

Design, Development and Trials of the AP.1-88 Hovercraft

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Read in London at a meeting of the Royal Institution of Naval Architects on April 12, 1984, Professor K.J. Rawson, M.Sc., R.C.N.C., F.Eng. (Vice-President) in the Chair.

SUMMARY: BHC's diesel powered craft, the AP.1-88, is a major step towards the production of a cheap and commercially viable amphibious hovercraft. The application of new skirt technology has enabled the power requirements to be greatly reduced and this, in conjunction with Hovertravel's experience in operating SR.N6s, has led to the design and construction of a replacement craft which has considerably reduced first and operating costs, is quieter and more robust than previous types. The first AP.1-88 entered passenger service across the Solent in March 1983 followed by the second craft in July. The paper includes a description of the craft, an insight into the design philosophy and concentrates on the trials and development and the changes incorporated into the production craft.

1. INTRODUCTION

The AP.1-88 (Fig. 1) was designed to meet the need for a medium sized, relatively simple amphibious hovercraft which would be cheaper in first and operating cost, quieter and more robust than the previous generation of craft produced by BHC.

Hovertravel Limited, who had operated the SR.N6 craft between the Isle of Wight and the mainland since 1965, had an urgent need for a replacement craft to put their operation on a more economic footing. Of similar significance was the pressure from environmentalists in the Solent area to reduce noise levels, with the renewal of Hovertravel's licence to operate being in doubt unless noise levels were reduced.

The development of the low pressure ratio, deep fingered skirt during the late 1970s significantly reduced the power requirements of amphibious hovercraft. The two SR.N4 Mk.2 craft operated across the Channel by Seaspeed (now Hoverspeed) were stretched by 55 ft to the Mk.3 or Super 4 configuration, increasing the all-up-weight from 200 to 300 tons and the payload by about 80%. This was achieved with only a small increase in power, the overall hp/ton being reduced by 25%, as illustrated in Fig. 2 (extracted from Ref. 1).

The AP.1-88 utilises these advantages in a different way, sacrificing the potential payload increase for the opportunity of using heavier, but considerably cheaper, power plants and structure.

2. DESIGN AND BUILD

The craft concept which evolved was a 60-90 seat craft based on the scaled-down planform of the SR.N4 Mk.3. The preliminary design studies had included an extensive programme of tests using the SR.N4 Mk.3 model and also a new AP.1-88 model. A cut-away illustration of the craft is shown in Fig. 3 and the leading particulars are given in Table I. This table shows the differences between the prototype configuration and the production version and also gives comparative data for the SR.N6 Mk.1S.

The detail design and building of the two pre-production/prototype craft were financed under a joint funding agreement between Westland plc, NRDC (now British Technology Group) and Hovertravel Limited. Under this agreement,

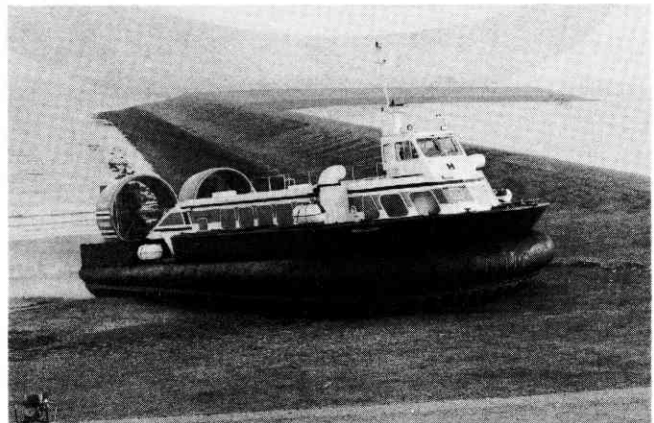


Fig. 1. AP.1-88 Prototype Craft

Hovertravel contributed their invaluable experience gained from fifteen years of hovercraft operations, prepared the drawings of the detail parts and carried out the final assembly of the craft. BHC, as the design authority, carried

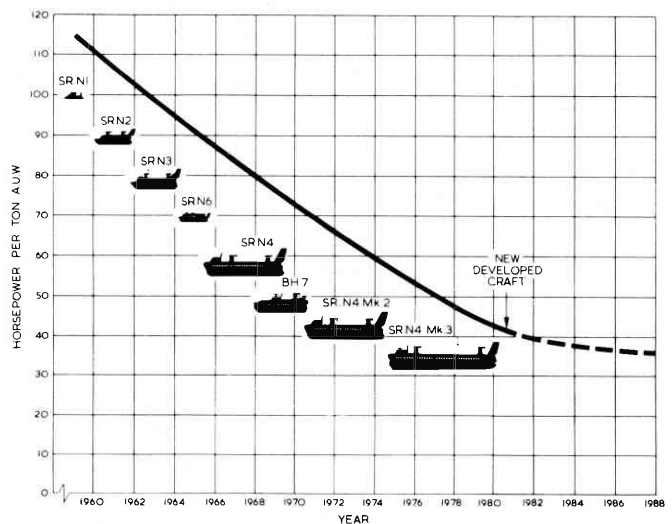


Fig. 2. Improvement in Power to Weight Ratio

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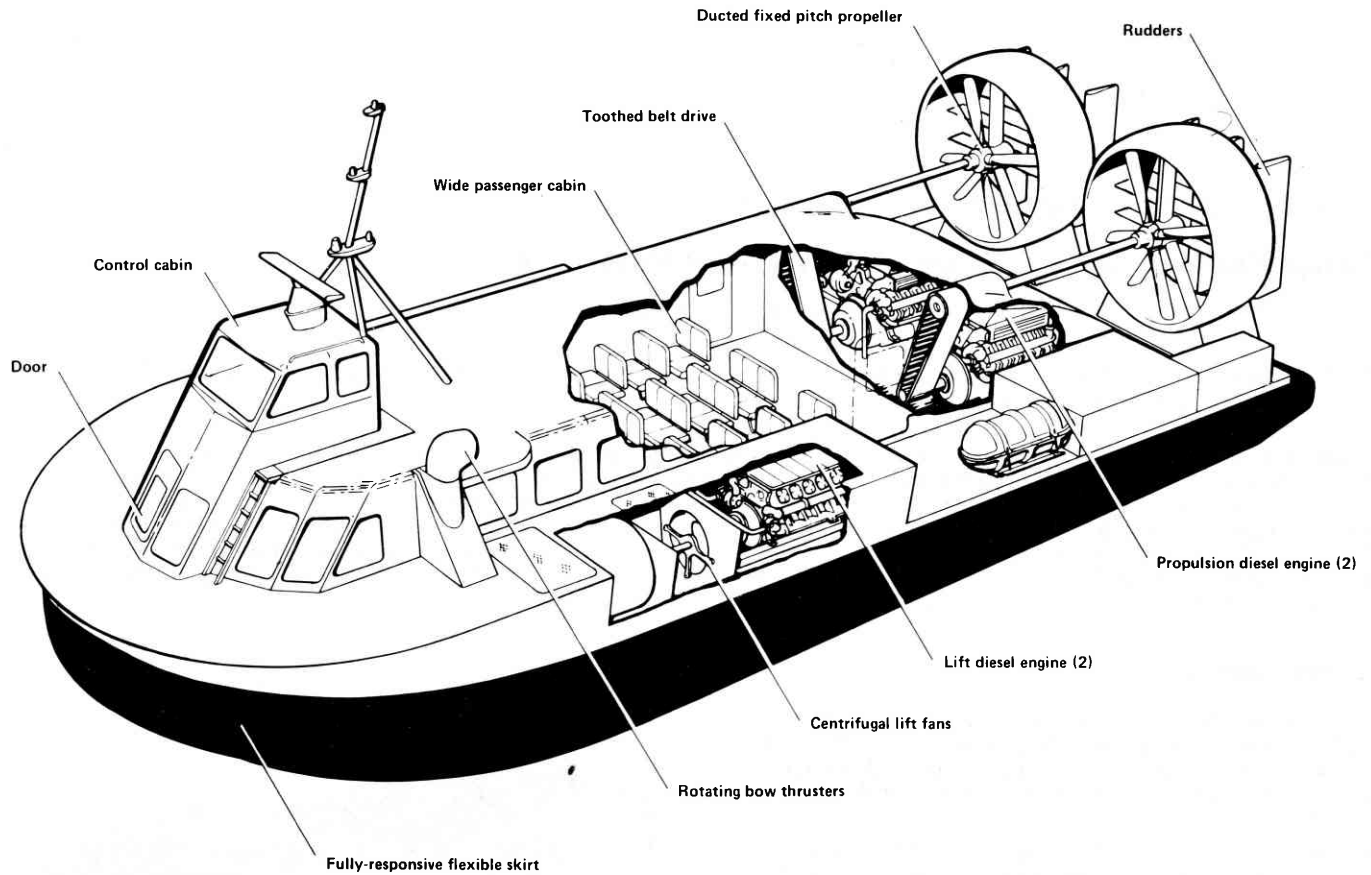


Fig. 3. Ap.1-88: Salient Features

TABLE I. Leading Particulars of AP.1-88 and SR.N6 Mk.1S

	Prototype AP.1-88	Production AP.1-88	SR.N6 Mk.1S
Overall length ft (m)	70.4 (21.45)	78.2 (23.85)	58.1 (17.71)
Overall beam ft (m)	32.8 (10.00)	32.8 (10.00)	25.75 (7.85)
Maximum AUW lb (kg)	72000 (32700)	85000 (38500)	29000 (13150)
Nominal Mean Skirt Depth ft (m)	3.5 (1.07)	4.5 (1.37)	4.0 (1.22)
Lift/Bow Thruster Engines	2 × 10 Cyl. Deutz Diesels 328 hp (245 kW) each	2 × 12 Cyl. Deutz Diesels 428 hp (319 kW) each	1 × Rolls Royce Gnome Gas Turbine 1000 hp (746 kW)
Propulsion Engines	2 × 12 Cyl. Deutz Diesels 428 hp (319 kW)	2 × 12 Cyl. Deutz Diesels 428 hp (319 kW) each	
Total Continuous Power hp (kW)	1512 (1128)	1712 (1277)	1000 (746)
Fans	8 × 2.75 ft (0.84 m) dia. centrifugal type	12 × 2.75 ft (0.84 m) dia. centrifugal type	1 × 7 ft (2.13 m) dia. centrifugal type
Propellers	2 × 9 ft (2.74 m) dia. Hoffmann Fixed Pitch	2 × 9 ft (2.74 m) dia. Hoffmann Fixed Pitch	1 × 9 ft (2.74 m) dia. Dowty Rotol Variable Pitch
Passenger Capacity	80	101	58
Normal Crew Complement	3	3	2

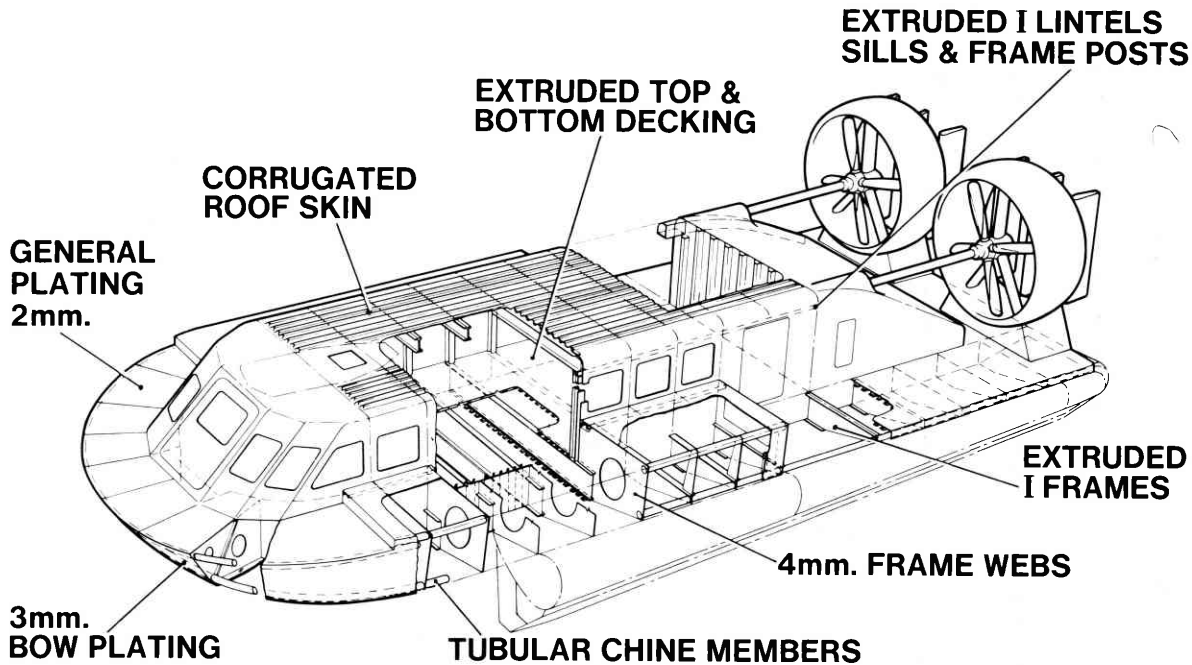


Fig. 4. AP.1-88: Structure

out all the basic design work, model testing and the trials programme.

The basic design, utilising welded alloy structure and diesel engines was a major departure from previous BHC practice, which had relied on aircraft construction techniques. Since the targeted timescale for construction was short, the boat building firm of Fairey Allday Marine at Gosport was sub-contracted to produce the main hull structure.

2.1 Structure

The change from high strength aircraft type aluminium alloys to weldable marine alloys was not an easy task (Fig. 4—extracted from Ref. 2).

The alloys used were approximately one third the strength (when welded) of the riveted light alloys previously employed and the minimum thickness of 2 mm, which was dictated by the welding equipment, was more than 4 times that of the thinnest plate used on previous designs. These two factors inevitably meant that a welded structure would be comparatively heavy, even when the design approach was modified to suit. For example, long extrusions were used to avoid transverse welds at highly loaded areas. The final result showed that the specific structure weight (per unit of cushion area) was roughly twice that of the SR. N6, although in terms of the fraction of craft AUW it represented an increase of only 25% to 29%.

The basic assembly is in the form of a central buoyancy tank, flanked by box structures either side housing the heavy diesel lift engines and the fans. This configuration contributes to a low centre of gravity and minimises any obstruction to the view from the cabin windows since the engines and fans are partially sunk below the level of the main deck.

From the cost aspect, every effort was made to reduce the number of components and fasteners in the structure by the incorporation of large extrusions.

Some of these extrusions were among the largest produced in Europe and were supplied by the Alusingen Company of Germany. The large I-beams used in the buoyancy tank are almost 9 m long, while some of the stiffened deck planking is laid down in 17 m lengths.

On the production craft, spot welding has been used in conjunction with thinner gauge materials for components such

as doors and hatches, resulting in both weight and cost savings as well as improved components.

The AP.1-88 has been designed with three landing pads to enable it to rest steadily on almost any landing site, whether flat or not. Also a patented landing pad extension system in the form of tubes which may be lowered down through the landing pads and locked into position, allows the craft to 'alight' 600 mm above its normal ground line, thus making skirt access that much easier for maintenance. Alternatively, an operator may prefer to build-in hydraulic jacks at a base and jack the craft up by, say 900-1500 mm for servicing the skirt and for bottom inspection.

Lifting is carried out by removing three special 'patches' on the roof and lowering cables to pick up the tops of the landing pad structures. It is envisaged that this will only be done for transportation of the hull or for shipping the whole craft.

2.2 Machinery

The decision to use Deutz air cooled diesel engines was made on the grounds of their comparatively light weight and low cost. The total cost of the four diesel engines in the AP.1-88 is less than 1/5th of an equivalent gas turbine, a factor which is also reflected in maintenance costs.

In addition, the diesel is attractive in terms of specific fuel consumption as is shown in Fig. 5 (Ref. 3), where the consumption per passenger mile is shown to be almost half that of the SR. N6. For this comparison the SFC of the diesel was taken as 0.35 lb/shp.hr compared to 0.63 lb/shp.hr for the Gnome gas turbine. In order to carry the additional weight, extra power has to be installed which tends to reduce the above advantage, but even so, from an economic viewpoint, the diesel engines are a clear advantage now that it has been possible to obtain a reasonable payload on a diesel engine craft. Even the use of relatively light weight, air-cooled diesel engines invoked a weight penalty of over 5 tons compared to the equivalent gas turbine engine. The power plant weight, rather than the weight of the welded structure, is responsible for reducing the disposable load/AUW ratio of the AP.1-88 to 22% compared to approximately 43% for the SR. N6 Mk. 1S.

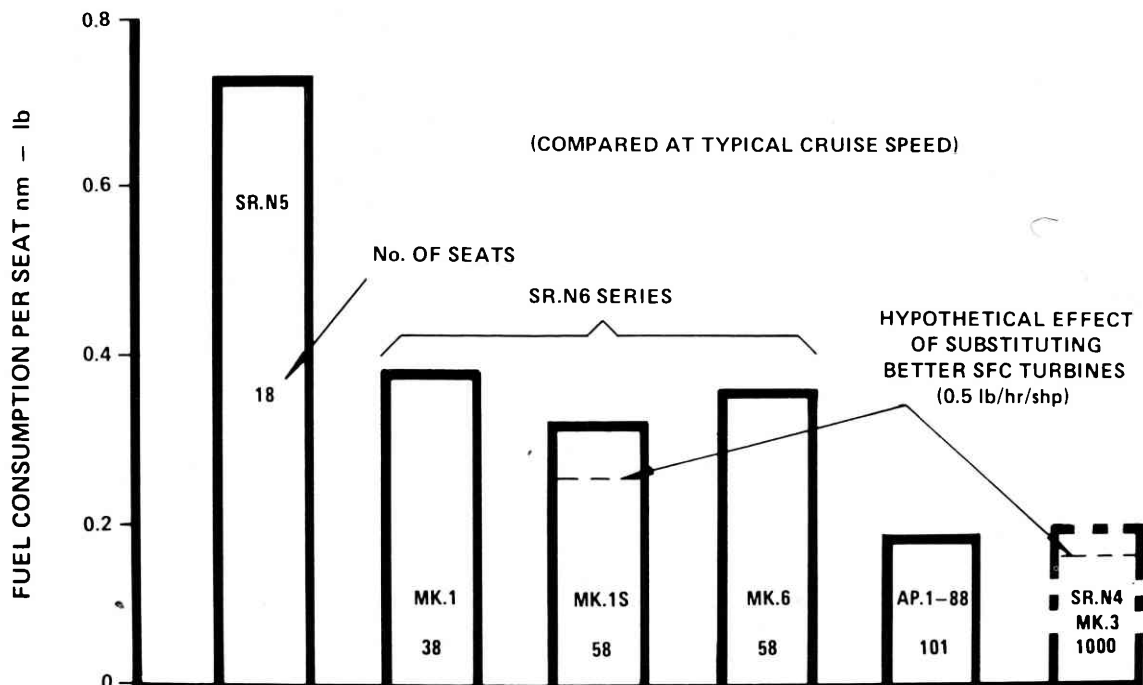


Fig. 5. Comparison of Fuel Consumption per Seat nm

The type of machinery arrangement was dictated by the available power range of the engines in the Deutz air cooled series. Thus two 10 cylinder engines drive the four small centrifugal fans on each side of the craft directly at the engine output rpm, three of the fans feeding the air to the cushion and one feeding the bow thruster on that side, so that the need for reduction gearboxes is eliminated. Two 12-cylinder engines drive the propellers.

This arrangement is fundamentally different from that employed on all previous BHC hovercraft which used the free turbine type of gas turbine engine (typified by the Rolls-Royce Gnome used in the SR.N5/N6 series and the Proteus used in the BH.7 and SR.N4 series), controllable pitch propellers and integrated lift/propulsion systems. In these cases, a limited interchange of power between lift and propulsion was possible by varying the propeller pitch.

On the AP.1-88, twin fixed pitch Hoffman propellers are used. The blades are of wood, sheathed in GRP and retained in a metal hub which allows the pitch to be adjusted if necessary. The propellers are mounted in ducts to increase the thrust at low airspeeds and also reduce propeller noise.

While these propellers are considerably cheaper than the variable pitch type, there were initially some reservations about their effect on the control characteristics of the craft, particularly with no reverse thrust. However, radio controlled model tests provided the designers with the necessary confidence to try such a system, and the approach has been justified by the very satisfactory controllability of the full scale craft.

The low cost philosophy was pursued in the transmission system, where, for propulsion, large toothed belts were used to transfer the engine output to the propulsion drive shaft at the appropriate rpm. These belts replaced two gearboxes together with the interconnecting shafting. Each belt is required to transmit over 400 hp and necessitated the use of the widest belt in the manufacturer's range (340 mm). With respect to the lift engines, the use of multiple fans enabled them to be tailored to the size which could be driven directly at engine rpm without the need for an intermediate gearbox.

3. PROTOTYPE TRIALS AND DEVELOPMENT

3.1 General

In July 1982, the first prototype AP.1-88 was launched from the Hovertravel works at Bembridge where the fitting out of the hull had been carried out. The craft was delivered to BHC's factory at Cowes at the end of its first sea sortie and it was based there for the ensuing trials programme.

Clearance of all craft systems to design requirements was accomplished during ground trials prior to the first sea sortie, and sea trials were conducted to demonstrate the safe handling characteristics of the craft and to obtain measurements of performance. Sea trials were also carried out in a wide range of sea conditions to gain CAA certification and a number of additional trials were conducted specifically for customer acceptance and future sales purposes. The trials programme comprised 105 operational hours during which the craft systems proved extremely reliable.

SR.N6 drivers were favourably impressed with the controllability of the craft and were mainly concerned with adapting to the rather different driving techniques associated with the separate lift and propulsion systems and the use of the bow thrusters for braking. The low pressure ratio skirt and the increased size and weight of the AP.1-88 resulted in considerable improvements in ride quality compared with the SR.N6 series.

Water speeds achieved during trials showed good correlation with predictions based on tank model data, the measured speeds in fact exceeding predictions in maximum wave heights greater than about 1 metre (Fig.6). Emergency overwater stopping distances ranging between 330 ft (101 m) and 440 ft (134 m) from initial speeds of 35 and 45 knots were readily demonstrated at a craft weight of 70,000 lb, and turning radii of 1000 ft (305 m) to 1300 ft (396 m) have been achieved at 30 to 40 knots. Satisfactory handling and control were demonstrated at craft weights of between 57,000 and 72,000 lb (25,900 and 32,700 kg) and the craft was safely operated in seas up to 8 ft (2.4 m) maximum wave height and in wind speeds of 33 knots mean, gusting to 40 knots.

As a result of the trials, the CAA issued a type certificate for the AP.1-88 which approves operation with fare paying

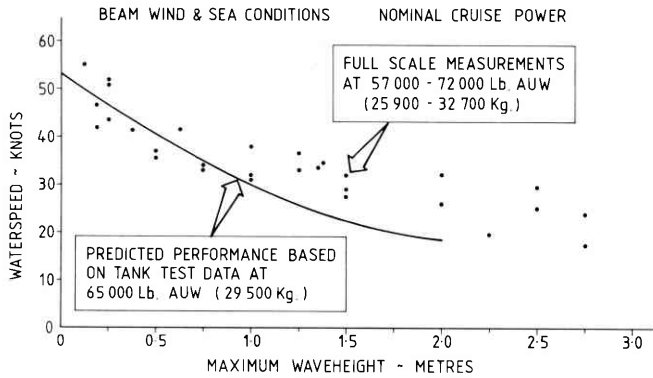


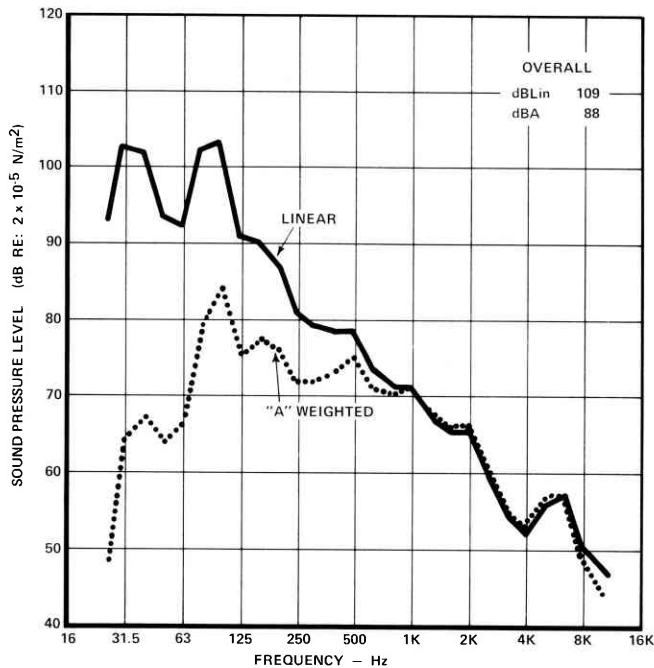
Fig. 6. Measured Waterspeed Performance (Beam Wind and Sea)

passengers in up to 1.5 metre significant seas and mean wind speeds of 30 knots, with gusts up to 40 knots.

3.2 Development Work

In view of the number of unfamiliar features of the craft, some development problems were expected during the trials, but these were few in number. The first to arise was associated with the cooling of the propulsion engine bay. The flow of engine cooling air from the bay was found to be inadequate, and in addition hot air was able to reach the transmission system, causing overheating of the transmission belt pulley bearings. This problem was solved by erecting a partition just forward of the propulsion engines to separate the engines from the transmission system, and fitting extra louvres in the roof of the engine bay.

During the initial stages of trials it was discovered that, due to under-inflation of the transverse stability trunks, the pitch stiffness was not as high as had been anticipated. Modification of the air feed so as to increase the internal pressure in the trunks provided a cure.



TYPICAL LEVELS IN PASSENGER CABIN OF PROTOTYPE CRAFT IN CRUISING CONDITION (MEASURED 11TH FEBRUARY 1983 BEFORE FINAL TRIM FITTED)

Fig. 7. AP.1-88: Internal Noise

Engine noise was not a problem and whilst exhaust silencers were originally installed, they were subsequently removed with no noticeable effect on the overall noise level.

External noise measurements made at various distances from the craft indicated, in general, levels typically 15 dBA lower than corresponding measurements on the standard SR.N6. Noise measurements made during approaches and departure manoeuvres at the Red Funnel ferry pontoon in Cowes harbour were very low and a number of European environmental authorities have expressed complete satisfaction with this aspect of the craft.

Measurements made in the cabin of the prototype craft gave overall levels in the range 86 to 89 dBA. Typical one-third-octave band levels are shown in Fig. 7. It goes without saying that we do not regard such levels as satisfactory and our aim is to reduce the overall level to between 75 and 80 dBA.

Most of the difficulty is due to noise generated within the lift systems. Experiments have shown that there would be nothing particularly difficult about reducing propulsion noise in the cabin to something of the order of 75 dBA.

The principal sources of lift system noise can be readily identified in both narrow-band and one-third-octave spectra. In the prototype craft, the lift engines are 10 cylinder, 4-stroke diesels which are typically running at something approaching 2300 rpm under cruising conditions. Referring to Fig. 7 we see:

- (a) A well-marked peak in the 40 Hz band which is obviously the engine 1st order. However, as an 'A' weighted* level, it is not very significant.
- (b) The 2½ order fundamental firing frequency which gives a massive 84 dBA peak in 100 Hz band. A reduction of at least 15 dB is required.
- (c) The 5th order, 2 × (firing frequency), giving a peak of 77 dBA.
- (d) A peak in the 500 Hz band, corresponding to the lift fan blade-passage-frequency. There is a secondary peak at twice this frequency (1 kHz). The relatively gradual fall-off in levels over the frequency range 300 to 2 kHz is probably a manifestation of broad-band noise generated by the fans.
- (e) A peak at around 6 kHz due to the engine turbochargers. However, the level is only 57 dBA and it is not of great significance.

The key to reducing cabin noise is to improve the isolation of the diesel engines from the structure of the craft. Ideally in any such system, the mobility of the isolators should be very high relative to that of the supporting structure (and that of the machine being isolated), but this is not easily achieved in a light-weight structure which has resonances close to the excitation frequency. Following mobility measurements carried out by the ISVR Wolfson Unit, the structure in the production craft has been stiffened considerably, and this modification, coupled with the provision of much softer isolators should give a much more favourable ratio of mobilities and reduce the transmission of structure borne noise.

Noise radiation from the windows has been tackled on rather similar lines, with much heavier transparencies supported in thicker, softer mountings. The effect of these and other lesser modifications to improve the acoustic environment in the cabin has yet to be determined but will be covered in the presentation of this paper.

*The 'A' weighted sound pressure level is generally regarded as the best 'single number' measure of subjective response to noise and, as such, is used as the basis for most environmental and hearing conservation specifications. The variation of the weighting with frequency is given in numerous standards but, for present purposes, reference may be made to Appendix 4 of the 'Code of practice for noise levels in ships' (Department of Trade, 1978).

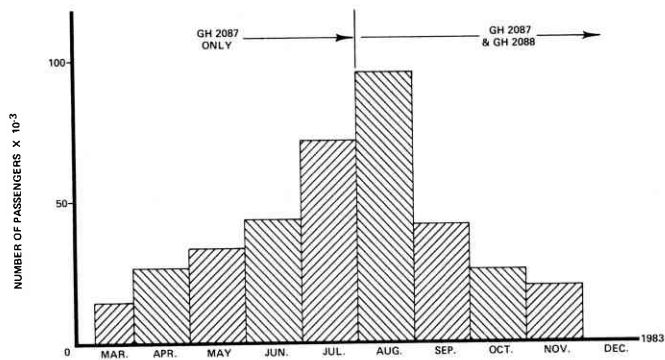


Fig. 8a. Passengers Carried; Monthly Breakdown for 1983

Also included in the trials was a series of propeller static thrust measurements. The technique employed for measuring the thrust was to tether the craft over water with the propulsion engines running but the lift systems shut down. In this way, the problems of ground contact friction and cushion thrust due to trim were avoided. The thrust was measured by means of a strain gauged load cell in the tethering cable.

The purpose of these tests was threefold; firstly to check that the static thrust predictions were being achieved, secondly to attempt to assess the effects of modifications to the surrounding installation (for example, removing the elevators and rudders, baggage panniers and rear fuel tanks) and, finally, to determine the effect of reducing the clearance between the propeller tips and the ducts.

The results of the tests suggested that, whilst the effect of 'clutter' around the ducts was, at least in the static conditions investigated, too small to be measured, reduction of the propeller tip clearance did produce a detectable thrust increase. Reducing the tip clearance from about $\frac{5}{8}$ inch (16 mm) to $\frac{1}{4}$ inch (6 mm) by attaching foam extensions to the blades resulted in an increase in thrust of about 5%.

4. ENTRY INTO SERVICE

Following the CAA and customer acceptance trials, the first of the two pre-production prototypes was handed over to Hovertravel Limited for entry into passenger service. On the 8th March 1983, the craft made its inaugural crossing between Ryde and Southsea, having first been named TENACITY by Sir Christopher Cockerell.

Passenger reaction to the AP.1-88 has been very favourable, most being impressed by the increased spaciousness of the cabin and the smoother ride qualities. The craft's external noise characteristics are also noticeably better than those of the MK.1S, this aspect being of particular concern to those living in proximity to the terminals.

Analysis of Hovertravel's AP.1-88 traffic statistics on the Ryde to Southsea route for the period 10th March to 30th November, 1983, results in the passenger traffic diagrams shown in Fig. 8. Fig. 8a gives the monthly passenger breakdown and Fig. 8b, the cumulative record. As indicated on the diagrams, the second craft (GH.2088) entered service at the end of July.

Average crossing times for the route, which is just under 4 n miles in length, are close to 9 minutes and an average load factor for the 9 month period of the order of 55% has been achieved. As will be seen from the diagrams, the seasonal effects are very marked, almost 100,000 of the total 372,500 passengers being carried in the month of August alone—average monthly load factor peaking at 65%.

Based on these trends, it may be forecast with some confidence that Hovertravel's AP.1-88 service is likely to have carried its first 0.5 million passengers by May, 1984. Up to the end of November, 1983, the two craft have accumulated

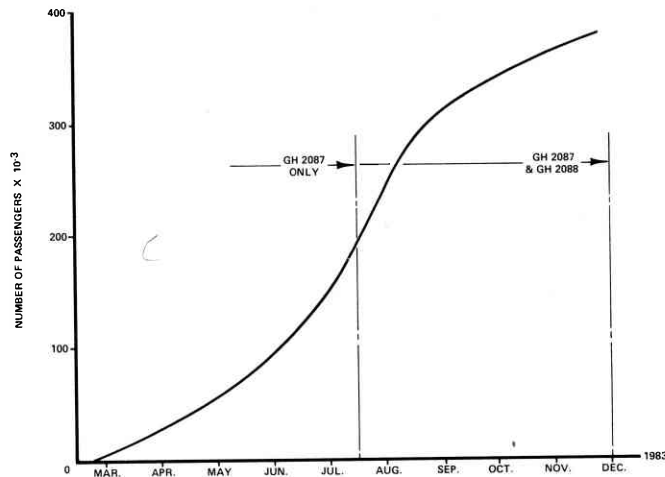


Fig. 8b. Passengers Carried; Cumulative Record for 1983

a total of 8,800 single crossings and the record of cancellations due to weather is only of the order of 1%.

5. PRODUCTION CRAFT

Final assembly of the first production craft has now been completed at BHC's Cowes factory. The main hull structure was again built by Fairey Marine; however, BHC has recently installed welding equipment to undertake 'in-house' construction of welded hulls for future production craft.

5.1 Craft Differences

The production craft differ from the prototype craft in several significant areas and the following is a summary of the principal differences:

- (a) The craft has been lengthened by two structural bays which is approximately 7.9 ft (2.4 m), thereby increasing the passenger capacity from 80 to 101. This two-bay stretch represents the largest feasible four-engined craft using air-cooled diesels from the current Deutz range, and the production craft will in fact be powered by four of the 12-cylinder engines. The commonality of engines/spares, etc., obviously favours the continued use of Deutz engines.
- (b) The additional power available from increasing the lift engine sizes from 10 to 12 cylinders will be absorbed in the substantially modified 12 fan (3 back-to-back pairs each side) layout of the lift/bow thruster systems (see Fig. 9). This is a major factor in maintaining the craft waterspeed performance at the increased craft maximum weight of 85,000 lb (38,500 kg), where the disposable load/AUW ratio has improved to 26%—see weight breakdown given in Table II. The bow thruster effectiveness, which is virtually doubled, will also provide considerably improved control power and reverse thrust for braking.
- (c) The 10-cylinder lift engines of the prototype each drive the four fan systems from the after end. In the production craft revised layout, the 12-cylinder engines are located further forward (between the two pairs of cushion fans and the forward pair of bow thruster fans), each engine driving both fore and aft (see Fig. 9). Since part of the stretch occurs at the aft end of the passenger cabin and the engine weight is greater, this forward engine 'shift' is necessary to match the craft basic CG and with payload centre. This, in turn, minimises the craft trim attitude changes (and, consequently the ballast fuel requirements) with passenger load variations between full and empty.
- (d) The propulsion ducts have been redesigned to further enhance the available thrust. This thrust increase is

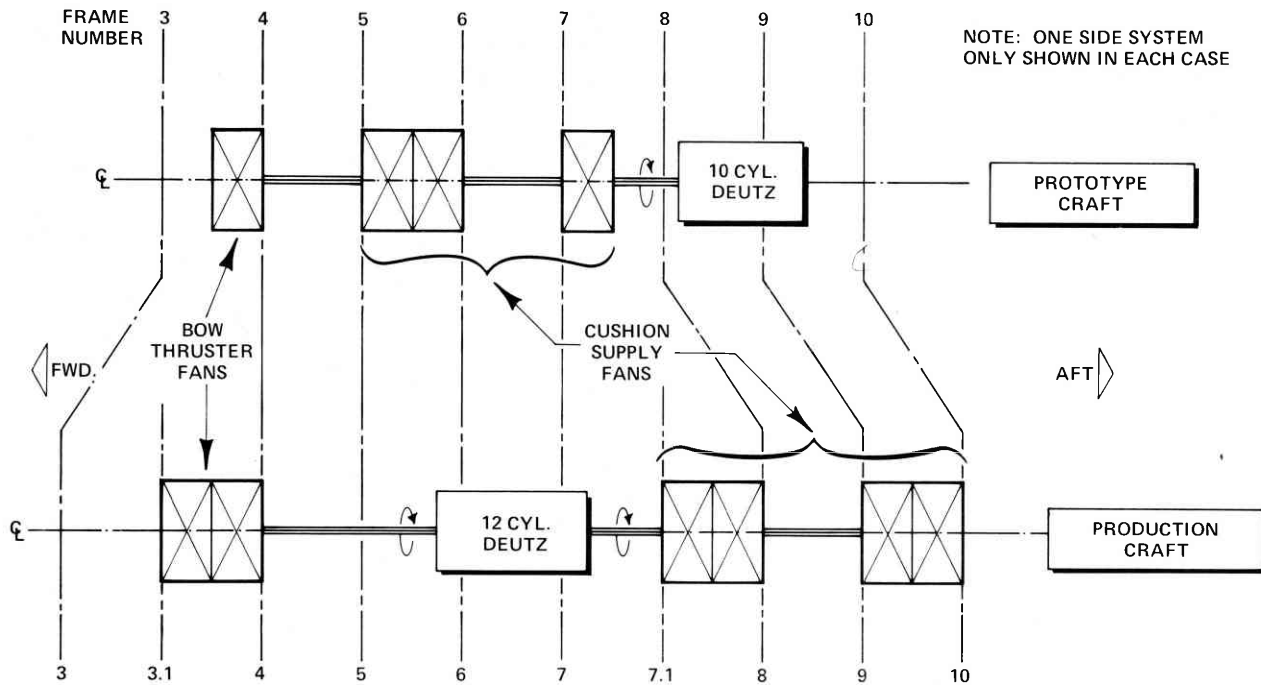


Fig. 9. AP, 1-88 Schematic Diagram of Lift/Bow Thruster System Revision

expected to be derived from improvements in both propeller and duct performance. The greater stiffness afforded by the deeper section employed in the revised duct profile permits use of a much reduced propeller tip clearance, and this accounts for the majority of the additional thrust.

- (e) The relatively shallow low pressure skirt fitted to the prototype (which tapers from 4 ft (1.22 m) at the bow to 3 ft (0.91 m) at the stern—see Fig. 10a) has been demonstrated to be entirely adequate for Solent operations. Based on the towing tank tests of the 1/6.5 scale dynamic model, the deeper skirt developed for the production craft (almost 30% deeper cushion—see Fig. 10b) is expected to afford additional protection from bow structure impacts in more exposed sea areas, and to provide further improvements in ride comfort. An increase in the operating limitations (in terms of limiting wave height) is also anticipated.

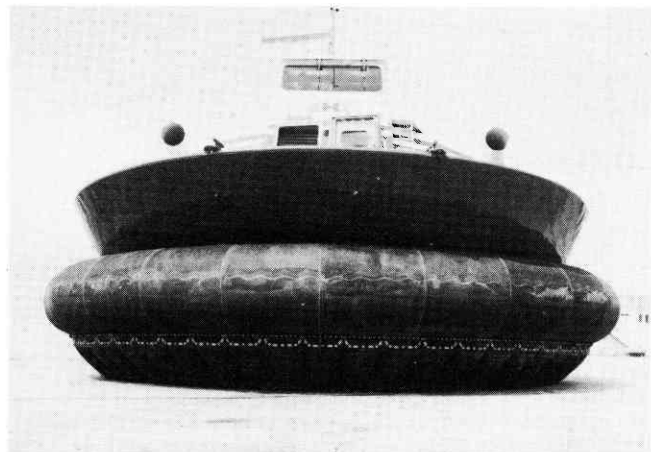
5.2 Model Testing

In view of the fairly substantial differences between the prototype and production craft, a new 1/6.5 scale dynamic model was built specifically for production craft development.

In addition to extensive towing-tank testing, considerable attention was given to development of the main propulsion ducts and revised lift/bow thruster system. An outline of the basic approach and results is provided in the following sub-sections.

TABLE II. AP, 1-88 Production Craft Weight Breakdown

Bare Structure	24,750
Machinery	19,700
Systems, Trim, etc.	13,150
Skirt	5,400
Disposable Load	22,000
Maximum AUW	85,000 lb (38,500 kg)



(a) Prototype Craft



(b) Production Craft

Fig. 10. Comparison of Bow Skirts

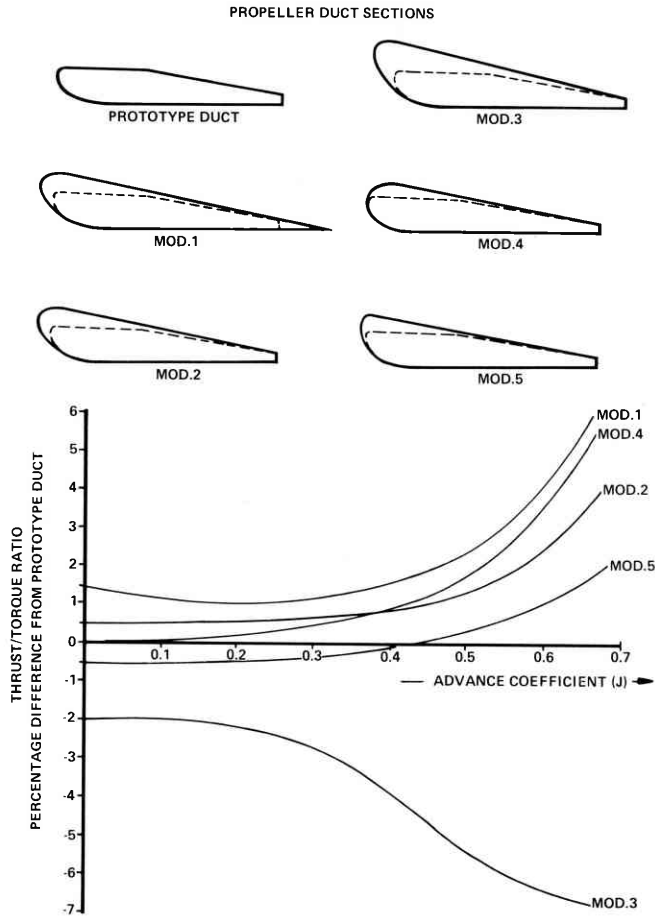


Fig. 11. Propeller Duct Development

5.2.1 Propeller Ducts

As already mentioned, bollard pull tests on the prototype craft suggested that there would be a fairly significant improvement in thrust if the propeller tip clearance could be reduced to something of the order of 5-6 mm. It was apparent that if this small clearance was to be achieved in practice, the duct itself would require to be made stiffer to minimise distortion in, for example, beam wind conditions. This implied a thicker duct section. At the same time, structural investigations suggested that increasing the thickness of the duct might also result in a useful saving in weight. A series of fairly simple comparative model tests was therefore undertaken with the object of assessing the effect on propulsive performance of increasing the thickness of the duct.

The tests were carried out at $\frac{1}{8}$ th scale in one of the wind tunnels at the Test Facilities of British Hovercraft Corporation Ltd. A single model propeller/duct assembly was mounted behind a scale representation of the rear end of the craft.

The model was instrumented to provide measurements of total thrust (propeller plus duct) and propeller torque. Since a stock propeller was employed, and in view of the possibility of scale effects, the results were assessed on a comparative basis using the original duct shape as a datum. The main basis for comparison was the ratio of total thrust (propeller thrust + duct thrust) to propeller torque. The results are summarised in Fig. 11 which shows this ratio expressed as a percentage change relative to the original duct profile plotted against advance coefficient (J) for each of five modified duct profiles.

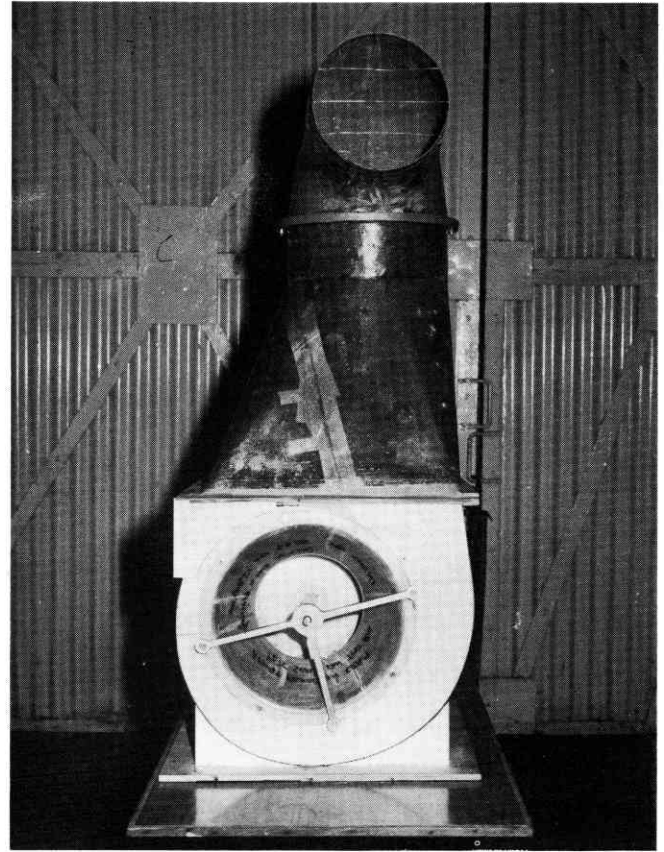


Fig. 12. $\frac{1}{2} \cdot 75$ Scale Model of Bow Thruster Unit

The tests indicated that useful increases in duct section thickness could be achieved without significant loss in performance. In fact, for all but one of the sections investigated, there appeared to be some gain in performance at high J values due to the elimination of the discontinuity on the outside surface of the duct section.

The profile finally selected was determined to some extent by manufacturing considerations but was very close to Mod. 4 on Fig. 11. It was felt that the small performance benefits to be gained by extending the trailing edge were not justified in view of the additional weight and manufacturing complexity, bearing in mind that the control surface pintles are mounted directly on the duct trailing edge. The weight saving finally



Fig. 13. Static Hovering Trials of First Production Craft

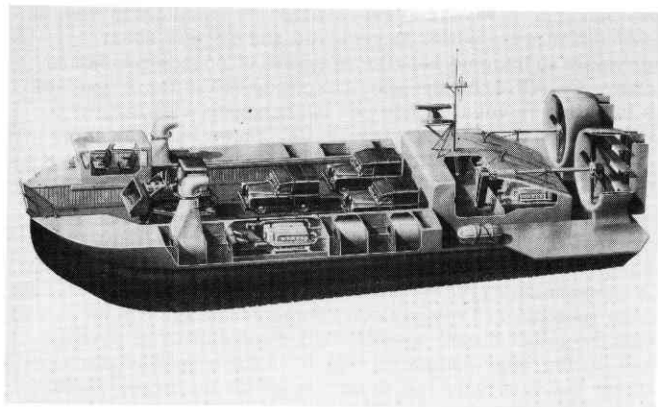


Fig. 14. Well-Deck Version

achieved by use of the modified duct section was in the order of 30%.

5.2.2 Bow Thrusters

In order to make the most effective use of the additional power from the 12-cylinder lift engines, a large scale model of one bow thruster unit (comprising a back-to-back pair of centrifugal fans in a volute feeding a rotatable nozzle) was manufactured and tested. Fig. 12 shows the bow thruster unit—modelled at 1/2.75 scale, giving 1 ft (300 mm) diameter model fan size.

The model was subjected to a systematic series of tests, the primary objective being to maximise the available thrust for a given power at 2, 200 shaft rpm. These tests embraced variations of thruster nozzle profile (including the addition of curved vanes), volute form and diffuser trunk geometry.

The model results confirmed that a simple 'box' type unit (as on the prototype craft) developed about 2.70 lb of thrust per hp. The thrust was marginally enhanced by the addition of curved vanes to the nozzle, but only with a corresponding power increase such that thrust efficiency was not improved. A 'shallow' volute combined with a developed diffuser trunk produced 3.16 lb of thrust per hp, which was an improvement of 17%. In this case, the addition of the curved nozzle vanes afforded approximately 2% further thrust improvement. Attempts to improve the nozzle shape, however, yielded only marginal gains (close to 1%) and were invariably associated with larger frontal area and/or heavy and more costly designs.

Based on the above evidence and further design studies, the bow thruster configuration utilising the 'shallow' volute, developed trunk and basic rotating nozzle (without vanes) was selected for the production craft. This arrangement is expected to provide twice the bow thruster effectiveness of the prototype, for a power absorption of order 1.80 times.



Fig. 15. Half Cabin Version

6. CONCLUDING REMARKS

The first production craft was wheeled out on the 28th November, 1983, and ground hovering trials commenced in mid-December (see Fig. 13). At that time, BHC had received orders for four of these craft.

Considerable interest has also been shown in well-deck and half cabin versions illustrated in Figs. 14 and 15 respectively.

ACKNOWLEDGEMENTS

The author is indebted to his colleagues at the British Hovercraft Corporation for their assistance in the preparation of the paper. Permission of Hovertravel Limited to publish operating statistics is also gratefully acknowledged.

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3. Leonard, J. C.: 'AP. 1-88'. High Speed Surface Craft Conference, May 1983.

DISCUSSION

Mr E. G. Tattersall, B.Sc., (Fellow): First of all, may I congratulate the author on a very polished presentation on this revolutionary amphibious hovercraft, the first real hovercraft, I think he says, to employ diesel engines. However, I would point out that sidewall hovercraft employed diesel engines right from the start.

My first question is to ask him whether he sees development of larger amphibious hovercraft using diesel engines? I appreciate that air-cooled diesel engines are rather few and far between these days. Can he perceive water-cooled engines that actually pick up water from the surface of the sea, and, perhaps, contain it for a while, while making the transition up slipways to the berthing points? Is this practical?

Secondly, a matter really of amplification. I would certainly like to see more information on variation of water speed performance in conditions other than beam wind and sea. What is the range of speeds, in head wind and seas, and following wind and seas?

Mr U. K. Gerry, D.Ae. (Member): I was particularly interested in the two ducted propellers. For marine propellers there is a great deal of comparative information and one can trace down the effects of camber, section incidence, chord ratio, and all the rest from this comparative information. There is very much less of such information available for airscrews in ducts. The author has a very nice series of tests here, but he has given us very little information about them, and it is tantalizing! It would be very useful if he could let us have more information on the various factors that go into getting these results, because they do not altogether fit in with the expected pattern.

Mr R. J. H. Todd (Member): I would like to congratulate the author on a very interesting paper. I would like to ask if he can ensure that some of the additional information that was shown, which he said was not included in the paper, can be included in the written reply.

I have a number of points on which I would welcome the author's comments. He touched very briefly on the military applications. I wonder if he would care to comment on the comparison between hovercraft and displacement craft, in

terms of pay-load, and how that relates to speed and sea performance, and whether, possibly, any operational analysis has been done to compare the performance of these types of craft?

I would just note that the US Navy have already made preparations for using hovercraft in the amphibious role. I understand, and I must say that my information is certainly not first-hand, that some of the problems they have had relate to operating ACVs in the enclosed space in their docking vessels. I believe the noise and spray presents a problem in these enclosed spaces. I wonder, has the author given any thought as to how these problems may be overcome?

Mr R. Du Cane (Member): I wonder if the author could give us some idea of how the skirt wear compares, as between travel over land and over water? Also as to what are the worst sort of water conditions that contribute to the highest wear? I realise that the texture of the land has an important effect, that if you are going over soft mud, or sand, the wear would be less than if you were going over gravel, but you have done quite a bit of work, apparently, over land, now, in Holland, and it might be rather interesting to know what the results, and comparisons were.

Mr D. K. Brown, M.Eng., R.C.N.C. (Fellow)(read by the Secretary): The AP. 1-88 seems to be a remarkable achievement in production engineering and one can only regret that cost figures cannot be revealed. I presume that the welded aluminium structure was found to be cheaper than a fibre reinforced composite but I should welcome some comment on this choice.

Have the vertical accelerations in known sea states been measured? A comparison with the HM 5 would be of considerable interest.

What is the operating speed in calm water at full load with maximum continuous power? The comparison in Fig. 3 of the previous paper⁽⁴⁾ shows the AP1-88 in a very favourable light and I should welcome this author's comments on such diagrams.

REFERENCE

4. Tattersall, E.G.: 'The HM 500 Series of Sidewall Hovercraft'. Paper 8, RINA Spring Meetings, 1984.

The Chairman, Professor K. J. Rawson, M.Sc., R.C.N.C., F.Eng. (Fellow): May I also ask a question about how much the availability of these craft depends upon the speed of the change facility of the engines? Are the Deutz engines extremely reliable, or unusually so?

AUTHOR'S REPLY

Firstly, I would like to thank the contributors for their interest in the paper and stimulating questions. I will attempt to answer them in the order in which they were raised.

Mr Tattersall asks about larger craft with water-cooled engines. There is no problem in fitting a diesel engine to an amphibious hovercraft other than that of weight and in this respect the difference between water-cooled and air-cooled engines is only one of degree. We do not consider it practical to pick up water for cooling since the scoop would be subject to significant hydrodynamic forces and would be very vulnerable. The solution is likely to be found in the car or motor vehicle approach where the heat is dispersed by means of a radiator or heat exchanger. Some water cooled diesels approached the selected air-cooled Deutz in terms of weight but they cost more and lacked the 'off-the-shelf' availability which was one of the major features we tried to incorporate in this craft. This was in an attempt to ensure that the operator could purchase spares locally and not necessarily from us when he lived, for example, in the Solomon Islands. For this reason, readily available commercial components were chosen wherever possible. All the electrics, for example, are 24 volts, instead of 400.

The problem of weight is exacerbated by increase in size of craft since more power is required and diesels seem inevitably to become heavier in terms of pounds per horsepower. On AP. 1-88, the specific power of the Deutz engines as installed is about 6-7 lb per horsepower; with larger engines this rises to perhaps 10-12. These figures can be compared with those for modern gas turbines which are about 0.5 lb per horsepower or less.

Thus on AP. 1-88 a conversion to turbines would save perhaps 10,000 lb allowing, if the space were available, a 50% increase in passenger payload. Conversely on the Super 4 a conversion to diesel power would swallow perhaps 70 tons of the nominal 110 ton payload. Some advantage can be gained from the lower diesel specific fuel consumption of perhaps 0.35 lb/shp/hour compared with 0.45 for a good modern gas turbine but generally and in particular at the larger sizes the diesel powered craft will burn a similar amount of fuel for a given passenger payload.

Where the smaller diesel, and particularly the Deutz, does score is in its capital and maintenance costs which when compared with current turbine practice are very low indeed. This is not the case with larger diesels whose capital costs approach those of the comparable turbines. Again the level of maintenance expertise is lower for the diesel than for the turbine which makes it very attractive to the operators.

Weighing the above features leads us to believe that the upper amphibious hovercraft limit for using diesels is likely to be about 125-150 tons for some time to come. Of course, if we were ever to build in large numbers, it is possible that engines designed specifically for hovercraft would become available and the limit could change dramatically.

Simple considerations show that beam, as opposed to head or following wind, conditions will be encountered 50% of the time. In practice, operators tend to reduce power down wind and sea such that the achieved performance is about that obtained in beam conditions. It follows that beam results will be achieved, other things being equal, 75% of the time. Into wind performance is generally lower than in beam conditions because the air drag is higher and the propeller thrust lower (although its efficiency is higher). It is of interest to note that high speed water propelled craft suffer less from this latter effect because tide speeds are very low compared with wind speeds.

Fig. 16 shows prototype and production craft performance in beam wind and sea conditions, and into wind and sea results of the production craft.

Mr Gerry requests more information on our ducted propeller tests. In reply I must first re-emphasise and amplify what was in the paper. In our original schemes the duct had an internal rubbing strip to enable us to keep the propeller tip clearance low but this was discarded on the grounds of complexity. The duct lines were drawn around a parallel section, assumed to be ideal for manufacturing purposes, elements of two conic sections and some straight lines. The trailing edge was truncated to facilitate the mounting of control surfaces.

As noted in the paper, our aim was to increase the duct stiffness by increasing the thickness and tests were conducted with the duct in an 'as installed' condition behind the superstructure of the craft so as to reproduce as far as possible all wake and interference effects. Thus the results are peculiar to the AP. 1-88 configuration.

Unfortunately commercial pressures precluded the systematic, detailed, test programme that would have given the answers that Mr Gerry required. Our general conclusion on duct performance is that in the craft operating range $J \leq 0.45$, major changes to the duct shape had very little effect. This could mean that they were uniformly bad, we prefer to think that we had it almost right to begin with!

Our first essay at operational analysis was on behalf of the United States Navy in the early 60s. The study was called Black Lace and it compared various types and combinations

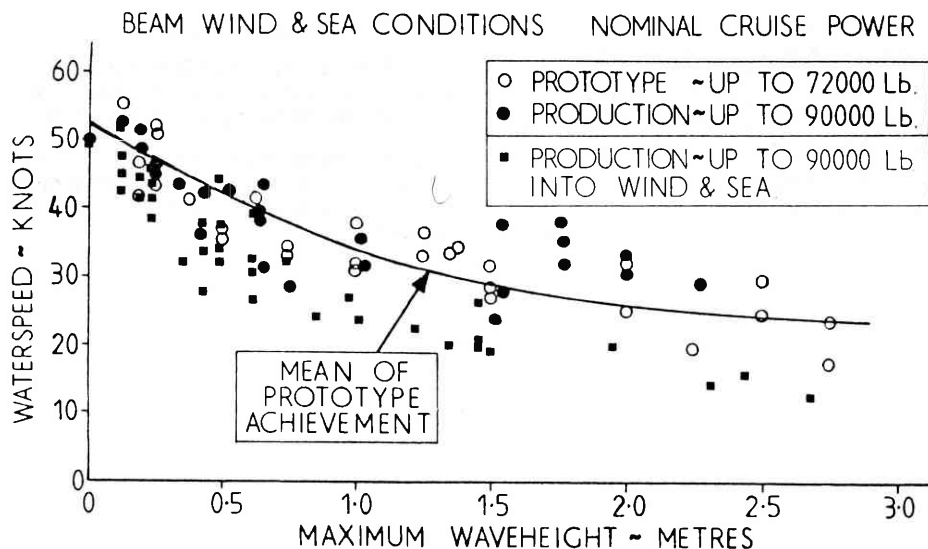


Fig. 16. Measured Waterspeed Performance of AP.1-88 in the Solent

of anti-submarine vehicle for convoy protection, barrier patrol and the like. Needless to say amphibious hovercraft showed up very well. More recently, we conducted a logistic support (LOTS logistic support over the shore) study for the US Army, again, hovercraft, assessed more realistically in the light of 20 odd years of practical experience, showed to good effect. We have offered our services to the MOD for similar studies, in particular for MCM to determine the optimum mix of vehicles, but these have yet to be accepted.

Our American licensees, Bell, carried out studies on amphibious assault on behalf of the US Navy and these were no doubt instrumental in obtaining for them the contract to build the Landing Craft Air Cushion, LCAC.

We are closely associated with this programme, being responsible for dynamic model design, manufacture and test and for skirt design and construction and are aware of the problems mentioned. Mr Todd is quite correct and the environment inside the enclosed wells of the support ships which will carry the LCAC has caused some concern. Spray and noise have been a worry but it is the build up of heat which occurs when several craft are preparing to leave at the same time that is the main problem. Running several gas turbines in the confined space will quickly raise the temperature to levels significantly above 'normal tropical' and so care has to be taken to ensure that all exposed equipment would continue to function correctly. Checks have shown, for example, that the skirt system (which is supplied by BHC) will be all right, even though the bonded joint strength will be somewhat reduced.

Mr Du Cane asks about skirt wear and how it is affected by the surface. Making a simple generalisation, there seems to be a threshold up to which a measure of overland operation makes no difference in the wear rate. Without ramp operation, the life would rise by about 50%. Over grass there would be very little wear. The worst surface we have ever experienced was in the Qattara Depression in Egypt, with uneroded chips. Operating at 50 knots over that gave finger lives of the order of 10 hours.

As far as water conditions are concerned, there is absolutely no doubt about what is worst. The calmer it is, and the higher the speed, the more the skirt wears, roughly proportional to the square of the speed, at least above about 25 knots. If the speed is kept down to about 25 knots one can get something like 2,500 to 3,000 hours out of a finger. On the Super 4s at 60 plus knots the lives are a few hundred hours when coupled with slipway operation twice in 25-30 miles.

The reason for the wear over water is the flapping of the material as it trails along the surface — there is up to about

500g acceleration in the plane of the fabric. All our materials for skirts are, in fact, batch tested by allowing them to flap in a high speed airstream because this technique produces the same type of failure as occurs in practice.

In reply to Mr Brown, we have used fibre re-inforced plastics in certain areas on the machine, mainly on complex shapes where it is cost effective. However, in general, and on flat areas in particular, welded light alloy using automatic machines is much the cheaper method and the resulting weight is very similar to FRP. In fact, until a satisfactory process is devised for the automatic lay-up of FRP, the rising cost of labour is likely to result in welded structure becoming progressively more attractive from an economic point of view.

Although each part of the craft was assessed separately from a cost and weight point of view and the most appropriate method employed, I think there is no doubt that there are areas of the craft where we could have gone further into using fibre reinforced plastics of one sort or another (the bow for example). However, we were influenced by discussions with a number of customers, two of which in particular were very insistent on not going to FRP in general. One was in the Gulf, on Kharg Island, where humidity for a large proportion of the time is up in the 90% region and the other was in the Prudhoe Bay area of Alaska. In both cases, they did not want to go to the sophisticated special equipment to make repairs to FRP but had no objection to doing riveting or welding.

As regards accelerations we would be quite happy to compare the AP.1-88 and HM5 but more information is required. As on any fast marine craft, vertical accelerations are very sensitive to encounter frequency which is a function of wavelength as well as craft speed. For any comparison between similar sized craft to be meaningful, therefore, the data must be for similar wavelengths. The limited acceleration data in Fig. 10 of Ref. 4 do not, unfortunately, give any details of the wavelengths.

Mr Brown asks about maximum speeds achieved and for comments on Fig. 3 of Ref. 4. The highest speed we have achieved over a measured distance with the AP.1-88 is 54 knots at a weight of 70,000 lb with the engine at cruise (i.e. max. continuous) rating. However, this was not in calm conditions. Under calm conditions we have achieved 51 knots but at the much higher weight of 90,000 lb, again at cruise power. At the normal maximum all up weight of 85,000 lb and at cruise power the maximum speed in calm conditions is approximately 52 knots. Fig. 3 and Table I of Ref. 4 quote a speed of 40 knots at the maximum all up weight. However, this is the specification speed that we guarantee to

the customer and is therefore very conservative. It represents the worst that one might expect to achieve, for example, after several years service with a poorly trimmed craft and a worn skirt. A realistic figure for 'transport efficiency' of the Production AP. 1-88, according to the definition used in Ref. 4, is arrived at as follows:

Maximum continuous speed at full load	52 kts
Number of passengers (See Table I)	93 (allowing for two toilets)

Total installed power (See Table I) 1277 kW

This yields a transport efficiency of 3.79 (compared with 3.12 quoted in Ref. 4) which is substantially better than the sidewall hovercraft figures quoted in Ref. 4.

Finally, in reply to Professor Rawson we have changed an engine in one night. So far the Deutz engines have proved to be extremely reliable and we understand that this is not unusual.