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HYDRAULIC LABORATORY REPORT NO. 18

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PROGRESS REPORT ON HYDRAULIC MODEL EXPERIMENTS FOR THE DESIGN OF THE TURBINE DRAFT TUBES FOR GRAND COULLEE POWER PLANT COLUMBIA BASIN PROJECT

by

L. E. Winkelhaus
G. J. Hornsby

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Laboratory Report No. 18
Hydraulic Laboratory
Compiled by: L. E. Winkelhaus
G. J. Hornsby
D. A. Wigle

Reviewed by:

Subject: Progress Report on Hydraulic Model Experiments for the Design of the Turbine Draft Tubes for the Grand Coulee Power Plant.

PURPOSE OF STUDIES

The generating units proposed for installation in the power plants at the Grand Coulee Dam will be the largest ever constructed. At the point of best efficiency the turbines will have an output of 150,000 horsepower when operating under a head of 335 feet, and the generators, which will be direct-connected, will be rated at 130,000 kilovolt-amperes. Nine of these units are to be installed in each of the two powerhouses. It is not unusual for large generating units to convert 97 percent of the mechanical energy input into electrical energy output; but for a turbine to convert as much as 93 percent of the hydraulic energy input into mechanical energy output is considered better than average. In the case of the generators, the high efficiencies have been obtained by isolating each source of energy loss and studying each separately. The same procedure should give similar results in the case of hydraulic turbines. With this in view it was proposed to study the hydraulics of the following features in the order named:

1. Draft tubes
2. Speed ring
3. Scroll case
4. Penstock gates

5. Bends in penstocks near entrance to scroll case.

In the case of the draft tubes particularly, at the normal operating head of 335 feet and discharge of 4,500 cubic feet per second per turbine at Grand Coulee, there will be a velocity head of 8.17 feet available for conversion to static head after deducting the exit losses of the draft tube. This head of 8.17 feet represents 2.44 percent of the total normal head at Grand Coulee, and it is possible for the draft tube to effect the output of the plant approximately to this extent. Frictional and eddy losses make it impossible to fully recover the energy available, but the draft tube still remains an important factor even under the head existing at Grand Coulee.

PROGRESS OF STUDIES

While it may have been more logical to study these features of design in the reverse order, in this case it was necessary to expedite the laboratory work since the contractor was already on the job and information had to be obtained as to the size and shape of the draft tube. Accordingly, the hydraulics of the draft tube were studied first. Two approaches were employed in these studies, (1) models of the draft tube to a scale of 1:62, and (2) a model of the scroll case, turbine and draft tube assembly to a scale of 1:24.

While design and construction of the two types of models were started simultaneously, due to the intricacy of the 1:24 model, the construction required considerably longer time such that the studies on the 1:62 model are now practically completed while the studies on the 1:24 model are only approximately 35 percent completed.

It is the purpose of this report to describe the progress at this time on both models.

DESCRIPTION OF TURBINE MODEL

The model of the turbine assembly consisted of a penstock, scroll case, and draft tube constructed of pyralin pressed into

shape from rectangular sheets one-tenth inch thick. The turbine runner was cast in one piece from a bearing metal known as "Government Genuine" babbit. The inlet vane diameter was 7.7 inches and the outlet diameter was 6.5 inches. The height of the inlet was 1.6 inches and the penstock had an inside diameter of 8.25 inches. The runner was designed for a specific speed of 34.4 and a theoretical velocity-peripheral speed ratio of 0.7. The movable gate vanes and the speed rings were cast from the same material as the runner. The turbine shaft was connected directly through a flexible coupling and a change gear box to a 3-horsepower, 3-phase, 220-volt motor, which had been converted into a synchronous motor for use as a constant-speed dynamometer. This dynamometer was suspended on ball bearings in such a manner as to rotate freely. The torque exerted on the dynamometer by the turbine was transmitted to a delicately balanced scale beam where its value was accurately determined by a system of movable weights.

The penstock of the model was connected to a pressure tank three feet in diameter and seven feet high. The head on the turbine was measured by a mercury U tube, one leg of which was connected to the penstock at the entrance to the scroll case and the other to the tailwater flume. The effective head acting on the turbine was in that manner measured directly.

Both models were supplied with water by an eight-inch single-suction centrifugal pump with a capacity of four cubic feet per second at a head of 25 feet. The water enters the model penstock through a bell-mouth entrance and flows through the turbine into the tailwater flume. The water is measured over a sharp-crested suppressed weir with a length of 2 feet as it returns to the pump sump for recirculation.

TEST PROGRAM ON TURBINE MODEL

The proposed program of tests on the 1:24 model include the individual study of each of the items outlined in paragraph 1.

The studies of the draft tube are to include efficiency tests of the type of draft tubes actually installed in the powerhouses at the Norris and Lower Tallassee Dams and of the draft tube proposed for installation in the Grand Coulee Powerhouses. The present design of the Grand Coulee draft tubes has been developed in the series of studies of the 1:62 model. A detailed description of these tests is included in this report. At this time the tests of the Norris type of draft tube have been completed and the data are being compiled and analyzed; the model of the draft tube for Grand Coulee is being constructed and will be ready for operation in about three weeks; and the designs for the model of the lower Tallassee type are being prepared.

DESCRIPTION OF DRAFT TUBE MODEL

At the time these tests were instigated, the contractor was ready to proceed with the construction of the substructures of the two powerhouses so that there was urgent need for sufficient information as to the space required for future draft tubes as well as a detailed design for such draft tubes as were to be included in the initial construction. Since so much time was required for the design and construction of the model turbine with all its appurtenances as to delay this detailed design, resort was made to the use of models of draft tubes carved from wood to expedite the studies. The first of these studies were made utilizing the tailwater flume for the 1:24 model, but after the initial information was secured and it became necessary to use this tailwater flume for the turbine model, a second flume was erected for additional tests on the 1:62 draft tube models. Both flumes are shown on figure 1.

The turbine model tailwater flume was fitted with a wooden orifice as shown in figure 2 and was used in the test of models 1 to 6 with all the variations in design. Models 6 to 12 with all the variations were tested in the second flume in which both the wooden orifice and a duplicate of it in brass were used for purposes

of comparison. Some additional tests on models 1 to 6 were made in the second flume. All of the models were constructed of wood, as shown on Plate 7, with the exception of models 8 and 9 which were made of galvanized iron. All tests were made with one of the vane rings and the crown plate, as shown in figure 2, in place above the orifice.

These vane rings were made of galvanized iron and were used to induce spiral flow in the throat of the models. This was done to simulate the various conditions of flow existing in a draft tube over the entire operating range of a turbine. Five vane ring assemblies were constructed as nearly similar as possible with the exception that the vanes in the first were set at 0°, the second at 7.5°, the third at 15°, the fourth at 30°, and the fifth at 45°. All angles of necessity being turned on the same arc in all assemblies. All of these vane rings, including the radial, or 0° vane, were used in testing the performance of the models.

TEST PROCEDURE ON DRAFT TUBE MODELS

Approximately 800 tests have been made on the 12 models of draft tubes, most of which were altered in various ways to form 25 distinct designs. The models had a 3-inch diameter throat, and were of both elbow and straight conical type. The comparative performance of the models is based on the external head necessary to produce a given discharge through the tube. The head is taken as the difference in elevation between the headwater and tailwater. The discharge was measured by the sharp-crested suppressed weir. The assumption is made that as the external head decreases, the losses due to all causes decrease, and the efficiency of the tube as a head regainer increases.

A set of data consists of a series of five readings, taken at intervals of thirty seconds, on the headwater and tailwater manometer, and on the hook gage measuring the head over the sharp-crested

weir. Mean values of these readings were used to determine the head on the model, and the head on the weir. The discharge was computed by the Francis formula, $Q = 3.33\ LH^{3/2}$. A correlation of the sharp-crested weir with a V-notch weir indicated that the computed discharges are approximately two percent lower than those of the V-notch weir in the range of heads measured. Velocity heads were computed by assuming a uniform distribution of flow across the throat of the draft tube. Velocity heads were plotted against external head on the model to form the diagrams shown on figures 14 to 27.

The relation between the discharge and the head is expressed by the equation

$$Q = CA\sqrt{2gh}$$

and $$C = \frac{Q}{A\sqrt{2gh}}$$

substituting $V = \frac{Q}{A}$

$$C = \frac{V}{\sqrt{2g}\sqrt{h}}$$

It was decided to compare the performance of the models by coefficients computed for a throat velocity of 8 feet per second. Substituting the above equation $V = 8$ ft. per sec.
Then

$$C = \frac{8}{\sqrt{64.4 \quad h}}$$

$$= \frac{0.998}{\sqrt{h}}$$

Using the diagrams on figures 14 to 27, the value of h corresponding to a velocity head of 0.998 is determined for each vane angle.

Dividing 0.998 by the square root of the heads gives values of C for each vane angle, which are shown on figures 28 to 38. Values of C increase as the performance of the tube improves.

Paint tests were made on all of the models with the exception of the two straight cones, models 8 and 9, for the purpose of showing the flow characteristics inside the models. The models were finished inside with black paint over which a coat of varnish was applied. This was done to give a very smooth surface, and the greatest amount of contrast between the inner surfaces of the models and the white paint used for the tests. In making the paint tests a fresh coat of white lead and oil was applied evenly with a brush over the inner surfaces of the models. The models were then placed in the test flume, and water was run through them for a period of six minutes at a threat velocity of 8 feet per second. The flowing water streaked the fresh paint, and indicated the direction and magnitude of velocities along the boundaries of the model.

Interpretations of the results of the paint tests, as shown on plates 1 to 7, are necessarily only qualitative. Areas of high velocities are characterized by finely etched lines while those of low velocities are distinguished by broader lines, not as well defined. Eddies are shown by curving lines and solid spots of white. Large areas of dead water are indicated by large white areas which show no streaking.

The first paint tests were made for all angles of whirl. It was found that characteristics of flow existing in the models at 0° angle of whirl were only intensified by the other angles of whirl. Therefore, comparisons between models can be made as well on the basis of tests at 0° angle of whirl as with a complete set. For that reason, a complete set of tests are shown on plate 1 for model 1 only, and results of all other tests are shown by pictures of flow at 0° angle of whirl.

DETAILS OF MODELS AND RESULTS

The original proposed design of draft tube for Grand Coulee is shown on figure 3 as model 1. It has an unsymmetrical elbow section due to the axis of the turbine being offset four feet from the center-line of the turbine bay, and because of an attempt to make the water discharge in a direction normal to the face of the powerhouse. Model 1-B resulted from changing the straight piers to piers with a warped upstream edge as the paint tests indicate they should be. The warped piers were superior to the straight piers only at 0° angle of whirl. Model 1-D resulted from lengthening the throat of Model 1-B, as shown in detail on figure 3. The results of the test on these three designs are shown on figure 14, 15, 28, and 35, and on plates 1 and 2. Plate 1 shows how the flow through the pier section is concentrated in one of the outside passages as the angle of whirl increases. At 0° angle of whirl there is a well-balanced distribution of flow through the three pier passages. At 15° angle of whirl the balanced distribution of flow is already upset, as indicated by the paint test. This effect continues to increase with an increase in the angle of whirl until at 45° the flow occurs almost entirely through a single outside pier passage. Under the condition of 45° angle of whirl there is even some indication of a reversal of flow in the roof of the opposite outside passage. These conditions were found to be characteristic of the flow through all of the elbow tube models tested. Model 1-A resulted from removing the piers from model 1. The effect is shown by a paint test on plate 2.

The design of model 2 is similar to model 1, except that in the former the narrower piers resulted in a narrower width of draft tube at the exit while maintaining the same areas of openings. The alterations in model 2 are shown on figure 4 as models 2-B, 2-C, 2-D, and 2-E. These alterations were made by filling the indicated areas with plasticine. Results of these tests are shown on figures 15, 16, 17, 29, 30, and 33, and on plates 2 and 3.

Model 3, shown on figure 5, has a lowered roof through the center passage and through the center of the elbow section. Model 3-A resulted from a further lowering of the center passage, and changes in the plan of the piers. Results of tests on models 3 and 3-A are shown on figures 18, 30, 31, and 34, and on plate 4.

The first design with a symmetrical plan is shown on figure 6 as model 4. The water discharges at an angle of about 86° with the face of the powerhouse. In model 4-A, the tube was narrowed in plan so that the line of the outside passage would be parallel to the construction joint of the turbine bay. This change did not reduce the effectiveness of the tube. Models 4-B, 4-C, and 4-D, resulted from changing the contour of the roof through the elbow and center passage as is shown on figure 6. Evidence is also shown on figure 38 that the roof of the pier section through the center passage should form an angle of about 7° with the horizontal. Any angle in excess of 7° results in the flow breaking away from the roof, and the formation of an eddy that reduces the coefficient of the tube. The results of tests on models 4, 4-A, 4-B, 4-C, and 4-D are shown on figures 19, 20, 21, 31, 32, and 34, and on plates 4 and 5.

The design of model 5, shown on figure 7, is the same as model 4 through the throat and part of the elbow section. The pier section of model 5 is the same as the pier section of model 4-A. Tests on model 5 indicate the same performance as for model 4-A. The results of tests are shown on figures 21 and 35, and on plate 5.

A constant area of cross-section through the elbow as computed in the design of model 6 (figure 8). The model failed to give the expected results due apprantely to large losses from impact on the floor of the elbow section. This impact was sufficient to cause a reversal of flow in the elbow as is shown by the

paint test on plate 5. Model 6-S was formed by placing a splitter in the joint between the upper and lower halves of model 6. The splitter was a thin piece of tin which extended across the entire width of the tube from section B (figure 8) around the elbow to section J, dividing the elbow section into two equal passages. The effect of the splitter can be seen by comparing the paint tests of model 6 with model 6-S (plates 5 and 6). The effect of the splitter on the coefficients is shown on figures 23 and 35. This is the type of design in which other experimenters have found that results in the models did not always hold for the prototype. Their experience has been that the prototype designs gave much better performance than the model tests indicated. In the Grand Coulee tests, the results of model tests with the splitter show superiority of performance over model 6 without the splitter. The elbow of model 6 was widened and the height of the outside passages was increased for part of their length to form model 6-A. Results of tests on models 6 and 6-A are shown on figures 22, 23, 35, and 36, and on plates 5 and 6. Model 6 was tested thoroughly in both flumes 1 and 2. Results in flume 2 were distinctly not as good as in flume 1. It is believed that the differences in the dimensions of the headwater and tailwater bays in the two flumes were responsible for the difference in results.

Tests were made later for the purpose of clarifying this difference in results. Model 3 was used for this purpose, and tests were made in flume 2 as it is shown on figure 1. These tests also indicated, as shown on figure 27, that results in flume 2 were not as good as in flume 1. Falsework was then constructed in the forebay of flume 2 to simulate as nearly as possible the conditions in flume 1. Subsequent tests showed an improvement in results in model 3 due to this change in the headrace. The tailwater bay was then lengthened four feet, and the tailwater

peizometer was moved four feet downstream. Subsequent tests on model 3 showed additional improvement in results due to the change in the tailrace. The combined effect of falsework in the headrace, and the lengthened tailrace was more than sufficient to eliminate the original difference in results existing between flumes 1 and 2. In comparing results of tests on models 1 to 6 with results on models 6-A to 12, allowance must be made for differences due to the two testing flumes. This difference amounts to about 0.07 in the coefficient at 0° angle of whirl, and decreases to about 0.03 at 45° angle of whirl. These differences must be added to the coefficients derived from tests on models 6-A to 12, to make them comparable with models 1 to 6.

The design in model 7 was suggested in a paper by Viktor Kaplan*. The original vertical opening of 0.75 inches at the exit (figure 10) did not give as satisfactory head recovery as when the opening was reduced to 0.50 inches. A further reduction to 0.375 inches in the vertical opening at exit apparently caused choking of the flow which resulted in less head recovery than for the 0.50 inches vertical opening. Results of these tests are shown on figures 24 and 36. A paint test of model 7 with a vertical opening of 0.50 inches at exit is shown on plate 6. It indicates considerable impact on the bottom plate since radial flow lines start from the center of the plate. There is also considerable separation of the direct from the curved section. This model was a theoretical approach to the problem of properly proportioning the areas of a draft tube from throat to exit. It showed such slight promise that tests were not carried farther.

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*Trans. World Power Conference, Barcelona Sectional Meeting, 1929, vol. 2, pages 41-61.

Tests were made on two straight cones (models 8 and 9, figure 10) for the purpose of comparing their performance with the elbow tube designs, and with results of tests made by the Newport News Shipbuilding and Dry Dock Company published by the Hydraulic Power Committee of the New England Division, National Electric Light Association.* One of the straight cones (model 8) was made to the same proportions as those of a cone included in these published results. The second cone was made to conform to a design tested by the Alabama Power Company. These cones were made of galvanized iron. The distance from the discharge end of the tubes to the floor conformed to the most efficient used in the Newport News tests and was sufficient in both cases to eliminate any effect of the floor upon the performance of the tubes. The results are shown on figures 25, 36, and 37.

The tests on models 10, 11 and 12 were made for the purpose of comparing the performance of the current design of the Grand Coulee draft tube with the performance of the designs used at the Norris Dam and at the lower Tallassee plant of the Alabama Power Company. The data from model 10 is shown on figures 11, 26 and 37 and plate 6; from model 11 on figures 12, 26 and 37 and plate 7; and from model 12 on figures 13, 27 and 38 and plate 7.

Model 11 is being modified to conform exactly to the design under test in connection with the Grand Coulee turbine model, and will be designated as model 11-A. A comparison will be made to determine whether the differences shown between models 10 and 11-A will also hold for the draft tube models of 6.5-inch throat diameter used with the turbine model.

In addition to the difference in size of the models which may affect the results, there is also the question of the effect on

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*National Electric Light Association, Proceeding, Vol. 87, pp. 617-633.

the results due to the 3-inch models being tested without a turbine runner, whereas the 6.5-inch models are tested with a turbine runner.

SUMMARY OF RESULTS AND CONCLUSIONS

The coefficient curves show that a better performance is almost invariably obtained at 7°30', than at 0° or 15°. A smooth curve drawn through the plotted points indicates that the best performance occurs at an angle of whirl of approximately 6 degrees. This slight angle of whirl probably assists in diverging the flow in the throat section, causing greater head recovery, without materially upsetting the velocity distribution in the elbow and pier sections. The effect of the higher angles of whirl is to upset the distribution of velocities in the elbow section to the extent that most of the flow occurs through one of the outside passages of the pier section, resulting in less head recovery and lower coefficients.

At the beginning of the tests, two piezometers were placed opposite each other on the upstream and downstream sides of the throat of the models at the top of the draft tubes. Draft heads were measured by taking the difference in the height of water columns in a manometer attached to the draft tube piezometers and to the tailwater piezometer. The average value of draft head taken from a series of five readings was divided by the velocity head at the throat to give a value called the "efficiency" of the draft tube. This method is commonly followed by experimenters but was abandoned in this work because it gave misleading results. Changes in efficiency were not consistent with changes in the coefficients. This discrepancy is probably due to the fact that the boundary velocities in the throat, which produce the measured draft heads, vary considerably from the average vertical velocities.

Some uncertainties arise in making comparisons of results obtained by different experimenters due to lack of information concerning headwater and tailwater conditions in the testing flumes and

to lack of information concerning the entrance conditions to the test orifices. All of these factors have considerable effect on the coefficients. As an illustration, there is an apparent difference of performance by the same model, as shown on figure 27, due to tests being made in two flumes of different dimensions. The effect on the external head, and, therefore, on the coefficient, of increasing the height of vane ring at the entrance to the test orifice, is shown on figure 19. Probably due to these factors, model 8 shows slightly better results than are shown by the similar design included in the tests published by the National Electric Light Association. Likewise, results on model 9 are not as good as the results obtained by the Alabama Power Company on a similar design.

In testing the elbow tube designs, efforts were made to eliminate eddy losses, and to increase the head regain of the tube by numerous alterations in the outline of the elbows, shape of piers, and contour of the roofs of the pier sections. All of the Grand Coulee models of elbow tubes start with a cone of 11 degrees included angle. This value of the included angle had been obtained in previous work by other experimenters as the most satisfactory for head regain.

The first major change in the proposed design of the draft tube was the elimination of an unsymmetrical elbow section due to the axis of the turbine being offset four feet from the center-line of the turbine bay. This was accomplished by turning the draft tube slightly so that the discharge from the tube occurs at an angle of about 86 degrees with the face of the powerhouse instead of normal to it. It was also necessary to reduce the width of the tube at the elbow section to obtain a uniform thickness of concrete between the outside passage of the tube and construction joint between bays. This was done without impairing the effectiveness of

the draft tube as subsequent tests proved.

Paint tests made on the elbow tube designs as shown on plates 1 to 7 indicate the separation of the direct flow from the top of the elbow section. Eddies form at this point which tend to prevent the fullest recovery through the pier sections. In an effort to prevent this separation of the direct flow from the face and the subsequent formation of large eddies, a number of changes were made in the roof of the tube, from the elbow through the center passage. The results indicate that better over-all performances are obtained in designs in which the roof of the center pier passage and the center of the elbow are made lower than the two outside passages. This is illustrated in the improvement of coefficient of model 4-B as compared to the coefficient of model 4 (figure 34).

The comparison of the latest Grand Coulee tube to the Norris and Lower Tallassee designs indicates that the Norris type is superior to the Grand Coulee, and that the Lower Tallassee is superior to both of the others.

The coefficients derived from the results of these tests are not considered to be quantitatively applicable to prototype designs. While the dimensions of the models are scaled from prototype designs, the velocities used bear no relationship to prototype velocities. A scaled velocity, based on the expected discharge in the prototype, would be 3.03 feet per second. For this velocity, the corresponding velocity head is only 0.143 feet. Differences in performance of the models under this small velocity head result in almost negligible changes in the external head. Coefficients were computed for velocities of 8 feet per second because differences in external head are amplified, and permit a more nearly accurate determination of the coefficients. The coefficients are more stable for velocities above 6 feet per second. Opposed to the foregoing advantages of comparing coefficients at velocities of 8 feet per

second is the fact that the resulting draft heads are far in excess of the draft heads that can be supported in the prototype. The models under these conditions are distorted, and the resulting coefficients are at best only qualitative.

In selecting a draft tube, it is the usual practice to choose the one which gives the best model performance, and past experience has indicated, especially in the case of simple elbow types, that such installations give highest efficiencies. Other experimenters, however, have found that while the introduction of a splitter, as described in this report, will show lower coefficients in the model, higher efficiencies may be expected in the prototype. At first thought this seems paradoxical and it is believed that further study of this phenomenon to ascertain its cause would be justified.

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L. E. Winkelhaus

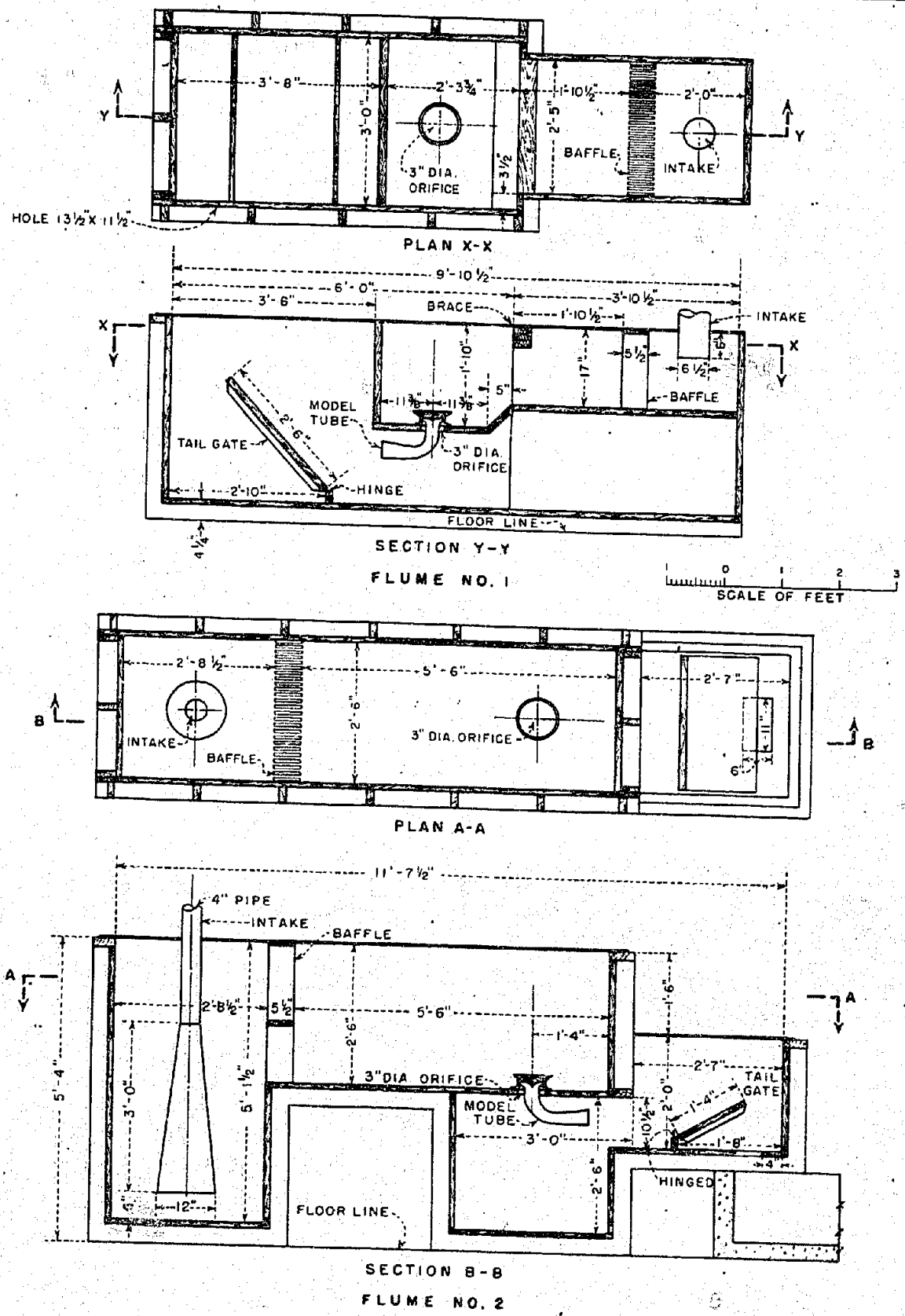
O. J. Horsby.

TABLE I

SUMMARY OF GRAND COULEE DRAFT TUBE MODEL TESTS

Model No.	Figure No.	Plate No.	Type	Origin of Design	Ratio Exit Area to Throat area	Coefficients of Discharge For Throat Velocity of 8'/sec. Max.	0°	7½°	15°	30°	45°	Remarks
1	3,14,28 33	1	Elbow	Design Dept.	3.63	1.54	1.52	----	1.47	1.10	0.81	Unsymmetrical elbow discharging normal to powerhouse wall.
1-B	3,14,28 33	2	Elbow	Laboratory Alteration of model 1	3.63	1.54	1.56	----	1.43	1.12	0.81	Piers with warped nose substituted for original pier design used in model 1
1-D	3,15,29 33	2	Elbow	Laboratory alteration of model 1	3.63	1.59	1.58	----	1.48	1.14	0.81	Increased vertical height with warped nose piers as used in 1-B
2	4,15,29 33	2	Elbow	Design Dept.	3.63	1.51	1.49	----	1.44	1.11	0.81	Unsymmetrical elbow discharging normal to powerhouse wall
2-B	4,16,29 33	3	Elbow	Laboratory alteration of model 2	3.63	1.50	1.48	----	1.42	1.11	0.80	Top of elbow filled in on model 2
2-C	4,16,29 33	3	Elbow	Laboratory alteration of model 2	3.39	1.56	1.53	----	1.45	1.13	0.81	Roof of center pier passage filled in on model 2
2-D	4,17,30 33	3	Elbow	Laboratory alteration of model 2	3.37	1.51	1.49	----	1.42	1.09	0.81	Top of elbow and roof of center pier passage filled in on model 2
2-E	4,17,30 33	3	Elbow	Laboratory alteration of model 2	3.22	1.56	1.53	----	1.44	1.12	0.81	Top of elbow and roof of center pier passage filled in on model 2
3	5,18,30 34	4	Elbow	Laboratory Design	3.63	1.54	1.51	----	1.43	1.11	0.80	Roof of side pier passages higher than center passage
3-A	5,18,31 34	4	Elbow	Laboratory Design	3.63	1.53	1.50	1.52	1.40	1.13	0.82	Outline of piers and roof of center passage changed in model 3
4	6,19,31 34	4	Elbow	Design Dept.	3.63	1.52	1.49	----	1.45	1.10	0.82	Symmetrical elbow, discharging at angle of 85° to power house wall
4-A	6,19,31 34	4	Elbow	Laboratory Alteration of model 4	3.63	1.52	1.49	----	1.45	1.13	0.82	Model 4 narrowed in plan at elbow
4-B	6,20,32 34	5	Elbow	Laboratory Alteration of model 4-A	3.30	1.56	1.53	----	1.45	1.13	0.81	Top of elbow and roof of center pier passage filled in on model 4-A
4-C	6,20,32 34	5	Elbow	Laboratory Alteration of model 4-A	3.14	1.55	1.52	----	1.42	1.10	0.81	Roof of center pier passage filled in parallel to floor of tube on model 4-A
4-D	6,21,32 34	--	Elbow	Laboratory alteration of model 4-A	3.39	1.54	1.51	----	1.46	1.12	0.81	Roof of center pier passage filled in parallel to center line of tube on model 4-A
5	7,21,35	5	Elbow	Laboratory Design	3.63	1.53	1.50	1.52	1.43	1.13	0.81	Roof of side pier passage higher than center pier passage
6	8,22,35	5	Elbow	Laboratory Design	3.32	1.28	1.23	1.26	1.26	1.08	0.77	Model had constant area through elbow section
6-S	23,35	6	Elbow with Splitter	Laboratory Design	3.32	1.41	1.41	1.40	1.32	1.03	0.77	Thin metal splitter on center line through elbow section of model 6
6-A	9,23,36	6	Elbow	Laboratory Design	3.33	1.30	1.27	1.29	1.30	1.08	0.77	Elbow widened, and roof of side pier passages raised on model 6
7	10,24,36	6	Hydra-cone	Laboratory Design	4.00	1.54	1.32	1.32	1.20	0.98	0.81	Theoretical design suggested in paper by V. Kaplan
8	10,25,36	7	Straight Cone	N.E.L.A.	4.00	1.79	1.62	1.71	1.69	1.33	0.85	--
9	10,25,37	7	Straight Cone	Alabama Power Co.	5.06	1.63	1.57	1.76	1.63	1.23	0.89	--
10	11,26,37	6	Elbow	Design Dept.	3.63	1.38	1.37	1.38	1.36	1.04	0.76	Latest Grand Coulee Design
11	12,26,37	7	Elbow	Morris Dam	4.47	1.46	1.42	1.46	1.38	1.04	0.76	Design used by T.V.A. at Morris Dam
12	13,27,38	7	Elbow	Alabama Power Co.	3.87	1.46	1.42	1.46	1.38	1.08	0.80	Design used by Alabama Power Company at Lower Tallassee Plant

FIGURE 1

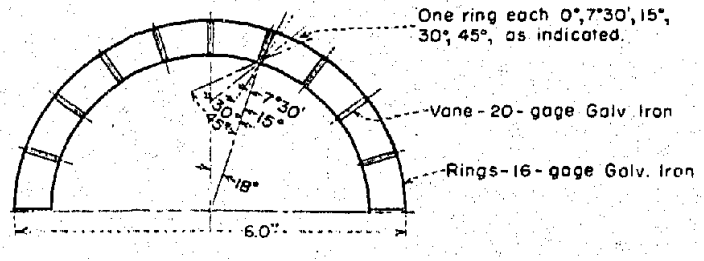


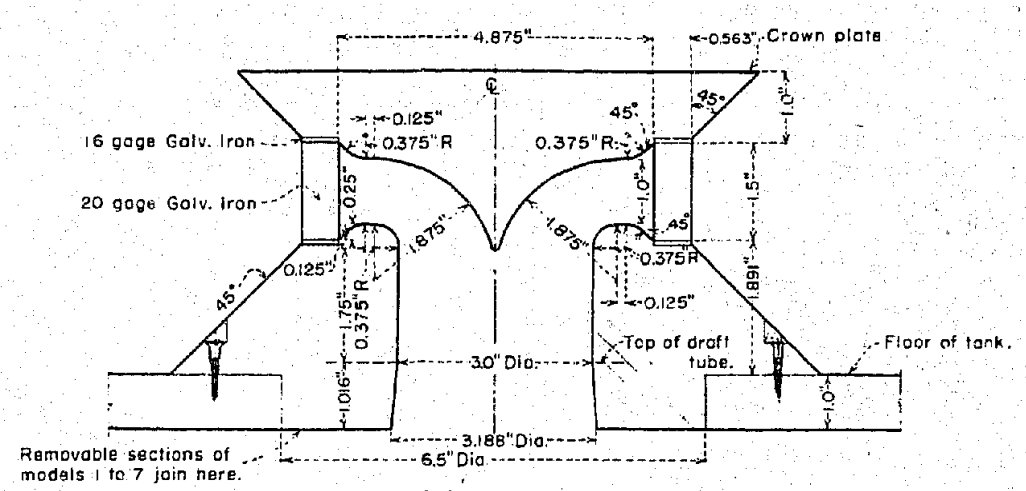
GRAND COULEE DRAFT TUBE MODEL TESTS

TEST FLUMES

222-D-1653

FIGURE 2





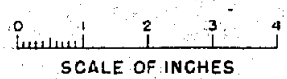
WOODEN ORIFICE WITH VANE RING AND CROWN PLATE

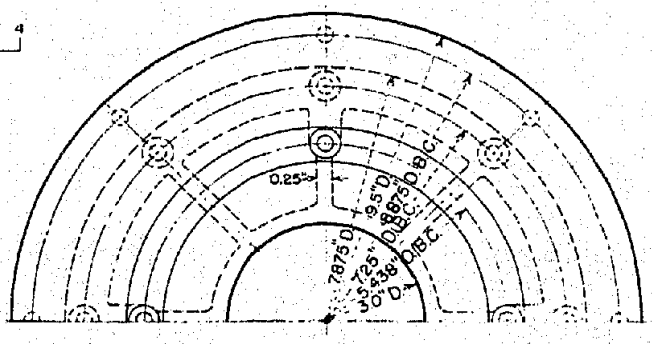
NOTE

Draft tube models 1 to 7, inclusive, attach directly to wooden orifice. Models 1 to 7 may also be attached to brass orifice by use of dutchman.

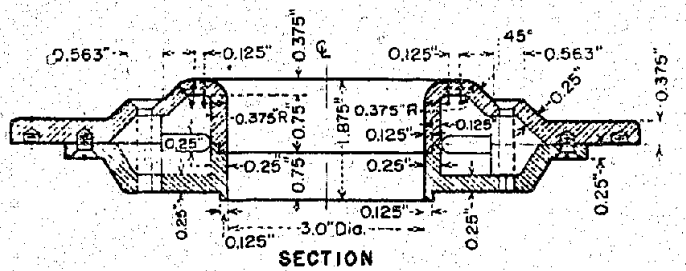
Models 8 to 12, inclusive, were only used with the brass orifice and draft tube collar.

The vane rings and crown plate shown on wooden orifice were also used on brass orifice.

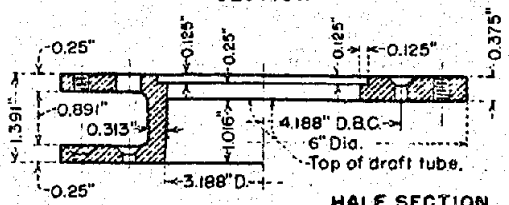




PLAN



SECTION



HALF SECTION - DUTCHMAN

HALF SECTION DRAFT TUBE COLLAR

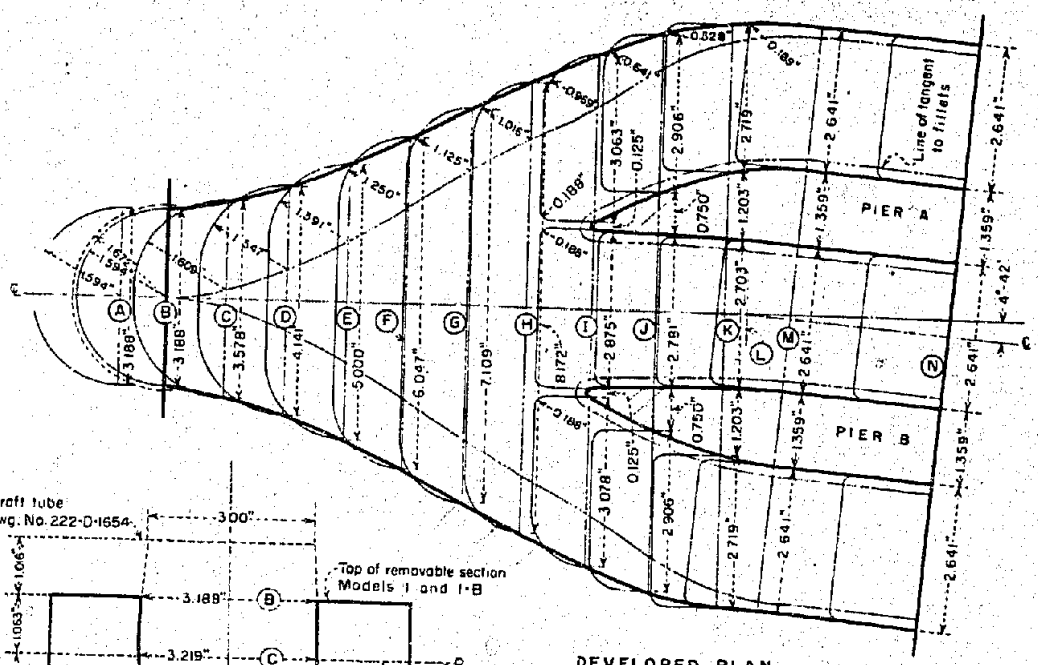
BRASS ORIFICE ASSEMBLY

GRAND COULEE DRAFT TUBE MODEL TESTS

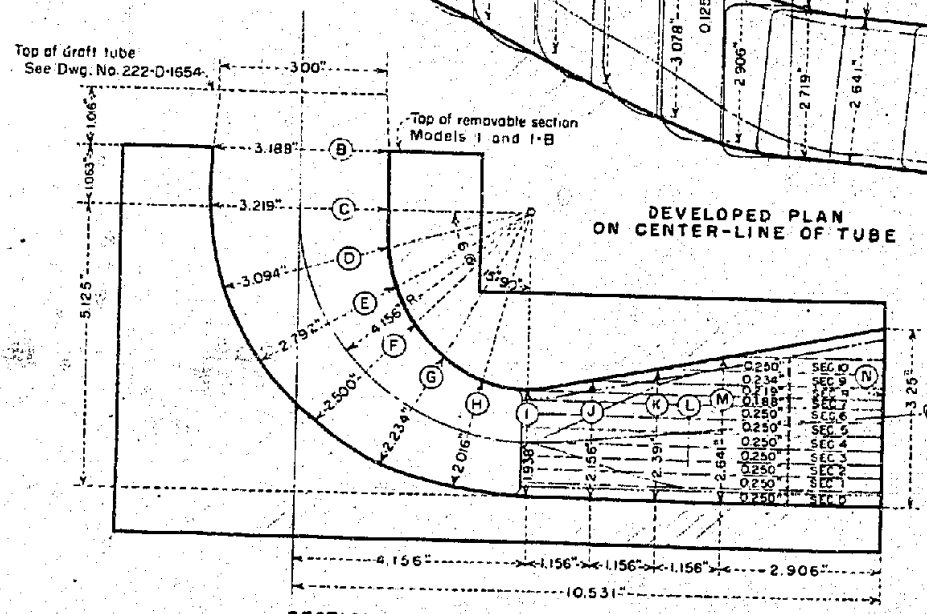
MODEL TEST ORIFICES

222-D-1654

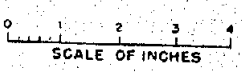
FIGURE 3



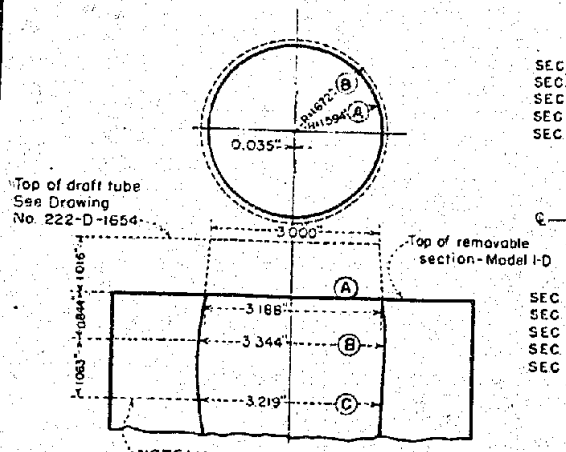
DEVELOPED PLAN ON CENTER-LINE OF TUBE



SECTION ON CENTER-LINE OF TUBE

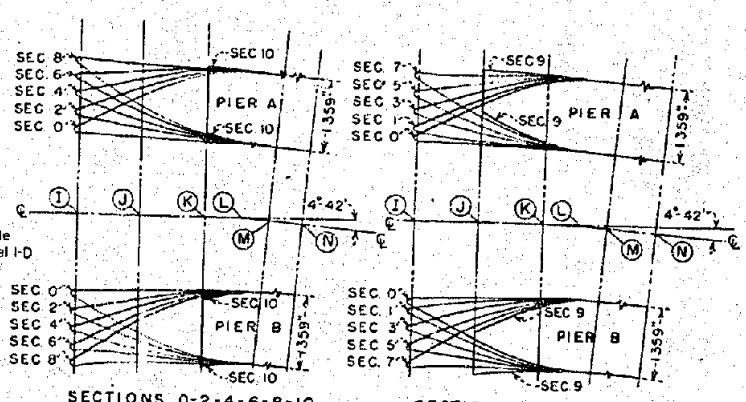


NOTE
0.188" Fillet top and bottom of warped piers.



NOTE; Model I-D is same in cross-section as Models I and I-B below station C

DETAIL OF THROAT OF MODEL I-D



SECTIONS 0-2-4-6-8-10 SECTIONS 0-1-3-5-7-9

DETAILS OF WARPED PIERS USED IN MODELS I-B AND I-D

EXPLANATION

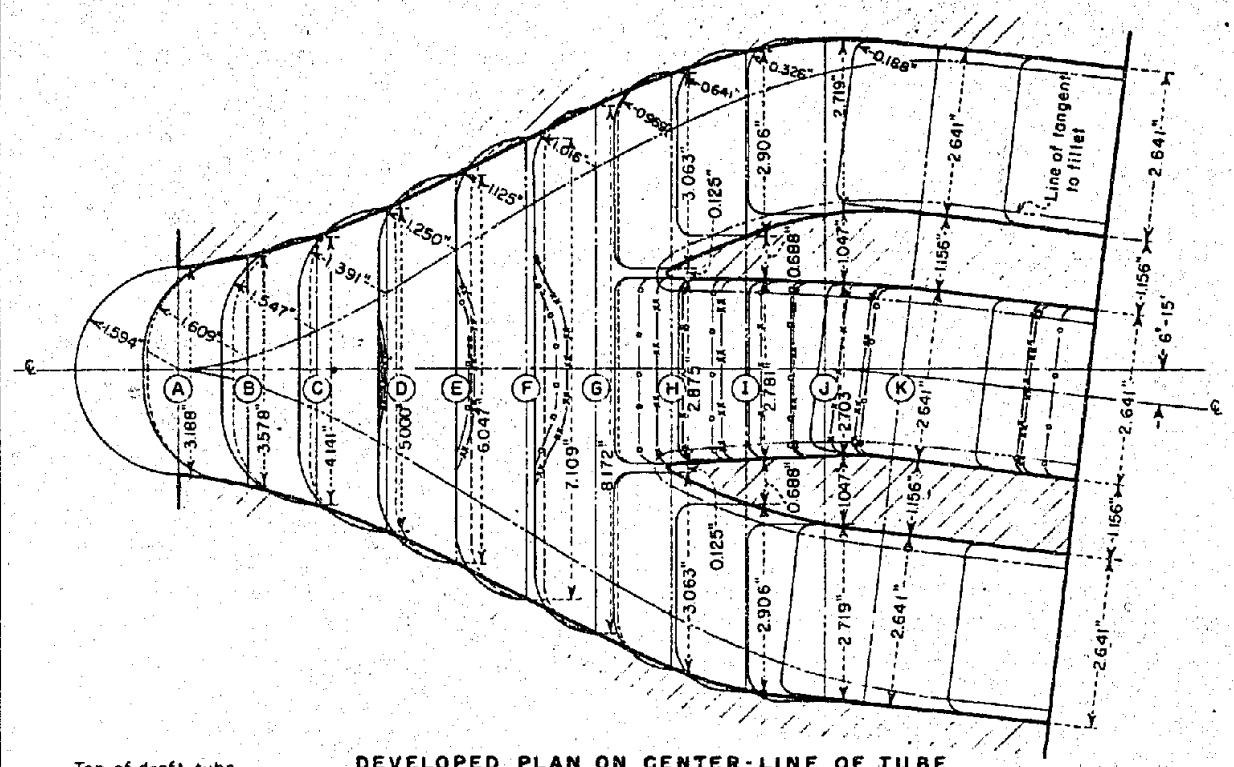
Model I. Straight piers as shown in plan.
Model I-B Warped piers
Model I-D Throat as shown in detail, warped piers.

GRAND COULEE DRAFT TUBE MODEL TESTS

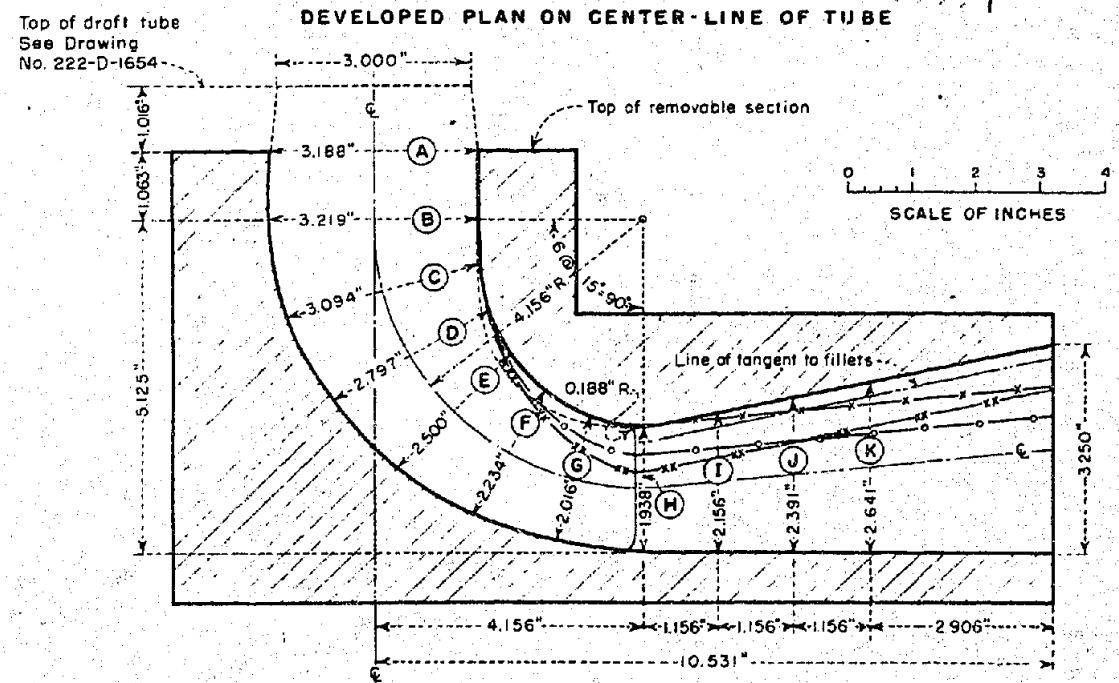
MODEL I

222-D-1655

FIGURE 4



DEVELOPED PLAN ON CENTER-LINE OF TUBE



SECTION ON CENTER-LINE OF TUBE

EXPLANATION

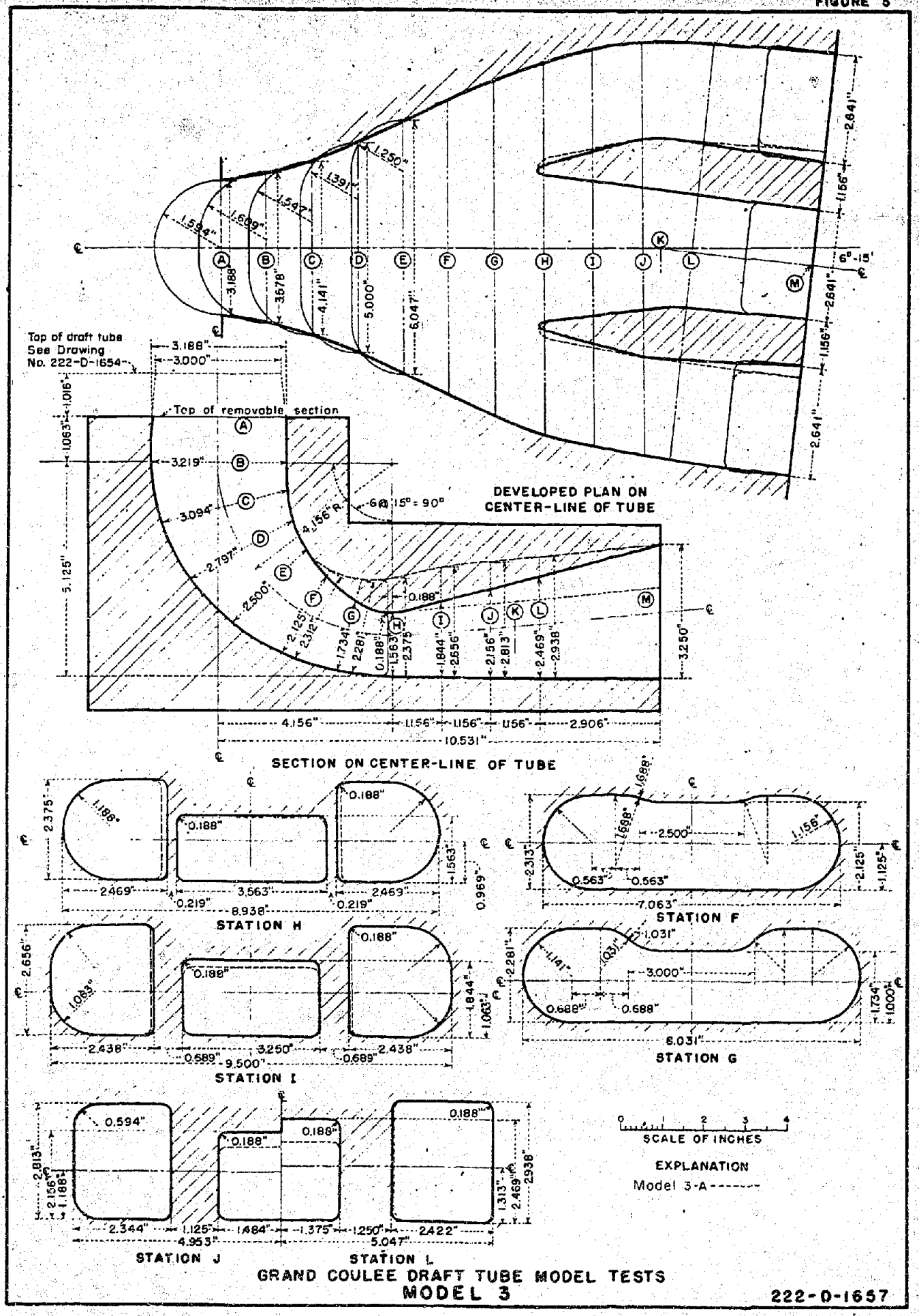
Model 2-B ------
Model 2-C —x—
Model 2-D —xx—
Model 2-E —o—

GRAND COULEE DRAFT TUBE MODEL TESTS

MODEL 2

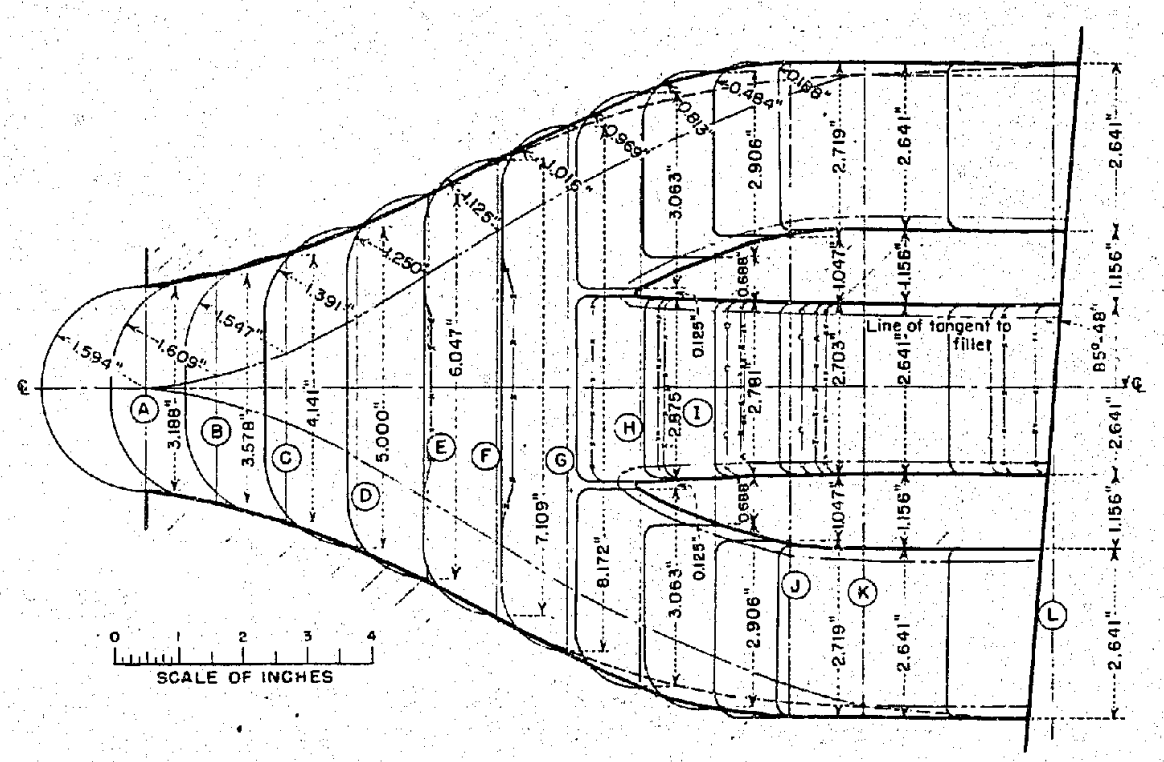
222-D-1656

FIGURE 5

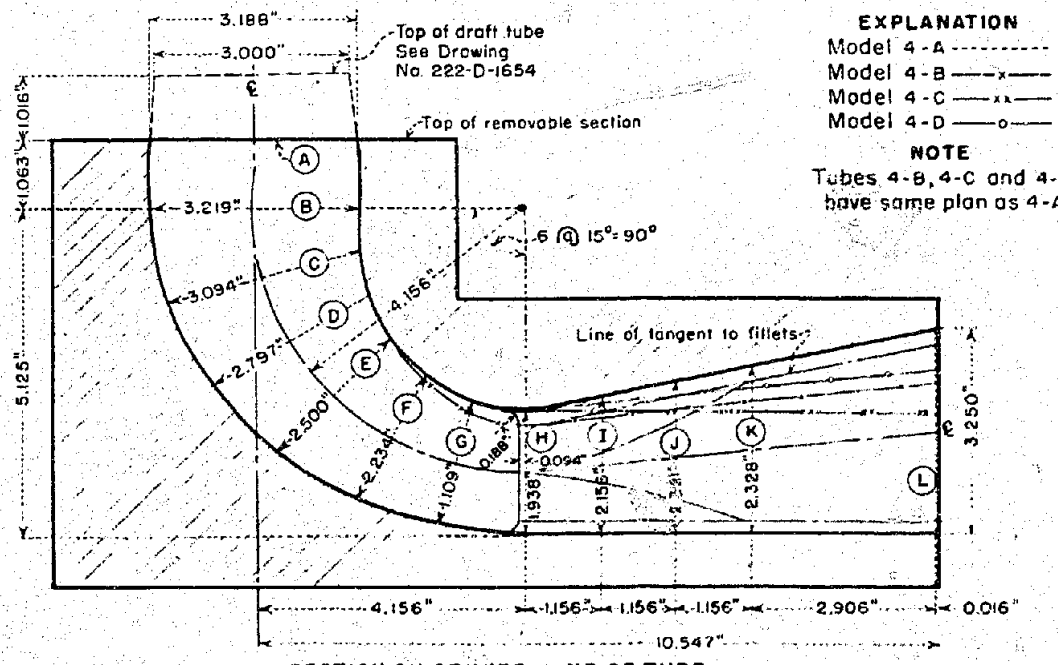


GRAND COULEE DRAFT TUBE MODEL TESTS
MODEL 3

222-D-1657



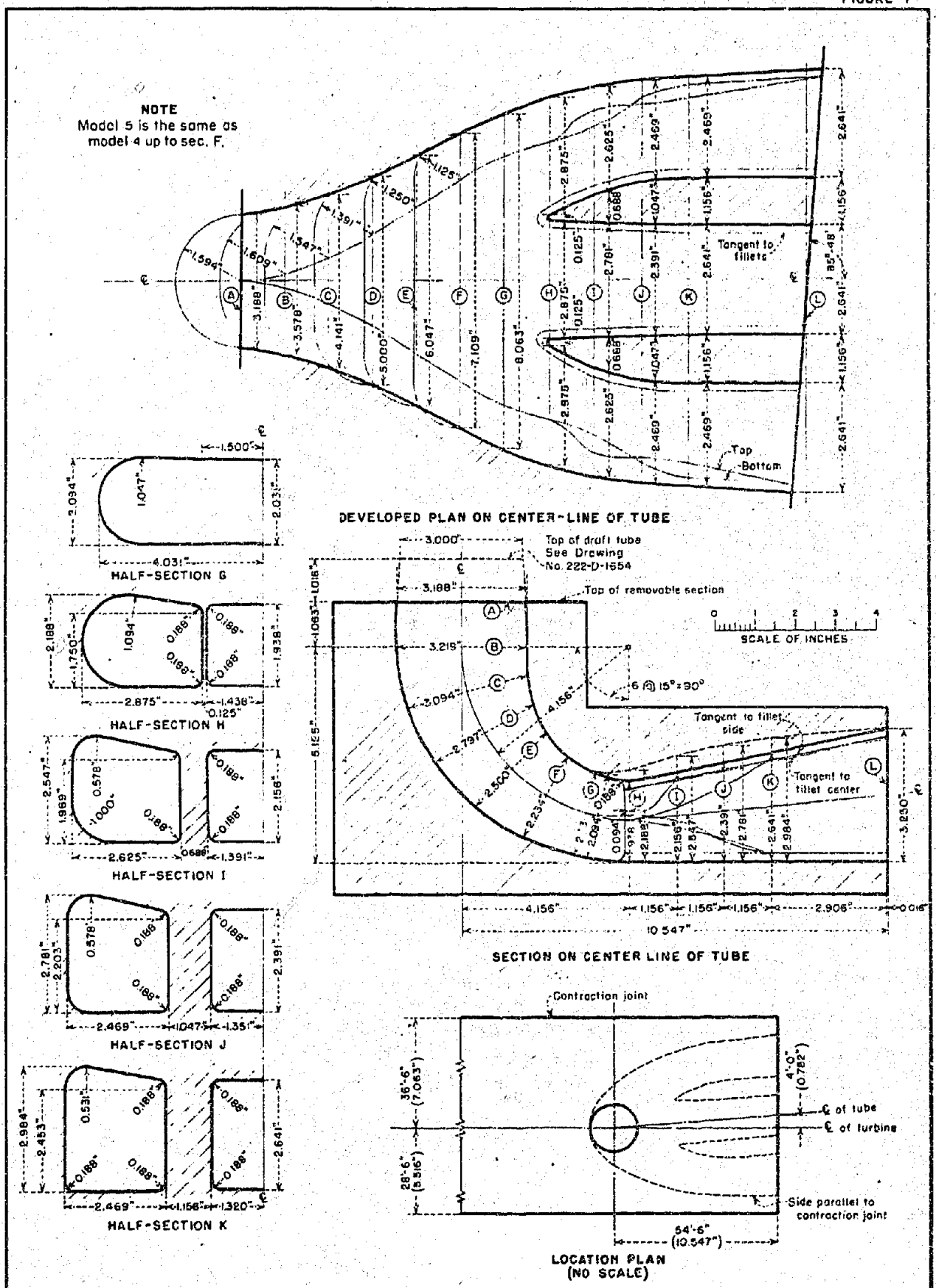
DEVELOPED PLAN ON CENTER-LINE OF TUBE



SECTION ON CENTER-LINE OF TUBE

GRAND COULEE DRAFT TUBE MODEL TESTS

MODEL 4

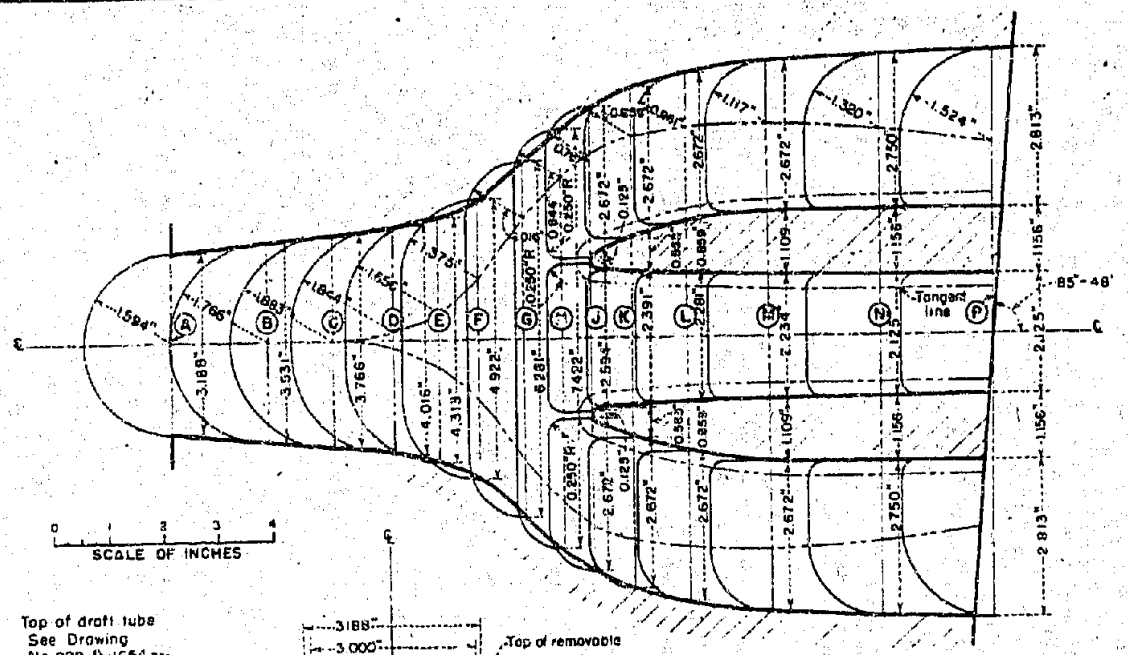


GRAND COULEE DRAFT TUBE MODEL TESTS

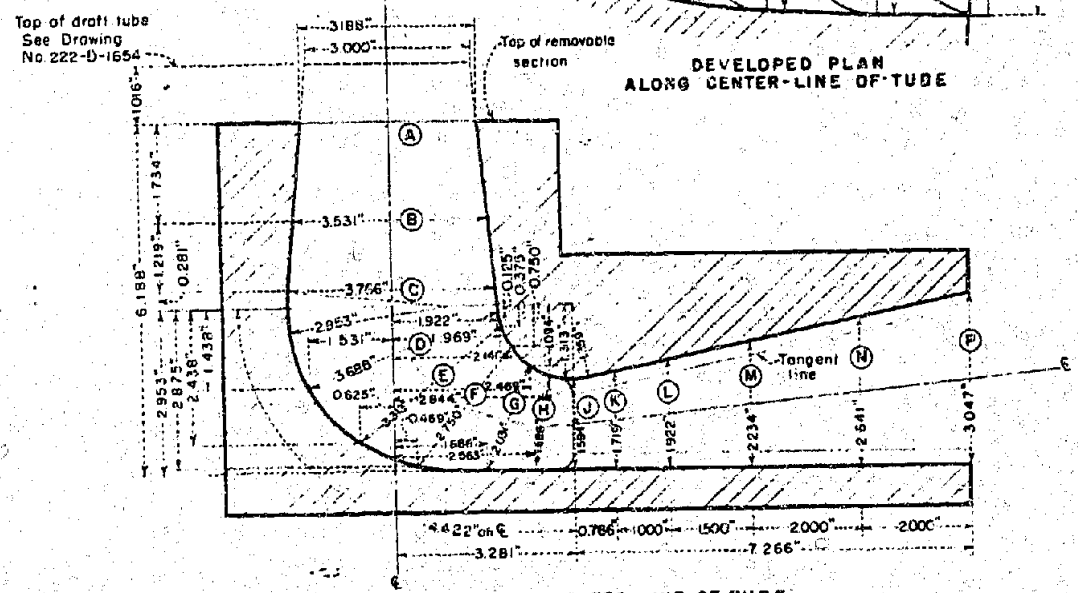
MODEL 5

222-D-1659

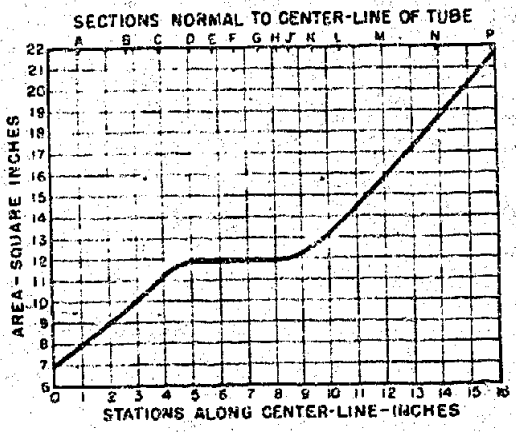
FIGURE 9



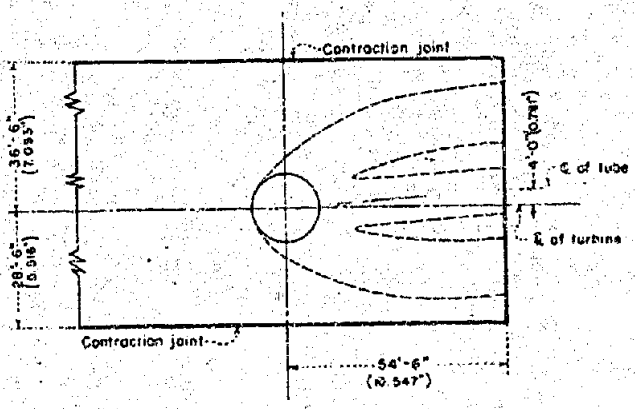
DEVELOPED PLAN
ALONG CENTER-LINE OF TUBE



SECTION ALONG CENTER-LINE OF TUBE



AREA CURVE

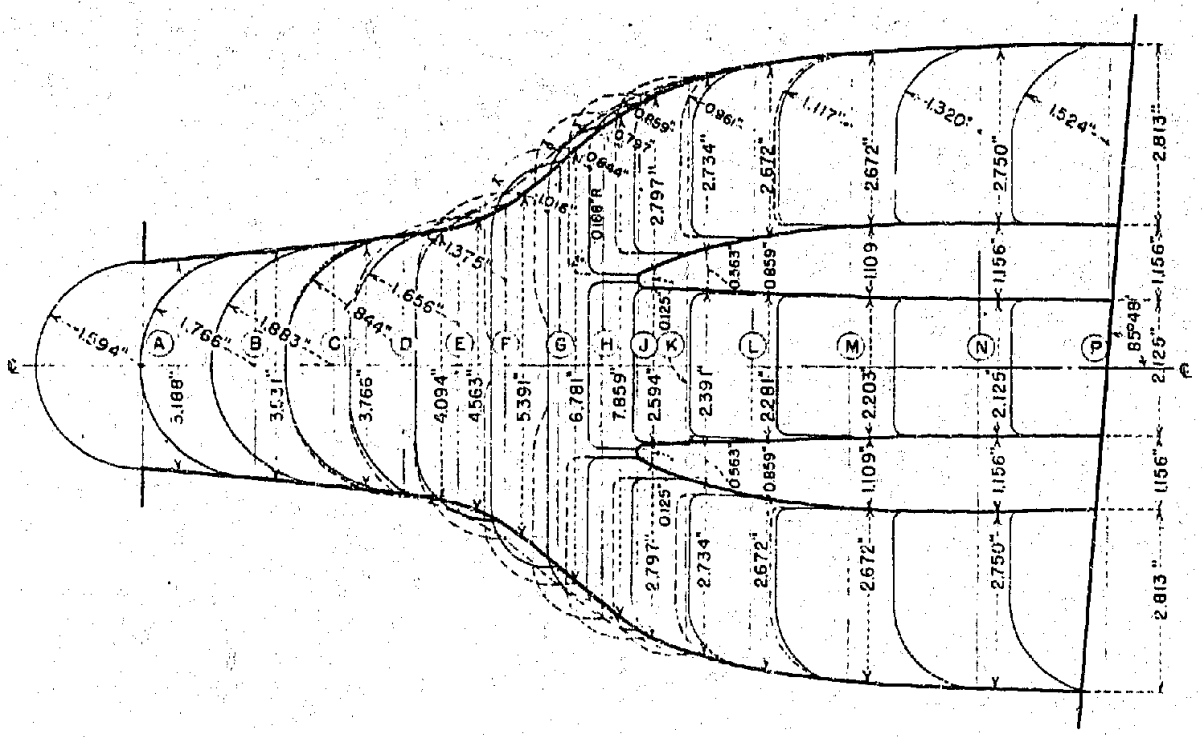


LOCATION PLAN
(NO SCALE)

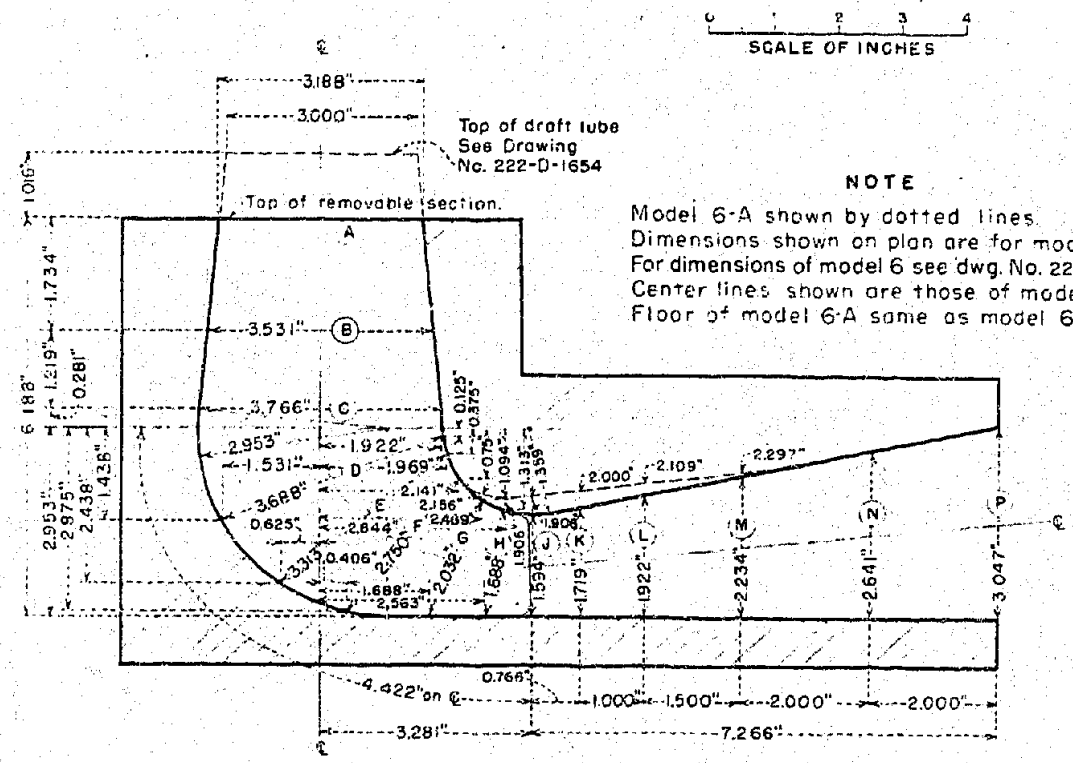
GRAND COULEE DRAFT TUBE MODEL TESTS
MODEL 6

222-D-1660

FIGURE 9



DEVELOPED PLAN ALONG CENTER-LINE OF TUBE



SECTION ALONG CENTER-LINE OF TUBE

NOTE

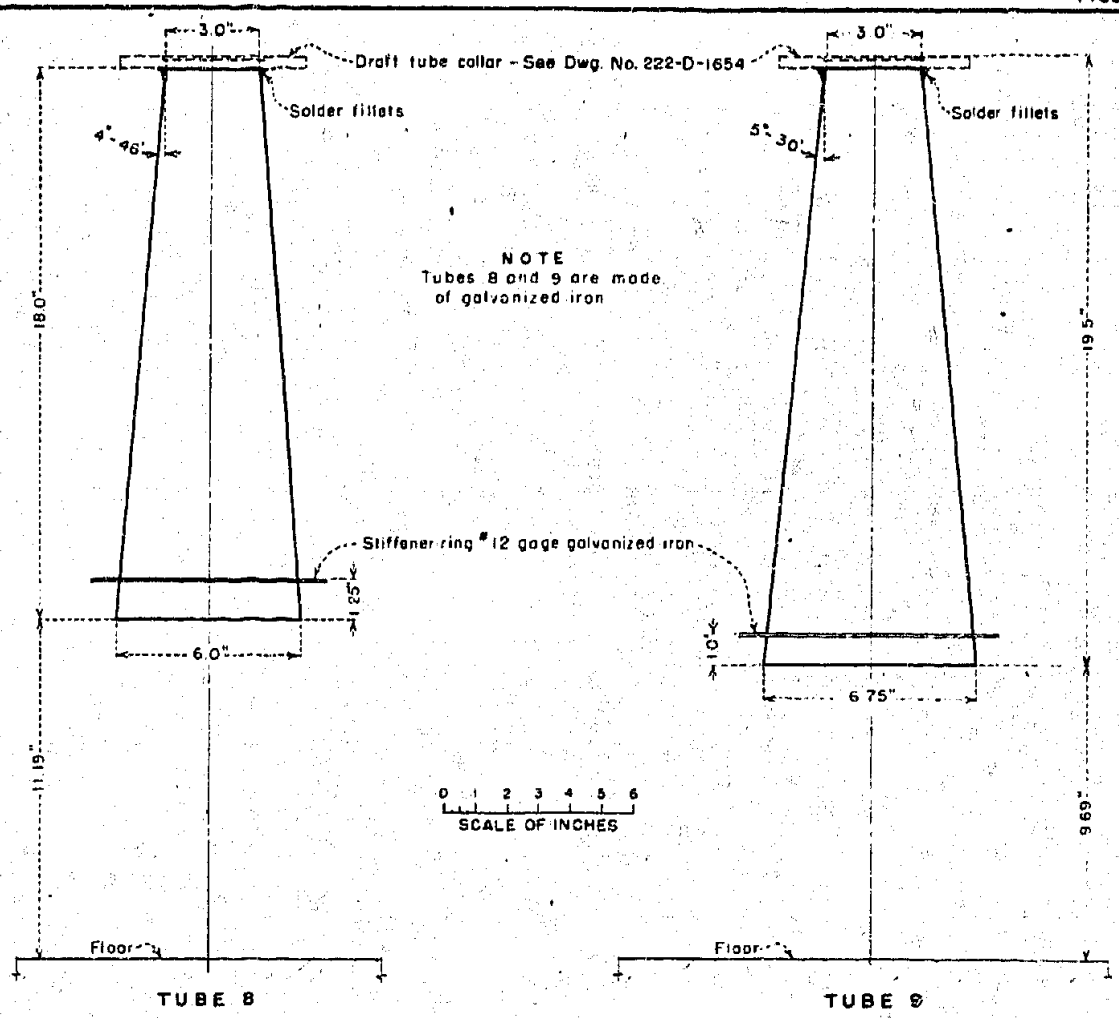
Model 6-A shown by dotted lines
Dimensions shown on plan are for model 6-A
For dimensions of model 6 see dwg. No. 222-D-1660
Center lines shown are those of model 6
Floor of model 6-A same as model 6

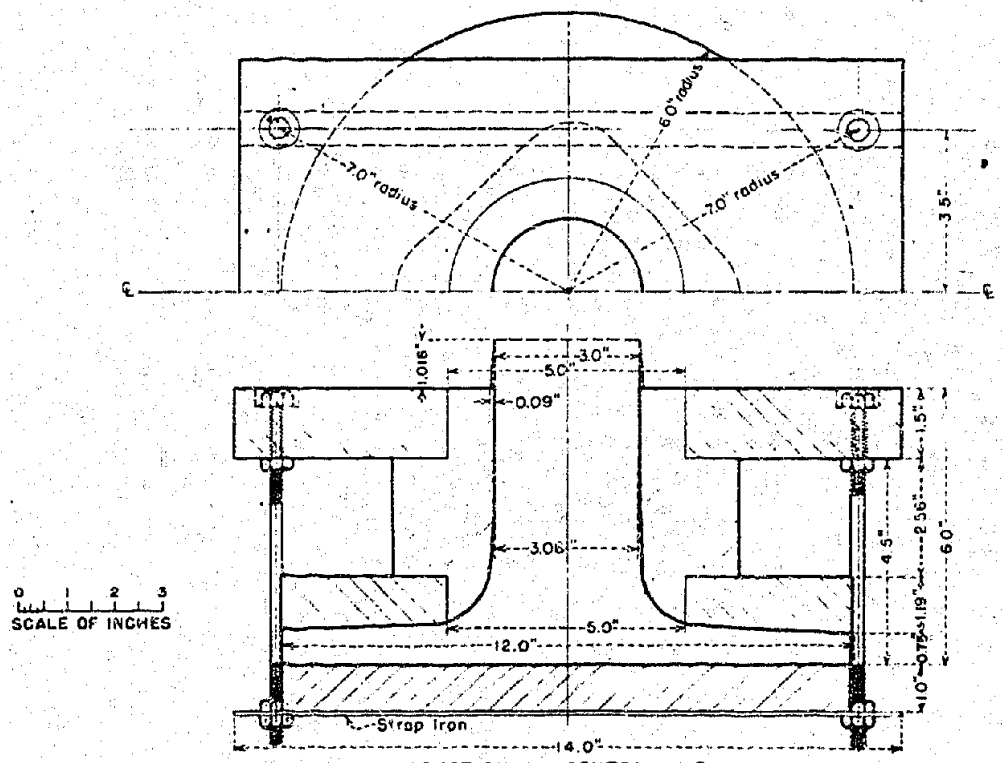
GRAND COULEE DRAFT TUBE MODEL TESTS

MODEL 6-A

222-D-1661

FIGURE 10



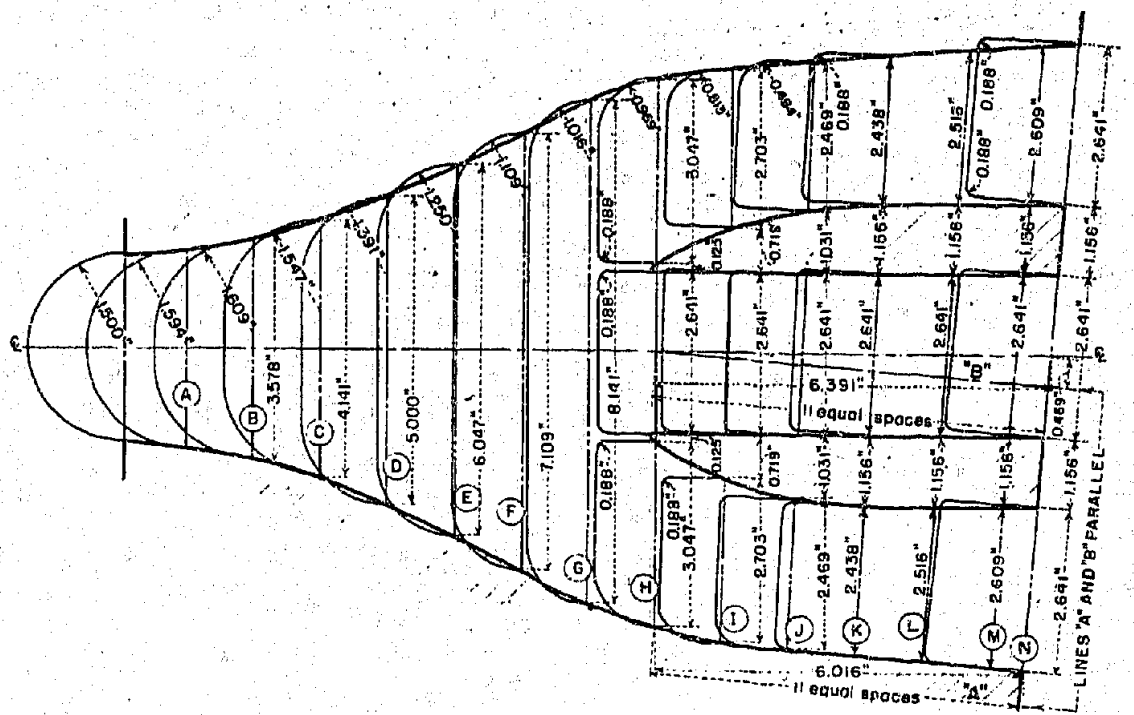


SECTION ON CENTER-LINE
TUBE 7

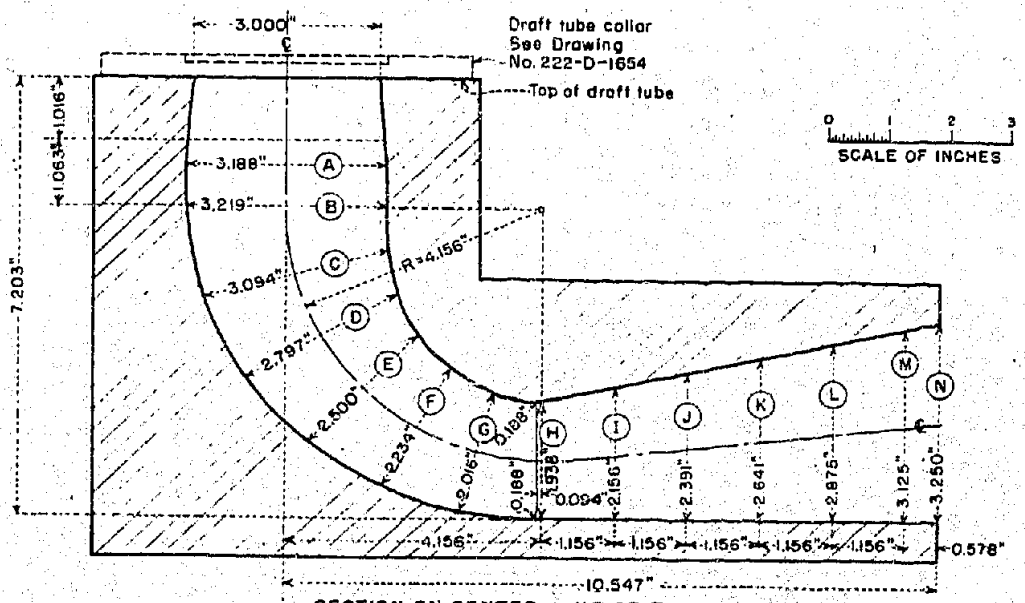
GRAND COULEE DRAFT TUBE MODEL TESTS
MODELS 7, 8, AND 9

222-D-1662

FIGURE 11

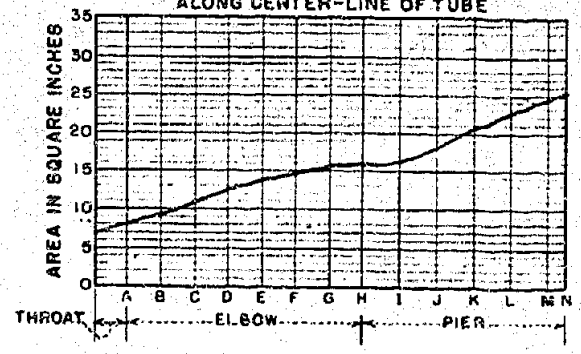


DEVELOPED PLAN OF TUBE ON CENTER-LINE



SECTION ON CENTER-LINE OF TUBE

CURVE SHOWING AREAS OF SECTIONS ALONG CENTER-LINE OF TUBE

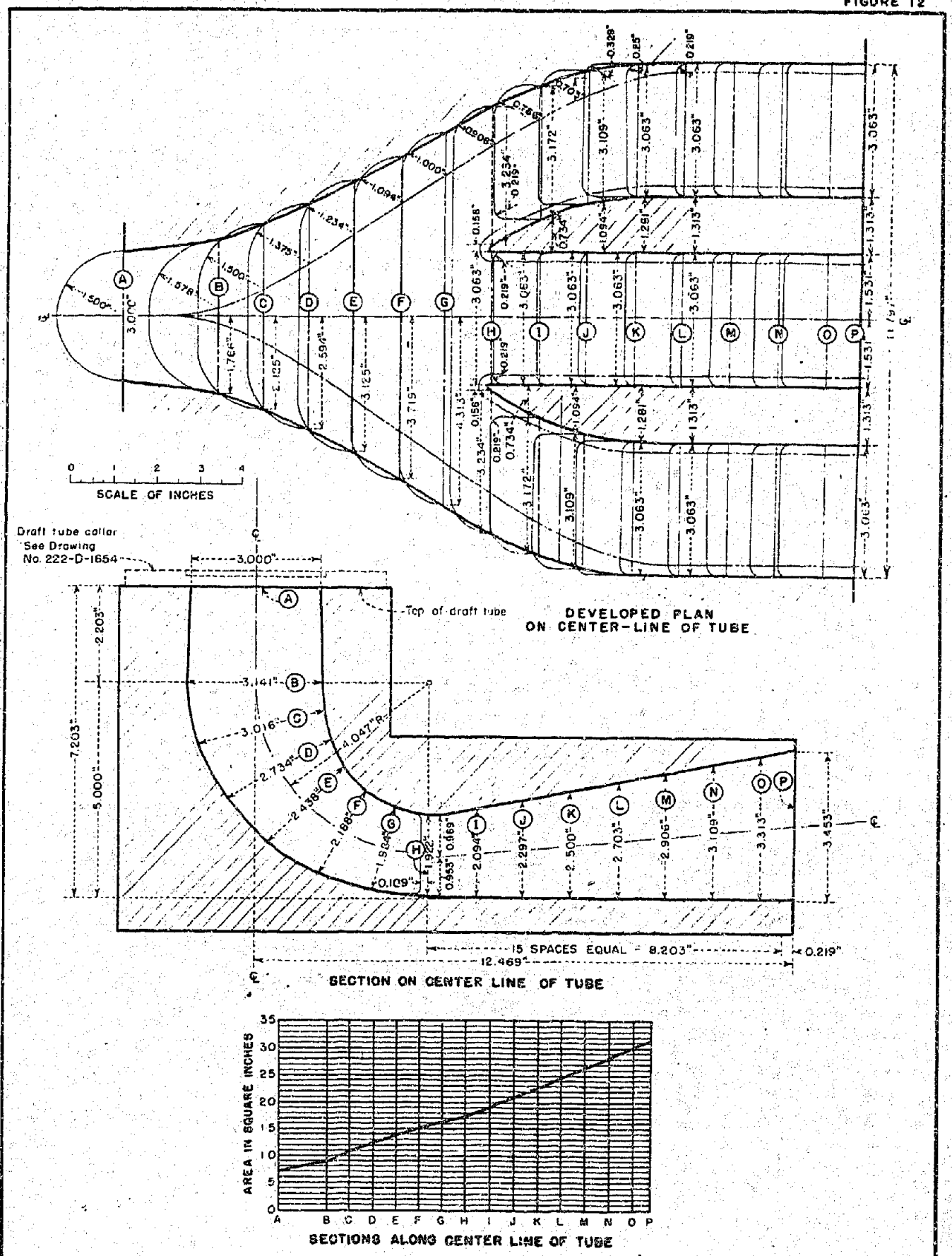


GRAND COULEE DRAFT TUBE MODEL TESTS

MODEL 10

222-D-1663

FIGURE 12

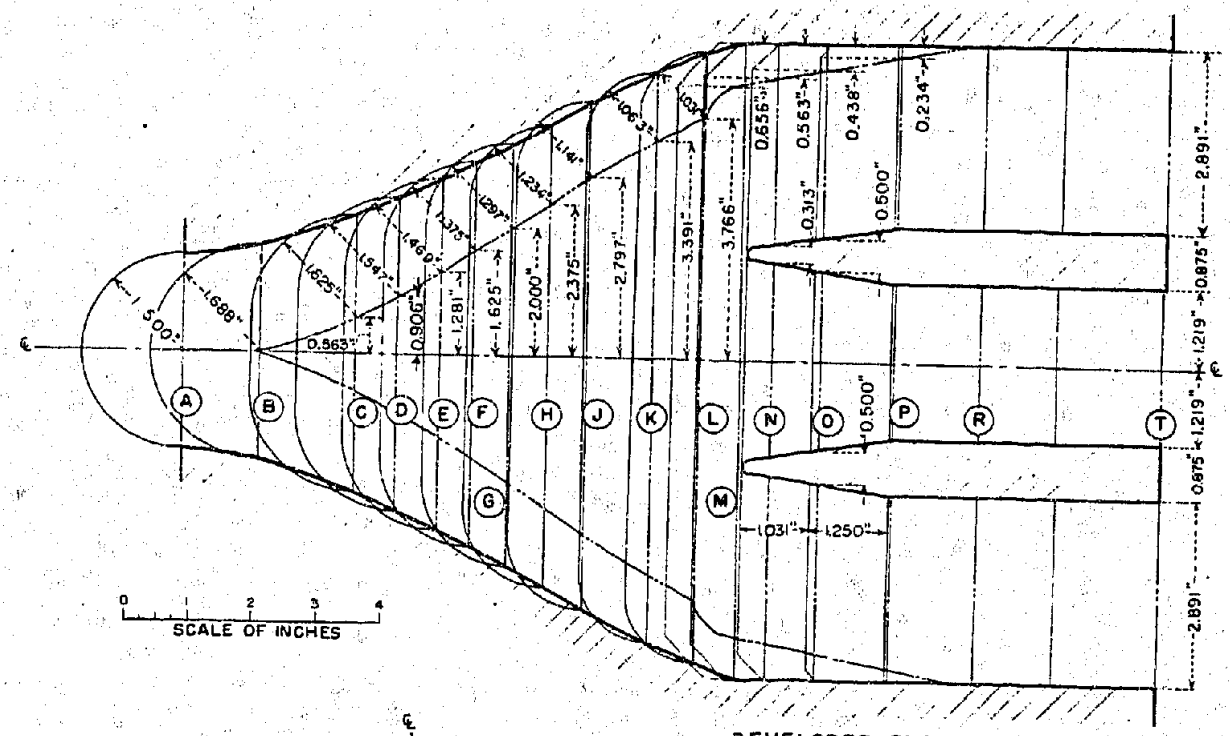


GRAND COULEE DRAFT TUBE MODEL TESTS

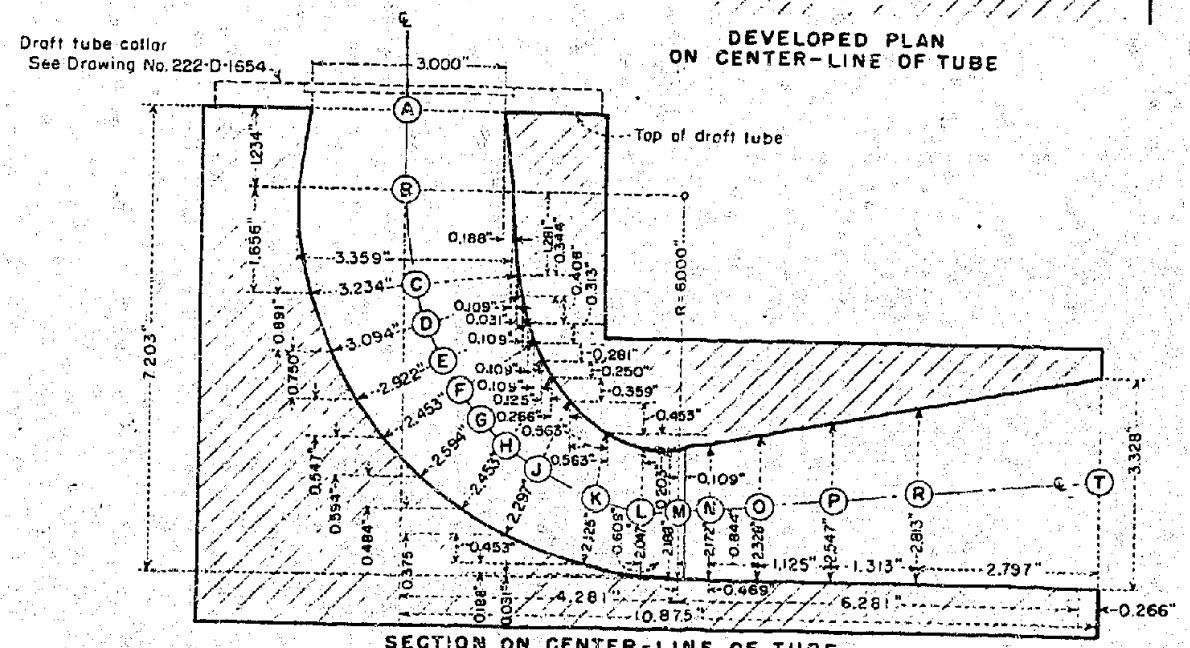
MODEL II (NORRIS TYPE)

222-D-1664

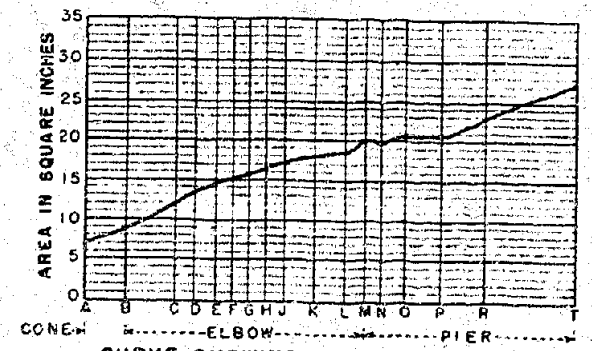
FIGURE 13



DEVELOPED PLAN
ON CENTER-LINE OF TUBE



SECTION ON CENTER-LINE OF TUBE

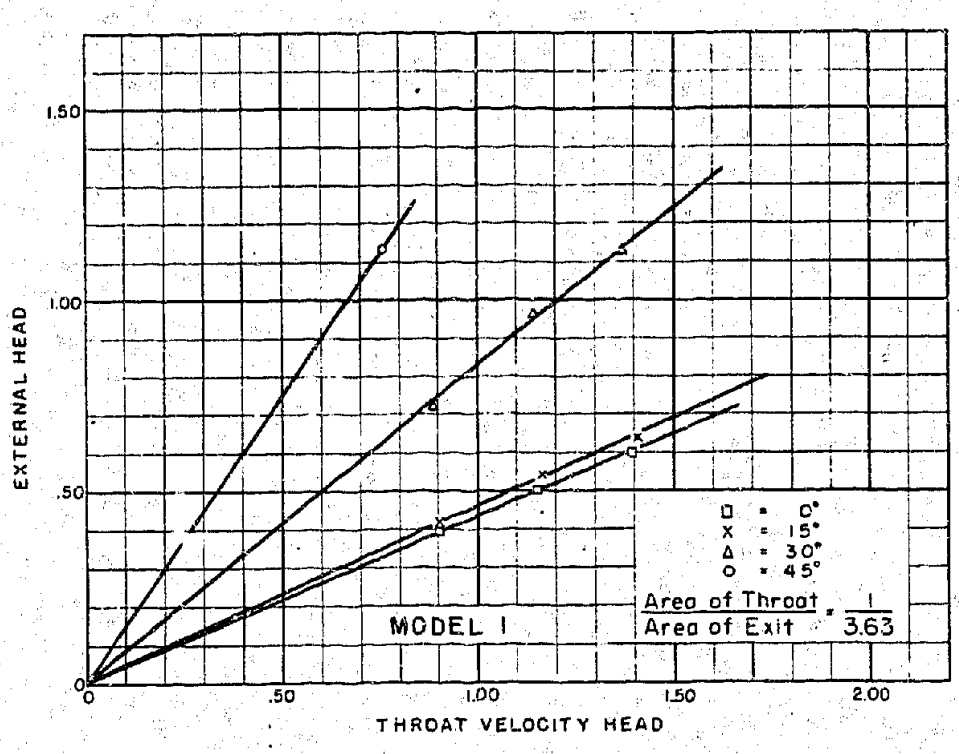


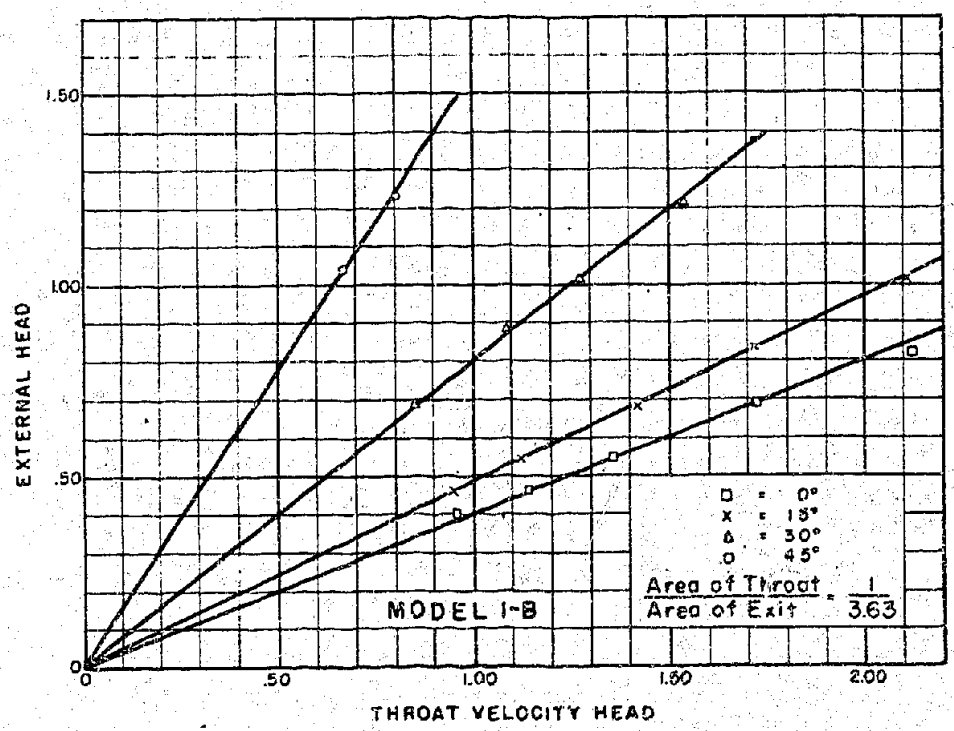
CURVE SHOWING AREAS OF SECTIONS
ALONG CENTER-LINE OF TUBE

GRAND COULEE DRAFT TUBE MODEL TESTS
MODEL 12 (LOWER TALLASSEE TYPE)

222-D-1665

FIGURE 14

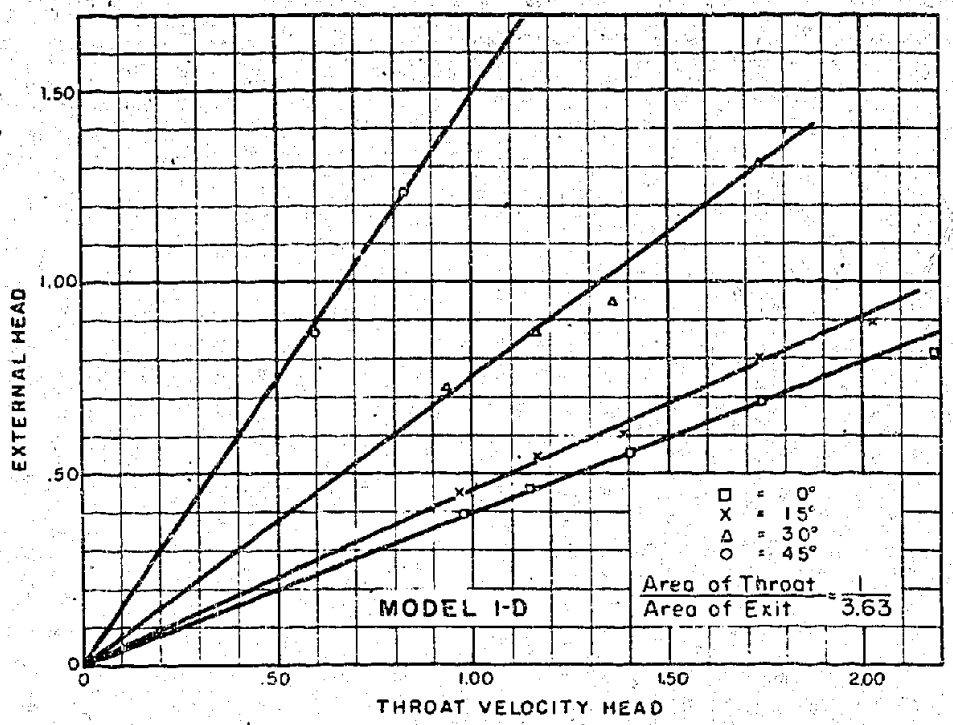


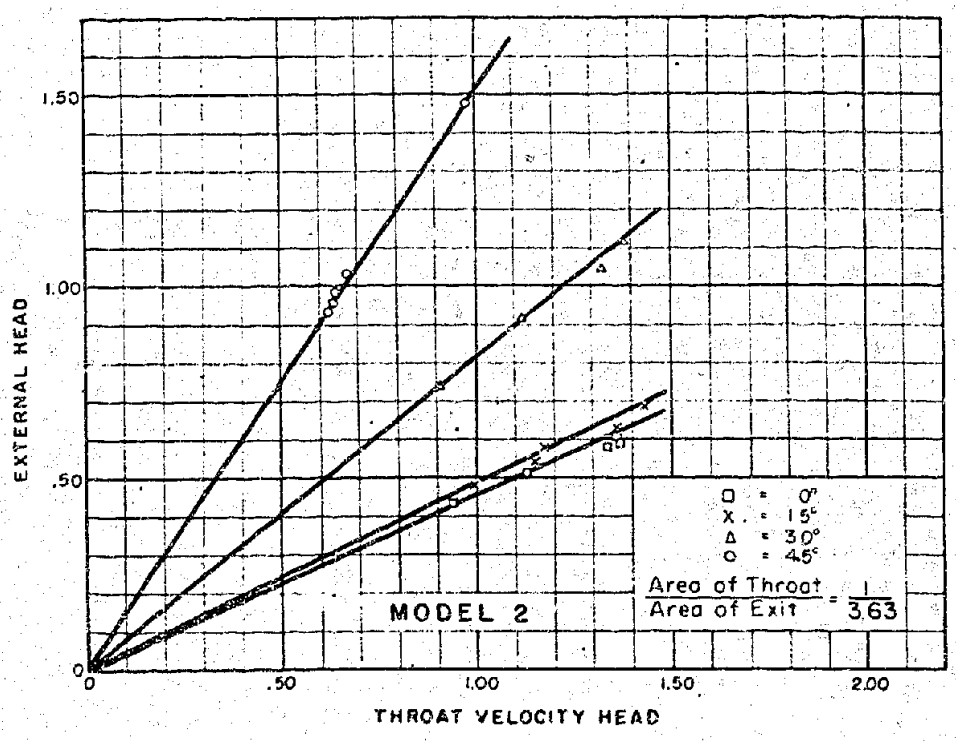


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

222-D-1666

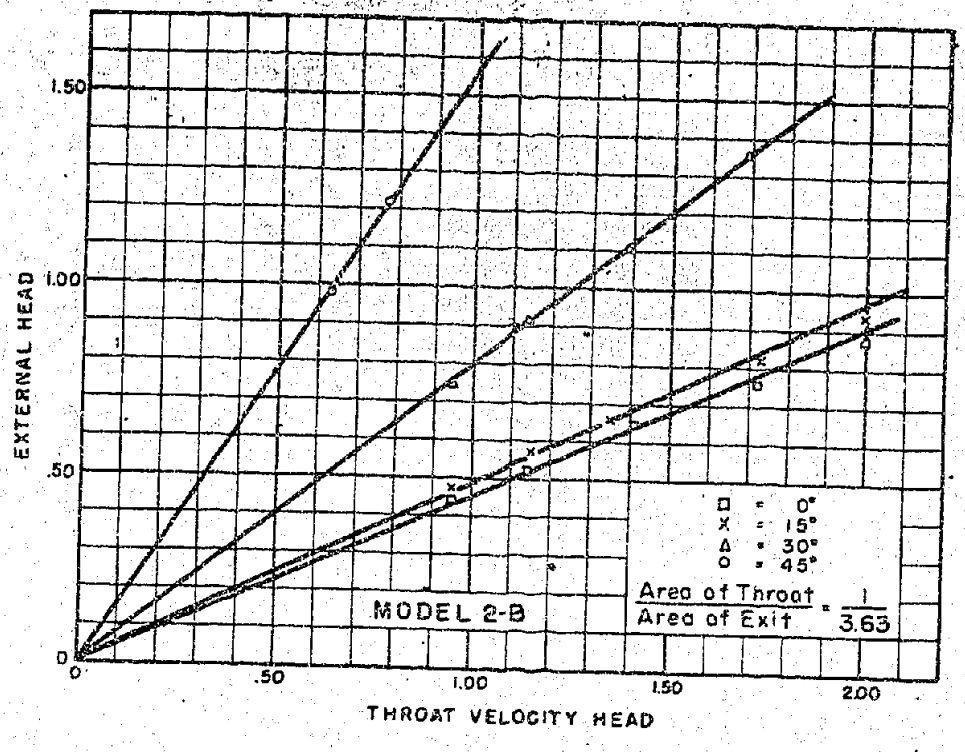


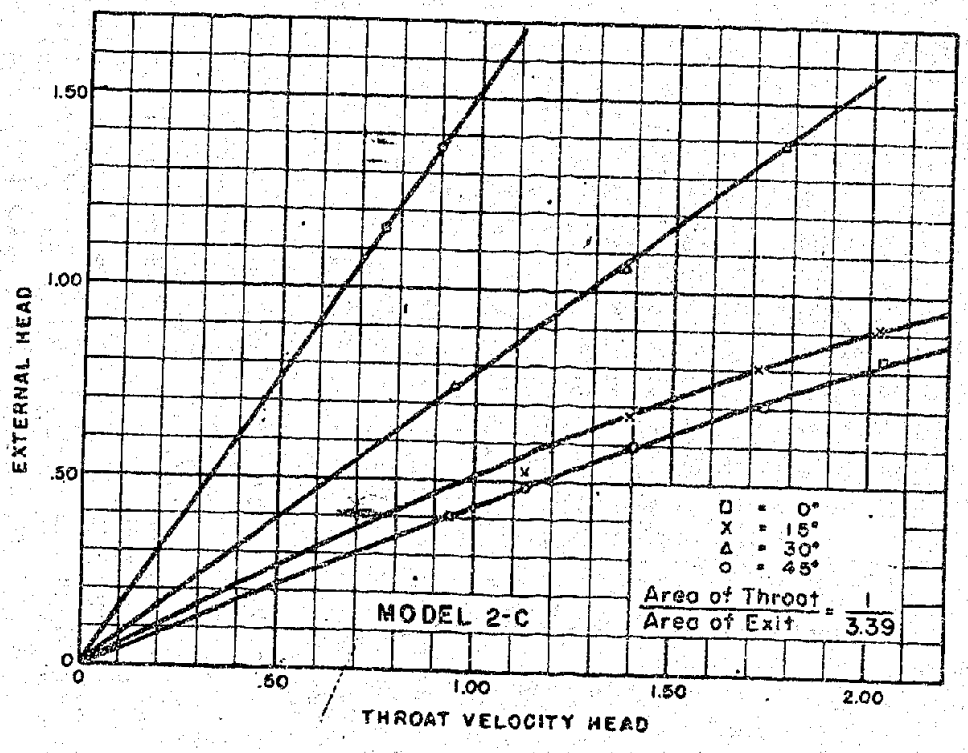


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

FIGURE 16

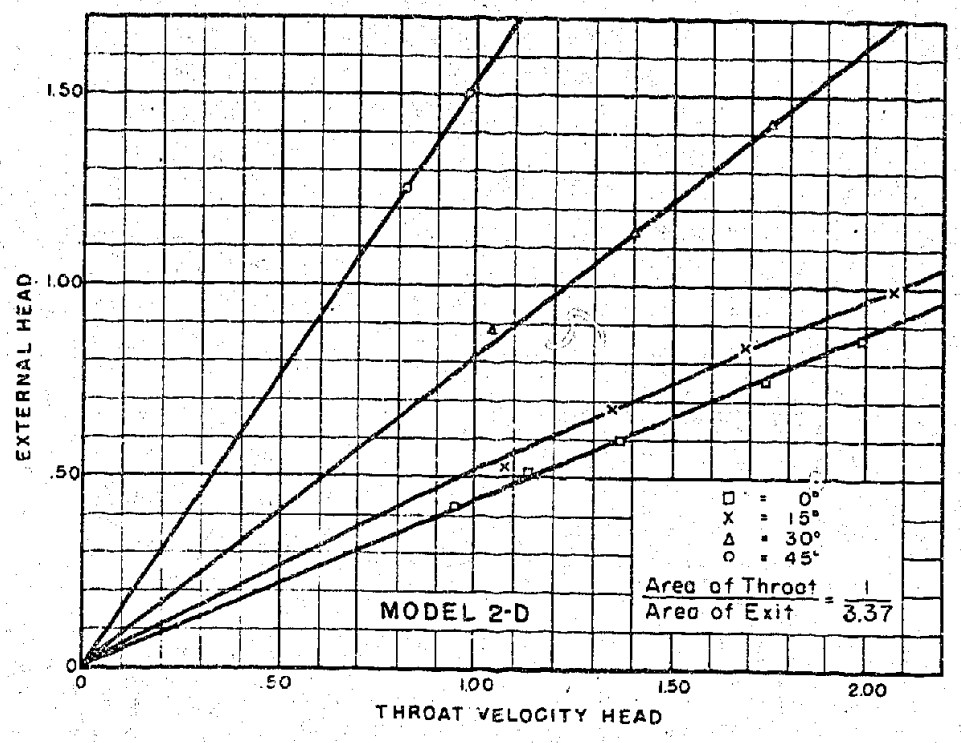


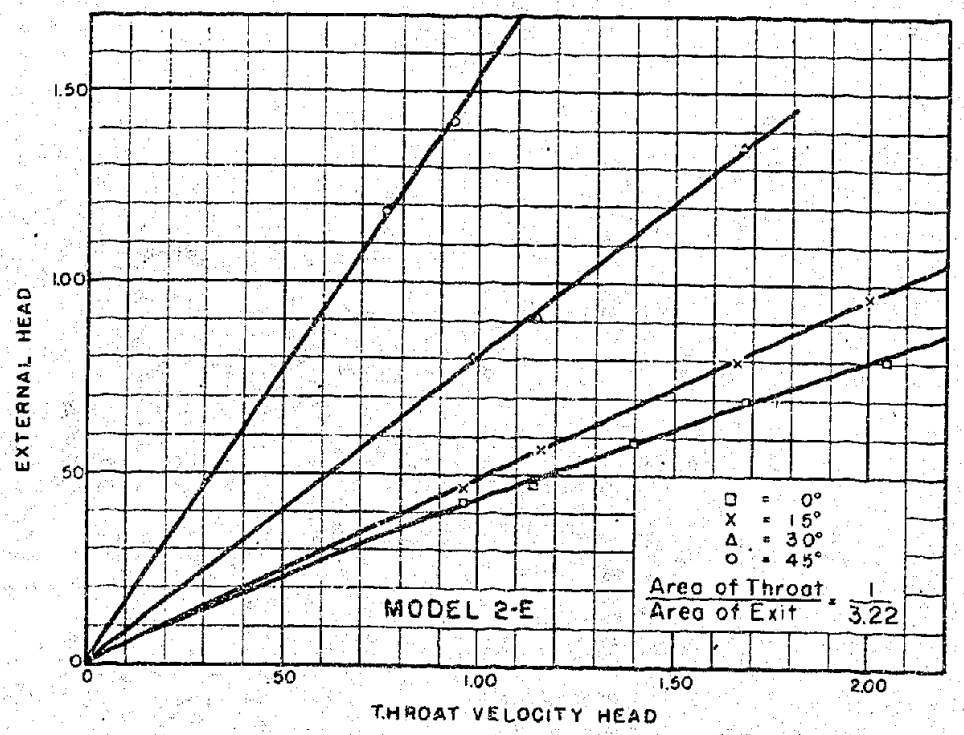


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

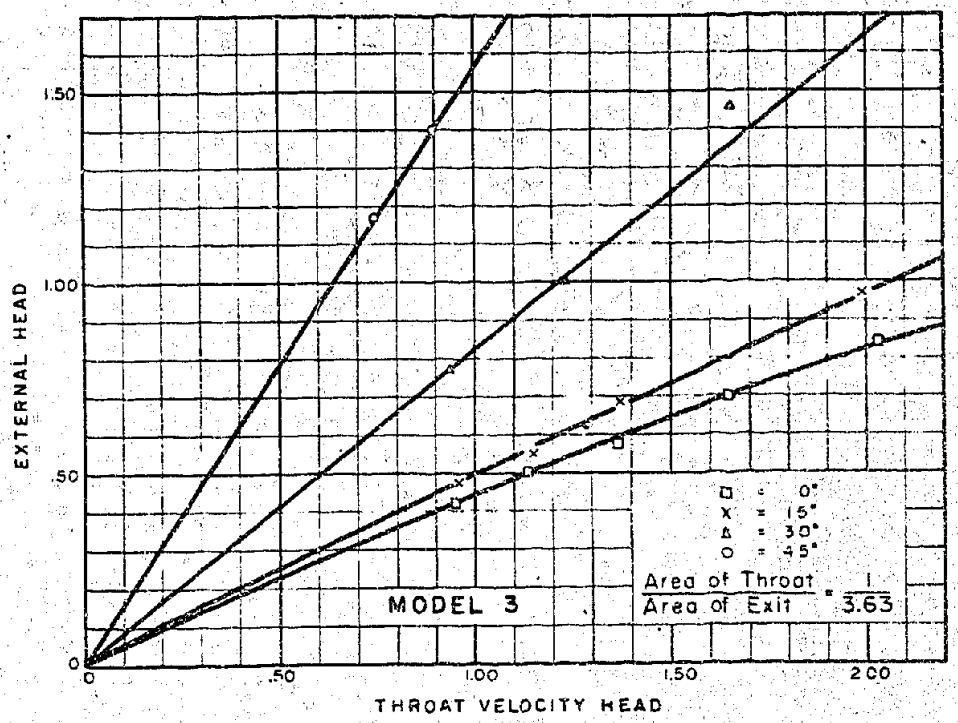
222-D-1668

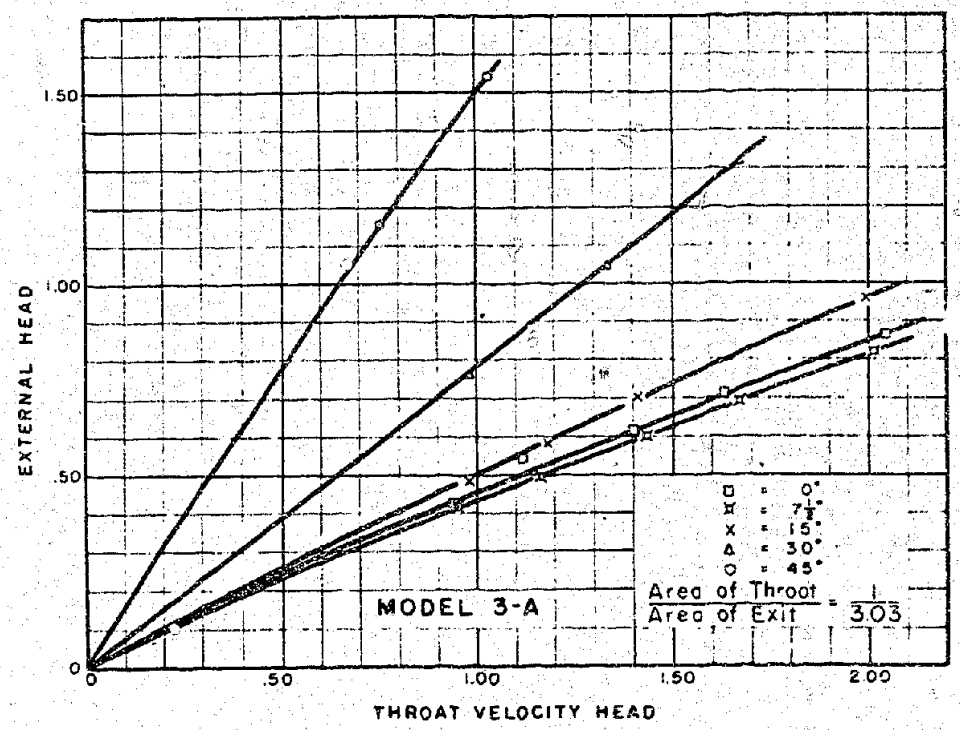




GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

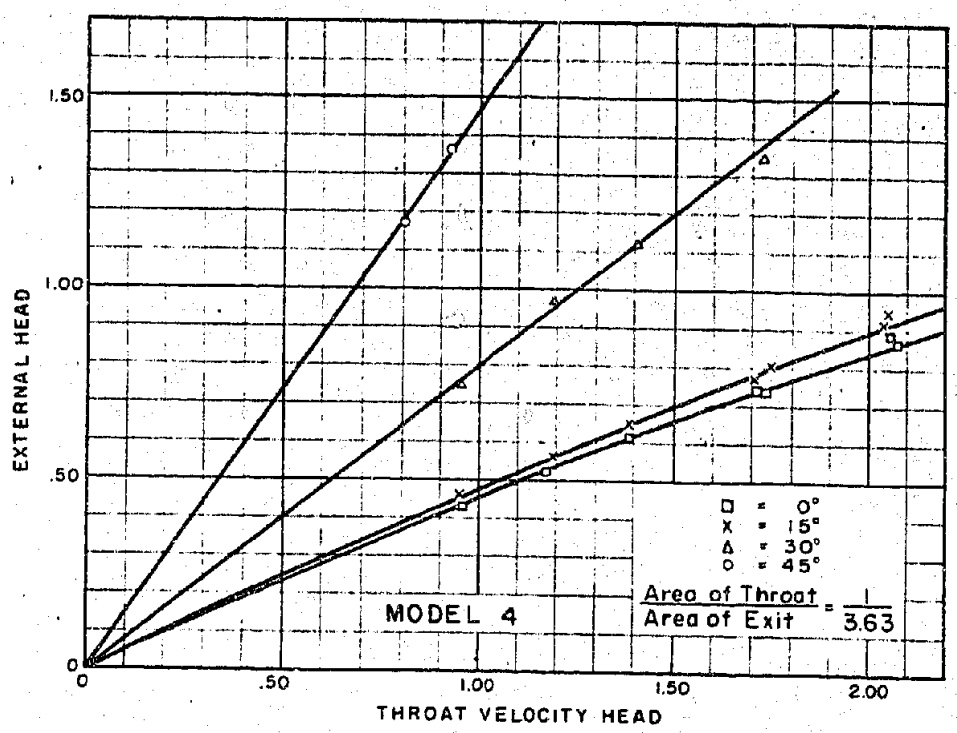


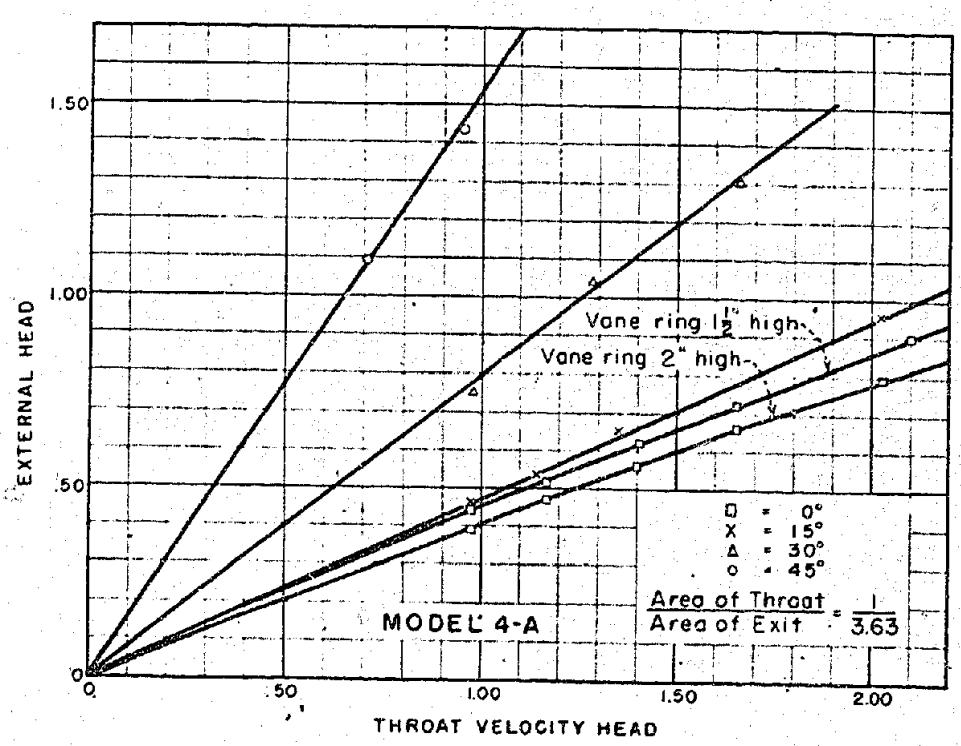


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

FIGURE 19

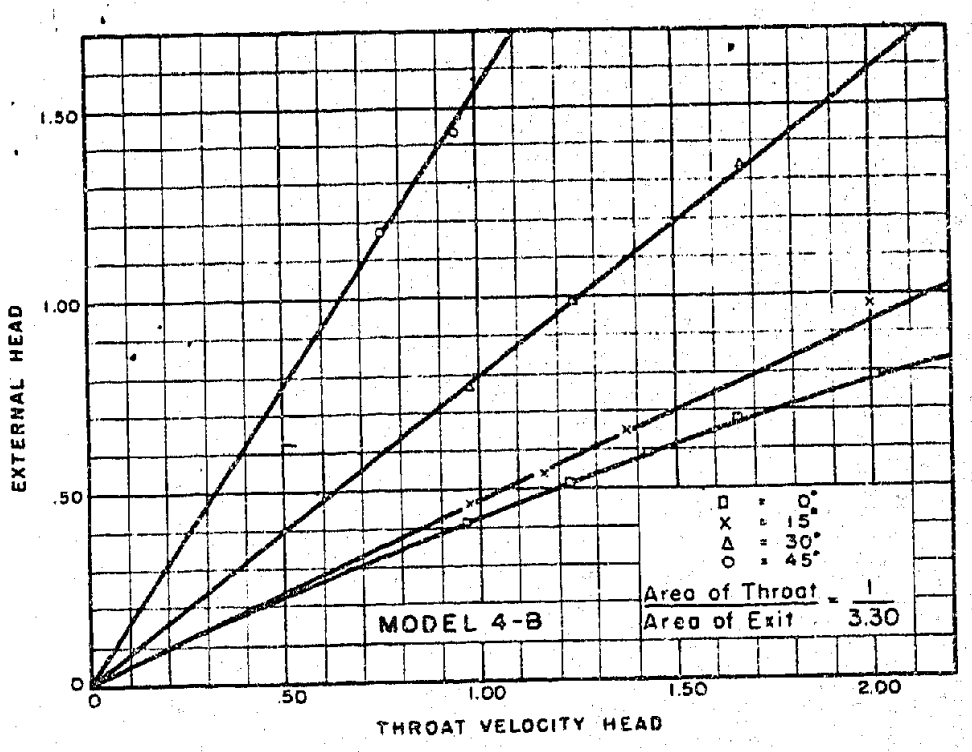


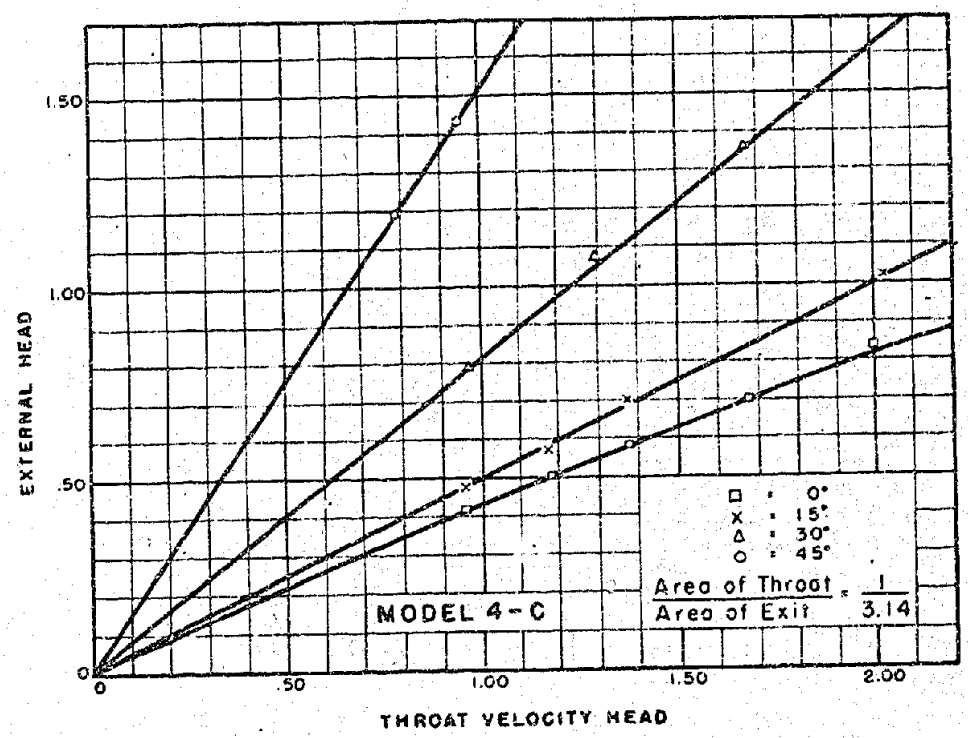


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

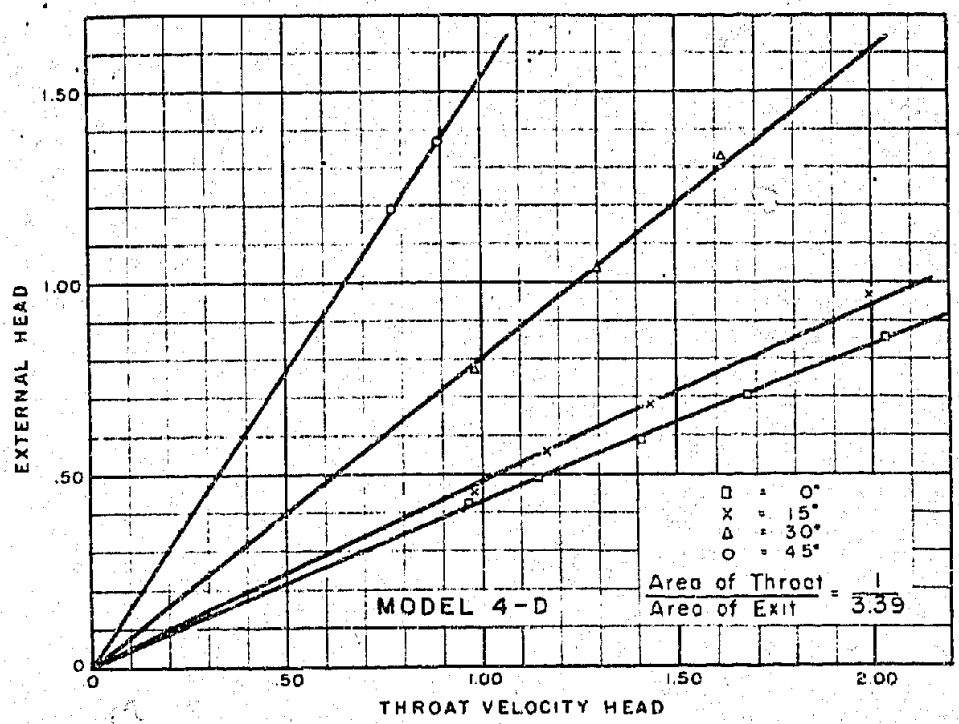
222-D-1671

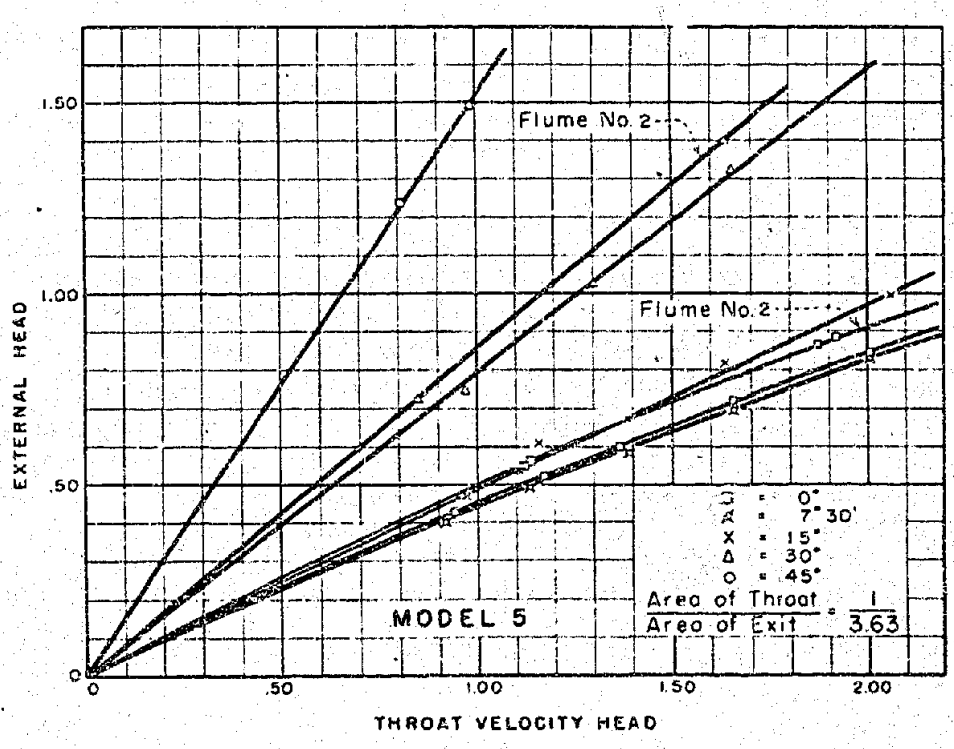




GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

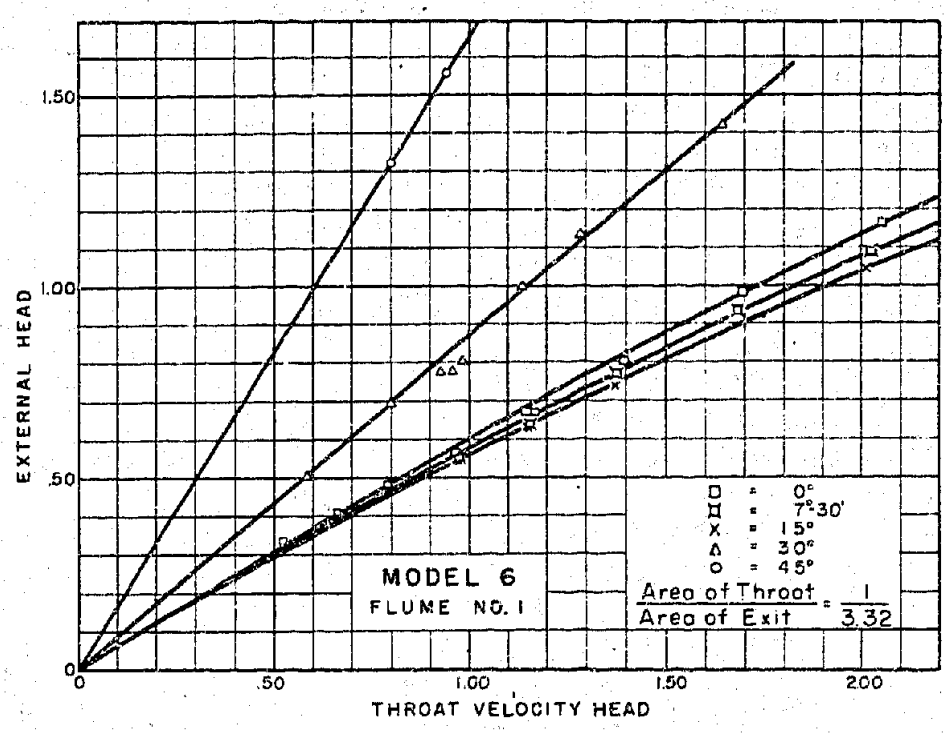


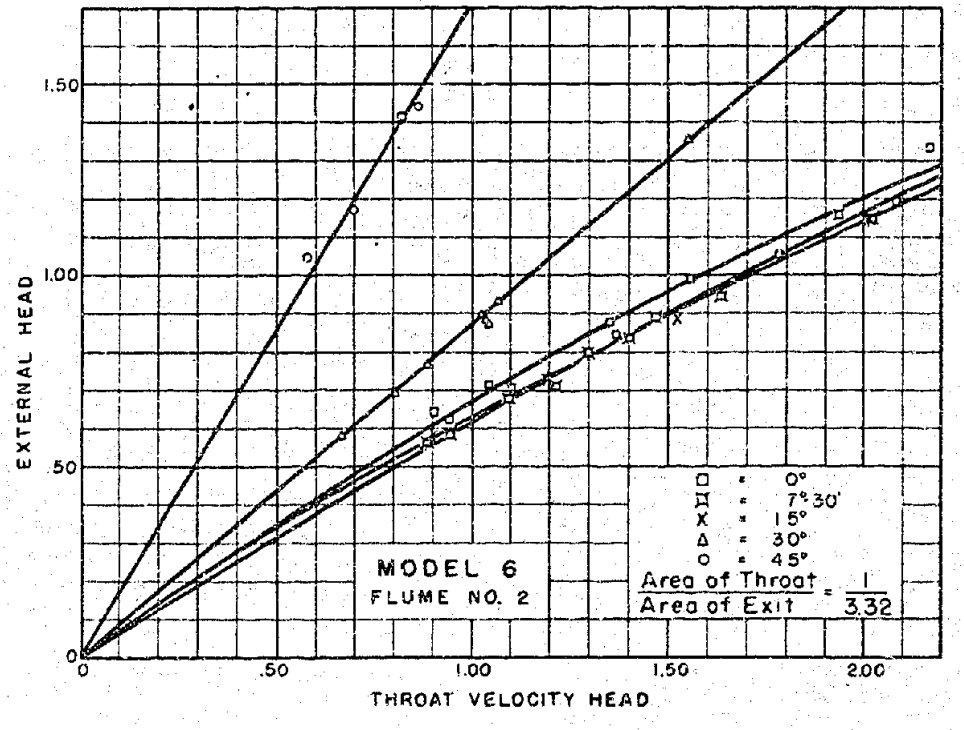


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

222-D-1673

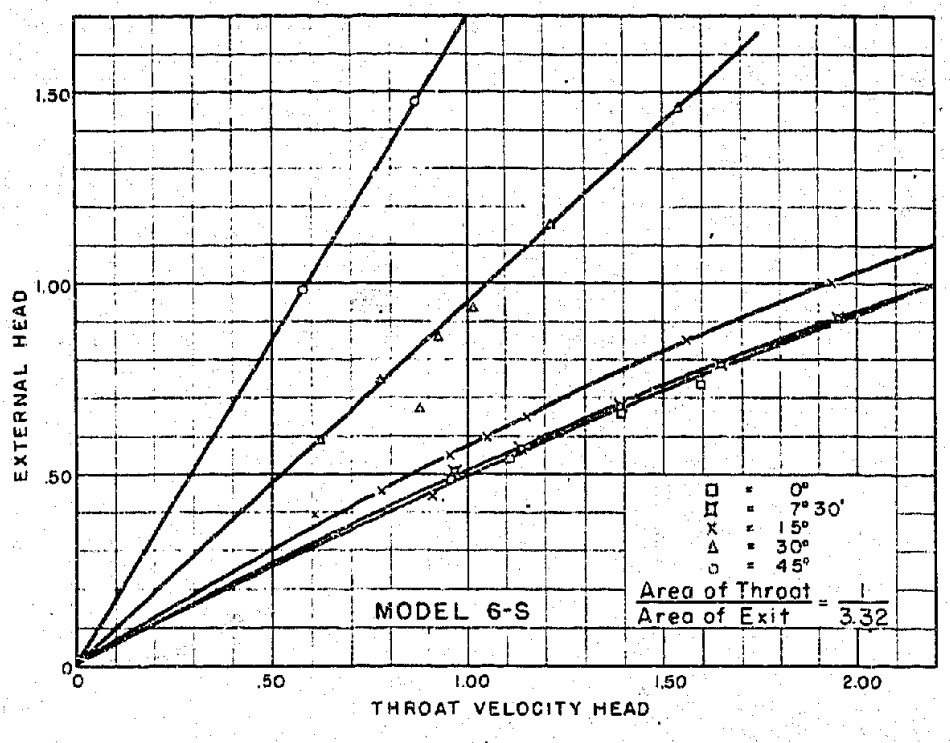


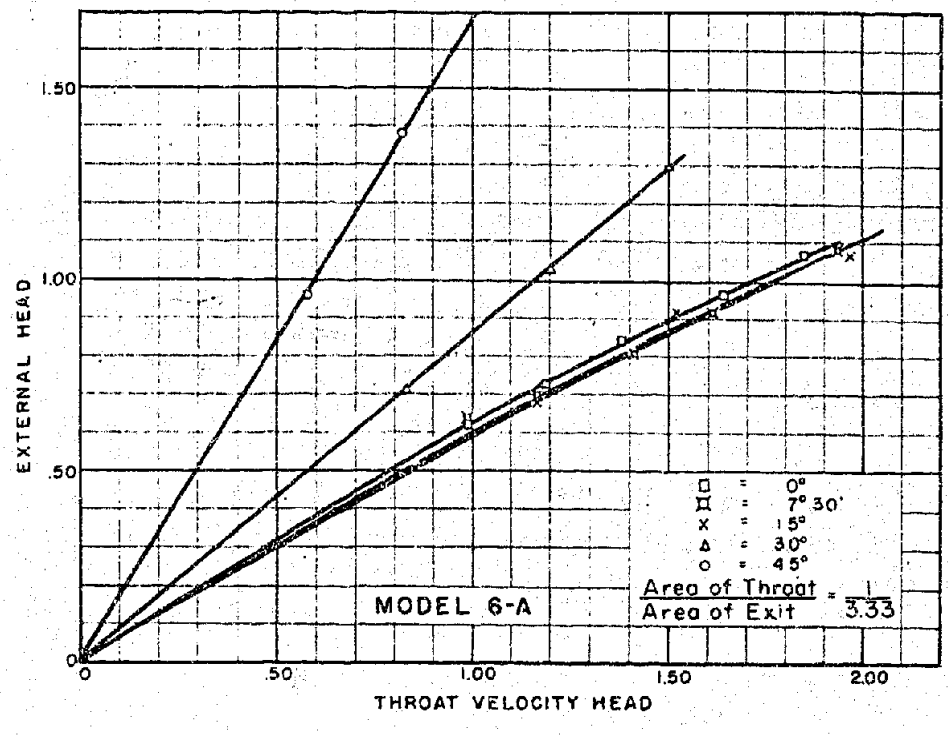


GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

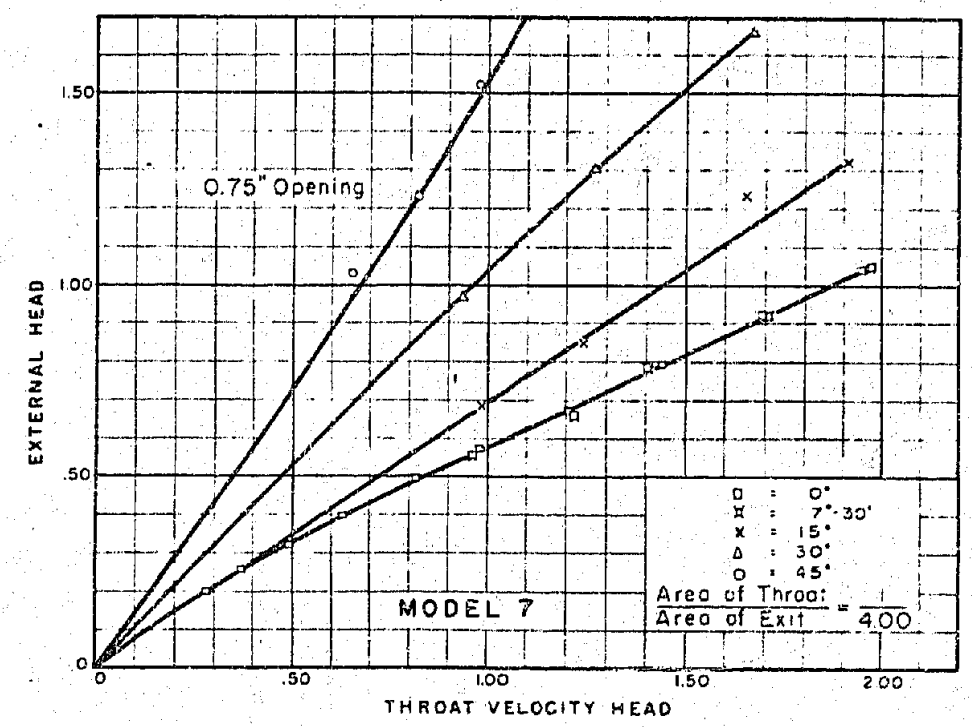
222-D-1674

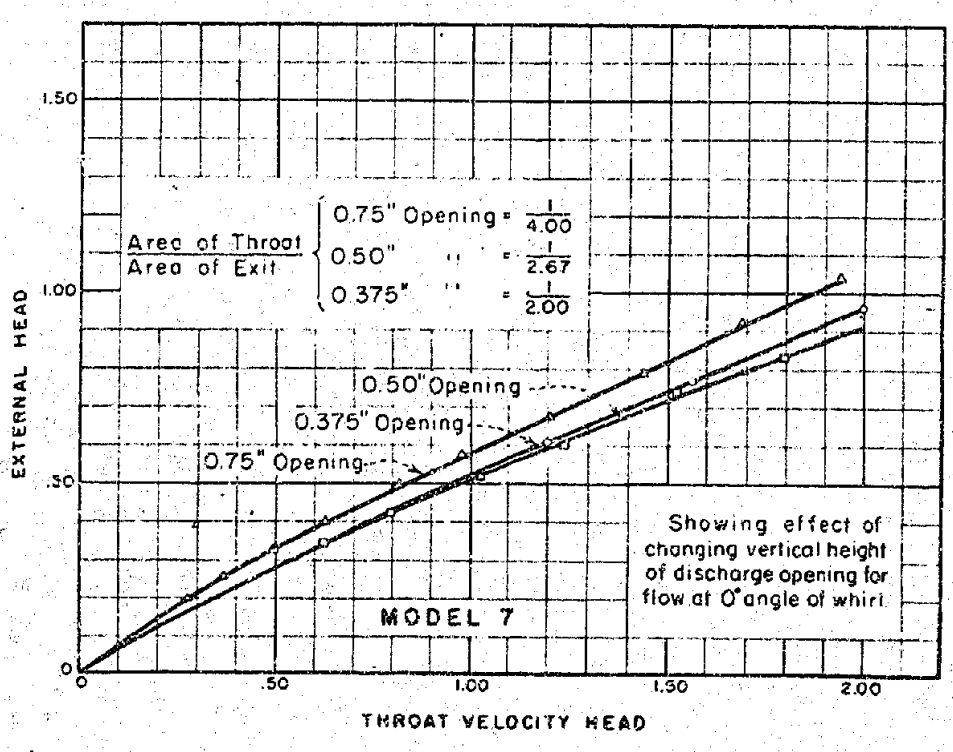




GRAND COULEE DRAFT TUBE MODEL TESTS

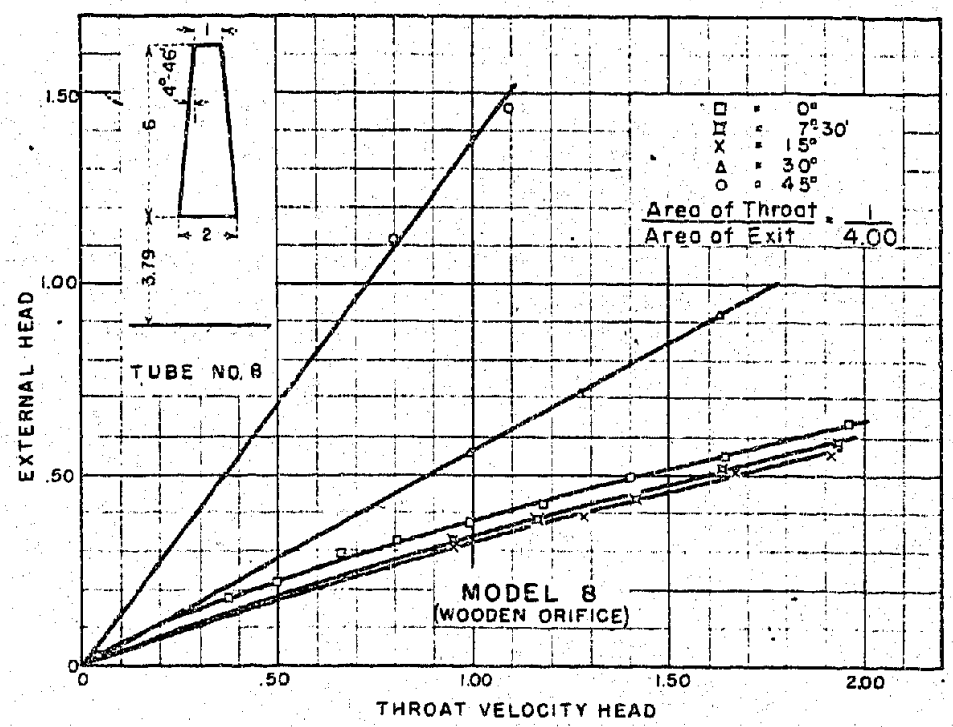
PERFORMANCE CURVES

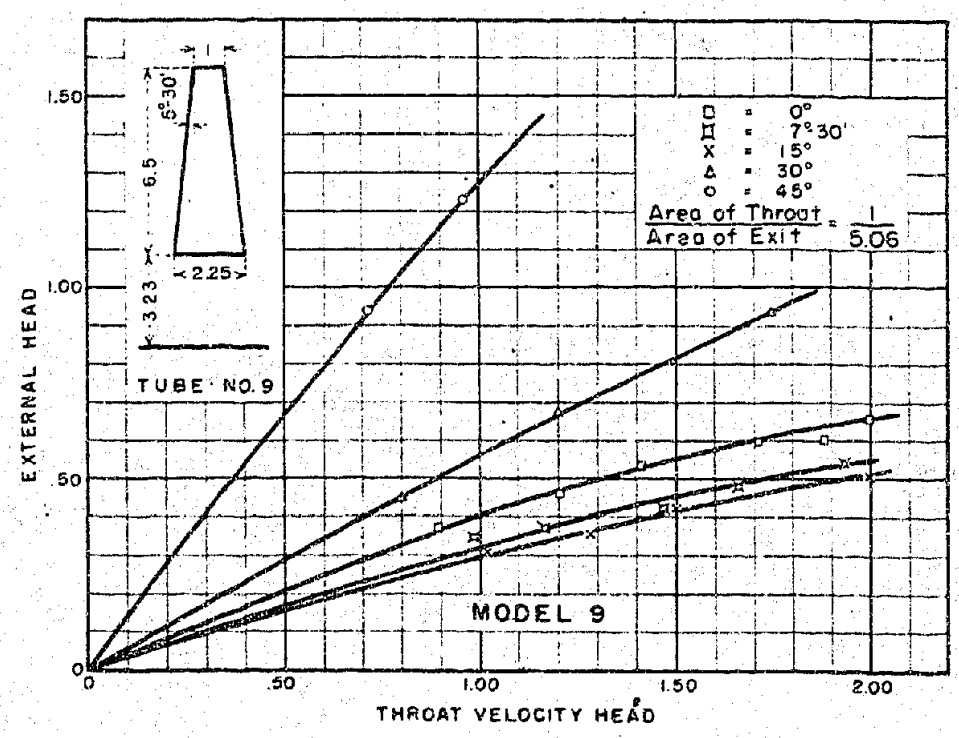




GRAND COULEE DRAFT TUBE MODEL TESTS

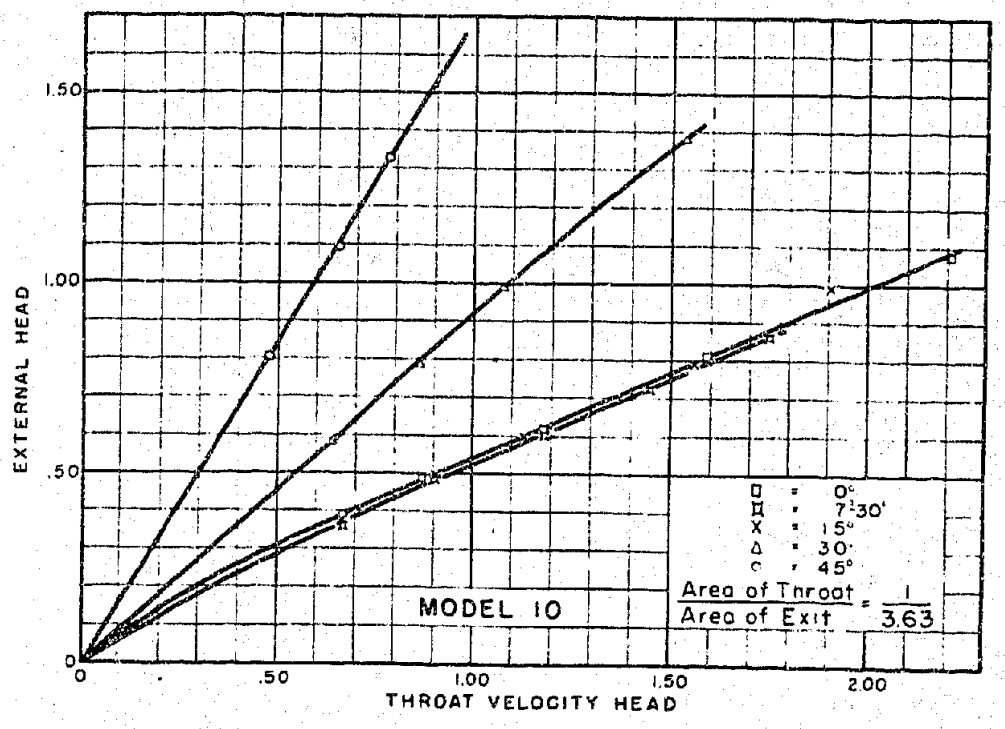
PERFORMANCE CURVES

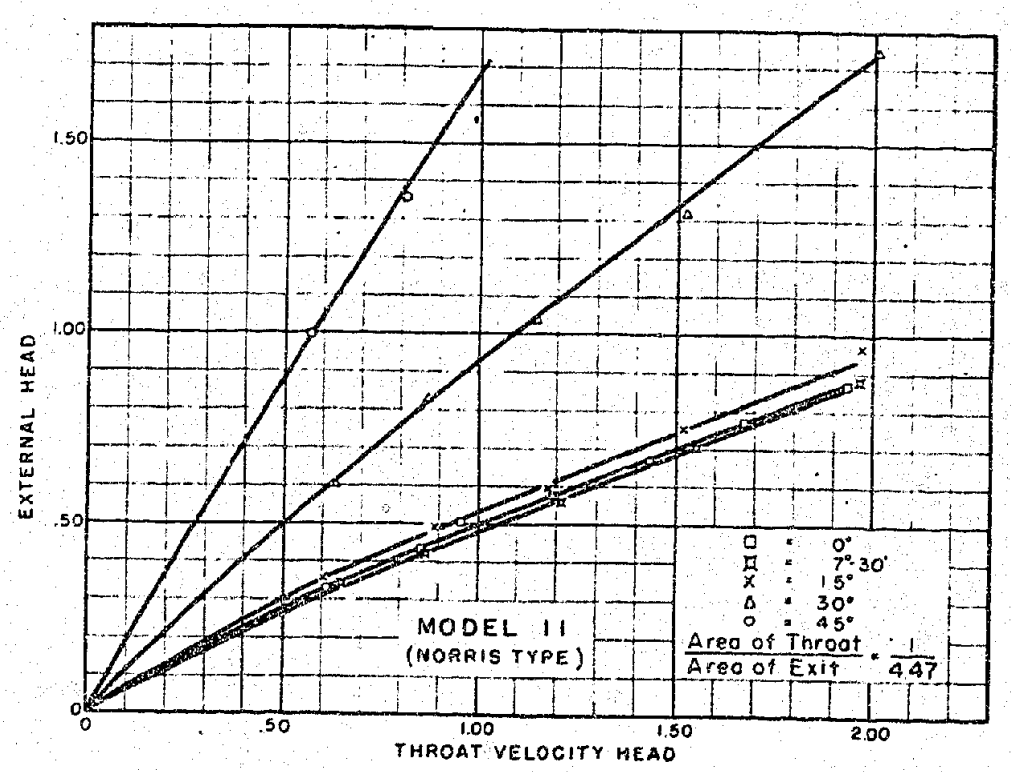




GRAND COULEE DRAFT TUBE MODEL TESTS

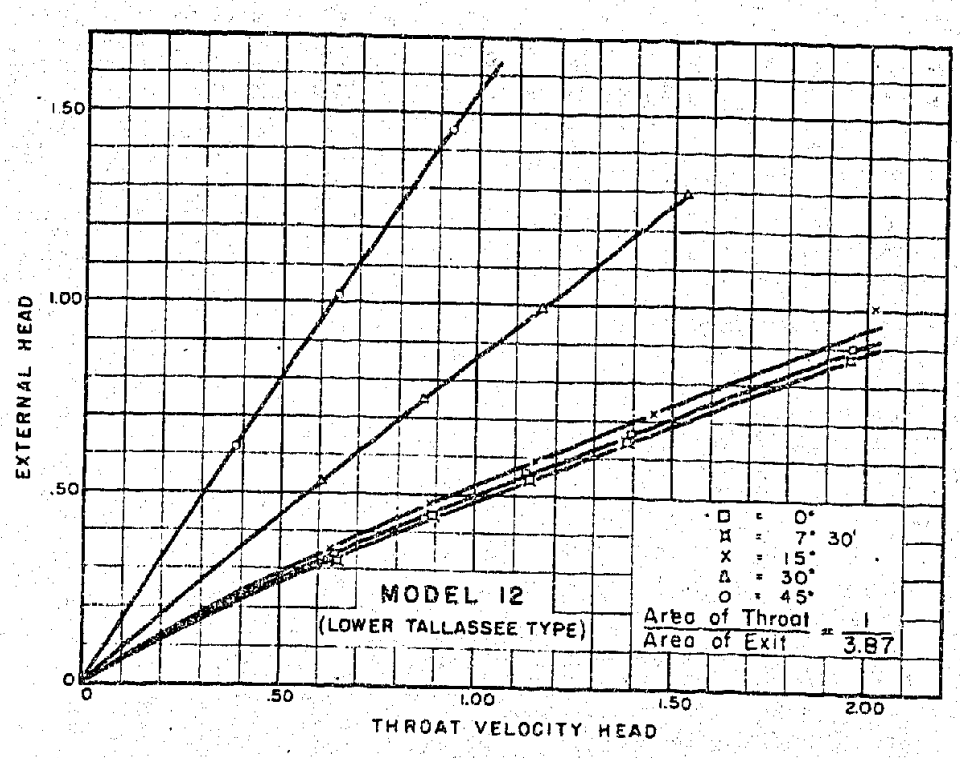
PERFORMANCE CURVES

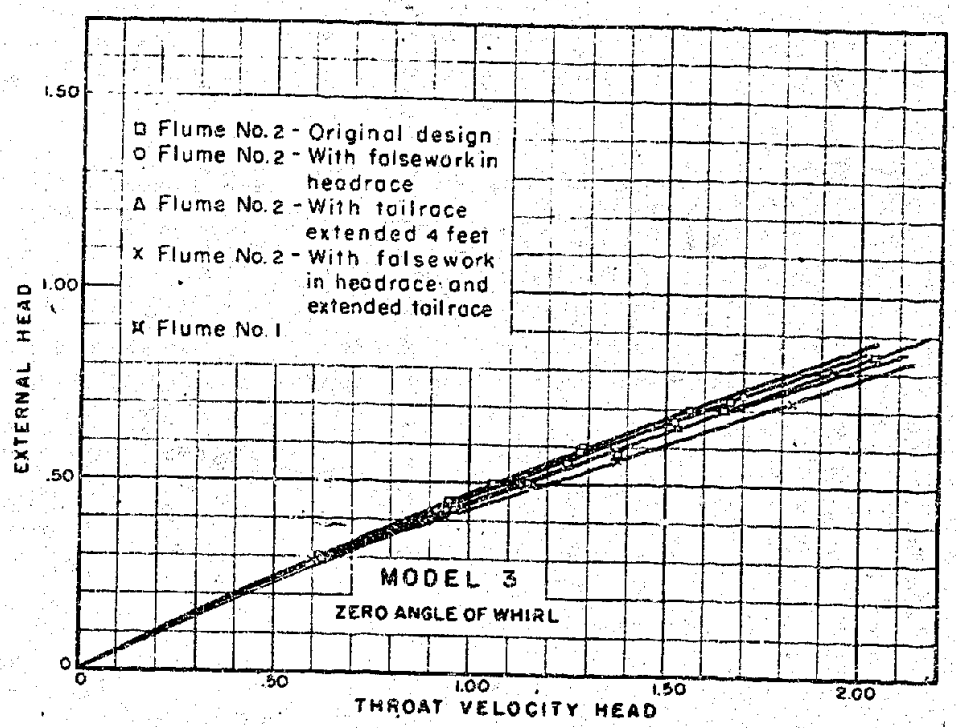




GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES

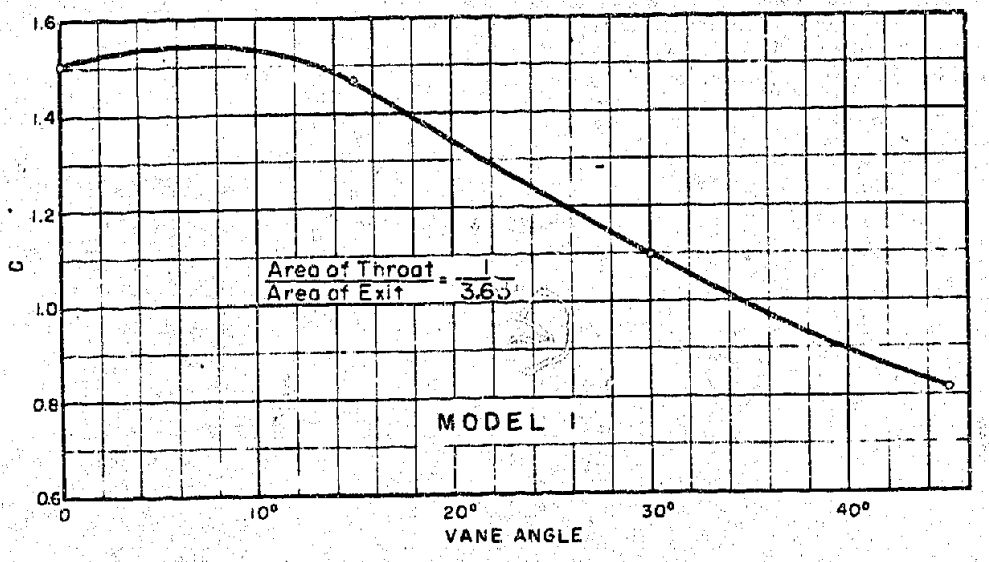


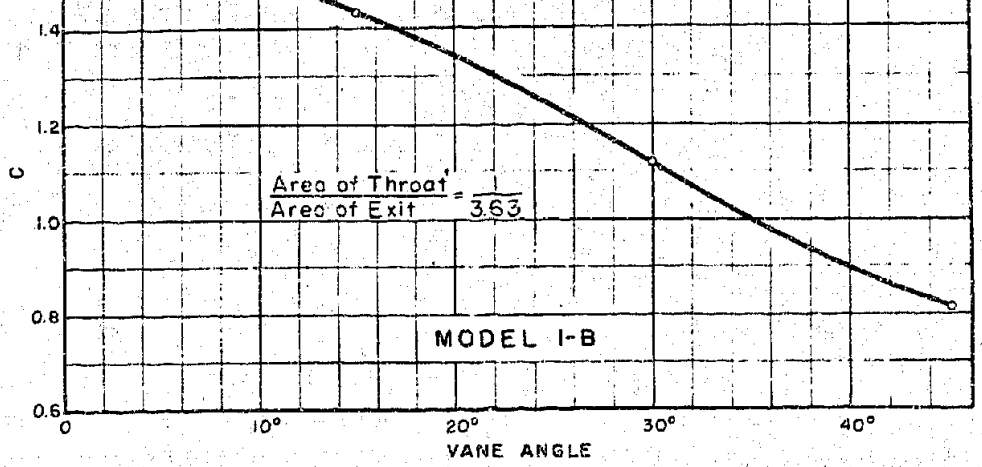


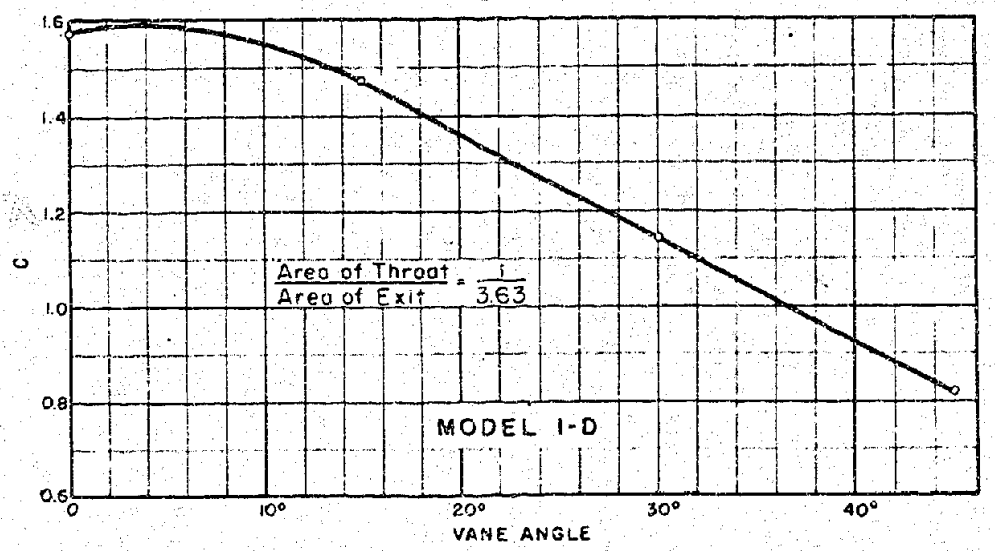
EFFECT OF TEST FLUMES ON TEST RESULTS

GRAND COULEE DRAFT TUBE MODEL TESTS

PERFORMANCE CURVES





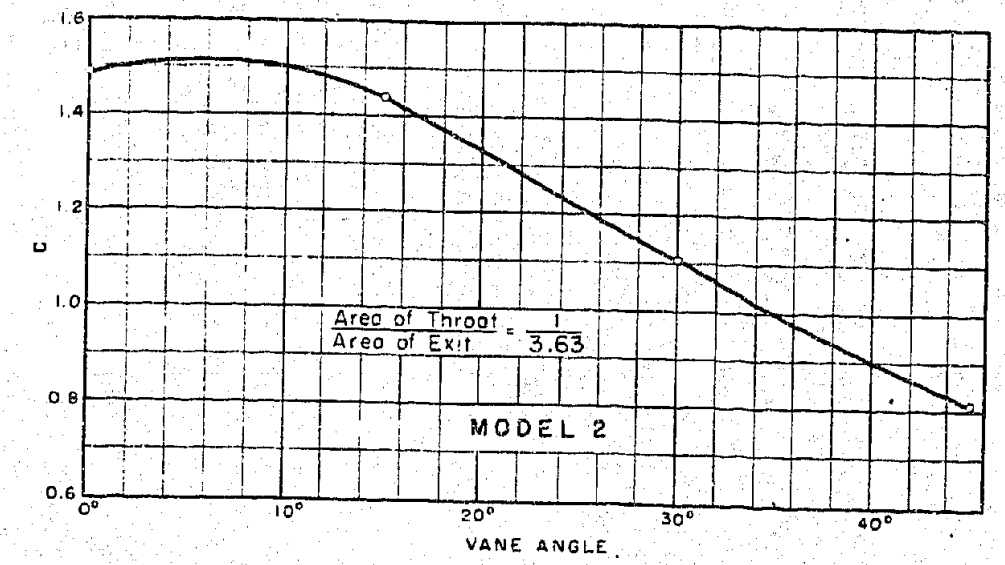


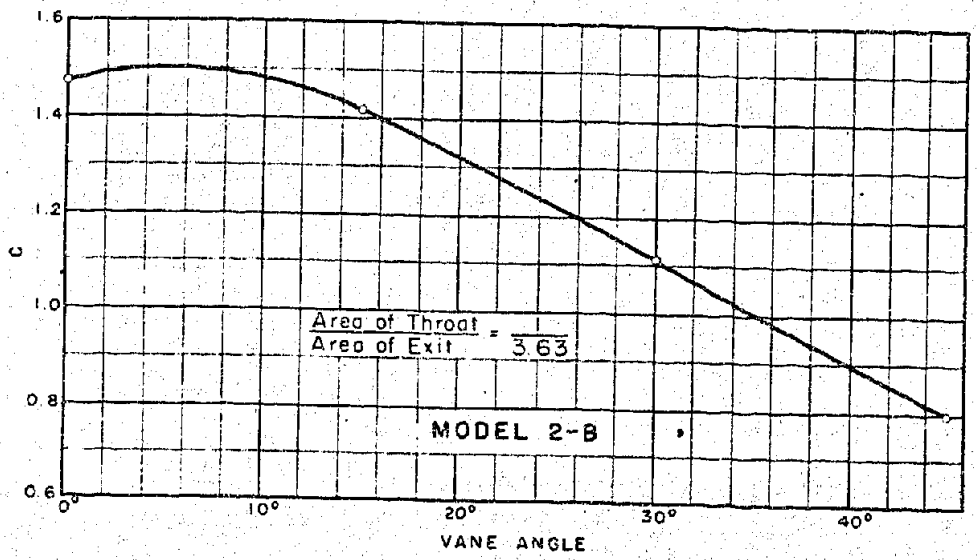
GRAND COULEE DRAFT TUBE MODEL TESTS

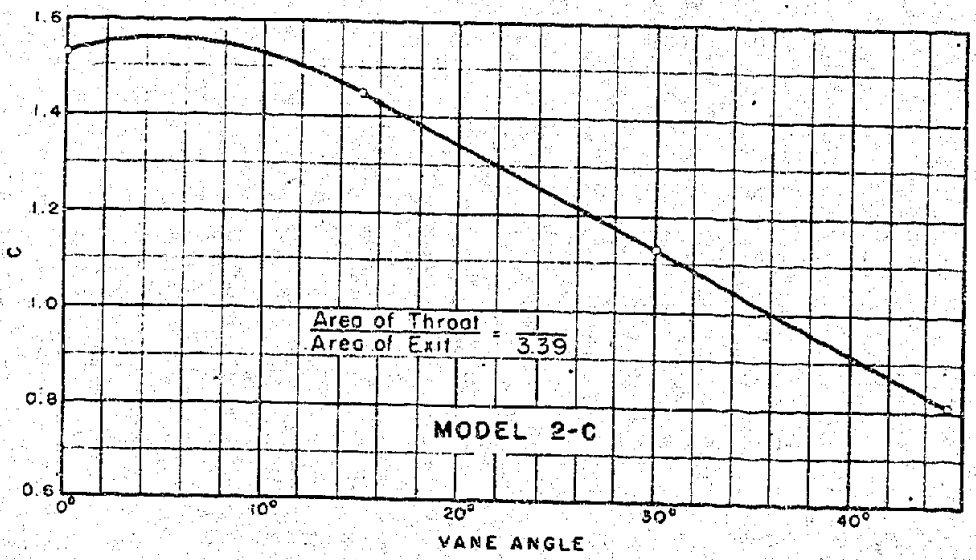
COEFFICIENT CURVES

222-D-1680

FIGURE 29





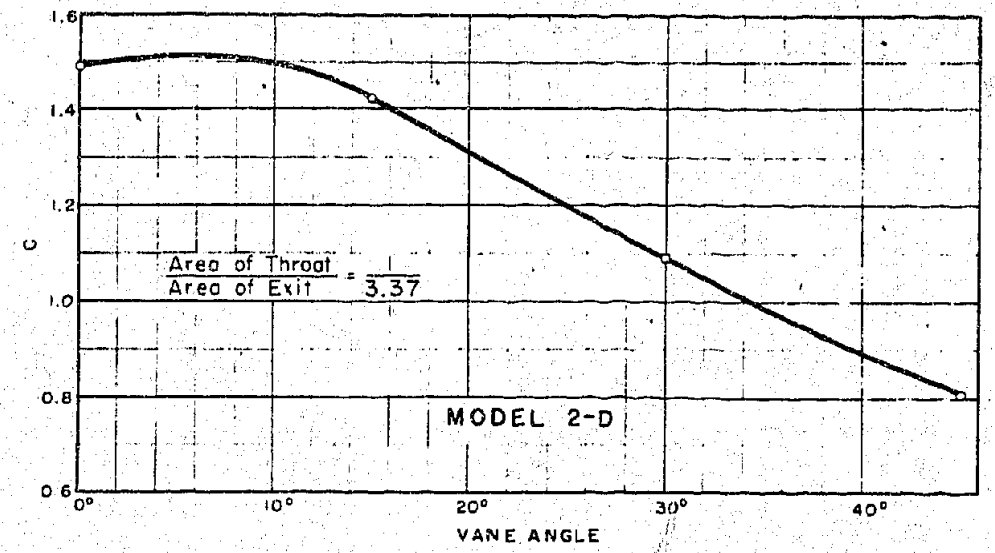


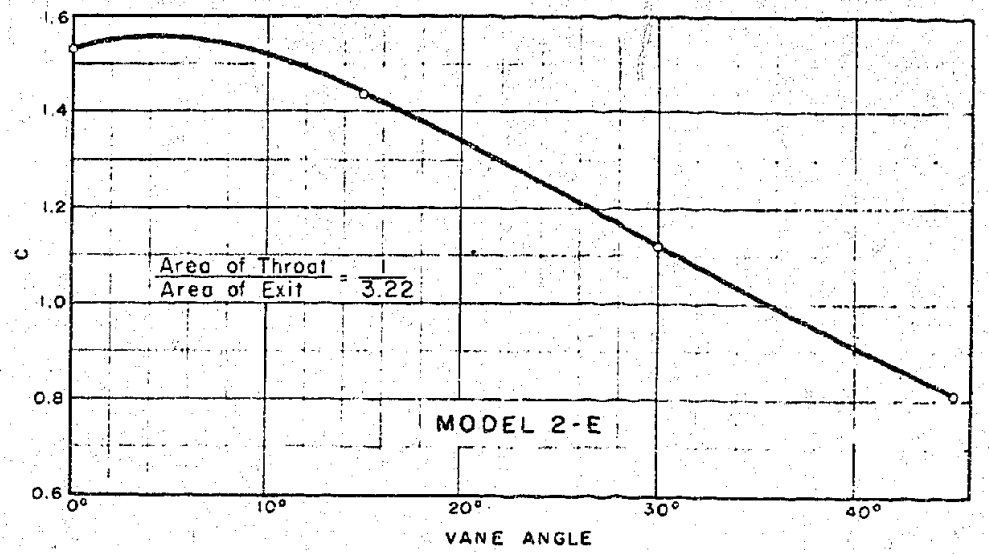
GRAND COULEE DRAFT TUBE MODEL TESTS

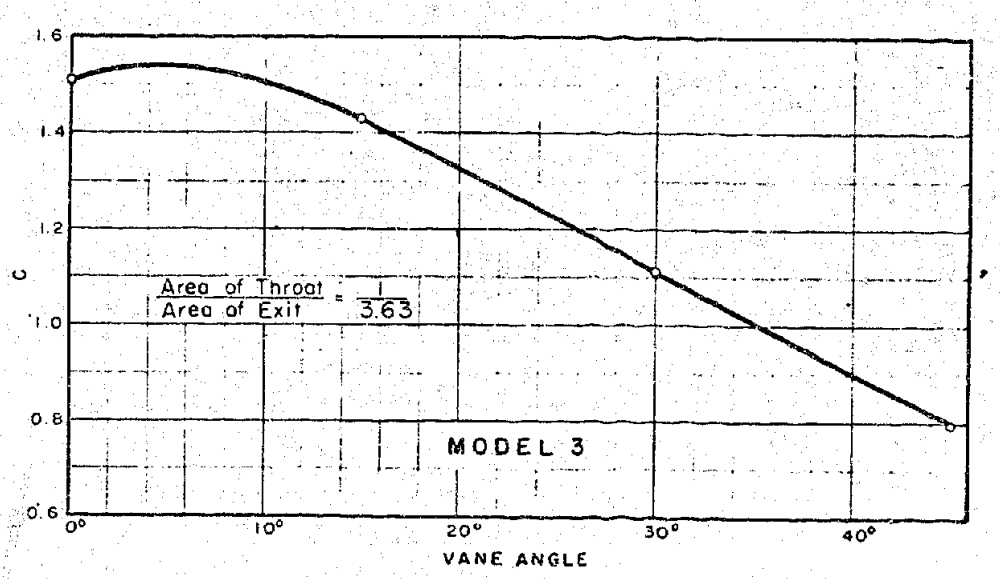
COEFFICIENT CURVES

222-D-1681

FIGURE 30



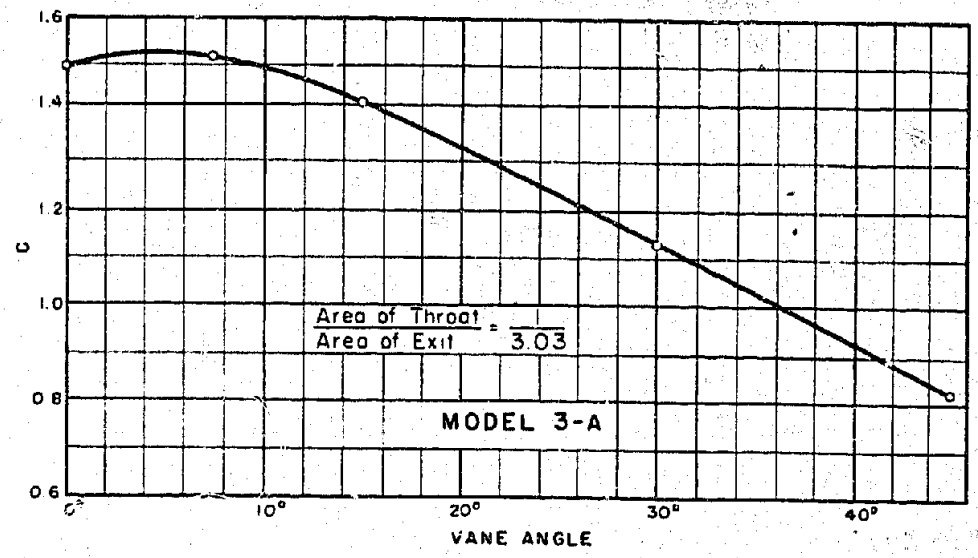


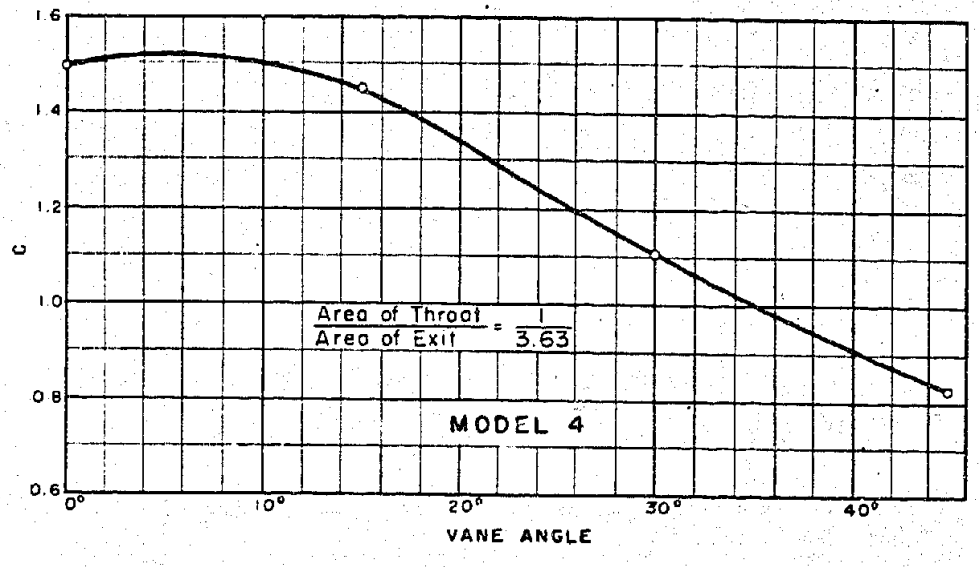


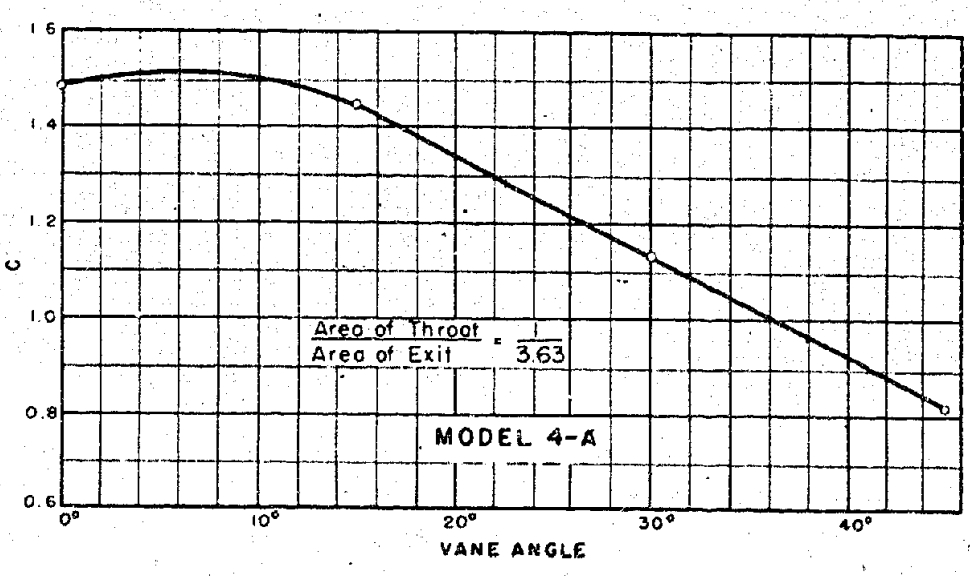
GRAND COULEE DRAFT TUBE MODEL TESTS

COEFFICIENT CURVES

222-D-1682



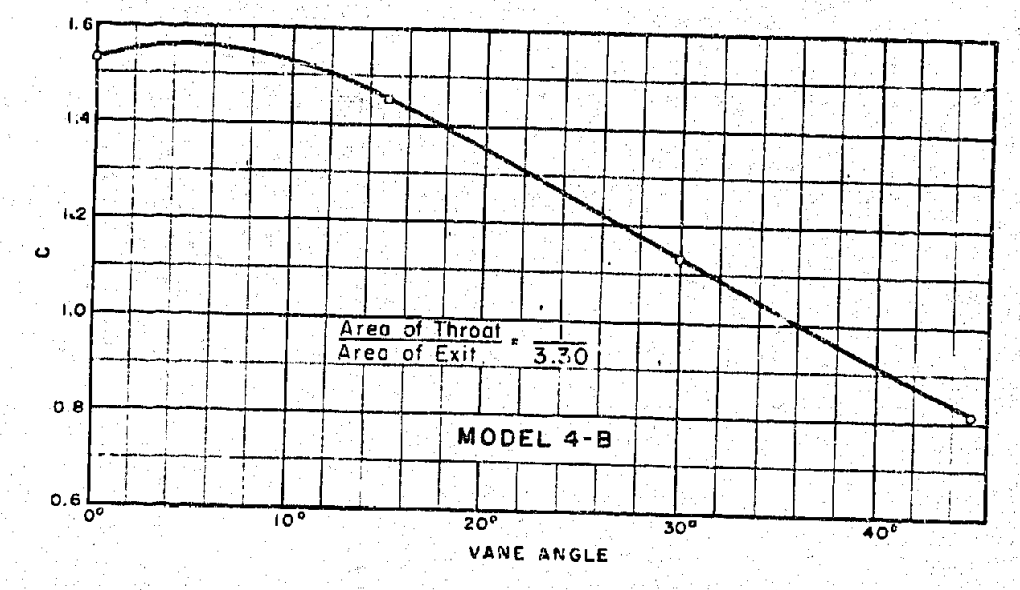


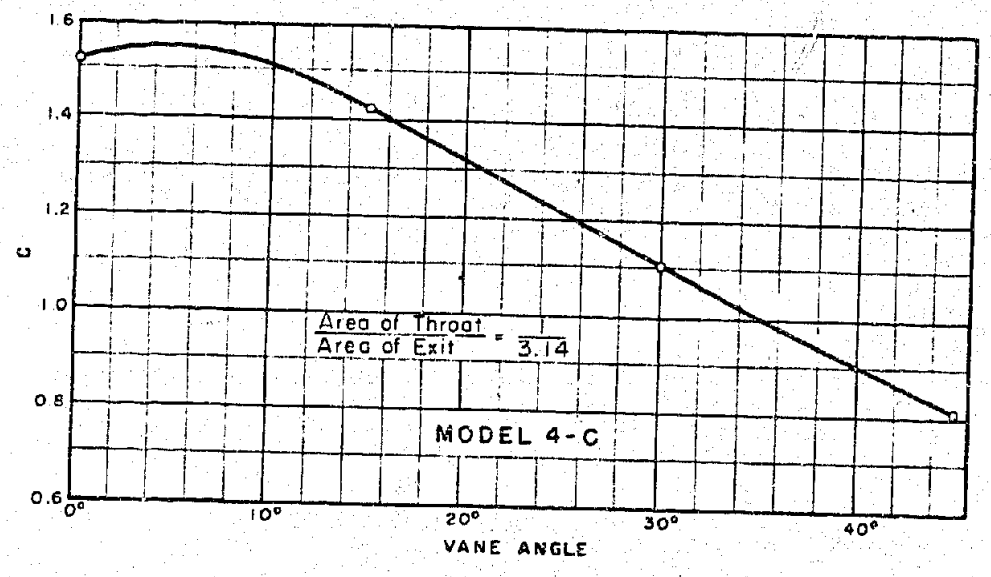


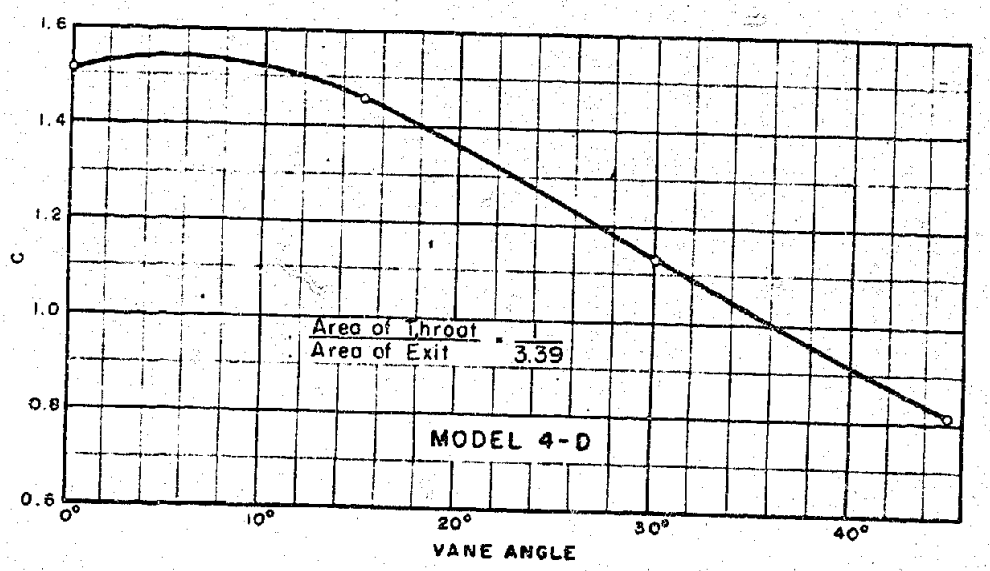
GRAND COULEE DRAFT TUBE MODEL TESTS

COEFFICIENT CURVES

222-D-1683



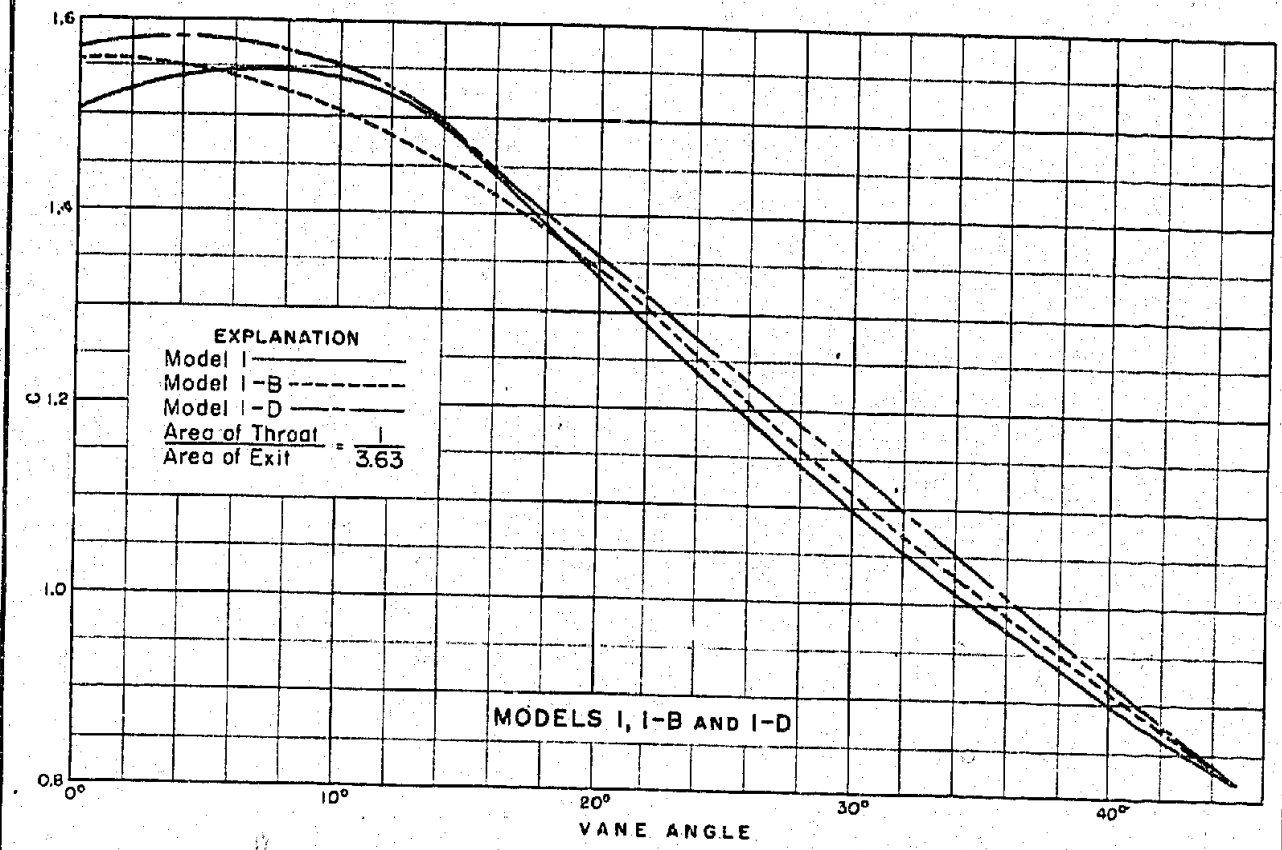


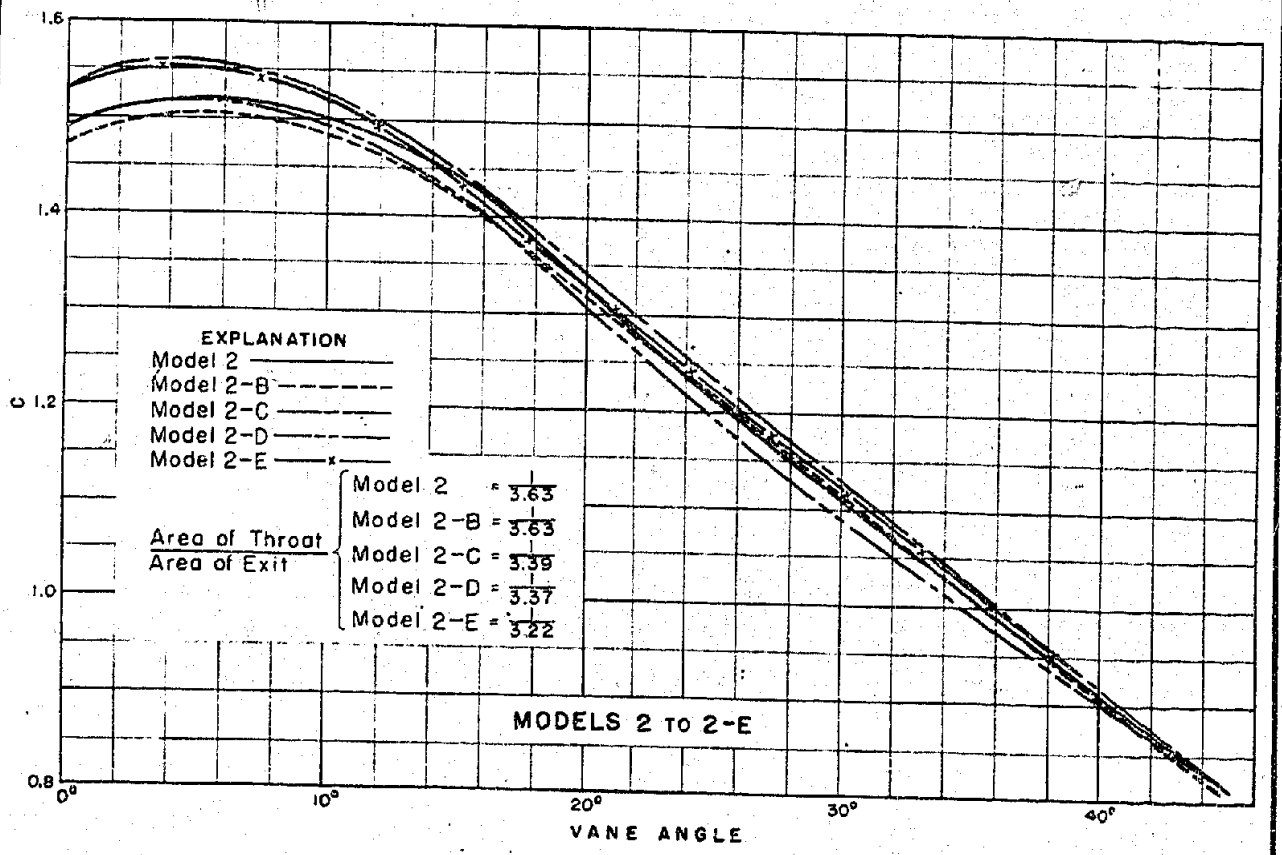


GRAND COULEE DRAFT TUBE MODEL TESTS

COEFFICIENT CURVES

FIGURE 33



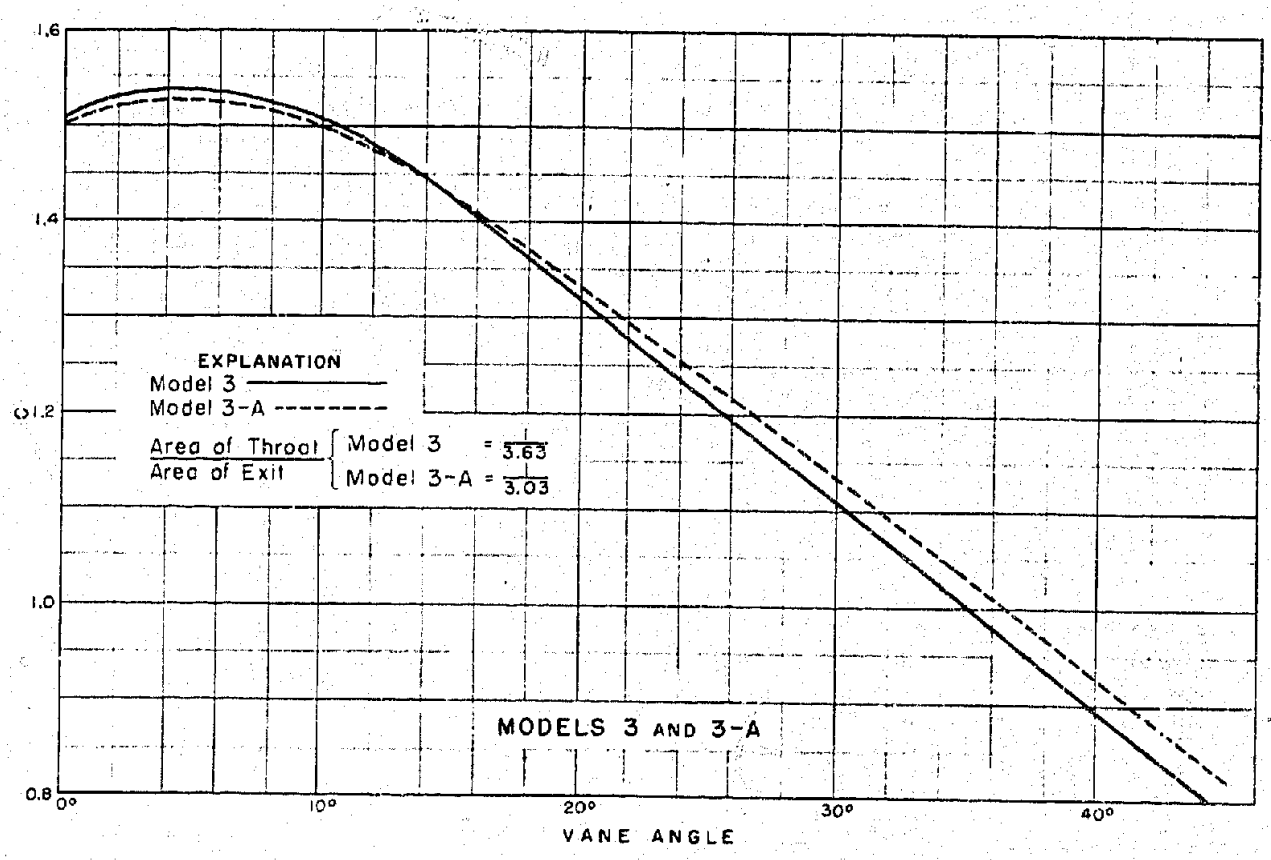


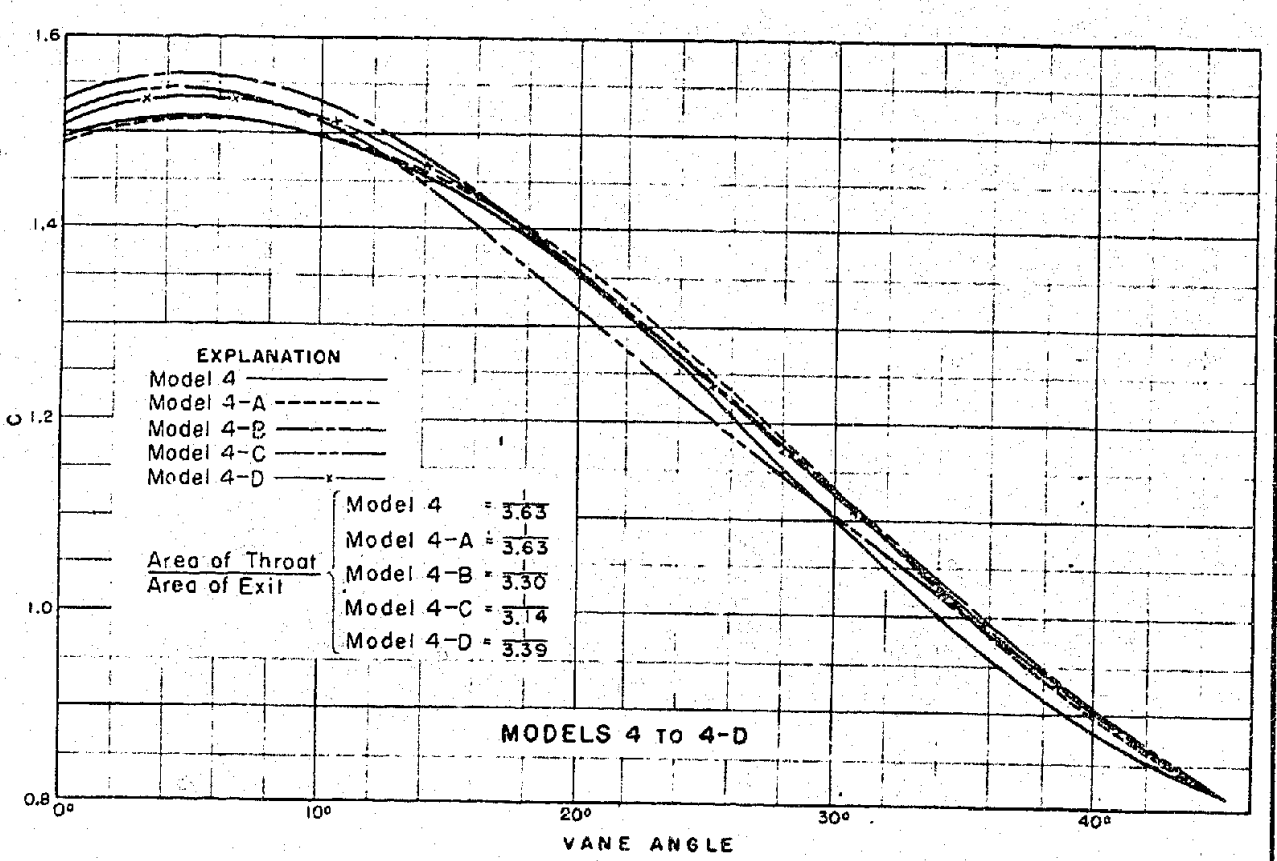
GRAND COULEE DRAFT TUBE MODEL TESTS

COMPOSITE COEFFICIENT CURVES

222-D-1685

FIGURE 34



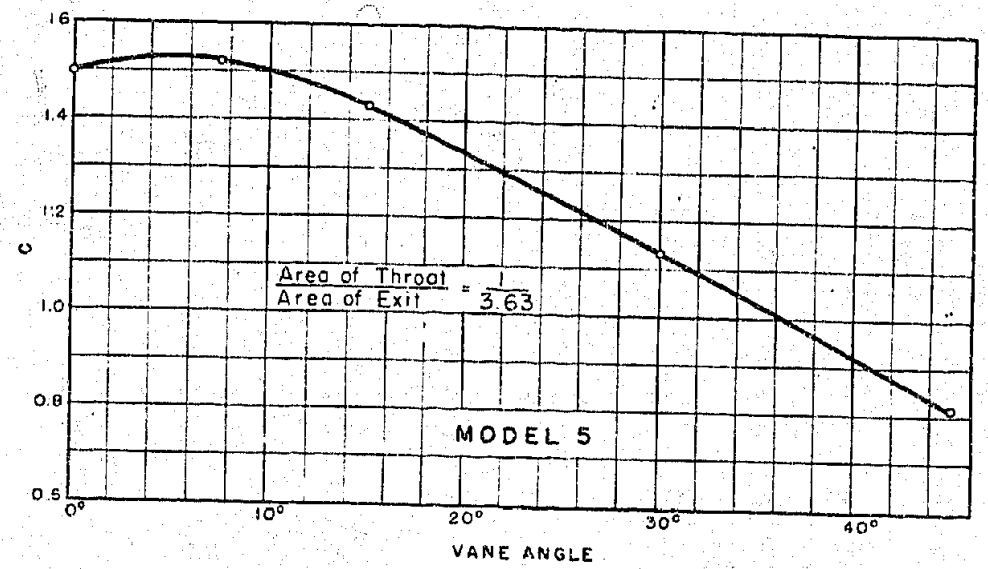


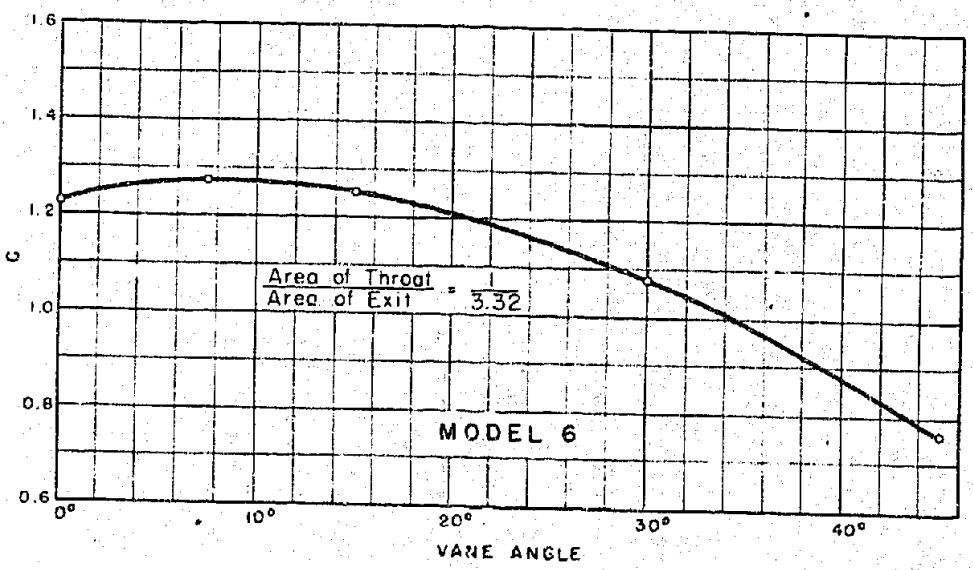
GRAND COULEE DRAFT TUBE MODEL TESTS

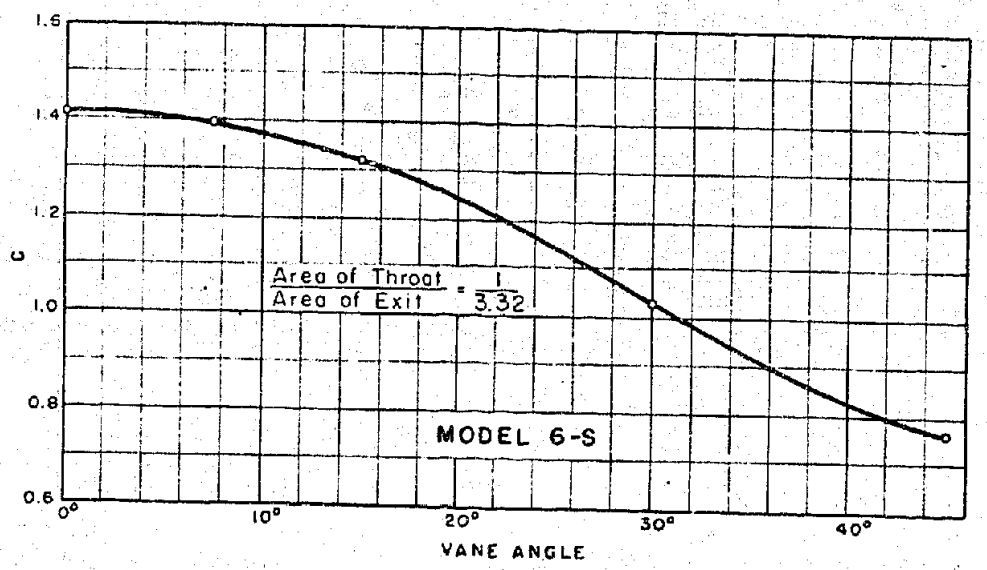
COMPOSITE COEFFICIENT CURVES

222-D-1686

FIGURE 35





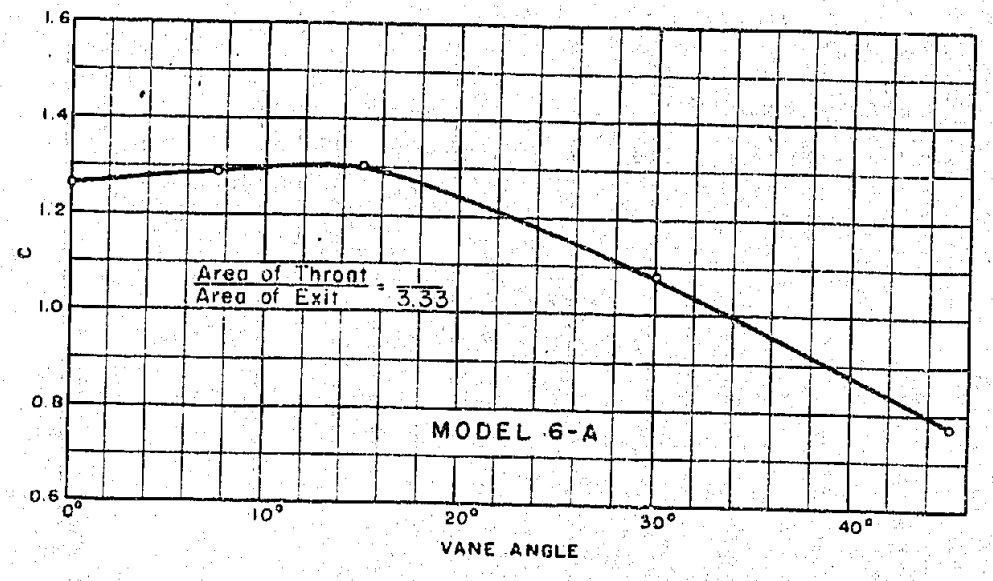


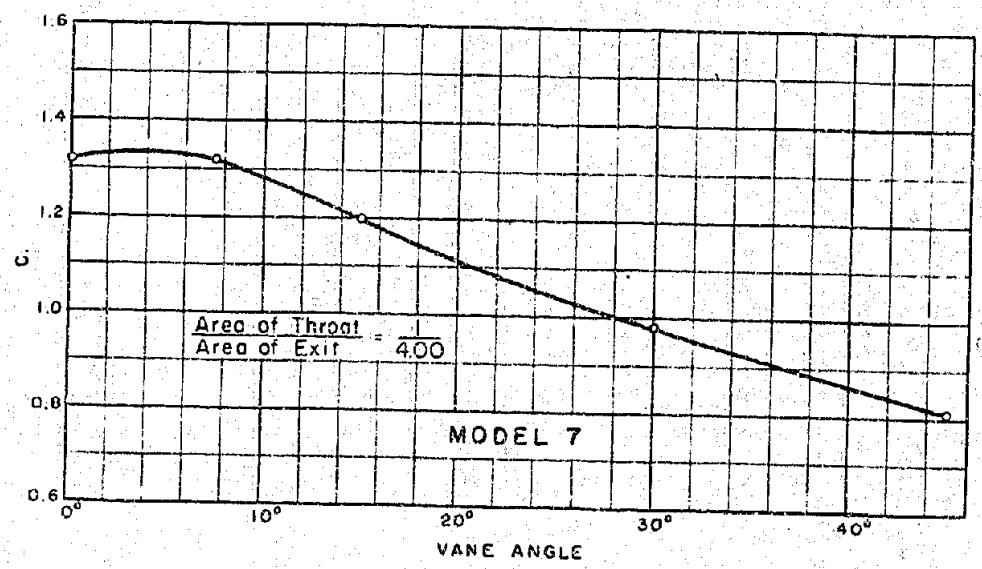
GRAND COULEE DRAFT TUBE MODEL TESTS

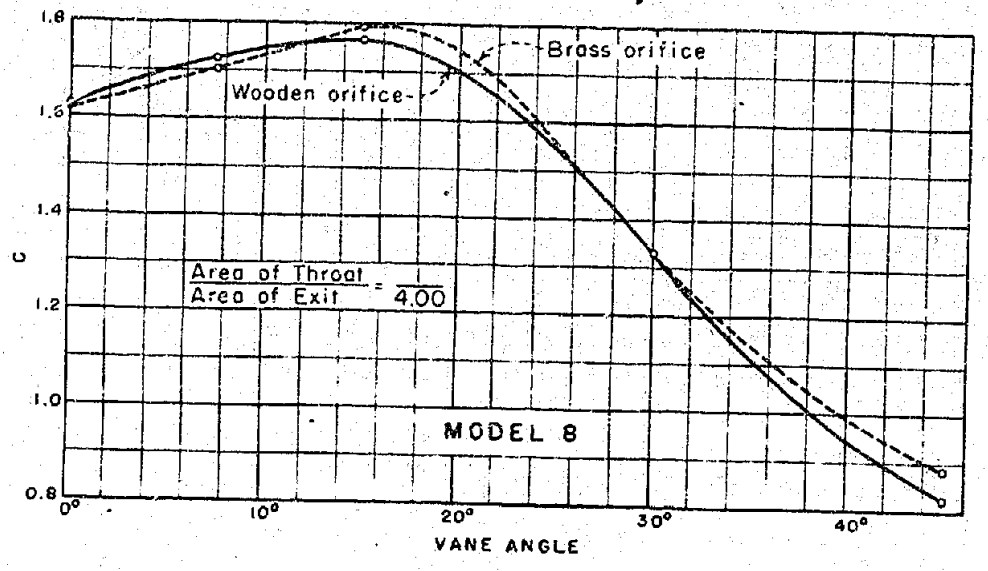
COEFFICIENT CURVES

222-D-1687

FIGURE 36





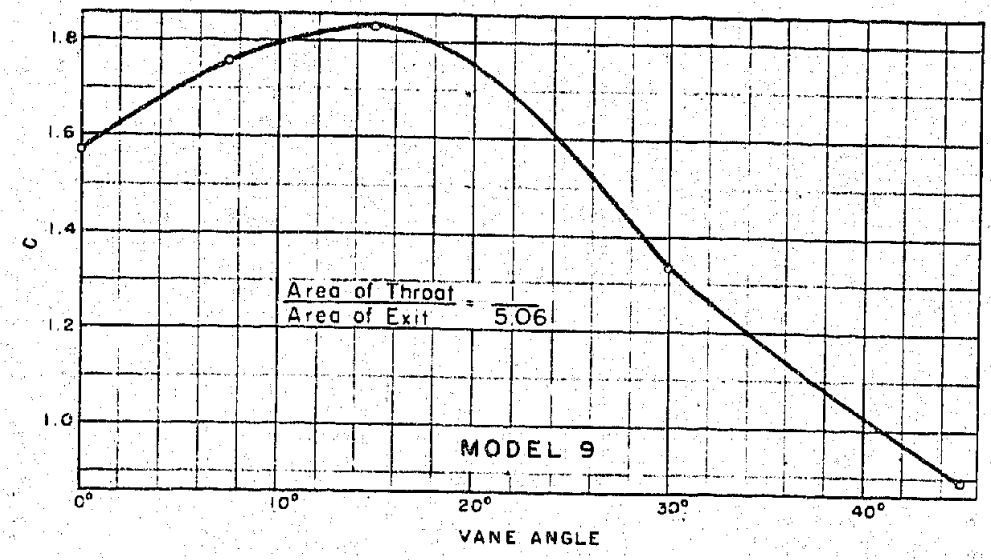


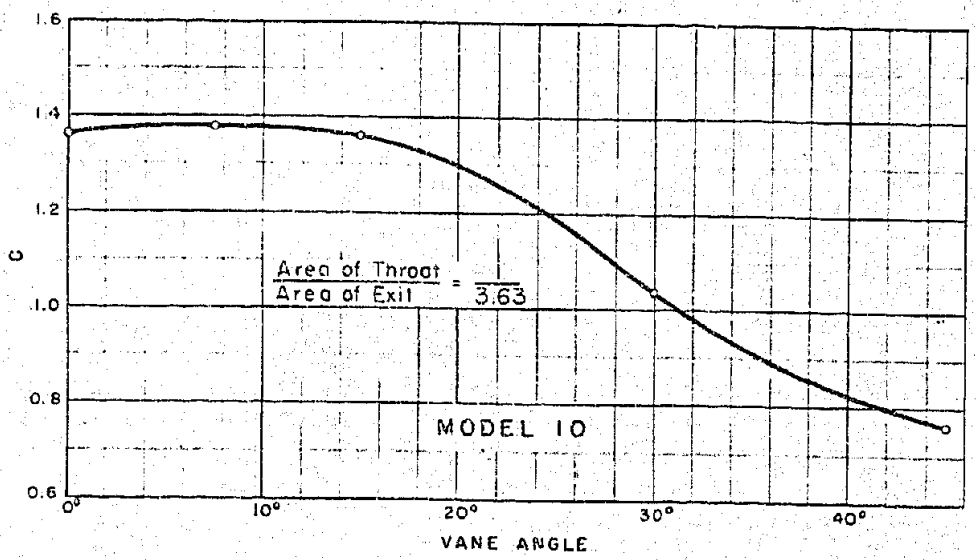
GRAND COULEE DRAFT TUBE MODEL TESTS

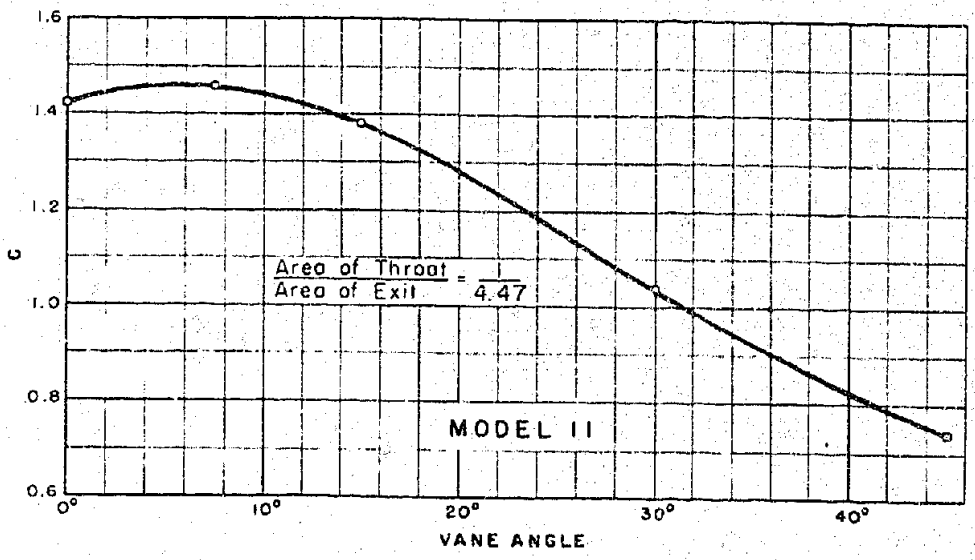
COEFFICIENT CURVES

222-D-1688

FIGURE 37



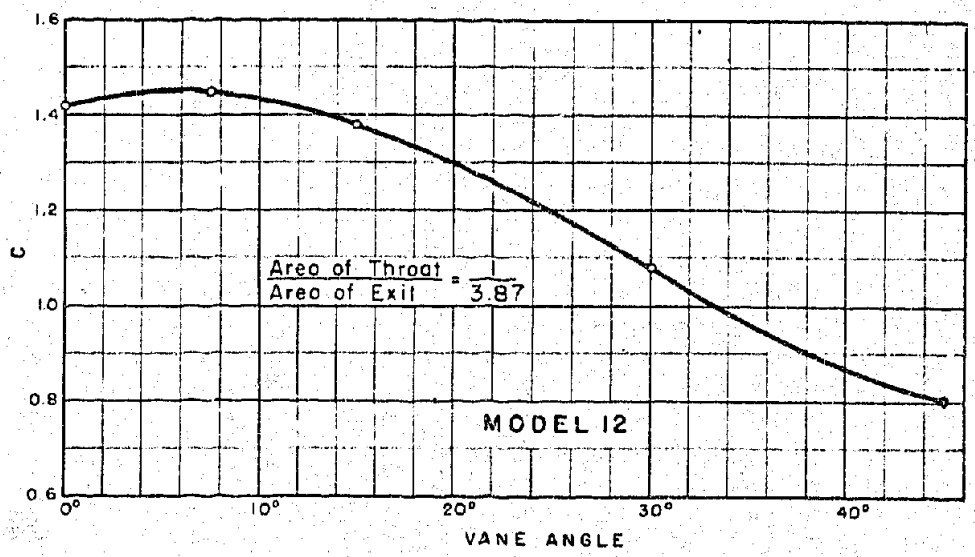


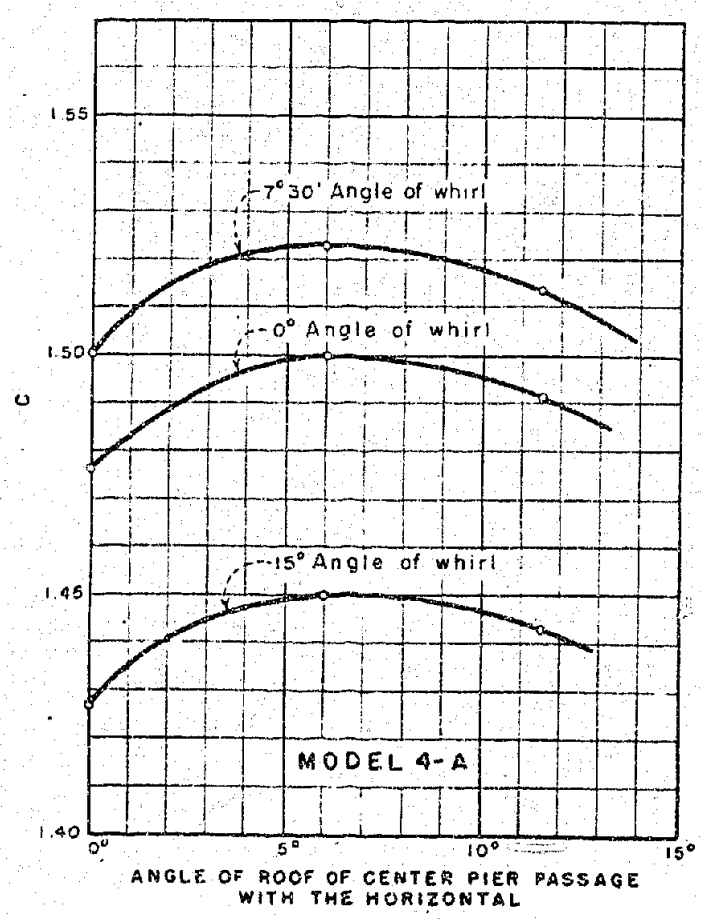


GRAND COULEE DRAFT TUBE MODEL TESTS

COEFFICIENT CURVES

222-D-1689

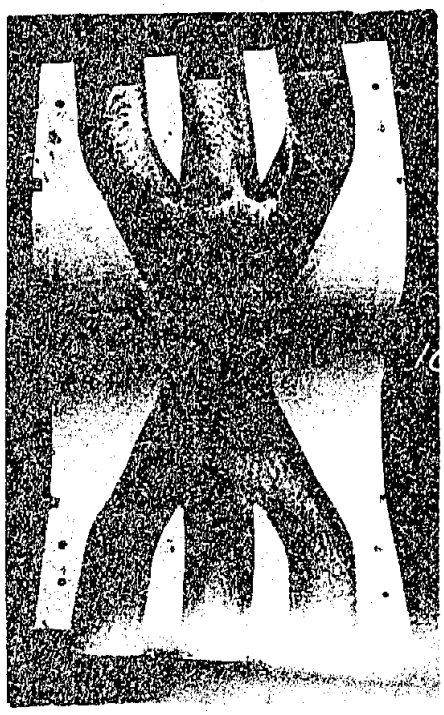




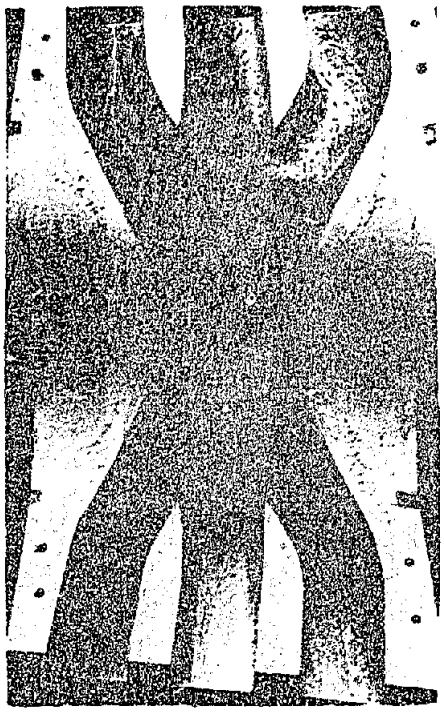
GRAND COULEE DRAFT TUBE MODEL TESTS

COEFFICIENT CURVES

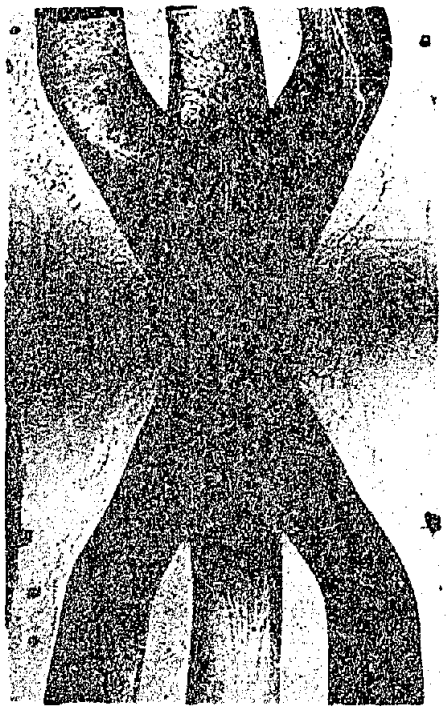
A. TUBE NO. 1
ANGLE OF WHIRL 0°



B. TUBE NO. 1
ANGLE OF WHIRL 15°



C. TUBE NO. 1
ANGLE OF WHIRL 30°

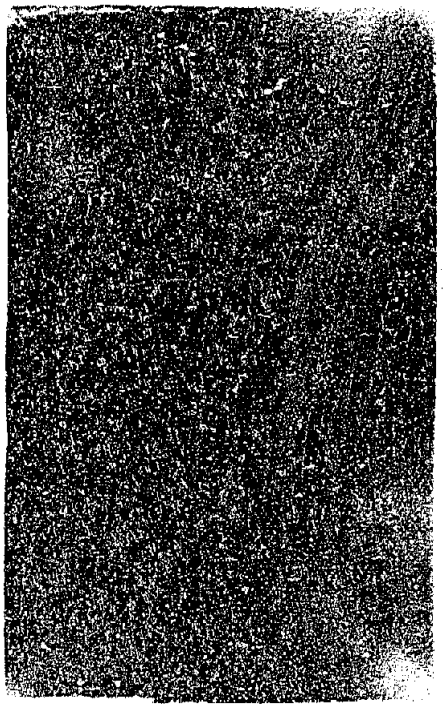


D. TUBE NO. 1
ANGLE OF WHIRL 45°

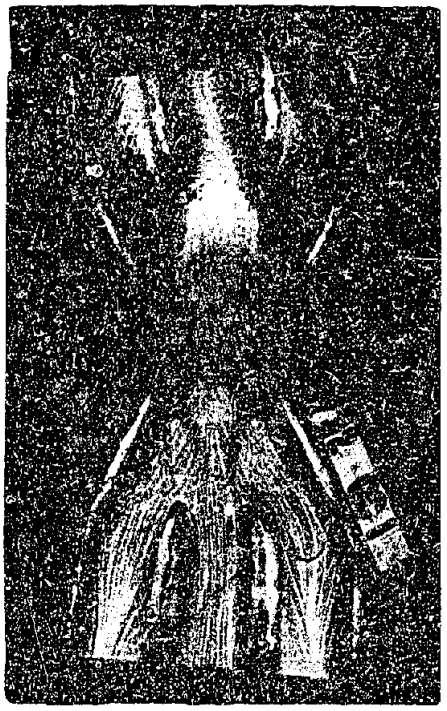
PAINT TESTS OF GRAND COULEE DRAFT TUBE MODELS.

A. TUBE NO. 1A
ANGLE OF WHIRL 0°

B. TUBE NO. 1B
ANGLE OF WHIRL 0°



C. TUBE NO. 1D
ANGLE OF WHIRL 0°

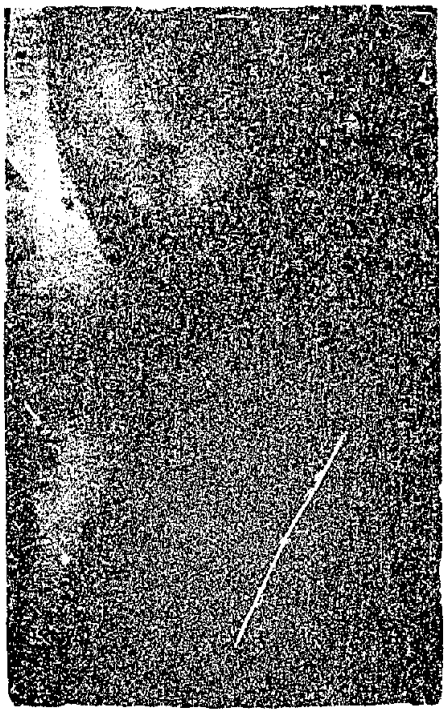


D. TUBE NO. 2
ANGLE OF WHIRL 0°

PAINT TESTS OF GRAND COULEE DRAFT TUBE MODELS.

A. TUBE NO.2B
ANGLE OF WHEEL 0°

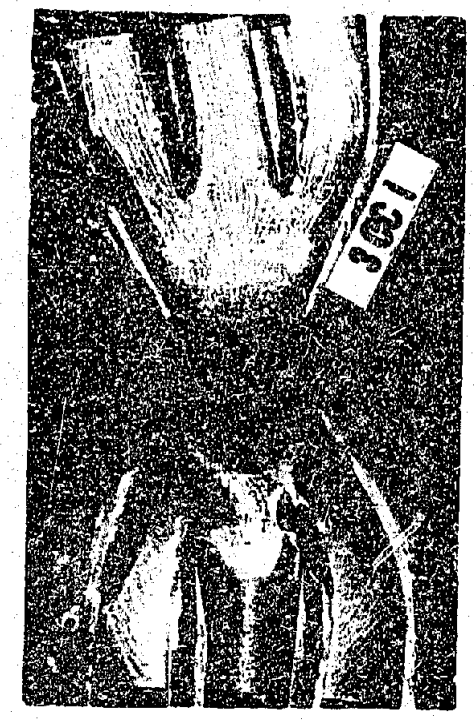
B. TUBE NO. 2C
ANGLE OF WHEEL 0°



C. TUBE NO. 2D
ANGLE OF WHEEL 0°

D. TUBE NO. 2E
ANGLE OF WHEEL 0°

PAINT TESTS OF GRAND COULEE DRAFT TUBE MODELS.



A. TUBE NO. 3
ANGLE OF WHIRL 0°

B. TUBE NO. 3A
ANGLE OF WHIRL 0°

C. TUBE NO. 4
ANGLE OF WHIRL 0°

D. TUBE NO. 4A
ANGLE OF WHIRL 0°

PAINT TESTS OF GRAND COULEE DRAFT TUBE MODELS.

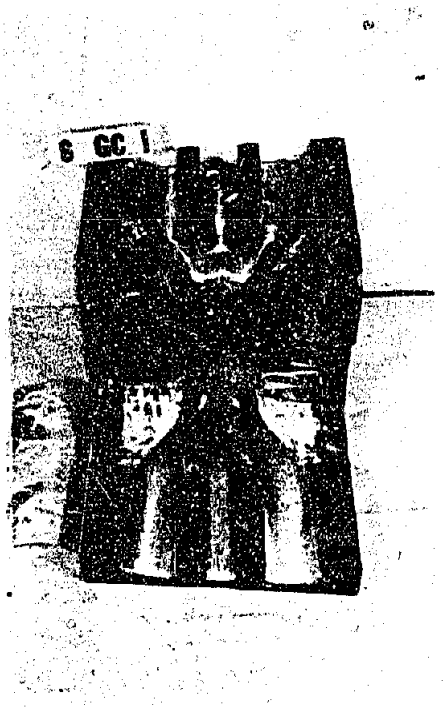
A. TUBE NO. 4B
ANGLE OF WHEEL 0°

B. TUBE NO. 4C
ANGLE OF WHEEL 0°

C. TUBE NO. 5
ANGLE OF WHEEL 0°

D. TUBE NO. 6
ANGLE OF WHEEL 0°

PAINT TESTS OF GRAND COULEE DRAFT TUBES MODELS.



A. TUBE NO. 6 WITH SPLITTER
ANGLE OF WHIRL 0°

B. TUBE NO. 6A
ANGLE OF WHIRL 0°

C. TUBE NO. 7
ANGLE OF WHIRL 0°

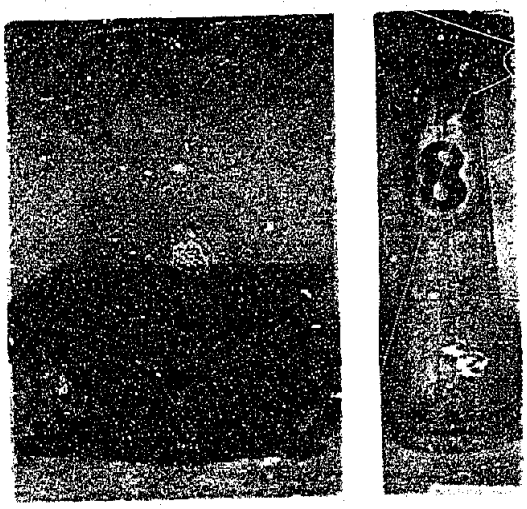
D. TUBE NO. 10
ANGLE OF WHIRL 0°

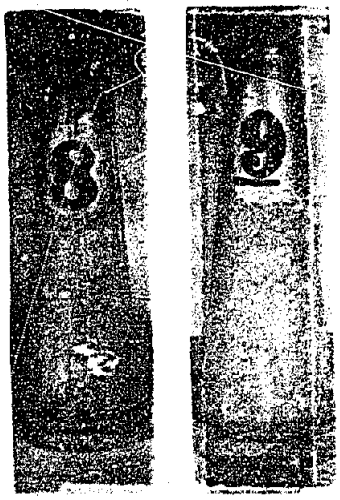
PAINT TESTS OF GRAND COULEE DRAFT TUBE MODELS.

A. TUBE NO. 11
ANGLE OF WHEEL 0°

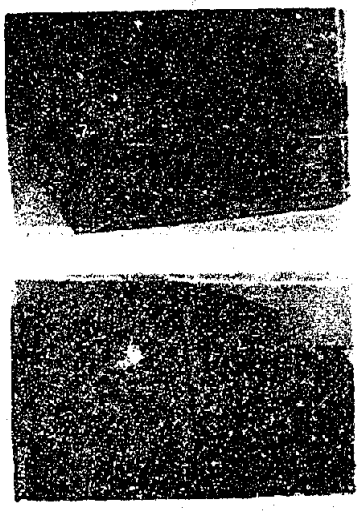
B. TUBE NO. 12
ANGLE OF WHEEL 0°

PAINT TESTS OF GRAND COULEE DRAFT TUBE MODELS.





C. TUBES 7,8 AND 9



D. TYPICAL ELBOW TUBE MODELS

TYPES OF GRAND COULEE DRAFT TUBE MODELS