard motors. In connection with this the author wishes to emphasize the quite considerable effect of the variable exhaust back pressure on the running of an outboard engine.

In the absence of actual operating experience it is prudent not to pre-judge the possible results. Nevertheless, a degree of optimism would appear to be more than justified.

During many thousands of hours of test running experience with high output two-stroke engines, the author has been very impressed by the obvious potential of the two-stroke powerhead for further development. It would seem that with greater attention to problems associated with ignition, lubrication and gas dynamics, a family of truly light-weight two-stroke engines of high specific output and reasonably low fuel consumption could be developed. These engines would not necessarily compete 'head-on' with existing engines, but may occupy a very useful 'half-way house' between the four-stroke engine and the small gas turbine.

With regard to the outboard motor, the author believes the industry to be on the threshold of entirely new standards of 'startability', reliability, endurance and silence. This will do much to ensure a high standard of functional capability and to stimulate demand.

This paper is written to identify some of the less obvious features and problems associated with the outboard motors. Much more could be written about many of the subjects discussed, but in most engineering projects early identification of the problems is of first importance, it being a matter of routine and perseverance to find the answers.

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APPENDIX

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