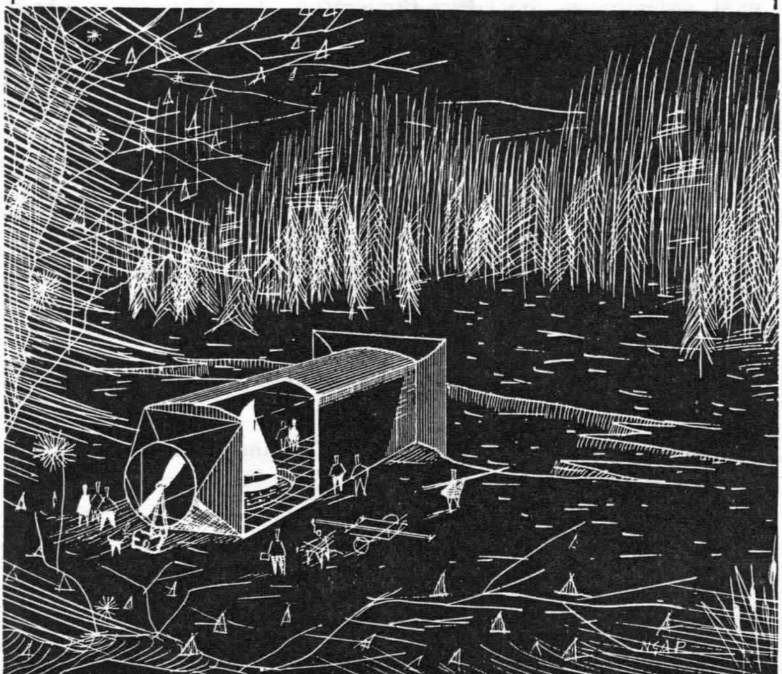
YACHT WIND TUNNELS

A.Y.R.S. PUBLICATION No. 24



THE WIND TUNNEL —*Norman Pearce*

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(Founded June, 1955)

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April, 1959.

EDITORIAL

If the A.Y.R.S. is to justify its objective as a RESEARCH Society, rather than as an organisation for study, it must produce either a Yacht Wind Tunnel or a test tank. In this publication, we have assembled all the relevant details of a wind tunnel which, if it is made, will convert our knowledge of sails into an exact science instead of the " rule of thumb " which has existed since the beginning of time.

We owe our greatest debt for our present knowledge to Mr. Richard Fairey and Mr. M. S. Hooper of the FAIREY AVIATION COMPANY. Mr. Hooper has been especially kind in giving us advice and answering questions. However, all our aeronautical members have been most helpful and ideas and suggestions have been pouring in since the project was first mooted. All of these are very valuable not only in producing designs for wind tunnels but also in producing the sense of knowing just what we are doing. In fact, the tunnel project has been discussed with so many members that it has virtually become a co-operative project.

Lord Brabazon, Sir Geoffrey Taylor, Sir Reginald Verdon Smith, Professor Squire, R. Haffner, R. Hardingham, Owen Dumpleton, A. Jeffrey and " Robbie are especially thanked for their help, efforts and suggestions. The drawings which illustrate the article have been most excellently drawn by Owen Dumpleton and A. Jeffrey. Mrs. Evans' suggestion of the use of an agricultural Dutch Barn to house the tunnel seems to be appropriate, if no other method is cheaper.

The wind tunnel as described here is largely based on the experience of the Hayes Yacht Wind Tunnel of Mr. C. R. Fairey (later Sir Richard) and could be made as suggested at full scale. If any great modifications of it are used, however, which might cause faults in the wind flow, a model tunnel would first have to be made to make sure that the full scale tunnel would have no faults.

It is unfortunate that the only site for the wind tunnel at present available is in the grounds of my own house which is rather far from the majority of yachtsmen and alternative suggestions will be considered. However, by the nature of my work, I have to stay at home a great deal and would be available to give instructions and help with the working of the tunnel and this would save the employment of a watchman of any sort. If the tunnel is not made of too permanent a nature, it could be moved at a later date if its use warranted the employment of a full time person in charge.

Scale. The publication is concluded by a most interesting article on " SCALE " by T. F. Arlotte which gives the fundamentals of the tank testing of models and how they are correlated with the full scale craft. This contains a most useful body of knowledge for members who wish to know more of test tanks and forms a good introduction for a design study for an A.Y.R.S. test tank, which we hope to start soon.

TEST TANKS

Having completed the design stage of the wind tunnel, it appears that we are likely to have a wall 46 feet long on one side which will be unbroken by doors or windows. With very little extra expense, therefore, we would be in a position to make a test tank about 40 feet long and about 3 or 4 feet wide and deep. This could be done by making one extra wall some 8 to 10 feet away from the wall of the wind tunnel and roofing the space. The test tank could then be let into the floor and the extra space could be used for bunks for members and equipment for making models both for the tunnel and tank.

The Value of Small Test Tanks. It is felt that many people think that only with the most expensive and accurate of test tanks can good results be achieved. That may be so but quite definite improvement in our yachts can also be achieved by a simple test tank of no great great complexity. In A.Y.R.S. publication No. 12 AMATEUR RESEARCH, two test tanks were described on pages 22, 23 and 24 which were apparently of value to their operators and F. Lagos, of Spain, has sent in figures which he got from a 33 foot by 2 foot 6 inch tank which indicate that the tests were quite accurate enough to learn a great deal from them. A 40 foot tank should therefore improve our knowledge of yacht hulls a great deal.

A Flowing Water Test Tank. Because there is a stream flowing near the wind tunnel, there is a strong inducement to design a flowing water test tank which would be roughly similar to the wind tunnel design described later in this publication with certain modifications because of the water surface. Such a tank would allow of more leisurely measurement of forces produced, the only difficulty being in the measurement of the water speed and of producing a stable water surface, free of standing waves. The study of test tanks of all kinds is proceeding with our interested members and we can but await results.

THE BRITISH A.G.M.

The meeting opened at 11.30 a.m. with Erick Manners in the Chair.

1. The minutes of the last meeting were read and adopted.

Proposed : L. Lamble. Seconded : A. B. Catt.

2. *Matters Arising.* The Secretary reported that Uffa Fox had accepted office as Vice President. A letter has been sent to the Corporation of Southend, thanking them for the facilities made available to the Society on the pier. The Chairman added that the Corporation had since made available to us an occasional mooring off the pier head from which experiments could be carried out at all states of the tide.

3. *Election of Officers.* Under the constitution, two Committee members are retired in rotation yearly. R. Prout and K. Pearce were retired and R. Prout and L. Lamble were elected.

4. *Financial Report.* The subscription for the current year has been raised to £1 to try and reduce the slight losses incurred in previous years. During discussion, it was agreed that, if possible, the price of casual sales should be kept at 2/6 as these bring the work of the Society to a wider public. It was felt that the extra five shilling which members paid was worth the facilities available to them. The final decision on the price of publications to the public was left to the publisher, after an explanation of some of the mysteries of the business. As a matter of interest, the income from casual sales is

twice the income from subscriptions. The Research Fund now stands at £10—6—0.

Acceptance proposed by L. Lamble. Seconded H. Reid.

5. *Committee's Report.* No specific projects had been undertaken by the Committee, but individual experiments covering a wide field had been undertaken by individual members. These will either be published or made available on request. The Committee felt that the pioneer work on the design and development of the modern catamaran, which has been carried out by our members, has had the desired result. The Society, by providing the lines of communication and publishing the results of experiments, has overcome much of the initial hostility and the catamaran is now established as a safe and efficient sailing craft. The Committee feel that the Society's efforts should now be concentrated on a new problem and that less prominence should be given to catamaran data in future publications.

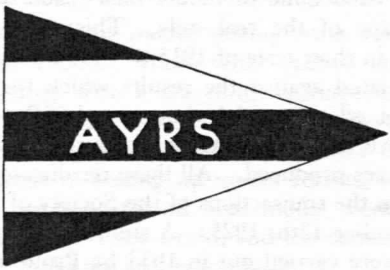
6. *Matters Arising from* 4 *and* 5. There was some discussion on the direction in which the Society should now concentrate its efforts. The most urgent problems were those associated with sails as a motive power. Very little theoretical or practical data exists on the efficiency and power of sails. The editor stated that, although much had been achieved in the last 5 years by the Society relying on individual experimenters, the time had come when, if the Society was to achieve any major results, we must concentrate on the more technical problems associated with sail. He felt that the editorship would have to be passed on to some one else at October, 1960, so that he could concentrate on research and that publications must inevitably become more technical. Land is now available for accomodating test gear and the editor felt that a thirty foot wind tunnel for testing light craft up to *Flying Dutchman* size was essential if accurate data on sails was to be obtained. Plans had been prepared of an open circuit (total loss) slow speed tunnel and the project is being costed. We have much valuable information on the problems of using this type of tunnel and, if the cost is reasonable, the Committee will consider how best to raise the money. Once the tunnel was operating, it was thought that it would be of sufficient practical use to members and other interested yachtsmen that there would be no difficulty in keeping it going. If the tunnel was successful, it could be rebuilt on the Society's own property and the "College of Yachting" founded.

7. *Policy for the Coming Year.* Apart from the wind tunnel

project, a real effort must be made to form regional groups so that members can work together and help each other by social contacts. The new list of members will be published in April, and it is hoped that by the autumn, regular meetings can be arranged in most parts of Britain. During the year, each member is asked to try and enrol a new member to the Society. By doing this, the Society could afford the wind tunnel without seeking outside help.

8. *The Preparation of a Bibliography.* Members are asked to assist by passing to the Hon. Secretary, Tom Herbert, the name of the book and its publisher when information of value to the Society is found.

9. *The Burgee Design.* All the designs submitted were carefully examined by the meeting and the design below was adopted.



The A.Y.R.S. Burgee

10. *Votes of Thanks.* A vote of thanks was proposed by John Morwood to Norman Pearce who has so kindly done many recent drawings for the publications. This was seconded by Erick Manners. A thank you was extended to those members who had made donations to the research fund or who had contributed articles and information. The A.Y.R.S. Hon. Secretary, Tom Herbert was thanked for his efficient work on behalf of the Society.

The meeting closed at 1.15 p.m.

YACHT WIND TUNNELS

Introduction. Aeroplane wind tunnels for studying models of aeroplanes, their wings and other features about them have a long history dating back to the mid-nineteenth century. Many of the early pioneers of flying used them to test out wing sections and it was due to the Wright brothers' tests that they finally managed to make a machine which their low powered engine could lift from the ground. It is a reflection, therefore, on yachtsmen's small appreciation of the value of such tests that there have been so few tests done on yacht sails. In favour of the yachtsman, however, it can be said that knowledge of the form and shape of wind tunnels which would serve his purpose has been woefully inadequate and hard to come by and those which would be fully adequate tend to be expensive. It is to be hoped that this publication will cover the subject in enough detail so that wind tunnels will soon be erected in all countries and produce a flow of results which will improve our sails enormously.

Early Sail Tests. Because it is usual to test models of aeroplanes and their wings in small tunnels, it was natural that the first tests of sails should have been done of model sails made of metal approximately to the shape of the real sails. This method was used by Warner and Ober in their tests of 1915 to 1921 and their wind tunnel results were correlated against the results which they obtained from the yacht *Papoose* whose model they tested. *Papoose* herself was given an exhaustive series of tests of pressure distribution over her sails and of the forces produced. All these results are most interesting and are reported in the transactions of the Society of Naval Architects of America, November 12th, 1925. A similar series of tests of much the same nature were carried out in 1933 by Professor Davidson and others at the Stevens Institute of Technology, Hoboken, New Jersey on the yacht *Gimcrack* and from these results, the well known " *Gimcrack Coefficients* " were produced from which the drive of a sailing yacht can be calculated approximately. These tests are described in the " Technical Memoranda " Nos. 10, 16 and 17.

Manfred Curry did some tests in the wind tunnel in Germany, on metal sail models of yachts in the 1920's, whose results are reported in his book " YACHT RACING. "

Olin Stephens towed models of sails upside down in the test tank and got some values for the forces produced in this ingenious way.

Sir Richard Fairey, in the September 1939 number of *Flight* and *Aeronautics*, vol. 1, No. 2, described the results of his experiments with a model of *Evaine*, the 12 meter which was used to tune up *Sceptre* for last year's *America's* Cup races. The Hayes Wind Tunnel, called after the town of Hayes, Middlesex, where the FAIREY AVIATION COMPANY is placed, was the first wind tunnel to be made exclusively to test yacht sails of more than tiny size. It was 15 feet high of a square cross section 12′ by 12′ and a wind speed of 7 to 10 miles per hour was used. Unfortunately, the results have never been published in any great detail.

Lord Brabazon's wind tunnel is described in detail in A.Y.R.S. No. 18, CATAMARAN DEVELOPMENTS and was made in the winter of 1947-8.

It is difficult to say what most of these wind tunnel experiments proved. Most of them took the forces acting on the model sail accurately and thus were able to establish " Coefficients " of thrust and side force. Sir Richard Fairey was interested in finding the best trim for the sails of *Evaine* but also produced some figures for the drive of the sails on all courses. Lord Brabazon tested a variety of sails in his tunnel to find out which would give the greatest power. However, nothing like a comprehensive series of tests have yet been made in any tunnel to find out even such a simple thing as the best shape for the sails of the common sloop rig.

Doubtless, other wind tunnels have been made and used to produce results and accounts of these should be collected by the A.Y.R.S. However, it will be the purpose of the present publication to describe a wind tunnel which will be satisfactory for testing yacht sails so that the results will stand for all time and to examine some variations of it which have been suggested. If possible, we hope to build such a tunnel and keep it in being so that any member may use it not only for research but also to improve his sailing skill.

WIND TUNNEL DESIGN

Size. The first point to decide in designing a wind tunnel for yachts is the size. Model sails may be used in a small wind tunnel which has been done by everyone up to now and this can give interesting results. Unfortunately, however, in order to make them as good as possible, the Reynolds number which is proportional to vl, where v is the windspeed and l is the average distance across the sail must be kept constant. This means that, if a model is used, the windspeed must be greatly increased. An example of this would be that, if the boom were only one fifth of that of full size, a tunnel windspeed of 50 miles per hour would resemble a natural windspeed of 10 miles per hour. This makes factors such as cloth stretching and stability impossible to measure and, in fact, takes the whole study from the hands of the practical yachtsman and places it in the province of the mathematician. Unfortunately, the practical yachtsman cannot understand the results which are produced, so this system can have no practical appeal and its results will be suspect.

A half scale model can be used. This is a near perfect solution within its limitations because Reynolds number does not have much effect at such relatively slight "scaling" and the yacht could be tested in such a way that a practical yachtsman could see with his own eyes how the wind was developing forces on the sails.

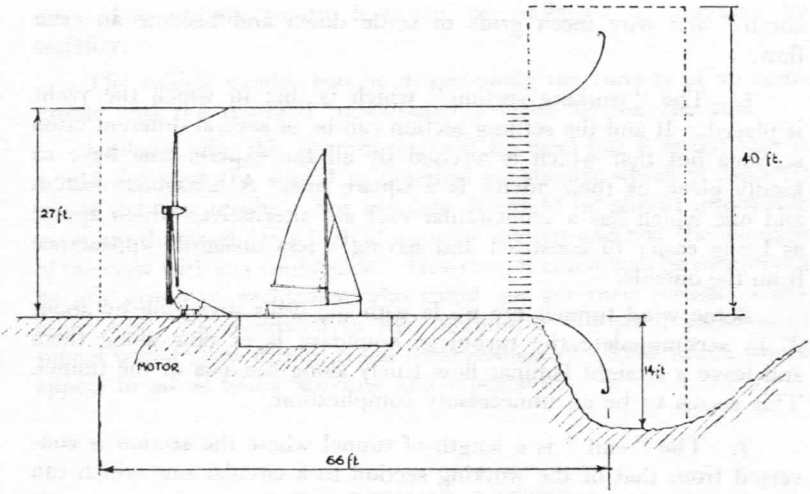
Finally, it is not impossible to make a wind tunnel large enough to accommodate a whole, full sized dinghy within it and to study not only the forces produced by the sails but also those produced by the hull, the rigging and the windage of the crew. This should really be a most satisfactory instrument for studying the yachtsman's sailing skill ; how he must sit and how he must trim his sheets for each course. He should be able to evaluate the best shape of both jib and mainsail for several strengths of wind and the people who run the tunnel should soon be able to appreciate and advise yachtsmen on what alterations are needed in their sails to get the greatest speeds.

Undoubtedly, then, the best and most satisfactory wind tunnel will accommodate a full sized dinghy and we should, at least, strive to attain that ideal. However, should we not be able to manage that for financial reasons, a half sized wind tunnel will be quite as good from a theoretical point of view, though it will not have as much appeal for yachtsmen and will be of small use in training their sailing skill.

The Structure of a Wind Tunnel. The object of a wind tunnel is to produce a smooth airflow of uniform speed (or wind velocity gradient) over the sails of a boat in order to measure the amount and direction of the force produced. It is the opinion of everyone that the tunnel should be of the "Pull through" type with a fan pulling wind over the boat. The diagram shows a tunnel design which is based on the Hayes Wind Tunnel of Sir Richard Fairey and it will be the basis for the tunnels to be described here. It will be noted that some latitude from aircraft wind tunnel practice is present which, apparently, is possible.

The tunnel consists of the following parts :—

1. The "surround" which is an "air smoother" consisting of wooden slats or wire gauze. This has the effect of retarding the outside air slightly and so allows lots of tiny jets of air to enter the



Longitudinal section of the tunnel

tunnel. This will abolish many large eddies in the outside air produced by the natural wind and objects near the entrance.

2. The " Bell mouth " which leads the air from the outside in as gently as possible. If this were not present, eddies would come from the edges of the tunnel from air which was being drawn in at right angles to the main axis of the tunnel.

3. The " air straightener " which may be a " honeycomb " system or a criss-cross of slats and it turns air coming from all directions into the direction of the main axis of the tunnel. It also acts slightly as an " air smoother. " In order to simulate the speed of the boat through the water, it may be given a " twist " of a few degrees because the forward speed of the boat gives the air it meets a slight " twist " due to the wind velocity gradient.

4. The " wind velocity gradient " grid which can consist of some wire fences placed on the floor of the tunnel. These are of varying height so that the air near the floor has to pass through more layers of this wire than that higher up. This slows it down more and hence the " wind velocity gradient " of the natural wind can be reproduced.

5. The " settling section " comes next. It is necessary to allow small eddies in the air which have been produced by the " honey-

comb " and wire mesh grids to settle down and become an even flow.

6. The " working section " which is that in which the yacht is placed. It and the settling section can be of several different cross sections but that which is advised by all the experts who have so kindly given us their advice is a square one. A hexagonal section and one which has a semicircular roof are alternatives which appeal as being easier to construct and having a less unsightly appearance from the outside.

Some wind tunnels are made with the walls diverging by about 2° to accommodate the turbulent boundary layer flow along them and leave a straight laminar flow truely along the axis of the tunnel. This seems to be an unnecessary complication.

7. The " exit " is a length of tunnel where the section is converted from that of the working section to a circular one which can accommodate the fan.

8. The fan, motor, belt drives etc.

9. The " exit smoother " is a wooden slat or wire mesh grid similar to that of the surround at the entrance to prevent the natural wind from effecting the wind produced by the fan.

THE A.Y.R.S. WIND TUNNEL

Size. The tunnel we should try to get should accommodate the largest Olympic dinghy, namely, the *Flying Dutchman*, which has a mast 25 feet above the L.W.L. This immediately gives us the size of the square working and settling sections which must be free of the top of the mast and must not unduly interfere with the eddy which forms there. Apparently, it is enough only to have one foot clearance between the top of the mast and the roof of the tunnel and, if we allow for someone having an extra foot in excess of the usual 25 feet, we have an inside height for the tunnel of 27 feet and this will be the breadth also.

The Surround " Air Smoother." The nature of this and details of its construction have not yet been decided. If one is content only to use the tunnel in conditions of dead calm, it can indeed be done away with but this would limit the operation of the tunnel mostly to the evenings and night and this is to be avoided, if possible. A grid of 2 inch by 1 inch slats or wire gauze seem to be the choices and it must be placed about 10 feet from the " Bell mouth. " A box of wire gauze was used in a very high speed wind tunnel described in the AERONAUTICAL JOURNAL of 1949 and appeared to be satisfactory. We are advised, however, that whatever the material, it should come back over the lips of the bell mouth by some feet, giving more than a foot clearance. If the tunnel is to be in the open, this screen must also keep out birds, mice and other unwanted animals

The Bell Mouth. This may have a quarter circle for its section whose radius is 10 feet and it should have a thick lip.

The Air Straightener. This could well be commercially made honeycomb. Its mesh should be, according to the best advice, 6 inches and its depth, 2 foot 6 inches.

The Velocity Gradient Fences. It is not known for sure if these are needed. If they are, ½ inch wire mesh should be enough and only wind speed measurement in the tunnel will tell us how many to have and how high each layer should be.

The Settling Section. In the design as we have been given it, this is 15 feet long and should allow all the eddies to settle down. On its side walls and just before the working section will be mounted two pitot-static heads connected by tubing to modified U tubes filled with xylol in which an air bubble has been trapped or other highly sensitive pressure gauge. These will give the wind speed in the tunnel by a formula for the " pressure heads. "

The Working Section. This will be 21 feet long and in this space will be a circular bath 20 feet inside diameter which will be filled with water to float the yacht being tested. A low rim at its edge will hold the spring balances which will take the thrust and side force produced by the sails, boat and crew.

The Exit. The exit where the section is converted from square to circular need only be some 7 feet in length. This is not a difficult constructional proposition. In the design as shown, the fan is 20 feet in diameter and this portion of the tunnel must therefore also reduce the size of the tunnel from 27 feet square to 20 feet circular.

The Fan Etc. The fan which at present we are thinking of using is one of Messers Airsrew and Jicwood's " Cooling tower " fans 20 feet in diameter, weighing some 500 lbs. and costing some £400. We are advised that the fan tip speed should not exceed about 500 ft/sec and the tip clearance from the surrounding ring should be as small as practical and not more than $\frac{1}{2}$ inch. The fan must be very securely mounted and be driven by a multiple V belt drive from the motor on the ground below.

An electric motor is most satisfactory, driven by a three phase power supply from the mains. About 7 h.p. for each 100 sq. ft. of cross sectional area of the working section is needed for a 10 m.p.h. wind. In our case of 729 square feet, 50 h.p. is needed which will cost about 7/6 ($1.00) per hour to run. A diesel engine of the same h.p. would cost about the same. A petrol engine developing this power would use 5 gallons per hour and be much more expensive. Electricity is to be preferred for convenience but, should the cost of bringing a three phase power supply to the tunnel be excessive, a diesel motor is the next choice.

Multiple V belt drive is a very dangerous thing to have on any machine unless very fully screened by wire or a wooden box.

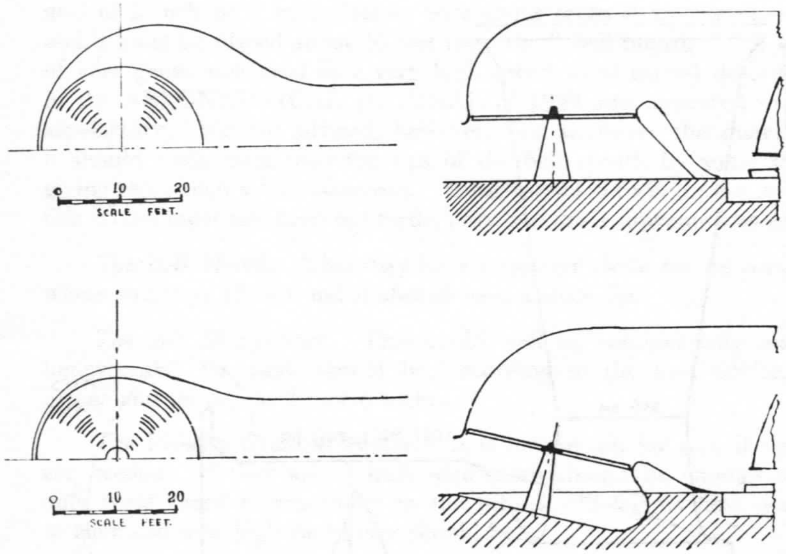
The Exit Surround. This will be of the same material as the entrance surround and placed 10 feet from the fan.

POSSIBLE MODIFICATIONS FOR ECONOMY

Such a tunnel as that outlined here would be absolutely satisfactory and give results which could be repeated at any time in a similar or larger tunnel. It is not believed that its final cost would be impossible for any yachting community to produce as long as its caretaking and maintenance were largely done by amateur labour. However, in order to make it quite certain that no chance would be missed of getting a wind tunnel should not enough money be available, all the modifications which might allow the tunnel to be made at less cost have been examined. These are :—

1. The use of a helicopter rotor instead of a bought fan. In fact, some time expired helicopter blades were actually found for the use of the A.Y.R.S. at no cost whatever. Then it was suggested that, due to the flexibility of these blades, it would be impossible to mount them vertically because of the " hinge lines and degrees of freedom " which I gather would produce a great deal of instability and risk of the blades breaking which would be dangerous.

The next thing examined was the use of the helicopter rotor with the blades horizontal — a duty for which they were designed. This entails turning the wind through a large angle at the exit of the tunnel

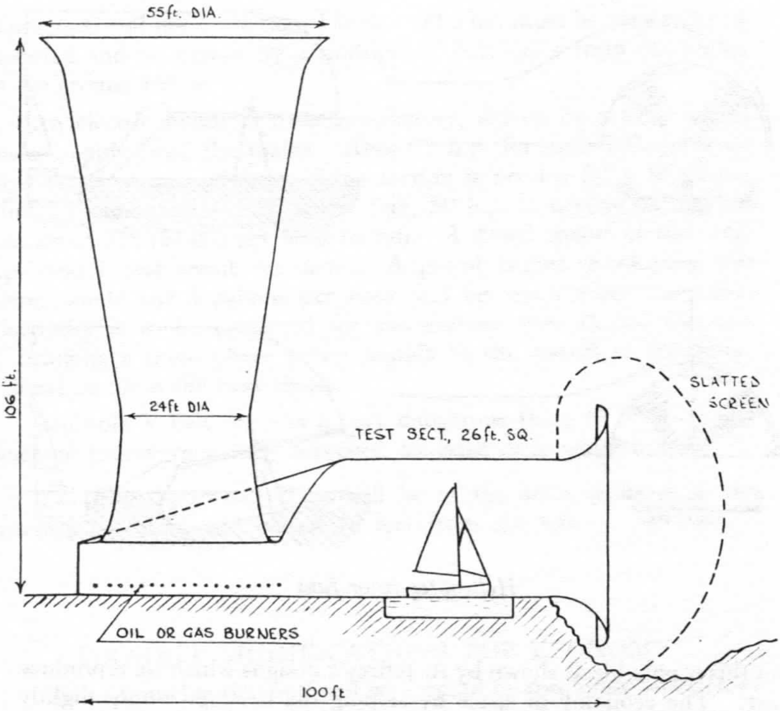


Helicopter rotor fans

but this is possible as shown by A. Jeffrey's designs which we reproduce here. The economy of space by sloping the helicopter only slightly will be noted. A cascade of guide blades would be necessary to help the air turn the corner.

2. *A Fan Substitute.* One of the early wind tunnels for aeroplane tests developed a windspeed of 60 m.p.h. by using a jet of steam to draw air out of it and this matter was examined to see if there could be any value in it for us. Steam extraction was not thought to be an economy as the boiler needed would be more expensive than the fan and motor of which we are thinking but the drawing by Owen Dumpleton shows how the air could be drawn out of the tunnel and forced up a chimney by heating it by a series of oil burners but the fuel consumption would be a gallon per minute or more.

3. Finally, there is the other solution of reducing the waste space at the top corners of the tunnel by having a semicircular or sloping roof. The cross section of the air affected by the sails of a yacht is roughly elliptical and there is something to be said for using a tunnel cross section of a similar shape. The difficulty here is the constructional one of fairing these shapes into the bell mouth and the



A hot air wind tunnel

fan. Aerodynamically, it is satisfactory as the wall effect of this tunnel will be almost negligible.

Summary. It would appear that the only way in which the tunnel might be more cheaply built is by the use of a helicopter rotor mounted horizontally. Some benefits might be obtained by having a semicircular or angled roof.

A MOVABLE TUNNEL SUGGESTION

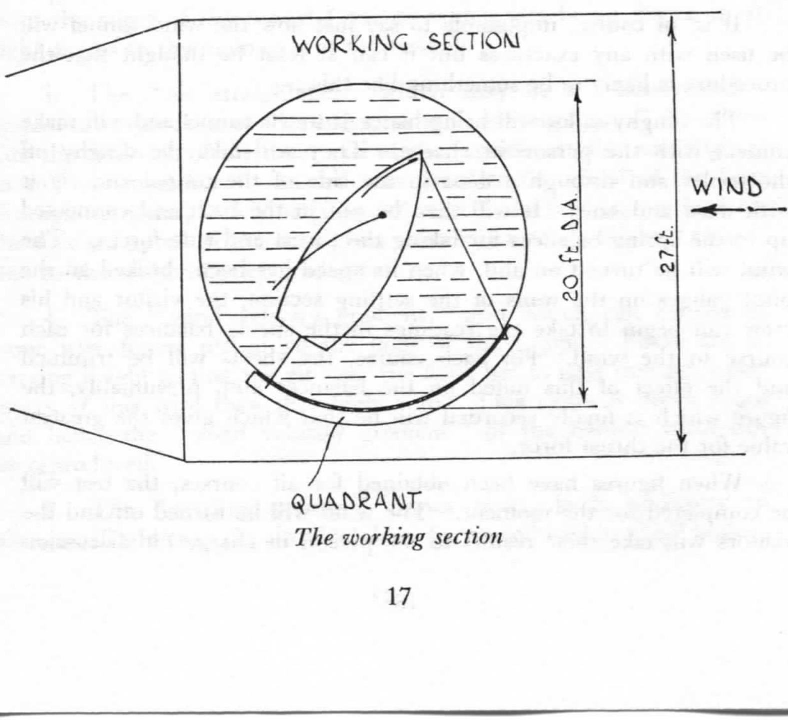
It has been suggested by several A.Y.R.S. members that we use a method which was used by Mr. R. Hafner during the war with great success. This is to buy a chassis from an old bus or lorry and build a wooden platform on it to which is fitted all the gear necessary for the measurement of the wind forces, together with wind speed indicator etc. The chassis would have to be ballasted to increase its stability.

The vehicle would then be driven along the runway of an aerodrome and the required measurements taken during the run.

Undoubtedly, this procedure could be used but it is felt that it would not have the appeal to practical yachtsmen which is essential to get the best results. For instance, it would be almost impossible to mount the dinghy in a bath of water of any size and take the windage of the crew with any confidence. However, it could well be considered by any group of yachtsmen who could not get their results in any other way. As compared to this method, a full sized yacht wind tunnel would allow careful result measurement of a kind which would appeal to all as being accurate and repeatable.

THE WORKING SECTION

The drawing shows a plan view of the working section. A circular bath is let into the floor of the tunnel which is 20 feet in inside diameter to accommodate the *Flying Dutchman* dinghy. It has a rim which sticks up 1 or 2 inches proud of the floor and is filled with water in which the dinghy being tested floats. The water is " topped



The working section

up " to a predetermined level according to the weight of the dinghy and an overflow pipe, placed at the downwind end of the bath, will prevent wetting of the floor.

For the common testing of dinghies, only the overall side force will be of interest and this will be taken by a wire span to either end of the craft on its centreline. The thrust force will be taken by a short wire to the mainsheet horse or a rudder pintle. Both thrust and side force will be taken by spring balances attached to a wooden beam of quarter circle shape placed outside the rim of the bath. This quarter circle beam can then be slid around the rim of the bath so as to " sail " the dinghy on each course to the apparent wind.

From the scientific interest point of view, on the other hand, one would like to know exactly where the true centre of effort of the sails lies and for this, two spring balances would be necessary for the side force, one fore and one aft. From the relative pull in each, the position of the true centre of effort of the sails can be found. This would necessitate a different method of attachment which would not be complex. The vertical height of the true centre of effort of the sails can be calculated from a simple stability test.

THE METHOD OF USE

It is, of course, impossible to say just how the wind tunnel will be used with any exactness but it can at least be thought that the procedure is likely to be something like this :—

The dinghy sailor will bring his craft to the tunnel and will make contact with the person in charge. They will take the dinghy off the trailer and through a door in the side of the tunnel and rig it with mast and sails. It will then be put in the bath and connected up to the spring balances for taking the thrust and side forces. The wind will be turned on and, when its speed has been checked an the pitot gauges on the walls of the settling section, the visitor and his crew can begin to take the readings in the spring balances for each course to the wind. For each course, the sheets will be trimmed and the effect of this noted on the balances and, presumably, the figure which is finally recorded will be that which gives the greatest value for the thrust force.

When figures have been obtained for all courses, the test will be completed for the moment. The wind will be turned off and the visitors will take their results to the person in charge for discussion of the figures. This discussion may result in the need for another series of readings which can again be discussed and advice given on the shape of the sail or any modifications needed.

The Mathematical Treatment. For general comparison with other tunnels and windspeeds, the figures for thrust and side force must be reduced to " Coefficients " which is done by dividing them by the mystical formula $\frac{1}{2}\rho$ A v^2, where ρ is the mass density of the air. A is either the total sail area or the rated sail area according to the rules of the class being tested, and v is the windspeed in feet per second. All results for publication will ordinarily be given in terms of coefficients so that sail plans of different areas tested in different windspeeds in different densities of air can be directly compared.

GENERAL RESULTS

Besides the practical value of the wind tunnel to any individual yachtsman as described in the last section, certain general results are likely to appear which can be examined by the more theoretical and mathematical of our members.

The Effect of Size. From a study of the thrust and side force coefficients of the *Cadet*, the *Firefly*, the *Merlin-Rocket*, the International 14 foot Class and the 505 or *Flying Dutchman*, all of which have approximately the same sail plan but of different sizes, one should be able to see if the coefficients become greater with increasing size, as they should from theoretical considerations.

The Effect of Windspeed. Similarly, the coefficients should become greater with increasing windspeed but this effect will only be very slight.

The Effect of Rig. The *Moth* and *Finn* are both cat rigged craft and their coefficients could be compared with those of the sloop rigged dinghies. This should settle some arguments as to the relative merits of the two rigs. Various rigs, such as have been already conjectured in our publications Nos. 9, 14 and 17 could also be tried out to see if any of them would produce better figures than the more orthodox rigs.

The Effect of Greater Flow. Sails are already being made by various sail makers of different amounts of " Flow " or belly. The amount of flow of each sail tested should be measured by running a line between the luff and leech at some predetermined level and measuring the distance from it to the sail at the farthest point. It is believed that the amount of flow has a great effect on the drive of a sail and we will be able to see the relationship between the amount of flow and the force produced.

The Effect of Plan Form. This includes aspect ratio and the amount of roach. From the relationship between the coefficients and these factors, we should be able to judge what is best.

The Effect of Full Length Battens. It is now definitely known that these produce more drive than short leech battens but it is not known by how much. Our force measurements will give us an exact answer to this.

Gale Effects. In the dinghy classes, it is, apparently, impossible to win races if reefed. They therefore always use full sail and usually allow the mainsail to " flag " when a strong puff of wind or a squall hits them. Only the jib is then drawing. It should be quite possible to evaluate how much is to be gained by having a flatter mainsail to lose force that way rather than to have a fuller mainsail and allow it to " flag. " It should also be possible to find out how the forces of a " flagging " sail vary with the windspeed up to the top windspeed we are able to produce in the tunnel and from this infer how they will continue to vary as the windspeed is increased still further.

The Effect of Crew Placing. The wind tunnel should be used with the crew in position so that their windage is taken into account in the resultant sail and boat forces. This would be of some value in finding out where best to place them for minimum resistance but they must also be placed to trim the boat effectively for minimum water resistance at various speeds and this will make this test of only limited value.

Wind Flow Patterns. Windspeed probes or other local wind velocity exploration devices may be provided to plot the wind flow patterns around the sails and to search for parasitic eddies. These will require highly sensitive pressure gauges but, to save money or for convenience, they could be connected in turn to the main velocity measuring instrument of the tunnel. Alternatively, the pressure distribution over the sails can be studied by making holes in them which are connected by tubes to pressure gauges as was done by Warner and Ober, Professor Davidson and others.

Other Tests. Other tests can also be done which may be of great interest but of only a small immediate practical importance such as that of lowering the boom, of streamlining the mast or having it twisting, above water hull shapes, bending booms, bending masts and a host of other things.

In all, there is a full time employment for the wind tunnel for a lifetime in just discovering what is best of the known variables as well as the perpetual use for the tunnel in training the skill of yachtsmen. One cannot see how a wind tunnel made to accommodate dinghies at full size can fail to be continually in use.

" SCALE "

By T. F. Arlotte, A.M.I.N.A., A.F.R.Ae.S.

The science of boat model testing owes much to the pioneer work of William Froude, whose tank, opened at Torquay in 1861, was the first facility with a travelling carriage and accurate instrumentation. At that time model tests were believed to be unreliable, but Froude showed that this misconception was due largely to faulty methods of analysis in scaling up model results, and his law of comparison is now the basis for all boat model work. There are now experiment tanks all over the world, and the demand for model testing is such that new tanks are still being built.

It can be shown that, for a body moving in the water surface, force is a function of Froude number ($V/\sqrt{gL}$) and Reynold's number (VL/ν),

where
$V =$ craft speed, ft/sec.
$L =$ craft length, ft.
$g =$ acceleration due to gravity
$\nu =$ kinematic coefficient of viscosity

$$\left.\begin{array}{l} = 1.229 \times 10^{-5} \text{ in fresh water} \\ = 1.282 \times 10^{-5} \text{ in sea water} \end{array}\right\} \text{at } 15^\circ\text{C}$$

In detail, the resistance is made up of frictional resistance (a function of Reynold's number) and the remainder, termed residual resistance, is due to wave-making and form and is a function of Froude number. It was Froude who first produced experimental evidence to justify the separation of resistance into these two components and thus provided the basis for converting model results to full scale.

Since it is clearly impossible to achieve identical Reynold's numbers, the practice is to employ identical Froude numbers and apply a suitable correction to the skin friction component.

For this purpose the part of the model coming into contact with the water should be geometrically similar to the full scale craft. If the model scale is λ, the scale of speed will be $\sqrt{\lambda}$ (e.g. if the model is 1/9th full scale, and the full scale speed is 18 knots, the required model speed is $18/\sqrt{9} = 6$ knots), the scale of wetted area λ^2 and of lift, weight and submerged volume λ^3. If the tank water is fresh, as usually preferred, and the full scale craft will operate in sea water, the scale of lift and weight will vary from λ^3 by the relative density of salt and fresh water.

If no correction were necessary for skin friction, the total resistance would scale similarly to the other forces. However, the skin friction

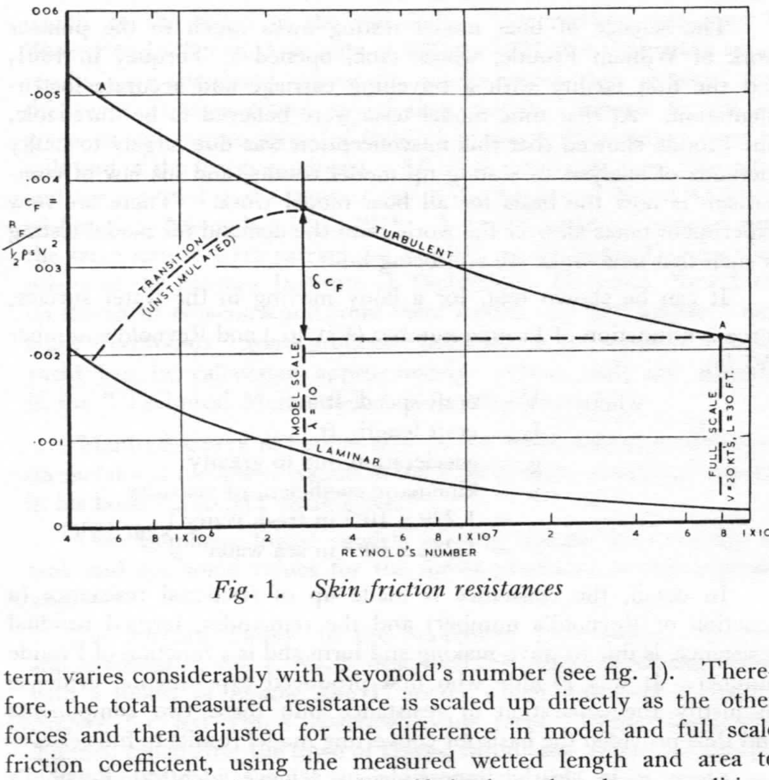


Fig. 1. *Skin friction resistances*

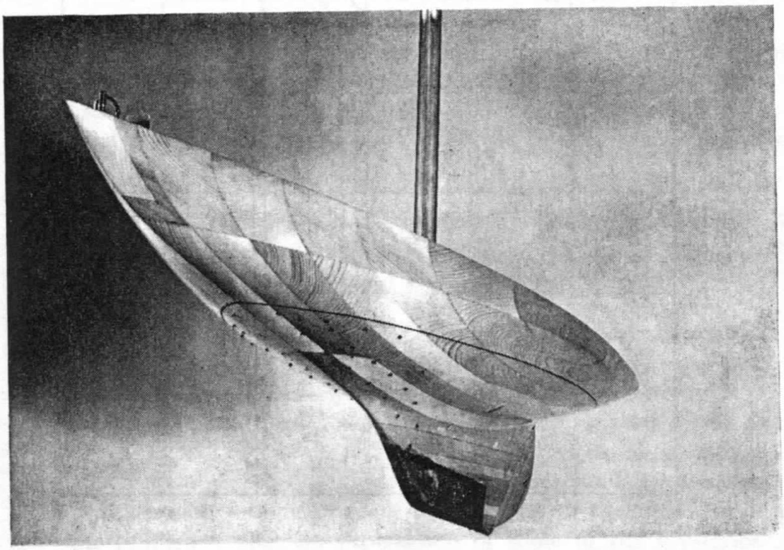
term varies considerably with Reyonold's number (see fig. 1). Therefore, the total measured resistance is scaled up directly as the other forces and then adjusted for the difference in model and full scale friction coefficient, using the measured wetted length and area to obtain the total friction forces (e.g. if the boundary layer conditions are turbulent in both cases, the friction coefficients then lie along curve AA in fig. 1, and,

$$\text{Full Scale Resistance} = (\text{Model Resistance}) \times \lambda^3 \times \frac{\text{density, sea}}{\text{density, fresh}}$$

$$- \delta\ R_F$$

It will be obvious from fig. 1 that this scaling process is dependent on a knowledge of the boundary layer conditions. At full scale Reynold's numbers the flow will normally be fully turbulent, so that line AA applies. However, for model conditions the flow may be partly laminar, and the friction coefficient will then lie below AA. If laminar separation occurs the drag in the boundary layer may be indeterminate and may lie above AA, and for this reason model Reynold's numbers below about 10^5 should be avoided if possible, and the model surface should be smooth.

The normal practice is to satisfy the requirements of the foregoing sentence, and then to ensure that the model skin friction coefficient lies along AA. This can be achieved by suitable positioning of trip wires or studs near the model bow, by rakes ahead of the model, or by applying a small vibration to the model. One method of checking



Studs at the entry to produce turbulent flow the boundary layer condition is by visual observation of ink streams injected into the flow. Accurate measurement of the wetted shape is required for scaling purposes, and this can be obtained by underwater photography, the paint spot technique or by spraying a solution of hydroquinone diacetate on the model bottom before running. The latter two methods show a trace of the flow pattern when the model is removed from the water.

Fig. 2 illustrates the close resistance correlation that can be achieved by using the correct scaling process, and shows the order of error which can be introduced if the friction correction is not made.

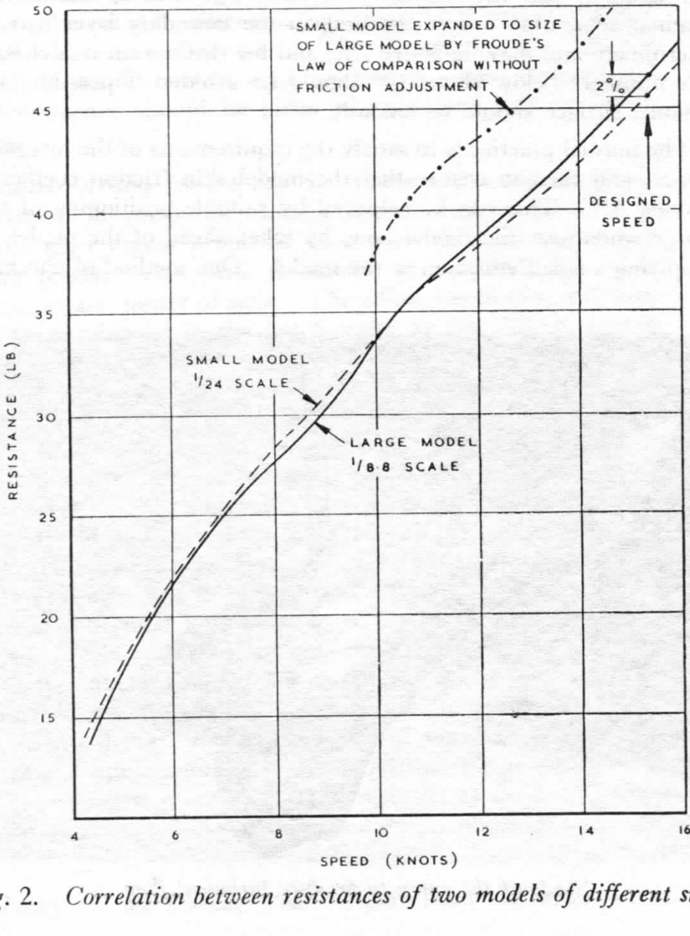


Fig. 2. Correlation between resistances of two models of different sizes

If a model of a power boat is being tested, the model is usually run with and without the propulsion appendages present. Care is then required in scaling up this resistance component, since the model appendage Reynold's number may be quite low. The final proof of the model resistance technique is, of course, obtained by comparison of predictions with full scale results, and it may be stated here that there is much evidence to support it.

The choice of scale for a model will depend upon the size of the tank and the available carriage speed. If the model is very large relative to the tank cross-section, a blockage correction will be required. In the case of a hydrofoil craft, the tank boundaries will influence the hydrofoil wave drag, so that a correction is required for this when scaling up to a craft operating in deep water. On high speed hydrofoil craft, cavitation may exert a profound influence on full-scale performance. This presents a difficulty in model testing, since cavitation is a function of actual speed. In this case, the scaled-up model results must be corrected for cavitation effects. The latter can be predicted theoretically from full scale tests, and from cavitation tunnel tests. (The cavitation tunnel is the hydrodynamic equivalent of the wind tunnel).

Fig. 3. Cargo ship model under test

Fig. 3 shows a model of a cargo ship under test in a modern towing tank. Scale tests are not, of course, confined to simple calm water resistance, trim and draught measurement. Stability can be studied, using dynamic models with correct scaled rotational inertias. Most towing tanks are equipped with wave-makers so that rough water behaviour can be studied.

Self-propelled models may be used, and manoeuvring tests can be made in special wide basins or in suitable natural locations. Radio-controlled models may often be used in such cases.

Perhaps the most interesting type of test carried out in towing tanks is that employed for yacht studies. Here the hull is free to heel and make leeway under the action of the water forces and applied sail force (see fig. 4).

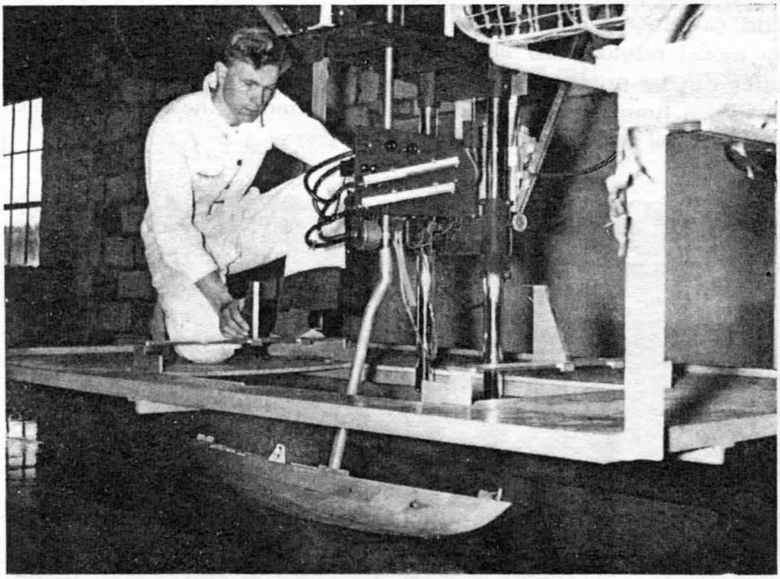


Fig. 4. A sailing yacht model under test

A question which is often asked is " Why make model tests ? "

Suppose a model of a merchant ship is tested. It is possible that systematic modifications may lead to a resistance reduction of up to 10%. Then, for an outlay of a few hundred pounds on tests, the saving on the fuel bill may amount to about £50 per day during the ship's operating life. Numerous other examples can be quoted to justify model tests. In the realm of small boats and yachts equally striking benefits may be derived, for a modest outlay which may be as low as £50 — £100. Yacht tests in particular have received little systematic study so far, and there is no doubt that advances in yacht performance could be made from model work using accurate instrumentation.

The author does not wish to detract from the type of amateur research advanced by the A.Y.R.S. (e.g. Publication No. 12). Much useful evidence can be derived from simple and cheap apparatus. If the results of such work appear sufficiently encouraging, then the amateur may feel justified in submitting his model for more rigorous tank tests.

Fig. 2 is re-produced from " The Hydrodynamics of Planing Hulls " by Murray, Transactions of the Society of Naval Architects and Marine Engineers, 1950.

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