assistant outside engineer manager, and later was appointed outside manager. Eventually he became assistant general engineer manager and held that position until his death.

Mr. Imrie was a member of the Belfast Association of Engineers. He died suddenly on the 11th November 1950.

GEORGE MERCER (Associate 13043) was born in 1892. From 1908 to 1913, while serving his apprenticeship with Alley and McLellan, Ltd., he attended the Royal Technical College, Glasgow. In 1913 he joined Maclay and McIntyre, Ltd., as a junior engineer and obtained a Second Class B.o.T. (Steam) Certificate in 1914. From 1917 until 1934 he was employed by Andrews and Company, of Glasgow, as a consulting engineer. In 1934 Mr. Mercer went to Bombay as works manager for A. C. Bottomley and Company, where he remained until 1941; he then returned to this country to an appointment as assistant maintenance engineer with George Cohen and Co., Ltd., of Leeds. From 1943 until 1946 he was chief mechanical and electrical engineer with Ferranti, Ltd., of Edinburgh, and from 1946 to 1948 he was plant manager to G. A. Harvey and Co., Ltd., Greenwich. In December 1948 he was appointed group engineer of the Bermondsey and Southwark Hospital Management Committee and, until his death on the 16th April 1951, Mr. Mercer was engaged in restoring and improving the engineering services in this group of hospitals which had been badly damaged during the late war. He was elected an Associate of the Institute in October 1950.

WILLIAM ARTHUR RICHARDSON (Member 9745) was born in 1904 and educated at St. Bee's public school in Cumberland. He served an apprenticeship with the Dublin Steam Trawling Co., Ltd., Vickers Ireland, Ltd., Vickers Armstrongs, Ltd., Barrow, Vickers Petters and Petters, Yeovil, and Vickers Ireland and James Robertson, Fleetwood, between 1921 and 1927. From 1927 to 1929 he was employed by the Dublin Steam Trawling Co., Ltd., and engaged in trials with Petters and Vickers at Barrow, on submarines and all classes of ships. In 1929 he was appointed superintendent engineer of the Premier Ice and Trawling Company, Dublin, and from 1935 to 1938 he was marine superintendent engineer of the Howth Trawling Company of the same city. From 1939 until the end of the last war he was the officer commanding the dockyard section, Haulbowline Marine Depot of the Marine Service of Eire, and chief surveyor. In 1946 he joined the Texaco Company of Ireland (now called the Caltex Company of Ireland) as a marine engineering expert and was thus employed until his death on the 16th April 1951. Mr. Richardson was a Member of the Maritime Institute of Ireland, an Associate Member of the Institution of Naval Architects, and was elected a Member of the Institute in 1943.

FREDERICK REGINALD ROGERS (Member 4040) was elected a Member of the Institute in 1920. He served an engineering apprenticeship from 1901 to 1907 at the Royal Naval Dockyard, Devonport, and on winning a Whitworth Exhibition he attended the Royal College of Science, of which he became an Associate. Mr. Rogers then held a teaching appointment at St. Helen's Technical College, was for some years lecturer in marine engineering at Cardiff Technical College, and in 1921 went to Birkenhead Technical College as head of the Mechanical Engineering Department. In 1935 he was appointed Principal of the College, a position he held until his retirement in September 1950. Mr. Rogers died on the 22nd May 1951.

LIEUTENANT(E) FREDERICK MIGUEL SHAW, R.N. (Graduate 10693) was one of the young men involved in the recent tragic loss of H.M. Submarine *Affray*. He was born in Kenya Colony in 1924, educated at Ampleforth College, York, and from there passed into the Royal Naval Engineering College at Keyham. During his course at Keyham he served during 1944 in H.M.S. *Belfast* and took part in the Normandy landings. After leaving Keyham in 1946, Lieutenant Shaw served in H.M. Ships *Liverpool* and *Diadem* and in September 1947 he was chosen to take a two-year course at the Royal Naval College, Greenwich. In August 1949 he joined H.M.S. *Illustrious* as flight deck engineer but in December 1950 he volunteered for duty in submarines and went to H.M.S. *Dolphin*, Gosport, for training. Lieutenant Shaw's father, Lieut-Colonel F. C. Shaw, O.B.E., was killed in action in the late war.

WALTER SOMMERVILLE (Member 10721), who died in Wellington on 22nd May 1951, had been associated for over forty years with the mercantile marine. He served an engineering apprenticeship with George Fraser and Sons, Ltd., Auckland, from 1904-09 and began a sea-going career as a junior engineer with the Union Steam Ship Company in 1910, serving in the *Maheno, Navua, Kurow, Tahiti* and *Koromiko*; he was chief engineer of the *Koromiko* when he resigned from the company during the 1914-18 war to join the New Zealand Expeditionary Force. He served in France and Belgium and later transferred to the Royal Naval Reserve as a lieutenant in the engineering branch. In 1922 Mr. Sommerville was appointed Secretary of the New Zealand Institute of Marine and Power Engineers, a position he held to the time of his death. In that capacity he achieved a high reputation for his ability and integrity. He was an ardent believer in round-the-table agreements, and there is evidence of his aptitude for conciliation in the fact that during his twenty-nine years as the New Zealand Institute's representative, every dispute was settled by negotiation. Representatives of the shipping companies, freezing companies, the Ship Owners' Federation, Government departments, various engineering organizations, the Returned Services Association and the Mayor of Wellington were among those present at the funeral service at Morris's chapel. Mr. Sommerville was elected a Member of the Institute in 1946.

FRANK WHITWORTH, J.P. (Companion 3726) died at Wanstead, E.11, on the 21st November 1950, aged sixty-nine. Mr. Whitworth was editor of the "Stratford Express", and chairman and joint managing director of Messrs. Wilson and Whitworth, Ltd. The printing of the Institute's TRANSACTIONS was carried out by this firm from 1913 to 1930, and Mr. Whitworth became a Companion of the Institute at the beginning of this connexion. At the funeral service tribute was paid by the Vicar of West Ham to Mr. Whitworth's personal qualities as "a great brother and server of man for many years", and later at the West Ham Court the Chairman of the Bench referred to Mr. Whitworth's long record of service in the civic and public life of West Ham. He leaves a widow and two sons.

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Sir Charles Parsons and Cavitation

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The 1950 Parsons Memorial Lecture entitled "Sir Charles Parsons and Cavitation" describes the pioneer work of Sir Charles Parsons in connexion with the problem of "cavitation" in marine propellers. Early letters reveal the difficulties which he encountered in connexion with the trials of the *Turbinia*. The vessel was first fitted with a single shaft, and the results obtained were extremely disappointing due to losses in the propeller. Many propeller arrangements were tried and it was not until after three years of experimenting that the final result was achieved, with nine propellers fitted on three shafts.

The first cavitation experiments carried out by Sir Charles in 1895 are described, including the making of the first small cavitation tunnel, in which quite good photographs were obtained showing the nature of the phenomenon.

Following a period of development during which the size of turbine installations for marine purposes increased considerably, the first large cavitation tunnel was built at Wallsend in 1910. Details are given of hitherto unpublished work carried out in this tunnel, with systematically varied model propellers, 12 inch in diameter, and the method of presentation adopted by Sir Charles in connexion with these tests is discussed. There follows a short description of the work which Sir Charles carried out to prove that the erosive action of cavitation was due to the collapse of the bubbles on the blades of propellers, and was mechanical in nature, and not chemical; and details are given of some tests in the Wallsend Tunnel in connexion with propellers for high-powered Atlantic liners showing the correspondence obtained between the photographs taken of the model propellers working in the tunnel under vacuum, and the erosion which occurred in service. Finally is reviewed briefly the modern approach to the problem of cavitation, and the developments which have taken place since the time of Sir Charles Parsons' early work, and shows that the main conclusions at which he arrived are still valid today, although slightly modified and extended in the light of recent theoretical and experimental research work.

I. INTRODUCTION

In preparing this lecture, I have derived many advantages from the study of the various notes and papers to which I have so kindly been given access, and not the least of these is the insight which I have obtained into the working of the mind and personality of Sir Charles Parsons, the greatest of marine engineers, in the development of an entirely new project, and also when beset with perplexing and almost overwhelming difficulties.

The question of providing suitable propellers was obviously only a very small part of the problem which confronted Sir Charles when he turned his attention, in 1893, to the development of steam-turbines for ship propulsion, but it proved to be a most prickly and thorny subject, and without his great genius for experimenting and his extreme perseverance it might well have caused the whole project to end in failure.

Even before the *Turbinia* was built, Sir Charles appears to have foreseen clearly, in framing his original patent specifications, that the problem of providing sufficient propeller blade area to carry the required thrust loading was likely to prove a difficult one, and when one considers that the idea of cavitation had not then emerged, and the effects of this phenomenon were quite unknown, his words "As the velocity is necessarily high, it will be advisable to place several fine-pitched screws on the shaft, in order to obtain a sufficient area of blade" and the rider which follows, "and one screw may be prevented from interfering with another or others by suitable guide blades or by other means" surely bear the mark of his great genius and inventiveness, as this was the solution towards which he turned when the results of his first trials with the *Turbina* proved to be disappointing.

There is evidence of his foresight also in his early assessment of the problem, when he stated that it was unfortunately necessary to start with a small high-revolution installation fitted in a small fast craft which would demonstrate the possibilities of his new engine by achieving extremely high speed, although the advantage of the turbine lay mainly in the achievement of extremely high powers, until then unknown, and that the problems of propulsion would become easier as the installations increased in size and the revolutions diminished.

Later, when the initial trials of the vessel proved that his worst forebodings had been correct, and the result, in ship speed, fell well below his expectations, he tackled the problem with characteristic energy. In the first place, a new torque-measuring coupling was devised which proved conclusively that it was the propeller and not the turbine which was at fault. To quote his own words again, "The results were unsatisfactory, and it was apparent that a great loss of power was taking place in the screw. To investigate the question thoroughly, a spring torsional dynamometer was constructed, and fitted between the engine and screw shaft. The measurements conclusively proved that the cause of failure lay entirely in the screw".

His second action was to investigate the problem with the aid of small models, to find out what was happening to cause this serious loss, and in the third place he immediately put in hand several schemes for propellers of alternative sizes, and also different arrangements of tandem- and triple-screw systems, which could be tried out on the ship, pending the results of his experiments.

Throughout his career, he appears to have turned to experiments on small models when practical difficulties were encountered, but he was always keen to try out alternative arrangements on the full-scale whenever possible, and his final success in the many fields which he covered, was mainly due to his extreme perseverence and "trial and error" methods, coupled with his intuitive genius in solving mechanical problems and his ability to reach important conclusions as a result of simple calculations.

In his experimental work on propellers, he was mainly interested in "seeing" what was happening, rather than in making detailed measurements or the routine collection of design data, which he left to others, and he always required comparative tests to be made, so that one screw could be directly compared with another, with a view to choosing the best practical arrangement.

In no branch of Naval Architecture, or Marine Engineering, has the influence of systematic research work been greater than in connexion with propellers, and our present methods of design are based almost entirely on the results of methodical series of experiments with small models, which may be used to analyse and explain the performance of full-size screws; as will be seen later, Sir Charles Parsons did a great deal towards initiating this procedure.

Our knowledge of propellers has advanced very considerably in the last fifty years. On the theoretical side the development of the aeroplane, with the concept of the aerofoil theory and the vortex-theory of propeller action, has acted as a great stimulus to marine propeller design; while, from the practical point of view, the testing of model propellers, both in open-water and in the "behind" condition, in accordance with the methods developed by Froude and Taylor, has provided the information required for a complete analysis of the problem, and the satisfactory correlation of ship and model results.

This was, however, not always so, and if we go back about sixty years, towards the end of last century, when Parsons was experimenting with the *Turbinia*, we may obtain a picture against which to appreciate his achievement in this sphere.

At that time, it appears that the dimensions of propellers were determined mainly on the basis of "slip", in conjunction with very simple momentum considerations. That is to say, it had been found from experience that successful propellers gave an apparent slip in service of approximately 10 to 12 per cent, and consequently the designer decided in advance that his propeller should work at this slip, so that if V was the expected ship speed, and N the intended revolutions per minute, then the so-called "speed of propeller" was given by NP, and a suitable value of P, the pitch of the propeller was obtained in this way, by applying the expected slip.

This pitch was then associated with a diameter slightly less than the loaded draft of the ship, and an assessment of the thrust was made on the basis of a very simple form of the momentum theory, using a volume of water projected from the ship in cubic feet per second given by the simple formula $RP(A - a)$, where R = r.p.s., P = pitch in feet and $(A - a)$ the area of the screw disk less the area of the boss, in conjunction with $(RP - v)$, where v was the ship speed in feet per sec.

This thrust was then compared with the estimated resistance of the ship at the expected speed, and if too large or too small, then the diameter was adjusted accordingly until a balance was obtained. The efficiency of propulsion was then either assumed by taking an arbitrary figure of 50 to 60 per cent based on previous experience, or an estimate was made of the total blade-friction, which was added to the "loss due to slip".

There were no clear ideas about suitable diameters, and it was not until much later that the conception of an "optimum diameter", in terms of slip or loading, emerged. In general, it was considered that the pitch-ratio should be made as large as possible, as it was considered that high pitch-ratios gave the best efficiency, but it is not clear how this high pitch-ratio was always to be obtained.

The blade areas in common practice were extremely small, based presumably on the idea of reducing the loss due to friction. It was also quite usual to make the diameter slightly larger than thought necessary by calculation, so that the propeller could be cut down if required, and, despite this precaution, it was frequently necessary to try several propellers before a satisfactory result was obtained, except when the installation was of a type very similar to previous jobs.

It was against this background that Sir Charles Parsons had to approach the problem of providing propellers for an entirely new type of installation.

There was no previous experience to be turned to for guidance and, in fact, the previous experience with propellers for slow-running reciprocating steam engines was probably misleading rather than helpful, as the new propellers were to work under entirely different conditions.

II. THE STORY OF THE TURBINIA TRIALS

The first record I have found of the *Turbinia* project comes in a letter dated 12th December 1893, in which Sir Charles mentions that they were "just starting preparations to build the hull", this letter having been written before the establishment of the first Marine Company. The vessel was 100 feet in length, by 9 feet beam, by 3 feet draft, the corresponding displacement being 44½ tons, and the eventual authenticated speed was 32·75 knots for 2,300 horse-power, although Sir Charles himself later referred to a speed of 34½ knots as having been achieved during the Naval Review at Spithead in 1897 (and 34¾ knots on the River Seine at the time of the Paris Exhibition).

The objects of the Marine Steam Turbine Company formed in 1894 mention turbines of 1,000 h.p. and upwards, having a speed of revolution of about 2,000 per minute, and the original turbine fitted in the *Turbinia* was designed to develop "upwards of 1,500 actual horse-power" at a speed of 2,500 revolutions per minute. This first marine turbine was of the radial-flow type, as Sir Charles had at that time just lost the use of his axial-flow patents, and it was used to drive a single two-bladed propeller 30 inch diameter × 27 inch pitch which is reported to have given the excessive slip of 48·8 per cent when running at 1,730 r.p.m. The second screw tried was a four-bladed screw which made 1,600 r.p.m. but gave similarly unsatisfactory results. Multiple propellers set on this single shaft about three diameters apart were then experimented with, and the best results were obtained with three screws having diameters of 20, 22 and 22 inch respectively, from forward to aft, all being of unity pitch-ratio. With this arrangement the slip was reduced to 37·5 per cent at 1,780 r.p.m., the corresponding speed being 19¾ knots. This result, which was achieved after seven different designs had been tried and no fewer than thirty-one sea trials had been carried out, was still extremely disappointing, and it was at this point that it was decided to replace the single turbine by distributing the power in three smaller units working in series and driving three separate shafts set well down in the boat, below the centre of gravity. This distribution of power on several shafts, which had also been envisaged and provided for in the original patent specifications, proved to be the final solution of the problem, although many more trials with different combinations of propellers were required before the desired result was achieved.

It was towards the end of 1895 that the single-shaft arrangement was replaced by the triple-shaft arrangement, the new turbines being made of the parallel-flow type which gave a slightly increased power at the design revolutions of 2,200, Sir Charles having in the meantime recovered the use of the earlier patents. The following extracts from letters give some idea of the troubles arising from cavitation which he encountered, and the progress which was made towards the final goal:—

26th March 1895. "I find on checking the speeds and revolutions that we have almost exactly 50 per cent slip against 33 per cent calculated. There, therefore, appears to be vacuum behind the blades, which the larger area of the new screw will correct in all probability. I am arranging also to fit a second screw in front of the rudder, to get more blade area".

28th March 1895. "There appears to be no objection to a two-bladed screw with great length of blade, say half turn to each blade, thus covering the whole disk-area of the screw with blade surface. The arrangement will eliminate the cutting or parting resistance due to a thick blade, as the length divided by the thickness will be large. One would like to make it with increasing pitch backwards. I make out that at 18 knots the slip of the present screw is 54 per cent, whereas 33 per cent is that calculated. There appears to be vacuum, and increased blade area will cure this. I will try a screw like the above on the model and also put one in hand for the boat".

30th March 1895. "For a speed of 30 knots, a thrust of somewhere about 6 tons appears to be necessary, and assuming the screw 28 inch diameter this gives a mean pressure of 21lb. over the disk area of the screw (the present screw is 32 inch diameter but the blades cover only about ⅓ of the disk area). Now its seems to me that water flowing into such a column of 28-inch diameter will necessarily part company and vacuum spaces be formed. For a screw 28-inch diameter the mean pressure works out 21·1lb. per sq. in. and it would appear that very little vacuum would be produced. A larger screw of the Archimedean type would give excessive skin friction. I therefore propose to make an Archimedean screw 28-inch diameter and on working it out we will have probably the moderate slip of 20 per cent. To assist this screw if necessary, I propose to place in front of it at a distance of about 4 feet a screw of 24-inch diameter Archimedean type, and of the less pitch of 19 inch (the speed of 30 knots and 2,400 revs. compares to a pitch of 15-inch exactly). This front screw will do half the acceleration and the aft screw (which would be reduced to 24-inch diameter if so assisted by the forward screw) would do the remainder. Besides this the velocity added by the front screw will be much dissipated before reaching the back screw. The skin friction of the two screws (the after one being reduced to 24 inch) will be about the same as the single 28-inch screw".

Possible date 3rd April 1895. Marked "Important". "In further reference to the propeller, the matter is now, I think, quite cleared up by a paper, proof of which I got this morning, by Thornycroft.

"He makes out from trials of the *Daring* and two other very high-speed boats that if the mean pressure of propulsion over the blade area exceeds 11¾lb. then vacuum, or as Froude has termed it 'cavitation' is set up, the slip goes up enormously as well as the power required for a given revolutions. In our present screw we have some 60lb. per sq. in. mean pressure on the blades and therefore enormous 'cavitation' set up.

"I think the best course will be to follow out our patent and put two screws one abaft the other, the front one of, say, 19 inch pitch and the after one 22 inch pitch, so as to gradually accelerate the water column in two stages, also make the screws of the Archimedian form with maximum blade area and keeping the diameter down to 28 inch. If two screws are not enough we will put on more".

3rd October 1895. "We had a preliminary run with the boat yesterday to Tynemouth and back. The boat travelled very smoothly indeed and with 60lb. steam and 9lb. vacuum the speed appeared to be between 18 and 20 knots".

17th September 1896. "Steaming easily got 21 knots, had expected 24 or 25. The sluggishness was due to mussels and barnacles. If we assume the skin resistance slightly more than double that of a varnished surface it brings today's results in accord with calculation, actual mean slip—33 per cent. The calculated slip was about 20 per cent".

28th December 1896. "I have been comparing results with the model resistances and to my surprise find that in the case of *Turbinia*'s speed and steam pressure at 29·6 knots the resistance corresponds to about 28·1 knots.

"I think our next alteration will be putting on the new propellers 24-inch pitch against the present 18-inch pitch. I think the turbines must be up to the full speed at 29·6 knots (viz., 2,400 revs.) and their efficiency will not be reduced by slightly slowing them. The new screws were put in hand a couple of months ago and are nearly finished".

5th January 1897. "The boat is going on to the slip the end of this week, we had a short run last Thursday and measured the thrusts. We also took the revolutions which were l.p. 2,450, i.p. 2,450, h.p. 2,650. The mean slip is now down to 20 per cent. I have been puzzled at the smallness of the thrust observed, considering the enormous h.p. developed and put it down at first sight to the screws not being the best obtainable, now that we have 9 instead of 3 only, as when they were found best for the single motor. I have been making calculations of skin friction of blades and comparisons with the data of other screws, and also Froude's papers, etc., and have made out a balance sheet of the horse-power developed and expended. There is necessarily some guesswork about it, but I think it is substantially correct. It shows the motors to consume only 10lb. of steam per effective brake h.p., that some 45 per cent of the whole developed power (i.e., 1,860) is going in blade friction against the water, and 20 per cent in slip, leaving 850 for useful propulsion, or thrust horse-power, which agrees with the resistance curves.

"This great waste in skin friction arises from two *very wide blades* covering 0·6 of the disk area (they must be wide to prevent vacuum) and the *fine pitch* 18-inch pitch, 18-inch diameter. Now that we have got the revolutions up to 2,450 or, say, 2,500 mean we can cut them down to, say, 1,900 without incurring a loss of more than 5 per cent or 7 per cent in the turbines. This being so, increasing the pitch to, say, 24 inch will at the same speed of boat reduce the skin friction in the ratio of $(\frac{3}{4})^2$ or by more than ½. I do not like to go beyond this at present, so I have put in hand another set of 9 screws exactly the same as the present ones only 24 inch pitch against 18 inch as at present.

"It is a comfort to think that Yarrow tried 24 sets of different screws and raised his speed from 20½ to 23 knots thereby. I think we have a greater rise in store for us, with the same steam consumption we had in the last trials".

7th March 1897. "We went out in the *Turbinia* on Thursday but it was blowing hard with sleet, so it was too rough outside and we got a run on the river. We estimate that we reached 31 knots on part of the run, and on Friday we luckily got a smooth sea with a long swell and got a long run and measured the feed water, altogether we covered 30 miles at 25½ knots. Two runs on the mile N. and S. gave a mean 28·12 knots. With the present screws No. 2 set, 24-inch diameter, 24-inch pitch, 6 propellers, the revolutions maximum were 1,900. The performance of these screws, which as you know were put in hand some 5 months ago and before the last trials (at which you were present) seems to confirm our own conclusions that smaller diameters and larger pitch ratios will give better results, and that our No. 3 set of 9 screws 18-inch diameter and 24-inch pitch will be more superior. The bottom of the boat is getting slimy and this will, with the roughness of the sea account for about 1½ knots.

"We are going to slip the boat this week and put on No. 2 set of screws which are ready. I expect we shall then reach 32 knots and steam steadily at 30 to 31.

"Prof. Ewing of Cambridge and Prof. Weighton of the Newcastle College are willing to come and make a joint report".

From the correspondence which is quoted above, and from other references, it appears that the shaft dynamometer which is referred to in the introduction, and which has been described and illustrated in the Parsons Memorial Lecture of 1938 by Mr. S. S. Cook, F.R.S., was made during the early part of 1895. Briefly, this showed that the maximum shaft horsepower developed at 2,400 revolutions per minute was 960 s.h.p., and as the e.h.p. had been estimated from model experiments it was concluded that an abnormally large loss of efficiency was taking place in the propeller or propellers. This led Sir Charles to investigate the problem of cavitation by means of special model propeller tests, and to the division of power on three shafts. The final propeller arrangement consisted of nine screws—three on each shaft—all having a diameter of 18 inch and a pitch of 24 inch, the projected surface ratio being about 0·46, which would correspond to a blade-area ratio of, say, 0·60, in modern terminology. With this arrangement speeds of the order of 32 knots were obtained during the early months of 1896 and the total power was estimated to be about 2,000 equivalent indicated horse-power.

During the following year, in April 1897, official trials were carried out under the supervision of Professor Ewing, F.R.S., about 20 runs being made on the measured mile at speeds from 6¾ to 32¾ knots. These showed that the propeller slip rose steadily from about 24½ per cent wings, 11 per cent inner, at 10½ knots, to 30·6 per cent wings, 26 per cent inner, at about 20 knots, and thereafter fell to 25·5 per cent wings, 16 per cent inner, at 32¾ knots. For the maximum speed, the revolutions of the wing shafts were 2,230 r.p.m. and for the centre shaft 2,000 r.p.m.

III. MODEL TESTS IN CONNEXION WITH THE TURBINIA

In the above review of the *Turbinia* trials, no detailed reference has been made to the model tests. The tests with towed models have been described in some detail by Mr. S. S. Cook, F.R.S., in the lecture mentioned above, but it is felt that a short summary may be repeated here, as it is of considerable interest to follow the course of these tests to the point where cavitation experiments began.

The first model tests were made in 1894 with a small model 2-feet long which was towed in a pond at Ryton-on-Tyne. With this model the tests were mainly concerned with the shape of stern and a flat stern was finally adopted to prevent squatting. It was also fitted with a strong rubber motor driving a single screw ½ inch in diameter and of unity pitch ratio, and a speed of about 6 knots was obtained with 18,000 r.p.m. at the propeller. The second model was 6-feet long. It was also fitted with a rubber motor but the propeller drive in this case was through a single-reduction spiral gearing, the propeller running at 8,000 r.p.m. at the working speed. The torque delivered to the propeller was assessed by means of an ingenious air fan arrangement with adjustable blades running in a light box fitted with internal blades, which could be substituted in place of the propeller. The revolutions were varied by adjusting the four blades until they agreed with those obtained with the screw, and the torque was then measured by means of a weighted lever fitted to the outer cover of the box. This 6-feet model was carefully towed at various speeds in a pond at the Heaton Works of the Company by means of a wheel and falling weights, with riders to give additional starting force, and then constant speed. The line used for towing had two markers 30 feet apart and the time was taken as these passed a fixed point. A very simple arrangement, but one which gave excellent results, as the results of tests carried out three years later on a 10-feet model at the Admiralty Experimental Works, Haslar, only gave two to three per cent difference.

It is interesting to note that this 6-feet model was also run in rough water in a quarry near Parsons' home with a view to judging the behaviour at sea in rough weather, and he remarks, "The screw did not appear to draw any air", thus showing that he appreciated this difficulty at this early stage. In this model, the screw was fitted slightly abaft the stern, the rudder being offset from the centre-line. These model tests, as might be expected, did not reveal the presence of cavitation, and it was not until many tests had been made with the *Turbinia* that this was suspected.

IV. THE FIRST CAVITATION EXPERIMENTS

These tests appear to have been started early in 1895, and in this connexion, I have received the following note from the Hon. Geoffry Parsons. "As far as I remember, the first cavitation experiments were made at Holeyn Hall (Wylam-on-Tyne), with a saucepan borrowed from the kitchen, the water being heated to the required temperature of a little below boiling point. The late Mr. A. A. Swinton took photographs, but I don't think they were very successful".

There is also a reference in Richardson's book (1911) to a circular tin vessel 12 inch in diameter, the screw being mounted on an axis passing through a gland in the side in such a position that its thrust was tangential to the direction of rotation of the water. By this means the screw worked at a moderate slip in the rotating water, and photographs were taken through a window in the side of the vessel. Parsons, himself, referred in 1897 to "a bath of water heated to within a few degrees of the boiling point", and the photograph which Richardson gives on Plate XXXV of his book appears to refer to a later copper tunnel, which is still in existence (see Fig. 1, Plate 1).

This small copper tank was clearly the forerunner of the modern cavitation tunnel. It consisted of an oval vertically disposed closed circuit of uniform rectangular cross-section, the screw shaft being inserted horizontally through a gland in the upper limb and driven from outside, first by means of a small vertical steam engine and later by means of an electric motor.

There were windows on either side of the upper limb through which successful photographs were taken. A plane mirror was fixed to an extension of the shaft This reflected the light from an arc lamp on to a parabolic mirror, one later covered with black material except for a narrow band. This lit up the screw for a fixed period at each revolution. The photographs had an exposure of 10 seconds at f/16 with fast plates. The duration of the illumination of the propeller during each revolution is stated by Richardson to have been 1/3,000 of a second. A lamp was arranged below the tank for the purpose of heating the water.

In connexion with the cavitation tests in this oval tunnel Parsons states, "To enable the propeller to cause cavitation more easily the tank is closed and the atmospheric pressure removed from the surface of the water above the propeller by an air pump. Under these conditions the only forces tending to hold the water together and resist cavitation are the small head of water above the propeller, and capillarity".

"The propeller is 2-inch diameter and 3-inch pitch; cavitation commences at about 1,200 revolutions and becomes very pronounced at 1,500 revolutions. Had the atmospheric pressure not been removed, speeds of 12,000 and 15,000 revolutions per minute would have been necessary, rendering observations more difficult".

"The shape, form and growth of the cavities about the blades could be clearly seen and traced. "It appeared that a cavity or blister first formed a little behind the leading edge, and near the tip of the blade; then as the speed of revolution was increased, it enlarged in all directions until at a speed corresponding to that in the *Turbinia*'s propeller, it had grown so as to cover a sector of the screw disk of 90 deg. When the speed was still further increased, the screw, as a whole, revolved in a cylindrical cavity, from one end of which the blades scraped

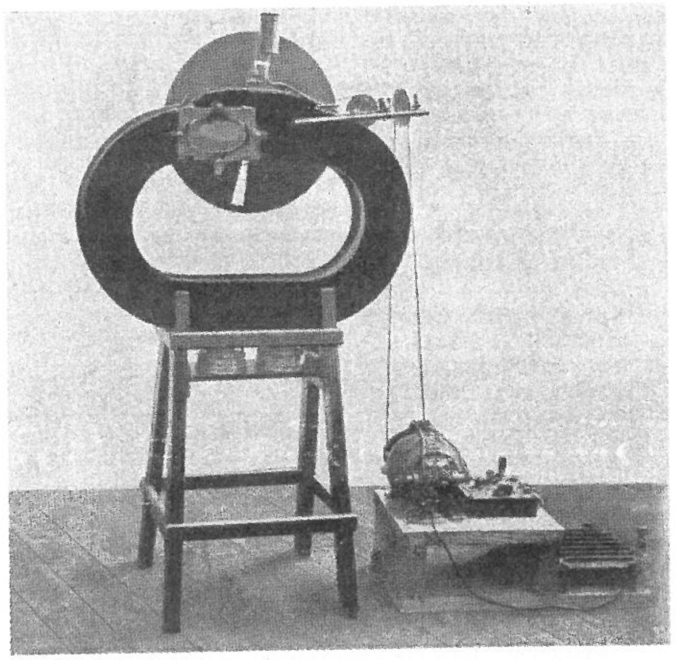


FIG. 1—*The first cavitation tunnel (1895)*

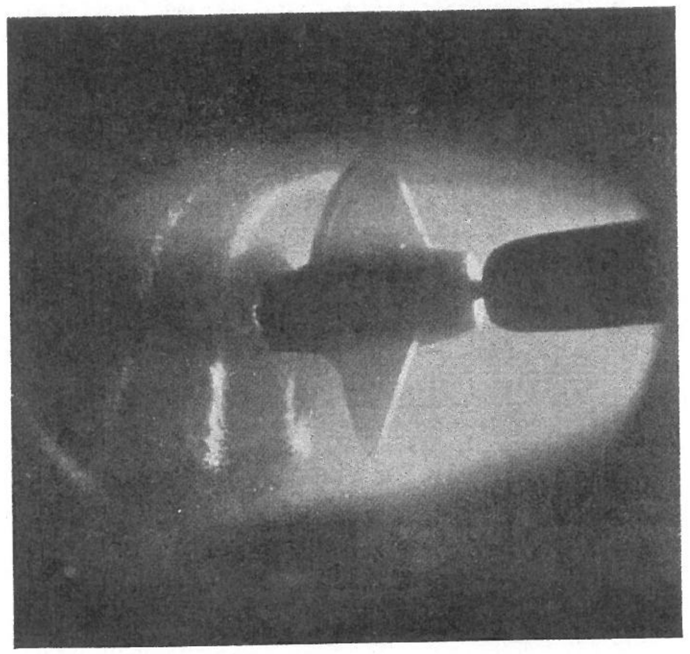


FIG. 2—*Cavitation photograph from small tunnel (1895). Propeller 2-inch diameter, 1,500 r.p.m.*

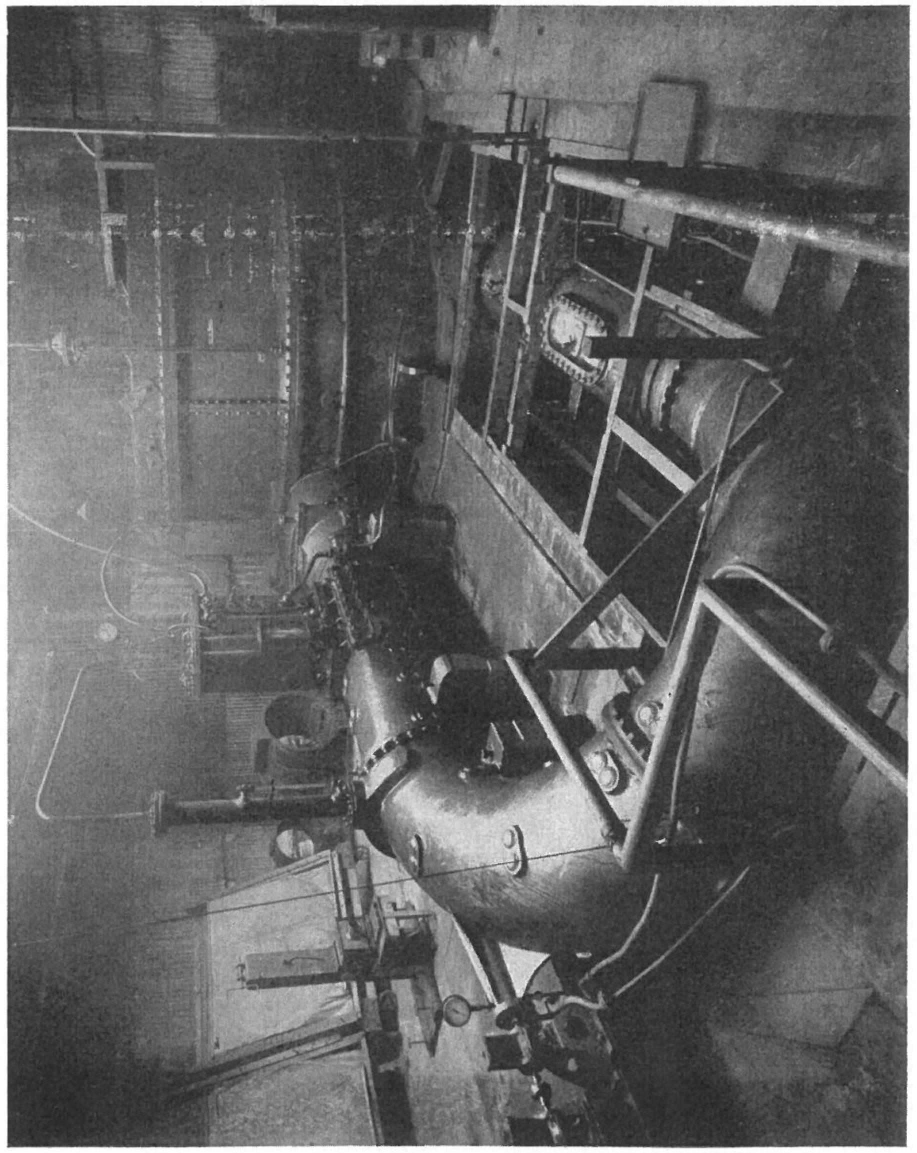
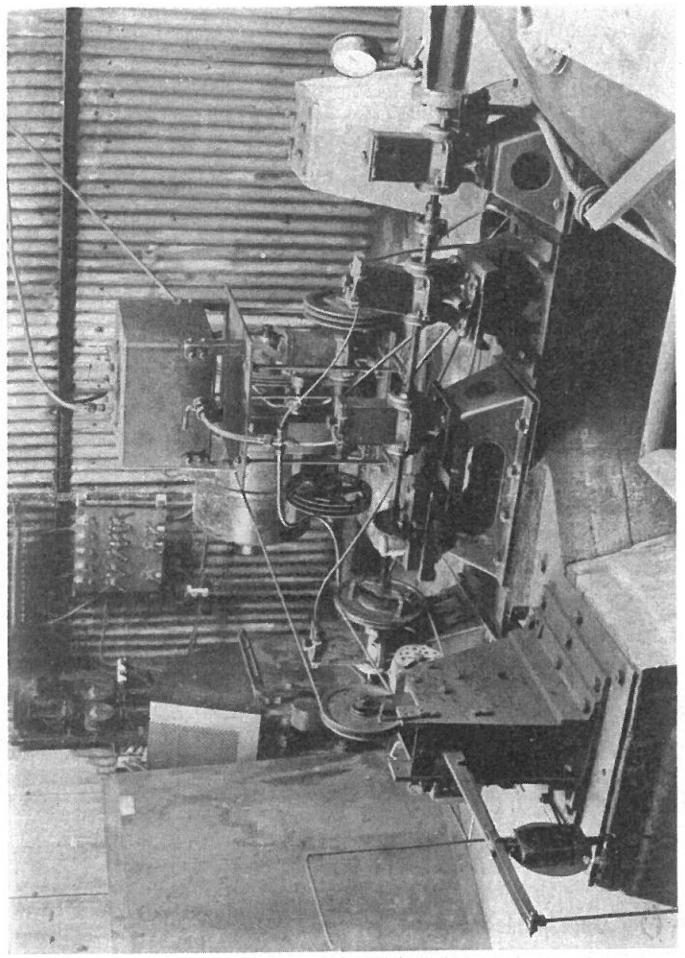
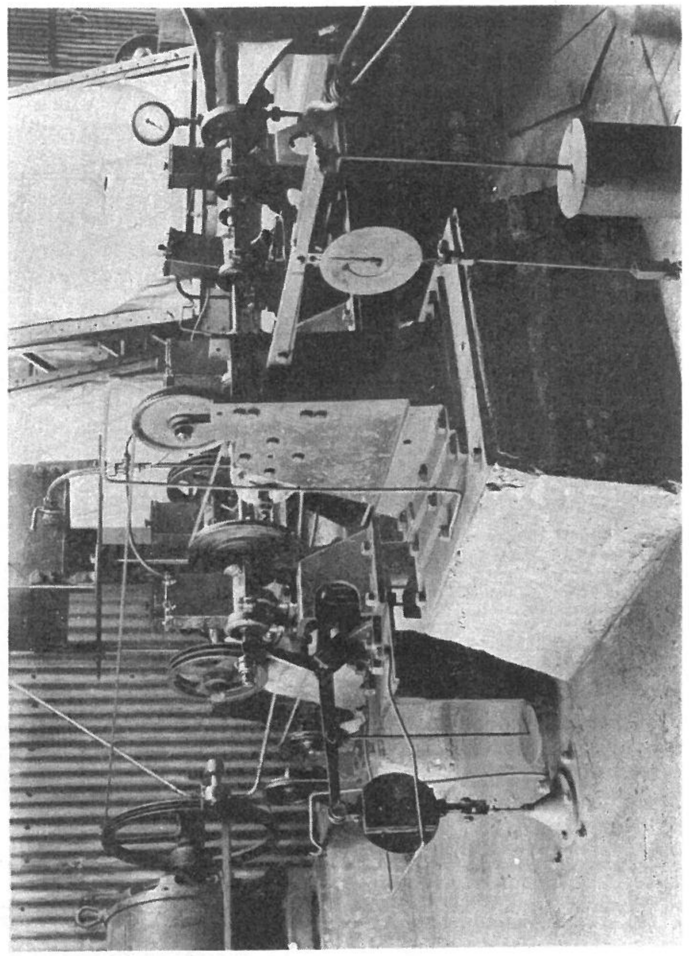


FIG. 3—*Parsons' large cavitation tunnel (1910). General view*





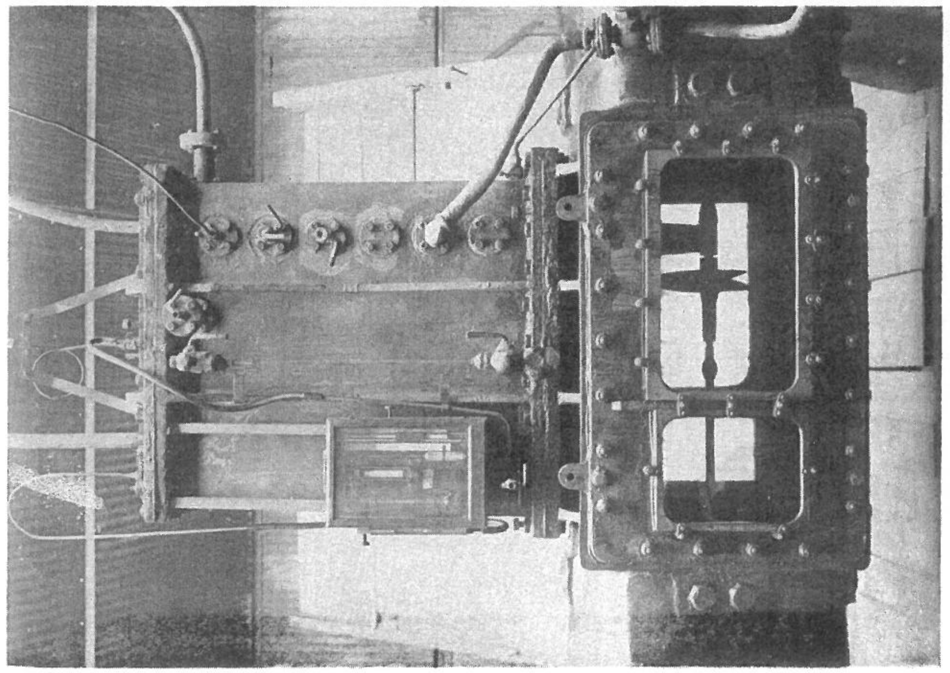


FIG. 6 *(above)—View of measuring section with vacuum chamber above (1910)*

FIG. 7 *(top right)—The model propeller drive and torque measuring gear (1910)*

FIG. 8 *(right)—Thrust measuring gear, at end of shaft (1910)*

IG. 18(a)—*Model propeller in tunnel. Slip 13 per cent. Face cavitation at leading edge*

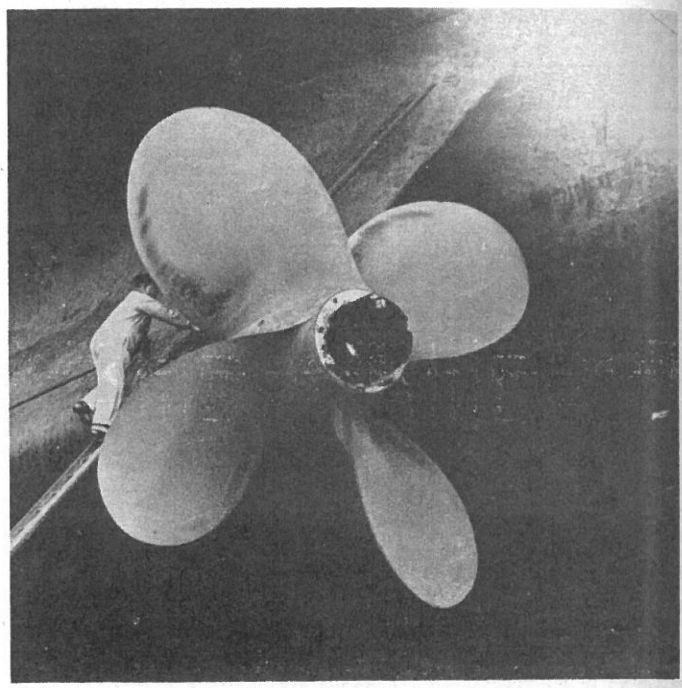


FIG. 18(b) *(above)—Actual propeller in service. Deep pitting on face near leading edge due to erosion*

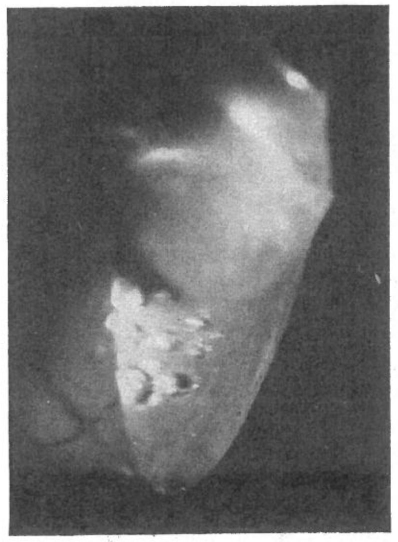


FIG. 20 *(left)—Model propeller No. 54 in tunnel showing back cavitation at 32·3 per cent slip*

off layers of solid water, delivering them to the other. In this extreme case nearly the whole energy of the screw was expended in maintaining this vacuous space. It also appeared that when the cavity had grown to be a little larger than the width of the blade, the leading edge, acted like a wedge, the forward side of the edge giving negative thrust" (see Fig. 2, Plate 1).

It is also of interest to relate the conclusions at which he arrived as a result of these tests, and the observations which he made at the time concerning the nature of cavitation and its avoidance in practice.

"The excessive slip of the propellers beyond the calculated amount, and their inefficiency, indicated a want of sufficient blade area upon which the thrust was distributed—in other words, the water was torn into cavities behind the blades. These cavities contained no air, but only vapour of water, and the greater portion of the power of the engine was consumed in the formation and maintenance of these cavities instead of the propulsion of the vessel".

"From these experiments it would appear that in all screws, of whatever slip ratio, there will be a limiting speed of blade, depending upon the slip ratio and the curvature of the back—in other words, on the slip ratio and thickness of blade; beyond this speed a great loss of power will occur; and that, should the speed of ships be still further increased, the adoption of somewhat larger pitch ratios than those at present used will be found desirable".

"Generally speaking, the effect is felt in the case of the real ship, not in the racing of the screw, but in loss of propulsion effect. In the model experiments, however, in hot water, the effect was both loss of propulsion effect and also racing, as would naturally be expected from the fact of greater vapour density of the water in the latter case rendering the cavities more stable. A series of model experiments on cavitation in cold water on the lines described would be extremely interesting, and probably instructive, but would require more elaborate, powerful and extremely high speed apparatus than was at our disposal".

Later, in 1900, he wrote "The inference to be drawn from these experiments seems to be that for fast speeds of vessels, wide thin blades, a coarse pitch ratio, and moderate slip, are desirable for the prevention of cavitation", and in 1899, in the course of his Presidential Address to the Institution of Junior Engineers he stated "Cavitation, which, though previously anticipated, was first practically found to exist by Mr. Thornycroft and Mr. Barnaby in 1894, and by them it was experimentally determined that cavitation commences to take place when the mean thrust pressure on the projected area of the blades exceeds 11¼lb. per sq. in. This limit has since been corroborated during the trials of the *Turbinia*". As a matter of record, it has been stated elsewhere that it was R. E. Froude who first used the term "cavitation".

It is also worthy of note that Sir Charles stated, in connexion with these experiments, that dynamometric measurements were taken of power and thrust with various widths of propeller blade, and Richardson records that when the blades of the propeller were broadened so that the projected area reached about 0·7 of the disk area, the falling off of the thrust was very small, even in boiling water. This is mentioned because this projected surface ratio of 0·7 appears to have been favoured by Sir Charles Parsons at that time, and also in later works.

V. THE PERIOD 1897 TO 1910

During this period the turbine was gradually adopted for larger and more powerful vessels, and, as the size of the installations increased, the number of revolutions per minute decreased—first from 2,000 to about 1,000 and then to 700 and 500, and later to 300 and 200 r.p.m.—and consequently the size of the propellers increased and the danger of cavitation diminished. At first Sir Charles appeared to favour the tandem or triple screw arrangement, but this was later abandoned in favour of the single propeller. The *Viper* (1898) 210 feet × 21 feet × 370 tons, for example had four shafts with two screws in tandem on each shaft, and she obtained a speed of 37 knots for 12,300 i.h.p.

The *Cobra* (223·5 feet × 20·5 feet × 390 tons) also had initially two screws per shaft but the number was later increased to three. The Clyde passenger boat *King Edward* (250 feet × 30 feet × 6 feet draft × 650 tons) built in 1901 had three shafts with two propellers on each of the wing shafts (755 r.p.m.) and one on the centre (505 r.p.m.), but later a single propeller was fitted to each shaft. In the *Brighton* (280 feet × 34 feet × 15·21 feet depth) built in 1903 there were three shafts and the h.p. turbine ran at 523 r.p.m. and the l.p. at 577 r.p.m. The equivalent i.h.p. was 6,500 and the speed 21·37 knots.

It is interesting to record the experience in the *Emerald,* 1903, which had originally two propellers on each wing shaft and one on the centre. Noise and vibration were experienced in way of the forward outer propellers and when these were removed ¾ knot extra speed was obtained for the same power. Later, single propellers of larger size were fitted to the outer shafts and the speed was increased by ½ knot. The loss in efficiency with the original tandem arrangement was attributed partly to interference and partly to cavitation. The tandem arrangement of propellers was thereafter abandoned and it is stated that this decision was later verified by tests on the *Turbinia* with a single propeller on each shaft.

The first application of helical spur gearing to drive a propeller was made by Parsons in 1897. The turbine was of 10 h.p. geared to two wheels, each wheel driving a propeller shaft. The revolutions of the propellers were 1,400 per minute and the gear ratio 14 to 1. The gear was single helical. In 1904 it was examined and found to be in perfect order. In 1909, Parsons decided to test turbines mechanically geared to the screw shaft in a typical slow-speed vessel and an existing cargo vessel named the *Vespasion* was purchased for this purpose. The gear ratio was 19·9 to 1, and the propeller ran at speeds up to 73 r.p.m. The experiment was successful and was followed by other installations with single-reduction and double-reduction gear, thus solving for the time being the major problems of cavitation due to high speeds of rotation of the propeller. The first destroyer with reduction gearing on both shafts was the *Leonides* built in 1912 and thereafter the direct drive arrangement was abandoned.

As the horse-power of the various installations had, however, continued to rise, the effects of cavitation began to be manifested in another form, namely erosion and pitting of the blades due to the high thrust loading. Sir Charles Parsons had continued his interest in the subject of cavitation and in 1910 built the first large cavitation tunnel at Wallsend (see Fig. 3, Plate 2). In this tunnel, which will be described in the next section, model propellers 12 inch in diameter were tested under cavitating conditions at speeds up to 14·3 feet per sec. and the tunnel continued in operation up to the time of his death in 1931.

VI. THE FIRST LARGE CAVITATION TUNNEL

This tunnel, the original drawings of which are reproduced in Figs. 4 and 5, consisted of a closed circuit about 66 feet long, the diameter of the main circular piping being 36 inch. As will be seen from the drawings, there was an upper limb in which the model propeller drive was situated, and a lower limb which carried the impeller which served to circulate the water at various speeds. To those familiar with recent developments in cavitation tunnels, the large settling tank 14 feet in diameter and 11ft. 6in. high, which formed one of the ends of the circuit, will be of particular interest. This tank was filled with vertical pipes about 6 inch in diameter, and the water which entered at a low level flowed up through these pipes and then ran out over the top of them into the main part of the container before entering the measuring section. The purpose of this tank was to obtain clear water, free from bubbles, in the measuring section, and it may therefore be regarded as the forerunner of the "resorber" fitted in connexion with several recent American tunnels.

The measuring section was approximately rectangular with

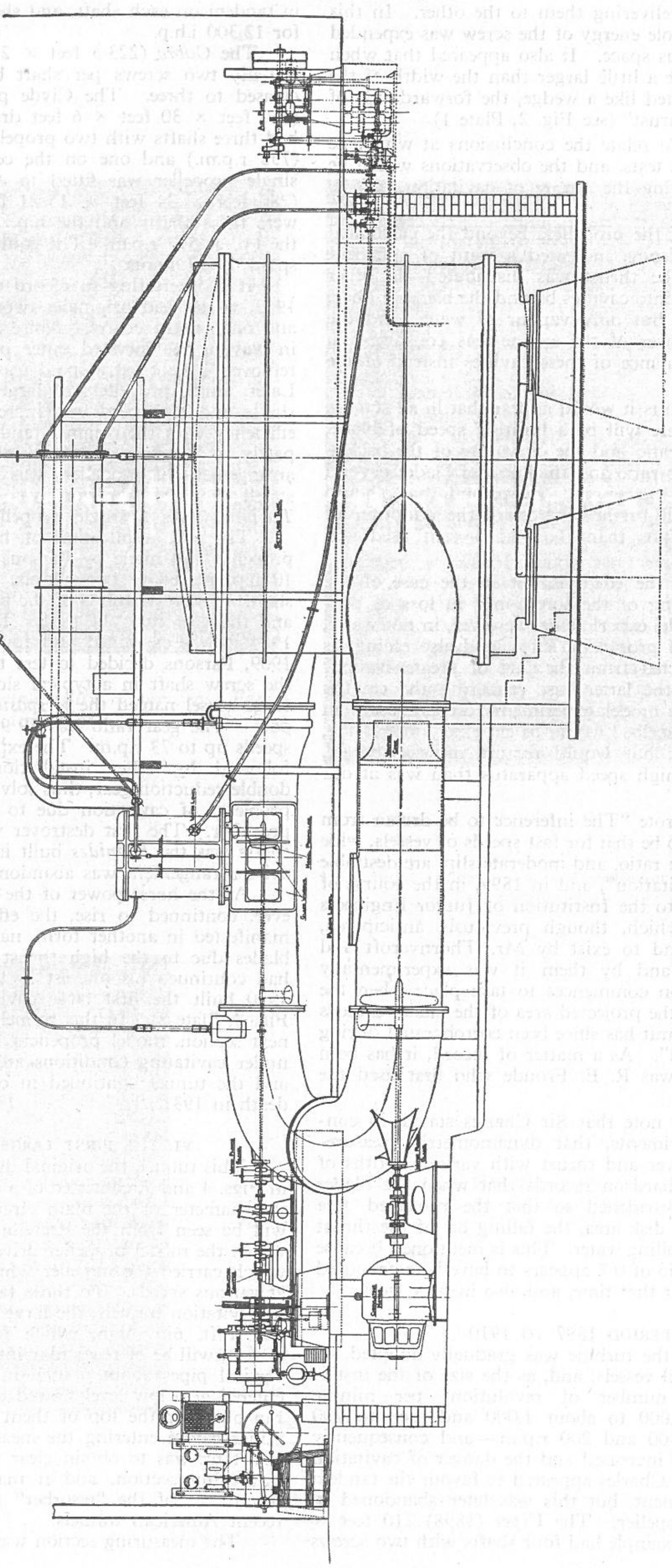


FIG. 4—*Original drawing of the 1910 tunnel (elevation)*

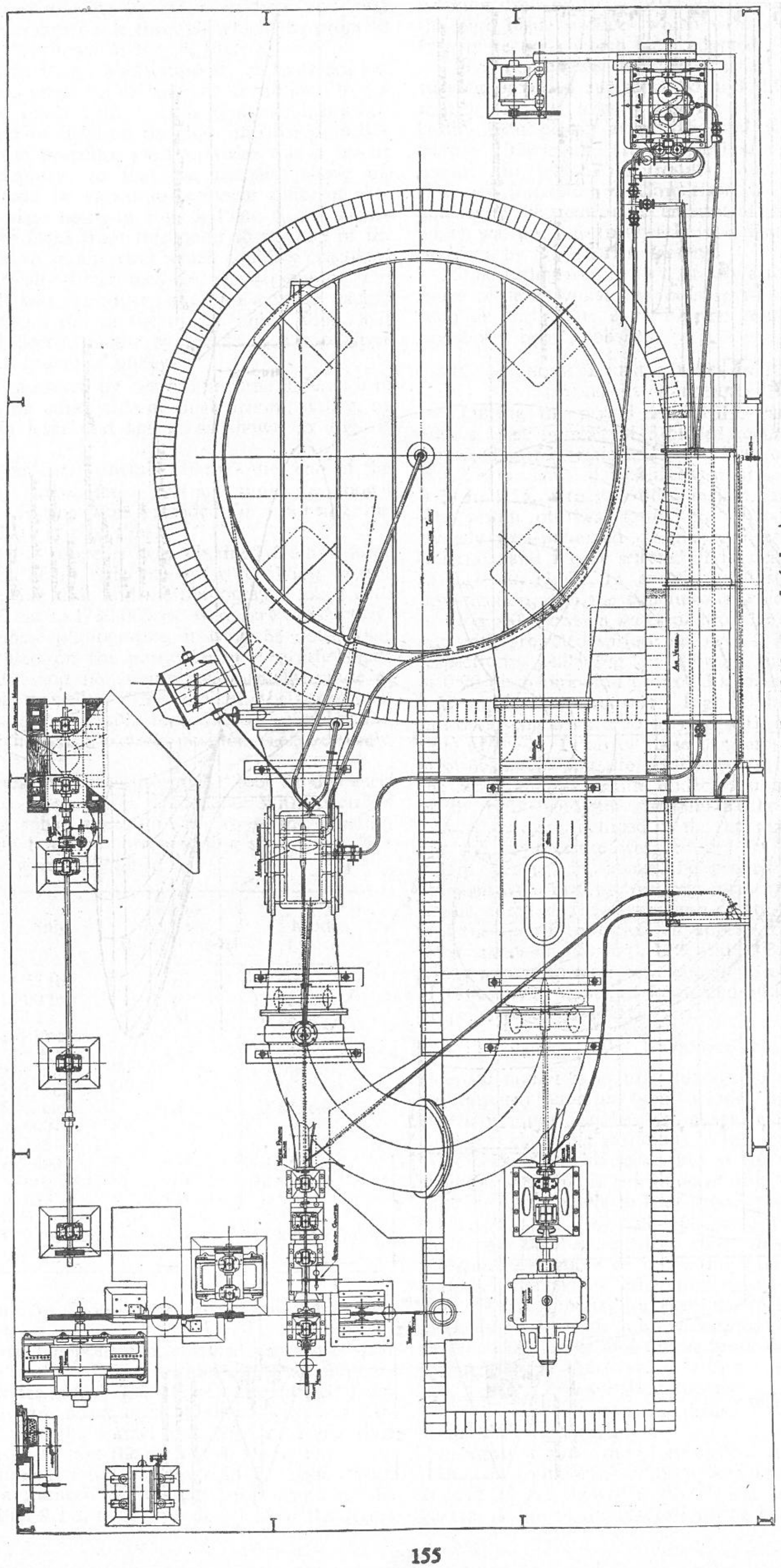


FIG. 5—*Original drawing of the 1910 tunnel (plan)*