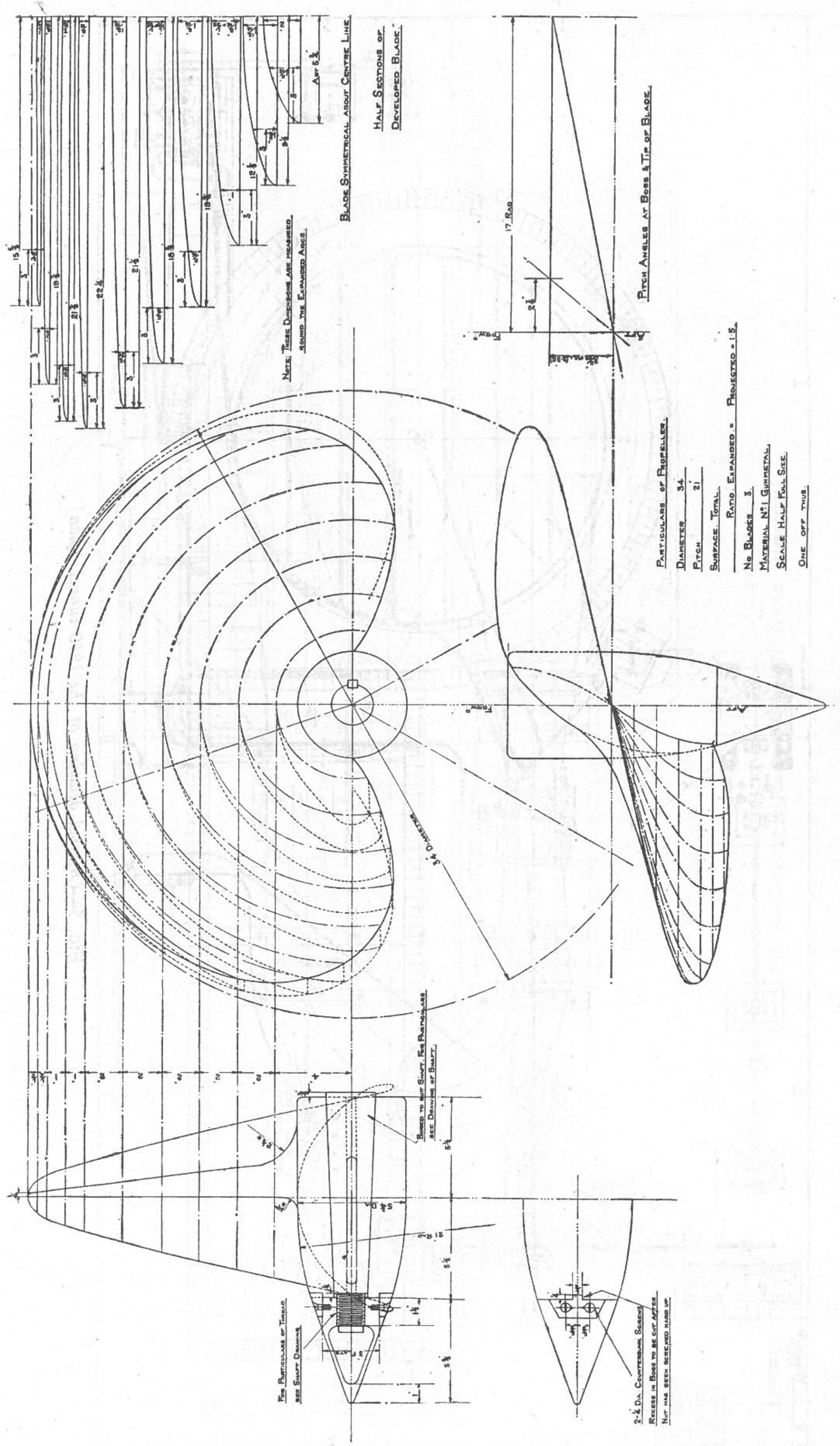

FIG. 9—*Wide three bladed destroyer propeller (1922)*

rounded corners, 2ft. 3in. wide by 2ft. 6in. deep, and large windows were fitted on either side through which the propeller could readily be seen, as shown in Fig. 6, Plate 3.

It was arranged to have a shaft support, or shaft-bracket, ahead of the working propeller to simulate conditions in the ship, and tests were made with various designs of brackets to determine the effect of these on the flow into the propeller. Immediately above the propeller position there was a header tank, or vacuum chamber, so that the pressure above the working propeller could be varied to represent different ship conditions. This is also shown in Fig. 6, Plate 3, and cross-connecting pipes were fitted from this point to the top of the large settling tank and to an air vessel which could be evacuated by means of an electrically driven reciprocating air-pump. The model propeller shaft was introduced through a water packed gland in the downstream end of the upper limb. This shaft was driven from an electric motor by means of a rope-drive which passed round a system of pulleys.

The torque was measured by determining the difference in tension in the ropes on either side of final driving pulley, by means of a weighted lever and spring as shown in Fig. 7, Plate 3.

The thrust was measured directly off the outer end of the shaft, also by means of a weighted level and pulley, as shown in Fig. 8, Plate 3. Means were provided for counting the revolutions of the shaft at any time.

Illumination of the propeller was obtained from a large searchlight, the light being reflected by a revolving mirror directly into the propeller disk, and the photographs taken with exposures of 1/20,000 sec. to 1/30,000 sec. were very satisfactory. In connexion with these photographs, it is to be noted that the camera was focused on the particular part of the blade which was of interest, and no attempt was usually made to photograph the whole propeller. This explains the appearance of one blade only in the photographs reproduced in Figs. 18 and 20, Plate 4, usually in the 6 o'clock position (i.e., vertically downwards).

The propellers tested were uniformly 1 foot in diameter, and they were tested at speeds in accordance with Froude's Law. The following table, taken direct from the existing records, shows clearly how the corresponding speeds, etc., for ship and model sizes were determined.

	Ship	Ratio between full and model	Model
Diameter	19·58 feet	d	12 inch
Pitch	18·00 feet	d	11·05 inch
Pitch ratio	0·92	1·0	0·92
V_s	28½ knots		
V_1	24·5 knots	$\sqrt{d}$	9·36 ft. per sec.
Immersion	22ft. 6in.		
Atmospheric	33ft. 0in.		
Total head	55ft. 6in.	d	2·83 feet
S.h.p. (per shaft)	39,500		
E.h.p. at 55 per cent	21,725		
Thrust	288,800 lb.	d^3	38·48 lb.
Exp. surface	190 sq. feet	d^2	72 sq. in.
Surface Ratio	0·633	1·0	0·633
Thrust lb. per sq. in.	10·55	d	0·534
Slip	18·8 per cent	1·0	18·8 per cent
Estimated r.p.m.	169·7		751

These figures are for propeller 54, the results for which are shown in Fig. 19.

From the records it appears that distilled water was used in this tunnel, and also that small quantities of copper sulphate were added to the water, which was cleaned and filtered from time to time. There are no records of air-content, but Mr. S. S. Cook recalls that the tunnel was run for some time under vacuum in order to take the air out of the water.

In this large tunnel, tests were made in connexion with the propellers for a number of warship propellers and the drawing shown in Fig. 9 has been reproduced from the actual working drawing for a destroyer built in 1922, as it indicates the high blade surfaces which were sometimes used, and the type of sections which were adopted.

Systematic tests were also carried out with propellers of varying projected surface ratio and different pitch-ratios, and records of these tests, which are still in existence, have very kindly been placed at my disposal for the purpose of this lecture. These indicate the method of testing, and also the manner in which the results were presented, which are extremely interesting in comparison with present day procedure, and reveal the tremendous amount of thought, time and energy which was put into these early investigations of the "cavitation" problem, by Sir Charles Parsons.

The author was, in fact, greatly astonished to find the wide range of tests which had been carried out in this tunnel, at such an early date as 1910, the results of which have not previously been published.

VII. METHODICAL SERIES TESTS IN THE LARGE CAVITATION TUNNEL AT WALLSEND (1910-1931)

During the period 1910-1914 Parsons carried out tests with a large number of 3-bladed model propellers of varying projected surface ratio and face-pitch ratio. The range of these experiments covered variations in projected surface ratio from 0·20 to 1·55, with variations in pitch ratio from 0·90 to 1·50. The results of these tests were embodied in a series of extremely well-presented diagrams, most of which are still in existence, and I have selected and assembled the results shown in Figs. 10, 11, 12, 13, and 15 to illustrate the breadth of this investigation, and the conclusions which may be drawn from it. Fig. 10 shows a series of propellers all of 1·24 pitch-ratio and with projected surface ratios of 0·20, 0·35, 0·50 and 0·70, respectively, while Fig. 11 shows a similar series with screws of 0·90 pitch-ratio and projected surface ratios 0·35, 0·50, 0·70, 0·85 and 1·55 respectively. Fig. 12 shows the effect of pitch-ratios varying from 0·90 to 1·50 with a fixed projected surface ratio of 0·70. In all of these diagrams the results of the tests at atmospheric pressure are shown on the left-hand side, and the corresponding results under vacuum are shown in parallel on the right-hand side. Insofar as the vacuum conditions are known, they are included in the diagrams, but generally speaking the air pressure was reduced to about 0·9 inch Hg or 0·45lb. per sq. in. above the propeller. The speeds were obtained from pressure readings taken from an internal venturi-nozzle, fitted in the lower limb of the tunnel at the exit side, and the tests in question all appear to have been repeated at water speeds of 8·6, 10·0, 11·9 and 14·3ft. per sec., respectively, which appear to have been chosen to represent full-size speeds of 18 knots, 21 knots, 25 knots and 30 knots, respectively, for a propeller diameter of 12·5 feet.

The value of the Cavitation Number $\sigma = \frac{p - e}{\frac{1}{2}\rho v^2}$ is not recorded and it is a little difficult to state this precisely, but an estimated value has been included in some of the diagrams. As the vacuum chamber was always exhausted for the vacuum tests, it is clear that variations in the σ value were not intended to be covered in this series, but as the water speed was varied, changes occurred in the value of this cavitation number, and Fig. 13, which refers to four model propellers of 0·90 and 1·0 pitch ratio, and 0·50 and 0·68 projected surface ratio, respectively, has been included to show this effect. This diagram illustrates a number of interesting points, and is very similar to those obtained by other investigators at a very much later date. There appears, for example, to be a change in effective pitch as between the tests at various σ values, and the point at which the thrust and torque break down occurs is advanced to low slips at the lower σ values. The curves also show a tendency for the $\frac{\text{cavitation thrust}}{\text{atmospheric thrust}}$ ratio to increase with slip at the lowest values of σ.

Most of these model propellers appear to have had segmental or round back sections, and the drawings of propellers 26 and 29 are shown in Figs. 14(a) and (b) to illustrate the general design of the blades and the boss-diameter ratio.

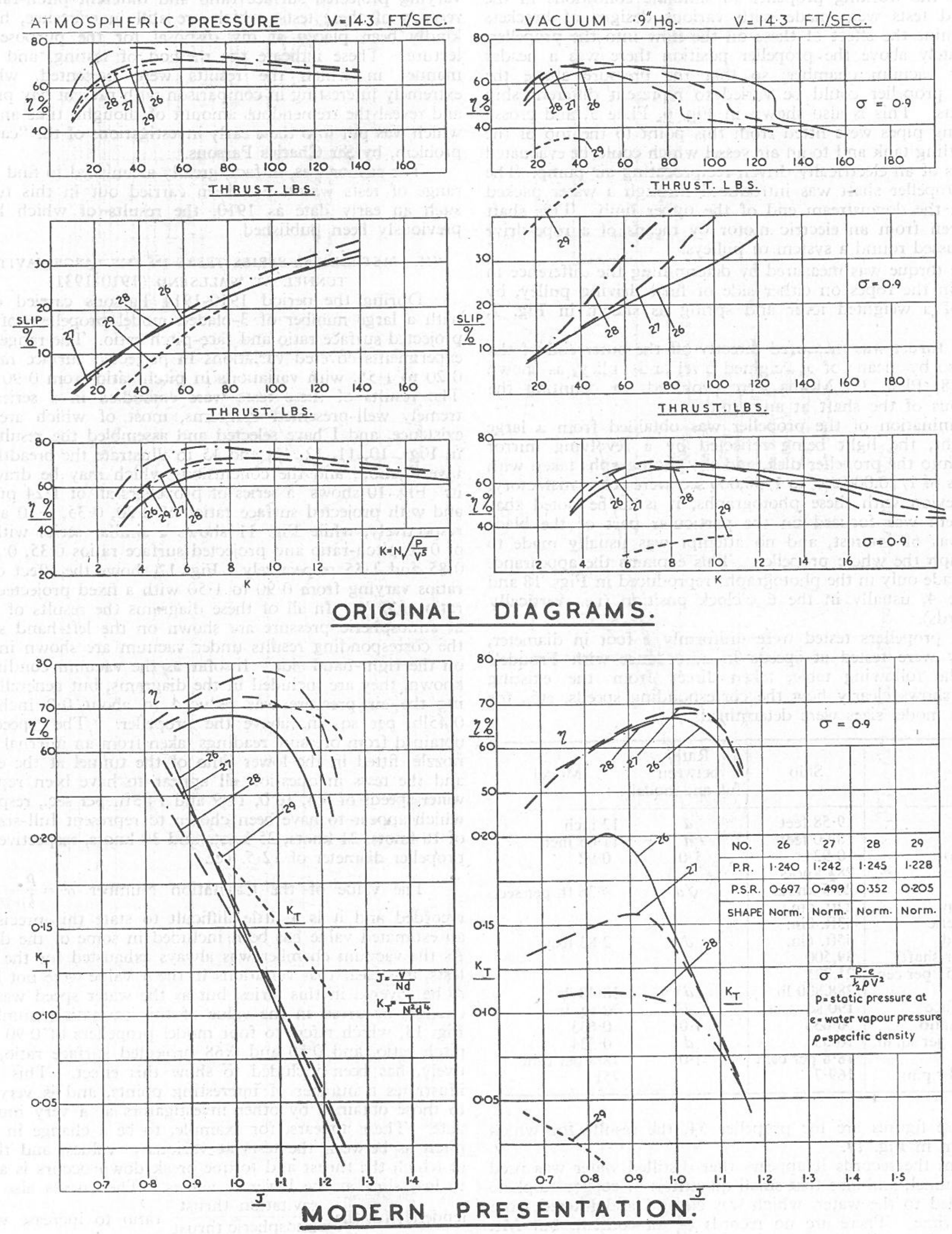

FIG. 10—*(1910-1914) Methodical Series Tests (1) Effect of blade area at 1·24 pitch-ratio*

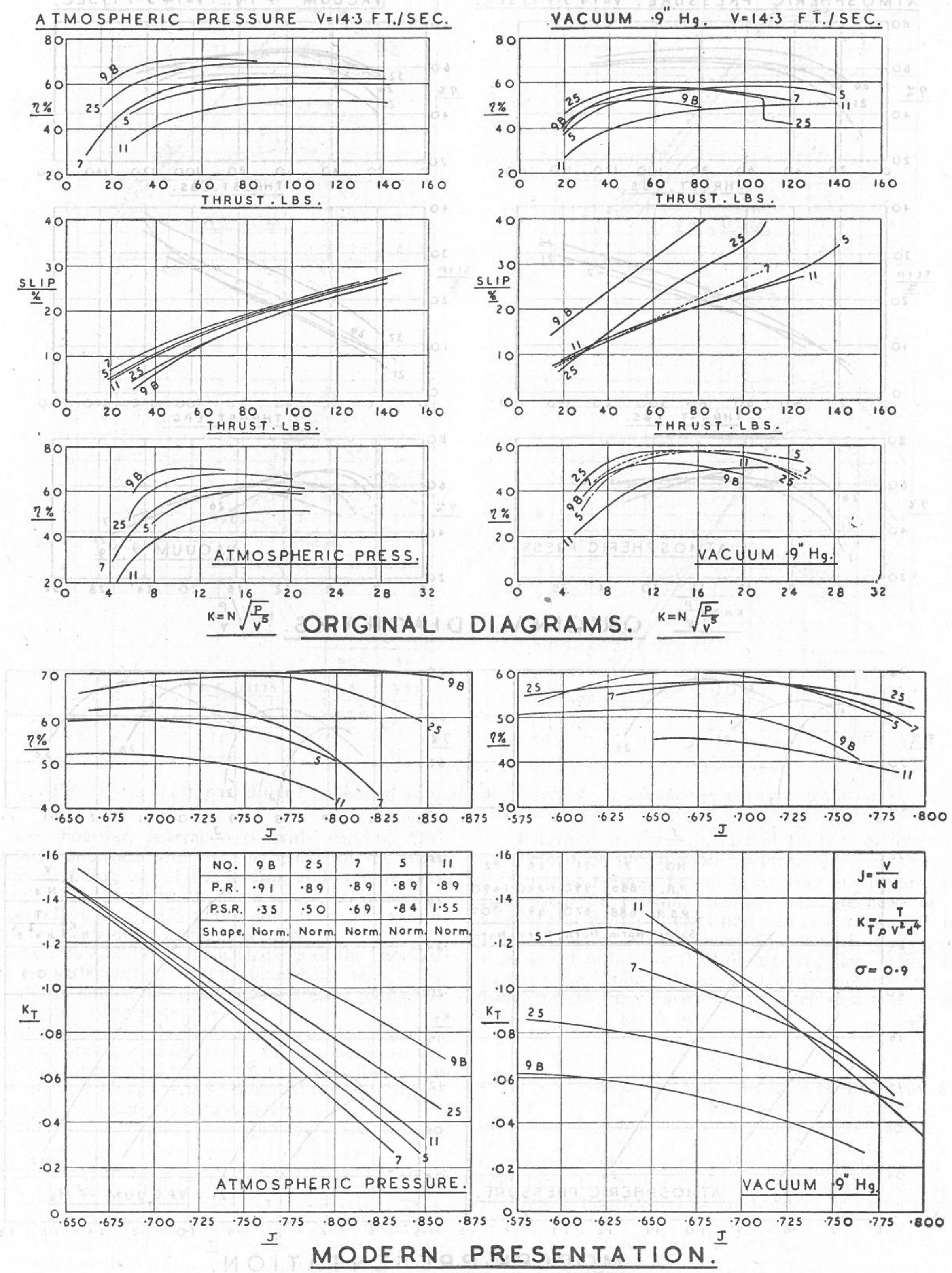

FIG. 11—*(1910-1914) Methodical Series Tests (2) Effect of blade area at 0·90 pitch-ratio*

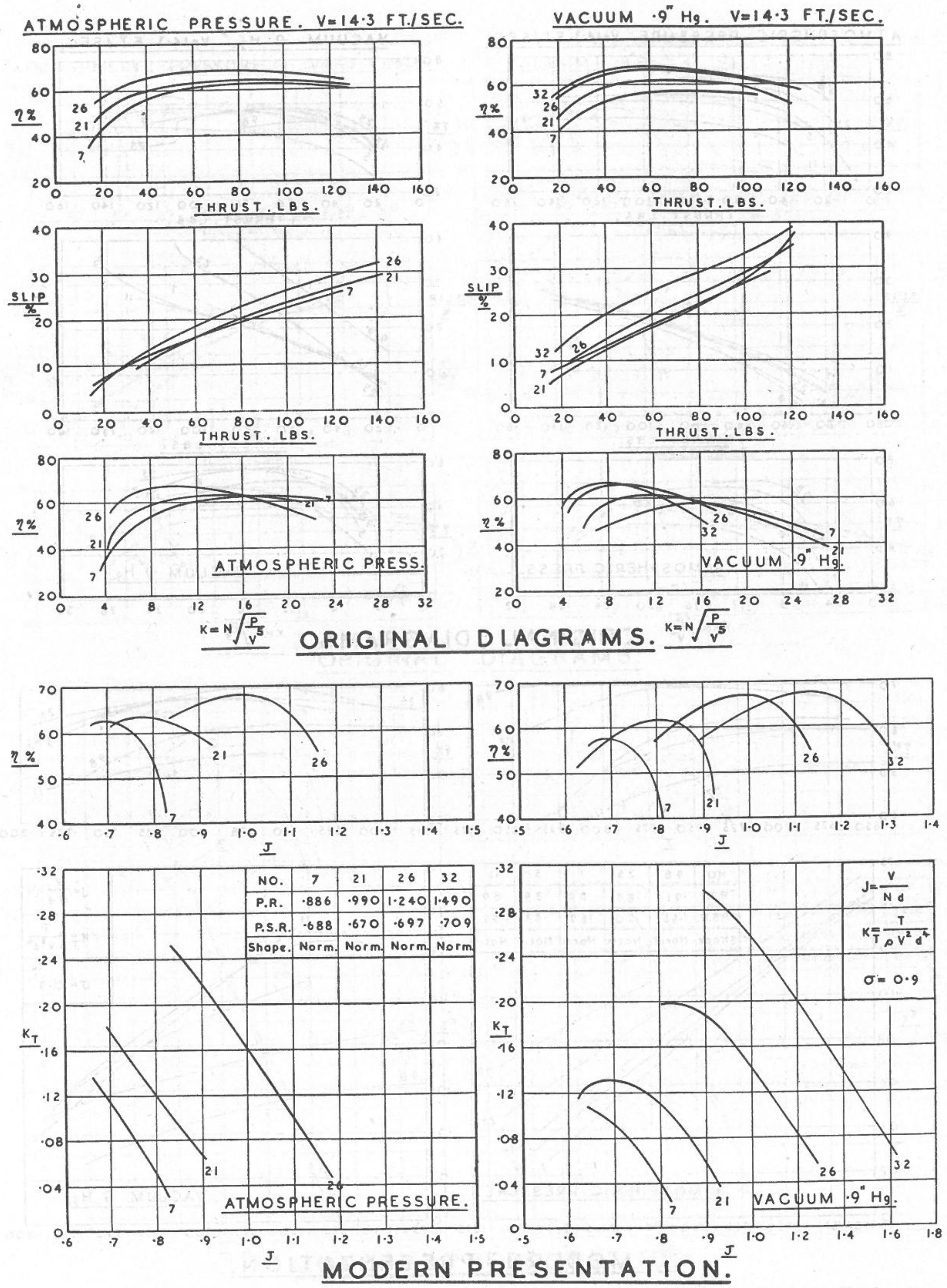

FIG. 12—*(1910-1914) Methodical Series Tests (3) Effect of pitch-ratio variation with fixed projected surface-ratio (= 0·70)*

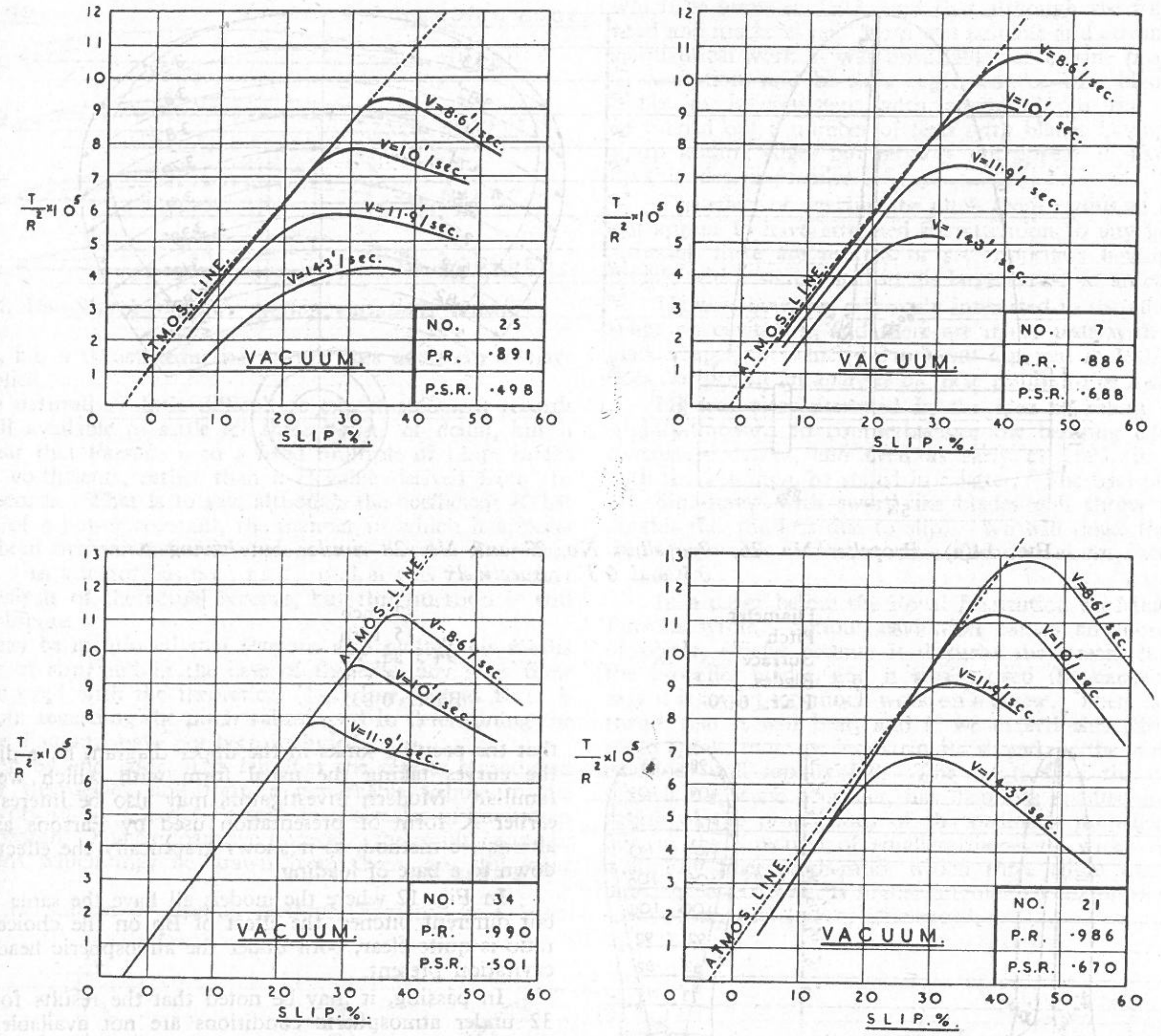

FIG. 13—*Thrust/revolutions² to base of slip, at various speeds of advance in vacuum condition*

There are, however, several tests with varying blade sections, mainly concerned with the sharpening of the edges, and the fining or filling out of the leading and trailing parts of the sections. Fig. 15 shows an interesting comparison between four propellers all of 1·25 pitch ratio and 0·70 projected surface ratio, but with different blade sections.

In propellers 26 and 35 the blade shape is of the "normal" symmetrical type, the sections being round-back with rather thick edges, and of similar type, but with a thick trailing part and a sharp leading edge, respectively.

In propellers 31 and 39 the blade shape is of the "scimitar" type, the sections being approximately of flat-faced aerofoil type with the maximum thickness ordinate moved forward to 0·47 of the width at 0·7*R* and to 0·37 of the width at 0·9*R*, and with the same edge thickness variation as above.

The section shape variation covered by these tests is therefore approximately as shown below in Fig. 16.

It is interesting to note the differences in efficiency between these several propellers, plotted to a base of slip, for the atmospheric condition and with vacuum, respectively. These are more or less in line with expectation in the light of modern developments, the aerofoil type showing to advantage under atmospheric conditions but falling off with vacuum.

It is also to be noted that "under vacuum" the aerofoil type with full leading edge is more efficient than the aerofoil type with a sharp leading edge, while, for the round back type, the sharp leading edge and fuller tail gives the better result.

Returning to Figs. 10, 11 and 12, it is of interest to note the method of presentation adopted.

In these figures, the top three pairs of diagrams are taken direct from the existing records. The method of plotting adopted was to record efficiency, slip and a factor *K* to a base of thrust in lb., with an auxiliary scale of thrust per sq. in. of projected surface for the full-size propeller. Thus the thrust loading at which breakdown occurred was clearly seen. Alternatively, the efficiency curves were plotted to a base of *K*, where this constant is given by

$$K=N\sqrt{\frac{P}{V^5}}$$

which is, of course, essentially the same as the Taylor Bp value. In this way, the effect of blade surface on efficiency is clear, and it is to be remarked that at moderate and high Bp loading the relative position of the curves for the propellers 26, 27 and 28 is completely reversed in the atmospheric and vacuum conditions, the higher surfaces showing to advantage when cavitation is present, and to disadvantage under the atmospheric loading.

Propeller 29 which is the very narrow bladed screw shown in Fig. 14 (b) gives a low efficiency under the atmospheric head, presumably due to the relatively high thickness-ratios, and under vacuum the result is disastrous.

In the lower diagram of Figs. 10, 11 and 12 the results given by the three upper diagrams have been converted to the modern K_T, J, η, presentation, and it is of interest to note

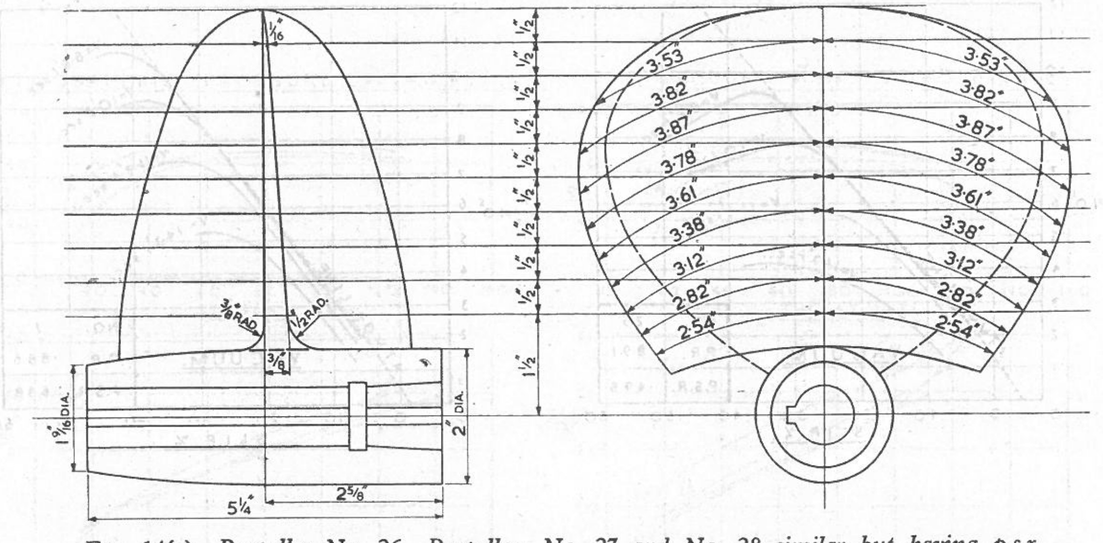

FIG. 14(a)—*Propeller No. 26. Propellers No. 27 and No. 28 similar but having p.s.r. 0·5 and 0·35 respectively*

Diameter	12 inch
Pitch	15 inch
Surface	94·5 sq. in.
Blades	3 r.h.
P.s.r. 0·70	B.a.r. 0·835

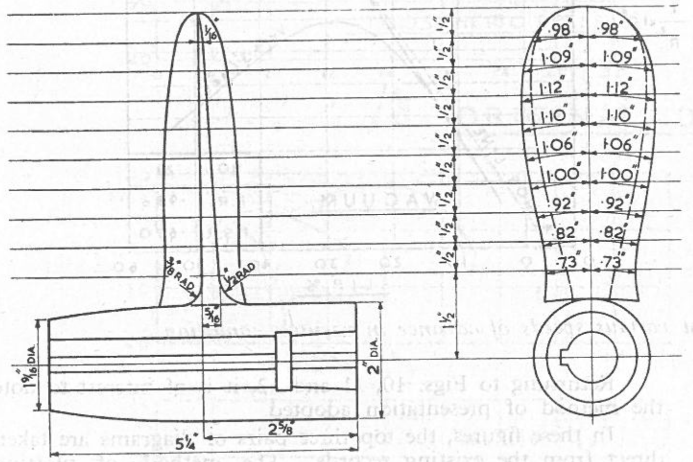

FIG. 14(b)—*Propeller No. 29*

Diameter	12 inch
Pitch	15 inch
Surface	28·25 sq. in.
Blades	3 r.h.
P.s.r. 0·2	B.a.r. 0·25

that the peculiar kinks in the upper diagram have disappeared, the curves taking the usual form with which we are now familiar. Modern investigators may also be interested in the earlier *K* form of presentation used by Parsons as a useful alternative method, as it shows graphically the effect of breakdown to a base of loading.

In Fig. 12 where the models all have the same blade area, but different pitches, the effect of Bp on the choice of pitch-ratio is quite clear, both under the atmospheric head and with cavitation present.

In passing, it may be noted that the results for propeller 32 under atmospheric conditions are not available, and also that as the original experiments were intended to be comparative, care should be exercised in applying these results quantitatively, since no corrections appear to have been applied, and there may be some errors arising from bearing friction, etc.

In connexion with the factor *K*, it should be added that it is not quite clear exactly what horsepower the *P* value in the formula $K=N\sqrt{\frac{P}{V^5}}$ represents, in Parsons original diagrams. Mr. S. S. Cook tells me that this was also used as a design coefficient and for that purpose the value of *P* was evaluated by multiplying the e.h.p. (naked) by 2, thus assuming a propulsive coefficient of 0·50. It appears that a wake factor was used in connexion with the determination of *V* for design

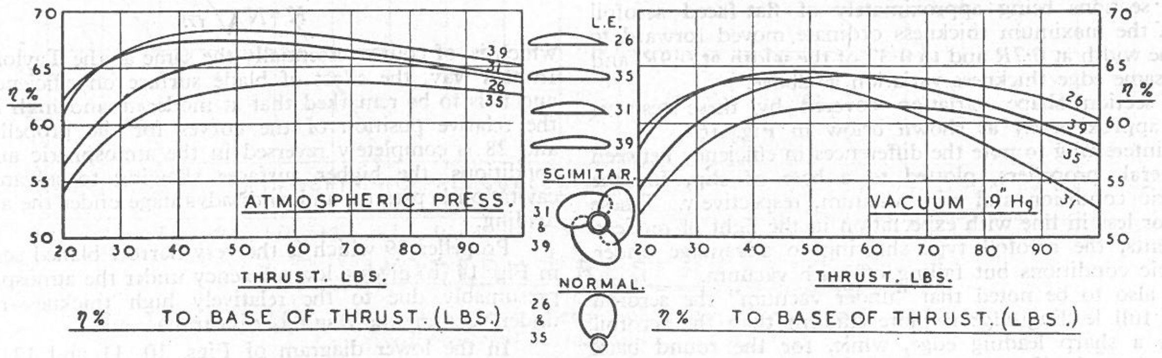

FIG. 15—*Effect on efficiency of varying section shape. (Pitch-ratio 1·25, p.s.r. 0·70.) Atmospheric conditions on left. With vacuum on right*

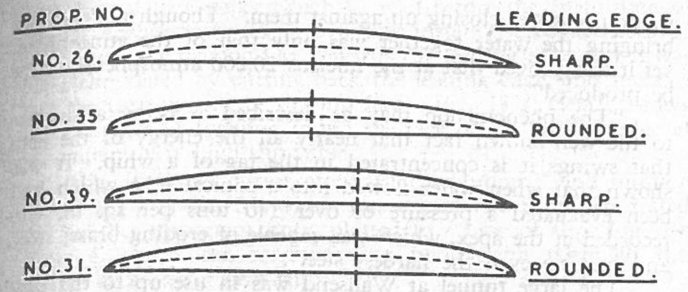

FIG. 16—*Sketch showing section variations tested*

purposes, but a thrust-deduction factor does not seem to have been applied.

It is naturally a little difficult to expect sufficient records to be still available to settle all these points of detail, but it seems clear that Parsons used a fixed multiple of t.h.p. in his propeller coefficients, rather than a *P* value derived from the torque records. That is to say, although the coefficient *K* has the form of a power constant, the manner in which it appears to have been derived makes it analogous to Taylor Bu rather than Bp. An attempt has been made to clear this issue farther by an analysis of the actual records, but this question is still a little obscure.

It may be mentioned that Parsons also plotted his results to a base of slip, and in the case of the efficiency lines these were compared with the theoretical (1-S) line, but as there is some doubt regarding the pitch values used in determining the slip, these diagrams have not been included.

Taken by and large, it is felt that the results reproduced speak for themselves, and form a remarkable tribute to the pioneer work of Sir Charles Parsons in the realm of cavitation tunnel research. For comparative purposes, the results, and the conclusions which may be drawn from them, are still valid today.

On the subject of aerofoil sections, Parsons, in a letter which he wrote in 1913, said that although the fish or "cod's head and mackerel tail" form was suitable and advantageous for aeronautical work, it was unsuitable for marine propellers, due to cavitation, and he then suggested "as thin blades and entrance as is consistent with strength". In this connexion, he carried out a number of tests with blades having extremely sharp leading edges but he does not appear to have followed up this idea in practice.

The effect of varying the pitch from radius to radius does not appear to have attracted his attention to any great extent, although there are records of six propellers having "variable pitch", which were tested in his large tunnel at an early date.

He was, however, extremely interested in the effect of blade shape on cavitation, and there are many tests with "scimitar" blade shapes, for which he took out a patent in 1907, but space does not permit an analysis of these results to be included here.

He was also interested in the idea of raking the blades slightly forward to counterbalance the bending effect due to centrifugal forces, and even as early as 1895, in connexion with the *Turbinia*, he stated in a letter, "The trial of the larger 3ft. 6in. screw with sword-like blades will throw more light on this (i.e. the loss due to slip). We will make the blades as thin as possible and cant them forward at an inclination of 1 in 10".

In a paper before the Royal Institution on May 4th 1906, Parsons wrote, "Serious cavitation causes an inordinate loss of power, chiefly because it disturbs the stream lines around the propeller blades, and it was proved (by experiment) how easy it is to put too much work on a screw. There is a limiting thrust that it will bear, and if we exceed this thrust it will, so to speak, more or less strip its thread in the water and its efficiency will rapidly fall. The solution of the problem, as regards the screw propeller, has therefore resulted in a modification of the proportions of the ordinary propeller, and has lain in the direction of smaller diameters, wider blades, and a slightly finer pitch-ratio, which three slight changes combined have led towards higher angular speeds of the propeller, without material loss of efficiency".

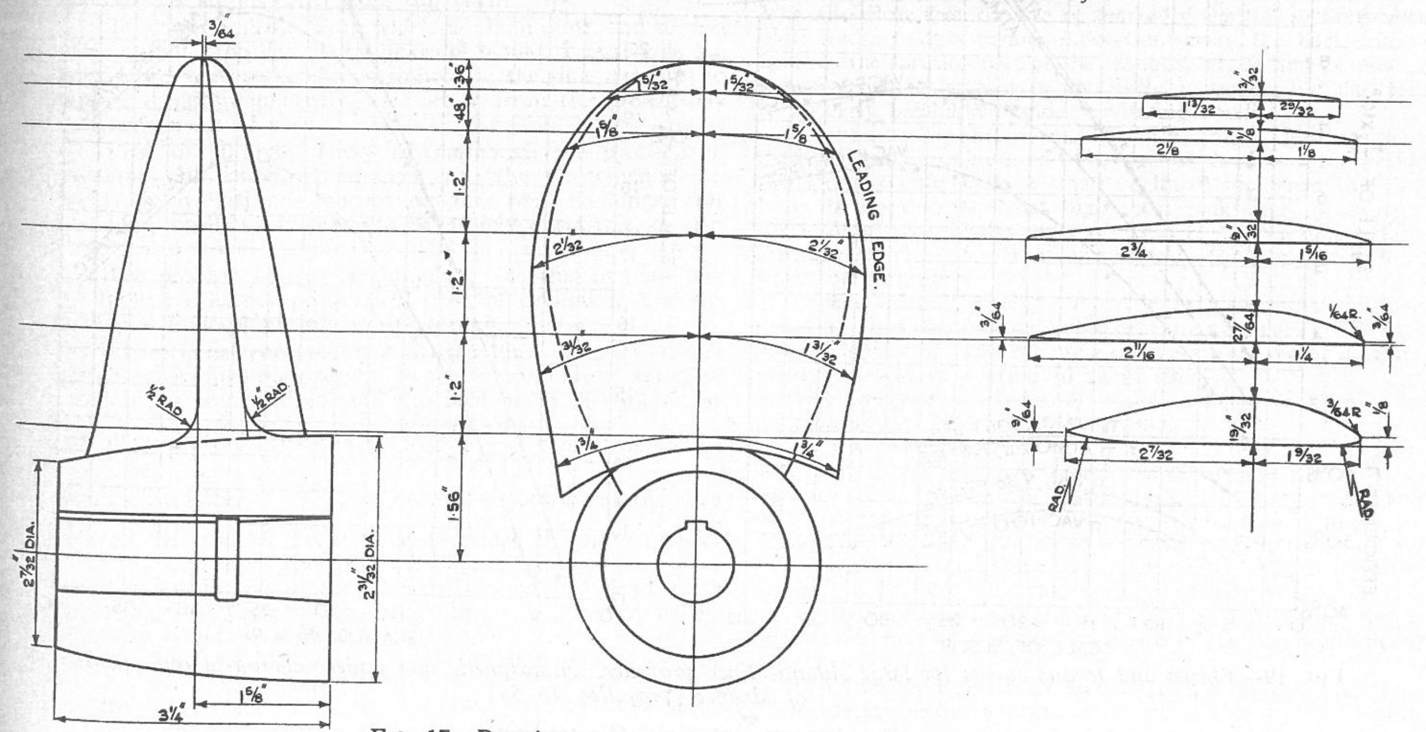

FIG. 17—*Drawing of liner propeller No. 50—aerofoil sections*

Diameter	12 inch
Pitch	12·48 inch
Surface	63·4 sq. in.
Blades	4 r.h.

There is also evidence, from his Presidential Address to e North East Coast Institution in 1912, that he had by that ne appreciated in an elementary way the idea of an "optium" diameter, in that he wrote, "the loss by slip and the ss by skin-friction are, in design, generally made similar in iantity, because if the former is reduced by increasing the ameter of the propeller, the latter is increased; therefore the ws of maxima and minima demand some approximation to [uality".

During the period 1914-20, Parsons appears to have irned his main interest in the subject of cavitation towards ie study of the nature of the cavitation bubbles, and the forces hich arise when they collapse on the blades.

He was Chairman of the Propeller Erosion or Corrosion ommittee of the Board of Inventions, which was appointed y the Admiralty in 1916, during the first World War, and, ssisted by Mr. S. S. Cook, he carried out the now famous xperiments upon the pressures which arise when a vacuous avity collapses in water. In this connexion, it was proved iat shock pressures as high as 180 tons per sq. in. could ccur, and that the erosive action was in the main not chemical, ut mechanical in nature. To quote his own words again, As the cavities collapse, the metal of the blades is, upon conict, severely bombarded by the water—a phenomenon closely esembling water hammer—with consequent erosion of the ietal, and vibration of the blades".

In 1919, he said, further "The erosion was due to the ntense blows struck upon the blades by the nuclei of the vacuous cavities closing up against them. Though the pressure bringing the water together was only that of the atmosphere, yet it was proved that at the nucleus 20,000 atmospheres might be produced".

"The phenomenon may be described as being analogous to the well-known fact that nearly all the energy of the arm that swings it is concentrated in the tag of a whip. It was shown that when water flowed into a conical tube which had been evacuated a pressure of over 140 tons per sq. in. was recorded at the apex, which was capable of eroding brass, steel, and in time even the hardest steel".

The large tunnel at Wallsend was in use up to the time of Sir Charles Parsons' death in 1931, and, amongst the many other investigations which were carried out, a number of cavitation tests were made in connexion with the propellers for several important Atlantic Liners.

To illustrate this work, Figs. 17, 18, Plate 4, 19, and 20, Plate 4, have been reproduced, showing respectively the correspondence obtained between the pictures taken in the tunnel and the erosion which occurred in service, and also typical curves of thrust and torque to a base of slip for a propeller of this class.

Fig. 17 shows the propeller drawing for a well-known Atlantic Liner, and Figs. 18(a) and (b), Plate 4, shows respectively the picture obtained in the tunnel at 13 per cent slip, and the erosion which occurred in the actual propeller. A model of this propeller was also tested in the Hamburg Tunnel, and details of the results obtained there were later given by

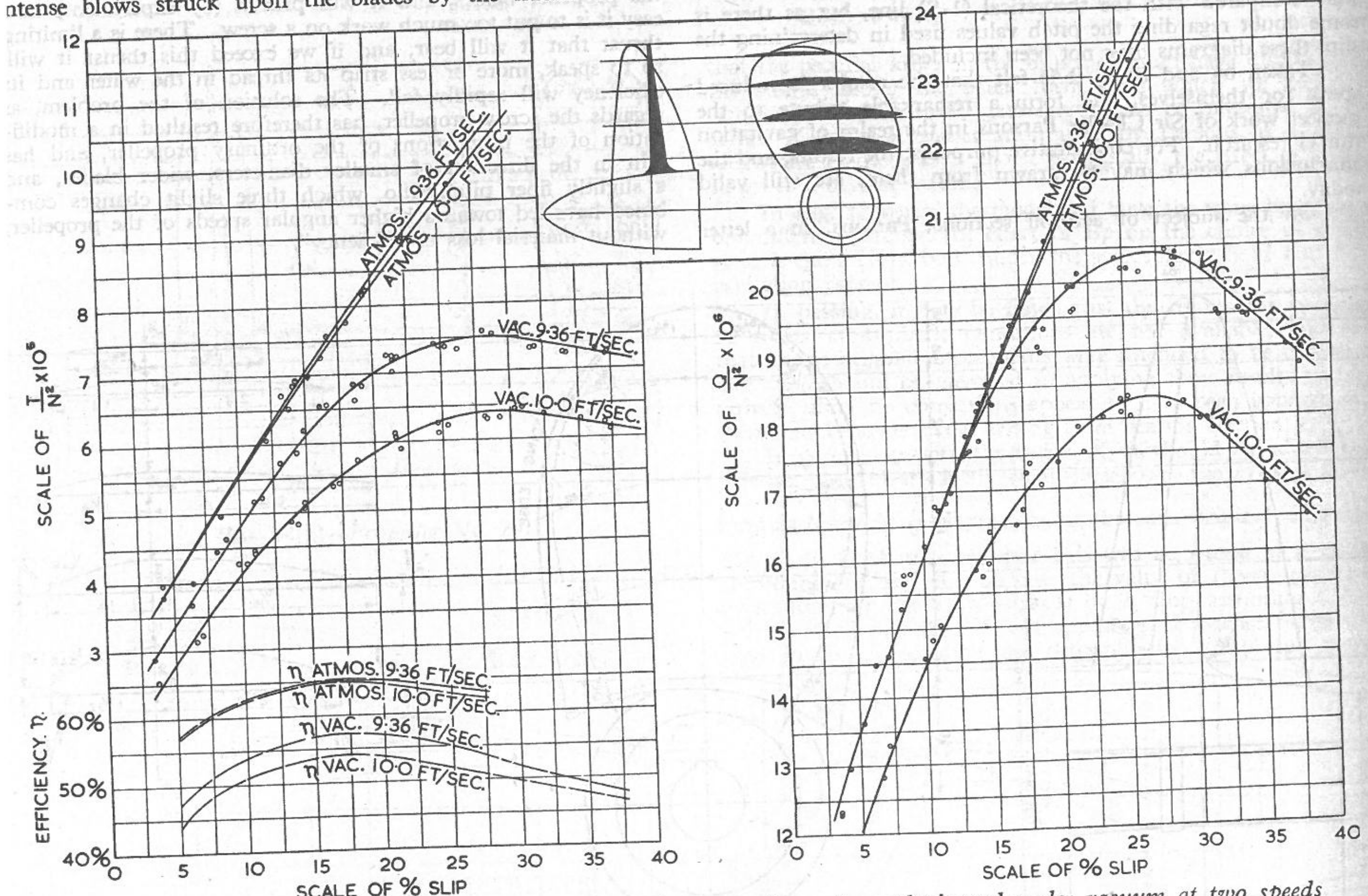

FIG. 19—*Thrust and torque curves for large Atlantic liner propeller. Atmospheric and under vacuum at two speeds of advance (propeller No. 54)*

T = thrust Q = torque

	Propeller	Model
Diameter	19·58 feet	12 inch
Pitch	18·00 feet	11·05 inch
Surface	190 sq. ft.	72 sq. in.
Blades	... 4	4

Dr. Kempf in a paper which he read before the Institution of Naval Architects in 1934. In this instance, erosion occurred mainly on the driving-face towards the leading edge and it was later eliminated by cutting back the leading edge, and increasing the turn-up on the driving face. Fig. 18(a) clearly shows the existence of foaming round the face of the leading edge at a comparatively high slip value.

Fig. 19 shows curves of thrust/(revolutions)² and torque/(revs)² for propeller 54, which was one of two propellers tested for another important liner, plotted to a base of slip. Fig. 20, Plate 4, shows the corresponding photograph taken in the tunnel at 23·3 per cent slip.

In this case, the main pitting occurred on the back of the blades towards the trailing-edge, although there was also some erosion on the face side towards the boss. Fig. 20, Plate 4, shows quite clearly the cavitation bubbles on the back of the blades, the foaming on the face having already disappeared at a quite low slip value. It is of interest to note that as the model propeller diameter was one foot, the parameters T/N^2 and Q/N^2 which were used can readily be converted to the modern K_T, K_Q constants. The vacuum tests were carried out at speeds of 9·36ft. per sec. and 10·0ft. per sec., the pressure head being reduced to 0·58 inch Hg with a water head of 2ft. 3in. at 440 deg. F. so that the tests cover a range of σ value from about 1·91 to 1·67. The particulars given on page 9 refer to a service speed of about 28½ knots, and the tests at 10·0ft. per sec. were intended to cover the somewhat higher trial speed.

VII. REVIEW OF MODERN DEVELOPMENTS IN RELATION TO SIR CHARLES PARSONS' WORK

Having described Sir Charles Parsons' experience in connexion with the cavitation of marine propellers, and the manner in which he tackled this important problem, both in practice and by experiments in his various cavitation tunnels, the question might well be asked as to where we stand today in relation to this subject; i.e. what advances have been made, and how far are his conclusions still valid?

To describe all the work which has been done, and to deal with current propeller theory in detail would, I fear, take too long, but I may perhaps be permitted in the time available to outline the position briefly, as I see it from the present-day designer's point of view.

First of all, may I say that although the problem of cavitation still exists, and in some cases this phenomenon can hardly be avoided, the modern designer need no longer fear that his propellers will prove to be entirely unsuitable, or that serious erosion will occur.

The problem has, in fact, resolved into that of obtaining the highest efficiency possible, in spite of cavitation, and the avoidance of local pitting or roughening.

The original conception of a fixed limit of unital thrust for all screws has disappeared, as the importance of speed of rotation has been realized, and this idea has been replaced by that of a limiting lift-coefficient $\left(\text{or } \frac{\text{thrust}}{\frac{1}{2}\rho A V^2}\right)$ dependent on the cavitation number $\sigma = \frac{p-e}{q}$, which may be defined as the ratio between the available pressure head divided by the parameter $q = \frac{1}{2}\rho v^2$, sometimes known as the impact pressure.

The conclusions of Sir Charles Parsons, and other early investigators of the problem, still hold good, however, to the following extent:—

(a) Adequate blade area is still the most sure means of avoiding cavitation.

(b) Thin blades are most desirable.

(c) Low-slips, or what is the same thing, small angles of incidence, are indicated by recent theoretical and experimental work,

but the following modifying, or extending conclusions have appeared:—

1. *There is no fixed conclusion possible as to high (or low) pitch-ratios being the most desirable, from the point of view of cavitation.*

Each set of conditions demands its own optimum pitch-ratio, which may be high or may be low according to circumstances. The optimum pitch-ratio (or, what amounts to the same thing) the optimum diameter is now seen to be dependent upon the loading coefficient Bp, the best propeller being that which permits the highest loading for a given efficiency, or the highest efficiency for a given loading. Fig. 12 illustrates this point very satisfactorily, and it will be seen that the best pitch-ratio increases as the loading coefficient K decreases.

Recent work also indicates that when cavitation is not present the optimum pitch-ratio is higher for propellers of large blade area ratio than for corresponding propellers of low blade area ratio, for a given loading coefficient K (or Bp) and theoretical considerations show that this is mainly governed by the drag of the blades. That is to say, as the blade drag increases the optimum diameter is decreased and the sections work at higher slip angles for optimum efficiency.

When cavitation is present to a marked extent, and the back of the blades may be completely denuded of water, there is reason to believe that the section drag decreases and is limited to the frictional drag of the pressure side. In these circumstances, the author has found it to be advantageous to decrease the pitch-ratio and increase the diameter until, taking the racing of the propeller into account, the blade incidence angles are reduced to about the same value as obtains when cavitation is not present.

2. *The importance of section shape and centreline camber are now recognized as having a very considerable influence on the peak suctions for a given section loading in relation to blade width.*

For example, it is now recognized that the adoption of flat-faced sections with large centreline camber is disadvantageous for the thick root sections of marine propellers, and it is therefore now usual to adopt only a moderate centreline camber for such sections, and to introduce turn-up of the face from the basic pitch-line at both the leading and trailing edges. It is also clear that the use of markedly aerofoil sections with bluff leading edges results in concentrating the back-suction towards the forward part of the sections, which may be advantageous when cavitation is not likely to occur, but can lead to an early breakdown under cavitating conditions.

Round-back sections, on the other hand, lead to more moderate peak suctions, and the suction load is more evenly distributed on the back at small angles of incidence, but they have the disadvantage that high local peaks may occur near the leading edge, if the angle of incidence is varying rapidly during the course of each revolution, due, for example, to local wake concentrations.

Special sections having a more or less uniform suction distribution, or a slightly favourable pressure gradient on the back at small angles of incidence are a comparatively recent development, and will be referred to again later.

3. *The radial distribution of blade area can influence the position at which cavitation occurs.*

For a given blade area (or given thrust per unit of area) a propeller blade may have either a wide-tip and narrow root, an approximately elliptical distribution, or a narrow tip and wide root, and it is obvious that this will have an influence on the position on the blade at which cavitation may occur. By means of the vortex-momentum theory the radial distribution of loading may be calculated with a fair degree of accuracy, and furthermore the distribution of pressure and suction round each section may be estimated by means of the now well-known Theodorsen method.

Thus the positions at which cavitation is likely to take place can be determined in advance by calculation, and modifications may be made to distribute the loading as evenly as possible, if this is found necessary. Experience shows that the positions at which erosion due to cavitation is likely to occur are, respectively,

(a) *At the tip,* due to the high peripheral speed.

(b) *At 0·7 radius,* due to the high loading carried by this part of the blade.
(c) *At the root,* due to the thick sections which are necessary for strength purposes (and possibly also due to blade interference or venturi effects).
(d) *On the boss itself.*

It will be evident, therefore, that each propeller design nust be examined on its own merits, according to the speed of rotation and thrust-loading, and in this connexion it is well to examine the conditions under which the sections will work, both on trial and in service, at the positions (a), (b), and (c), mentioned above. It is also worth noting here that as the blade is widened at any part it may also be made thinner, for equivalent strength.

It is difficult to lay down any precise ruling as to the best radial distribution of blade surface, but from experience I would suggest a distribution which is only slightly wider in the outer parts than the elliptical chordal width distribution, and not in extremely wide-tipped distribution, such as is sometimes adopted for heavily loaded screws.

time. There is some reason to believe that the calculated Ludwieg and Ginzel curvature corrections are rather higher than experience with actual propellers would suggest as being most suitable, and this problem is clearly a subject for systematic tests in the cavitation tunnel and on the full scale.

It is interesting to note in this connexion that Sir Charles Parsons in 1895, in the letter dated 28th March quoted on page 3 stated "One would like to make it (the propeller) with increasing pitch backwards", thus clearly anticipating this effect.

To illustrate the foregoing remarks, Fig. 21 has been included as an example of a modern propeller designed to work at high revolutions, and with high thrust loading, under conditions in which cavitation is difficult to avoid. This propeller was designed and made in 1943, and incorporates most of the features discussed above. It is of interest to note the hollow-faced sections in the outer parts, changing to sections with low centreline camber and a rounded face at the root of the blades, and to mention that this propeller was completely machined by planing on both the face and back of the blades, to a

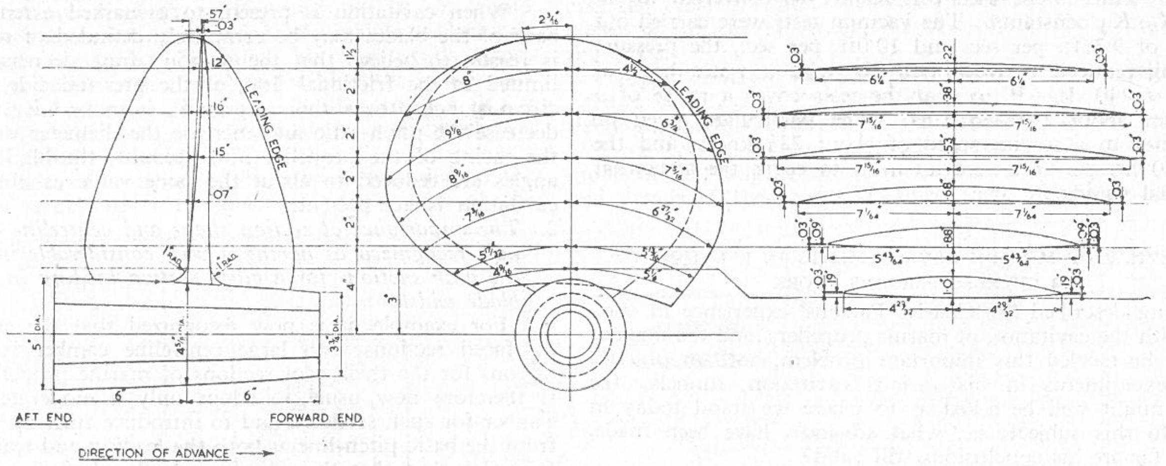

FIG. 21—*Drawing of a modern propeller for high revolutions and high power*

Diameter	... 27 inch
Pitch	... 35 inch
Surface	440 sq. in.
Blades	 3
S.h.p.	1,420 at 2,230 r.p.m.

. *The radial distribution of pitch can be varied to reduce the loading at critical positions.*

It is clear that variations in the local pitch angles from the niform pitch distribution may be adopted with advantage, lthough for a given total load it is evident that the unloading f one part of the blade must entail an increased load at other arts, and this must be closely considered in conjunction with em (3) above. One advantage of pitch reduction at the root that this allows a greater width of blade, and slightly thinner oot sections, to be fitted on a given length of boss.

. *The centreline camber of the outermost sections is important.*

With wide thin blades of low aspect-ratio, it is certain hat due to the action of the propeller itself the flow across he outer parts is curved, and for this reason the camber which obtained with a long thin flat-faced section is not sufficient allow for this effect. This has been realized for some considerable time, and although thin wide blades with a hollow ace in the outer parts are difficult to make, owing to the bsence of reference points once the hollow face is cut, this eature has been adopted with advantage in a number of heavily aded screws over the past ten years or so. It is only quite ecently, however, that any clear theoretical guidance has been nade available to designers in this connexion, due mainly to he work of Ludwieg and Ginzel, and this question is one which s the subject of a great deal of examination at the present

tolerance of 0·01 inch at all points, this being necessary to secure the required accuracy of section shape for the onerous conditions of loading. This propeller was fitted to a small fast craft, and was successful in obtaining a substantial increase in speed, of several knots, for the same revolutions and power, as compared with the best result obtained with several previous propellers having much wider blades, and segmental sections from root to tip.

Finally, a few words may be added about modern cavitation tunnel research, and the problems at present under consideration.

Since the first large cavitation tunnel was erected by Parsons in 1910, many similar tunnels have been built. There are now five in this country, at least four in America, and one in Holland, France, Sweden and Spain, respectively.

In these, models up to 18 inch in diameter may be tested at water speeds up to 36 feet per sec., although the majority of current testing is carried out at between 12 and 20 feet per sec.

Such tests are usually made with varying pressures above the water surface, so that a complete history of the performance of a screw may be obtained at various values of σ, the cavitation number already referred to.

The problem of correlating these tests with full size ship data still presents some difficulties, and in some tunnels it is necessary to apply a correction factor of from 0·70 to 0·85

to the σ values, in order to secure similar conditions in the tunnel and on the ship, although it would appear that with the large models of 16 to 18-inch diameter this is no longer necessary. One of the difficulties is concerned with the effect of air dissolved in the water, and it has now become current practice to control the air-content of the water in the tunnel.

Natural sea water has a high air-content, and it would appear that this causes cavitation to occur earlier than would be expected in water which has been denuded of air. This question is one which is being carefully studied at the present time, and, with a view to establishing standard methods of testing, experiments are being made with the same model screws in a series of tunnels.

The influence of Reynolds Number, or scale effect, is the subject of other similar tests, as it has become clear that model propellers under say 9 inch in diameter are considerably influenced by this effect.

Recent developments in cavitation research have been concerned mainly with the so-called "uniform velocity", or "laminar flow" type sections, and with the effects of curvature in way of the outer sections.

Blade sections designed to give a suction distribution which is more or less linear over the whole of the back, but which increases slightly towards the trailing edge, for small angles of incidence, have been used in practice in this country for about twelve years. In adopting such sections it was hoped to avoid cavitation and serious erosion by reducing the maximum suction for a given load, and also by moving the maximum suction ordinate towards the rear part of the section.

As there had been no previous experience, it was thought that the overall efficiency might be adversely affected, but this was considered to be of secondary importance, relative to the achievement of uniform suction.

Tunnel tests carried out at Hamburg in 1938, showed, however, a slight gain in efficiency as compared with propellers of more conventional design, and this has been confirmed by subsequent experience. In service over a number of years, such screws have been found to be remarkably free from cavitation, erosion or pitting. Typical examples of the sections referred

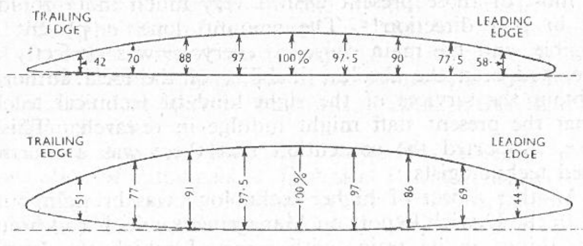

FIG. 22—*Drawing of uniform suction type sections*

to are shown in Fig. 22 which has been reproduced from my paper on Reversible Propellers read before the Institute in 1948.

During recent years, sections of this type have attracted the attention of aeronautical engineers, not because of their uniform-suction characteristic, but because of the possibility of achieving low drag values, due to increased laminar flow, and a stable boundary layer far back along the sections. Consequently, a number of alternative sections, known as "laminar flow" aerofoils have been developed and these have been tested in various wind-tunnels, and also in flight. These new sections are now available to the marine propeller designer, and apart from their application to heavily loaded screws there is a possibility that they may allow smaller blade surfaces to be adopted for propellers bearing only a moderate or light loading.

This is the subject of current research work, and is closely associated with the study of flow curvature in way of the blades.

Recent work on the Continent and in America has shown a tendency towards the adoption of hollow-faced sections of the Karman-Trefftz type having sufficient face camber to develop the required lift at nose-tail incidence, allowing for a curved flow in accordance with the Ludwieg and Ginzel theory, but I am inclined, by experience, towards the adoption of sections having a moderate face-camber and working at a small positive angle of incidence, as this corresponds to the usual condition for optimum efficiency, when section-drag is taken into account.

ACKNOWLEDGMENTS

I am highly appreciative of the great privilege which has been accorded to me by the Council of the Institute, in asking me to present this Lecture, on what is perhaps one of the most interesting aspects of Sir Charles Parsons' work.

I am extremely indebted to the Directors of the Parsons Marine Steam Turbine Co., Wallsend, for the books, papers, photographs and other records, which they have so kindly allowed me to use and especially to the Hon. Geoffry L. Parsons for the excellent collection of personal letters which he has placed at my disposal. I have quoted freely from these original letters and papers, with the object of recording, as far as possible, Sir Charles Parsons' own ideas and opinions, in his own words.

My special thanks are due to Mr. S. S. Cook, F.R.S., who has helped and guided me throughout the preparation of the manuscript, and has, by his excellent memory of the events which took place, enabled me to present a much more faithful picture of Sir Charles Parsons' work on cavitation, than I could possibly have done alone.

Finally, I have to record my thanks to my personal colleagues, Mr. A. Emerson, M.Sc., Mr. B. Baxter, B.Sc., and Mr. L. Sinclair, for their most valuable assistance in analysing the records and in preparing the various diagrams which have been included.