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Hovercraft Propulsion

by

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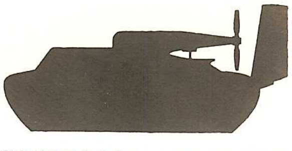

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Hovercraft Propulsion

Mr. Lindsey was educated at Liverpool Institute High School and Selwyn College, Cambridge. He joined Armstrong Siddeley Motors Ltd. as Apprentice (Pupil) in 1933 and became Deputy Chief Engineer in 1945, and Chief Engineer in 1950. In 1952 he became a Director of this Company and was Technical Director from 1956–1959.

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In a comparatively short paper such as this it is quite impossible to cover adequately the whole field of hovercraft propulsion. The author has therefore decided to confine his attention to the more restricted field of the propulsion of " Marine " or rather amphibious hovercraft of the flexible skirt type. This limitation in the scope of the paper has the additional advantage that most practical operational experience today has been obtained with this type of vessel.

basic propulsion requirements

Unlike other vessels the hovercraft always uses a proportion of its " propulsive " power to produce the direct lift required for hovering and this proportion varies from 100% during static hover to about 40% at full speed. Fig. 1 shows the effect of this characteristic in the shape of the curve relating the b.h.p. required from its propulsion machinery to its forward speed. For comparison a typical curve for a Fast Patrol Boat of about the same size is also shown. Two features of the hovercraft curve are immediately apparent. One is the high power required at very low speeds due to the lifting fan and the second is the pronounced " hump " in the curve at about 20 knots which is due to the hydrodynamic behaviour of the water surface under the craft and is analogous to the " hump " which occurs in the curve for a hydrofoil.

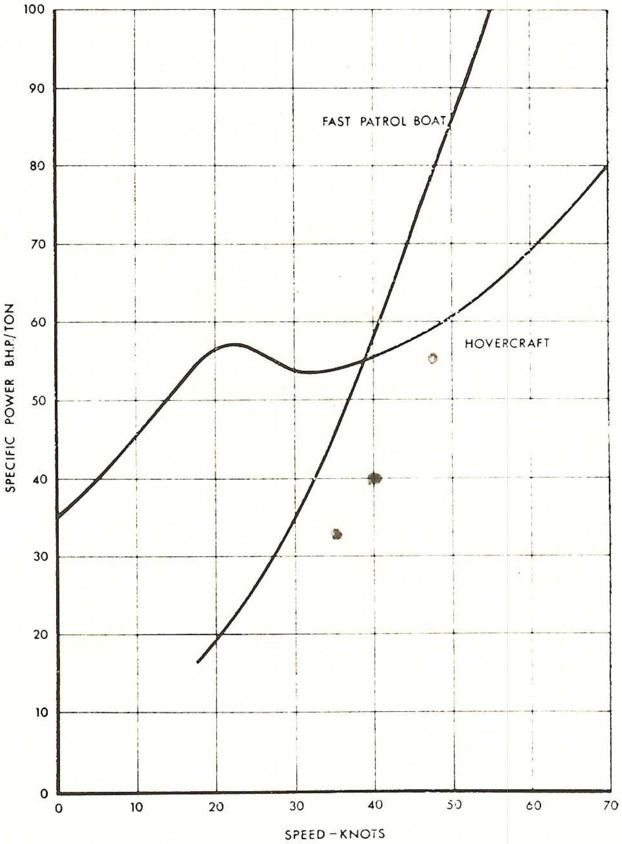


Fig. 1. Variation of specific power (bhp/ton) versus speed for a hovercraft and a fast patrol boat

TABLE I
COMPARISON BETWEEN GAS TURBINE AND DIESEL ENGINES

Weight Category	Gas Turbine %	Diesel Engine %
Basic craft less engines	56·7	56·7
Engine	3·6	25·0
Fuel	9·4	5·7
Payload	30·3	12·7
Total	100·0	100·0

Endurance	4 hours	
Diesel	Weight	7 lb/bhp
	Sp. cons.	0·385 lb/bhp.hr.
Gas turbine	Weight	1·0 lb/bhp
	Sp. cons.	0·65 lb/bhp.hr.

It is obvious from Fig. 1 that it is only at the high speed end of its speed range that the hovercraft develops its superiority to the more conventional vessel and that despite this great superiority it still requires a high specific power amounting to some 80 b.h.p./ton at 70 knots. Specific powers of this order lead to an engine requirement where specific engine weight is the overriding consideration.

The marine gas turbine based on aero engine background is therefore an obvious choice. In fact it is not going too far to state that such an engine is the only possible choice. Table I shows the effect of substituting Diesel engines with a specific weight of 7 lb./b.h.p. for gas turbines weighing 1 lb./b.h.p. in a 150-ton hovercraft.

Despite the much reduced fuel consumption of the diesel engine the payload is reduced by 58% for an endurance of four hours. Such a penalty in payload is quite unacceptable.

The propulsion problem as far as engines are concerned therefore reduces to that of finding the best available gas turbine engine and ensuring that its installation arrangements provide safe and reliable engine controls and protect the engine from environmental hazards.

To some extent the "lift" or "propulsion" roles of the engines can be considered separately. In fact some hovercraft have had not only different engines for lift and propulsion but different engine types. The first experimental SRN.1 for example used a reciprocating petrol engine for driving the lift fan and a small turbo-jet engine for propulsion.

The proportion of power required for the two functions is a very variable quantity in the wide range of operational conditions and if separate engines are used it is necessary to provide a total engine installed power which is the sum of the maximum power requirement at any time for the two purposes. This power is generally considerably in excess of the maximum power required for both purposes at any one time. Any reduction in total installed power not only reduces power plant cost but also reduces power plant weight which is an important benefit.

It is therefore usual to combine the lift and propulsion drives as is shown in Fig. 2, which shows diagrammatically the arrangement of the single Gnome engine in an SRN.5 hovercraft. The engine is connected via a bevel gearbox to the lift fan and drives the propeller directly. The pitch of the propeller can be varied so as to reduce or increase the power required at any r.p.m. over a wide range. The fan power is a function of the r.p.m. alone — roughly a cube law.

It is a feature of this arrangement that the gas turbine chosen must be of the free turbine type, that is that the power turbine speed must be independent of the power level selected which is a function of the speed of the engine's compressor turbine shaft. Thus the lift power can be altered by varying the power turbine speed while the propulsion power is varied by altering the propeller pitch.

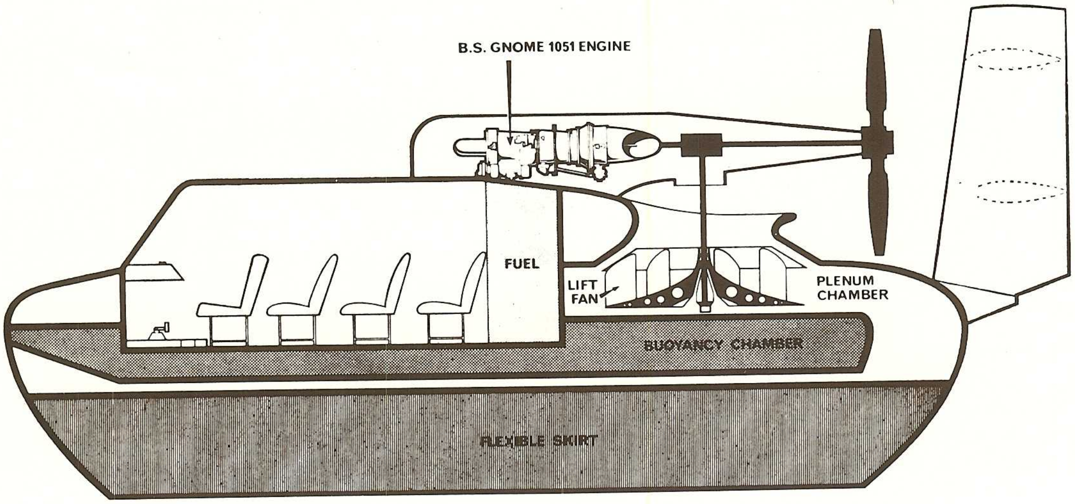
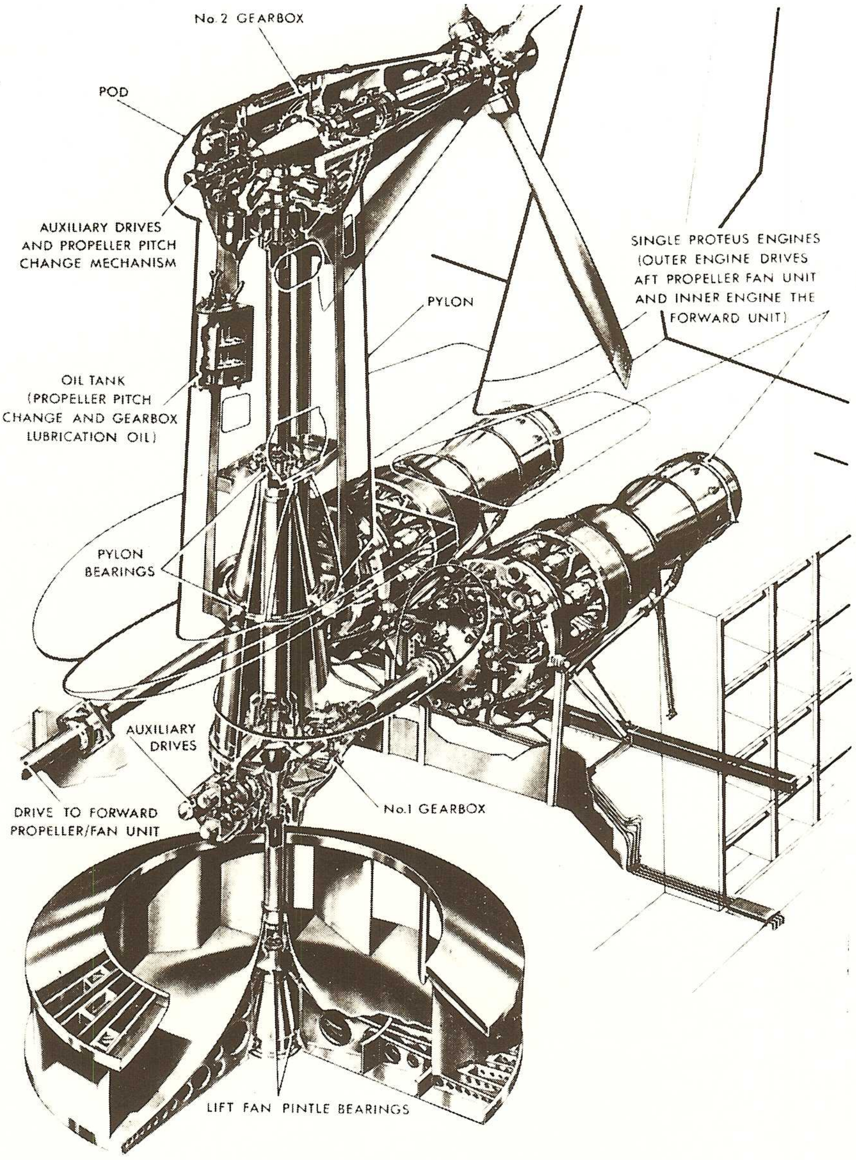


Fig. 2. Diagrammatic arrangement of the Gnome engine in an SRN.5 hovercraft

Fig. 3. Installation of Proteus engines in the SRN.4 hovercraft



The development of a free turbine engine of this type is a very expensive and lengthy process and it is unrealistic to imagine that the possible hovercraft market could support the development of a suitable engine. Fortunately eminently suitable engines are available from the aircraft engine industry which by means of comparatively minor but important modifications can be adapted to their new role.

The fact that the hovercraft designer is faced with the necessity of using existing engines does influence the range of hovercraft size which is possible. He can choose the number of engines used in the craft but this number will probably be between one and four. Single engined craft are the cheapest and simplest solution although the questions of manoeuvrability, safety and reliability are better answered with multi-engined craft while the comparison with the aircraft world leads one to believe that with more than four engines availability will suffer and costs will tend to rise unacceptably.

On this reasoning larger hovercraft will need larger engines. The present range of sizes used covers the SRN.5 and SRN.6 with a single Gnome engine with a cruise rating of 900 b.h.p., to the SRN.4 with four Proteus engines giving a cruising power of 13,600 b.h.p. If craft size and therefore power requirements increase to multiples of the SRN.4/Proteus size it does not seem that engine availability will be the main problem. Marine gas turbines based on aero engines can certainly cover a power range up to units of 25,000 b.h.p. but the problem then arises of how to convert such large units of power into lift and propulsion. To achieve adequate propeller efficiency at what are by aircraft standards very low speeds, propeller disc loading must be kept low and very large propellers would be needed. Not only is the design of suitable propellers difficult but the problem of installing them in the craft and providing the necessary transmission is formidable. Other methods of propulsion such as water jets are already being considered but the fact remains that the provision of suitable means of using the engine power for propulsion and lift is one of the most difficult problems facing the designer of future very large hovercraft.

At the present time two engines from the Rolls-Royce range have become hovercraft engines. These are the Marine Gnome and the Marine Proteus — both are modified aero engines. Only the Gnome has up to the present had actual experience in hovercraft propulsion and has already some 39,000 hours of operational experience. The Marine Proteus has however been used widely as a marine engine in numerous high-speed vessels — these engines have achieved some 41,000 hours operation at sea. Table II shows the range of hovercraft which fit these engines.

power plant installation

The power plant installation design involves two main considerations :

(a) The mechanical installation of the engine, its control system and the transmission system to the propeller and lift fan, and,

(b) The arrangement for protecting the engine from the effect of difficult environmental conditions.

The main mechanical features of a typical installation are well illustrated in Fig. 3 which shows the Proteus installation in the British Hovercraft Corporation's SRN.4.

TABLE II
HOVERCRAFT TYPES AND ENGINES USED

Hovercraft Type	*Engine*	*No. of engines*	*Total cruise power bhp*	*Craft A.U.W. tons*
SRN.5	Marine Gnome	1	900	7
SRN.6	Marine Gnome	1	900	9·2
SRN.3	Marine Gnome	4	3600	37·5
BH.7	Marine Proteus	1	3400	45
BH.8	Marine Proteus	2	6800	80
SRN.4	Marine Proteus	4	13,600	165

The engine mounting is straightforward and the engine power is delivered by 1,500 r.p.m. shaft from the free power turbine via a reduction gear in the front of the Proteus. The power is taken into a spiral bevel reduction gearbox having output shafts at the top and bottom of the box to the vertical propeller and fan driving shafts respectively. This gearbox is equipped with a power take-off to drive an auxiliary gearbox with drives for pressure and scavenge lubricating oil pumps and also a hydraulic pump for the pylon and fin steering controls.

The upper gearbox mounted on top of the pylon turns the propeller drive through 90 deg., with a speed reduction of 1.16/1. The centrifugal fan is directly driven by the lower vertical shaft.

Fig. 3 shows one pair of the four engines in the craft;

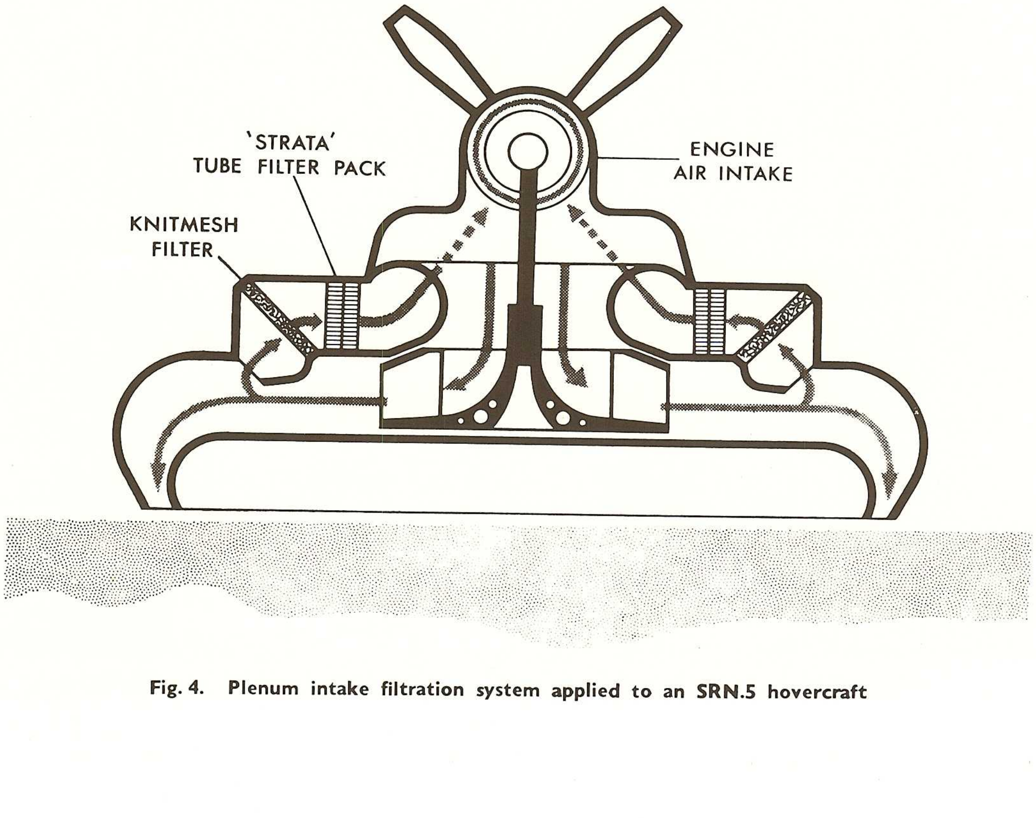


Fig. 4. Plenum intake filtration system applied to an SRN.5 hovercraft

Fig. 5. An SRN.5 hovercraft operating in heavy sand cloud during static hover

the second engine of the pair drives a similar pylon system mounted forward through a cardan shaft which forms an extension of the engine output shaft.

The pylons are rotatable through ±35 deg. for control purposes.

Although this seems a complicated mechanical system it has been designed on similar lines to the earlier systems in the SRN.2, SRN.3 and SRN.5 hovercraft and operating experience has shown the whole transmission system to be remarkably trouble free.

As yet there has been no operational experience on the SRN.4 and it is necessary to look at its smaller sister the SRN.5 for practical experience of environmental conditions.

One of the most remarkable features of hovercraft history to date has been the extraordinary rate at which operating experience has been obtained and the wide range of environments in which craft have already been operated. From this point of view it is the ability of the hovercraft to operate over widely differing terrains which has yielded this experience and also set the designers of the craft and its power plant a variety of problems which had to be solved quickly.

Naturally it is the military authorities who have explored the more exotic conditions but all the environmental problems are met in greater or less degree by ordinary commercial users.

As far as the engines are concerned the main hazards can be summed up by what has come to be known as the Three S's—Salt, Sand and Snow.

The ingestion of salt laden air into a gas turbine engine can lead to both temporary loss of power and permanent damage to the hot portions of the engine — in particular the turbine blading. Fortunately the problems had already been met in operating the Marine Proteus and other engines at sea, particularly in Fast Patrol Boats. The fight against salt has been well documented and the position can be briefly stated that by careful attention to salt excluding devices in the intake and by special modification to the engine to minimise its susceptibility to salt corrosion, permanent damage due to salt can be reduced to an acceptable level at the maximum gas temperatures that are used today in marine turbine engines. The fact that hovercraft produce more and better spray than other vessels has not proved to be a special difficulty as the Knitmesh filters used are most effective even in these conditions. The temporary loss in power due to salt accumulation in the compressor blading in exceptionally severe conditions can be counteracted by the permanent installation of adequate washing facilities.

The battle with salt is however not yet completely won but the hovercraft engine is in no worse position than other marine turbine engines in this respect. The rapid increase in sea going experience with many types of marine turbine engines throughout the world will ensure continued improvement in the effectiveness of salt protection.

It became evident very early in the history of hovercraft operation that sand ingested into the turbine engines could cause serious trouble with compressor blade erosion. The damage is cumulative and depends upon the amount and particle size of the sand in the air and the time the craft has to operate under these conditions. Although great progress has been made in keeping sand out of the engines their life is inevitably reduced when operating in sandy terrain.

Fig. 4 shows the intake arrangements made for operating under desert conditions. The severity of these conditions can be seen in the picture of an SRN.5 hovering in the Libyian desert shown in Fig 5.

A very useful degree of momentum separation is first obtained by taking advantage of the centrifugal effect of the lift fan. The air for the engine is taken

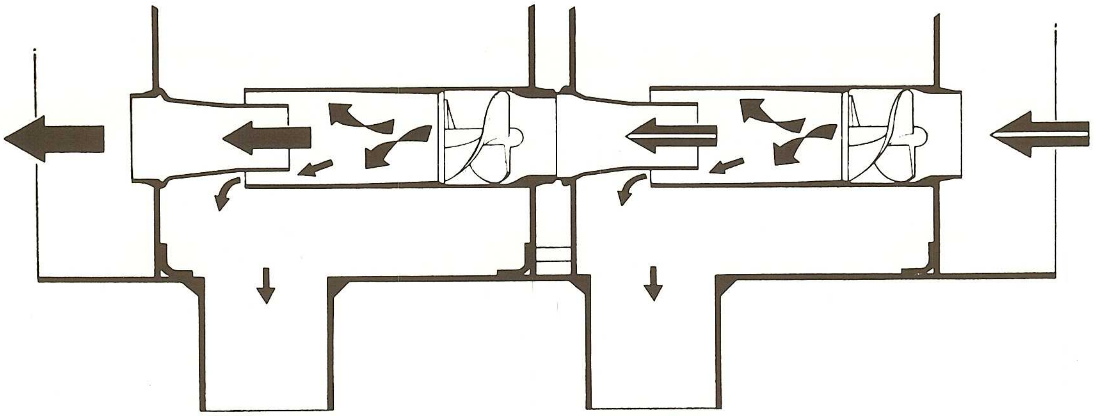


Fig. 6. 'Strata' vortex separator tubes

from the lift fan plenum chamber, turned through an acute angle and then passed through a standard Knitmesh filter bank and then through a bank of vortex separators known as "Strata" tubes.

Fig. 6 shows the vortex separators in more detail. There are two banks of these "Strata" tubes in series and rig tests showed that they have a separating efficiency of 99% for particles of five microns. In conjunction with the separation already achieved by the main lift fan this means that only a very tiny proportion of damaging particles should reach the engine.

These results were confirmed during trials of an SRN.5 craft in the North African desert which involved some 32 hours of engine operation under appalling sand cloud conditions. The engine behaviour was satisfactory throughout the trials and the subsequent strip of the engine showed negligible blade erosion. The Gnome engine fitted to the craft has very tiny compressor blades which are known to suffer severely from erosion in quite mild conditions of sand ingestion if proper filtering is not provided.

The basic intake arrangement described above without the Strata panels has been shown to be very effective under arctic conditions. Before conducting arctic trials there was considerable doubt about ice formation in the intake and possible complete blockage of the Knitmesh filters with snow or ice particles, although the engine itself was equipped with the normal anti-icing features.

During the trials at the mouth of the MacKenzie River in North West Canada temperatures ranged from about freezing point to −25 deg. C. It was found that by arranging for the engine exhaust gas to mix with the air entering the lift fan sufficient preheating of the intake air could be achieved to avoid any trouble. Like all gas turbines ample power is available under cold conditions and this pre-mixing did not affect the craft performance. The engine exhaust remained clean enough to avoid any deterioration of the engine due to exhaust products.

It has been possible therefore to show in a short space of time that the difficult operating conditions which can be met due to the very versatility of the hovercraft can be dealt with provided the proper precautions are taken.

engine maintenance

In such difficult conditions the cost of operation is of secondary importance as the provision of rapid transport in such conditions is the main objective.

In normal commercial operation however the cost of operation is a very vital matter and the purchase, operation and upkeep of the power plants is a significant proportion of the total cost.

It has been shown earlier in the paper that due to the high specific power required for hovercraft the gas turbine engine is a necessity. It is unfortunate that small gas turbines are expensive engines and in fact for a given degree of sophistication there is a relationship between engine size and engine cost/h.p. Very approximately over the range of 1,000 h.p. — 30,000 h.p. the price/h.p. will vary inversely with the cube root of the power for similar types of engine.

Fuel costs/h.p./hr. will be the same on the assumption that the engines are similar in other respects than size.

Repair and maintenance costs depend upon how much it costs to overhaul the engine and how often must this be done.

Considering first the overhaul cost this can really be divided into three sections :

(i) The cost of stripping, inspecting, rebuilding and testing the engine.

(ii) The cost of supplying new parts to replace those damaged or worn in service

(iii) The cost of supplying new parts which have reached their retirement life

The cost under section (i) is constant for a given engine while that under section (ii) will tend to vary, being of course less for an engine which has been used carefully.

Section (iii) needs further explanation. Lightweight gas turbines have a number of highly stressed rotational components which under normal running conditions run at comparatively high temperatures. Every time an engine undergoes a start-run-stop cycle each of these components undergoes a stress cycle largely due to centrifugal stresses but also due to temperature stresses incurred during the warming-up process.

The engine therefore behaves as a sort of fatigue test machine and if it is possible to take this fatigue process to failure not only will the component break but in the case of a heavy item — for example a turbine disc — the broken parts could not be contained in the engine and form a very real safety hazard. The licensing authorities — in the case of this country the Air Registration Board — whose job it is to ensure public safety, insist that the safe fatigue limit is never exceeded. Although design criteria are of importance in this respect clearance can only be obtained by an actual demonstration that the component in question has actually been subjected to more cycles without failure than can occur during the service life of the part before retirement.

Retirement lives of certain vital parts are usually increased by taking a part which has reached its current retirement life and subjecting it to further cyclical tests in an engine on the test bed and showing it still remains free from failure or signs of failure.

In the case of an engine such as the Proteus which has a long background in civil aircraft, this process is largely completed and it is only the different operating conditions in a hovercraft that need review. In the case of the Gnome, hovercraft quickly outran helicopter experience and the process of demonstrating improved retirement life capability is still proceeding.

From the point of view of retirement life hovercraft engines are badly placed due to the very short time cycle involved in a normal hovercraft service. For example, on even a comparatively long crossing such as the English Channel the engine will be subjected to more than twice the frequencies of engine cycling than is normal in current airlines, and hence the retirement life of the engine components will be half that for the same engine in an aircraft. On shorter passages the situation is, of course, worse, although some alleviation can be obtained by leaving the engine at idling at the end of a passage.

To sum up this analysis of routine overhaul costs, the cost of engine overhauls in terms of cost per operating hour can be written :

$$Cost/hour = \frac{A + B + \sum \frac{C}{R/H_0}}{H_0}$$

where A is the fixed charge for stripping, inspecting and rebuilding an engine

B is the cost of replacing worn out parts

C is the cost of replacing parts that have reached their retirement life

H_0 is the declared Time Between Overhauls

R is the retirement life of the special parts affected

B will depend to a large extent on the route over which the engine is operated and on the care with which the engine is operated. It is also affected by H_0 as some parts of the engine just wear out at a constant rate and for these parts $\frac{B}{H_0}$ is constant.

C is nearly a fixed sum for any engine but it is obviously desirable to have R/H_0 as big as possible. In any case R/H_0 must be a whole number and for the most difficult component in hovercraft operation over short routes it will probably be 2 but can easily be 1.

All the foregoing refers to routine overhauls only and take no account of the additional running costs incurred due to premature failures for any cause. In the early stages of any operation these premature failures tend to be frequent and therefore have a very pronounced effect on operating costs. It is important to diagnose the causes of these failures quickly and to eliminate them if the operation of the craft is to be economically viable.

Increasing the T.B.O. (H_0) and the retirement life of parts is necessarily a slow process as it is the behaviour of the engines themselves in service which provides the necessary data. The process is speeded up as far as is safe and practicable by the practice of "leap frogging" engines. In this method certain engines which reach their declared overhaul time are treated as samples and if they are in good condition the T.B.O. of other engines in service is increased and the first few engines reaching this new T.B.O. are in their turn treated as samples. However as T.B.O.'s increase to 1,500 hours and above, information on which to base further extension of T.B.O. is gained rather slowly unless a very large number of engines are in service.

All this is very unpleasant both for the pioneer operator and the pioneer engine supplier. The early costs are inevitably high and someone must pay them. The use of established engines is very helpful in this respect as to a large extent the cost of this learning has already been paid.

The history of the SRN.3, SRN.5 and SRN.6 hovercraft provides an extreme example of the problems and expense involved in this process.

Not only were the craft and the engine small which increased specific costs but the operating conditions that were to be met were largely unknown and proved at times to be very difficult. In addition the engine itself although possessing an impressive background of operation in military helicopters had not been developed to the point where it would achieve long times between overhauls.

It first started serious hovercraft work in 1964, only three years ago, and in that time the engines have built up a total of nearly 40,000 hours of operation. It is also fair to say that during the period the engine has been used as a "trial horse" not only for the suitability of the hovercraft as a commercial passenger carrying vehicle but also to a large extent for the formulation of the rules for certification.

Despite this the T.B.O. has been raised from 500 hours to 1,500 hours and much of the background has been obtained for a further increase to 2,000 hours. There has been, perhaps understandably, some 37 premature failures up to October 1967 and Table III gives details of the occurrences and the reason for them.

Nearly 60% of these have been due to three causes :

(i) *Compressor blade erosion.* This is an ever present hazard if the craft is operated over sandy or dusty terrains without the provision of the filtration system which has recently been developed. Even with the system fitted engine life will probably be shortened if the craft is used in desert conditions.

(ii) *Turbine "burn-out".* Although improvements to the automatic engine protection system and

TABLE III
PREMATURE REMOVALS OF MARINE GNOME ENGINES FROM SRN.5/6 HOVERCRAFT
(as at 31st October 1967)

Reason for removal	*Number of removals*			*Removal as %*
	Civil craft	*Military craft*	*Total*	
Power turbine blade tip rub	1	–	1	2·7
Compressor blade erosion	3	4	7	18·9
Compressor foreign object damage	2	2	4	10·8
Engine immersed in sea water	1	1	2	5·4
Fire in turbine exhaust	1	–	1	2·7
Turbine overheated	9	2	11	29·7
Oil sump cracked at Stage 3 nozzle	3	–	3	8·2
Compressor front bearing oil seal failure	1	–	1	2·7
Compressor 5th stage blade failure	1	–	1	2·7
Turbine rotor seizure	1	–	1	2·7
Power turbine No. 5 bearing failure	2	–	2	5·4
Reported excessive vibration	–	1	1	2·7
Fuel pump and c.f. filter over-tight	1	–	1	2·7
Inability to start (excess carbon build-up)	1	–	1	2·7
TOTALS	27	10	37	100·0

more experience of engine handling by the drivers have greatly reduced the frequency of these failures in recent times, it is now thought that some positive means of restricting the rate of engine throttle movement, which would be quite acceptable from the operational point of view, must be provided if such expensive failures are to be eliminated.

(iii) *Compressor foreign object damage.* Fitting a suitable wire mesh grille over the engine intake has largely overcome this problem.

With the advent of the larger hovercraft powered by the Proteus engine, engine maintenance cost/h.p. will be substantially reduced. Not only is the engine appreciably cheaper in terms of cost/h.p. due to its larger size but its much greater background of experience both as a civil aircraft engine and as a marine engine give it a much better start as regards T.B.O. and the retirement life of its components. Once the teething troubles are over progress in the reduction of engine maintenance costs should quickly lead to a figure for the Proteus of the same order as that for the Gnome today, which means a specific cost of between half and one third of the Gnome figure.

the future

The future pattern of hovercraft propulsion is difficult to see. Certain aspects however seem fairly clear and may be stated as follows :

(i) Hovercraft like other high speed craft will need lightweight engines.

(ii) The most likely source of suitable engines will be marinised aircraft turbine engines. These can be made available over a range of sizes which will cover every conceivable need but the range will be covered by a number of discrete engine sizes round which the craft must be designed.

(iii) The maximum engine size that can be used with the present conception of lift fan/airscrew propulsion power plant is approached with the Proteus installation. Unless multi power plants are accepted with the resulting real difficulties of complexity and craft availability, new propulsion means must be found to suit really large craft.

(iv) It is difficult to imagine the application of large powers with an acceptable propulsion efficiency at about 70 knots without resorting to some form of water propulsion. For a purely marine craft modern propeller developments and the rapid progress of water jet propulsion would seem to provide an adequate solution. Even in the marine case this destroys the true hovercraft's great advantage of being able to get out of the water for high speed but acceptance of the implication of water propulsion might well lead to improvement in manoeuvrability. Fortunately the capability of amphibious operation tends to become less important in the larger sizes of craft.

(v) One might therefore hazard a guess that on power plant considerations the "true" hovercraft will not grow in size much beyond that which can be propelled by engines of up to 5,000 h.p. Bigger craft will be purely marine craft which will remain in contact with the water and use the water for propulsion.

(vi) These craft will require high power lightweight turbines, perhaps up to 30,000 h.p. and it is likely that a water jet propulsion system of some type will have to be developed. This is a formidable task and before it could become a practicality the problems of water jet propulsion will have to be solved in the smaller sizes. This will undoubtedly result in a new generation of craft of the same size as those of today but designed as true ships with water jet propulsion.

acknowledgments

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