HYDRAULIC MODEL VORTEX STUDY
GRAND COULEE THIRD POWERPLANT

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16. ABSTRACT

Hydraulic model studies of the Grand Coulee Third Powerplant forebay indicated detailed vortex studies should be made. Vortex modeling is difficult because of lack of similitude between model and prototype. A literature search disclosed an Equal Velocity Method of vortex modeling and this method was used in this study. Without model trashracks, air-entraining vortices readily formed, and with model trashracks vortex action was reduced. Rafts, either floating or submerged, suppressed vortex formation. Investigations were made to determine the prototype area in the forebay that may be susceptible to vortex action and need raft protection. The report has 35 figures and gives a detailed description of the investigation. (8 ref)

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Engineering and Research Center
Denver, Colorado

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Special thanks to, T. J. Rhone for use of his personal file of vortex literature and to W. M. Batts for his patience, determination, and expertise in taking the photographs shown in this report.

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FIGURES

PURPOSE OF THE MODEL VORTEX STUDY

The purpose of the model vortex tests was to: (1) determine whether air-entraining vortices will form near the penstock intakes of the Grand Coulee Third Powerplant and (2) study the use of rafts for preventing formation of air-entraining vortices.

CONCLUSIONS AND RECOMMENDATIONS

1. There is insufficient information to define unacceptable vortex conditions at the Grand Coulee Third Powerplant. The effect of vortex action upon the prototype trashrack structures and turbines is unknown.

2. There are no hydraulic model similitude laws that accurately correlate hydraulic model vortices to the prototype operation. Test results from the hydraulic model were primarily qualitative.

3. The hydraulic model tests indicated the possibility that air-entraining vortices could occur in the forebay channel near the intakes of the Grand Coulee Third Powerplant.

4. Without model trashracks, vortices were generally the most severe in the region immediately in front of the intake. This region was very susceptible to vortex development and the continuation of a developed vortex. The model trashracks occupied and restrained a portion of this vortex-prone region from contributing to vortex action.

5. Hydraulic model tests indicated that vortex severity increased as the number of operating units increased.

6. Rafts placed in the hydraulic model were successful in eliminating formation of air-entraining vortices.

7. Operation of the prototype structure will be needed to verify the results obtained from the hydraulic model vortex study.

8. Observations of vortex conditions are recommended during prototype operation. Three types of observations are necessary:

a. Prototype observations to determine the extent of a vortex problem and to determine whether rafts are needed.

b. If rafts are needed, further vortex observations will be required to verify adequacy of the raft design guidelines.

c. As a safety precaution, observations will be necessary to assure that structural damage does not occur. These observations should be made during initial opertion of each newly installed unit and with all previously installed units operating.

APPLICATIONS

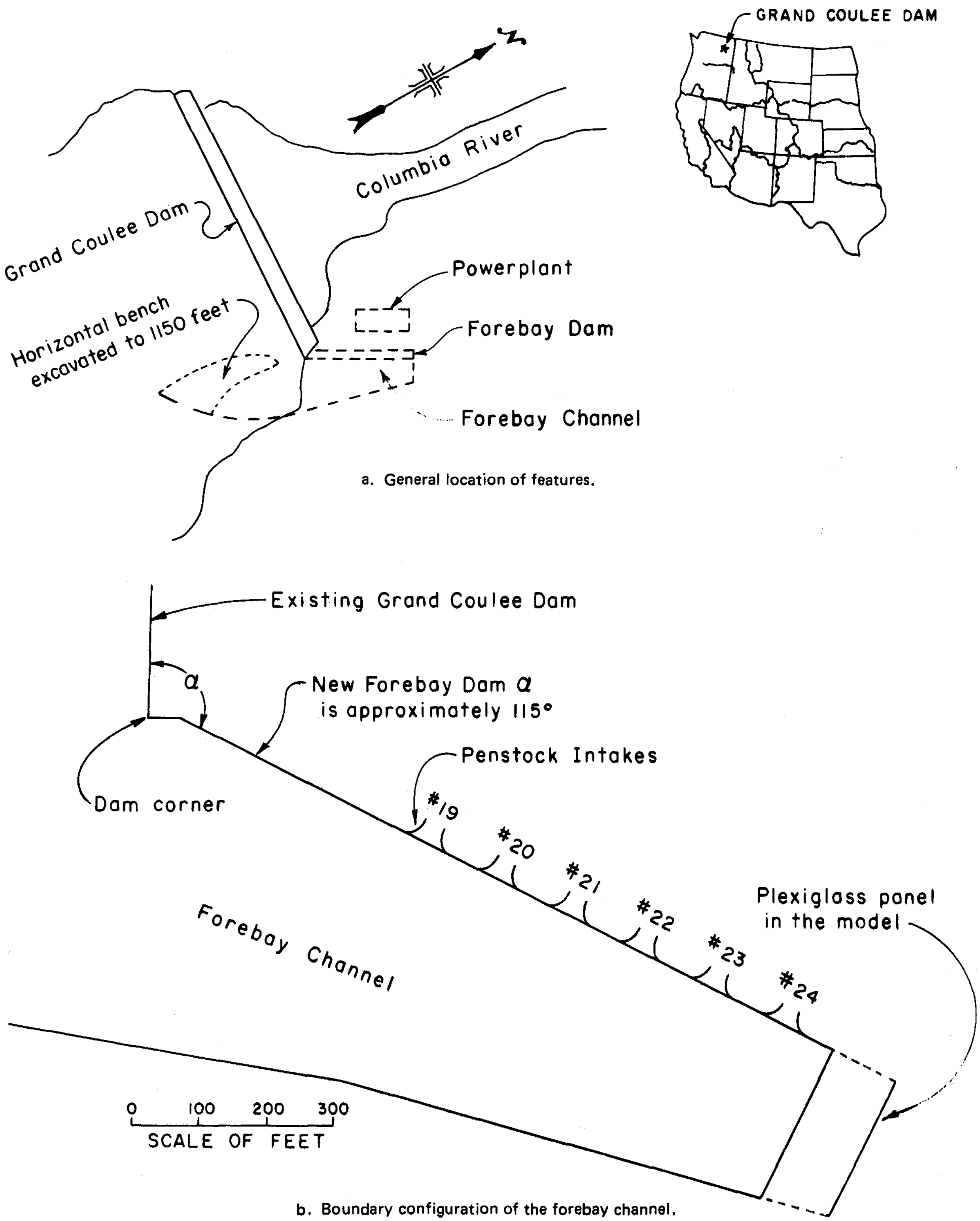
Hydraulic model studies were completed specifically for the geometry and flow features of the Grand Coulee Third Powerplant. However, accuracy of vortex modeling appears suspect for model scales of this size (1:120). Therefore, the value of applying the results contained in this report ultimately will be determined by the actual operation of the prototype structure. Should prototype operation prove the model studies successfully simulated the vortices, then the value of this report will be enhanced. Enhancement would not be in the sense of simply applying a raft to reduce a vortex problem, since this is a common procedure, but rather in the nature of contributing information to the technology of vortex modeling. This report should also provide a rough measure of the effectiveness of the Equal Velocity Method for studying vortex problems.

INTRODUCTION

Grand Coulee Dam, constructed between 1933-42, is located on the Columbia River in the State of Washington. Since that time, there has been better regulation of the riverflow by dams upstream from Grand Coulee, and also an increased demand for peaking electric power. To meet this demand, Grand Coulee Third Powerplant was added with an ultimate design for 12 generating units, constructed in stages of six each. The first six generating units are presently under construction with expected unit installation at 6-month intervals. The location of the powerplant with respect to the Grand Coulee Dam is shown in figure 1a, the penstock intakes and general size and shape of the forebay channel in figure 1b, and a sectional view of the Forebay Dam and waterways in figure 2.

Two hydraulic model studies [1] and [2] *, were made concurrently with the active design stages of the Grand Coulee Third Powerplant. King's study [1], using a geometric length scale of 1:120, assisted in developing a design of the forebay channel and tailrace for both 6- and 12-unit powerplant configurations. Rhone's study [2] assisted in developing the design for the shape of

*Numbers in brackets designate references listed at the end of this report.



a. General location of features.

b. Boundary configuration of the forebay channel.

Figure 1.—Hydraulic features of Grand Coulee Dam.

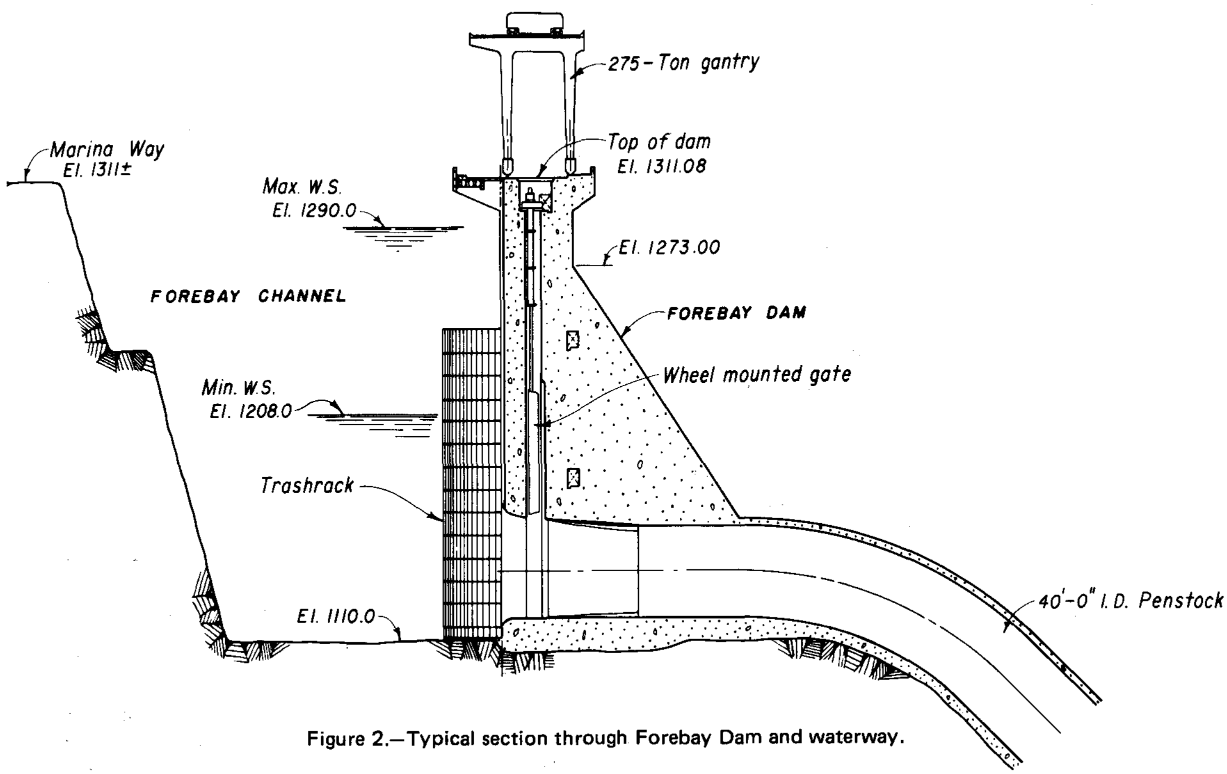


Figure 2.—Typical section through Forebay Dam and waterway.

the entrance, the transition from the rectangular opening near the face of the dam to the circular penstock, and both vertical bends of the penstock. Rhone's model tests, at a length scale of 1:41.75, were made with one penstock discharging from a head box.

During King's investigation, vortices were noted and observed after the recommended configuation was obtained for the forebay channel and tailrace. These tests were made with the model Froude number discharge and with various modes of unit operation and water surface elevation. While making these tests there were no trashrack structures in front of the penstock intakes. In general, the vortices were of short duration and in some instances air bubbles were taken into the penstocks. A problem of vortex similitude was recognized and tests with a smaller model scale (larger size model) would be necessary to develop modifications to alleviate the vortex problem.

In Rhone's study, the geometric model scale was smaller and vortex tendencies were observed. However, results from these tests were not necessarily indicative of the prototype vortex problem because the model had only one penstock. The model did not have the approach flow geometry of the forebay channel and therfore did not duplicate the water currents approaching the intakes. For better simulation of prototype water currents, tests were made where the approach flow entered directly in front of the entrance, and also from the left side so that the flow turned 90° to enter the penstock.

After completion of both studies, [1] and [2], a review and evaluation were made concerning the vortex problem. Further and more intensive hydraulic model tests were believed to be beneficial, including the testing of rafts to suppress objectionable vortex action.

MODELING VORTICES

Hydraulic modeling of vortices is a problem because of the lack of similitude between model and prototype. Berge [3] states, "It is obvious that Froude, Weber, and Reynolds numbers should be used in dealing with the question of similitude." However, an accurate relationship among these three numbers when applied to vortex modeling is not known.

Angelin and Larsen [4] made a statement which illustrates the acuteness of observation a hydraulic modeler must have for vortices in a Froude scale model:

> "It is the experience of the Swedish State Power Board Hydraulic Laboratory that, if a tendency of a vortex can be identified in a model based on Froude scaling—it may be sufficiently strong to be air entraining or it may be weak so that it is necessary to search for it with dye traces—a vortex will also occur in the prototype, however deep it may be. For example, a vortex was observed in both a 1:100 and in a 1:25 model of bottom outlets to the diversion tunnel at the

Messaure Dam. A strong and active vortex was observed in the prototype although the gate openings in this case were about 180 ft (55 m) under the water level. The gate shafts were well aerated, the jets submerged, and there was no underpressure. The vortex was so strong that boats, from which flow measurements were carried out, were in danger of being caught in the vortex and drawn down."

Thus, there is the implication that a vortex may be scarcely detectable in a Froude scale model, but a very awesome occurrence in the prototype.

Denny and Young [5] reported a modeling technique that somewhat overcomes the deficiency of vortex Froud number modeling. While studying vortices in pump sumps, they found that a Froude scale model did not have an air-entraining vortex. But the prototype, operating under the same flow conditions as tested in the model, did have an air-entraining vortex. They showed that if the model discharge was greater than the Froude number discharge, an air-entraining vortex could be formed in the model. Thus, the model could be adjusted to provide some simulation of prototype vortex action. They further substantiated their technique with additional model tests, using greater than Froude number discharges, and checked model test results with prototype operation. These tests were mainly for pump sumps and model length scale ratios of 1:16 and less. This vortex modeling technique was designated the Equal Velocity Method because the model was operated with the same intake velocity as that computed for the prototype.

The Equal Velocity Method involves model tests under many different conditions of water depth and penstock velocities. For each test condition, observations are made to determine whether an air-entraining vortex forms, and data points are plotted on a graph similar to the one shown on figure 3. A boundary line or envelope curve is drawn between the air-entraining and non-air-entraining data points. The area below the curve represents conditions where there is danger of air-entraining vortices in the prototype.

Denny and Young [5] commented about a shape characteristic of the boundary curves:

> "The shape of the boundary curve varies with the circumstances but in general the curves have one limb tending to become asymptotic to a constant velocity and another limb tending to become asymptotic to a constant depth. In other words there is one region at low intake velocities where the critical submergence is very dependent on velocity through the intake, and another at high intake velocities where the critical submergence is not very dependent on velocity. The transition between the two regions is more abrupt in some cases than in others."

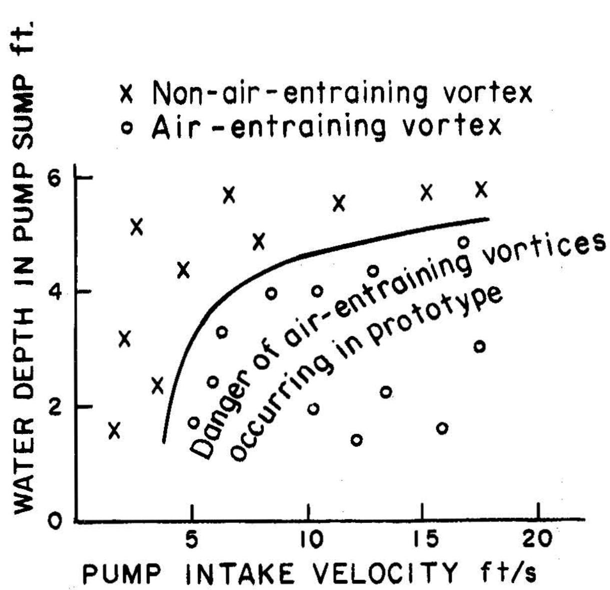


Figure 3.—Example plot of vortex data using the Equal Velocity Method.

Thus, the vertical (constant velocity) and horizontal (constant depth) limbs of the boundary curve were important indicators for vortex action in the model. For lower model velocities, the vertical limb shows velocity as a very critical and sensitive factor. Air-entraining vortices will form in the model only after attaining some minimum threshold velocity. Thereafter, the vortex becomes insensitive to velocity and the water depth is the critical and sensitive factor. Relatively small increases in water depth prevented formation of air-entraining vortices.

The vertical and horizontal limbs of the boundary curves have very important implications toward vortex modeling. Once the threshold velocity (vertical limb of the curve) is attained vortices form in the model, and for velocity increases thereafter the water depth (horizontal limb of the curve) is critical for preventing vortex formation. Therefore, it appears that a penstock model velocity which is greater than the Froude scale velocity, but considerably less than the prototype velocity, is sufficient for vortex model testing.

Linford [6] used the Equal Velocity Method with a 1:200 length scale ratio hydraulic model, and his vortex studies were for hydroelectric powerplant intakes. With Froude number criterion, the model penstock velocity of 1.06 ft/s (0.32 m/s) represented a prototype penstock velocity of 15 ft/s (4.6 m/s). Model tests were made with various combinations of intakes open, various model penstock velocities, and over a range of reservoir water surface elevations. Test results on graphs similar to the one on figure 4 indicated a 5 ft/s (1.5 m/s) threshold velocity was sufficient to produce air-entraining vortices in the model. This model velocity is one-third of the 15 ft/s prototype velocity. (This observation is of special significance to the Grand Coulee Third Powerplant model vortex tests where model penstock velocities were limited to about 30 percent of the prototype velocities.)

For Linford's study [6], vortex formation was objectionable at certain water surface elevations. As a corrective measure, a vertical baffle was placed near the intake to inhibit water circulation. With the baffle in place, the water surface elevation necessary to submerge or prevent vortex formation was reduced. Effectiveness of vortex prevention for the baffle is shown by the boundary curve (b) on figure 4. The baffle was constructed in the prototype. Observations were made of vortex conditions occurring at the prototype, and within normal reservoir operation levels, no objectionable air-entraining vortices formed. This satisfactory prototype operation provides some verification for using the Equal Velocity Method in making model vortex studies.

Both Denny and Young [5] and Linford [6] suggest that an unknown measure of safety occurs by using the Equal Velocity Method for vortex modeling since the model vortex conditons may be more intense than those occurring in the prototype. Therfore, if the vortex is prevented in the model, the solution is believed to provide an unknown degree of safety in the prototype.

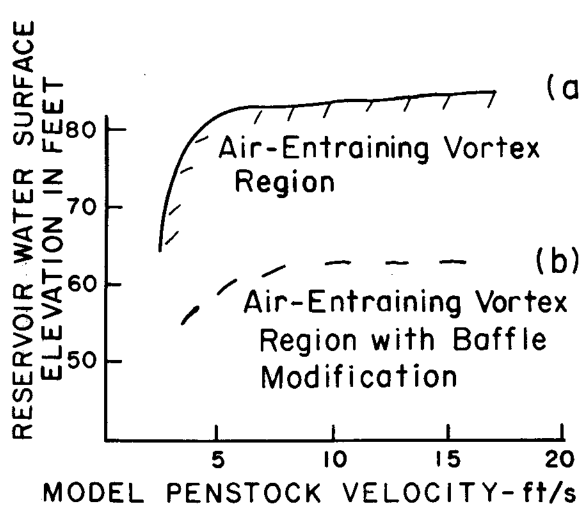


Figure 4.—Example of boundary curves showing vortex conditions of a model study.

To summarize, within the present technology of hydraulic modeling, there is no accurate similitude law for modeling vortices. Therefore, vortex model testing is of a qualitative nature.

THE MODEL

The experience of previous investigators weighed heavily with respect to continuing the study at the 1:120 geometric scale of the Grand Coulee Third Powerplant model. Because lack of time and high costs prevented construction of a larger model, additional vortex tests were made with the existing model, figure 5. Three features of this model differed from the prototype: (1) A clear plastic panel at the end of the model forebay channel was 10 inches (0.25 m) too far from the centerline of unit 24. See figures 1b and 5. This resulted in an increase of 100 feet (30 m) in the prototype forebay channel length of 1,140 feet (347 m). Photographs of vortex action were made through this plastic panel. (2) The penstock intake openings at the face of the model Forebay Dam were 33 feet (10 m) wide by 47 feet (14 m) high, from a previous trial design, instead of 39.5 feet (12 m) wide by 50 feet (15 m) high. (3) Topography in the model where Grand Coulee Dam and the Forebay Dam meet was at elevation 1250 (381 m) instead of elevation 1200 (366 m). The influence of these three features on the test results was considered negligible.

Water was supplied to the model from the permanent hydraulic laboratory pipe system and entered the model through a vertical pipe in back of a rockfilled baffle. See figure 5. This baffle was used to calm and smooth the approach of water into the model reservoir. Venturi meters and mercury manometers, volumetrically calibrated together, were used to measure model discharges. Some topography of the excavated area where waterflow approaches the forebay channel was not included in the model. This area was excluded because of model size limitation and would have extended past the rockfilled baffle.

Discharges through the model penstocks were controlled with rectangular sheet metal sliding gates that passed perpendicularly through the penstocks. The location of these gates corresponded to the prototype penstocks entry to the powerplant. In making model tests with various combinations of penstocks, equal gate openings representing equal discharges were set for the operating units. Differences in individual penstock discharges may have occurred because of variations in approach flow to intakes and vortex formation.

Froude number discharges with large geometric scale models have been reported inadequate for modeling vortices. Therefore, the Equal Velocity Method was used, so far as possible, for making the hydraulic model

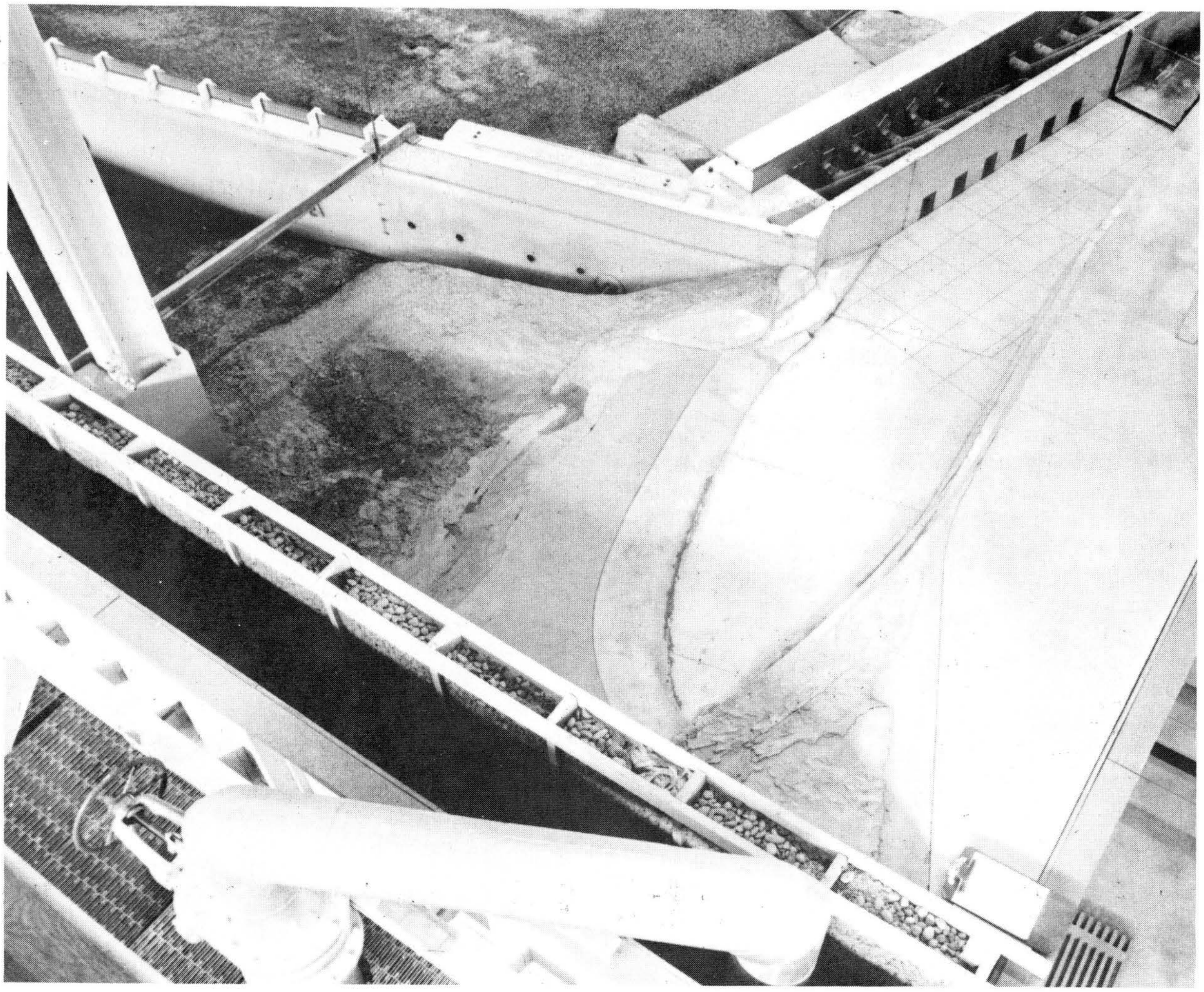


Figure 5.—Grand Coulee Third Powerplant hydraulic model. Photo P1222-D-76651

vortex studies. This method indicated the possibility of providing the most information on the occurrence of vortex action in the forebay channel of the powerplant.

The existing model had limitations in using the Equal Velocity Method for vortex testing. Model penstock velocities were dependent upon the head difference between the water surface elevations of the forebay channel and the tailrace. The highest obtainable model penstock velocity was 8 ft/s (2.4 m/s). Thus, only one-third of the prototype velocity could be attained in the model instead of the full prototype velocity as required by the Equal Velocity Method. As noted in the Modeling Vortices section of this report, the prototype velocity may not be necessary. However, there is the predicament that the limited model discharges may not produce vortex solutions that have a degree of safety.

Construction of the prototype was in progress during the model testing, and changes to the prototype structure would have been extremely costly. If changes were to be made, these changes should be unquestionably accurate and proven to be economically justified. Precise information on vortex conditions that would be acceptable for prototype operations did not exist. Therefore, the point at which it would be economically justifiable to make changes to the prototype was not known. Rafts floating on the water have been successfully used to prevent formation of air-entraining vortices and was the one solution with flexibility which could be tested in the model.

TERMS USED IN DESCRIBING VORTEX ACTION

Various words, such as circulation, rotation, swirl, eddy, vortex, filament, thread, rope, vortex tail, air core, air entraining, and others are used to describe vortex action. Some of these words are interchangeable, but may have subtle differences in describing vortex action. The use of these words is illustrated with the aid of figures and the following descriptions.

Eddy, dimple, and vortex tail describe water surface appearance and can also denote the degree of vortex air core development. A quantitative distinction has not been made between an eddy and dimple or a dimple and vortex tail. However, in a qualitative sense, the depression of an air cavity downward from the water surface is greater for a vortex tail than for a dimple, and the depression of a dimple is greater than an eddy. See figure 6. The depression of an eddy is very slight and is observed by reflection of light from the water surface, whereas, a vortex tail is more readily seen because of the air cavity extending below the water surface.

Development of the vortex air core was used in this study as a criterion for qualifying degrees of vortex severity:

1. A fully developed air-entraining vortex has a continuous air core extending from the water surface into the intake, figure 7a. Near the water surface the air core has a funnel shape and below the water surface a rope-like appearance.

2. A partially developed air-entraining vortex does not have a continuous air core, as shown in figure 7b. The air core extends only part way down from the water surface and ends with a vortex tail. Occasionally, small bubbles may be dragged from the vortex tail, travel down the longitudinal axis of the vortex, and enter the intake.

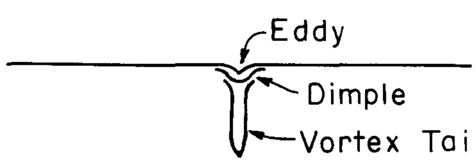


Figure 6.—Relative comparison of eddy, dimple, and vortex tail.

3. A lesser developed vortex is one with a tail which is non-air entraining, and air bubbles are not dragged from the tail. See figure 7c. Dye placed in the vortex tail is carried downward into the intake, forming a filament which reveals location of the vortex axis.

4. A weakly developed vortex with no air core and only a small eddy on the water surface, indicates presence of the vortex, and is shown in figure 7d. Dye placed in the eddy shows water rotating around the central axis and drawn along the vortex axis.

Eddy and swirl both denote a rotating movement of water. A large eddy may be a small swirl, but qualitatively a swirl is considered larger than an eddy.

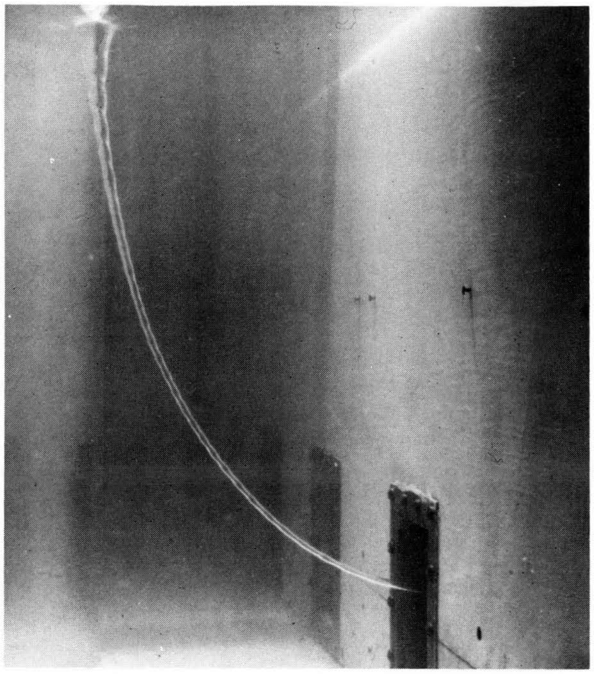
A vortex has certain inherent properties. Near the water surface there is a spiraling inward flow, toward the central axis, with increasing angular velocity (ω = radians/second) as the water approaches the core. Dye placed near the water surface and adjacent to the vortex axis disclosed a much slower rotational motion at a 1- to 2-inch (25- to 50-mm) radial distance than that occurring in the vortex core. See figure 8a. If quantity and velocity of the rotating water is sufficient, then the centrifugal force of the whirling mass pulls water outward from the central axis and an air core is formed. However, rotational motion of water about an axis can occur without the central core of a vortex. Swirl is an example as shown on figure 8b. In the case of a swirl, the angular velocity remains nearly constant, proceeding from the outer edge to the central axis. There were many instances where swirls occurred in the model. The action of dye in water can show the difference between a swirl and an organized vortex. When a vortex developed from a swirl, the organizational structure of the vortex was shown by the collection of dye into a centralized vortex filament, figure 8c.

Vortex action was the occurrence of rotating water acting in the manner of an organized vortex.

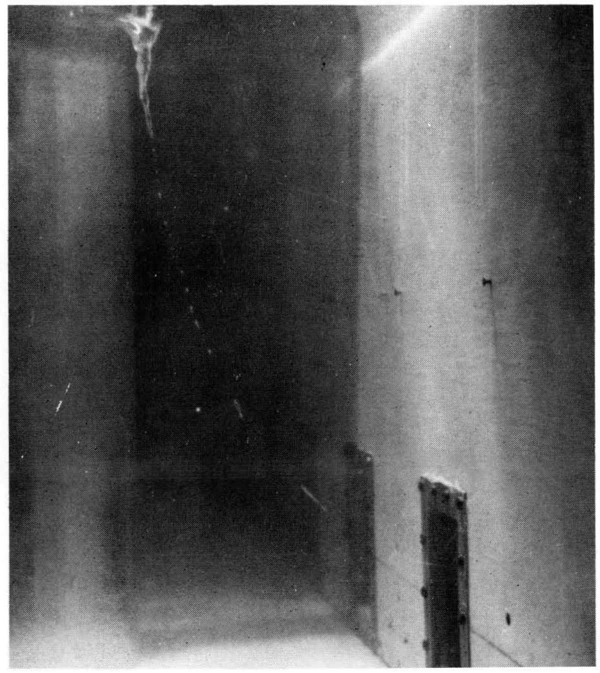
INITIAL TESTS WITHOUT TRASHRACKS

The Tests

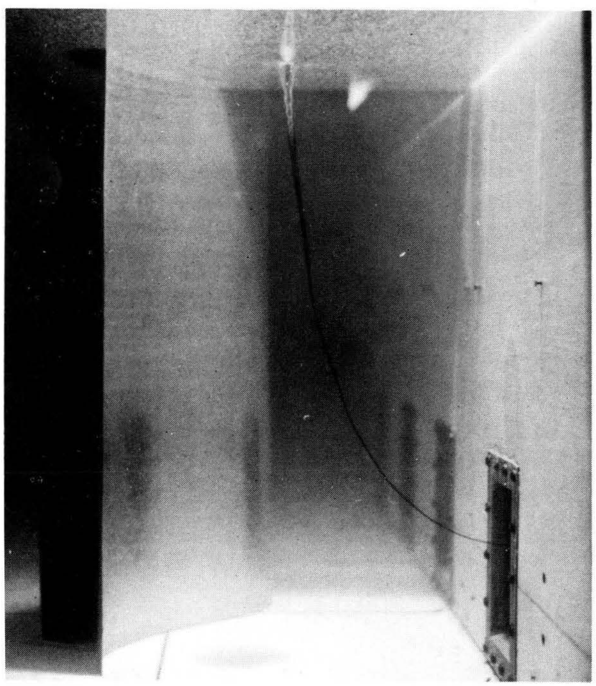
It was unknown whether model trashracks were essential for the vortex tests. Previous model tests [1] indicated that vortices formed for a short time. Possibly, air-entraining vortices for the Grand Coulee Third Powerplant may be of a marginal nature, and the



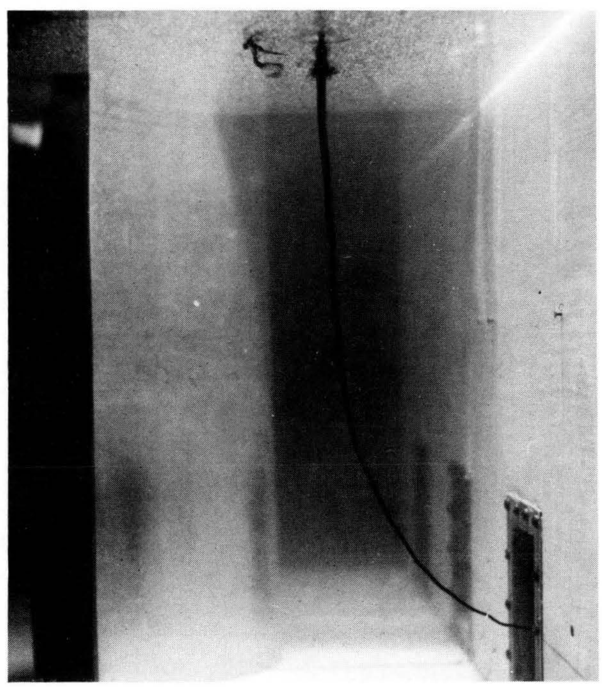
a. Fully developed vortex. Photo P1222-D-76652



b. Partially developed vortex. Photo P1222-D-76653

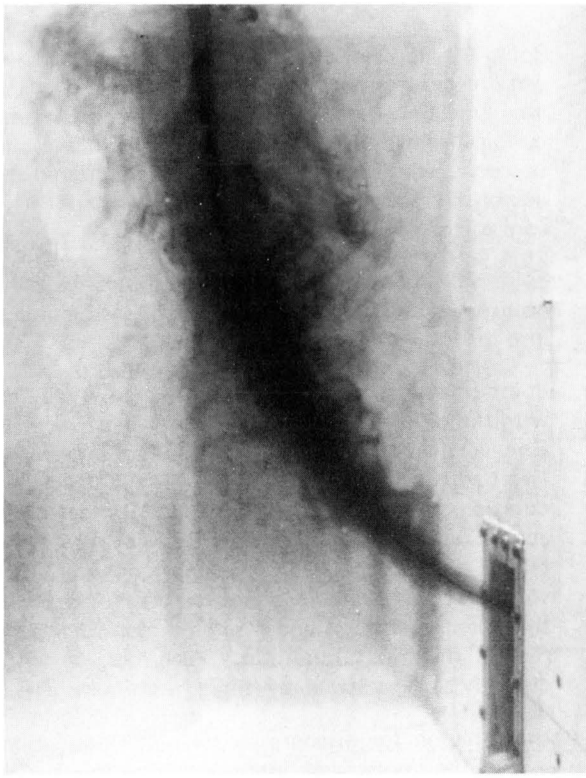


c. Lesser developed vortex. Photo P1222-D-76654



d. Weakly developed vortex. Photo P1222-D-76655

Figure 7.—Degree of vortex development. Photographs taken through the plexiglass panel at the end of the model forebay channel. The picture of the vortex near the water surface may appear confusing because of the mirror image on the water surface.



b. Swirl. Photo P1222-D-76657

a. Vortex traced by dye injected at the center of and off center from the vortex. Photo P1222-D-76656

c. Vortex which developed from a swirl. Photo P1222-D-76658

Figure 8.—Examples of rotational motion.

problem would be more easily detected by tests without trashracks.

Observations of vortex action were made for the six-unit forebay configuration (fig. 1b) for the following selected modes of unit operation:

1. Unit 19,
2. Units 19 and 20,
3. Units 19, 20, and 21,
4. Units 19 through 24, and
5. Staggered unit operation, where some interspaced units were inoperative.

These observations were made to obtain boundary curves between conditions of air-entraining and non-air-entraining vortices.

Tests were made within the minimum and maximum prototype operational water surface elevations of 1208 (368 m) to 1290 (393 m) and with different model penstock velocities, as indicated by the Equal Velocity Method. It was found easier to set a model discharge instead of a given penstock velocity. Tests were made with model discharges that were a multiple of the Froude number discharge for one prototype unit. Thus, a model discharge of 0.2 ft^3/s (0.0057 m^3/s) corresponded to a 31,000 ft^3/s (878 m^3/s) prototype unit discharge. In this report the designation 1Q refers to one Froude number discharge passing through each operating unit, 2Q for two Froude number discharges, and 3Q for three Froude number discharges.

Generally, the method of model operation was to set a discharge and then vary the forebay water surface elevation by changing the penstock gate openings. Flow conditions in the model were allowed to stabilize before judgments were made about vortices. Stabilization of the water surface elevation was determined by using a point gage and taking readings at time intervals of 5 to 10 minutes. The water surface was assumed stable when it did not raise or lower more than 0.002 foot (0.61 mm) for a 5-minute period. However, stabilization of vortex conditions was not so definite. When only a slight change was made in model flow conditions, such as a small decrease in water surface elevation for a given discharge, 10 minutes appeared to be sufficient for vortex observations.

However, there were times when the model operated at a constant water surface elevation for 30 minutes before an air-entraining vortex formed. Generally, these longer times occurred when establishing major new flow conditions such as: (1) the beginning of the day, (2) changes in model discharge, and (3) changing the number of operating units.

Observations of the Vortex Action

General.—All the vortices that naturally occurred in these tests were of an intermittent type, where the vortices formed and then dissipated. In many instances there was the same pattern of vortex development where a general water circulation or swirl existed near a penstock entrance and organized vortex action would develop in the swirl. Rotational velocity increased in the central part of the swirl, a dimple formed, increased in size, formed a vortex tail, and then formed an air core. Thus, observations showed that the presence of a steady swirl occurring near a penstock intake can signal a vortex-prone area. Other times, vortices formed from eddies and entered the flow region of an intake.

Results of the vortex observations were plotted to obtain the boundary curves shown on figure 9. Differentiating between non-air-entraining and air-entraining vortices was sometimes a matter of personal judgment. Vortices for these tests could be smaller than those shown in figures 7a, 7b, and 7c. However, if one or two bubbles were momentarily pulled away from the tail of the vortex air core, then the vortex was judged to be air entraining.

Severity of vortex action.—Severity of vortex action is of a qualitative nature and very dependent upon the model observer. To estimate the severity or intensity of a vortex, the factors considered were: (1) rotational speed of the water, (2) quantity of rotating water, (3) vortex characteristics, including size and extent of the air core, (4) frequency of occurrence, and (5) time duration of the vortex action.

An attempt was made to quantify the severity of vortex action by observing the number of air-entraining vortices that occurred in a time interval and the time duration of the individual continuous air core vortices. These observations were made for four different model test conditions designated A, B, C, and D on figure 9. Notes on the observations follow:

Point A.—Observations were made for a 10-minute time interval. Three air-entraining vortices, of the type where bubbles from the vortex air core entered the intake, occurred during this period.

Point B.—Observation time of 5 minutes with the occurrence of nine air-entraining vortices. Of these nine vortices, seven were the type where only bubbles from the vortex tail entered the intake, and two were where a continuous air core entered the intake. Duration of the individual continuous air core vortices was less than 5 seconds.

Point C.—Observation time of 5 minutes with the occurrence of five vortices that released bubbles into the intake.

Point D.—Observation time of less than 5 minutes with the occurrence of seven air-entraining vortices. Five vortices released bubbles into the intake and two had continuous air cores of 10- and 15-second durations. For this model test condition, the vortex action rapidly changed modes between that of a bubble-type vortex and a continuous air core vortex. It was difficult (if not impossible) to make the observations, set and reset the stopwatch, and record the time durations. Therefore, tests to quantify vortex action by timing were terminated.

Another reason for discontinuing timing observations was that the mode and intensity of vortex action appeared random in nature. There were instances when only a swirl-type motion was occurring. Then, a well-defined vortex would develop and persist for a 1/2- to 4-minute time span. Afterwards, there could be another lengthy interval (3 to 10 minutes) before the appearance of vortex action. To obtain vortex timing data of sufficient accuracy to categorize different test conditions of discharge, modes of unit operation, and water surface elevation, longer observation times of 15- to 30-minute time intervals may have been necessary. It was doubtful this information would be directly applicable to the prototype; therefore, qualitative observations of vortex severity were left to the discernment of the model observer.

Severity of vortex action was a function of model discharge. Vortex action was more severe for the higher discharges, whether by increasing the discharge for a given mode of unit operation, or by increasing the number of operating units at the same discharge. Vortices became air entraining as the model discharge increased, as shown for units 19 and 20 on figure 9. To help show that vortex conditions in the model became more severe with an increasing number of operating units, the three boundary curves of figure 9 were placed on one graph for comparison. See figure 10. No air-entraining vortices occurred when operating only unit 19, but air-entraining vortices did occur for the combined operation of units 19 and 20, and when operating more units, air-entraining vortices occurred at a smaller unit discharge.

Key of data point symbols

- • Eddy
- o Vortex with dimple or tail
- x Air-entraining vortex

(A),(B),(C) and (D) Comments in report about time duration of vortex action

(E) Photograph of vortex action figure 18b

(F) Photograph of vortex action figure 12

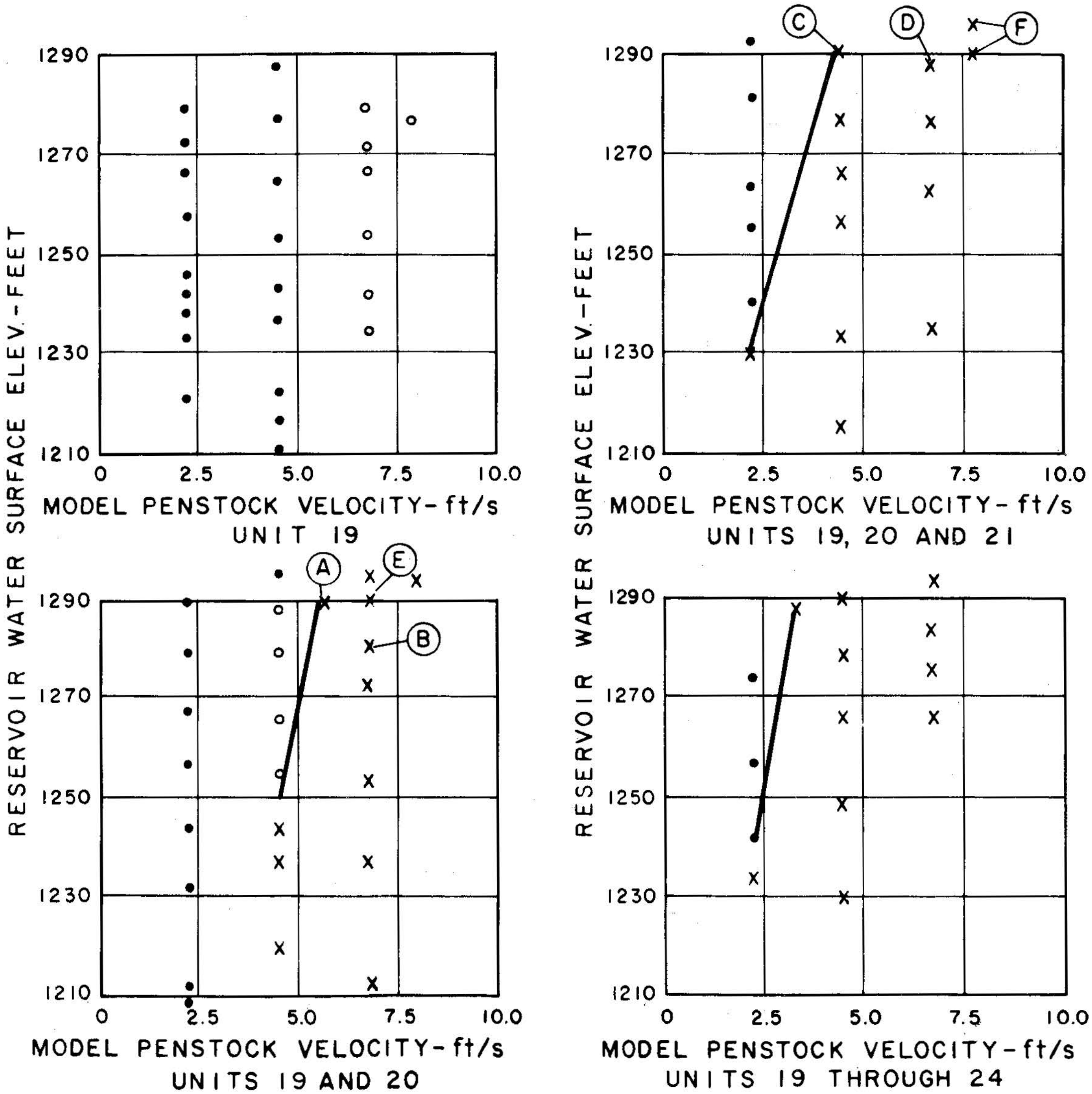


Figure 9.—Boundary curves of vortex conditions for different modes of unit operation.

One maxim relating to vortex occurrence is that increasing the water depth above an intake can submerge or suppress formation of air-entraining vortices. Thus, there was an expected correlation between vortex severity and water surface elevation. The slanting curves of figure 10 indicate a slight decrease in vortex severity with a greater water depth. However, vortex severity did not correlate as well with respect to the water surface elevation when model discharges were greater than needed to form air-entraining vortices. Vortex action at a lower submergence appeared more violent, but the action was less frequent and of shorter duration than that of the higher water surface elevations. Apparently, at lower submergence and higher discharges, water velocities into the model forebay produced unsteadiness of flow near the intakes. Vortices could not so readily persist under these conditions.

Location of vortex action.—Vortices occurred predominantly at the first operating unit downstream from the juncture of the Grand Coulee and Forebay Dams. For example, when units 19, 20, and 21 were operating together, unit 19, which was closest to the corner, had the more predominant vortex action. Similarly, when units 21, 22, and 23 were operating together, the predominant vortex action occurred at unit 21. A lesser amount of vortex action occurred at the last downstream operating unit and infrequent vortex action occurred at the middle unit. The vortex at the upstream operating unit rotated counterclockwise viewed from above and the vortex at the downstream unit generally rotated clockwise.

During staggered unit operation, where some of the interspaced units were inoperative, vortex action could occur at each operating unit, but the predominant action occurred at the first upstream operating unit. See figure 11. Staggered unit operation had the tendency to move vortex action of the first unit farther out from the Forebay Dam, as shown in figure 11a.

Location of a vortex, with respect to an intake, influenced the vortex severity. A vortex would start forming 40 to 100 feet (12 to 30 m) (prototype) in front of an intake. Then the vortex traveled towards the intake in a direction generally perpendicular to the Forebay Dam and increased in intensity. Approaching the Forebay Dam, the vortex would change direction and travel parallel with the Forebay Dam in either an upstream or downstream direction. This parallel movement could be over an 80-foot (24-m) distance before the vortex dissipated. If the vortex traveled downstream and an adjacent unit was operating, the vortex air core could switch over and enter the adjacent intake. Figure 12 shows different locations of the vortex with respect to the intake.

The location of vortex action with respect to the first operating unit varied with discharge in the model forebay channel. For these tests there were two methods of increasing discharge: (1) hold the number of operating units constant and increase the discharge of each unit, or (2) increase the number of units and hold the discharge from each unit constant. Figure 13 shows a sketch of varying locations of vortex action for the first method of increasing discharge. As the

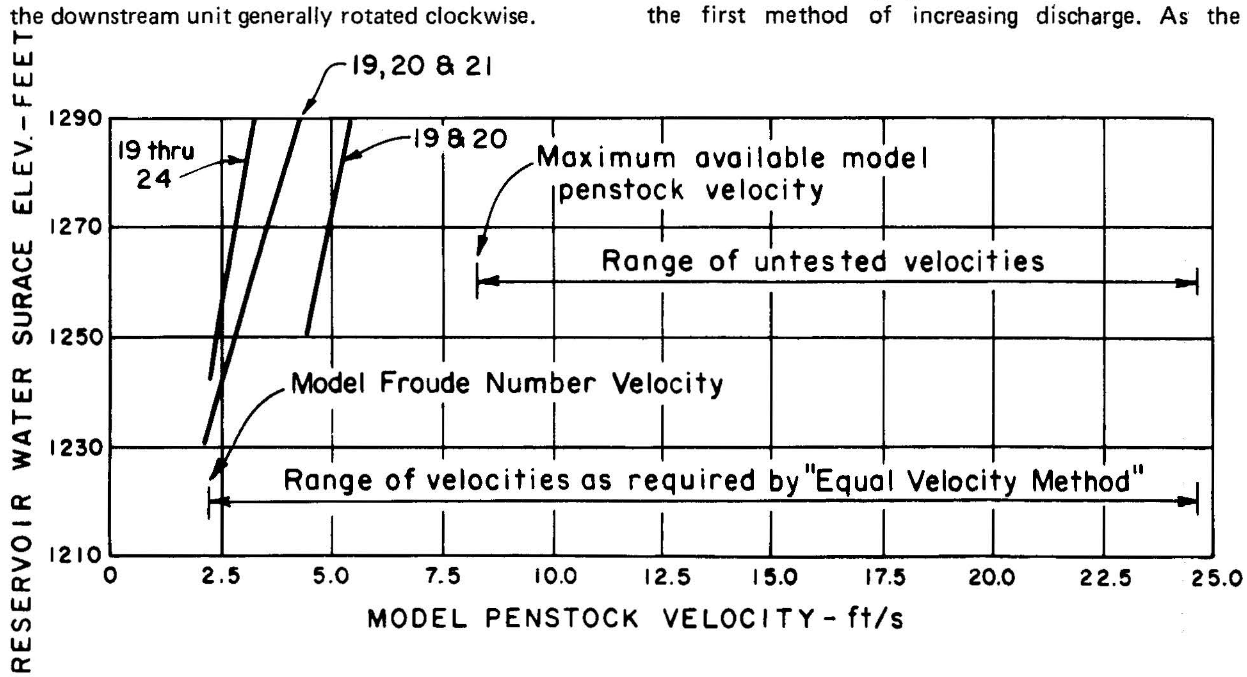
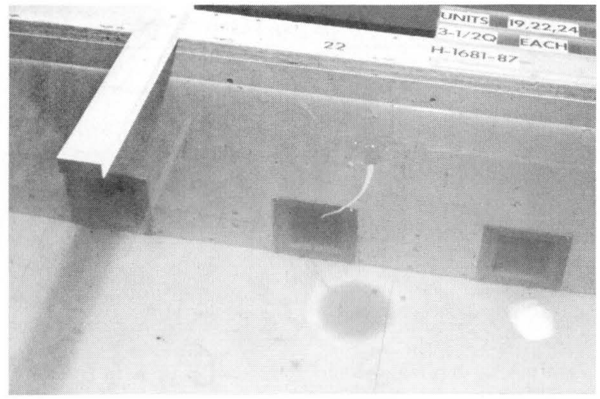


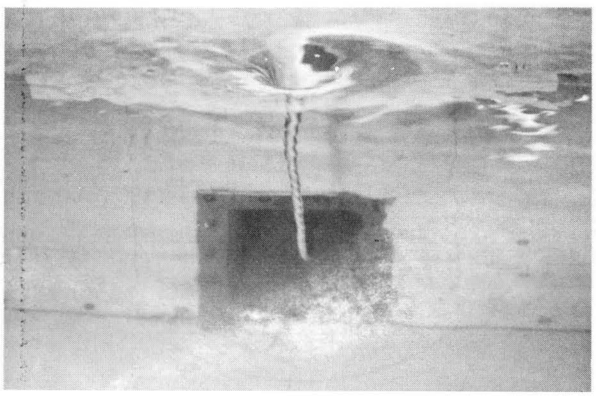
Figure 10.—Comparison of tests for different modes of unit operation.

a. Unit 19. Photo P1222-D-76659

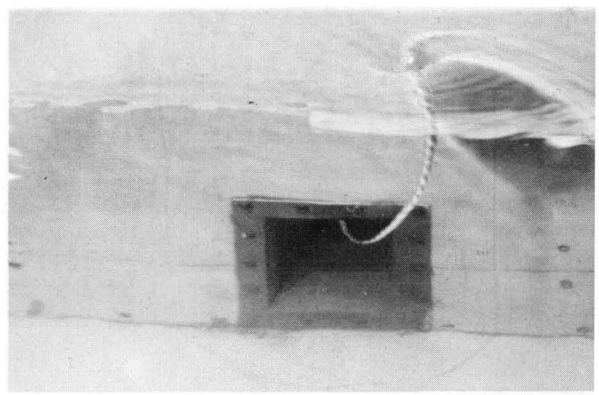


b. Unit 22. Photo P1222-D-76660

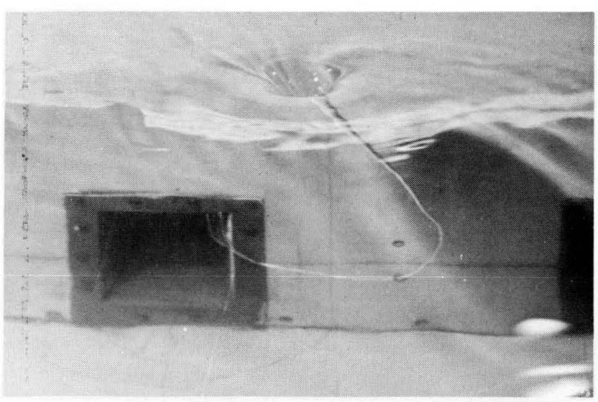
Figure 11.—Vortex action at units 19 and 22. Operation of units 19, 22, and 24 with 3-½Q each at water surface elevation 1290 (393 m).



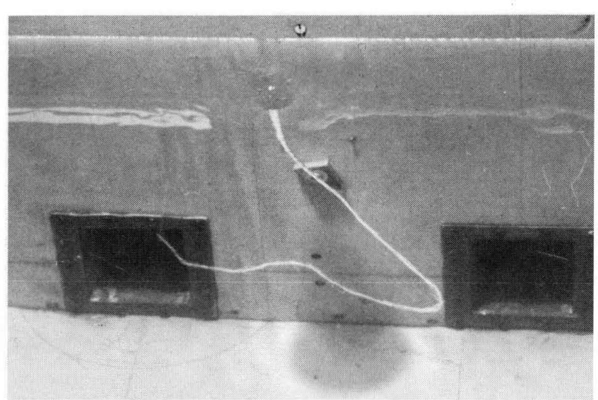
a. Severe vortex directly in front of the intake. Photo P1222-D-76661



b. Vortex beginning to diminish and move downstream. Photo P1222-D-76662



c. Vortex moved downstream midway between intakes 19 and 20. Photo P1222-D-76663



d. Vortex air core about to enter intake 20. Photo P1222-D-76664

Figure 12.—Severity of the vortex relative to the intake. Units 19, 20, and 21 operating at about 3-½Q each at water surface elevation 1290 (393 m).

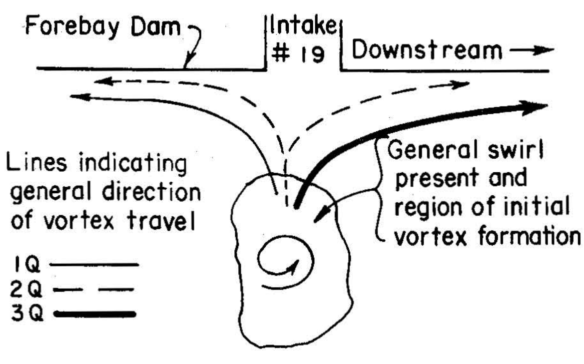


Figure 13.—Varying location of vortex action with respect to discharge.

discharge increased, there was a slight downstream displacement of the vortex formation region, and the direction of vortex travel changed from upstream to downstream movement along the Forebay Dam.

Interpretation of Tests

These hydraulic model tests indicated the possibility that air-entraining vortices could occur in the forebay channel near the intakes of the Grand Coulee Third Powerplant. Also, the Equal Velocity Method of vortex testing may produce distortion about the location of vortex action. Therefore, care should be used in applying model test results to predict location of vortex action in the prototype.

TESTS WITH TRASHRACKS

Background

In the investigation by Babb, et al., [7] most of the model tests were made without trashracks installed in the model. In this structure the trashracks were flush with the face of the dam. The investigators concluded that "they (the trashracks) were incapable by themselves of reducing the formation of large vortices." Thus, it was first thought that the model trashrack structures would not be necessary for the Grand Coulee Third Powerplant vortex study. However, the Coulee trashrack structures protuded from the face of the dam, and tests were made to determine their effect on vortex formation.

Trashrack Structures

The trashrack structure was 135 ft (41 m) high and, at the furthermost point, extended 24 ft (7.3 m) from the Forebay Dam. Relative size of the trashrack with respect to the intake is shown in figure 2. In plan view, the structure was a series of 10.75-ft (3.3-m) chords, formed by a 46-ft (14-m) radius and 120° arc, see figure 14. The individual vertical bars on the front face of the trashrack were of a 5-½- by 5/8-in. (140- by 16-mm) cross section and were spaced 7 in. (180 mm) apart. Because of the numerous individual structural components and the model scale ratio, it was

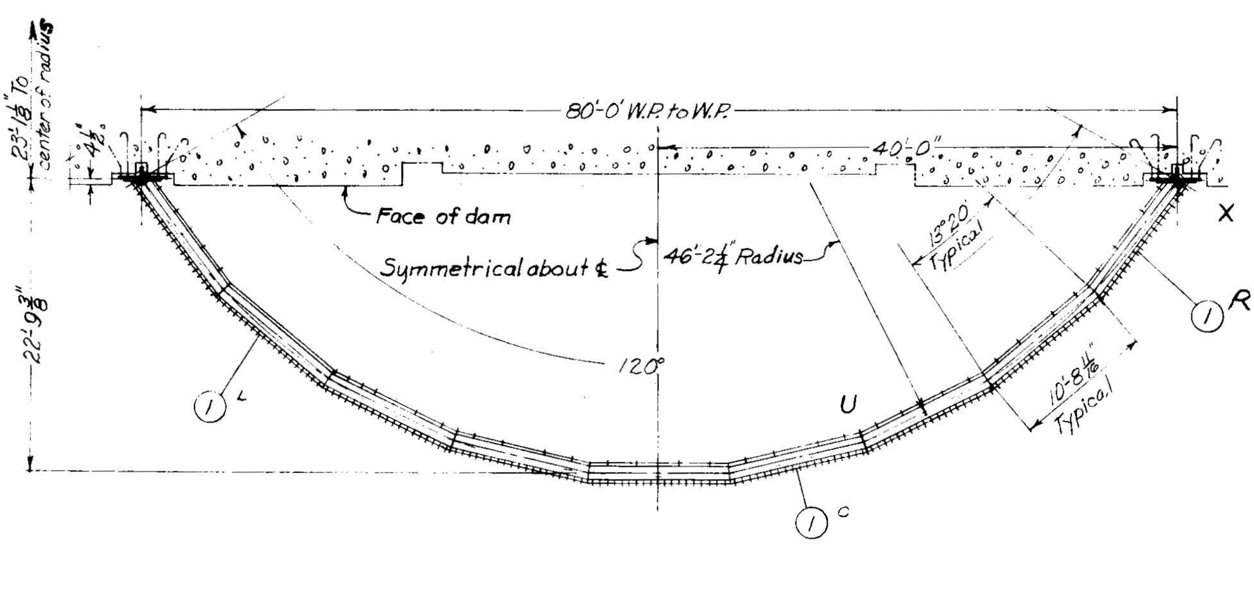


Figure 14.—Plan view showing shape of trashrack.

impractical to construct the model trashracks to the 1:120 geometric scale. Therefore, a commercial screen was used to represent the model trashracks, and the screen mesh size was chosen to provide anticipated resistance characteristics of the prototype.

The calculated design headloss for the prototype trashracks was about 0.1 ft (30 mm) of water, and debris collection against the trashrack could increase the head loss to 0.5 ft (150 mm) of water. Thus, tests were made to find a mesh screen size that could provide a model loss equivalent to a prototype head loss between 0.1 to 0.5 ft of water.

A screen was shaped with a 47-ft (14-m) radius and placed in front of intake No. 19, see figure 15. The prototype chord segments were not reproduced in the model, but the screen extended 24 ft (7 m) from the headwall. Thus, the screen represented the outermost location of the vertical trashrack bars.

Head loss measurements were made with the model water surface elevation between 1243 and 1246 (379 and 380 m). The top of the prototype trashrack was at elevation 1245 (379.5 m). To increase the model head loss and thus provide for an easier measurement of head loss, a model discharge of 0.59 ft^3/s (0.017 m^3/s) was used (three times the Froude number discharge for one unit). The model was operated at a constant flow without the screen and a measurement made of the water surface elevation. Then, with the model still operating, the screen was placed in the model for another water surface measurement. The screen head loss raised the water surface elevation 0.020 ft (6.1 mm) over a 1-hour period. This Δh of 0.020 ft (fig. 16), represented the model trashrack head loss for a penstock velocity three times greater than the design velocity. The formula:

$$h = K\frac{V^2}{2g}, \text{ or } K = \frac{2gh}{V^2}$$

where

h = head loss, ft,
V = velocity, ft/s,
g = acceleration of gravity, ft/s^2, and
K = trashrack head loss coefficient.

was used to solve for the head loss that would occur for a model design velocity. In the following equations, subscript 1 designates conditions for the design velocity, and subscript 3 designates conditions for the 3Q or three times normal velocity. Assuming the trashrack head loss coefficient is constant for flow at the two velocities, then:

$$K = \frac{2gh_1}{V_1{}^2} = \frac{2gh_3}{V_3{}^2}, \text{ and } h_1 = h_3\left(\frac{V_1}{V_3}\right)^2$$

Since $V_3 = 3V_1$, then:

$$h_1 = h_3\left(\frac{V_1}{3V_1}\right)^2 = \frac{h_3}{9} = \frac{0.020}{9}$$

$$= 0.002 \text{ ft } (0.61 \text{ mm}), \text{ model.}$$

The prototype head loss of 0.002 x 120 or 0.24 ft (73.2 mm) was greater than the 0.1 ft (30 mm) calculated minimum prototype head loss, but less than the 0.5 ft (150 mm) for the debris restricted rack. This 0.24-ft value was considered satisfactory and the trashracks were constructed for easy placement and removal from the intakes. See figure 17.

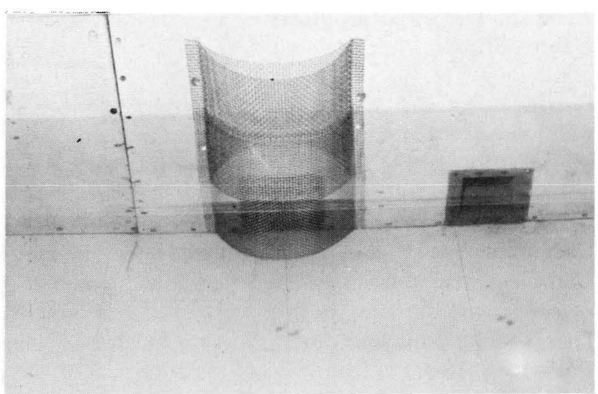


Figure 15.—Method of placing commercial screen in model to make model trashrack resistance test. Photo P1222-D-76665

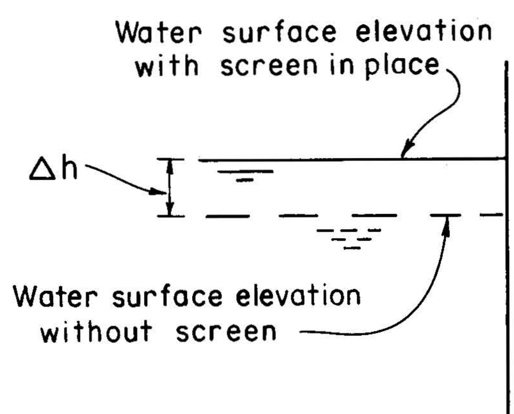


Figure 16.—Definition sketch for Δh.

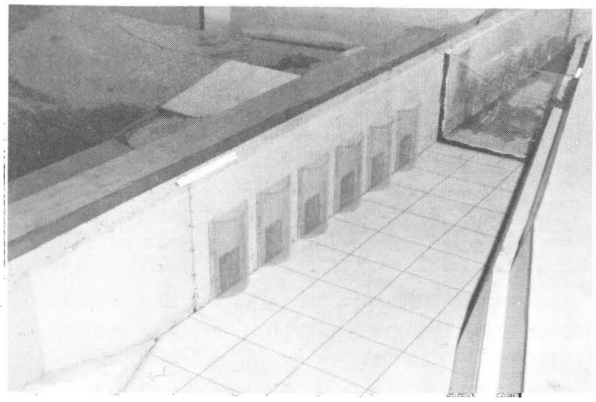


Figure 17.—Installation of the model trashracks. The trashracks were made with three different sizes of screen; the small screen size trashracks are shown. The plexiglass panel defines the end of the model forebay channel for the six-unit configuration. Photo P1222-D-76666

Test Results

The model trashracks had a definite suppressive effect upon vortex severity as shown in figure 18. With trashracks there was only a dimple on the water surface showing the presence of a vortex, but without trashracks a more severe vortex formed where a continuous air core entered the intake. For a slightly more severe vortex test condition with 3-unit operation at a 3-½Q discharge, vortex tails formed. See figure 19.

For some modes of unit operation with model water surface elevations between 1208 and 1220 (368 and 372 m), air-entraining vortices were observed inside the trashracks. These water surface elevations were below the top of the trashrack, and the vortices occurred in the semicircular area between the trashrack and Forebay Dam. The vortices would form and break up in less than 3 seconds. These short-time vortices did not appear to entrain very much air.

Boundary curves for the Equal Velocity Method could not be obtained with the simulated trashracks in place. With the exception of vortices within the trashracks, no air-entraining vortices were observed.

Tests Using Model Trashracks Constructed with Large Mesh Screen

After viewing the suppressive effect of the model trashracks on vortex action, the choice of the size of the screen mesh was questioned because of possible excessive model head loss. The model trashracks may have overly restricted vortex formation. Therefore, model tests were made using two screens of larger mesh size. All screen sizes used for model trashracks are listed in the following tabulation:

Screen Used for Model Trashracks

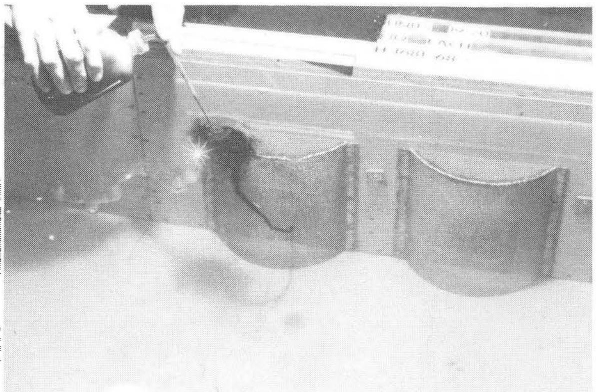
Designated screen size[1]	Screen mesh[2]	Wire gage[3]	Prototype head loss[4]
Small	8	27	0.24
Medium	6	20	0.1
Large	4	23	Very small—not measured

[1]Designated screen size—name given to a specific commercial screen for descriptive purposes.
[2]Screen mesh—number of holes per linear inch, measured center-to-center of wires.
[3]Wire gage—size classification of the wire used to construct the screen.
[4]Prototype head loss—Equivalent prototype head loss in feet of water.

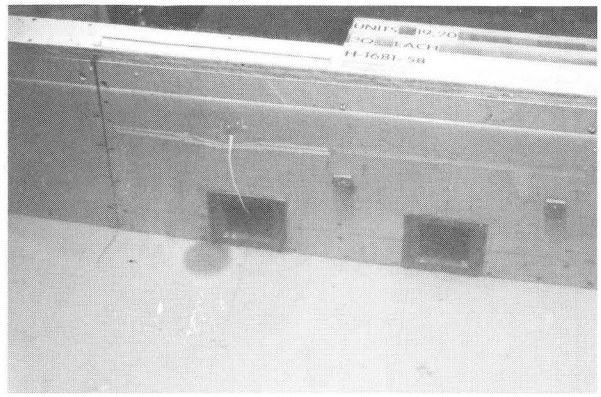
Three model trashracks with the medium screen were constructed and tested. The vortex action with this size screen was slightly more severe than with the small eight-mesh screen. Only one model trashrack was constructed with the large screen and this trashrack was placed in intake No. 19. The vortex action was slightly more severe with the large screen than with the small screen trashrack, and the tails of the vortices penetrated slightly deeper below the water surface with the large screen. From these qualitative tests, it was concluded that the prototype trashrack structures will have a suppressive effect upon vortices.

Effect of Trashrack Structures Upon Vortices

Further tests were made to gain a better insight as to the reason the model trashracks had a suppressive effect upon vortices. Observations were made using dye as a tracer. The trashracks provided frictional resistance to the circulation or swirl of water in the region above the intakes, see figure 20. In previous tests without trashracks, the most severe vortices occurred in this region. See figure 12a. (In this figure, note the penciled lines on the wall and floor showing location of the trashrack.) Also, the front face of the trashrack resisted circulation of the vortex core, see figure 21.

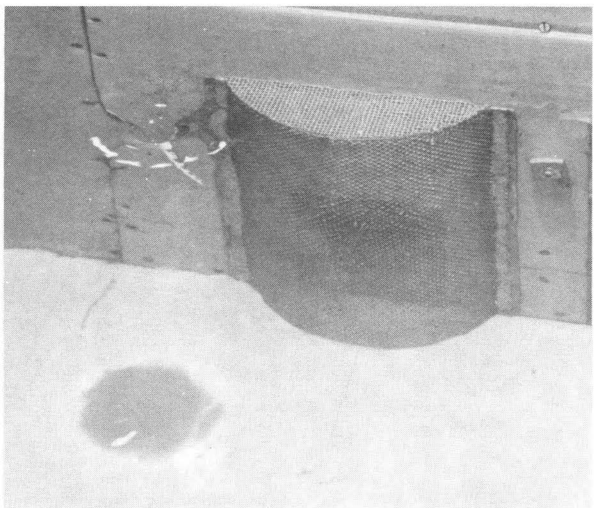


a. With trashracks. Photo P1222-D-76667

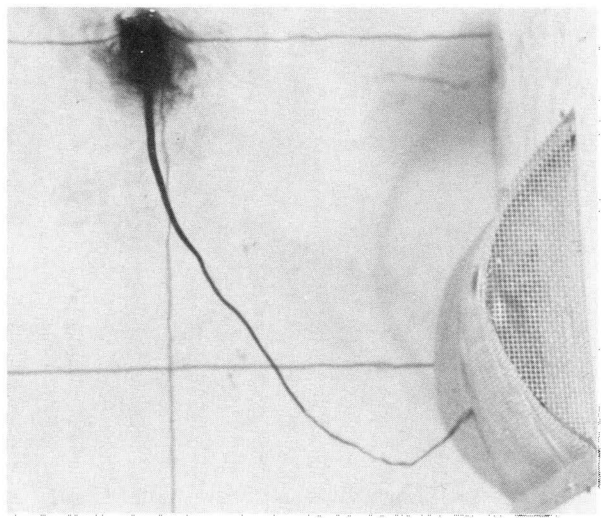


b. Without trashracks. Photo P1222-D-76668

Figure 18.—Vortex action with and without model trashracks. Units 19 and 20 operating 3Q each, and water surface elevation 1290 (393 m).

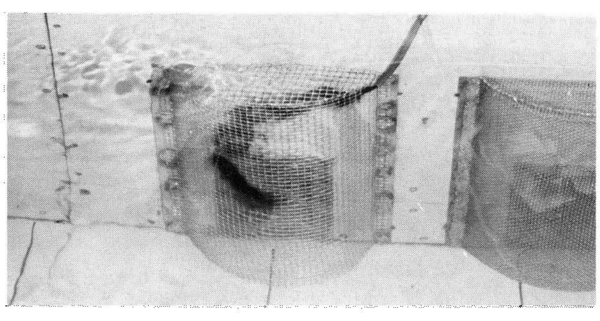


a. Vortex tail formed near unit 19. Photo P1222-D-76669

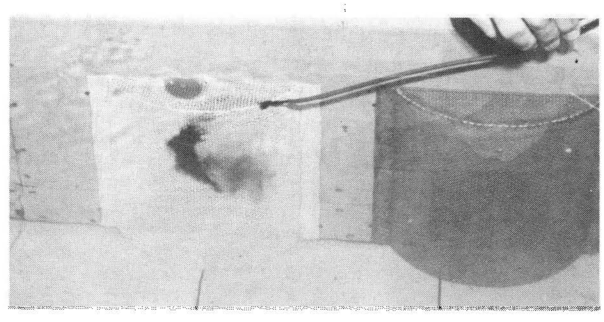


b. Dye injected in the vortex at water surface shows vortex filament entering unit 19. Note that this vortex is approximately 120 feet (37 m) out from the headwall and 100 feet (30 m) upstream from the centerline of intake 19. Photo P1222-D-76670

Figure 19.—Vortices with model trashracks. Units 19, 23, and 24 operating approximately 3-½Q each, and water surface elevation 1290 (393 m).



a. Large mesh screen. Photo P1222-D-76671



b. Small mesh screen. Photo P1222-D-76672

Figure 20.—Model trashrack provides friction to swirl of water above intake 19. Dye trace shows water entering top of trashrack, circulating within the trashrack, exiting in front of trashrack, and then reentering the trashrack. Units 19, 20, and 21 operating, 3-½Q each, water surface elevation 1290 (393 m).

a. Well-developed vortex with a small core of rapidly circulating water. Photo P1222-D-76673

b. Vortex has moved closer, trashrack face resists vortex core circulation. Because of friction, the circulation speed has reduced and the vortex core widens. Photo P1222-D-76674

c. Vortex partially dissipated. Photo P1222-D-76675

d. Vortex dissipated with some remaining circulation passing over the trashrack. Photo P1222-D-76676

Figure 21.—Dissipation of a vortex on the trashracks. Units 19, 20, and 21 operating, 3-½Q each, water surface elevation 1290 (393 m).

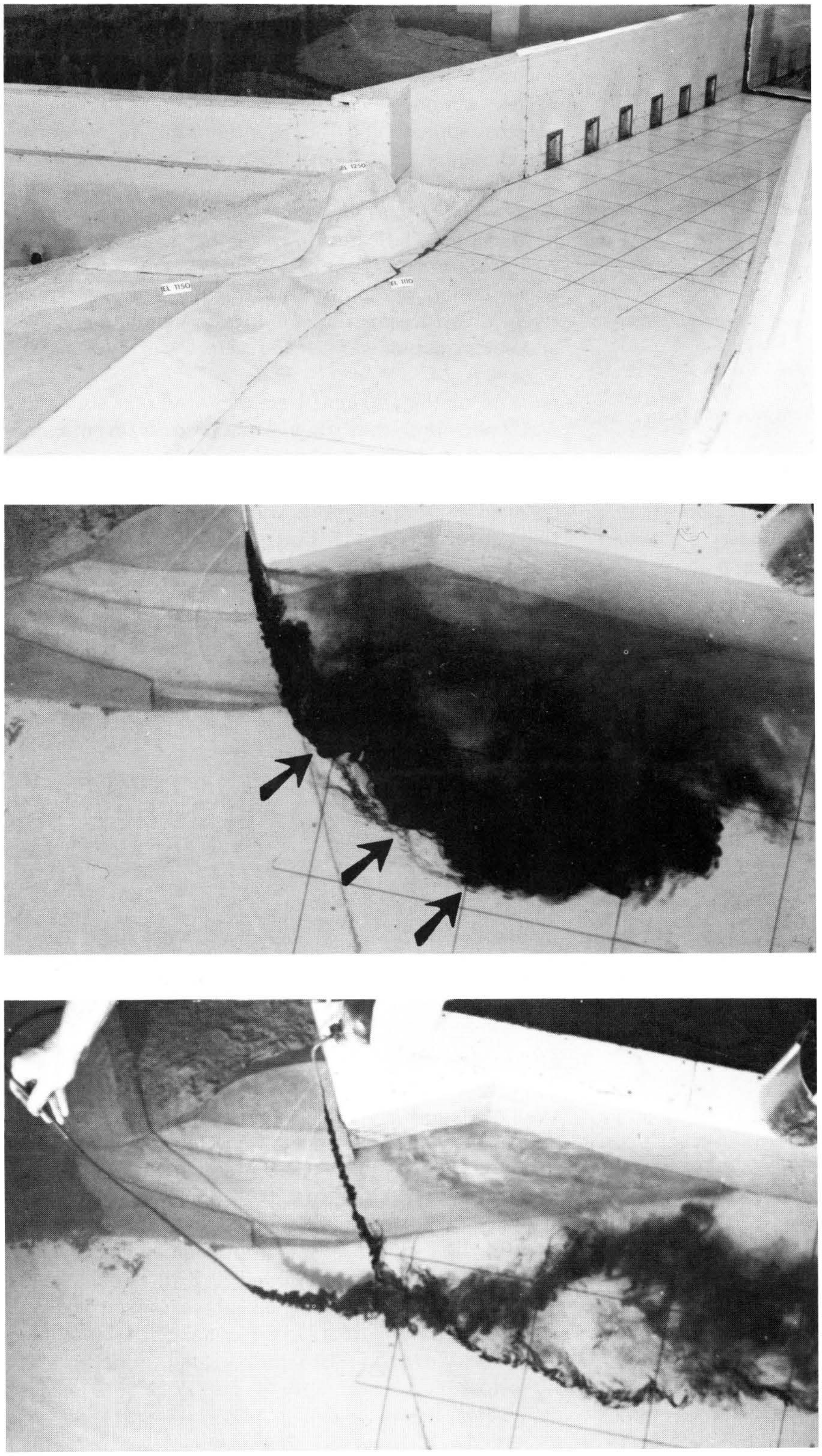
EFFECT OF UPSTREAM GEOMETRY ON VORTICES

Hydraulic Flow Conditions from the Forebay Channel Entrance

Topography near the forebay channel entrance is irregular. The bottom of the forebay channel is at elevation 1110 (338 m). A level bench at elevation 1150 (350 m) connects the forebay channel with the reservoir, and there is a sharp corner at the intersection of Grand Coulee Dam and the Forebay Dam. These features are shown in the photo on figure 22a.

The sharp corner caused a complex set of flow features. Water flowed along the face of Grand Coulee Dam, separated from the corner, and moved somewhat perpendicularly into the forebay channel. In addition, the flow that was alined with the forebay channel passed beneath this separated flow. These flow features are shown in figure 22. At the boundary of the separated flow, there was a shear zone where eddies were generated and traveled to the intakes, see figure 23. These eddies are indicated by the three arrows on figure 22b. When traveling downstream, the eddies could either dissipate or collect into larger size eddies.

The mode of unit operation determined the travel distance of the larger size eddies. With units 23 and 24 operating, the eddies could travel nearly the whole length of the model forebay channel. When units 19, 20, and 21 were operating, the eddies only traveled to unit 19.



a. Model topography near the dam corner. Grid has a 100-foot (30-m) spacing with origin at face of Forebay Dam and centerline of intake 19. Photo P1222-D-76677

b. Waterflow along face of Grand Coulee Dam separates from the corner. Photo P1222-D-76678

c. Flow alined with forebay channel passes beneath the separated flow. Photo P1222-D-76679

Figure 22.—The forebay channel entrance. Units 19, 20, and 21 operating, 3Q each, water surface elevation 1290 (393 m).

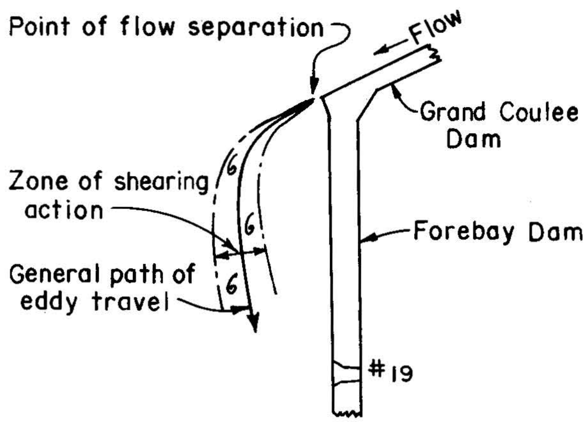


Figure 23.—Schematic of flow conditions resulting from the dam corner.

The large eddies appeared to initiate vortex formation. For some test conditions, there was a region where a general swirling motion of the water movement occurred in front of an intake. When a large eddy entered this region, the rotational speed in the swirl increased and a dimple formed in the water surface. The dimple would either dissipate or continue to develop into a vortex.

Corner Modification Tests

Tests were made to determine whether the flow separation from the dam corner was crucial with respect to vortex formation at the intakes. Three different corner modifications were used in an attempt to guide the waterflow directly down the forebay channel and prevent flow separation from occurring at the dam corner. The model test conditions were: (1) reservoir water surface elevation 1290 (393 m), (2) units 19, 20, and 21 operating with three times the Froude number discharge through each unit, and (3) with and without model trashracks.

Observations and analysis of the tests.—The three different corner modifications and their effect upon flow separation are shown in figure 24. A sizeable corner modification was required to aline the water surface currents directly down the forebay channel, but with guidewall No. 3 there was only minor flow separation.

With guidewall No. 3 in place, there was a decrease in vortex severity. This was especially true for the "without trashrack" test condition. Without the guidewall, an air-entraining vortex with a continuous air core readily formed and entered intake No. 19. With the guidewall, vortex severity was reduced to where only small bubbles occasionally pulled off the vortex tail and entered the intake.

The decrease in vortex severity was less noticeable with the trashrack in place. In this case, determination of vortex severity was made on the basis of less frequent vortex action. Evidently the direction of surface currents approaching unit 19 influenced the location of vortex action. See figure 25 where a is the angle of approaching surface currents. For the greater angle, the water surface currents more directly approached the headwall and deflected from the headwall. Thus, swirl was produced in front of the intake. With the smaller angle, deflection could not so readily occur, swirl was swept downstream from the intake, closer to the wall, and vortex action was not so severe.

Because of the apparent lessening of vortex activity, it was concluded that flow separation from the dam corner contributes to vortex formation, but was not the sole cause of the problem. Also, the model was believed to produce more intense flow separation than the prototype. Model waterflow from the reservoir could not so readily aline itself directly into the forebay channel. Because of model size limitation, reservoir topography directly alined with the forebay channel was not included. Prototype water surface currents may be more alined with the forebay channel.

MODIFICATIONS NEAR INTAKES FOR VORTEX PREVENTION

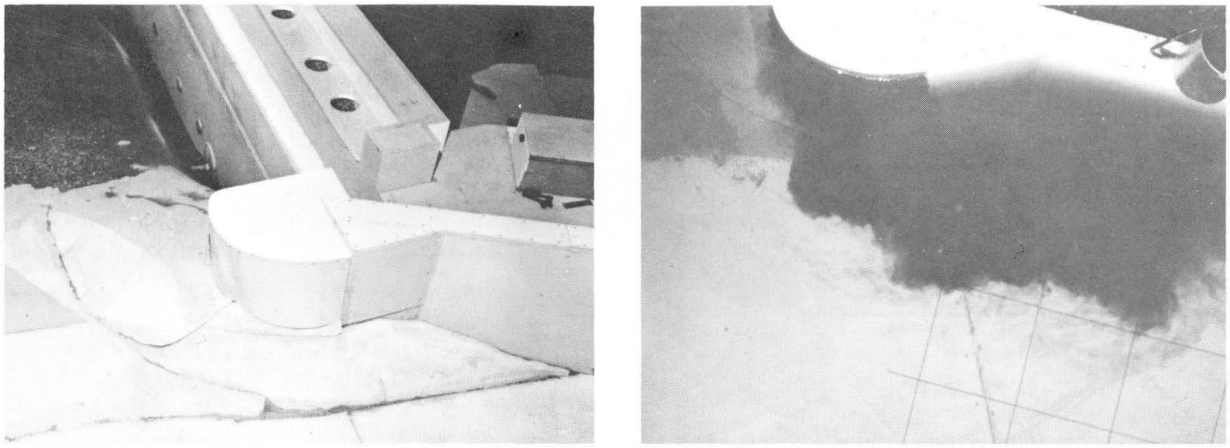
General

Two modifications near the intakes were tested for vortex prevention. One modification was to the intakes and the second was an addition of deflection vanes above the intakes.

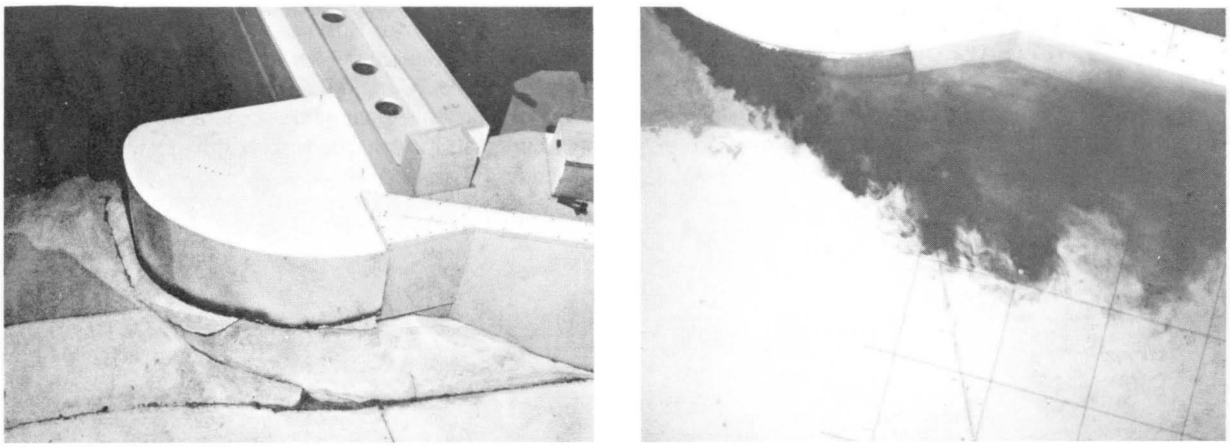
Curved Entrances

Two different curved entrances were tested. The purpose of the entrances was to provide a lower entrance velocity and to eliminate the 90° turn of water flowing into the intakes.

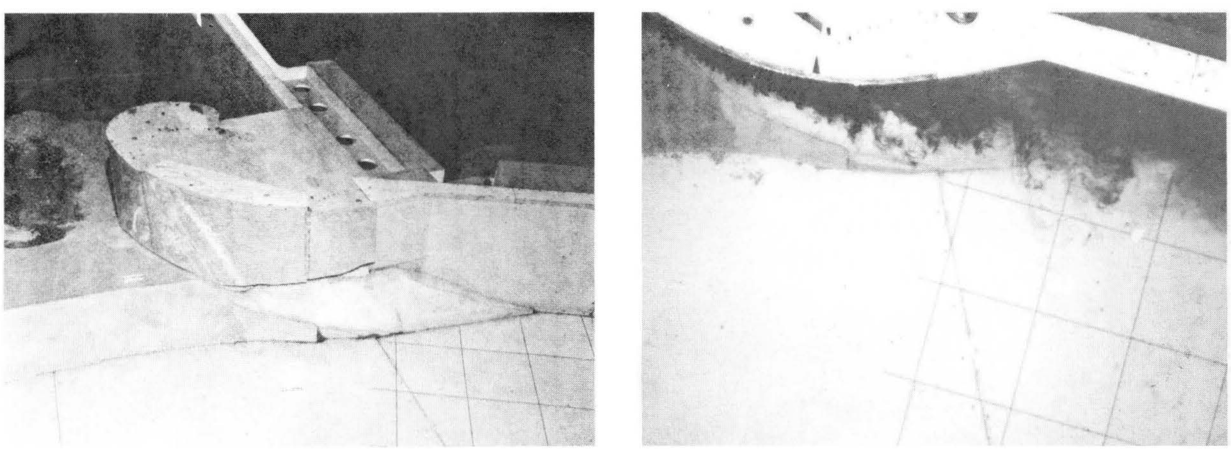
For the first curved entrance design, the face of the intakes was located at a 45° angle with respect to the headwall, figure 26a. The intake openings were approximately 74 ft (22 m) square, and a curved transition was made into the existing model intakes. Air-entraining vortices formed, see figure 26b. Because the water region above the curved entrances was susceptible to swirling, the headwall was extended above the intakes to exclude the region. However, air-entraining vortices still formed, as shown on figure 26c.



P1222-D-76683 a. Guidewall No. 1. P1222-D-76680



P1222-D-76684 b. Guidewall No. 2. P1222-D-76681



P1222-D-76685 c. Guidewall No. 3. P1222-D-76682

Figure 24.--Corner modifications and effect upon flow separation.

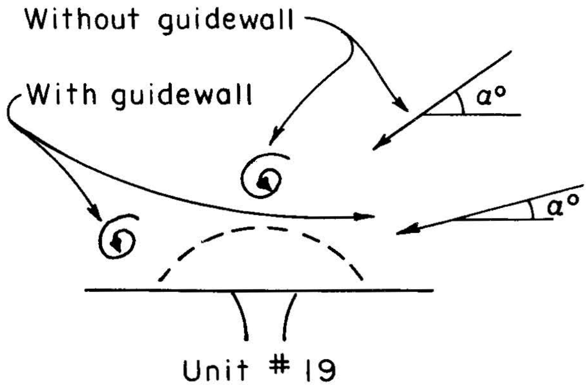


Figure 25.—Comparison of flow features with and without guidewall No. 3 in place.

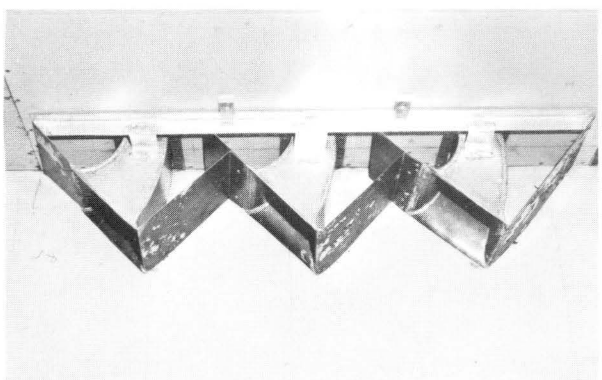
The second curved entrance design had intakes at a 70° angle with the headwall, and the intakes were 33 ft (10 m) wide by 70 ft (21 m) high, see figure 26d. Air-entraining vortices occurred for this entrance, and extending the headwalls above the water surface did not prevent formation of air-entraining vortices.

Deflection Vanes

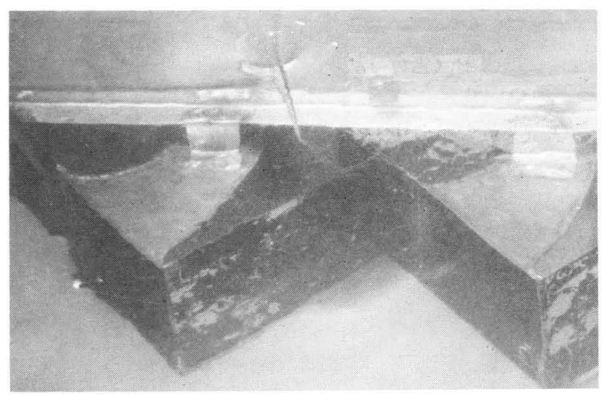
Deflection vanes, having prototype dimensions of 20 ft (6 m) wide by 40 ft (12 m) high, were placed in the water above the intakes. See figure 27. The purpose of the vanes was to inhibit rotational movement of the water above the intakes. There was some decrease in vortex severity, but air-entraining vortices still formed.

GENERATION OF A VORTEX FOR MAKING TESTS AND OBSERVATIONS

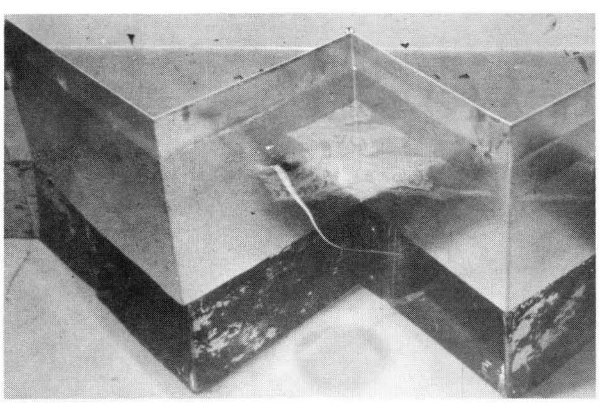
Because of the intermittent nature of vortices that occurred in the model, it was difficult to make judgments and observations concerning these vortices. A stronger and more persistent vortex was needed for better evaluations. Therefore, a steady vortex was generated in the model by placing a piece of sheet metal in front of intake No. 24. A circulation of water produced by the sheet metal generated a vortex that was larger and much more severe than vortices which



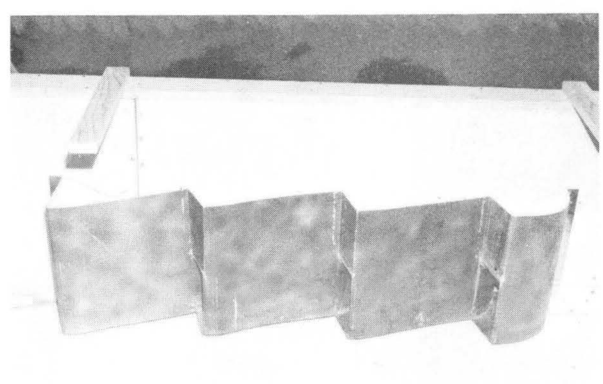
(a) Photo P1222-D-76686



(b) Photo P1222-D-76687



(c) Photo P1222-D-76688



(d) Photo P1222-D-76689

Figure 26.—Curved entrances. For (b) and (c), units 19, 20, and 21 operating, 3Q each, water surface elevation 1290 (393 m).

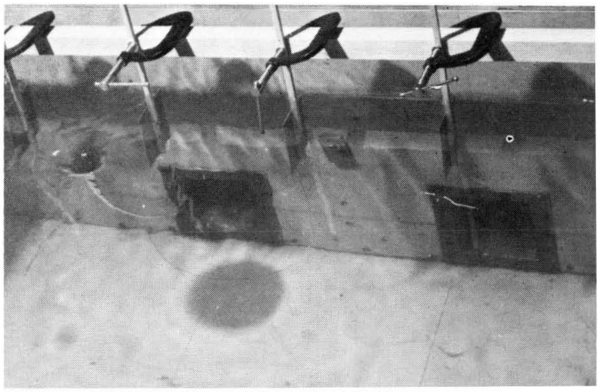


Figure 27.—Deflection vanes. Air-entraining vortex at unit 19. Units 19, 22, and 24 operating, 3-½Q each, water surface elevation 1290 (393 m). Photo P1222-D-76690

naturally occurred in the model. See figure 28. Severity of the generated vortex could be decreased by decreasing the discharge through unit 24. To improve observations, a plexiglass wall was placed at the downstream end of the model, and photographs of vortices were made through this wall. Hereafter, the term "generated vortex" will be used to distinguish this vortex from vortices that naturally occurred in the model.

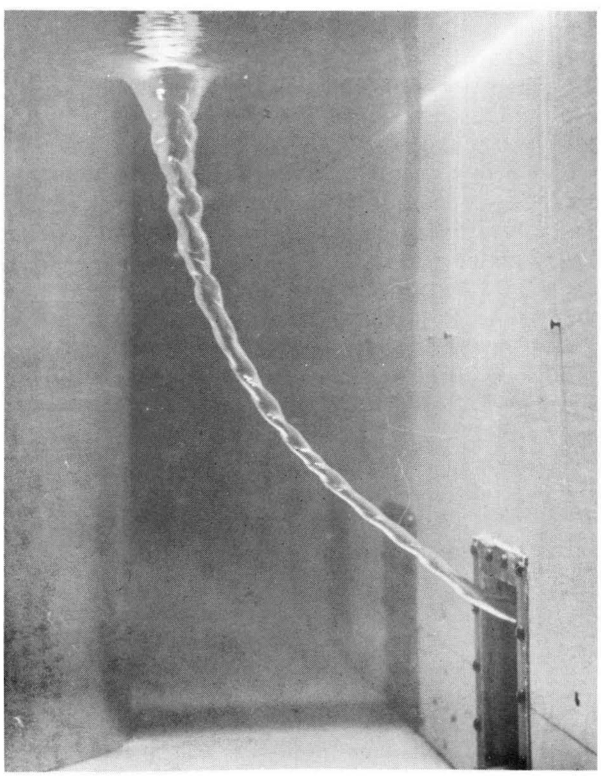


Figure 28.—Generated vortex—strongest condition. Photo P1222-D-76691

RAFT TESTS

Initial Tests

Initially, raft tests were made for vortices that naturally occurred in the model. The rafts were made from strips of plexiglass, and small cubes of styrofoam were taped on the corners to make the rafts float. Various rafts were tested, see figure 29. Two rafts were tried, each 80 by 80 ft (24 by 24 m) with 10-ft (3-m) grid spacing. One raft was 8 ft (2.4 m) deep and the other 4 ft (1.2 m) deep. These rafts were placed in vortex-prone areas of the model and observations made. Both rafts prevented vortices and no distinguishable differences of water swirl were noted between the two rafts. Thereafter, only 4-ft deep rafts were tested.

Additional rafts that were 80 by 80 ft (24 by 24 m) and 60 by 60 ft (18 by 18 m), having 20- and 10-ft (6- and 3-m) grid spacing were tested. No discernible difference was detected to determine whether the 10-ft-grid raft was better than the 20-ft-grid raft or whether the 80- by 80-ft raft was better than the 60- by 60-ft raft. All rafts appeared to work equally well when placed over a vortex. However, more effort was needed to assure that the 60- by 60-ft raft was positioned over the vortex-prone area.

All natural forming vortices of the model tests were of an intermittent type. The vortex would begin from an eddy or swirl, increase in severity, and then dissipate. Generally, during this time the water surface location of the vortex was not stable, but traveled with respect to the headwall of the dam. The travel path length of the vortex from its beginning to end could exceed 100 ft (30 m). Rafts for the hydraulic model tests did not cover the complete area of the vortex travel paths. The tests were made while the rafts were held in a stationary position. If the raft was positioned near the center of the vortex formation area, the raft was effective in preventing objectionable vortices. Also, the raft was effective when positioned where the traveling vortices had their most severe development. Vortices would form beyond the raft and dissipate when passing beneath the raft.

All the 4-ft (1.2-m) deep rafts were tested while submerged 20 ft (6 m) below the water surface. The submerged rafts prevented formation of air-entraining vortices. These submerged rafts appeared slightly more effective than the floating rafts in reducing the formation of vortices.

The rafts performed well both with and without the model trashracks in place.

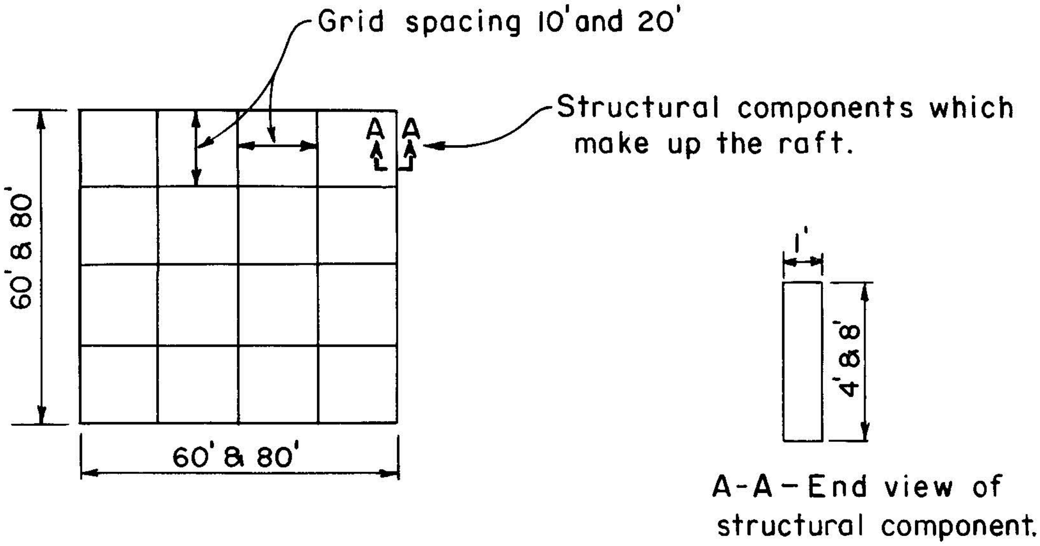


Figure 29.—Definition sketch for dimensions of model rafts tested.

Tests in the Generated Vortex

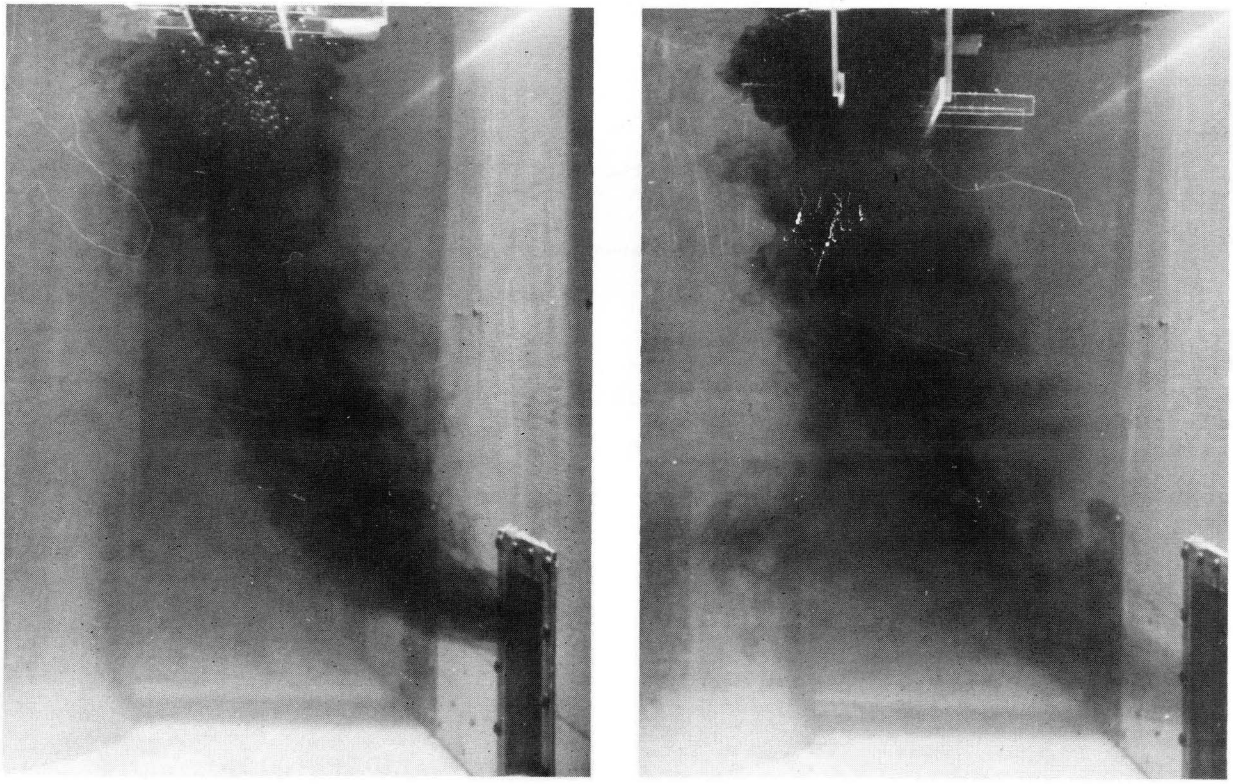
Floating rafts.—Various floating rafts were tested in the generated vortex, and all the rafts prevented formation of an air-entraining vortex. However, there was a swirling motion in the water beneath the floating raft, figure 30a. An organized vortex was not present because a central core was not visible as a dye filament, similar to figures 8c and 8d. The smaller 60- by 60-ft rafts were somewhat less effective than the larger 80- by 80-ft rafts in preventing a vortex.

The floating rafts disrupted the converging circular water surface currents normally present in an organized vortex. In a developed vortex, the motion of water surface currents is a spiraling inflow toward the center of the vortex. The raft prevented the converging portion of this motion, but a very substantial circular motion still remained as swirl beneath the raft. Also, the raft produced turbulent velocity fluctuations to the swirl, and unsteadiness of flow can be detrimental to vortex development. The 10- to 20-ft (3- to 6-m) raft grid spacing was believed optimum in producing turbulence to the swirl, figure 31a, and also appear optimum to the areal extent of the spiral, figure 31b.

Submerged rafts.—Rafts that were submerged 20 ft (6 m) below the water inhibited vortex formation slightly more than when floating, see figure 30b. Judgments about raft effectiveness were made by observing the swirling motion of dyed water flowing past the raft and into the intake. Because of the structural manner used in submerging the model rafts, four vertical members attached to floats (fig. 30b), the submerged rafts provided more resistance to swirling than the floating rafts. Therefore, comparisons of effectiveness between the two modes of raft installation are probably invalid for these tests.

Other tests were made where the submergence depth was varied. The raft location was moved from the water surface, down along the vortex axis, and then against the intake. The two 60- by 60-ft floating rafts with 10- and 20-ft grids were used. Floats were removed, two 1/8-in. (3.18-mm) diameter metal rods were attached to each raft, and the rafts could be positioned without undue additional resistance. It appeared the best submergence depths were between 20 and 60 ft (6 and 18 m) below the water surface, and the submerged rafts were perceived to be slightly better than the floating rafts for vortex prevention. However, the 20-ft raft grid spacing appeared to be approaching the maximum grid size. Occasionally, for time periods less than 2 seconds, a centralized dye filament was observed to form and pass through the central 20-ft grid of the raft. The dye filament would break up from turbulence in the swirling water or when the filament passed near or over an individual raft member.

The passage of an organized vortex core through a raft grid depended on flow velocity passing through the raft. A high velocity confines or stretches the vortex core into a smaller volume. When the 20-ft grid raft was placed vertically across the intake opening against the headwall, an organized vortex developed. The air core would pass through a raft grid and then enter the intake. By moving the raft a model distance of less than 2 in. (50 mm) away from the headwall, the vortex air core would be destroyed and the severity of the vortex was considerably decreased. With the 10-ft raft grid, an air-entraining vortex did not form under these test conditions.



a. Floating raft. Photo P1222-D-76692

b. Submerged raft. Photo P1222-D-76693

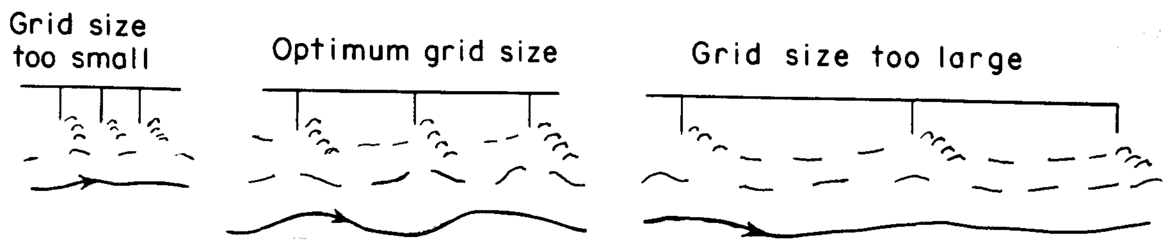
Figure 30.—Raft tests in the generated vortex. Raft size is 60 by 60 feet (18 by 18 m) with a 20-foot (6-m) grid. Before placing raft, vortex was similar to figure 28.

A raft submerged only a small distance below the water surface reacts on the upper portion of a vortex and is similar to a floating raft. However, a raft submerged a substantial distance below the water surface reacts on the lower portion of the vortex. To distinguish between the upper and lower portions of a vortex, note figure 21a. In this figure, dyed water shows a funnel shape for the vortex, and the upper portion of the vortex near the water surface occupies a relatively large volume with low velocities; the lower portion occupies a small centralized core with higher velocities. The submerged raft (one reacting on the lower portion of a vortex) provides resistance to the high-velocity zone of the vortex. This resistance must be sufficient to prevent the swirl of water above the raft from developing into a vortex. If the resistance is insufficient, dyed water in the swirl shows development of an organized vortex. A centralized dye filament forms and passes through the raft, and the raft loses a very large degree of effectiveness.

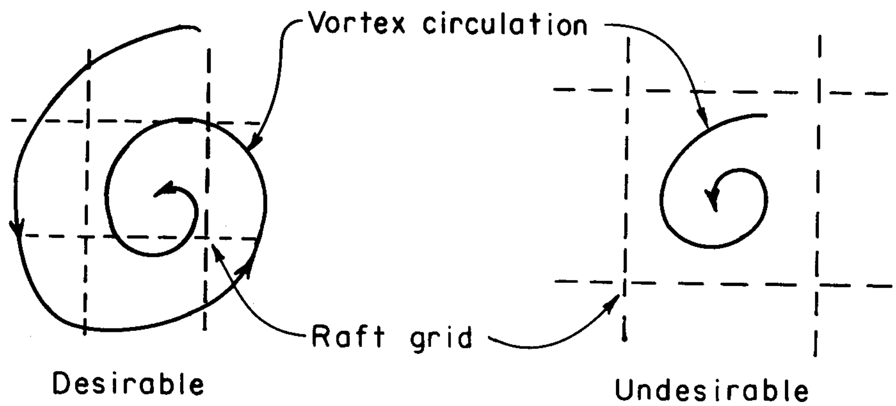
Analysis of the Raft Tests

Because of the intermittent vortices of the initial tests, there was difficulty in judging the effectiveness of the rafts. Whether the raft substantially or partially influenced the vortex breakdown was unknown. There was always the uncertainty that the intermittent vortex was about ready to break down. With the stable and persistent generated vortex, the uncertainty was removed, and the raft definitely broke up the vortex. Also, the generated vortex was much more severe than the intermittent vortices that naturally occurred in the model. Therefore, in the event the hydraulic model did not simulate severe enough vortices, the breakup of the generated vortex is believed to provide a measure of safety in the raft tests.

Both floating and submerged rafts prevented formation of air-entraining vortices in the model. However, there still remained a swirl to the water. Effect of the rafts was to prevent development of an organized vortex. Interpretation of the test results indicated a smaller margin of error of the raft grid size for submerged rafts than for floating rafts.



a. Effect of raft grid spacing on turbulent velocity fluctuations that produced unsteadiness to the swirl beneath the raft.



b. Relation of the raft grid to the vortex circulation.

Figure 31.—Qualities of the raft grid spacing that appeared conducive to vortex suppression.

INFORMATION FOR RAFT DESIGN

Background

The designers requested information for making a preliminary raft design. Thus, the designers could consider the raft design and determine whether it was necessary to build additional features (to accomodate rafts) during construction of the Grand Coulee Third Powerplant and Forebay Dam.

Recommended Hydraulic Guidelines for Raft Design

Model test results were reviewed, measurements of rotational velocities made, and the data were interpreted to provide the following hydraulic design guidelines for raft design:

1. Grid spacing between structural components of the raft can vary from 10 to 20 ft (3 to 6 m) but should not be less than 10 ft.

2. The depth of the raft should be such that 4 ft (1.2 m) of the floating raft extends below the water surface.

3. The area of appreciable vortex occurrence is 60 by 400 ft (18 by 122 m), see figure 32. This is for a three-unit installation, and the preliminary design should provide raft protection for this area.

4. For esthetic reasons the raft could be completely submerged. In the model tests, rafts submerged 20 to 60 ft (6 to 18 m) appeared slightly more effective than floating rafts. It is recommended that the grid spacing for a submerged raft be no greater than 10 ft (3 m).

5. The raft should be designed to withstand normal water surface velocities of 6 to 9 ft/s (1.8 to 2.7 m/s) and also localized high rotational velocities of vortex action. The tangential velocity of the rotational motion is 15 ft/s (4.6 m/s).

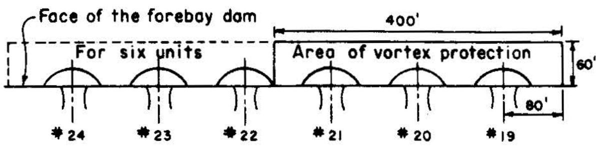


Figure 32.—Forebay area suggested for vortex protection.

6. Flexibility in raft design is desirable since vortex conditions could occur differently in the prototype than in the model. Because accuracy of the guideline information is unknown, changes in the raft may be required. Such changes could be area of the raft coverage, grid size, and raft depth. Also, it would be advantageous if the individual raft components could be readily joined together while floating in the forebay channel.

Rationale for Determining the Guidelines

Location and area of raft coverage.—For most operating conditions, vortex action was confined to a local region bounded by a square varying between 40 by 40 to 100 by 100 ft (12 by 12 to 30 by 30 m). Depending upon units operating, these severe vortices could occur throughout the zone shown in figure 32.

A vortex would form in one location, travel some distance, and dissipate at another location. Severity of the vortex was a function of the distance from the face of the Forebay Dam, for both with and without trashrack tests, figures 21 and 12. A raft, extending a 60-ft (18-m) distance from the Forebay Dam, destroyed the vortices even though the vortices may have formed beyond the 60-ft distance. However, there was one test condition where vortices formed a considerable distance away from the headwall, figure 19b. Although this vortex was located 120 ft (36 m) from the headwall, it was not considered as severe as vortices closer to the Forebay Dam. Should this vortex action occur, and be objectionable in the prototype, the raft coverage distance of 60 ft shown in figure 32 will be inadequate.

Raft protection over the semicircular area immediately above the trashrack is unnecessary, see figure 32. When a vortex moved into the water region above the trashrack, the vortex was dissipated, figure 21d. By not covering the semicircular area, a floating raft will have the freedom to move through water surface elevation 1208 to 1290 (368 to 393 m).

Raft grid and raft component dimensions.—These dimensions were obtained directly from rafts used in the model tests. Structural components were 1 ft (0.3 m) thick (prototype dimensions) from which the model rafts were constructed. In a hydraulic sense, component thickness was not believed crucial, but should be determined by structural considerations. The grid size for a submerged raft acting on the lower portion of a vortex was believed to be critical. Therefore, the grid size for a submerged raft was specified to be no larger than 10 ft (3 m) and, if structurally convenient, may be smaller. However, a raft submerged less than 2 ft (0.6 m) below the water surface acts on the upper portion of a vortex, and in this case the raft is believed more effective with a grid spacing of 20 ft (6 m) but no less than 10 ft.

Velocities the raft may need to withstand.—The velocity guideline information is not definite. Various and different surface currents may occur near the intakes, depending upon the units or combination of units operating and the formation of vortices. Three different type surface currents may act upon the raft:

1. Normal water surface currents.—Velocity produced by normal waterflow down the forebay channel that may act on the total raft area. This information was obtained from velocity measurements given in reference [1] and was for a condition of 12 operating units with a water surface elevation of 1208 (368 m).

2. Swirl water surface currents.—Velocity resulting from swirl-type motion. For swirl motion, the velocity is directly proportional to the radius, and velocities are higher on the outside of the swirl than in the inner region.

3. Vortex water surface currents.—Velocity resulting from vortex motion. For vortex motion, the velocity is inversely proportional to the radius, and the velocity is higher at the inner region of the vortex.

In model observations, vortices occupied a smaller circular area than swirls. While swirls and vortices may act at various locations on the raft, these high rotational velocities do not act on the entire protection area shown in figure 32 at a given instant.

An attempt was made to measure rotational velocities that occurred in the model. The method for making the rotational velocity measurements was crude. Results of these measurements are given as a tangential velocity (feet per second and for prototype dimensions) and were obtained from determining a rotational velocity (ω, radians per second) that acted at a given radius.

A raft was submerged approximately 20 ft (6 m) below the water surface in the generated vortex (strongest condition). A somewhat stable swirl was produced and dye was placed in the swirling water above the raft. Then, visual observations determined the time for the dye to rotate one revolution. The observed tangential velocity was 4 ft/s (1.2 m/s) acting at a 10-ft (3-m) radius.

A ping pong ball, 1.5 in. (38 mm) in diameter, was used in measuring rotational water surface velocities of vortex action. The ball, hung from a piece of light sewing thread, readily rotated when placed in the central portion of the vortex. With the aid of a stopwatch and counted revolutions, rotational speed of the ball was determined. Two conditions of vortex action were measured, both for a 1290-ft (393-m) water surface elevation. The first condition was for intermittent vortices, units 19, 20, and 21, operating at 3Q each. The ball floated in the vortex air core and was only slightly drawn down into the vortex. Therefore, the rotational velocity spinning the ball was assumed to act at the 1-in. (25-mm) diameter of the ball surface. (The model scale was 1 in. equals a 10-ft prototype length.) The measured tangential velocity was 11 ft/s (3.4 m/s) acting at a 5-ft (1.5 m) radius. The second condition was for the generated vortex (strongest). In this case the ball had to be pulled with the thread to prevent being drawn down into the vortex, and the ball was allowed to submerge halfway. Thus, the rotational velocity was assumed to act at a 1.5-in. diameter on the ball. Tangential velocity was 16 ft/s (4.9 m/s) acting at a 7.5-ft (2.3-m) radius.

At first glance, vortex velocities may appear as unduly high for raft criteria because if the rafts function properly, there should not be appreciable vortices. However, there is the condition of vortices forming beyond the raft and then traveling beneath the raft before dissipating. In the model tests, these vortices before dissipation were very much less severe than the generated vortex. However, the velocity as determined from the generated vortex was used as a criterion because the intent was to give velocity guideline information believed to be the maximum.

ACTION OF VORTICES ON THE TRASHRACK STRUCTURES

Previous model tests showed the trashrack structures definitely had a suppressive effect on vortices. However, organized vortices still occurred, as shown on figure 21. Tests were made with the model trashracks to gain some insight on how the vortex may act on the prototype trashracks. Each screen size model trashrack was placed over intake No. 24 and subjected to action of the generated vortex, see figure 33. With smaller screen sizes, vortex severity, and air core penetration decreased.

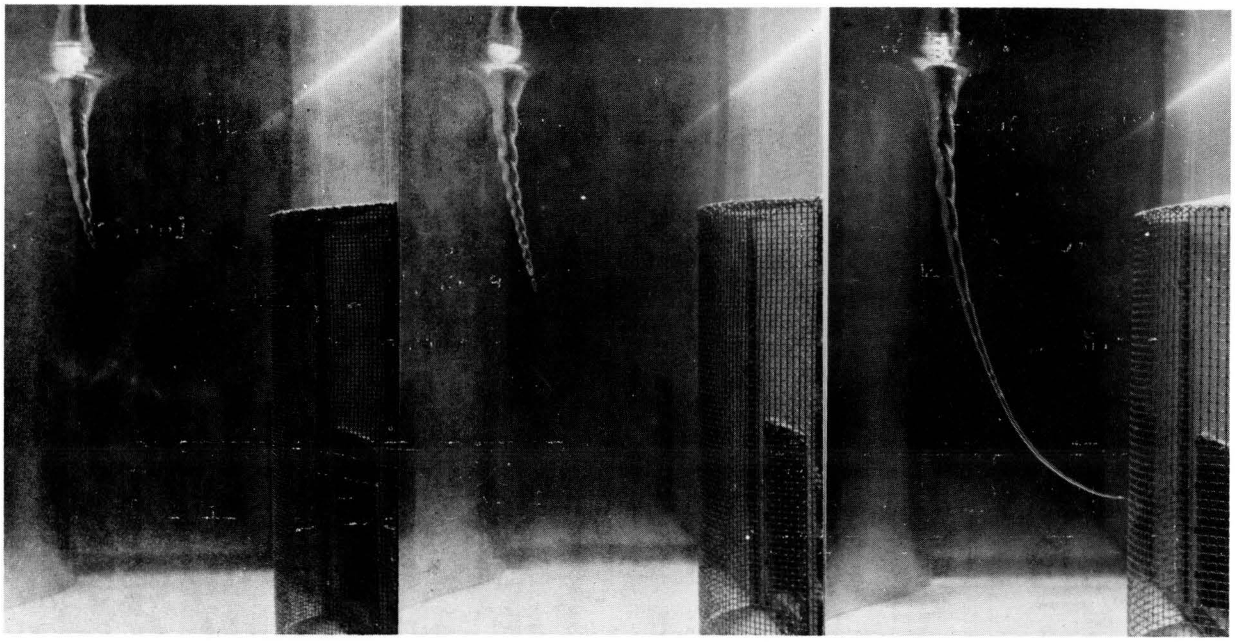
Dye injection into the vortex, figure 34a, gives the appearance of an enlarged core. Flow resistance at the screen impedes the high core velocities and slightly alters development of the vortex. An illustration of this concept is shown in figures 34b and 21b.

Vortex core spreading caused by resistance depends on velocity of the flow field surrounding the core. When a submerged raft was placed against intake No. 24, the high velocity impelled the developed vortex core through the raft grid. Thus, core spreading may be minimal if the flow field velocity is high. The effects of the resistance may be quickly carried downstream and not allowed to propagate upstream along the vortex core. Notice the difference of vortex core spreading in figure 34. The velocity flow field at the point of screen resistance was believed higher for figure 34a than for figure 34b. There is an interdependency among the flow field, development of the vortex core, and resistive action of the trashrack to the vortex.

The difference in the reaction between the model and prototype trashracks to a vortex core velocity is unknown. The surface areas for model and prototype trashracks were similar, but the geometric shape was different for structural elements of the model and prototype trashracks. Wires of the model trashracks were a circular cross section; whereas, the vertical bars of the prototype trashracks will be of a rectangular cross section, see figure 35. Because of these differences, the prototype structure may provide more flow resistance to rotational velocities than the model and thus reduce vortex development.

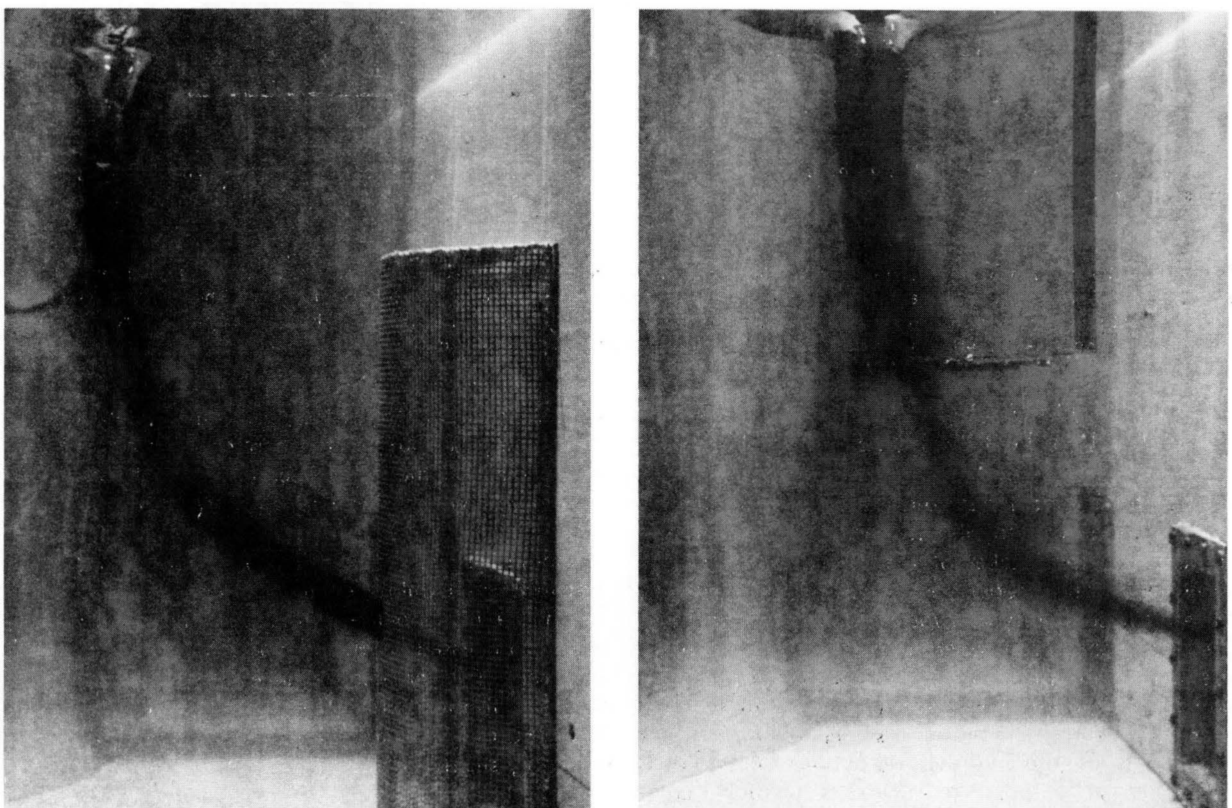
If the prototype trashrack provides appreciable resistance to a vortex core, there is the potential of a considerably enlarged vortex core. Core velocities will be slower and act on a comparatively larger area than that shown in figure 21a. However, should this resistance not develop or if a high flow field velocity of water surrounding the core prevents the resistance from propagating upward along the core, then a well-developed vortex core may act on the trashrack.

The core of a developed vortex acts on a local and small area of the trashrack, figure 21a. Velocities in the vortex core are very high and could produce a high localized moment on a comparatively small area of the trashrack. Consideration should be given as to the effect this moment may have on a prototype structure.



a. Small-size screen. b. Medium size screen. c. Large size screen.

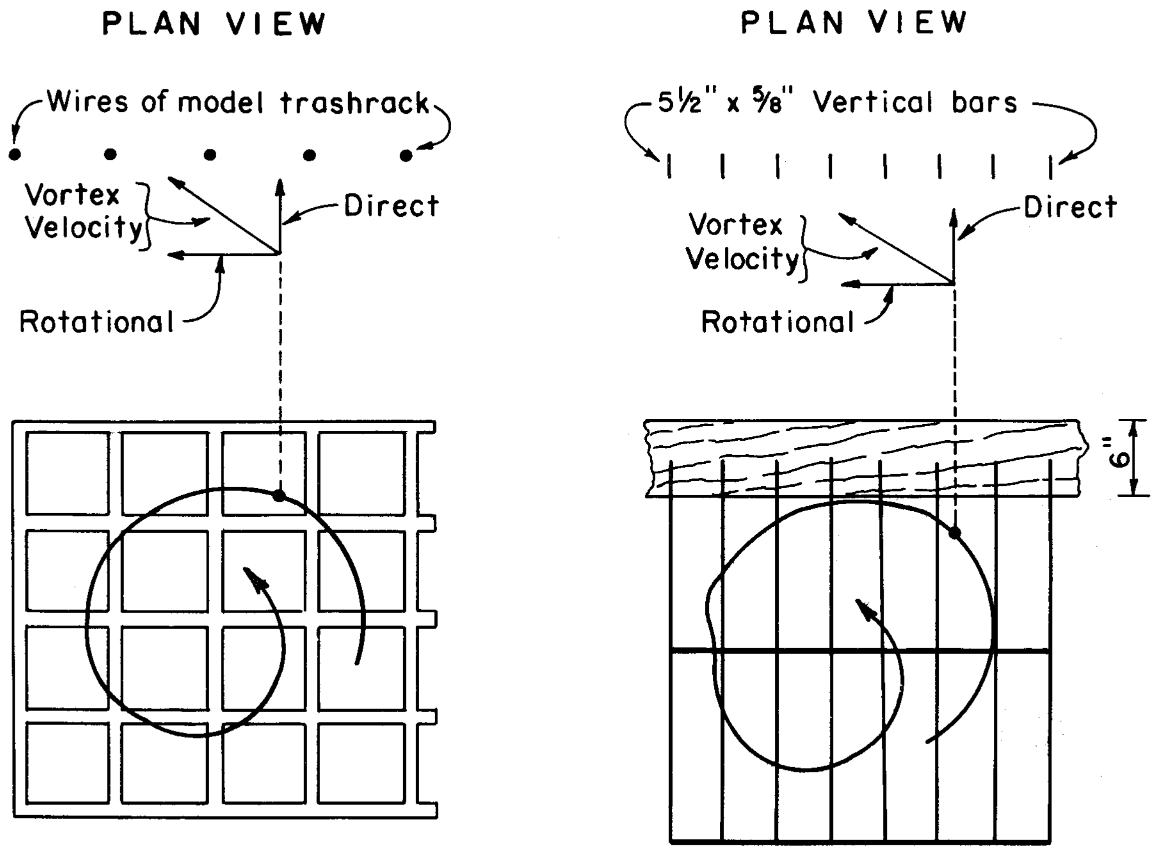
Figure 33.—Model trashracks in the generated vortex. Photo P1222-D-76696



a. Small size screen model trashrack in the generated vortex, and dye showing core of organized vortex. Photo P1222-D-76694

b. Screen placed horizontally in core of the generated vortex which retards core velocities and enlarged the vortex core above the screen. Photo P1222-D-76695

Figure 34.—Frictional resistance to fast rotating velocities of the vortex core.



Front view of 1/2 by 1/2 in. (13 by 13 mm) segment small size screen model trashrack.

Front view of 5 by 5 ft (1.5 by 1.5 m) segment prototype trashrack.

Figure 35.—Comparison of a relative area between the model and prototype trashracks. On the front views, the spiral represents a vortex core. There is probably a corkscrew-type motion as the vortex core flows through the trashrack. The plan views show velocities acting at a given point. With respect to the trashrack, the vortex velocity is divided into direct and rotational components. The 5-½-in. (140-mm) vertical bars are believed to resist rotational velocities better than circular bars.

NECESSITY FOR, AND COMMENTS ABOUT, PROTOTYPE OBSERVATIONS

Results of the model tests did not produce a reliable and definite answer to whether there will be a vortex problem near the intakes of the Grand Coulee Third Powerplant. The model test results did, however, indicate the possibility of a vortex problem developing. Therefore, prototype operation should be closely observed to determine whether a vortex problem exists and whether the vortex is of sufficient magnitude to be potentially harmful to the trashracks, turbines, or other parts of the hydraulic structure. Because the magnitude of a possible vortex is unknown and considering the huge size of the hydraulic structures, it is imperative that observations be made at the very onset of operation for the first unit. If the vortex problem appears dangerous, then the system could immediately be shut down. These observations should also be made at the initial operation of each new unit and repeated with all installed units operating.

It should be kept in mind that the first unit will probably not exhibit the most severe vortex action. The hydraulic model tests indicated that the vortex severity increased as the number of operating units increased. The greatest change in vortex severity occurred with an increase from one to three operating units. Further increase in the number of operating units only slightly increased the vortex severity.

The increase of vortex severity is especially significant with respect to the installation sequence of the first three units. Installation of the units were planned at

6-month intervals. A beneficial factor of this installation sequence is that the worst vortex conditions will not occur during the initial operation of the Grand Coulee Third Powerplant. There should be time for observation and study to determine whether raft installation will be necessary. However, estimating flow conditions for a more severe vortex while observing less severe conditions will be difficult. Rafts that work well for the less severe conditions may be inadequate for the more severe conditions.

The prototype observations may also provide the means for verifying guidelines for the rafts as obtained from the model tests. The information should prove or disprove: (1) location where raft coverage is needed, (2) dimensions of raft, and (3) velocity acting upon the raft. Rahm [8] gives some description about making prototype velocity measurements and observations.

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Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-72) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, it gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron (μ)
Inches (in)	25.4 (exactly)	Millimeters (mm)
Inches	2.54 (exactly)*	Centimeters (cm)
Feet (ft)	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters (m)
Feet	0.0003048 (exactly)*	Kilometers (km)
Yards (yd)	0.9144 (exactly)	Meters (m)
Miles (statute) (mi)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers (km)
	AREA	
Square inches (in^2)	6.4516 (exactly)	Square centimeters (cm^2)
Square feet (ft^2)	*929.03	Square centimeters
Square feet	0.092903	Square meters (m^2)
Square yards (yd^2)	0.836127	Square meters
Acres	*0.40469	Hectares (ha)
Acres	*4,046.9	Square meters (m^2)
Acres	*0.0040469	Square kilometers (km^2)
Square miles (mi^2)	2.58999	Square kilometers
	VOLUME	
Cubic inches (in^3)	16.3871	Cubic centimeters (cm^3)
Cubic feet (ft^3)	0.0283168	Cubic meters (m^3)
Cubic yards (yd^3)	0.764555	Cubic meters (m^3)
	CAPACITY	
Fluid ounces (U.S.) (oz)	29.5737	Cubic centimeters (cm^3)
Fluid ounces (U.S.)	29.5729	Milliliters (ml)
Liquid pints (U.S.) (pt)	0.473179	Cubic decimeters (dm^3)
Liquid pints (U.S.)	0.473166	Liters (l)
Quarts (U.S.) (qt)	*946.358	Cubic centimeters (cm^3)
Quarts (U.S.)	*0.946331	Liters (l)
Gallons (U.S.) (gal)	*3,785.43	Cubic centimeters (cm^3)
Gallons (U.S.)	3.78543	Cubic decimeters (dm^3)
Gallons (U.S.)	3.78533	Liters (l)
Gallons (U.S.)	*0.00378543	Cubic meters (m^3)
Gallons (U.K.)	4.54609	Cubic decimeters (dm^3)
Gallons (U.K.)	4.54596	Liters (l)
Cubic feet (ft^3)	28.3160	Liters
Cubic yards (yd^3)	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters (m^3)
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb) (gr)	64.79891 (exactly)	Milligrams (mg)
Troy ounces (480 grains)	31.1035	Grams (g)
Ounces (avdp) (oz)	28.3495	Grams
Pounds (avdp) (lb)	0.45359237 (exactly)	Kilograms (kg)
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms (kg)
FORCE/AREA		
Pounds per square inch (lb/in^2)	0.070307	Kilograms per square centimeter (kg/cm^2)
Pounds per square inch	6894.76	Pascals (Pa), or Newtons per square meter (N/m^2)
Pounds per square foot (lb/ft^2)	4.88243	Kilograms per square meter (kg/m^2)
Pounds per square foot	47.8803	Pascals (Pa), or Newtons per square meter (N/m^2)
MASS/VOLUME (DENSITY)		
Ounces per cubic inch (oz/in^3)	1.72999	Grams per cubic centimeter (g/cm^3)
Pounds per cubic foot (lb/ft^3)	16.0185	Kilograms per cubic meter (kg/m^3)
Pounds per cubic foot	0.0160185	Grams per cubic centimeter (g/cm^3)
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.) (oz/gal)	7.4893	Grams per liter (g/l)
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.) (lb/gal)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds (in-lb)	0.011521	Meter-kilograms (m-kg)
Inch-pounds	1.12985 x 10^6	Centimeter-dynes (cm-dyn)
Foot-pounds (ft-lb)	0.138255	Meter-kilograms (m-kg)
Foot-pounds	1.35582 x 10^7	Centimeter-dynes
Foot-pounds per inch (ft-lb/in)	5.4431	Centimeter-kilograms per centimeter (cm-kg/cm)
Ounce-inches (oz-in)	72.008	Gram-centimeters (g-cm)
VELOCITY		
Feet per second (ft/s)	30.48 (exactly)	Centimeters per second (cm/s)
Feet per second	0.3048 (exactly)*	Meters per second (m/s)
Feet per year (ft/yr)	*0.965873 x 10^{-6}	Centimeters per second
Miles per hour (mi/h)	1.609344 (exactly)	Kilometers per hour (km/hr)
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2 (ft/s^2)	*0.3048	Meters per second^2 (m/s^2)
FLOW		
Cubic feet per second (second-feet) (ft^3/s)	*0.028317	Cubic meters per second (m^3/s)
Cubic feet per minute (ft^3/m)	0.4719	Liters per second (l/s)
Gallons (U.S.) per minute (gal/min)	0.06309	Liters per second
FORCE*		
Pounds (lb)	*0.453592	Kilograms (kg)
Pounds	*4.4482	Newtons (N)
Pounds	*4.4482 x 10^5	Dynes (dyn)

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories (kg-cal)
British thermal units (Btu)	1,055.06	Joules (J)
Btu per pound	2.326 (exactly)	Joules per gram (J/g)
Foot-pounds (ft-lb)	*1.35582	Joules (J)
POWER		
Horsepower (hp)	745.700	Watts (w)
Btu per hour (Btu/hr)	0.293071	Watts
Foot-pounds per second (ft-lb/sec)	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9, then subtract 17.78	Celsius or Kelvin degrees
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 834-401

ABSTRACT

Hydraulic model studies of the Grand Coulee Third Powerplant forebay indicated detailed vortex studies should be made. Vortex modeling is difficult because of lack of similitude between model and prototype. A literature search disclosed an Equal Velocity Method of vortex modeling and this method was used in this study. Without model trashracks, air-entraining vortices readily formed, and with model trashracks vortex action was reduced. Rafts, either floating or submerged, suppressed vortex formation. Investigations were made to determine the prototype area in the forebay that may be susceptible to vortex action and need raft protection. The report has 35 figures and gives a detailed description of the investigation. (8 ref)

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DESCRIPTORS—/ *vortices/ eddies/ hydraulic similitude/ hydraulic models/ *model tests/ forebays/ hydraulic structures/ trashracks/ entrances
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