EXPERIMENTS ON CAVITATION

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Thesis presented for the degree of

Master of Engineering by

Palmer Savage

McGill University

September, 1933

degree rec'd 1934.

EXPERIMENTS ON CAVITATION

Thesis presented for degree of Master of Engineering by Palmer Savage, McGill University, September, 1933.

Contains brief historical summary; outline of existing theories regarding production of cavities, pitting, noise and vibration; record of experiments conducted using vane to produce cavities; some results of endurance tests with relationship between microstructure of cast iron and its pitting; conclusions; bibliography.

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BRIEF HISTORICAL INTRODUCTION

The term "cavitation" was first used in 1894 during the trials of the torpedo-boat destroyer "Daring" in England. It was noticed that when the ship was driven over a certain speed, a rapid increase of propeller slip, and very low efficiencies resulted. Mr. S. W. Barnaby, who was making the tests, gave as the reason, that, "at high surface pressure, and high speed, the water cannot flow along the back of the blades, thus causing cavities, (cavitation)". [1]He also showed at this time that this cavitation occurred when the thrust per square inch of projected blade area exceeded a certain amount; (in this case $11\frac{1}{4}$ lb.)

With the development of the steam turbine for ship propulsion, and the resulting higher speed of propellers, the problem became quite important, and considerable investigation was made concerning the phenomenon in England and Germany.

In the hydro-electric field, as high-speed propeller and Kaplan runners came into common use, cavitation became a source of trouble in three ways, - first, loss of power and efficiency; second, pitting of runners and draft tube liners; and third, noise and vibrations, sometimes sufficiently powerful to cause damage to machinery and buildings. (Francis runners also caused trouble, but not in the same degree as the higher speed turbines).

[1] Hydraulische Probleme, - Prandtl, Foettinger, Thoma, p. 14.

Similar difficulties were experienced with centrifugal pumps.

Early experience in Europe in attempting to predict the performance of full-size high-speed runners from model prototypes proved very disappointing, and it was appreciated that a serious study of the matter was necessary if high-speed runners were to be built successfully.

The first experiments in studying the phenomenon of cavitation were made in Europe. Little regard was given to the fundamentals of cavitation, the main object being to secure designs which would give satisfactory service. (The pioneer work of this type in America has been done at the experimental laboratory of the Shawinigan Water and Power Company at Shawinigan Falls. During the past ten years investigation of the effect of cavitation on model turbines has been carried out in this laboratory).

At Hamburg, however, in 1914, Prof. Foettinger and Prof. Spannhake carried out a large number of experiments on the study of cavitation itself, produced under controlled conditions. (See Hydraulische Probleme, - Prandtl, Foettinger and Thoma, 1926).

When Prof. Wilhelm Spannhake succeeded Dr. Thoma as Visiting Professor of Hydraulics at the Massachusetts Institute of Technology in the fall of 1931, he began the first work of investigation into cavitation itself in America, sponsored by the Safe Harbor Water Power Corporation.

The apparatus used at McGill University was designed on the principle used by Prof. Spannhake at Boston, which is the same as that used by several European investigators.

GENERALLY ACCEPTED THEORIES ON THE CAUSES OF CAVITATION, PITTING, NOISE AND VIBRATION

CAVITATION. Cavities will form in a fluid whenever the absolute pressure on a fluid particle is decreased approximately to the vapor pressure or below it.

Before the absolute pressure reaches the vapor pressure of the fluid, part of the gases dissolved in the fluid begin to come out of solution. (The gases released depend upon the nature of the fluid and where it is found. In the case of ordinary water as found in hydro-electric work, they are largely oxygen, some carbon dioxide, nitrogen, etc.). As the pressure decreases still further, the fluid vaporizes, so that the cavities consist of a mixture of released gases and fluid vapor. (The pressure in the cavity, then, will be the vapor pressure of the fluid, plus some small pressure due to the gases).

The lowering of pressure sufficient to cause the production of cavities can be produced in different ways. One of the most important cases occurs in the steady flow of fluids when acceleration takes place. In cases of moderate acceleration, the transformation of energy will take place approximately according to Bernoulli's equation, -

$$\frac{p}{w} + \frac{v^2}{2g} + z = \text{constant}$$

p = pressure of the fluid at any point

v = velocity of the fluid at that point

z = elevation of the point above some datum

w = specific weight of the fluid

Cavitation may occur in a runner from two causes, - design and setting. The first is the explanation given by Mr. Barnaby in 1894, (see page 1), in connection with ship propellers. If the shape of the blades is such that the water cannot follow them, cavities will naturally result. This holds good for ship propellers, turbine runners and centrifugal pump runners. In the setting of a turbine, a high suction head is almost always desirable in respect to power house construction. It is easily seen that in the case of a high speed runner, where the kinetic head at exit may easily be of the order of 30% of the total operating head, a very high suction head will result if much of this energy is to be regained in the draft tube. Thus a high setting of such a runner is almost sure to result in extremely low pressures at the exit tips of the blades, with a resultant production of cavities. This is well illustrated by the installation of double runner units at Holtwood over twenty years ago. The lower units have caused no trouble whatsoever, whereas the upper runners have required considerable care to keep them in working condition. The only difference in this case is the difference in suction head on the runner.

PITTING, NOISE, AND VIBRATION. It was at first thought that the pitting of propellers was due largely to chemical or electrolytic action, or a combination of the two. This idea was easily conceivable, since the gases coming out of solution due to cavitation are very rich in oxygen, and metals like cast iron and steel pitted much more easily than the softer but more chemically resistant bronzes. It was soon appreciated, however, that the excessive pitting which was being obtained could not be explained by simple corrosion. The pitting of plate glass at Hamburg during the experiments by Prof. Foettinger and Prof. Spannhake shows rather conclusively that the pitting is not necessarily chemical, since glass is not subject to corrosion. Dr. Thoma, however, in the 1926 "Hydraulische Probleme" in which this work is reported, counsels against taking this as absolute proof that the action is entirely mechanical. With reference to these tests he says, -

"Concerning the most interesting tests reported by Mr. Foettinger, I would not conclude that pitting has been developed merely on account of mechanical action. Glass has no great strength, and is very brittle, and is, therefore, mechanically rather unsatisfactory. Tests carried out with material which is chemically less resistant, might prove, on the contrary, that pitting is developed also without any mechanical action. This is not, however, a reason to believe that pitting in water turbines is merely due to chemical action. Against the opinion that pitting is a consequence of mechanical action, the following fact is to be mentioned: with water turbines, the resistance of the material against pitting depends in a high degree on its chemical properties, this resistance being, for instance, generally much greater for bronze than for stronger steel. Apparently, in most cases, pitting is developed by a simultaneous action of mechanical and chemical processes".

A report made in 1917 by the special committee appointed by the British Admiralty to investigate pitting says, "The conclusions arrived at are that the corrosion of the propellers is very slight, but that the erosion is serious, and is caused by the hammer action of the water on the propeller blades, produced by cavities closing up on the surface of the blade".[1]

Parsons, in a paper on the investigation into the causes of corrosion or erosion of propellers also bears out this theory, concluding that corrosion is slight, but erosion is serious.[2]

The explanation of how sufficient mechanical force can be produced under the conditions of cavitation to cause rapid and violent pitting of metals is as follows. Consider one cavity in the form of a small bubble. As has just been mentioned, this

[1] Engineering, - Englesson, Apr. 16, 1926.

[2] Engineering, - Parsons, Apr. 18, 1919.

bubble contains gases which were in solution in the water, and, comparatively, a large volume of water vapor. If now this bubble moves with the stream flow to a point of higher pressure, the water vapor will recondense very readily. The reabsorption of the gases, however, does not take place so easily.[1]

Since the gases redissolve so slowly compared with the condensation of the water vapor, the small quantity of gases will be highly compressed by the impact of the collapse caused by the rapid condensation of the vapor content of the bubble. If this transition from the low to the high pressure area be sufficiently rapid, this compression may take place in an infinitely short time, and the pressure developed in the small bubble of gas may be enormous. Rough approximations show that it is possible to create a pressure of about a thousand atmospheres in this way. (See page i). Since this compression takes place in such a short time, the process will certainly not be isothermal. It may be adiabatic, but is most likely polytropic. European investigators have attempted to estimate what the temperature rise may be, but so far only very rough approximations have been accomplished. It is certain, however, that with even very slight variations from the isotherm, very high temperatures may result. If now this minute

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[1] Tests carried out by Dr. Peters in connection with Prof. Spannhake's work at the Massachusetts Institute of Technology showed this fact very clearly. A mechanical analysis was being made of the behaviour of water containing dissolved gases when subjected to pressures less than atmospheric. This was being done, as it was thought that the quantity of gas in solution would have an influence on the pressure in the cavities and consequently upon the

store of concentrated energy becomes lodged in some small crevice in the surrounding metal, it may cause destruction either by explosion, or by heating the metal to its melting point, or by a combination of the two. The explosion of such a bubble when merely in contact with the surface and not caught in a crevice might well cause considerable damage, but would not dislodge pieces of metal so easily.

This explanation accounts for the fact that open-grained metals like the cast-irons are so easily attacked, while metals with compact surface texture, although softer, (e.g. Bronze), show greater resistance. It also explains why rough-finished surfaces pit relatively easily, and why pitting accelerates rapidly once it has set in,- (presence of crevices).

The terrific noise and vibration set up as in hydraulic turbines is caused by the impact of collapse of thousands of cavities of all sizes.

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pitting. The apparatus consisted of a small vessel connected to a calibrated burette, in which the pressure could be reduced by lowering a reservoir filled with mercury, connected to it by a length of flexible tubing. It was found that the water began to effervesce when the pressure was reduced to about one-half the atmospheric pressure. When the pressure was restored, there remained a small bubble of gas at the top of the burette which showed no apparent tendency to redissolve, even if the apparatus were left standing overnight. Continued repetitions of this treatment always resulted in a slight amount of air being extracted.[1]

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[1] Cavitation Research, - A progress report by the Safe Harbor Water Power Corporation. March 24, 1933.

TESTS CONDUCTED AT MCGILL UNIVERSITY

The first cavitation tests at McGill University were made in the winter of 1931 - 32. There was little time to devote to this work, but it was thought that possibly conditions might be found under which pitting could be easily produced, so that an apparatus could be designed, both to study such conditions, and to run endurance tests on different metals.

The apparatus first used (fig. 2), was similar in principle to that used by Prof. Foettinger and Prof. Spannhake at Hamburg in 1914,[1] in that a vane was used to produce cavitation. The angle of this vane to the stream flow could be varied to produce different conditions of flow. Whereas, at Hamburg, a closed circuit was used, the pressure being produced by two centrifugal pumps, it was convenient here to draw the water from the mains, and run the discharge to waste.

A series of tests was run under different conditions of inlet pressure up to 113 lb. per sq. in., and pressure distributions below the baffle were observed, measurements being taken with an open mercury manometer. The curves were of the form shown in fig. 3. It is seen that due to lack of proper provision for throttling the discharge, that the pressure rise below the vane is very gradual. Consequently, the collapse of the cavities does not take place sufficiently rapidly as to cause high compressions.

[1] Hydraulische Probleme, 1926, Prandtl, Foettinger, Thoma, p. 36.

Following this, the baffle was removed, and a converging and diverging section used as shown in fig. 4. Since the same side plates were used as with the baffle, none of the piezometer openings were actually in the cavitation volume, but it was thought that an idea of the pressure distribution in the stream flow should be obtained before going to the expense of fitting up new reading apparatus. The fairly sharp angle of divergence was designed with the idea that it would cause a sufficiently rapid pressure rise that throttling would be unnecessary. The curves, however, were again of the form shown in fig. 3.

A sheet of transparent xylonite was then substituted for one of the metal side pieces. Just below the throat, the water became quite milky in appearance due to the presence of small bubbles of gas which had come out of solution. This milky appearance persisted throughout the length of the apparatus, indicating that there was nowhere near a complete collapse of the cavities.

Although there was a great noise of hammering, and a sound similar to that of a high tension spark, accompanied by apparent terrific punishment of the apparatus, no pitting could be detected after several long runs. It was first thought that the lack of pitting was entirely due to the slow pressure rise, and consequent lack of high compressions and concentration of the collapse. More recent tests, however, have shown that finished rolled steel, such as was used in this apparatus, is very difficult to attack. It is just possible that pitting might have been produced on cast-iron or glass under the same conditions. A cast-iron plug at approximately the location of the last piezometer opening, (see fig. 4), showed no signs of pitting, but the pressure curve at this point was practically horizontal, so it would not be expected. (If time permits, tests will be run with this apparatus using cast-iron plugs set in the steel plates, approximately at the end of the diverging section, fig. 4).

A peculiar phenomenon was noticed while these readings were being taken. In all cases, the openings of holes in the group #1 to #6 inclusive, thereby admitting air to the stream flow, caused a marked decrease in the vacuum gauge reading at any of the holes in this group. With the same connection, the opening of #7 or #8, or both jointly, restored the reading to the value found when all the holes were closed. (Slight differences were of the order of probable observational error). On the other hand, with the vacuum gauge connected to #7, the admission of air at the holes #1 to #6 inclusive caused a large increase of vacuum at #7, while air admitted at #8 caused a small decrease. (See figs. 5, 6 and 7).

Apparently this change of pressure is due to alterations of the stream line flow. Admission of air would certainly create a stagnation point, which would influence the stream lines. It is quite conceivable that such alterations could cause pressure variations of the magnitude shown in the curves.

Since little had been accomplished with this apparatus, it was discarded in the fall of 1932, and the apparatus shown in fig. 8 designed. This was converted from equipment built for the study of pressure distribution over vanes, and as a result was slightly makeshift. It was, however, far in advance of the old apparatus in every way, one great advantage being the comparative ease with which the test section could be dismantled and reassembled.

DESCRIPTION OF APPARATUS. The apparatus as a whole is shown in fig. 8. The water enters the apparatus through a six-inch main, under a maximum pressure of about 120 lb. per sq. in. (This maximum is not maintained throughout the day, however, about 95 lb. per sq. in. being the pressure when the outside demand is at its peak). The inlet is controlled by a six-inch gate valve, - the gate valve being used to insure a minimum head loss at this point. The inlet pressure gauge is located in this six-inch line, where the velocity head is practically zero. (The maximum rate of flow recorded was about 0.4 cfs. This would give a velocity in the six-inch pipe of

$$\frac{Q}{A} = \frac{0.4}{\pi (0.25)^2} = 2 \text{ ft. per sec. (abt.)}$$

This gives a velocity head of $\frac{v^2}{2g} = \frac{4}{64} = 0.06$ ft., which is negligible). The water then enters a bronze casting, A, (fig. 8), two feet long, which reduces the waterway from a six-inch circular, to a two- by three-inch rectangular section, matching the entrance to the test section, B. (This section is described later).

From the downstream end of the test section, also two by three inches, the water flows into a diverging section C, identical with A. The lower end of section C is connected to a six-inch flange, drilled and tapped for a three-inch pipe. The three-inch pipe was used, as there was no more six-inch in stock, whereas there was plenty of three-inch available, as well as a three-inch gate valve for the discharge control. It was also thought that in case it was desired to have a suction head on the discharge, that it would be very difficult to make a six-inch pipe run full to create the suction. The sudden contraction from the six-inch to the three was sufficiently far downstream that no disturbance was created at the test section. In this three-inch pipe was placed an oil thermometer well, and in the elbow, as shown, a pressure gauge. The pressure at this point has no particular meaning, but the gauge was used as a means to re-set the discharge throttle valve at any desired position. That is, if the inlet gauge read, say 80 lb. per sq. in., and the discharge gauge, say 20 lb. per sq. in., the conditions in the apparatus could be duplicated at any time by simply setting these PRESSURES again. Of course the temperature could not be controlled. The discharge ran first into a measuring tank of approximately 375 cubic feet capacity, which was connected to the sewer by a six-inch gate valve. The discharge valve was placed about three feet above the bottom of the tank so that the discharge could take place freely into the air, or by adjusting the valve to the sewer, could be submerged under water, up to about six feet.

The inside of the test section, (a bronze casting), was originally two by three inches. Since the water used was being run to the sewer, it was thought that the flow through a section two inches deep would be excessive, and would be of no advantage over, say, one inch. Consequently, the plate shown in fig. 9 was made to cut down this depth to $1\frac{1}{8}$ inches. It was not made less, because it was not desirable to accelerate the water too rapidly. The present depth seems, however, a little excessive, as the flow is considerable, and it is likely that just as good results could be obtained with less water by reducing this section still more.

The profiles used to produce the cavitation are shown dotted in fig. 9. (The location of the test pieces will be explained later). Fig. 10 shows a full-size detail of these profiles. The copper shim was used because the profiles had been made slightly too thin.

The location of the piezometer openings is shown in fig. 11. With the exception of #1, they are all in the top face. #1 was placed in the centre of the profile, just below the throat. The holes were located so that the edges just touched the edges of the profiles. They were made very carefully to insure uniformity, and were slightly countersunk to remove any burrs which might affect the readings. Section AA shows the relationship of the sheet carrying the openings to the rest of the apparatus.

The measuring apparatus again consisted of ordinary open mercury manometers. Owing to the great pressure fluctuations, it was not considered necessary to use any particular refinements on this apparatus.

TESTS. This apparatus was ready for preliminary work early in January, 1933. The first tests were run with the object of finding a profile of such a shape that reasonably rapid pitting could be produced without using too great a quantity of water. For economy, the first profiles used were made up of close-grained wood, - either maple or birch, - thoroughly impregnated with paraffin. The angles used approximated angles which had been successfully used by Prof. Spannhake at Boston. No pressure measuring apparatus was used on the first sets of profiles, as it was thought that an inspection of the flow through the transparent cover would be sufficient to show up any great errors in design. This proved to be the case, - for instance, fig. 12A indicates the interference of flow at the throat found in the first set of profiles, while fig. 12B shows how this was cleared up by decreasing the angle of convergence slightly, and rounding off the sharp corner at the throat.

The fourth set of profiles were apparently all that could be desired, as far as could be seen, so the cover sheet was fitted up with piezometer openings as shown in fig. 11. The pressure distribution curves as shown in figs. 13 and 14 were then observed. These were taken for any one pressure, within the limits of no collapse and no cavitation. (e.g., in fig. 14, with the pressure at hole #0 = 60 lb. per sq. in., below the discharge pressure of 10 lb. per sq. in., there was no collapse of cavities within the test section, while above the discharge pressure of 30 lb. per sq. in., there was no cavitation). Great difficulty was experienced in making the readings due to the great fluctuations, especially in the area of collapse. However, by throttling, and taking the mean reading of several observations, fairly smooth curves were obtained. This unsteadiness was not experienced at hole #1, which was in the centre of the profile, and in the cavitation volume. The curves were not all that was expected, due apparently to the location of the piezometer openings. It has been the experience of other investigators that the pressure in the cavitation volume is practically constant at a value slightly above the vapor pressure. This would give a curve of the form shown in fig. 15. Now, since the pressure at hole #1 was very steady at approximately the vapor pressure, and holes below this in the cavitation volume showed considerable variation, it would seem that there was some leakage between the profile and the cover plate which was causing these fluctuations. This theory was borne out later when a pressure hole was located in one of the stainless steel profiles in the area in which considerable variation had been experienced. (See fig. 10). The pressure then became absolutely steady at that point, at a value just above the vapor pressure.

In spite of these drawbacks, however, the curves were very satisfying in that they showed that excellent control of the pressure distribution was easily obtained, and that the pressure rise could be made as rapidly as desired, making the collapse of the cavities almost instantaneous. (For instance, in fig. 14, when the pressure at hole #0 is 60 lb. per sq. in., and the discharge pressure is 30 lb. per sq. in., the pressure rises from - 13 ins. of mercury to + 30 ins. of mercury in one inch of flow. The effective head causing flow is (60+15) lb. per sq. in., so that, considering the coefficient of discharge as unity, the velocity at the throat becomes

$$v = \sqrt{2gH} = 8\sqrt{75x2.3} = 105 \text{ ft. per sec.}$$

Therefore the time taken for the rise from -13" to +30" is of the order of $\frac{1}{12x105} = \frac{1}{1260}$ sec.).

The test pieces as shown in fig. 9 were then made. The upstream one was placed at the point where pressure rises under most conditions were most rapid. The lower one was placed at the end of the diverging section just to see if any violent action was taking place there, as it was just about this point that pitting was obtained in Prof. Spannhake's apparatus. The first plugs were placed with the object of making sure that pitting would take place where it was expected. As a result, cast-iron was used on account of its susceptibility to attack. The xylonite cover sheet was replaced by a sheet of rolled steel, as it was thought that some of the force of the collapse was being lost through the high elasticity of this material. After a run of 96 hours, the apparatus was dismantled, and the upper cast-iron plug found badly pitted. Apparently it had been placed exactly in the centre of the area of maximum destruction, for the wooden profiles were also damaged for a short distance, (about half an inch), upstream and downstream of the upper plug. The lower plug and the polished steel plate were apparently untouched, although the lower plug had turned yellow due to oxidation of its surface. A second cast-iron plug was placed in the upper hole, and another test run to make sure that the pitting could be obtained again. After 72 hours the same condition was found as before, - namely the upper plug badly pitted, and the steel plate and lower plug unaffected.

Following this, the profiles shown in fig. 10 were ordered from the Dominion Engineering Works, who were supplying test pieces for endurance tests. These were ordered of bronze, but since the contractor had some stainless steel of convenient size, permission was given to make them of this material instead. This proved very successful, as it resisted corrosion perfectly, and was much harder than bronze would have been. Provision was made for placing three test pieces at the same point for two reasons. First, water economy, for in endurance tests, three pieces could be tested at the same time. Second, to see if there was any difference in the quality or violence of the pitting in the different locations.

After considerable delay, the profiles were delivered about the first of August, with enough test pieces to begin endurance tests. The first work was done on different cast-irons, and following that, on bronzes. During the tests on the bronzes, a piezometer opening was made in a profile as indicated in red on fig. 10. (This was mentioned at the bottom of page 16). It was carefully drilled $\frac{1}{16}$ inch diameter, and countersunk as before. This was connected to an absolute pressure gauge by means of a brass plug screwed through the steel cover plate and profile. (fig. 16). This was done to check the figures obtained for the pressure in the cavitation volume. Although the pressures obtained at hole #1 as mentioned before were within one- to two-tenths of an inch of mercury of the barometric pressure minus the vapor pressure of the water, it was thought that the readings obtained by means of a good absolute gauge would be more reliable. Also, as mentioned before it was desired to check the pressure in the cavitation volume as found by the holes in the top plate. Great care was taken to have the mercury clean and dry, so that the readings obtained would be accurate, and the assumption that the pressure would be as shown in fig. 15 was rather well borne out, in that an exceedingly steady pressure of between one- and two-tenths of an inch of mercury in excess of the vapor pressure of the water was obtained.

The quantity measurements made gave no surprising results. As had been expected, as long as there was cavitation below the throat, the position of the discharge valve did not alter the flow. The flow was governed by the head at the throat, which was the gauge pressure at hole #0 plus the atmospheric pressure, since the discharge was taking place into the cavitation area, in which the absolute pressure is practically zero. The increased flow through the valve is maintained by means of the increased pressure behind it. The velocity curves are shown in fig. 17. The points on the experimental velocity curves should be quite accurate, as they are the means of several readings. Whereas at Boston, apparently the constant in the equation $Q = CA\sqrt{2gH}$ was found to be unity, in this case it was somewhat less, - something of the order of 0.8 to 0.9, which seems quite reasonable.

The endurance tests were run at a line pressure of about 90 lb. per sq. in., and a discharge pressure of 25 - 30 lb. per sq. in. The pressure at the centre of the test plugs was about 5 lb. per sq. in.

The chemical analysis and length of test is given for the test pieces. In the case of the cast-irons, the Brinell and Rockwell C. scale hardness are also given. (SEE TABLE, P. 21)

Photographs of all test specimens were made after being pitted. Figs. 18, 21 and 24 show the cast-iron specimens, and figs. 27 and 28, the bronzes. As seen from the photographs, the bronzes were not badly attacked, the action being more a hammering than pitting.

CAST IRON

SPECIMEN	CHEMICAL ANALYSIS						HARDNESS		TESTED HRS.	REMARKS
	C	Mn	P	S	Si	Mo	Brinell	Rockwell C		
#4CI	2.79	0.855	0.163	0.131	2.15	-	235	23.1	95	See figs. 18, 19, 20.
#4CIHT.	Composition same as #4CI. Heated to 1600°F - 1 hr. Quenched in oil. drawn at 900°F, for 2 hrs.						302	33.7	72	See figs. 21, 22, 23.
#5Mo	2.76	0.975	0.083	0.105	1.75	0.74	241	25.3	95	See figs. 24, 25, 26.

BRONZES

SPECIMEN	CHEMICAL ANALYSIS						TESTED HRS.	REMARKS
	Cu	Sn	Zn	P	Pb	Ni		
#503C	90.0	9.5	0.25	0.10	-	-	215	See fig. 27.
#485C	88.5	7.0	2.0	Trace	1.5	1.07	300	See fig. 28.

P.21

This same effect, but to a less marked degree was noticed on the rolled steel filler plate and the stainless steel profiles. These were not photographed. The pitting of the cast irons proved somewhat of a surprise. Although one was plain, another heat treated, and a third contained molybdenum, they all pitted to about the same degree and in a very similar manner. (figs. 18, 21, 24). To find the reason for this, photomicrographs were taken, and hardness tests made on the three specimens. Figs. 19, 22 and 25 show the great similarity in grain size and graphite structure of all the specimens. Figs. 20, 23 and 26 show the structure of the matrix. The matrix of the plain cast iron is largely pearlite, (fig. 20). Under heat treatment, this was changed to the hard martensite, (fig. 23), but of course the graphite structure was practically unchanged. The matrix of the molybdenum alloy is apparently a sorbito-pearlite, (fig. 26), and therefore likely slightly harder than the plain cast iron. As mentioned before, the graphite structure was very similar in all three, and it will be noticed that the pitting structure is very similar to that of the graphite. Fig. 25 actually shows the bottom of two pits which were not entirely polished out of the specimen. It is seen that these are located approximately where one would expect to find a flake of graphite. The conclusion is that the pitting apparently begins in the graphite, so that the occurrence of this element is the governing factor in the beginning of pitting, the hardness of the matrix having little effect.

Possibly the harder metal would resist erosion to a greater extent after the graphite had been washed away, but here again it is apparent that with an interlocking graphite structure as is common, that this erosion might well procede deeper and easily loosen small pieces of metal. It would be interesting to see just what does happen as the erosion goes on. In this respect, tests on white cast iron, where there is no graphitic carbon would prove very interesting. It would be well to remember that such uniform and fine-grained iron as tested would not likely be produced in large castings.

DISCUSSION. On the whole, possibly the most important result of the tests is the production of an apparatus in which the pitting action can be produced at will.

On the whole, it would appear that the existing theories as presented are borne out, although results are too few to be very conclusive. It is apparent, however, that the well-finished, close-grained materials, (bronze test pieces, steel filler plate and profiles), resist the pitting action to a marked degree, although they are battered severely. In this respect, apparently the harder material stands up better. The coarse-grained cast irons are of little value, containing, as they do, graphite, where simple erosion may easily start a fissure to allow the compressed gas bubbles to enter and do their destructive work.

It is to be hoped that this work may be continued so that more conclusive results will be obtained, especially to answer the following questions.

1. How close to the vapor pressure must the pressure in the cavities be reduced before pitting sets in? (This is of extreme importance for the designer of turbines and pumps).

2. What effect has the gas content of the water on the pitting?

3. Further photomicrographic study of pitted metals to see what relation exists between the microstructure and the pitting.

ESTIMATES OF PRESSURE RISE IN CAVITY

DUE TO SUDDEN CONDENSATION OF WATER VAPOR CONTENT

(Translated from "Hydraulische Probleme", Foettinger, p. 21)

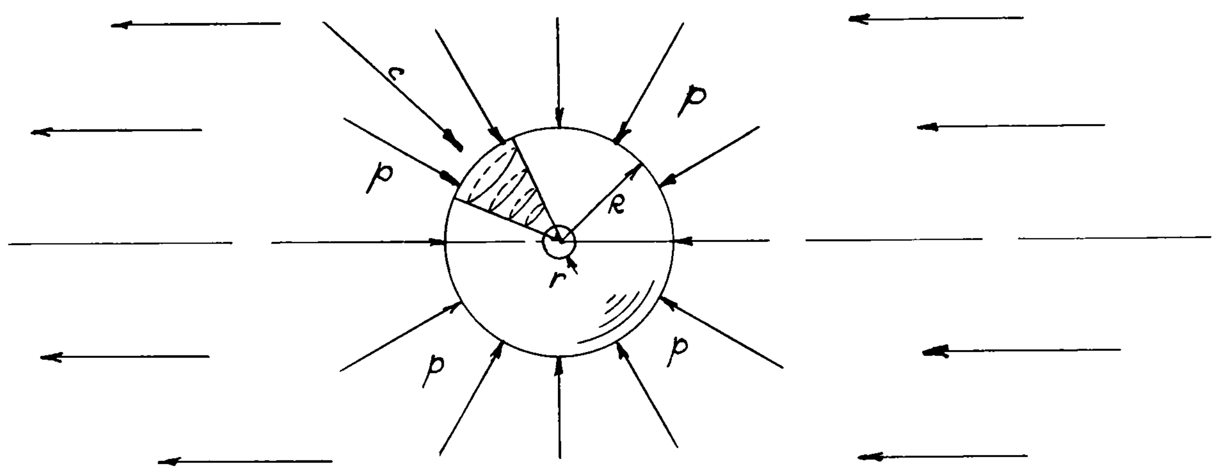


fig. 1

If we take a sphere-shaped vacuum bubble, (fig. 1), in approximately homogeneous flow from the zone of the steam pressure pd into the zone of higher pressure p, work is performed on the vapor content by the diminution of the original volume of the bubble V to the content of the gas residue v, (in this case negligible.) This is given by the equation,

$$(p - pd)(V - v),$$

which is approximately

$$pV = p.\frac{4}{3}\pi R^3$$

This work is first converted into the kinetic energy of the resulting radial velocities "c", and afterwards is converted into the production of impulse-like, exceedingly high compressions of the residue of the gas. The radial velocity of the original radius of the bubble R is

$$c = 0.82\sqrt{\frac{p}{w} \quad g \quad \frac{r}{R}}$$ (w = specified weight of the liquid)

The impact, (the time integral of the pressure, = $\int_0^t pdt$ during the time t), becomes

$$P_t = 0.82\sqrt{p \cdot \frac{w}{g} \ \frac{R^3}{r}},$$

where r is the small radius of the bubble at the beginning of the impact, (collapse respectively causes compression). For the small actual times of impact (t = 1/100 to 1/1000 of a second), we obtain local maximum pressures of thousands of atmospheres. This approximation does not only apply for whole spheres, but also for any spherical sector; for instance, a half-sphere or a cone.......

The huge order of magnitude of the resulting maximum pressure P can also be estimated by disregarding the potential theory, but by equating the work of the external pressure to the work of isothermic compression, whence

$$P = p_d \, e^{\frac{1}{\varepsilon}\left(\frac{p}{p_d} - 1\right)}$$

where εV represents the amount of gas contained in a bubble of initial volume V, (with reference to pd), and p is the above - mentioned external pressure of the bubble.

for example if pd = 0.0237 Atmospheres (water at 20°C)

$$\varepsilon = 0.25$$

$P/pd = 3.5$

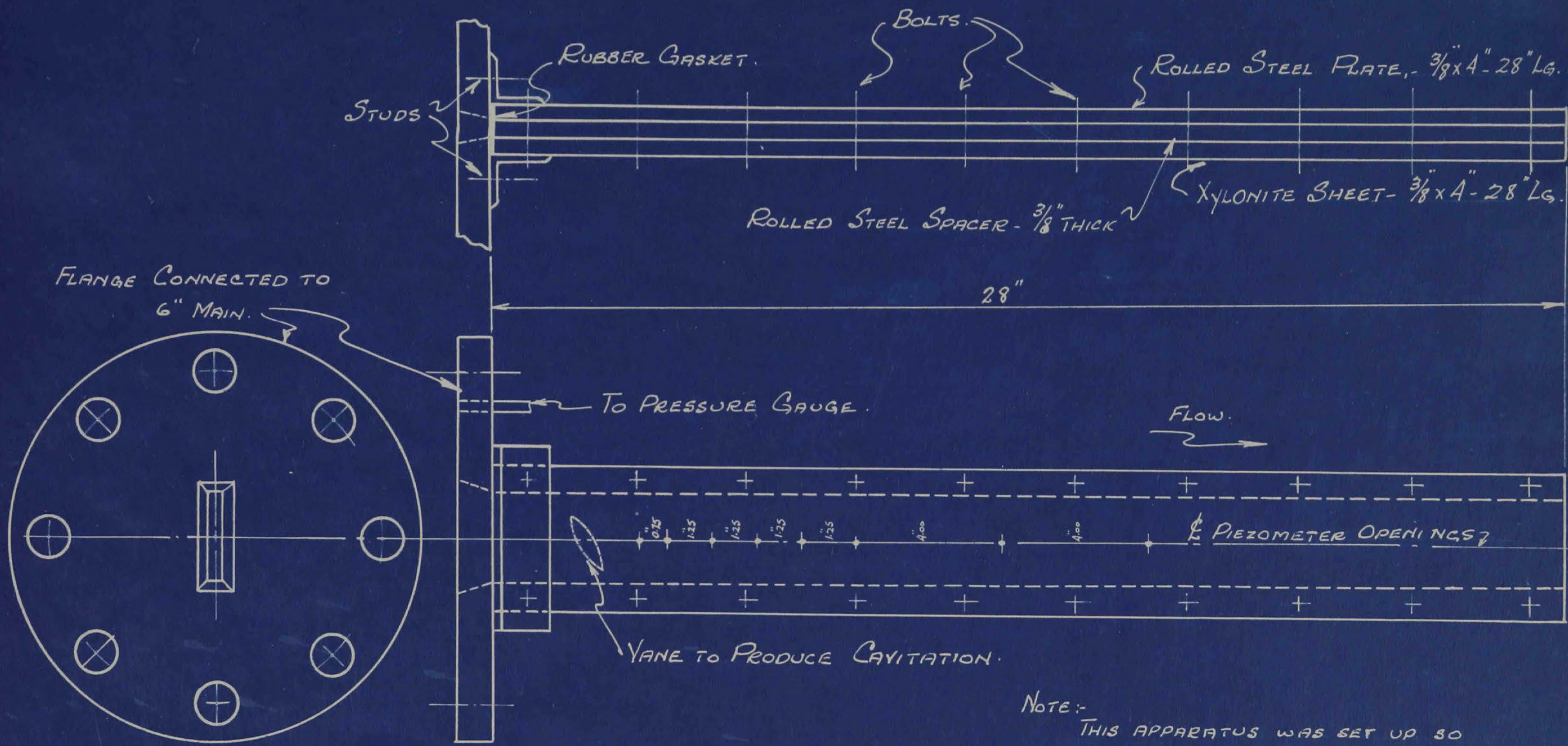
$p = 0.083$ atmospheres,

a pressure of $P = 22{,}000\ pd = 520$ atmospheres results ....
This equation applies under the assumption that besides the compression itself there is also the work $P \delta V$, that is, that therefore the walls of the pores which enclose the compressed bubble have to give way to an explosive action. If this is not the case, - that is, if only compression takes place, we get e - times the maximum pressure,

$$P' = eP \qquad (e = 2.7......)$$

This gives P' approximately equal to 1400 atmospheres...........

Unfortunately a more accurate estimate is exceedingly difficult, as we have not only to consider the elasticity of the fluid and of the solid wall, (its plasticity), but also the conduction of heat of the fluid and the walls and of the residual gas, especially the temperature jump at the boundary between different media.



NOTE:- THIS APPARATUS WAS SET UP SO THAT THE FLOW WAS VERTICALLY DOWNWARDS INTO THE MEASURING TANKS.

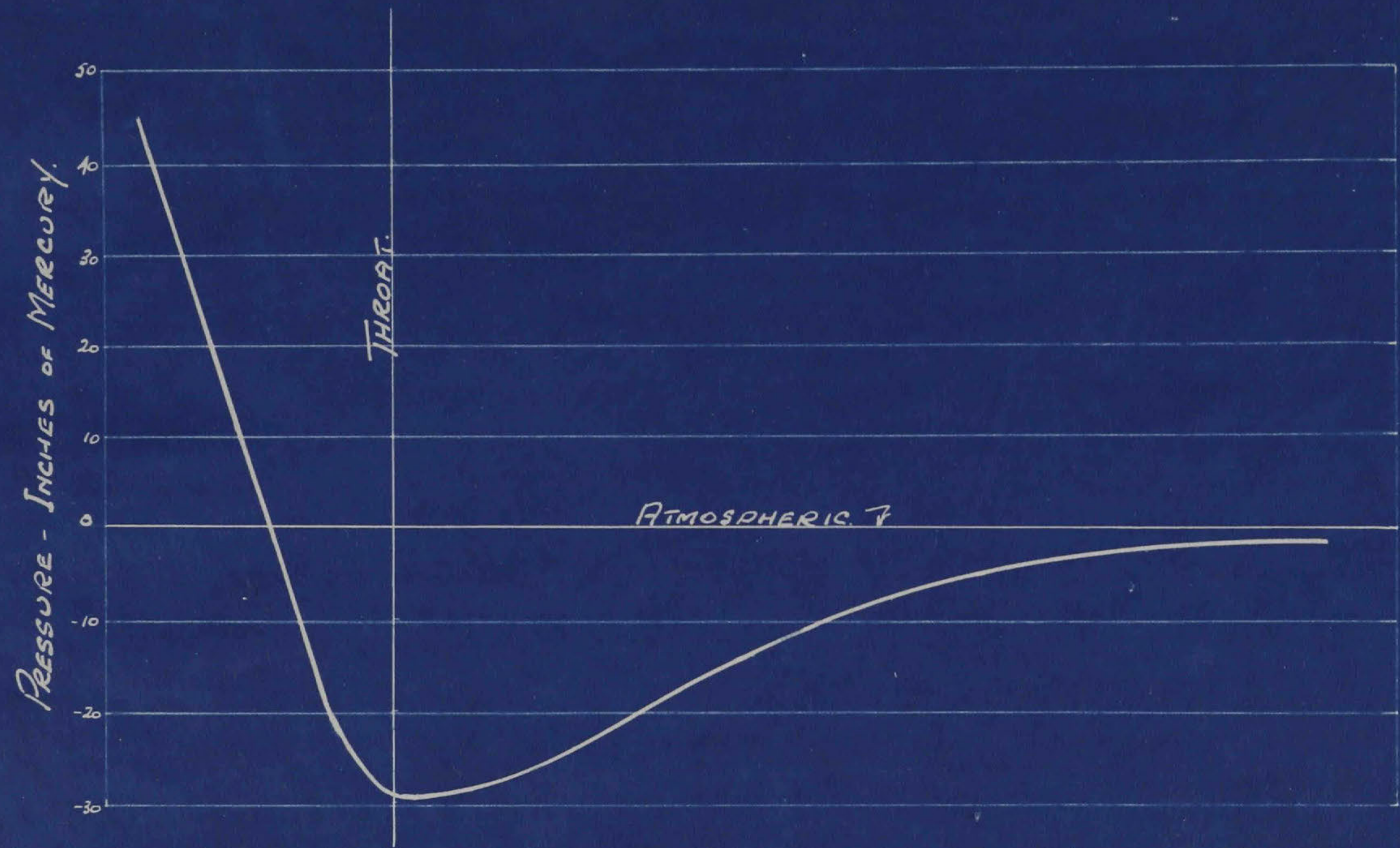
SKETCH OF ORIGINAL APPARATUS.

SCALE:- 1/4" = 1"

(SEE ALSO FIG. 4)

FIG. 2.

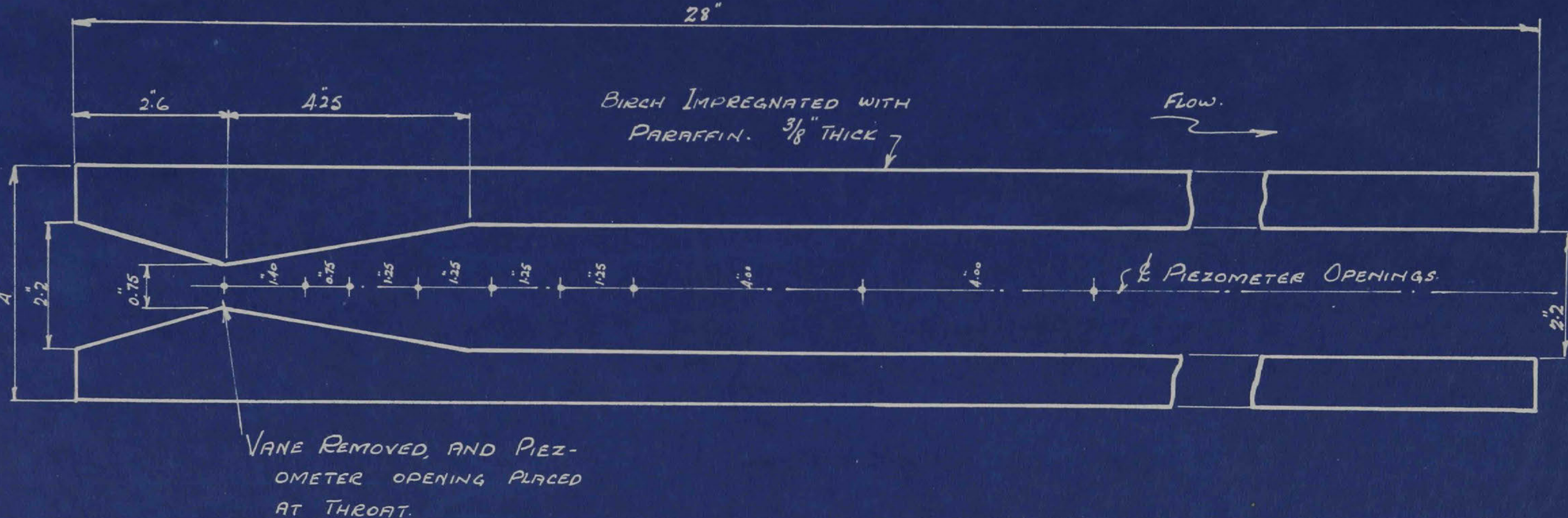
FIG. 2.



FORM OF PRESSURE DISTRIBUTION CURVES FOR
APPARATUS SHOWN IN FIGS. 2 & 4

FIG. 3. P.S.

FIG. 3. P.S.



SKETCH OF PROFILES USED IN APPARATUS IN FIG. IN PLACE OF VANE.

SCALE 3/8" = 1"

SEE ALSO FIG. 2.

FIG. 4.

P.S.

FIG. 4.

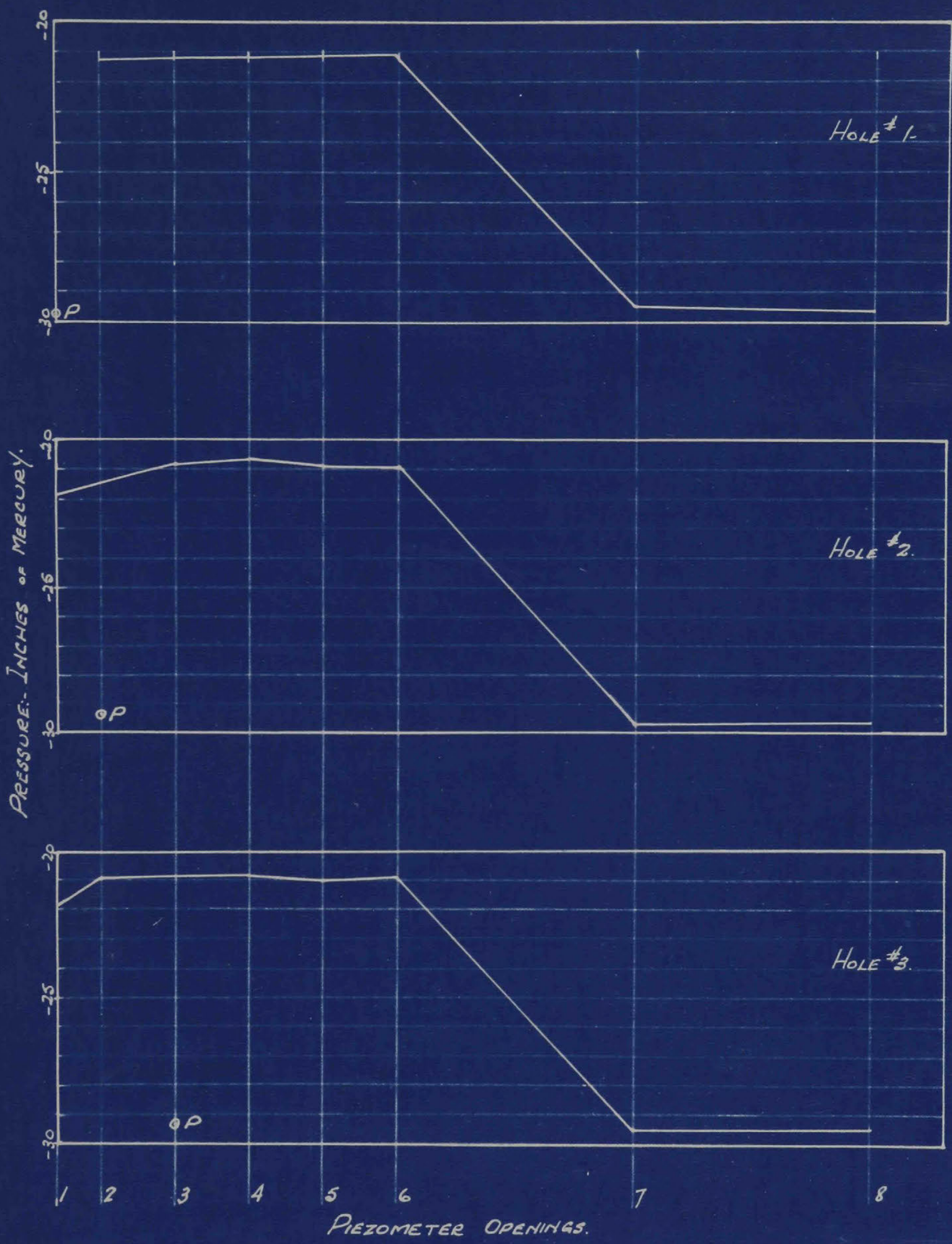


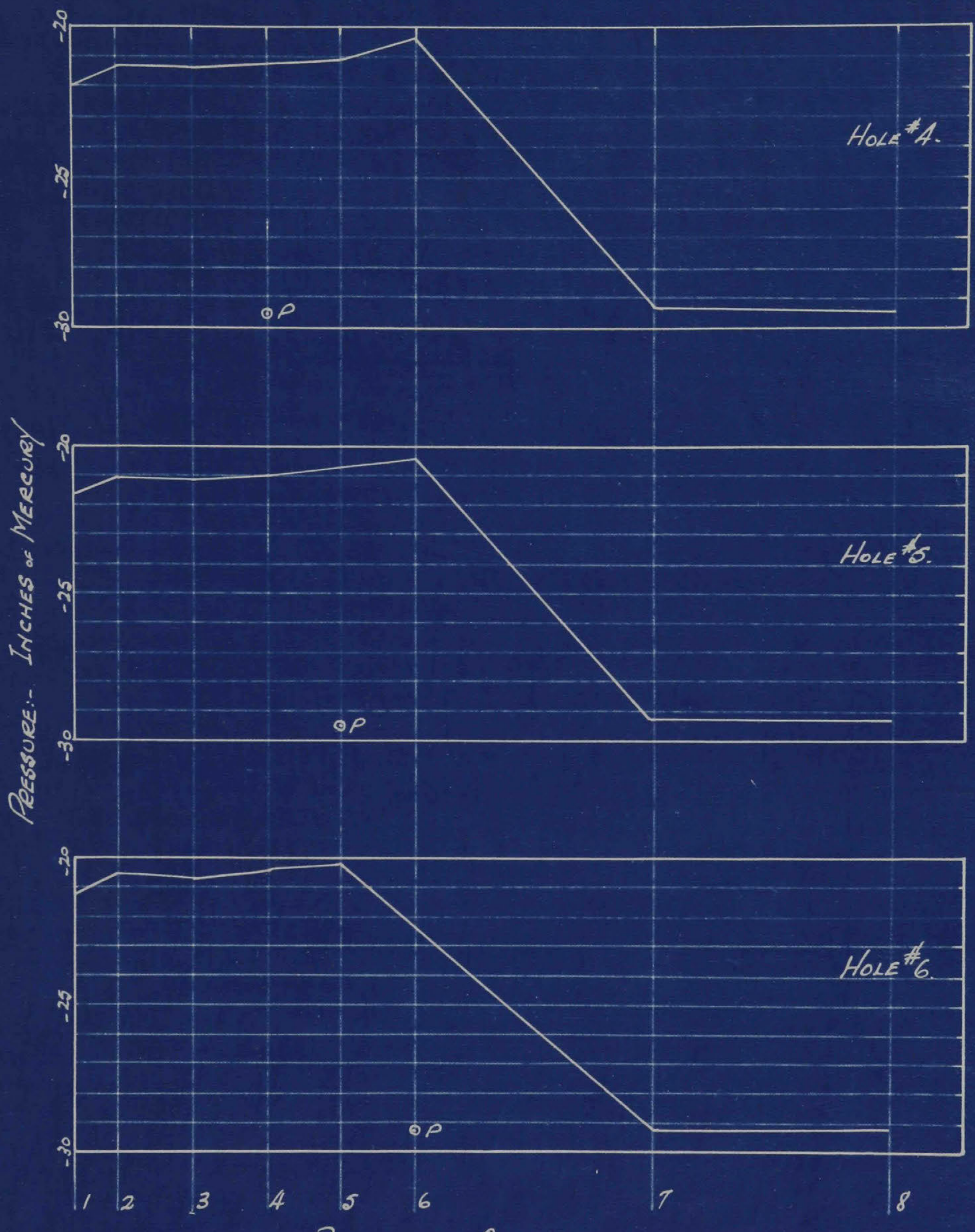
Fig. 5. P.S.

See Also Figs. 6 & 7.

See Notes - Fig. 7.

Fig. 5. P.S.

FIG. 6 P.S.



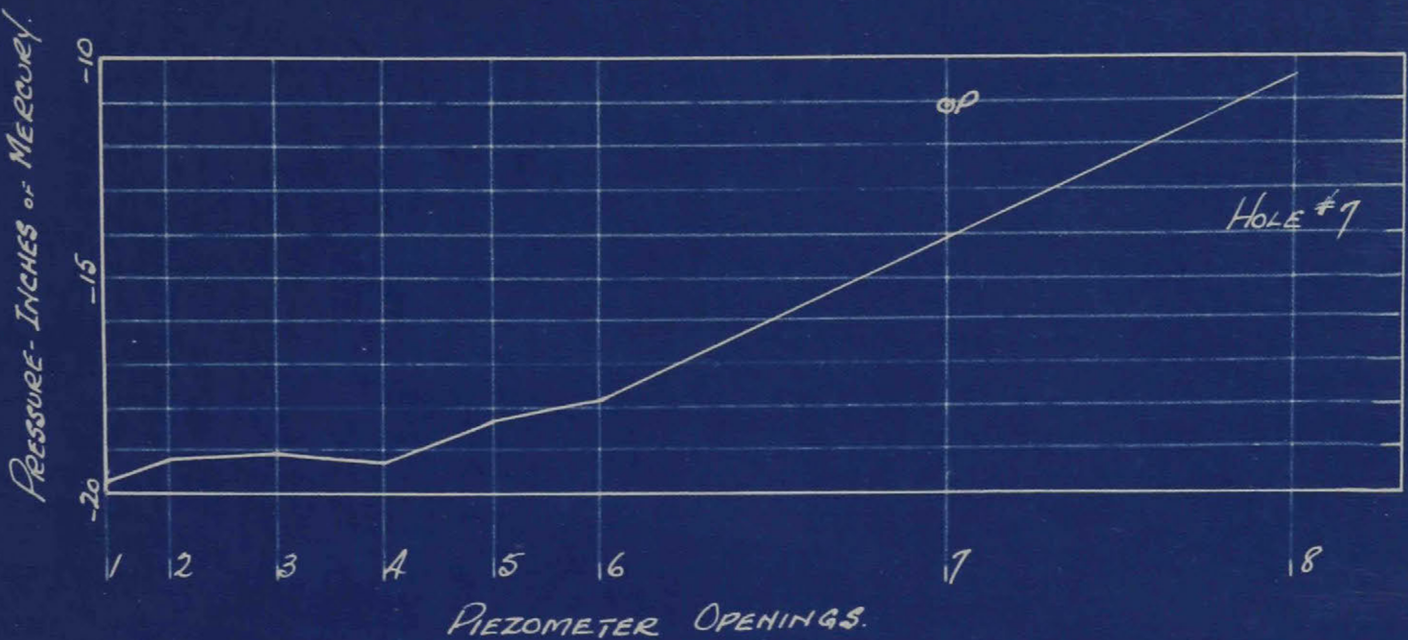
See Also Figs. 5 & 7.

See Notes - Fig. 7.

Fig. 6.

P.S.

FIG. 7. P.S.



NOTE:- THE CURVES SHOWN IN FIGS. 5, 6, AND 7 ARE THE PRESSURE READINGS AT THE PIEZOMETER OPENING NOTED AT THE RIGHT HAND SIDE OF THE CURVE, WHEN AIR IS ADMITTED SUCCESSIVELY AT HOLES 1 TO 8. "P" IS THE PRESSURE AT THAT PARTICULAR POINT WITH ALL HOLES CLOSED.

E.G. - IN THE ABOVE CURVE, THE PRESSURE AT POINT 7, ALL HOLES CLOSED IS -11.15 INCHES OF MERCURY. IF AIR IS ADMITTED AT 1, THIS BECOMES -19.75" AT 2, -19.23" AND SO ON.

APPARATUS IN FIG. 4 BEHAVED IDENTICALLY, BUT MAGNITUDE OF CHANGES WAS SLIGHTLY DIFFERENT.

FIGS. 5, 6, & 7. - BEHAVIOUR OF PRESSURE DISTRIBUTION IN APPARATUS SHOWN IN FIG. 2, ON ADMISSION OF AIR AT DIFFERENT POINTS IN THE STREAM FLOW.

SEE ALSO FIGS. 5 & 6.

FIG. 7.

P.S.

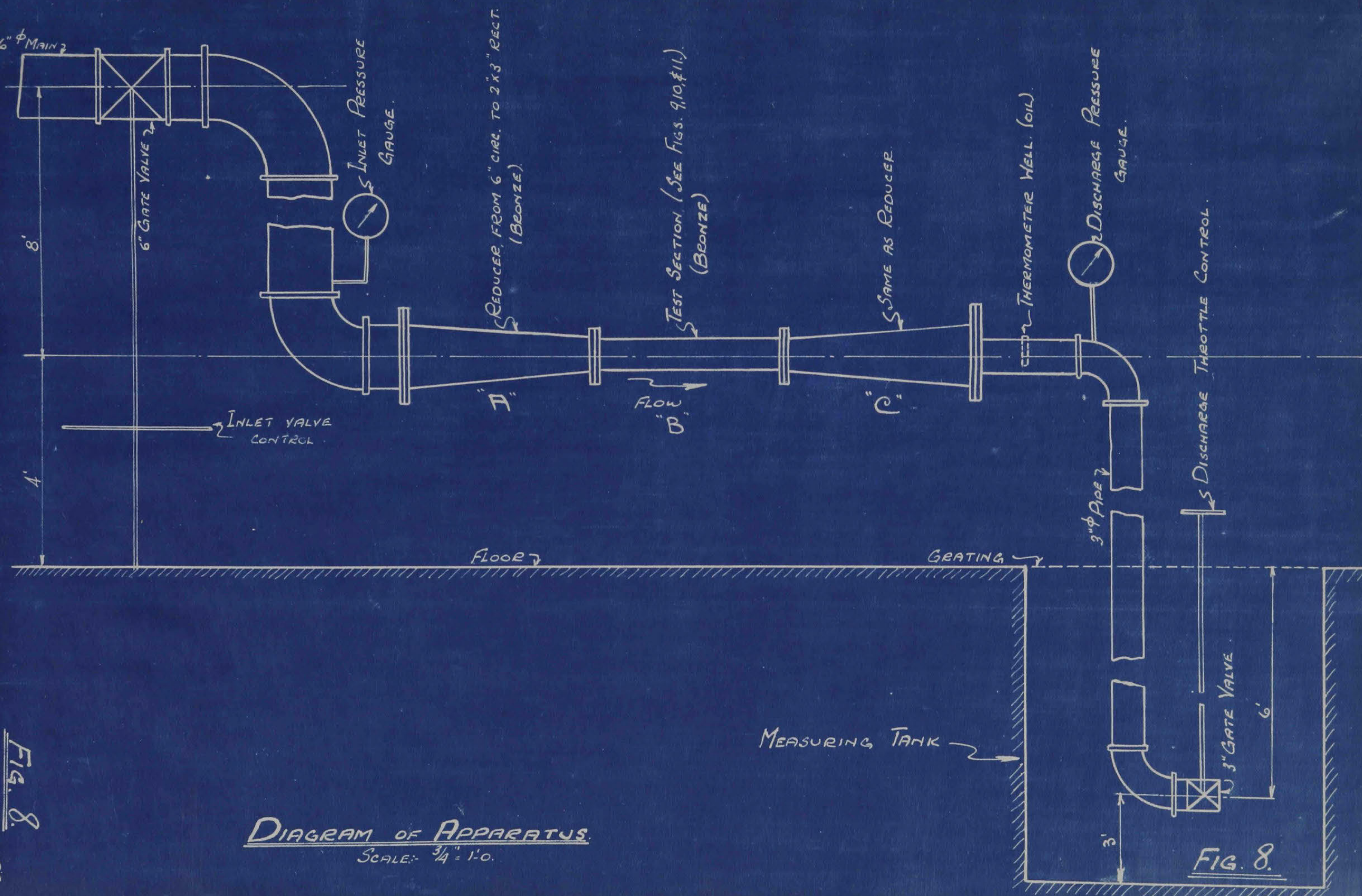
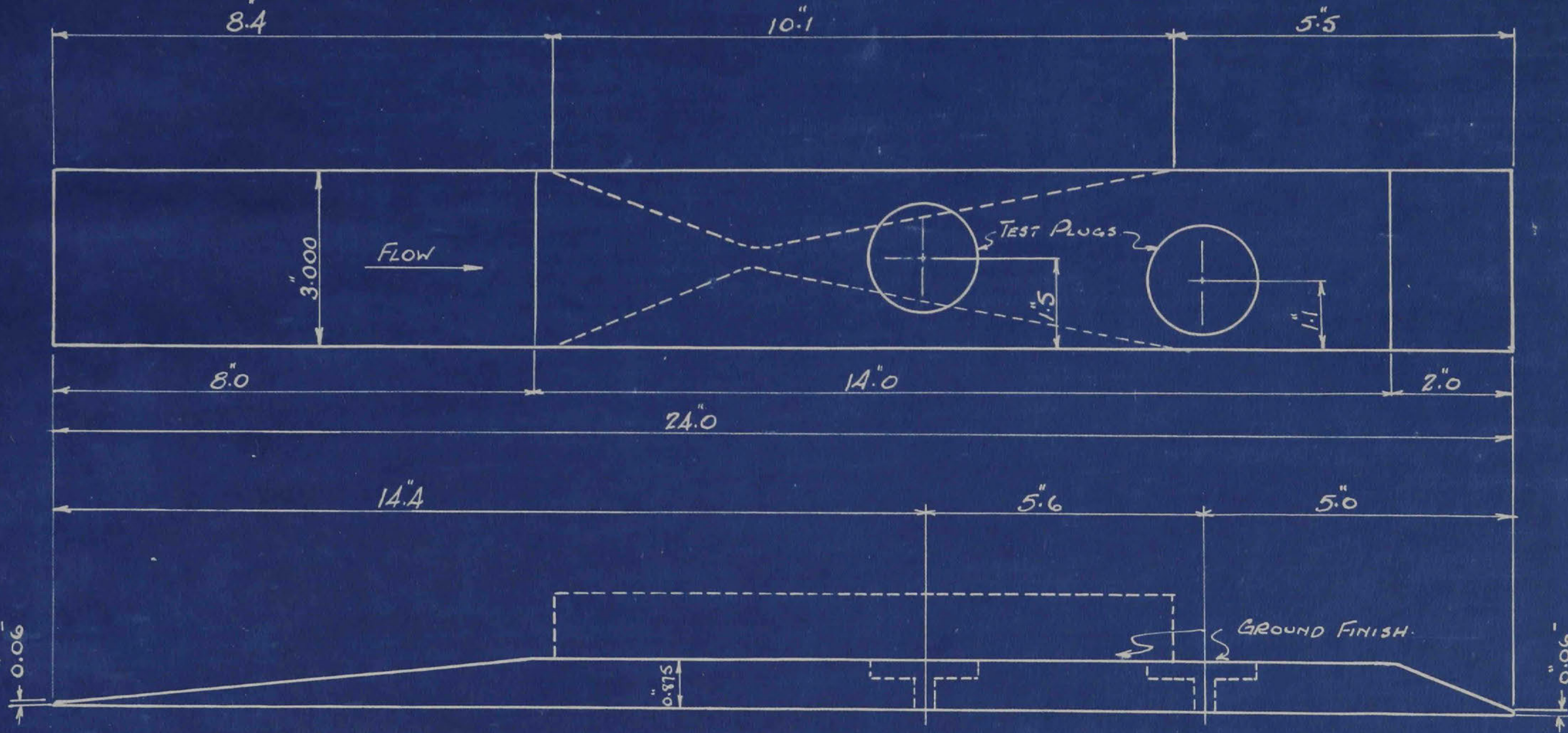


Diagram of Apparatus
Scale:- 3/4" = 1'-0.

Fig. 8.

P.S.



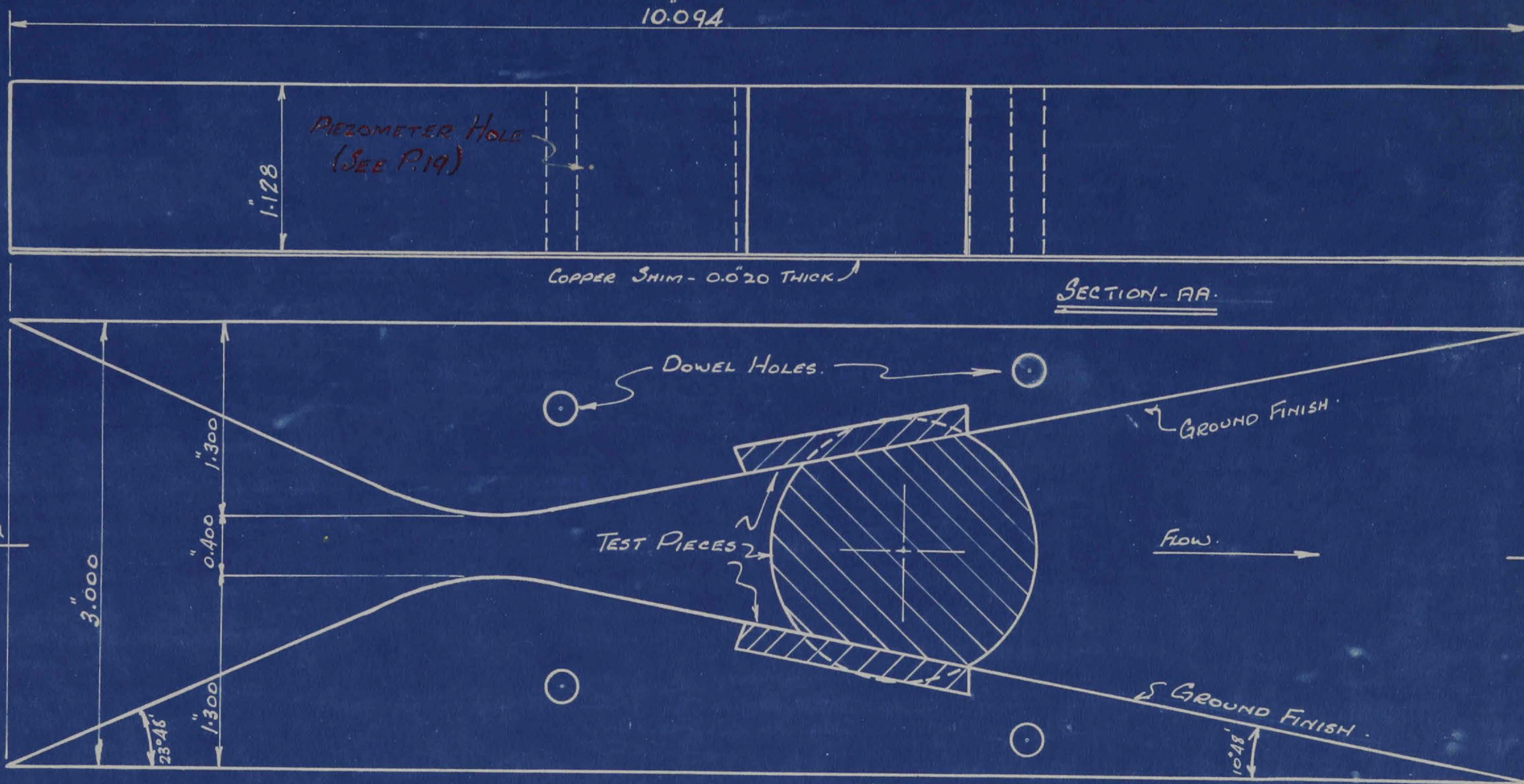
ROLLED STEEL PLATE.

DETAIL OF PLATE TO REDUCE WATERWAY, SHOWING LOCATION OF TEST PLUGS.

SCALE:- 3/8" = 1"

FIG. 9.

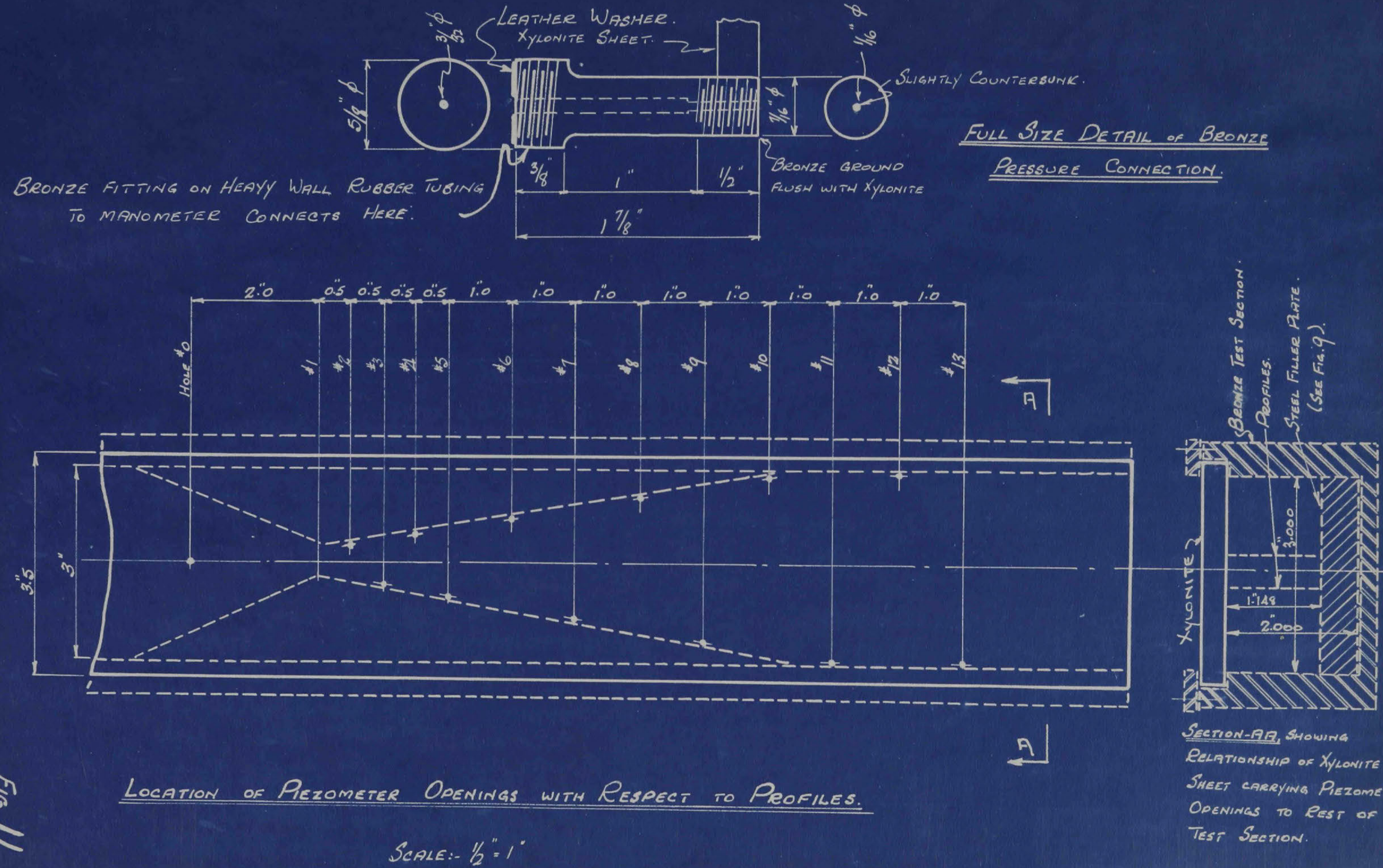
FIG. 9.



Full Size Detail of Stainless Steel Profiles.

Fig. 10.

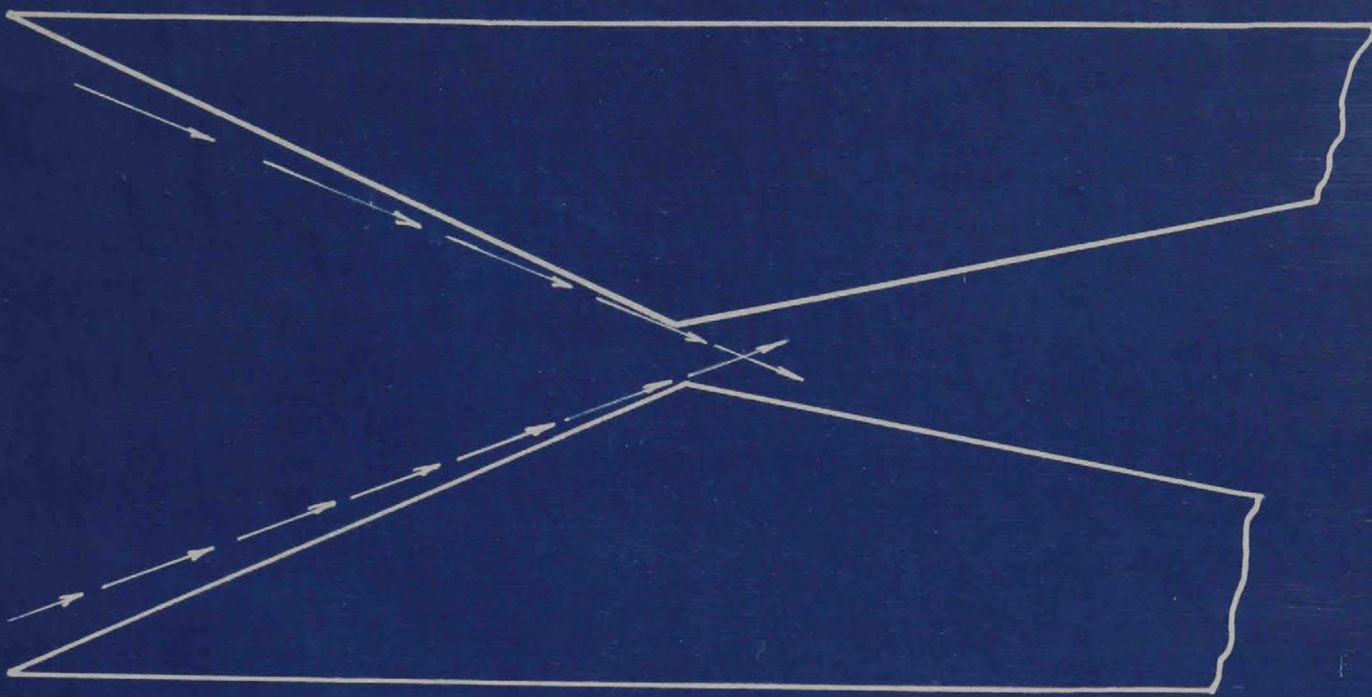
Fig. 10. P.S.



LEATHER WASHER.
XYLONITE SHEET.
3/32" ϕ
5/8" ϕ
1/16" ϕ
1/16" ϕ
SLIGHTLY COUNTERSUNK.
3/8"
1"
1/2"
1 7/8"
BRONZE FITTING ON HEAVY WALL RUBBER TUBING TO MANOMETER CONNECTS HERE.
BRONZE GROUND FLUSH WITH XYLONITE
FULL SIZE DETAIL OF BRONZE PRESSURE CONNECTION.
2.0"
0.5"
0.5"
0.5"
0.5"
1.0"
1.0"
1.0"
1.0"
1.0"
1.0"
1.0"
1.0"
HOLE #0
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
#13
A
A
3.5"
3"
BRONZE TEST SECTION.
PROFILES.
STEEL FILLER PLATE (SEE FIG. 9).
XYLONITE
3.000"
1.149"
2.000"
LOCATION OF PIEZOMETER OPENINGS WITH RESPECT TO PROFILES.
SCALE:- 1/2" = 1"
SECTION-AA, SHOWING RELATIONSHIP OF XYLONITE SHEET CARRYING PIEZOMETER OPENINGS TO REST OF TEST SECTION.

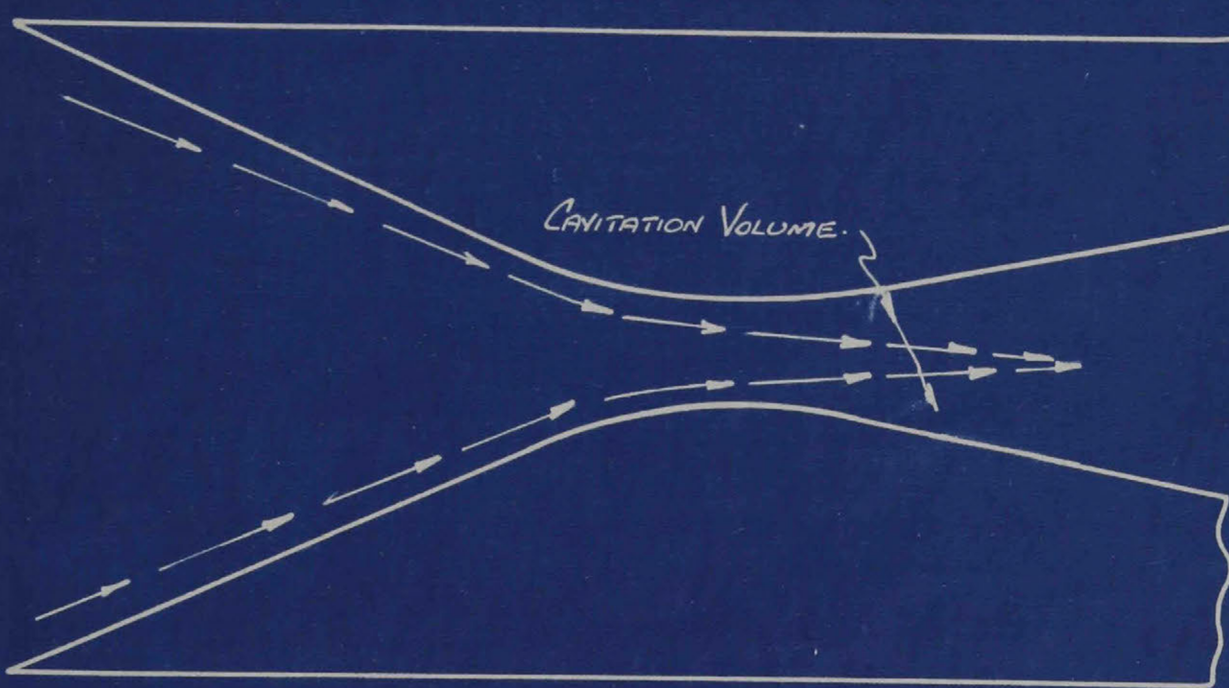
FIG. 11.

R.S.



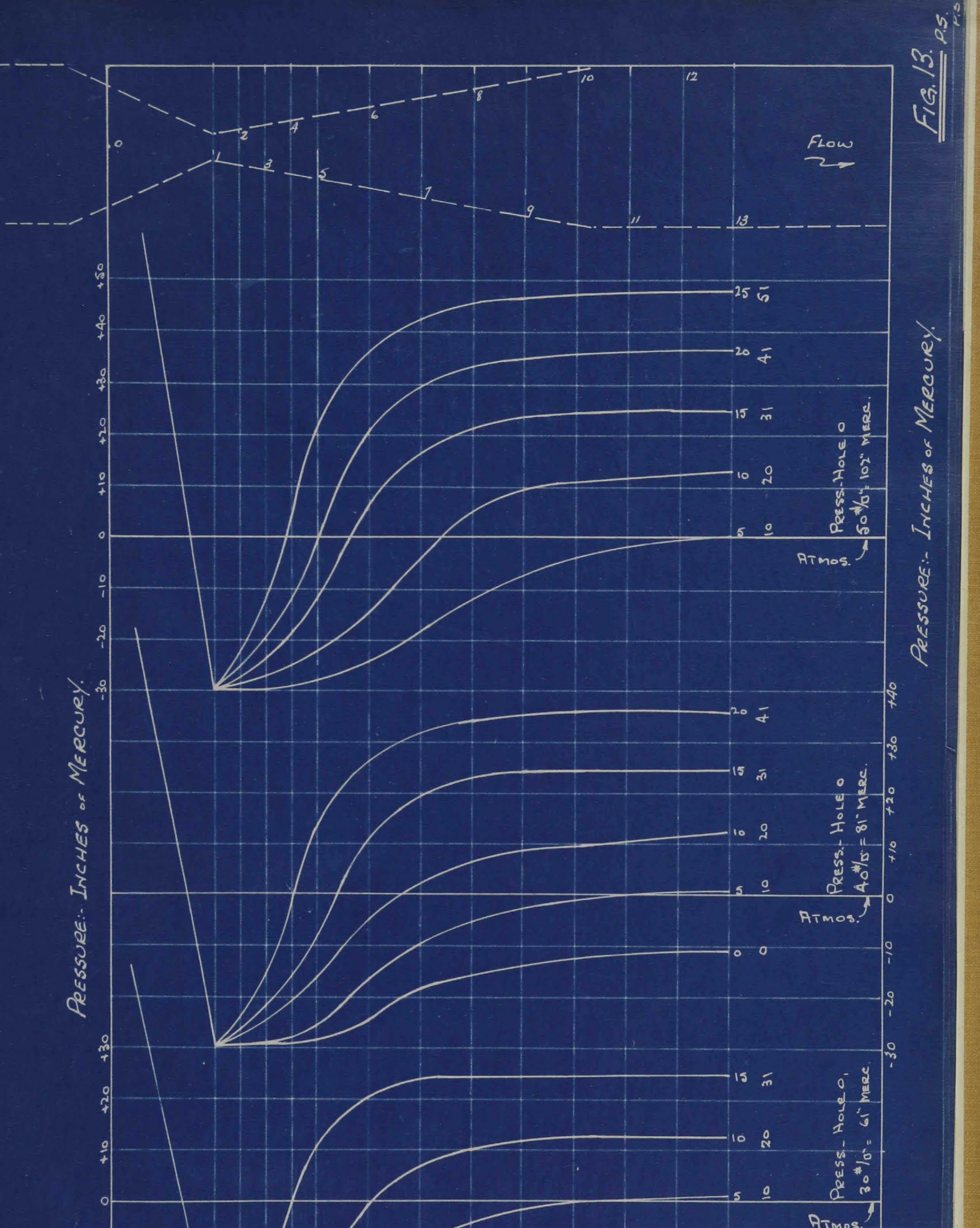
Interference of Stream Lines at Throat Due to Sharp Angle of Convergence.

Fig. 12A.



Correction of Above by Decreasing Angle and Rounding Throat.

Fig. 12B.



PRESSURE DISTRIBUTION CURVES. APPARATUS FIG. .   FIG. 13.

P.S.

FIG. 1A.

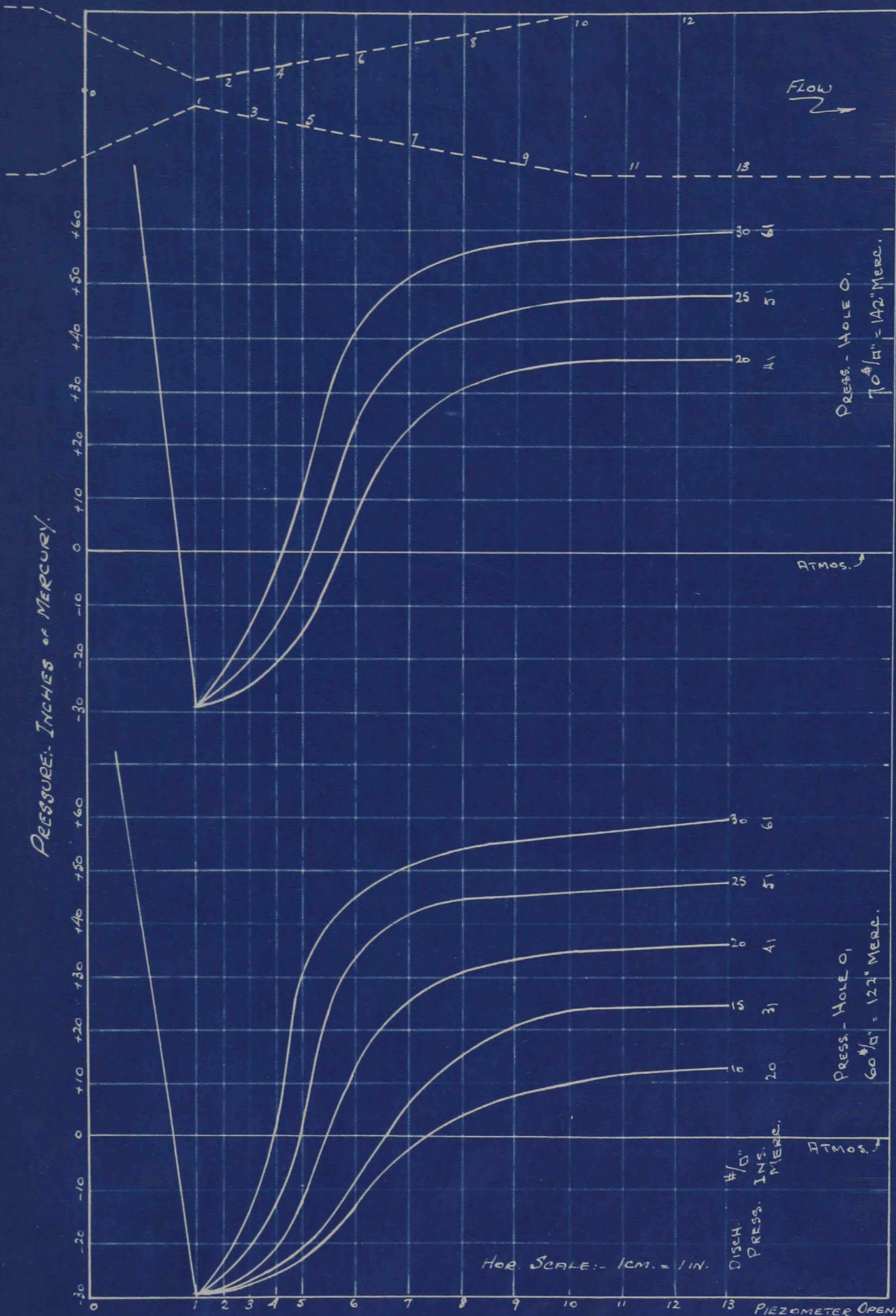

FLOW
PRESSURE:- INCHES OF MERCURY.
PRESS. - HOLE 0, 70#/□" = 142" MERC.
PRESS. - HOLE 0, 60#/□" = 122" MERC.
ATMOS.
ATMOS.
DISCH. PRESS. #/□" INS. MERC.
HOR. SCALE:- 1CM. = 1IN.
PIEZOMETER OPENINGS.

FIG. 1A.

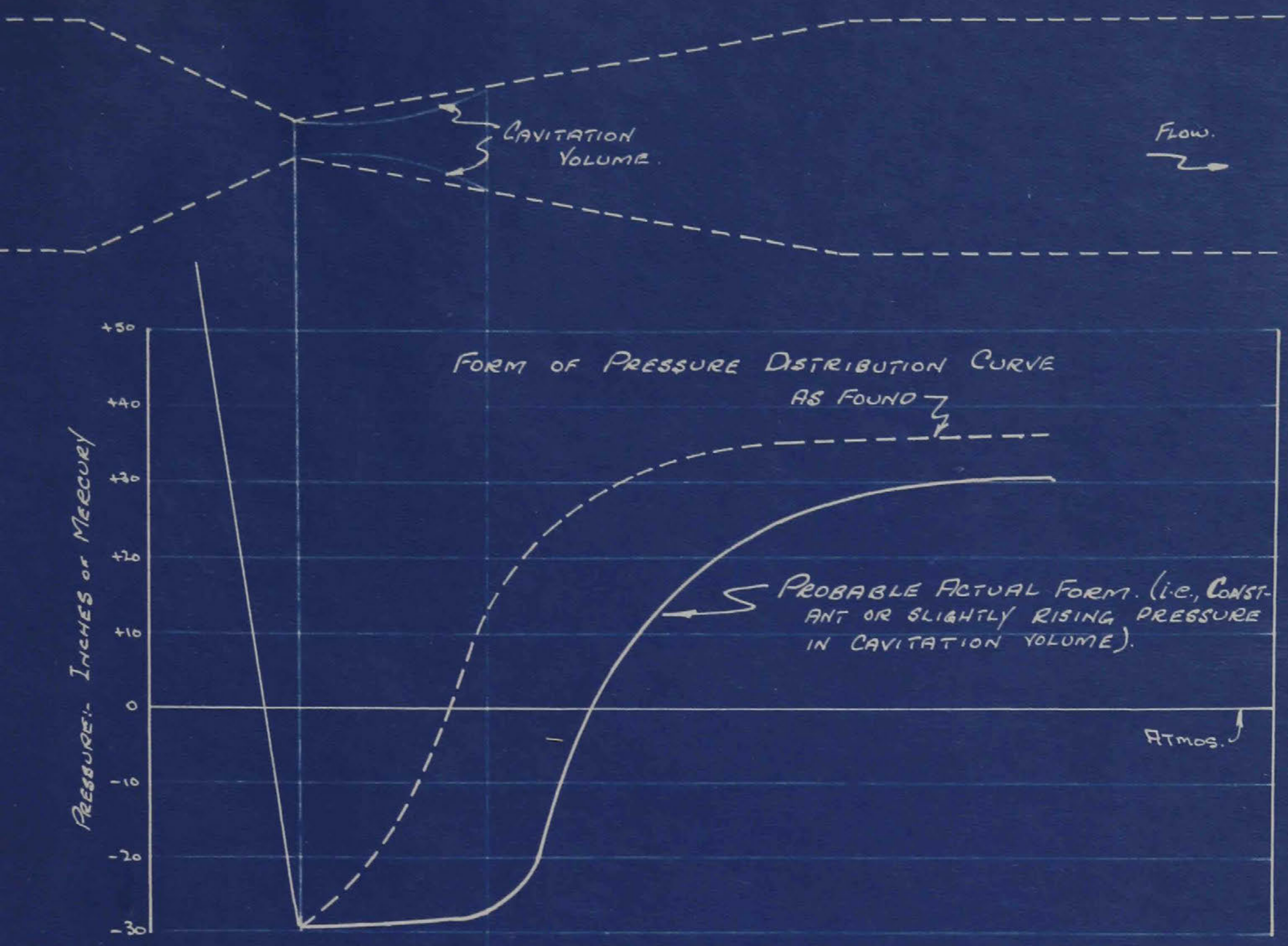
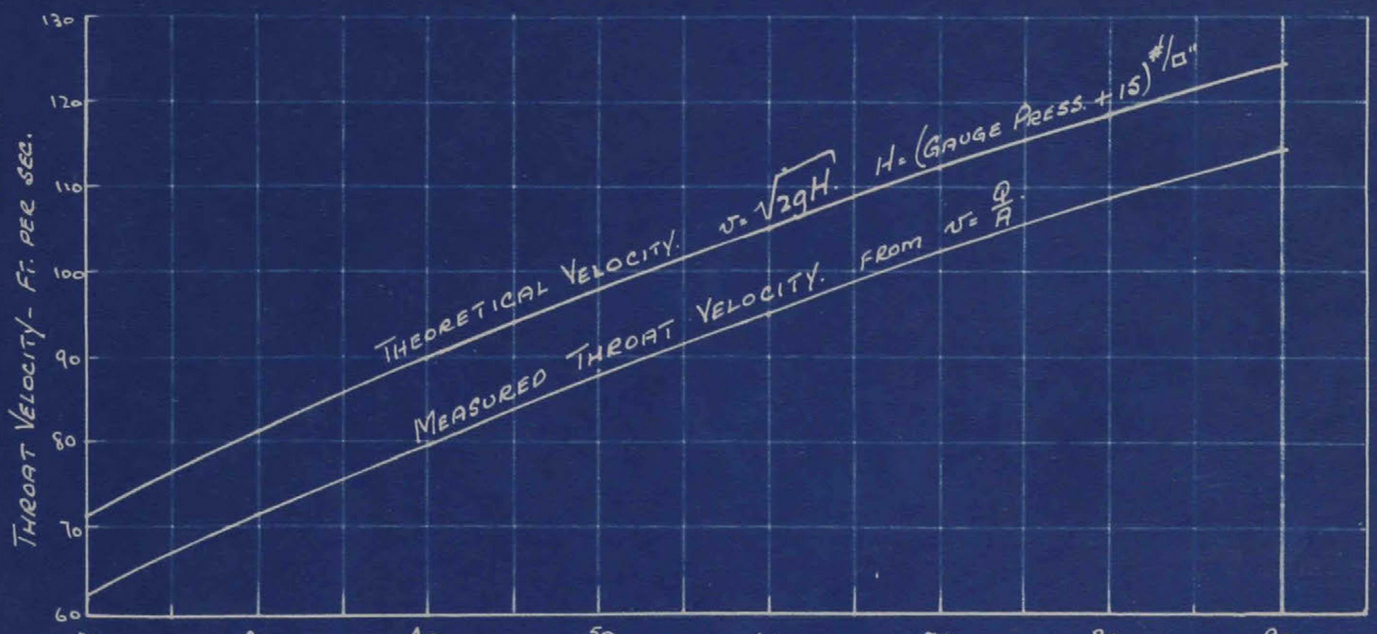


FIG. 15.



VELOCITIES OF FLOW AT THROAT, - THEORETICAL & ACTUAL.

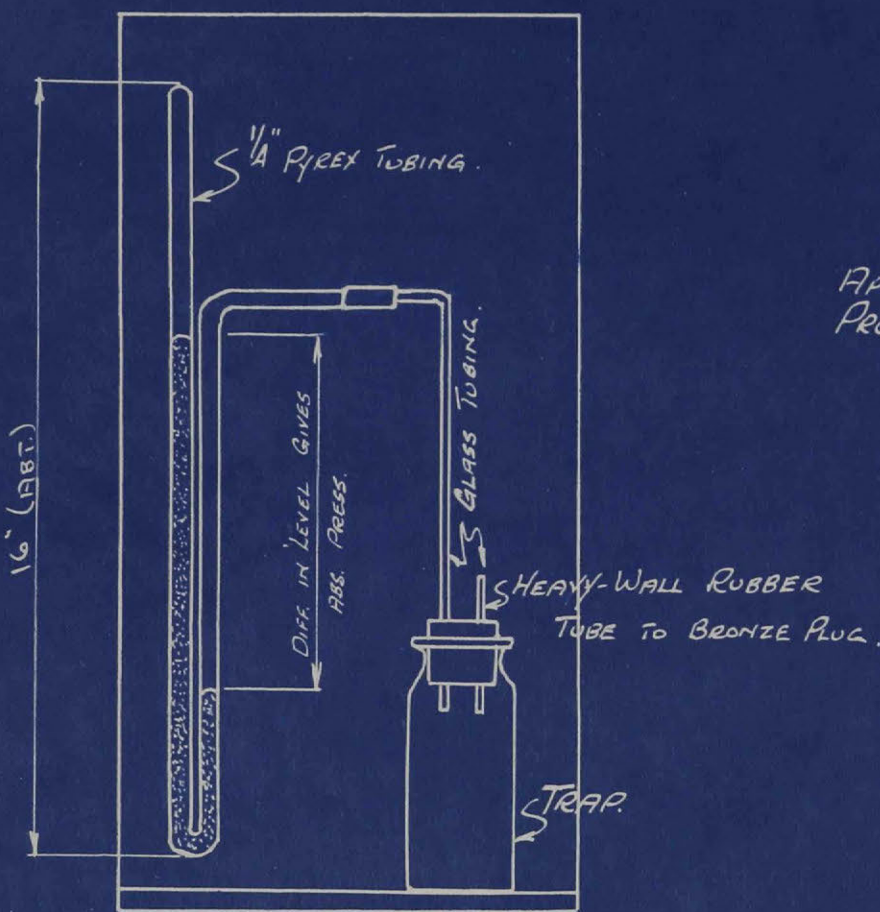
FIG. 17.

FIGS. 15 & 17.

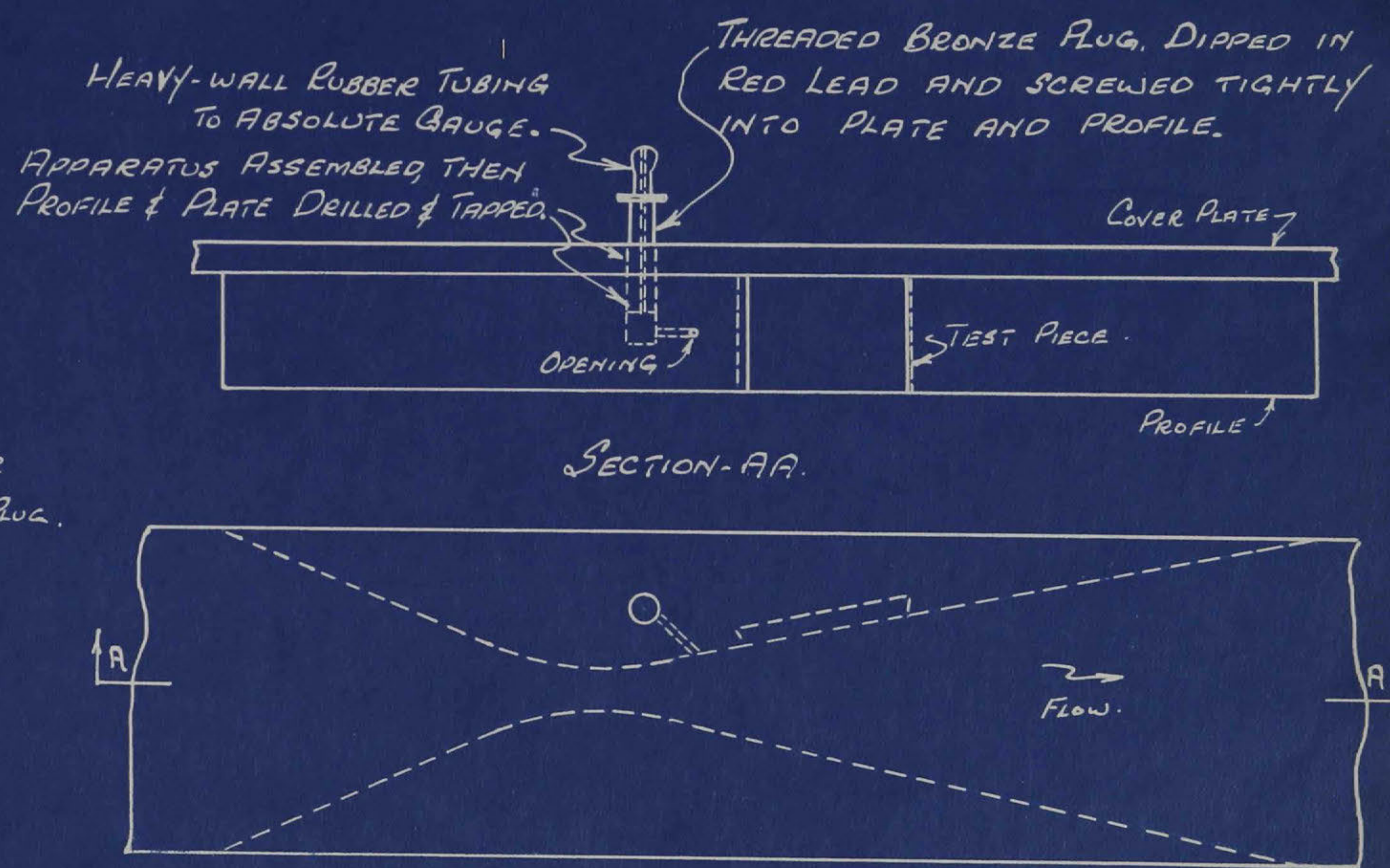
FIG. 16 ON NEXT PAGE.

FIGS. 15 & 17.
FIG. 16 ON NEXT PAGE.

P.S.



Absolute Gauge.



Scale:- 1/2" = 1"

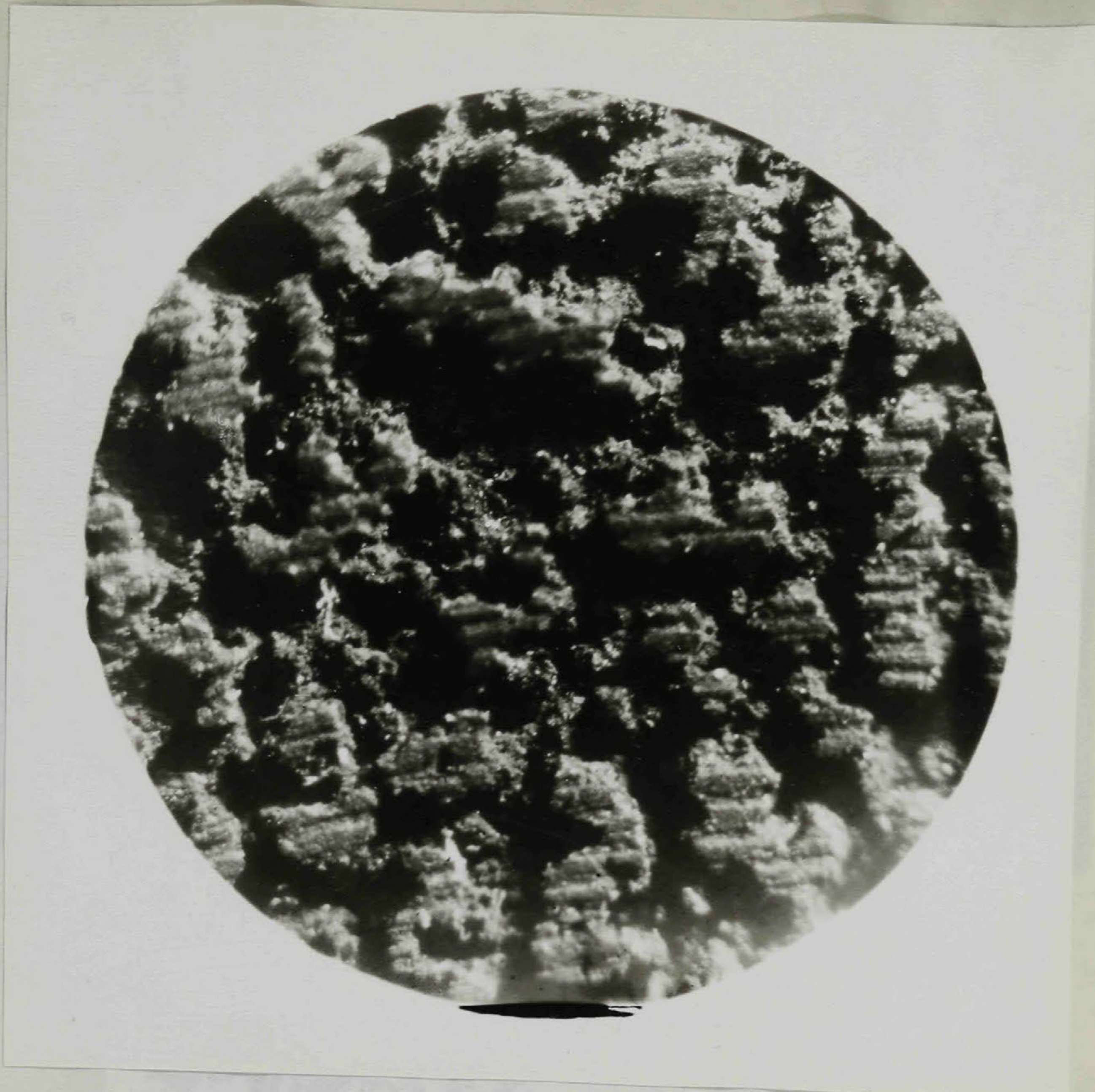
Fig. 16.

P.S.

Fig. 16.

P.S.

FIG. 18.



CAST IRON - #A.C.I.

MAGNIFICATION:- 28 DIAMETERS.
EXPOSURE:- 95 HRS.
COMPOSITION:- C.- 2.79 %
Mn.- 0.855%
P.- 0.163%
S.- 0.131 %
Si.- 2.15 %

HARDNESS:- BRINELL - 241
ROCKWELL - C-23

SEE ALSO FIGS. 19 & 20.

FIG. 18.

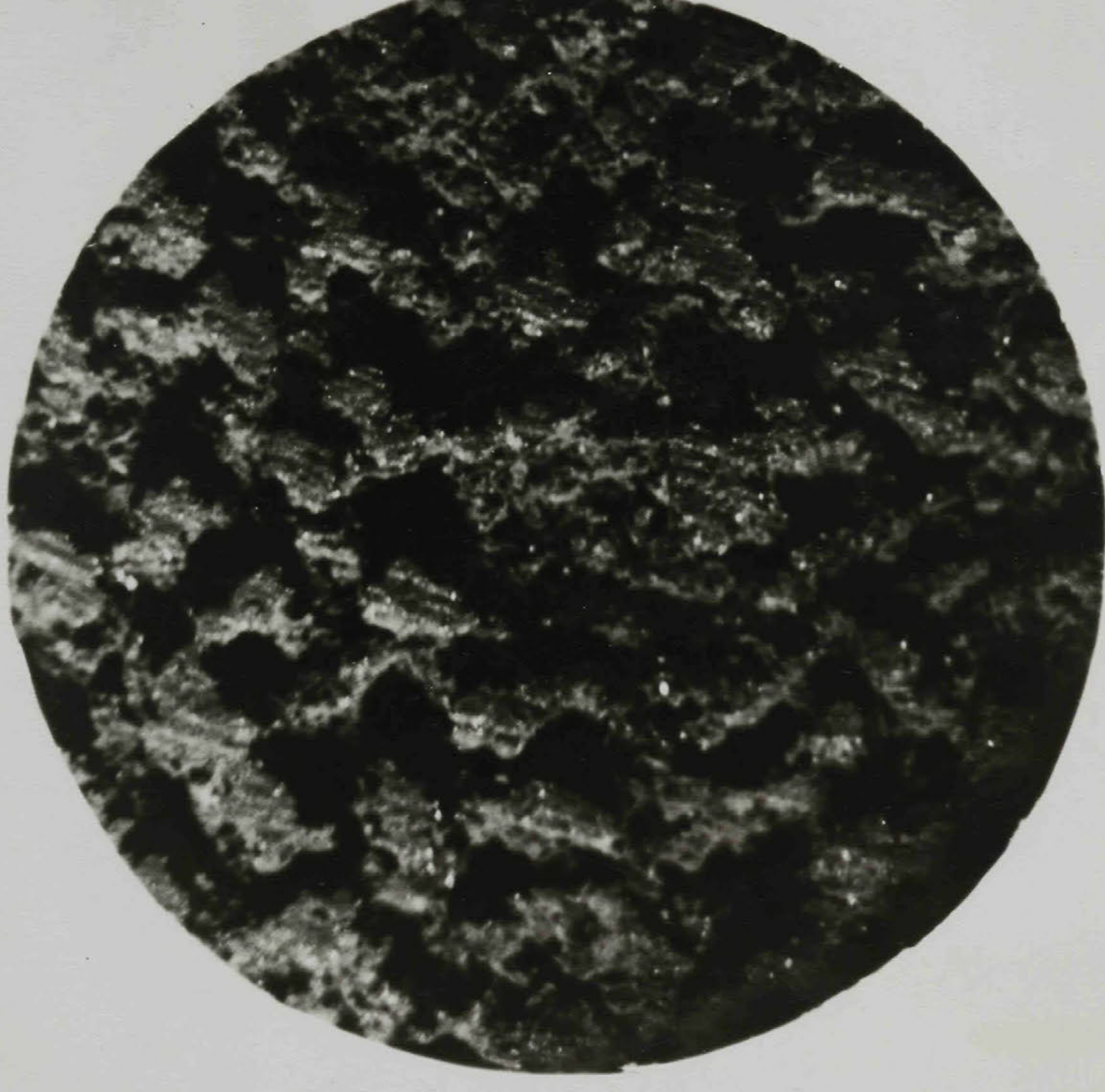
Fig. 20. - Etched. - x1000.

Fig. 19. - Plain Polished. - x100.

Cast Iron - #ACI.

See Fig. 18.

FIG. 21.



CAST IRON- #4C.I.H.T.

MAGNIFICATION:- 28 DIAMETERS.
EXPOSURE:- 72 HRS.
COMPOSITION:- C.- 2.79 %
Mn.- 0.855 %
P.- 0.163 %
S.- 0.131 %
Si.- 2.15 %

HEAT TREATMENT:- HEATED TO 1600°F. - 1 HR.- QUENCHED IN OIL,- DRAWN AT 900°F.- 2 HRS.

HARDNESS:- BRINELL, - 302
ROCKWELL-C. - 34.

SEE ALSO FIGS. 22 & 23.

FIG. 21.

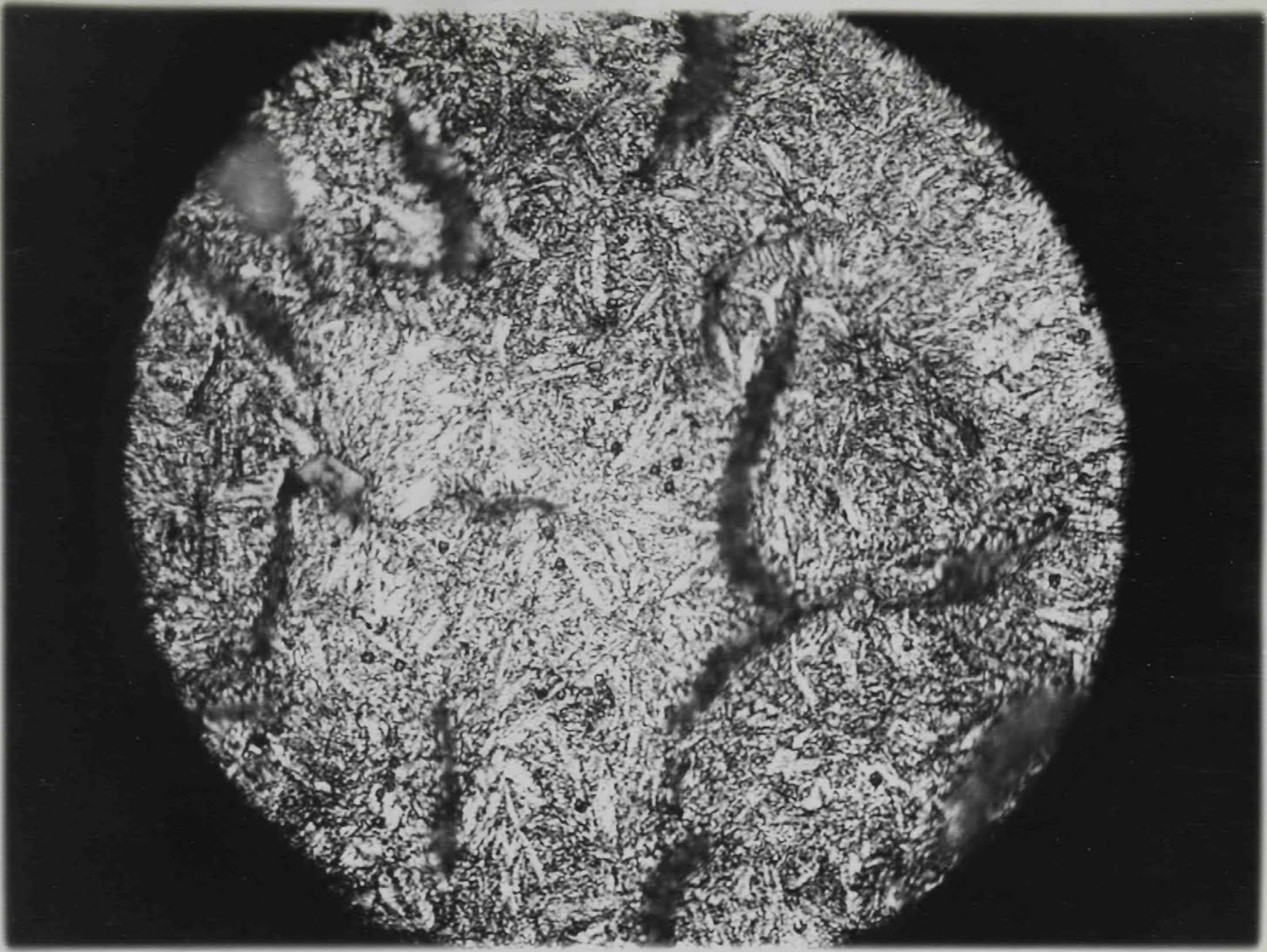


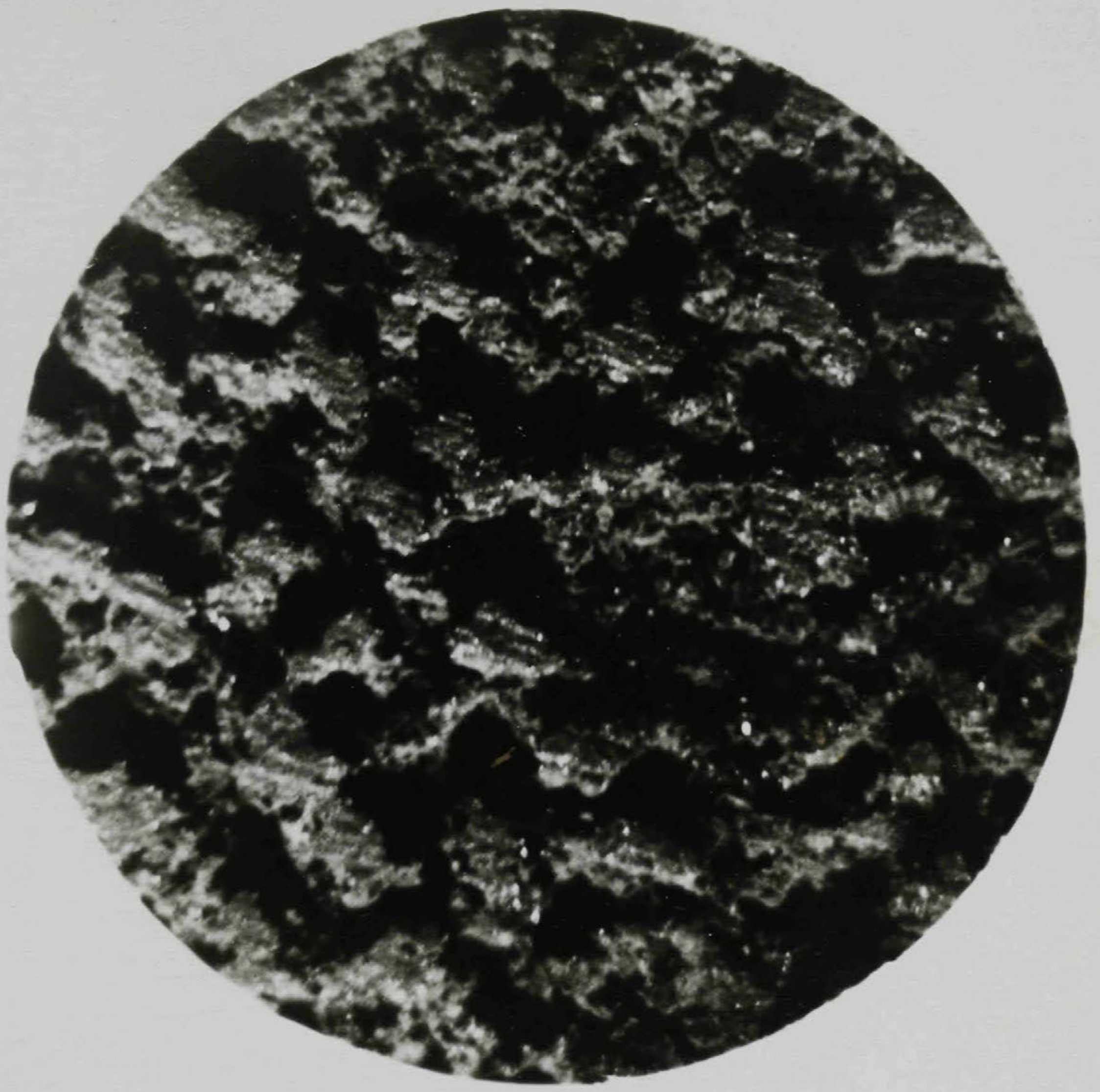
FIG. 23.- ETCHED.- X1000.

FIG. 22.- PLAIN POLISHED.- X100.

CAST IRON.- #AC.I.H.T.

SEE FIG. 21.

FIG. 24.



CAST IRON - #5 M.O.

MAGNIFICATION:- 28 DIAMETERS.
EXPOSURE:- 95 HRS.
COMPOSITION:- C. - 2.76 %
Mn. - 0.975 %
P. - 0.083 %
S. - 0.105 %
Si. - 1.75 %
Mo. - 0.74 %

HARDNESS:- BRINELL - 241
ROCKWELL - C. - 25.

SEE ALSO FIGS. 25 & 26.

FIG. 24.

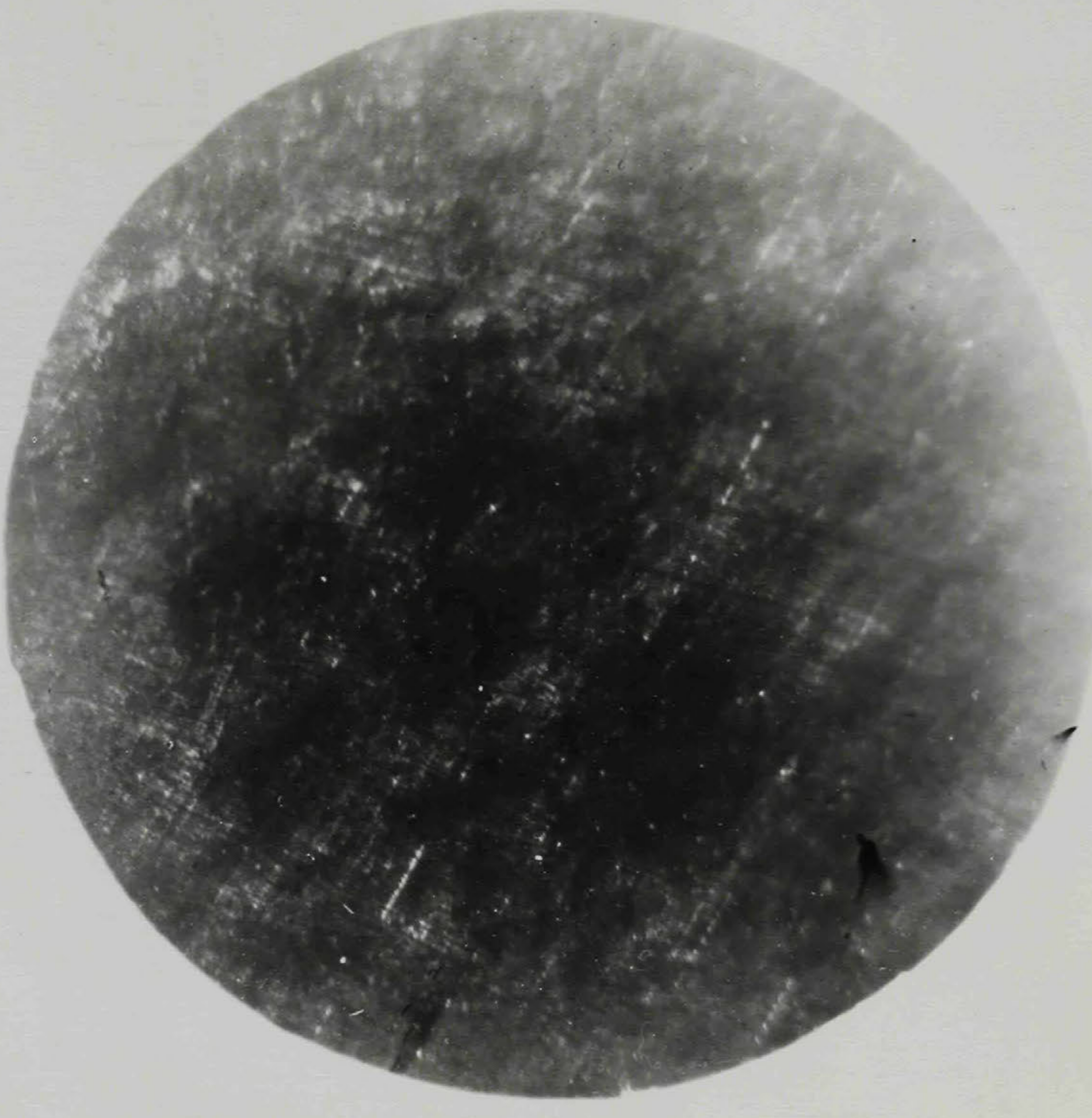
FIG. 26.- ETCHED.- X1000.

FIG. 25.- PLAIN POLISHED.- X100

CAST IRON.- #5 M.O.

SEE FIG. 24.

FIG. 27.

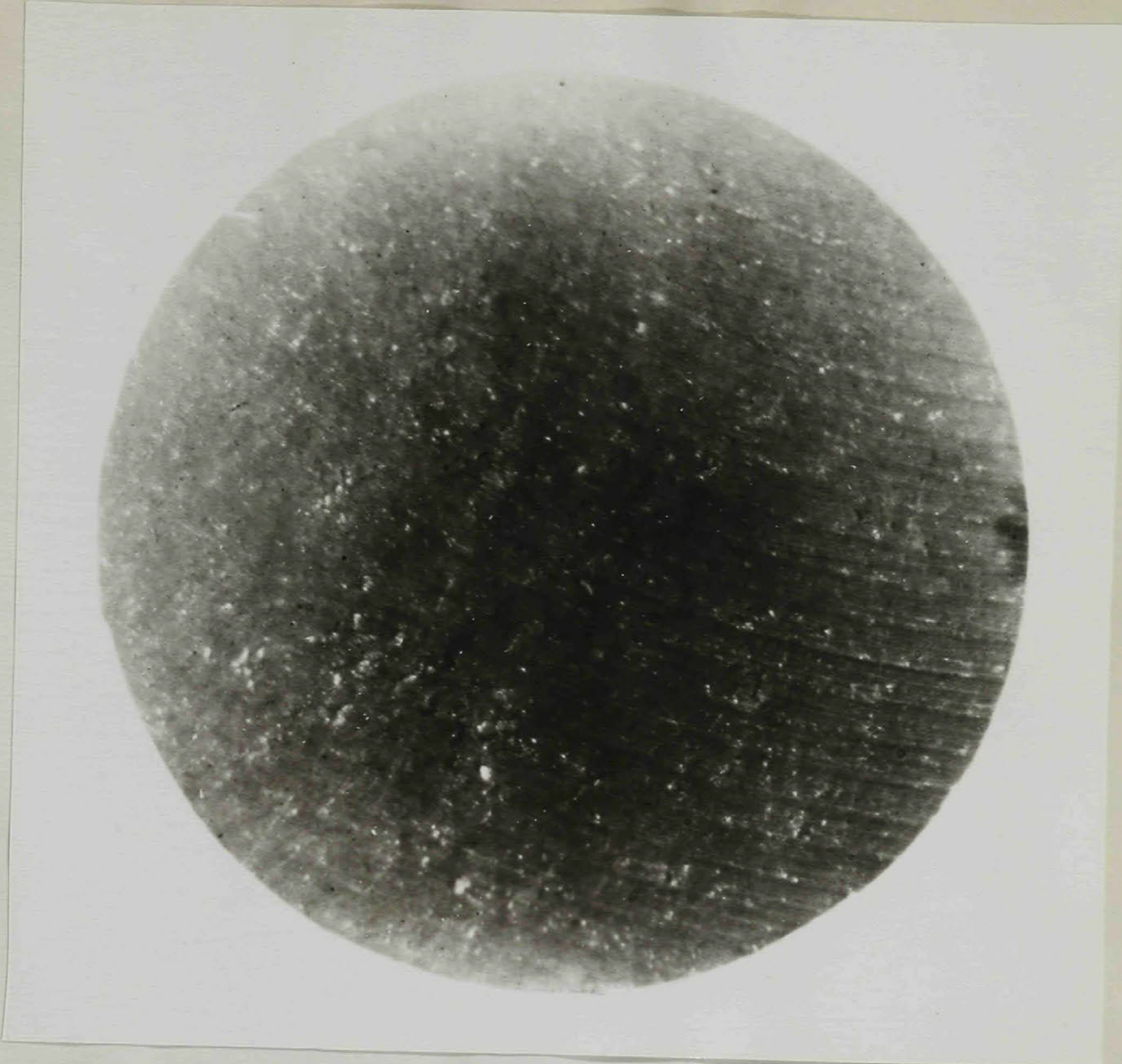


BRONZE - #503-C.

MAGNIFICATION:- 28 DIAMETERS.
EXPOSURE:- 215 Hrs.
COMPOSITION:- Cu. - 90.0 %
Sn. - 9.5 %
P. - 0.10 %
Zn. - 0.25 %

FIG. 27.

FIG. 28.



BRONZE - #485-C.

MAGNIFICATION:- 28 DIAMETERS.

EXPOSURE :- 300 HRS.

COMPOSITION:- Cu.- 88.5 %
Sn.- 7.0 %
Pb.- 1.5 %
Zn.- 2.0 %
Si.- 1.0 %
P.- TRACE.

FIG. 28.

BIBLIOGRAPHY

This bibliography was made as complete as possible with the time and information at hand. It contains entries on phases of cavitation, corrosion and erosion in turbines, pumps and ship propellers. The date of 1894 was chosen as a beginning, since it was at that time that the term "cavitation" came into use. It is probable that there is little on the subject previous to that time.

The entries are arranged chronologically, - first the periodical articles, then books.

The sources of information are miscellaneous, but are largely from the Engineering Index, and the Industrial Arts Catalogue.

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5 The slip of screw propellers. (Ueber den Rücklauf der Schiffsschraube). H. Hügli. Schiffbau. Dec. 23, 1901.

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4 figs.

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* _OF CAVITATION; RESULTS OF CAVITATION TESTS; OTHER METHODS -

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Study for purpose of collecting actual experience data from operating companies in United States and Canada, and to classify and analyse these data in such fashion as to throw light on causes of and means of preventing pitting.

36 Turbines and the cavitation problem. E. Englesson. Engineering, vol. 50, no. 15, Apr. 13, 1926, pp. 471 - 474, 6 figs.

With particular reference to Kaplan and propeller turbines; cause and effect of cavitation and its serious consequences; conclusions arrived at by Committee of British Admiralty; factors affecting cavitation limit; cavitation laboratory at Verkstaden; experiments with oscilloscope.

37 The Kaplan and propeller turbines and the cavitation problem. E. Englesson. Engineering, vol. 121, no. 3146, Apr. 16, 1926, pp. 484 - 486, 7 figs.

Review of investigations of cavitation phenomenon; factors which influence occurrence of cavitation, namely, static suction head, axial velocity of exit from runner, and length of blade in direction of flow compared to pitch of blade; describes special cavitation laboratory installed at Verkstaden Kristinehamn.

38 Pitting of hydraulic turbine runners. Power Plant Engineering, vol. 30, no. 12, June 15, 1926, pp. 704 - 705, 1 fig. see also Power, vol. 63, June 15, 1926, pp. 946 - 948.

Total draft head forms greatest single factor in determining its absence or occurrence. (Abstract). Subcommittee report before National Electric Light Association.

39 Pitting of hydraulic turbine runners. Electrical News, vol. 35, no. 15, Aug. 1, 1926, p. 40.

Causes of this form of corrosion and methods for its prevention.

40 Cavitation in hydraulic turbines (La cavitation dans les turbines hydrauliques). J. Hybl. Bulletin Technique de la Suisse Romande, vol. 53, no. 7, Mar. 26, 1927, pp. 79 - 81, 5 figs. See translated abstract in Water and Water Engineering, vol. 29, no. 346, Oct. 1927, p. 424; and translation in Spanish in Ingenieria & Construccion, no. 55, July, 1927, pp. 353 - 355, 5 figs.

Review of paper read before Academy of Science of Czechoslovakia, analyzing phenomena of cavitation.

41 A theoretical investigation of the phenomenon of cavitation in screw propellers. J. Tutin. London, Edinburgh & Dublin Philosophical Magazine & Journal of Science, vol. 4, no. 20, July, 1927, pp. 17 - 28, 3 figs.

Formation of cavities on propeller blades; momentum theory found incorrect; new set of equations derived and applied to blade elements of actual propeller; problem of eliminating cavitation considered in light of present theory.

42 Das Rhein, Kraftwerke Ryberg, Schworstadt (Hydraulic practice in Europe). D. J. McAdam, jr. Proceedings of the American Society of Testing Materials, 13th meeting, vol. 27, 1927, pt II, Technical papers.

43 Uber Hohlraumbildung, Kavitation in Wasserturbinen. (Concerning formation of cavitation in water turbines). Escher Wyss-Mitteilungen, Ackeret, March, 1928.

44 The highest permissible suction head in hydraulic turbines. (Das hoechstzulaessige Sauggefaelle von Wasserturbinen). J. Ackeret, Schweizerische Bauzeitung, vol. 91, no. 11, Mar. 17, 1928, pp. 135 - 136, 2 figs.

Theoretical discussion calling attention to so-called dynamic suction head, which is important factor in design of Kaplan and propeller turbines and in prevention of cavitation.

45 Kaplan and propeller turbines (Kaplan-und Propeller-turbinen). H Pflieger-Haertel. Elektrotechnische Zeitschrift, vol. 49, nos. 12 and 13, Mar. 22 and 29, 1928, pp. 461 - 466 and 496 - 499, 30 figs.

Mar. 22, includes article on prevention of cavitation.

46 Arrangements for testing of turbines at the machine works at Kristinehamn (Anordningar for provning av turbiner vid Verkstaden Kristinehamn). H. Lind. Tekniska Foreiningens I Finland Forhandlingar, vol. 48, nos. 4 and 5, Apr. and May, 1928, pp. 72 - 81 and 103 - 108, 11 figs.

May: Causes of cavitation; description of cavitation; laboratory completed in 1924, and its testing methods; description of high-pressure laboratory and its operation.

47 Cavitation. J. Tutin. Shipbuilder, vol. 35, no. 213, May, 1928, pp. 313 - 317, 9 figs.

Seeks to develop method of investigating conditions UNDER which given propeller will cavitate. Paper read before Institution of Naval Architects.

48 Cavitation phenomena in hydraulic turbines. J. Ackeret. Bulletin Technique de la Suisse Romande, vol. 54, no. 9, May 5, 1928, pp. 99 - 102, 6 figs. See English abstract in Mechanical Engineer, vol. 50, no. 7, July 1928, pp. 549-550.

Shows causes of low pressures occurring and localizes critical points in turbine; author considers low-head turbine having draft tube. Abstracted from Escher Wyss Mitteilungen, no. 2.

49 Destruction of turbine blades by wear. (Odeleggelse av Turbinskovler ved Taering). H. Thoresen. Teknisk Ukeblad, vol. 75, nos. 20 and 21, May 18 and 25, 1928. pp. 197 - 201 and 209 - 214, 13 figs.

May 18: Studies made to ascertain cause of wear of certain parts of turbines, especially hollows of blades; effect of vacuum and other causes; methods of laboratory established for purpose in Kristinehamn, Sweden.

May 25: Various theories as to cause of cavitation and results of laboratory experiments; stage has been reached when Francis turbines may be constructed without risk of cavitation, with reasonable specific speed for falls of average height; methods of repairing wheels damaged by cavitation.

50 Corrosion and cavitation in hydraulic turbines. (Corrosions et cavitations dans les turbomachines hydrauliques). A. Metral. Revue Générale de l'Electricité, vol. 23, no. 26, June 30, 1928, pp. 403H - 416H, 5 figs.

Treats of hypotheses for explaining corrosion and also phenomenon of cavitation in hydraulic turbines; reports some tests on impact action of water drops at high speeds on moving metal walls at Brown-Boveri testing laboratory at Baden, Switzerland.

51 Maximum permissible suction head on water turbines. J. Ackeret. Mechanical Engineer, vol. 50, no. 7, July, 1928, pp. 547 - 549, 2 figs.

Claims that by properly selected profile and proper selection of diameter, ~~together with proper selection of diameter~~, together with proper selection of shape of blade, further advance may be made in degree of utilization of higher heads of water; turbine designer reaches limit where cavitation phenomena sets in. Abstract translated from Schweiserische Bauzeitung, Mar. 17, 1928, p. 135.

52 Aerofoil theory of propeller turbines and propeller pumps with special reference to the effects of blade interference upon the lift and the cavitation. F. Numachi. Journal of the Society of Mechanical Engineers of Japan, vol. 31, no. 136, Aug. 1928, pp. 530 - 583, 4 figs.

Writer has deduced theory of these machines in light of theory of airfoil; preliminary study of theory of blade interference; theory of propeller turbines and of propeller pumps. (In English).

53 Some interesting European hydraulic turbine research. B. R. Van Leer. American Society of Mechanical Engineers - Advance paper for meeting, Dec. 3 to 7, 1928, 8 pp., 14 figs.

Certain turbine researches and their results, which although publicly known in Europe, are not generally known in America. Includes notes on cavitation. Bibliography.

54 Progress in hydraulic turbine design, Kaplan and propeller turbines. Permissible elevation above tailwater level, limits of high pressure, etc. Oesterlen. V. D. I. Zeitschrift, vol. 72, no. 50, Dec. 15, 1928, pp. 1831 - 1841, 27 figs.

55 Die Anwendung des Zeitdehners beins Studium von Kavitationsercheinungen. (The use of high speed moving pictures for the study of cavitation phenomena). H. Mueller. Die Kinotechnik, vol. 10, issue 17, 1928.

56 Aerofoil theory of propeller turbines and propeller pumps with special reference to effects of blade interference upon lift and cavitation. F. Numachi. Tohoku Imperial University, Technology Report, vol. 8, no. 3, 1929, pp. 411 - 412.

Functions expressing numerically and graphically effects of interference upon lift and pressure at point of incipient cavitation in terms of pitch, chord and blade-angle design; formulas for selection of profile form, size and blade angle of a partial turbine and formula in order to check cavitation trouble. (In English).

57 Some interesting European hydraulic research. B. R. Van Leer. Hydraulics (American Society of Mechanical Engineers Transactions), vol. 51, no. 6, Jan. - Apr. 1929, pp. 57 - 64 and (discussion) pp. 64 - 66, 14 figs.

Includes notes on draft-tube and cavitation research. Bibliography.

58 Kaplan on propeller turbines. Genie Civil, vol. 94, no. 19, May 11, 1929, pp. 453 - 456, 13 figs.

Comparative study.

59 Corrosion of metal by flowing water. Engineering, vol. 128, July 12, 1929.

60 Einflussder Kopfform von Schaufelprofilen bei kreisetradern auf die Kavitation. Pötter. V. D. I. Zeitschrift, vol. 73, Aug. 10, 1929, pp. 1123 - 1124

61 Cavitation in hydraulic turbines (La cavitazione nelle turbine idrauliche). G. Buechi. Energia Elettrica, vol. 11, no. 6, Nov. 1929, pp. 1117 - 1129, 19 figs.

Compilation presenting results of recent experiments and studies made in hydraulic laboratories in Germany, United States and Sweden, on cavitation and corrosion of blades of Francis and Kaplan turbines and Pelton wheels; aerodynamic study of distribution of pressures on turbine blades; prevention of cavitation.

62 A contribution to the design of a propeller turbine of axial flow type. K. Kanesige. Journal of the Society of Mechanical Engineers of Japan, vol. 32, no. 151, Nov. 1929, pp. 440 - 453, 8 figs.

New method for determination of chief dimensions of axial-flow water turbine of propeller type, except runner itself, which is to be designed under given conditions; its characteristic features are: Introduction of index number which represents characteristics of guide apparatus into ordinary design formulas, provision of diagrams which may enable turbine designers to select some numerical coefficients with special reference to cavitation phenomena and hydraulic efficiency of runner. (In Japanese).

63 A new criterion of cavitation. J. M. Irish. Journal of American Society of Naval Engineers, vol. 41, no. 40, Nov. 1929, pp. 597 - 607, 2 figs.

Methods of propeller design which neglect cavitation are faulty and are cause of failure of certain propellers; determining factors are pressure on s. h. p. and tip speed; by plotting these on chart which is presented, presence of cavitation may be foretold.

64 Mechanics of hydraulic turbine pressure regulation. Arnold Pfau. American Society of Mechanical Engineers, Advance paper no. 34 for meeting Dec. 2 - 6, 1929, 17 pp., 20 figs.

65 Diffusors of modern hydraulic turbines. (I moderni diffusori nelle turbine idrauliche), G. Buechi. Energia Elettrica, vol. 6, no. 12, Dec. 1929, pp. 1201 - 1210, 32 figs.

Prasil theory of draft tubes; theory and features of conical draft tubes, circular diffusors, Kaplan curved-axis

diffusor, White and Moody hydraucone regainer; Voith, Escher Wyss curved and partitioned draft tubes, etc.

66 Mechanical vibrations in penstocks of hydraulic turbine installations. J. P. Den Hartog. Transactions of the American Society of Mechanical Engineers, Hydraulics, vol. 51, Paper no. 13, p. 101.

67 Uber den gegenwartigen Stand der Kavitations-forschung. (Concerning the present state of research on cavitation). H. Mueller. Die Naturwissen-schaften, vol. 16, issue 22.

68 Einfluss der Kavitation auf die Leistung von Schiffsschrauben (Influence of cavitation on the power of ship's propellers). A. Bets. Transaction of III Internationalen Kongress für technische mechanik.

69 Cavitation in and consequent vibration of the draught tube of a water turbine. O. Miyagi. Tohoku Imperial University, Technology Reports, vol. 9, no. 2, 1930, pp. 279 - 308, 7 figs.

Formulas to determine rate of discharge by which cavity is first produced, as well as radius of cavity in relation to discharge; axial velocity of water due to cavitation is calculated; form of cavity is shown and counterflow state of gas in it is explained. (In English).

70 Cavitation in hydraulic turbines. F. Johnstone-Taylor. Power Plant Engineering, vol. 34, no. 4, Feb. 15, 1930, pp. 236 - 238, 4 figs.; see also abstract in Mechanical Engineer, vol. 52, no. 5, May, 1930, pp. 538 - 539, 3 figs.

Analysis of causes of cavitation, factors influencing corrosion and means of avoiding cavitation.

71 On the vibration of draft tube of water turbine. S. Uchimaru and S. Kito. Tokyo Imperial University, Journal of the Faculty of Engineering, vol. 18, no. 8, Feb. 1930, pp. 213 - 270, 39 figs.

Theoretical mathematical analysis of causes and methods of preventing vibrations of draft tubes, of hydraulic turbines running on part load, based on theory of vibration of columnar

vortex confined in cylindrical space; also report on experiments on vibrations of cylindrical draft tubes; effect of placing disc at bottom of tube; effect of introduction of air into draft tube. (In English).

72 Experimental and theoretical investigations of cavitation in water. Experimentelle und theoretische Untersuchungen ueber Hohlraumbildung (Kavitation) im Wasser . J. Ackeret, V. D. I. Zeitschrift, vol. 7, no. 9, Mar. 1, 1930, p. 264.

Investigation of simple types of flow, such as those round blades, through channels, and past spheres, has been done at Goettingen; it was found that many apparently widely different types of cavitation are of quite common characteristics; investigations show that at core of bubbles shock pressure is sufficient to cause observed breakdown of materials.

73 Causes and prevention of corrosion on hydro machinery. R. S. Quick. Power, vol. 71, no. 9, Mar. 4, 1930. pp. 347 - 350, 7 figs.

Corrosion and erosion of water-power machinery occurs under many conditions; causes of these actions and preventions that may be applied by designers and operating engineers; consideration is also given to economics oc applying these correctives.

74 Cavitation in and consequent vibration of the draught tube of a water turbine. O. Miyagi. Journal of the Society of Mechanical Engineers of Japan, vol. 33, no. 2, June, 1930, pp. 57 - 59.

Theoretical consideration of governing factors of draft tubes.

75 Cavitation of warship propellers. (Kavitationsanfang bei Kriegsschiffsschrauben). Werft-Keederei-Hafen, vol. 11, nos. 16 and 17, Aug. 22, 1930, pp. 361 - 362, and Sept. 7, 1930, pp. 377 - 378, 4 figs; see also translated abstract in Marine Engineer and Motorship Builder, vol. 53, no. 637, Oct. 1930, pp. 397 - 398.

Schmidt method of detecting cavitation consists of plotting propeller torque constant against apparent advance of screw; applying method, author shows that successful screws work better in cavitation than others; review of work of Commander Irish, U. S. N., illustrating attitudes of various Admiralties towards cavitation.

76 Pitting in water turbines. E. Englesson. Engineer, vol. 150, no. 3901, Oct. 17, 1930, pp. 418 - 421, 16 figs.

It has been found that frequently sudden and severe pitting, which appears in water turbines as well as propellers, is consequence of cavitation; factors which cause cavitation; bubbles and pitting; microscopic investigations of pitted turbine parts; accelerating action of corrosion in pitting; what can be done to avoid pitting; properties of materials to resist pitting by cavitation; test results.

77 On the vibration of conical draft-tube of water turbine. S. Uchimaru and S. Kito. Tokyo Imperial University, - Journal of the Faculty of Engineering, vol. 19, no. 4, Oct. 1930, pp. 71 - 106, 28 figs.

Experiments on flow of whirling water in conical draft-tube; ideal state of flow of whirling water in conical draft-tube; vibration of water column in conical draft-tube; boundary conditions to be satisfied by vibratory motion of water column; approximate formula for natural frequency of vibration of water column; experiments on vibration of conical draft-tube.

78 The variable pressure water tunnel of the U. S. Experimental Model Basin. H. E. Saunders. Society of Naval Architects and Marine Engineers. Advance paper, no. 10, for meeting Nov. 13 - 14, 1930, 6 pp. 6 figs. on supp. plates.

Experimental model basin, in its research work on propellers, produced cavitation deliberately and observed its phenomena; apparatus consists of closed water circuit of cast-iron pipe with activating impeller in lower half and open jet chamber in upper half, where model propeller is placed; cavitation is defined as formation of voids in way of moving object in stream when and where absolute static pressure is reduced practically to zero. Bibliography.

79 Ship propulsion problems. Cavitation. Vibration. J. De Meo. Shipbuilding and Shipping Record, vol. 36, no. 25, Dec. 18, 1930, pp. 735 - 736.

Only way to avoid entirely phenomenon of cavitation is to adopt unchallengable remedy by placing each screw blade in separate revolving plane; one correct pitch would then be sufficient element; by taking away screw propellers from their actual orthodox position abaft hulls, and by placing them, instead, in central submerged hull zone amidships, ship's vibration would disappear.

80 Variable pressure water tunnel of U. S. Experimental Model Basin. H. E. Saunders. Transactions of the Society of Naval Architects and Marine Engineers, vol. 38, 1930, pp. 205 - 210 and (discussion) 211 - 217; see also Shipbuilder and Marine Engine-Builder, vol. 38, no. 251, Apr. 1931, pp. 348 - 350, 4 figs.

81 Zur Frage des Kavitationseintritts (Occurrence of cavitation). H. Lerbs. Werft-Reederei-Hafen, vol. 12, no. 13, July 1, 1931, pp. 243 - 244, 4 figs.; see also brief translated abstract in Marine Engineer and Motorship Builder, vol. 54, no. 647, Aug. 1931, p. 317.

With marine propeller, choice of highest lift coefficient to obtain highest lift-drag ratio is seriously limited by occurrence of cavitation; for marine work it is essential to know relation between peak suctions and lift coefficient for any particular blade section; high local velocities can still be met at low lifts and author outlines analysis establishing this possibility.

82 Cavitation of large turbine runners. A. S. Robertson. Electrical News, vol. 40, no. 16, Aug. 15, 1931, pp. 35 -36 and 38, 3 figs.; see also Hydro-Electric Power Commission, Ontario, Bulletin, vol. 18, no. 10, Oct. 1931, pp. 368 - 373, 4 figs. and Electrical Canada, vol. 8, no. 12, Dec. 1931, pp. 24 - 26, 4 figs.

Average maintenance costs amount to about $450. per runner per year using electric arc welding.

83 Laboratories de turbines hydrauliques en Europe et essais de cavitation. A Ténot. Bulletin de la Société des Ingénieurs Civils de France, vol. 84, Sept. 1931, pp. 1541 - 1581, plates 195.

84 Maintenance by electric welding machines. A. S. Robertson, Contractor's Record, vol. 45, no. 35, Sept. 2, 1931, pp. 1053 - 1055, 4 figs.

Application to turbine runners; cavitation or pitting; experience of Ontario Hydro Commission; stainless steel experiments.

85 Die Turbinen des Rheinkraftwerkes Ryburg - Schwoerstadt. (Turbines of Rhine Power Plant Ryburg-Schwoerstadt). V. D. I. Zeitschrift, vol. 75, no. 38, Sept. 19, 1931, pp. 1181 - 1187, 16 figs.

Installation and operation of four Kaplan turbines developing 38,000 h.p. at 75 r.p.m. each; dimensions and design of principal components, with particular regard to bearings; model tests for investigating most economic shape of concrete suction pipe, most favorable shape of blade, cavitation problems, etc.

86 Anti-cavitation marine propeller. Scientific American, vol. 145, Oct. 1931, p. 260, illus.

87 Schnellaufende Turbomaschinen fuer Fluessigkeiten. (High-speed turbines for liquids). W. Hahn. V. D. I. Zeitschrift, vol. 75, no. 42, Oct. 17, 1931, pp. 1293 - 1296, 17 figs.

Solution of difficulties concurrent to high speed; determination of dimensions and conditions for different operating conditions; pressure distribution over blade; investigation of cavitation limits by model tests; corrosion problems.

88 Electrolytic pitting of hydraulic turbine runners. A. H. Myers. Electrical News and Engineering, vol. 40, no. 23, Dec. 1, 1932, pp. 35 - 36, 3 figs.

Extreme case of hydraulic-turbine-runner pitting taking place over number of years; effect of pitting on runners operating since 1914, illustrates two types of pitting occurring simultaneously on medium specific speed runner in single installation

89 Note sur la theorie des hélices calcul des couples et des poussées détermination des pressions locales prévision de la cavitation. R. Brard. Association Technique Maritime et Aéronautique, Bulletin, no. 36, 1932, 00. 713 - 735, (discussion) 736 - 748.

Notes on theory of propellers; calculation of moments and thrusts; determination of local pressures and cavitation.

90 Cavitation et changement de régime étude expérimentale sur la cavitation des hélices. R. Legras. Association Technique Maritime et Aéronautique, Bulletin, no. 36, 1932, pp. 803 - 827 (discussion) 828 - 834.

Experimental investigation of cavitation phenomena of ship propellers with particular regard to variation in speed.

91 Cavitation experiments on model propeller. G. Kempf and H. H. Lerbs. Transactions of the Institute of Naval Architects, vol. 74, 1932, pp. 165 - 168 (discussion), 169 - 185; see also Shipbuilder and Shipping Record, vol. 39, no. 12, Mar. 24, 1932, pp. 351 - 352; Shipbuilder and Marine-Engineer Builder, vol. 39, no. 264 (Annual Int. No.) Apr. 1932, pp. 264 - 266; and Engineering, vol. 133, no. 3455, Apr. 1, 1932, pp. 410 - 411 (discussion) 393; and French translation in Bulletin Technique du Bureau Veritas, vol. 14, no. 5, May, 1932, pp. 122 - 123.

Results of cavitation experiment made by Hamburg Tank; reliable basis on which constructor can depend, and by means of which he can design propellers of high specific pressure for high-speed ships; literature on cavitation regarding screw propulsion.

92 On model experiment of water turbine draught tubes. O. Miyagi. Tohoku Imperial University, Technology Reports, vol. 10, no. 3, 1932, pp. 30 - 44.

Theory of flow in draft tube; flow is in state of compound vortex with central core rotating like solid bar; neither compound vortex nor cavitation follows law of similarity; relation between efficiencies of actual draft tube and model. (In English).

93 Cavitation of large turbine runners. A. S. Robertson. Canadian Engineer, vol. 62, no. 2, Jan. 12, 1932, pp. 13 - 14 and 48. Indexed in 1931, from various sources.

94 Pitting of hydraulic turbine runners. A. H. Myers. Electrical World, vol. 99, no. 7, Feb. 13, 1932, pp. 328 - 329.

Examples of installations that exhibit corrosion pits from spot oxidation and also from electrolytic action; causes of two phenomena and corrective measures adopted.

95 Cavitation of hydraulic turbine runners. Engineering, vol. 133, no. 3454, Mar. 25, 1932, pp. 366 - 367.

Runners of 52,000 -hp. machines in Queenston power house, Ontario; pitted areas are repaired by electric welding; after chipping out pitted material, new is built up layer by layer, using soft iron for underlying layer, and flux-coated steel rod, of 60,000 lb. per sq. in. ultimate strength, for surface.

96 Propeller cavitation. Y. Amari. Zosen Kiokai (Society of Naval Architects of Japan). Journal, vol. 49, Apr. 1932, pp. 153 - 170.

Causes and natures of various kinds of cavitation in marine screw propeller; author's method of dealing with effect of cavitation in propeller design; principle of thrust indicator. (In Japanese).

97 Cavitation experiments on a model propeller. G. Kempf. Engineering, vol. 133, Apr. 1, 1932, pp. 410 - 411; see also (abstract) Engineer, vol. 153, Apr. 8, 1932, p. 386; and (discussion) Engineering, vol. 133, Apr. 1, 1932, p. 393; and Engineer, vol. 153, Apr. 8, 1932, p. 386.

98 Die Druckverteilung an Joukowski-Profilen. F. Weinig. Werft-Reederei-Hafen, vol. 13, no. 10, May 15, 1932, pp. 143 - 145, see also brief English abstract in Marine Engineer & Motorship Builder, vol. 55, no. 658, July, 1932, p. 260.

Pressure distribution around Joukowski profile can be exactly calculated; routine calculation and its results are reviewed; graphic method of calculation is developed; investigations show that Joukowski profile is only useful for heavy loading; for lighter loads better profiles can be developed.

99 Korrosion durch Kavitation in einem Diffusor. H. Schroeter. V. D. I. Zeitschrift, vol. 76, no. 21, May 21, 1932, pp. 511 - 512.

Report on preliminary experiments made at Kaiser Wilhelm Institute for Hydrodynamics at Gottingen; observations on progress of cavitation in diffusor lined with gray cast iron, zinc or bakelite C.

100 Problems of ship propulsion. G. S. Baker. Engineer, vol. 153, no. 3985, May 27, 1932, pp. 582 - 583.

Account of conference organized by Society of Friends and Supporters of Hamburg Tank held at Hamburg, May 18 - 19th; meetings were divided into five sections dealing with different aspects of ship propulsion; frictional resistance; wave resistance; propeller working and cavitation; interaction between hull and propeller.

101 Untersuchungen ueber Propellerprofile mit verminderter Kavitationsempfindlichkeit. H. Holl. Forschung auf dem Gebiete des Ingenieurwesens, vol. 3, no. 3, May - June, 1932, pp. 109 - 120.

Investigation of propeller cross-section with diminished cavitation sensitivity; measurement of pressure distributions in wind tunnels as basis for estimation of profiles, used for blades of ship propellers, Kaplan turbines, and other centrifugal machines; results of measurements on 16 models; theoretical pressure distribution with symmetrical curve profiles and with Joukowski and Betz profiles.

102 Cavitation and its influence on hydraulic turbine design; Paints and corrosion. National Electric Light Association Publication, no. 222, June, 1932, 20 pp.; see also Power Plant Engineering, vol. 36, no. 17, Sept., 1932, pp. 674 - 676.

Extended report of proceedings and discussion at spring meeting of Hydraulic Power Committee; cavitation and its influence on hydraulic turbine design, W. Spannhake; bibliography references; bibliography on cavitation; paints and corrosion, C. G. Fink; Personnel of Hydraulic Power Committee.

103 Cavitation research at Safe Harbor, Holtwood and M. I. T. C. F. Merriam. The Baltimore Gas & Electrical News, vol. 21, no. 2, July 1932.

104 Causes and effects of cavitation in hydraulic turbines. W. Spannhake. Power, vol. 76, no. 1, July, 1932, pp. 40 - 41.

Simple formula by which conditions conducive to cavitation can be expressed; theoretical basis of this formula is given in curve and diagram which shows progressive changes in pressure on particle of water while flowing through turbine; pressure on particle increases as it passes down penstock and enters scroll case, where pressure begins to decrease due to increase in velocity. Before National Electric Light Association.

105 Recherches experimentals sur la naissance des cavitations. D. Riabonchinsky. Académie des Sciences - C. R., vol. 195, no. 3, July 18, 1932, pp. 205 - 208.

106 Kavitation und Kavitationskorrosion. I. Ackeret. Werft-Reederei-Hafen, vol. 13, no. 16 and 17, Aug. 15, 1932, pp. 239 - 240 and Sept. 1, pp. 253 - 255; see also brief English abstract in Marine Engineer & Motorship Builder, vol. 55, no. 661, Oct. 1932, p. 354.

Aug. 15: Cavitation and erosion; by means of test pieces mounted upon rotating wheel and exposed to striking water jet, loss in weight for various materials as function of number of impacts were studied; diagram given showing that erosion commences very slowly but subsequently increases rapidly; actual hydrodynamic forces in impact were measured.

Sept. 1: Tests carried out in new cavitation tank at Hamburg; on three-bladed model screws of Schaffran type covering range of pitch and area ratios; three stages of cavitation influence are distinguished; diagram showing loss in efficiency for various stages of cavitation, and diagram showing inter-relation of pitch and area upon cavitation.

107 Cavitation. G. S. Baker. Engineer, vol. 154, no. 3997 and 3998, Aug. 19, 1932, pp. 187 - 188 and Aug. 26, pp. 212 - 213.

Definition; how cavitation is brought about; suggestions for design of propellers, putting general theories and ideas into practice; design of propellers; cavitation thrust limits.

108 Profilmessungen bei Kavitation. O. Walchner. Werft- Reederei-Hafen, vol. 13, no. 17, Sept. 1, 1932, pp. 251 - 252; see also brief English abstract in Marine Engineer & Motorship Builder, vol. 55, no. 661, Oct. 1932, p. 354.

Cavitation tests on blade sections at cavitation ring tank at Goettingen; blades were of usual propeller segmental sections for three thickness ratios; cavitation first produces foaming and, only when more pronounced, causes loss in lift and increase in drag; diagrams show extent of foaming over blade for all pressure ratios and incidence angles.

109 Kraftmessungen an Widerstandskoerpem und Fluegelprofilen im Wasserstrom bei Kavitation. E. Martyrer. Werft-Reederei-Hafen, vol. 13, no. 17, Sept. 1, 1932, pp. 252 - 253; see also brief English abstract in Marine Engineer & Motorship Builder, vol. 55, no. 661. Oct. 1932, p. 354.

Cavitation tests on cylinders and blade sections; systematic investigation made at Aix-la-Chapelle on nature of cavitation in its effect upon resistance of cylinders and upon lift and drag of airfoils over usual incidence angle range, in connection with design of propellers for torpedoes.

110 Cavitation studies. Scientific American, vol. 147, Sept. 1932, p. 171, illus.

111 Cavitation its cause and influence on hydraulic turbine design. Power Plant Engineering, vol. 36, no. 17, Sept. 1932, p. 674 - 676.

112 Die Ausdehnung des Kavitationsgebietes. F. Weinig. Werft-Reederei-Hafen, vol. 13, no. 17, Sept. 1, 1932, p. 255; see also brief English abstract in Marine Engineer & Motorship Builder, vol. 55, no. 661, Oct. 1932, p. 354.

Calculation of linear extent of cavitation; results of tests making use of two plates, one placed perpendicular to flow and second placed abaft first; separation of two plates gives extent of cavitation behind first plate.

113 Praktische Erfahrungen mit Propellern, die bei Kavitation arbeiten. W. Schmidt. Werft-Reederei-Hafen, vol. 13, no. 17, Sept. 1, 1932, pp. 256 - 257; see also brief English abstract in Marine Engineer & Motorship Builder, vol. 55, no. 661, Oct. 1932, p. 353.

Practical experience with propellers working in cavitation; bifurcation is point at which cavitation first affects forces on blade; determination of power loss for any speed due to cavitation, and its application to many naval vessels; particular logarithmic presentation of trial data adopted to bring out cavitation features.

114 Prevention of pitting caused by cavitation in water wheels. T. C. Stabley. Bulletin of the National Electric Light Association, vol. 19, no. 9, Sept. 1932, pp. 539 - 545.

Studies confined to Francis type of turbines made of ferrous metals, cast or fabricated plate; methods and materials should be equally effective for both propeller and Kaplan wheels; deterioration of runners; overcoming pitting by welding; easy welding jobs; rubber vs. steel, etc.

115 Cavitation in large hydraulic turbines. A. P. Thurston. Engineering, vol. 134, no. 3482, Oct. 7, 1932, p. 415.

116 Low head hydro electric development. A. V. Karpov. American Institute of Electrical Engineers, Advance paper, no. 32 - 129, for meeting Oct. 10 - 13, 1932. 14 pp.

Includes: Modern design theories.

117 Sur l'usure des turbines hydrauliques par erosion et corrosion. M. Dutoit and M. Monnier. Association Suisse des Electriciens Bulletin, vol. 23, no. 21, Oct. 14, 1932, pp. 537 - 547

Wear of hydraulic turbines by erosion and corrosion; present status of research on problem; mechanical wear due to impurities in water; chemical wear by corroding agents; cavitation and mechanism of cavitation progress; illustrations from practical experience. Before International Electricity Congress in Paris.

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