PREDICTION OF DISSOLVED GAS AT HYDRAULIC STRUCTURES

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16. ABSTRACT Various hydraulic structures including spillways and outlet works affect the dissolved gas content of the flow. Depending on the structure and conditions, the structures may: (1) aerate flows depleted in dissolved gas, (2) create supersaturated dissolved gas levels in the flow, or (3) reduce supersaturation levels in the flow. An analysis is presented which may be used to predict the effect of a wide variety of hydraulic structures on the dissolved gas content of the flow. Parameters considered include dissolved gas levels in the flow upstream from the structure; water temperature; barometric pressure; velocity, shape, and orientation of the flow entering the stilling basin; stilling basin geometry; and tailwater depth. The analysis is developed from prototype data. Included are several example applications with detailed descriptions of the procedures involved. (6 ref)

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UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

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The studies discussed in this report were undertaken and supervised by the former Reaeration Methods and Devices Team for the Reaeration Research Program Management Team. The analysis was developed and the report written by Mr. P. L. Johnson of the Hydraulics Branch, Division of General Research.

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CONTENTS

LIST OF FIGURES

CONTENTS - Continued

LIST OF TABLES

FOREWORD

The control and enhancement of water quality in Bureau of Reclamation reservoirs and reservoir releases have become increasingly important as a result of the expanded use of reservoirs not only for irrigation but for municipal and industrial water supply, recreation, and as an important fishery resource. As a result of this changing emphasis, a multidisciplinary team was appointed to investigate dissolved gas problems; principally, reaeration needs, and recommend appropriate solutions. A Bureauwide survey conducted by the team indicated dissolved oxygen deficiency and supersaturation of dissolved gases as priority subjects for investigation. A monitoring program to evaluate the aeration capabilities of the various types of outlet works and spillways used by the Bureau to release water from its impoundments was, therefore, initiated in May 1972. With the attainment of sufficient data, an analysis was initiated with the objective of developing a generalized predictive technique. This report presents the resulting technique and illustrates its use with sample problems.

CONCLUSIONS

1. The dissolved gas levels that will result from the passage of flow through a hydraulic structure can be predicted, when given: the velocity head of the inflow jet at the tailwater surface, the angle of

penetration of the jet into the tailwater, the shape of the jet, the basin length and depth, the water temperature, the barometric pressure, and the initial dissolved gas levels in the reservoir.

2. The basic equation developed to predict the resulting dissolved gas levels is:

$$C(t) = C_s + (C_I - C_s)\, e^{-Kt}$$

where: C(t) is the dissolved gas concentration created in the flow by the hydraulic structure, C_I is the dissolved gas concentration in the reservoir, C_s is the saturated dissolved gas concentration at a depth which is two-thirds the tailwater depth, t is representative of the length of time during which gas is being dissolved, and K is a constant that varies with structure and operating condition. A method is developed for prediction of the K value.

3. Because of the large variety of structures that may be encountered, it will not be possible to directly analyze some structures by the techniques presented. Insight and direction on handling these special cases are given.

INTRODUCTION

With the increased interest in the effects of hydraulic structures on the dissolved gas content of the flow, it becomes desirable to be able to predict how particular structures operating under specific conditions will change the dissolved gas content. This predictive ability would not only be applied to existing facilities, but would also be used to evaluate structures during the planning and design phases.

At existing facilities, a predictive ability would enable the operator to select, where alternative methods of release exist, the method of release that would have the most desirable effect on the dissolved gas content of the flow. Most dams have at least two methods by which flow can be released - a spillway and an outlet works. Prototype data that have been collected indicate that the change in the dissolved gas content of a flow depends on the type of structure through which the flow passes, the magnitude of the discharge, the barometric pressure, and the water temperature. To establish operating criteria for each structure based on actual measurement of resulting dissolved gas levels would be a difficult task. Not only are there a great number of structures that would have to be studied, but each one can operate over a wide range of discharges. The amount of discharge through a structure at any particular time, in many cases, depends on the weather and the season. Some structures, such as many outlet works, quite frequently operate throughout their discharge range. Other structures, such as many spillways, may never approach their maximum discharge capabilities. Operating criteria based on direct measurement, in many cases, cannot be achieved. A predictive ability could, however, yield an understanding of a structure's potential and allow preparation for the possible consequences, even if the structure had never operated.

The other area for application is in planning and design. With a predictive ability, designers would have one more factor which could be considered in structure selection. Depending on the situation, it is conceivable that the dissolved gas potential might be the controlling factor in the design. Such a situation could be a structure on a river which has a significant fishery. If a stream is tranquil, the dissolved gas level created by a release might extend many miles downstream. With high levels of supersaturation, this situation could be of serious consequence. A predictive ability would yield recognition of such conditions, and the structure could be designed to minimize the high levels of supersaturation. In a similar manner, planners could evaluate the potential effects of hydraulic structures and include these findings in their decisionmaking.

One other point should be made: A predictive analysis would have application at both ends of the dissolved gas problem (both reaeration and supersaturation). The gas transfer mechanism is the same for both cases. The analysis would also have application to all gases including the predominant two - nitrogen and oxygen.

The consideration of the effects of a structure on dissolved oxygen and nitrogen may result in two very different problems. Oxygen is active in various biological processes, while nitrogen is inactive. That is, while nitrogen levels may remain constant at values set by the physical conditions of the flow, dissolved oxygen levels may be changing as a result of biological action. An example of this might be in a reservoir. Initially, the dissolved gas levels of both oxygen and nitrogen are equal to the levels established by the inflowing stream. The nitrogen, being relatively inert, will maintain this level for quite some time. The oxygen, however, especially in the lower depths of the reservoir, may be depleted from the decaying of organic material. Thus, if water is then withdrawn from the reservoir, it may be low in dissolved oxygen and yet may conceivably be high in dissolved nitrogen. Furthermore, the water may be high in biochemical oxygen demand (BOD) that would reduce the dissolved oxygen level in the stream below the dam. The analysis of a specific release from a structure could then include both reaeration of the flow and dissolved gas supersaturation. The physical processes involved in either case would be identical. The analysis would indicate how effectively structures increase depleted gas levels, as well as indicate whether supersaturated conditions might be created.

Such predictive methods have been developed for the spillways of the U.S. Army Corps of Engineers dams in the Columbia River Basin.[1]* Most of these structures are geometrically similar. They are low head, run-of-the-river structures, with gate-controlled ogee spillways. The stilling basins are likewise of similar design. This similarity enabled the development of a predictive analysis that is satisfactory for the structures considered. However, it cannot be generally applied to structures whose configuration varies from those on which the analysis is based. The Bureau has few structures that correspond to these Columbia River Basin dams. In general, Bureau structures vary widely in type and size. Thus, a more generalized predictive analysis is required if it is to have significant application in Bureau of Reclamation work.

As a basis for development of the analysis, prototype data collected included the following parameters:

1. The reservoir water temperature, dissolved oxygen concentration, and dissolved nitrogen concentration at the elevation from which the water is withdrawn.

2. The discharge and a record of the gates or valves that water is passing through, where a controlled flow is involved.

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

3. The tailwater elevation, temperature, and dissolved oxygen and nitrogen concentrations.

4. The barometric pressure.

5. Photographs of the structure operating and drawings of the structure.

By fall of 1973, the monitoring program of the Bureau's Engineering and Research Center had reached 16 sites and had observed 24 structures in operation. Forty-nine different operating conditions had been studied. Information on most of this program is given in a progress report[2] which was prepared for the Reaeration Research Program Management Team. In addition, an extensive monitoring program has been undertaken by the PN (Pacific Northwest) Region of the Bureau of Reclamation. The PN Region has closely studied Grand Coulee Dam[3] and has made limited observations at 36 other sites[4]. The Upper Missouri Region of the Bureau has likewise done monitoring at Yellowtail Afterbay Dam. Combined, these data were considered to provide an adequate base from which the predictive analysis could be developed.

ANALYSIS

Because of the wide variety of structures that may be encountered, the following discussion, although quite detailed, may not adequately describe all situations that arise. A section containing several sample problems based on prototype structures and prototype data follows the analysis. It may be useful to refer to this section in conjunction with the analysis to obtain a clearer understanding.

To start the study it was recognized that the process of gas transfer across an interface is described by the equation:

$$dC(t) = K\,[C_s - C(t)]\,dt \qquad (1)$$

or in other words the rate of gas transfer $[dC(t)/dt]$ is directly proportional to the difference between the existing dissolved gas concentration $[C(t)]$ and the 100 percent saturated gas concentration (C_s). The constant of proportionality is K. Equation (1) can be rewritten as follows:

$$dC(t) = -K\,[C(t) - C_s]\,dt \qquad (2)$$

Because C_s is a constant, it is also known that:

$$\frac{dC(t)}{dt} = \frac{d[C(t) - C_s]}{dt} \qquad (3)$$

The substitution from equation (3) is made and then if both sides of equation (2) are divided by $[C(t) - C_s]$ the result is:

$$\frac{d[C(t) - C_s]}{[C(t) - C_s]} = -K\,dt \qquad (4)$$

Integrating both sides yields:

$$\ell n\ [C(t) - C_s] + A_1 = -Kt + A_2 \qquad (5)$$

where: A_1 and A_2 are constants of integration. Now by setting B equal to $A_2 - A_1$, the result is:

$$\ell n\ [C(t) - C_s] = -Kt + B \qquad (6)$$

Raising e to the equal terms from equation (6) then yields:

$$C(t) - C_s = e^{-Kt + B} \qquad (7)$$

If e^B is then called A

$$C(t) = C_S + Ae^{-Kt} \tag{8}$$

It is known that when $t = 0$, $C(t) = C_I$ (the reservoir dissolved gas level). Thus:

$$C_I = C_S + Ae \ = C_S + A \tag{9}$$

or

$$A = C_I - C_S \tag{10}$$

Therefore, the final form of the equation is:

$$C(t) = C_S + (C_I - C_S)\ e^{-Kt} \tag{11}$$

An important note is that $C(t)$, C_S, and C_I are not percentage figures, but are the actual dissolved gas concentrations in milligrams per liter of water.

Equation (11) shows that the resulting dissolved gas level, C(t), below a hydraulic structure depends on the dissolved gas level in the reservoir, the potential (saturation) dissolved gas level in the stilling basin, the length of time that gas is being dissolved into the flow, and a constant that would be expected to vary with the specific hydraulic structure and operating condition. In studying these parameters, it should be observed that the dissolved gas concentration in the reservoir is independent of structure configuration, operating condition, water temperature, and barometric pressure. This indicates that through the computations of this analysis, the value of C_I will be either set at a known level or assumed. The other three parameters (C_S, t, and K) depend on some, if not all, the factors (structure, operating condition, temperature, and barometric pressure). Efforts were, therefore, directed at evaluating C_S, t, and K computationally.

C_S, the potential dissolved gas saturation concentration level in the stilling basin, depends on basin depth, water temperature, and barometric pressure. The absolute quantity of dissolved gas that water can hold is controlled by two factors, the water temperature and the pressure on the water. Figure 1 is a plot of the saturation concentration versus the water temperature for oxygen and nitrogen. Note that at 24° C water can hold about 40 percent less nitrogen than at 0° C. The implication of this is that for a given situation, the warmer the water the smaller the value of C_S will be. Thus, for a given C_I the differerence between C_S and C_I also becomes smaller with warmer temperature,

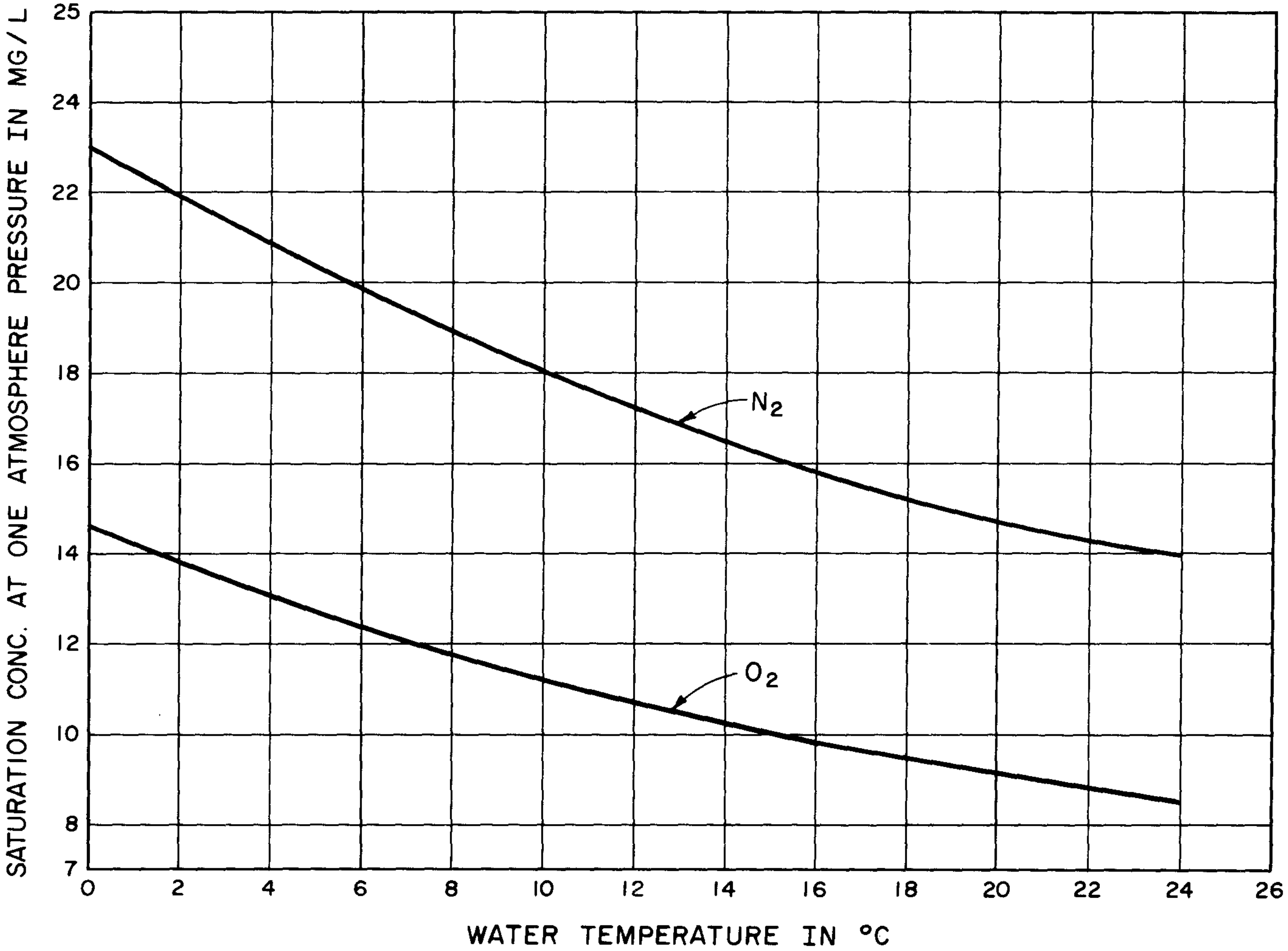


Figure 1. Dissolved gas saturation concentrations.

which in turn reduces the rate of gas transfer, equation (1). This would result in a reduced absolute C(t), but not necessarily a reduced percentage of saturation. Likewise, the greater the pressure on the liquid, the more dissolved gas it will hold. Therefore, with increased pressure the saturation concentration becomes larger and the rate at which the gas dissolves also becomes larger. The potential pressure obtained in a stilling basin depends on the depth of water over the flow in which the gas is being dissolved and the barometric pressure. Thus, surface water at sea level will hold 33 percent more gas than surface water at an elevation of 8000 feet (2400 m). Also, water at the surface of a pool will hold 50 percent less gas than water at a depth of 34 feet (10 m). In other words, the amount of dissolved gas that water will hold at saturation is directly proportional to the absolute pressure on the water. Barometric pressure is basically controlled by the elevation at which the structure is located, with daily fluctuations that result from atmospheric conditions. The effects caused by daily fluctuations in atmospheric pressure are not large but they may be significant and should be considered in the evaluation of C_s. In this analysis, measured barometric pressures were used when available. When measured values were not available, a standard atmosphere (table 1) was assumed and barometric pressures were computed. The depth of water over the flow in which gas is being dissolved generally depends on the depth of water in the stilling basin. Thus, variations in the tailwater elevation will have some effect. Throughout this analysis, a

Table 1

STANDARD U. S. ATMOSPHERE

Elevation ft, m.s.l.	Pressure mm Hg
-1,000	788
0	760
1,000	733
2,000	707
3,000	681
4,000	656
5,000	632
6,000	609
7,000	586
8,000	564
9,000	543
10,000	523
11,000	503
12,000	483

water depth equal to two-thirds of the depth of the water in the basin was used to compute saturation concentrations. It was felt that initially the compact jet from a spillway or outlet would penetrate the stilling basin to its floor. The flow would then be deflected downstream and out of the basin. As the flow moved through the basin it would be diffused and its velocity reduced. This diffusion would be linear and, therefore, result in a triangular pattern with the average depth through the diffusion being two-thirds of the total water depth in the basin. In time the flow will diffuse so that it is evenly distributed through the basin depth. For this completely diffused flow, the average depth would be half the total basin water depth. Bubble rise mechanics might also affect the selection of the average flow depth. First, as a bubble passes through the basin its size is reduced as its gases are dissolved. Thus, the bubble's terminal rise velocity would also be reduced. The result would be that for such a bubble, in quiet water, the average pressure would be somewhat less than half the total basin water depth. In reality, the water is not still; the bubbles are swept horizontally and circulated in eddies. Often the bubbles may be deflected to the surface with the flow instead of rising to the surface on their own. When such a deflection occurs the average depth could be considerably greater than half the total depth. With consideration of these factors the two-thirds depth was selected as representative of an average depth for the average dissolving time. It is realized that the two-thirds value is very rough and has no consideration for basin width and length, or inflow conditions. The two-thirds value may be representative for high and moderate discharges, but there could be small discharges that might not penetrate to the basin floor. However, prediction of average flow depths for individual discharges and structures would be a difficult task. Such predictions would have little more accuracy than the two-thirds depth value. A major point of support for the two-thirds depth assumption is the fact that later applications have proven the assumption reasonable.

Evaluation of C_s is achieved by summing the barometric pressure and two-thirds of the water depth in the basin and dividing this total pressure by standard atmospheric pressure (760 mm of Hg) to obtain the average absolute pressure on the dissolving bubbles in terms of standard atmospheres. This average pressure is then multiplied by the dissolved gas concentration, for the desired water temperature from figure 1, to obtain C_s.

The next parameter from equation (11) to be considered is t. The length of time, t, is the time that the inflowing jet with entrained air is under pressure in the stilling basin and, thus, the length of time that gas is being dissolved into the flow. Initially, t revealed two possible limitations that could control its value. First, it would seem that given sufficient time, the entrained air bubbles would rise to the surface of the flow and, thus, not dissolve. In some cases it would seem that an evaluation of this bubble rise time could be used to represent t. On the other hand, situations might occur where the flow with entrained air would pass through the basin and be deflected to a shallow depth of flow in a fairly short time. Therefore, the actual length of time required for the flow to pass through the basin could represent t. During this analysis the assumption was made that either of these time periods might be critical in specific situations. For each flow condition and structure studied, t was evaluated for both limitations. The smaller of the two computed values of t was considered most applicable to the particular situation and was then used in the remainder of the analysis.

An idealized flow geometry was assumed when it was realized that small bubbles rise more slowly than larger ones, that flow conditions in the basin were quite complex, and that the simplified concept of direct bubble rise to the water surface was not true. An analysis was performed four times using four different terminal bubble velocities, to evaluate t based on the bubble rise time. For bubbles smaller than 0.01 inch (0.25 mm) in diameter, the t value based on the basin retention time was almost always smaller than the t value based on bubble rise time. Likewise, when bubbles with a diameter of 0.03 inch, (0.76 mm) were used as the standard, the t value based on the bubble rise time was nearly always smaller. When these time intervals were later inserted into equation (11), a 0.028-inch (0.71-mm) diameter bubble with a terminal velocity of 0.696 ft/s (0.212 m/s) yielded the most consistent results with respect to observed prototype conditions. Likewise, when an analysis was developed that predicted K, equation (11), from two dimensionless parameters, the 0.028-inch (0.71-mm) diameter bubble yielded values of K that were consistent with the predicted values of K based on the basin retention time.

Evaluation of t based on the bubble rise time ($t_{0.696}$) would be, if strictly pursued, a very complex computation which would probably produce questionable results. The vertical dimension of the water jet that the bubble rises through is rarely constant. Even before the jet enters the stilling basin, its thickness is usually changing. The jet may be accelerating as it drops to the basin, it may be decelerating as a result of flow surface losses or air resistance, its vertical angle of flow may be changing, or the jet might be spreading. Once the jet is submerged in the stilling basin it will begin to diffuse. In addition, the jet may be spread by the flow surfaces of the basin and the vertical angle of the flow may also change within the basin. All these factors cause variations in the vertical jet dimension and, therefore, variations in the jet's potential to hold the bubble and carry it to the deeper regions of the basin where pressures are high. Also, the eddies in the basin will disrupt the bubble rise process and may either increase or reduce the bubble rise time. Likewise, as the bubble is dissolved, its size and, therefore, its terminal velocity, are reduced. Because of the complexity, a simplified analysis was used and $t_{0.696}$ was evaluated by dividing the vertical jet dimension at the tailwater surface by the terminal rise velocity of the bubble (0.696 ft/s (0.212 m/s) for the 0.028-inch (0.71-mm) diameter bubble). This evaluation of t indicates the jet's potential to carry entrained air to the high pressure regions and hold it there. The procedure for the computation of t based on the bubble rise is:

1. Assume the velocity head of the flow at the tailwater surface equal to the reservoir water surface elevation minus the tailwater surface elevation.

2. Evaluate the flow velocity at the tailwater surface from the head found in 1 above.

3. Divide the discharge by the velocity to obtain the cross-sectional area of the flow at the tailwater surface.

4. Divide the cross-sectional area by the flow width to obtain the flow depth.

5. Divide the flow depth by the cosine of the angle of penetration (the angle at which the jet enters the tailwater surface) to obtain the vertical dimension.

6. Divide the vertical dimension by 0.696 (the terminal bubble velocity) to obtain $t_{0.696}$.

At times exceptions can be applied to 1. If for a particular structure it is obvious that the difference between the reservoir and tailwater surface elevations is not representative of the velocity head, then appropriate modifications should be made. An example of this is

Fontenelle spillway which has a bathtub-shaped side channel crest (figs. 8 and 9). The flow drops approximately 20 feet (6 m), goes through a hydraulic jump and then passes down the spillway chute to the stilling basin. In this case, the 20-foot (6-m) drop was subtracted from the velocity head as computed in 1. Another structure with similar consideration would be a baffled apron drop. In this type of structure much of the energy in the flow is dissipated on the apron. For such a drop, the velocity head of the flow when it passes through critical depth at the top of the chute is a reasonable value to assume for the velocity head at the tailwater surface. In general, if head loss appears to be significant for a particular structure being studied, and yet no clear-cut evaluation of this loss is available, the total analysis should be made both with and without the head loss. In this manner the significance of the head loss can be determined.

To compute the flow retention time (t_{flow}) in the basin, divide the path length (x) of the flow by the average flow velocity (V_{avg}) along the path. The path length is generally controlled by the basin shape. The path length is the distance from which the jet enters the tailwater pool to where the majority of the flow is directed toward the surface and, therefore, into a lower pressure zone. If a large portion of the flow is deflected upward at a point by baffle piers or some other feature, this point might be considered the end of the path. This could be the case even if the actual stilling basin continued beyond the point of deflection. If, on the other hand, it appears that the jet might flow beyond the stilling basin and still remain deep in the pool, a path length longer than the stilling basin might be selected. Examples of path length selection are included with the sample problems.

The next step in the analysis is to compute the average flow velocity (V_{avg}) over the path length. From the previous analysis of bubble rise time, the jet velocity at the tailwater surface (or at the start of the flow path) has been evaluated. To determine the average flow velocity, the velocity at the end of the path must be found. This is done through the use of figure 2 which is a summary of information from studies of jet diffusion by Yevdjevich[5] and Henry[6]. Through the application of figure 2 the maximum velocity in the jet at the end of the path can be found. Observation of velocity distributions in jet diffusions indicates that half the maximum velocity would be an approximation of the average jet velocity at the end of the flow path. This average jet velocity might also be evaluated by dividing the discharge by the channel cross-sectional area (Q/A). Whichever end point velocity proves to be the larger should be used since the average jet velocity at the end of the path could be higher, but not lower, than Q/A. The velocities at the beginning and end of the flow path may then be averaged. When this average is divided into the flow path length, the basin flow retention time (t_{flow}) is obtained. As with the previously discussed parameters, this evaluation of the basin flow retention time is

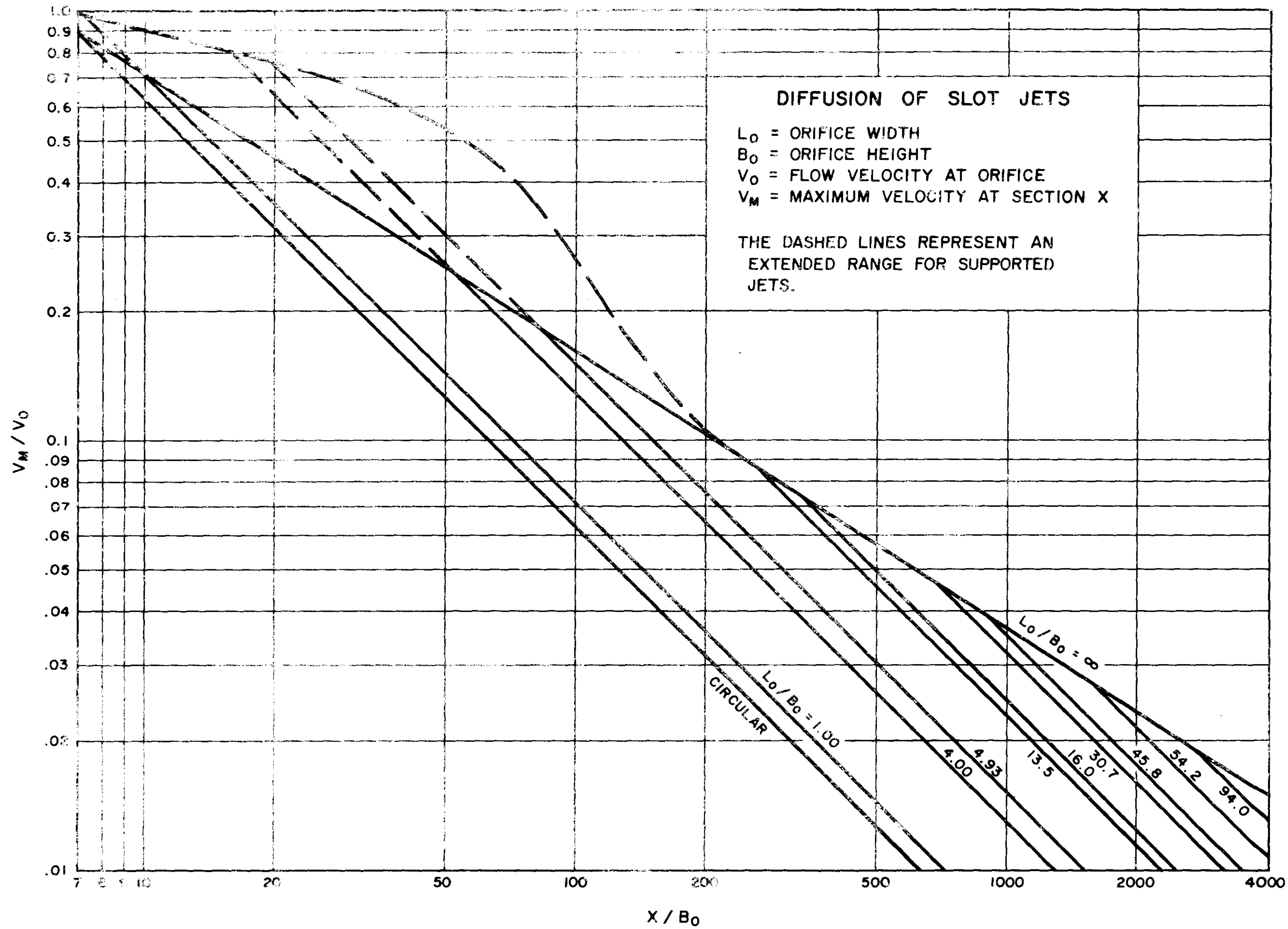


Figure 2. Diffusion of slot jets.

simplified and, therefore, not an exact representation of the true value. However, since this analysis is applied equally to all structures studied, the results can be considered relative indicators of the retention time. The analysis, therefore, supplies a mechanism for comparison of retention times between structures and operating conditions. As previously stated, the value of t to be used in equation (11) is the smaller of the two values of t ($t_{0.696}$ or t_{flow}) computed.

The final term in equation (11) to be evaluated is K. K is unlike the other terms in that it is not directly representative of any specific physical parameter. K is a measure of the ability of a structure, operating under particular conditions, to dissolve gas. It is, therefore, representative of the degree of aeration and of the rate at which the water at the gas-liquid interface is replenished. To make this point clearer, imagine several different release structures all withdrawing from a common, mixed reservoir. In this manner, the values of the initial dissolved gas concentration (C_I), the water temperature, and the barometric pressure would all be constant. Furthermore, the structures could all be designed with stilling basins which had the same tailwater depth and tailwater surface elevations. Thus, in addition, the potential dissolved gas level (C_S) and the velocity head (H_V) where the jet enters the basin are also constants. It is then conceivable that the various structures could be operated in such a manner that their resulting time values (t) were also equal. If the resulting dissolved gas concentrations [C(t)] were measured their values would vary from structure to structure. A hollow-jet valve and its basin might cause higher dissolved gas levels than a needle valve and its basin. A chute spillway and its basin might cause higher dissolved gas levels than a slide gate and its basin. Flow into a highly baffled basin might produce higher dissolved gas levels than flow into a conventional hydraulic jump basin, and so forth. The only variable left in equation (11) to which this difference can be attributed is K.

It appears that K depends only upon the hydraulic action in the basin. Attempts to find a predictive procedure that could be used to evaluate K resulted in the curves shown in figure 3. To obtain these curves, the prototype data were manipulated into various parameters until the desired results were found. Only dissolved nitrogen data were used in the development. This was largely attributable to the stability of the nitrogen. At a few of the reservoirs, data were collected at several depths. These data indicated that dissolved oxygen concentrations may vary widely throughout the depth of a reservoir but that dissolved nitrogen concentrations are fairly constant. At other reservoirs dissolved gas data were collected only near the surface and not at the withdrawal elevation. Therefore, if dissolved nitrogen and oxygen concentrations are measured at the reservoir surface and the withdrawals are made from deep in the reservoir, the measured values of the initial dissolved gas levels (C_I) are probably more accurate for nitrogen than

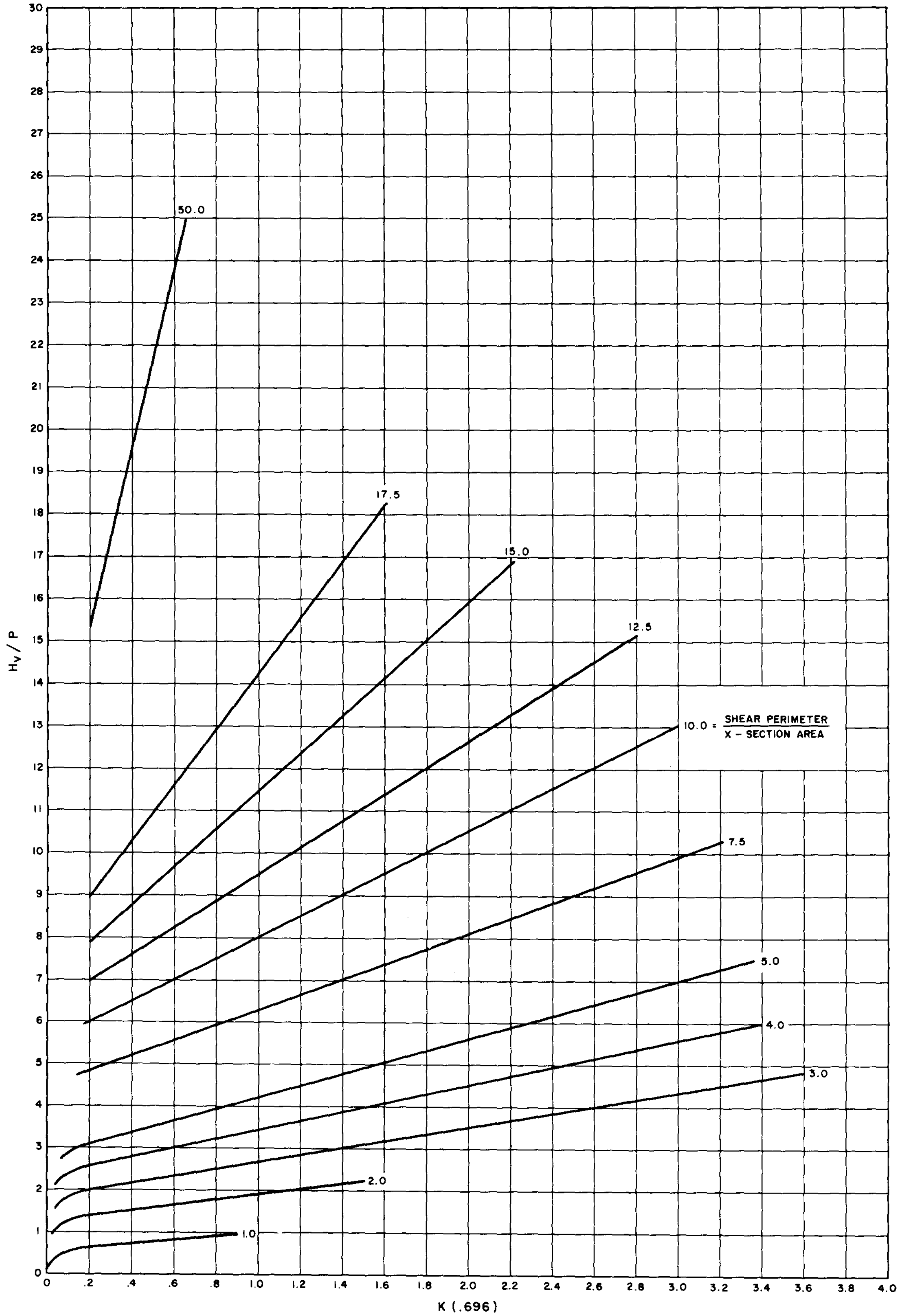


Figure 3. K prediction curves.

oxygen. Even though dissolved nitrogen data were used as a base for the analysis, application of the analysis for observed prototype conditions indicates that resulting dissolved oxygen levels may also be predicted.

From figure 3 note that the value of K depends on two parameters. The first is H_V/P, or the velocity head at the tailwater surface divided by the appropriate flow path length. H_V/P is an energy gradient parameter for the flow; it relates the amount of energy in the flow to the path length in the basin over which the energy reacts. The greater the value of H_V/P, the more turbulent the basin flow and the larger the resulting K value. The path length used is the one that corresponds to the value of t used. If t_{flow} is applicable, then the value used for P would be the path length used to evaluate t_{flow} (X). But if $t_{0.696}$ is applicable, the above path length is adjusted to determine the effective path length (X_A) for the time interval. To compute the effective path length (X_A), the flow deceleration is assumed as linear and the ratio of $t_{0.696}/t_{flow}$ is used to determine the velocity drop along the effective path length (X_A). The average velocity (V_X) along the effective path was then computed and multiplied by $t_{0.696}$ to determine the effective path length (X_A). The other parameter on which the value of K is based is a ratio of the shear perimeter of the jet to the jet's cross-sectional area (A_{flow}) at the tailwater surface. This parameter is a measure of the jet compactness. The shear perimeter for a jet is defined as the length of the jet's perimeter over which a shearing action is occurring between the jet and the water in the stilling basin pool. Thus, for a free jet plunging into a pool the shear perimeter would equal the total perimeter of the jet; whereas, for flow passing down a chute spillway and into a basin, the shear perimeter would be the chute width at the tailwater surface. Situations exist where the walls of the stilling basin are offset from the jet entering the basin. If this offset is small, questions may arise as to whether the sides of the jet should be included in the shear perimeter. This is a judgment factor and is probably best handled by individual consideration. Another common structure that might raise a similar question would be a hollow-jet valve discharging into a pool. Although the flow would have a ring-shaped cross-section, only the outside perimeter should be included in the parameter evaluation. In general, if it appears that significant shear will occur along the section of perimeter in question, then those lengths should be included in the analysis. The shear perimeter divided by the jet's cross-sectional area is not a dimensionless parameter. It has a dimension of ft^{-1}. Shear perimeters should always be computed in feet and cross-sectional areas should always be computed in square feet.

With the evaluation of K from figure 3, equation (11) may be applied and the resulting dissolved gas concentration [C(t)] determined. It should be noted that the analysis, as it has been developed, is largely empirical. The prototype data were used extensively to evaluate the coefficients that are applied throughout the analysis. This empirical approach is almost mandatory, however, because of the complexity of the flows being considered. Very few of the situations studied have clearly defined flow conditions that are well suited for direct analysis. Not only are the jets that leave the spillway chutes, the valves, and the gates often quite complex; many times the stilling basin pools are equally complex. The resulting jet diffusions in the stilling basins are, therefore, different from anything that has been considered in generalized studies. Any analysis of these flow conditions would be quite involved and the resulting accuracy would be questionable. However, it should be noted that the resulting coefficients do have a rational basis and are representative of the physical parameters. The coefficients can be interpreted to yield additional insight into the significance of the various factors.

One other point should be made: Although some entrainment of air is needed for the dissolved gas uptake to occur, the amount of entrained air required seems to be quite small. At some of the prototype structures observed (such as Yellowtail afterbay sluiceway), releases were exposed only briefly to the air. In some of these cases, the water surfaces of the releases were also relatively smooth. Thus, little air was entrained. This conclusion was verified by the small quantities of air that were observed returning to the tailwater surface. And yet, in some instances, the structures with the above flow characteristics were among the worst in creating supersaturated conditions. Therefore, it should be assumed that if any air is entrained by the operating structure, then the quantity of air will not be a limiting factor with respect to the dissolved gas levels created.

EXAMPLE APPLICATIONS

The following examples were chosen to represent different situations that may be encountered. Included with each example are drawings of the structure and photographs of it operating. The computations are described step by step. All critical points and all judgments or approximations are discussed. The following calculations are based on prototype data and, therefore, the results of the analysis are compared to actual field findings. Variations between the observed and calculated dissolved gas levels may be attributed to several factors. First, and probably one of the most important, is that the entire analysis was based on average prototype data. Therefore, some structures will fit the analysis better than others and some structures will yield more accurate predicted results. Although this error should not be large, it could amount to plus or minus 5 percent. A second significant source of variation would be errors in measuring the prototype dissolved gas levels. The chemical analyses used are not completely accurate, but even more important, samples may be collected from regions that are not representative of the total flow. Errors of large magnitude may or may not be obvious. In several cases, two or more readings were available which gave some additional verification. Variations resulting from errors in data collection may be small or they may be quite large. It is conceivable that errors of up to 50 percent could occur. Application of the analysis and use of the graphs may also result in some error, but this error should be less than plus or minus 2 percent.

Example 1

Yellowtail Afterbay Dam sluiceway

The following information is known:

Reservoir water surface elevation = 3196 feet

Tailwater surface elevation = 3168 feet

Barometric pressure = 677 mm Hg

Water temperature = 4.4° C

Discharge = 3,550 ft^3/s

Reservoir dissolved nitrogen level = 104 percent

Reservoir dissolved oxygen level = 85 percent

The structural dimensions in figure 4 and the photographs in figure 5 are also available. From these sources the following terms are deduced:

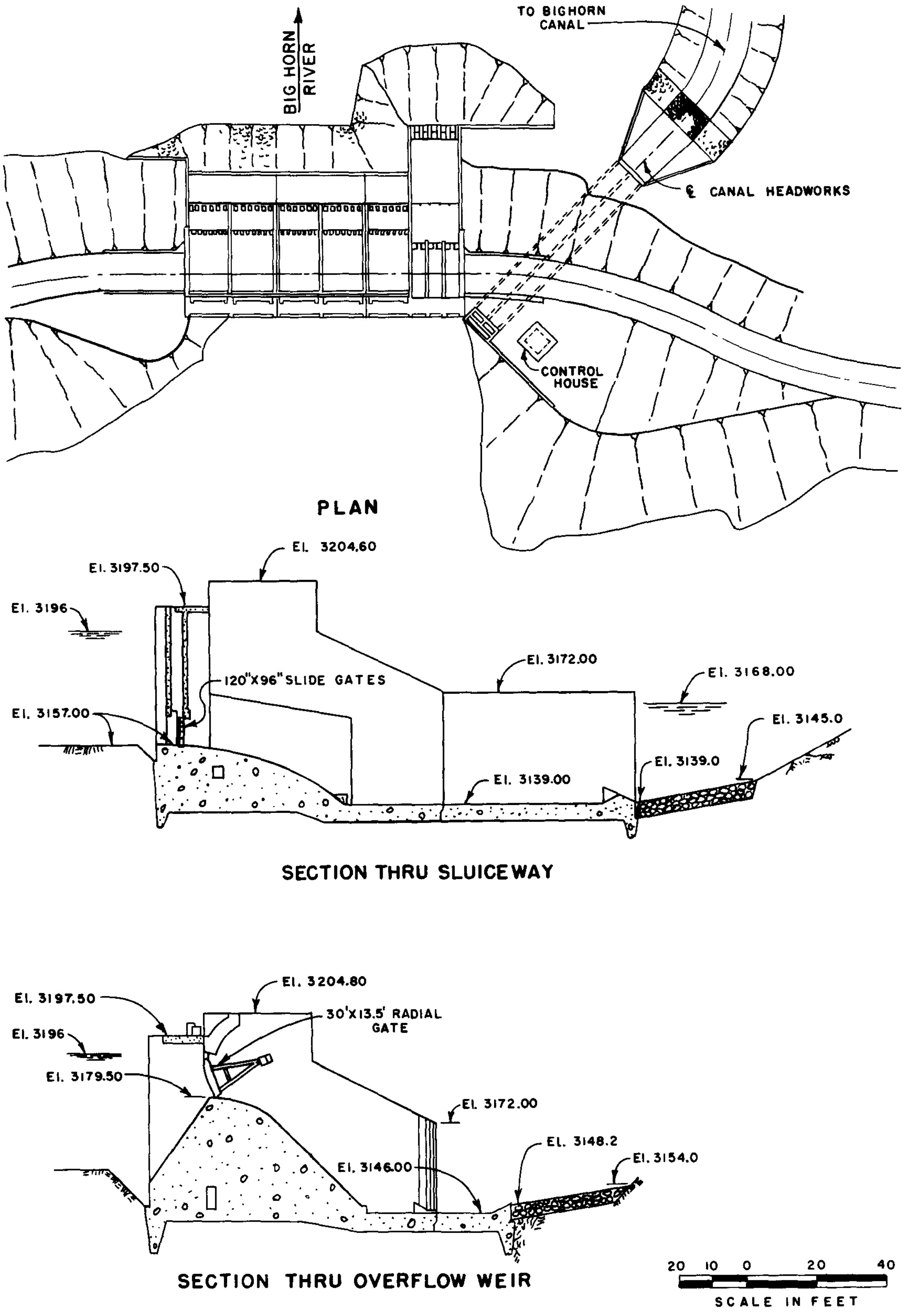
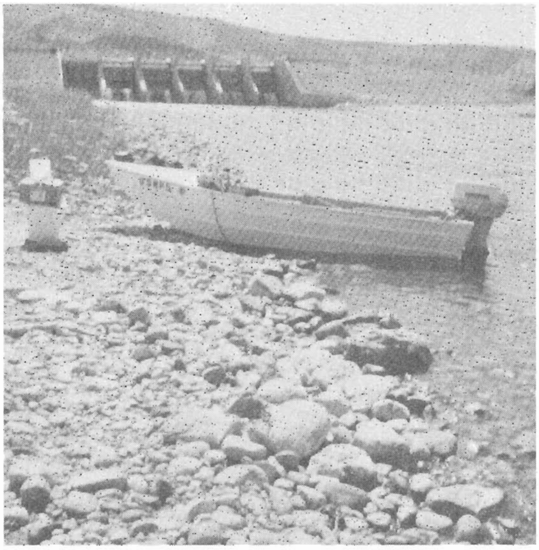
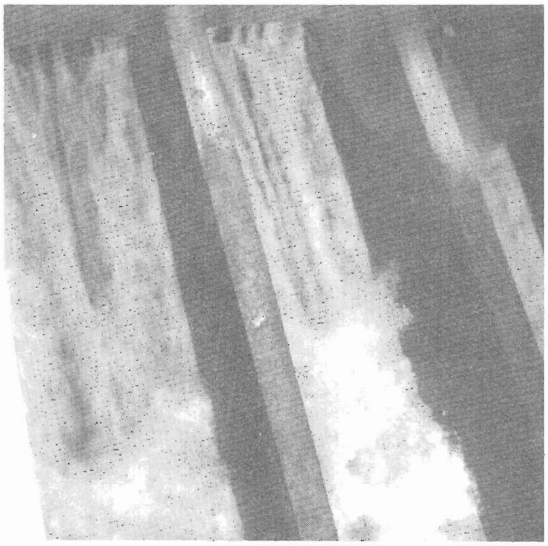


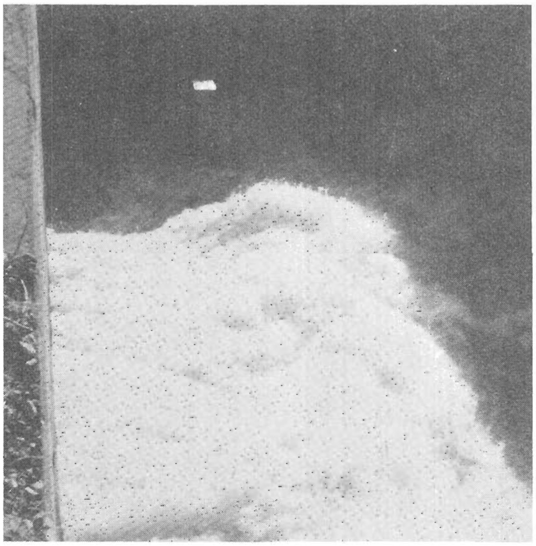
Figure 4. Yellowtail Afterbay Dam - Plan and sections.



Afterbay Dam. Photo P459-D-74135



Flow beneath slide gates.
Photo P459-D-74136



Flow in sluiceway hydraulic jump basin. Photo P459-D-74137

Figure 5. Yellowtail Afterbay sluiceway at 5,000 ft^3/s.

H_V = 3,196 - 3,168 = 28 feet

Angle of jet penetration $\approx$ 25°

Water depth in the basin = 3,168 - 3,146 = 22 feet

Basin flow path length $\approx$ 95 feet

Observe that no head loss was included in the evaluation of the jet velocity head (H_V). For this structure, this assumption should be valid in that the flow path between the release gate and the stilling basin pool is short and unobstructed. Because of the changing angle of the flow surface as it enters the stilling basin, the angle of penetration was approximated to be 25° below horizontal. The water depth in the basin of 22 feet (6.7 m) was computed for the deepest portion of the pool. Finally, the flow length (X) of 95 feet is approximately the distance from the point where the jet would attain significant penetration to the end sill of the basin. It was reasoned that at the end sill a large portion of the flow will be deflected upward, the flow would no longer be under the higher pressure and dissolving of gases in the basin would be complete. These approximations are quite rough, but attempts to refine the evaluations would yield only slight improvements and in general would not be worthwhile. It is also felt that since similar approximations have been applied to all structures studied and since the design curves were developed from similar approximations, the overall analysis has built-in compensation factors that should result in the correct prediction.

As the first step in the analysis, the absolute dissolved nitrogen concentration in the reservoir is evaluated. This is done by referring to figure 1 and obtaining the nitrogen saturation concentration fcr the specific water temperature (4.4° C) and multiplying it by the relative reservoir dissolved nitrogen level (104 percent).

$$C_I = (1.04)\ (20.7\ mg/l) = 21.53\ mg/l$$

Note that this equation has not been modified to reflect a barometric pressure that is other than one atmosphere (760 mm Hg). Results of studies using a barometric pressure modification were less accurate than if the modification were not applied. The reason for this is uncertain.

Next, the potential absolute dissolved nitrogen level (C_S) for the stilling basin is computed. As stated before, the potential dissolved nitrogen level depends on the barometric pressure, water temperature, and water depth in the basin. The average water depth over the flow while the gas is being dissolved is assumed to be two-thirds of the water depth in the basin. Using this approximation an average total pressure, including barometric and water, on the flow in atmospheres is computed and multiplied by the absolute dissolved nitrogen concentration obtained from figure 1.

$$C_s =$$

$$\left[\frac{677 \text{ mm Hg} + \dfrac{\frac{2}{3}\,(22 \text{ ft of } H_2O)(304.8 \text{ mm/ft})}{13.55 \text{ mm } H_2O/\text{mm Hg}}}{760 \text{ mm Hg/atmosphere}}\right] [20.7 \text{ mg/l/atmosphere}] =$$

$$27.43 \text{ mg/l}$$

Note that this term has been adjusted to reflect the barometric pressure and, thus, the structure's elevation. As stated before, if the barometric pressure is unknown, estimate the elevation of the structure and by interpolation select the corresponding pressure from table 1.

Two of the terms (C_s and C_I) in equation (11) have now been evaluated.

$$C(t) = C_s + (C_I - C_s)\ e^{-Kt}$$

The length of time (t) that gas is being dissolved is the next term of interest. It must be evaluated by the two procedures. First, it will be evaluated based on the 0.696 ft/s, terminal bubble rise velocity. To do this, the vertical dimension of the jet at the tailwater surface is found. The 28-foot velocity head (H_V) yields a velocity (V_o) of 42.5 ft/s. The discharge is then divided by the velocity to obtain a flow cross-sectional area (A_{flow}).

$$A_{flow} = 3{,}550 \text{ ft}^3/\text{s} \big/ 42.5 \text{ ft/s} = 83.5 \text{ ft}^2$$

The preceding equation gives the cross-sectional area for three gates. Assuming equal flow through each results in a flow cross-sectional area of 27.8 ft^2 for a single gate. When equal flow conditions are assumed for the gates, the analysis of each individual gate is identical and, thus, the analysis of the flow for only one gate will predict the performance of the entire structure. If the flow cross-sectional area is then divided by the gate width (8 feet) the flow thickness (B_o) is found.

$$B_o = 27.8\ ft^2/8\ ft = 3.48\ feet$$

Since the flow is not horizontal, the flow thickness (B_o) must be divided by the cosine of the angle of penetration to obtain the vertical dimension of the jet (Y).

$$Y = 3.48\ ft/\cos 25° = 3.48\ ft/0.9063 = 3.84\ feet$$

If this distance is then divided by the terminal bubble velocity, a time ($t_{0.696}$) is obtained.

$$t_{0.696} = 3.84\ ft/0.696\ ft/s = 5.517\ seconds$$

The length of time (t) may also be evaluated by considering the time that the flow is at an effective depth in the basin. To do this, the curves in figure 2 are used. First, the flow path length (X) is divided by the jet thickness (B_o).

$$X/B_o = 95\ ft/3.48\ ft = 27.30\ feet$$

The flow width (L_o) is then divided by the jet thickness (B_o).

$$L_o/B_o = 8\ ft/3.48\ ft = 2.30\ feet$$

Figure 2 is then referred to and the ratio of the maximum velocity (V_m) within the velocity distribution at the end of the flow path to the initial flow velocity (V_o) is obtained.

$$V_m/V_o = 0.36$$

or

$$V_m = (0.36)\ (42.5\ ft/s) = 15.3\ ft/s$$

If the average flow velocity (V_{avg}) at the end of the path is then assumed to be one-half of V_m then an average velocity (V_x) over the path length can be determined.

$$V_x = (15.3\ ft/s/2 + 42.5\ ft/s)/2 = 25.1\ ft/s$$

An average velocity at the end of the path based on cross-sectional area and discharge (Q) would be:

$$V_{avg} = [3550/(22)(28)] = 5.8 \text{ ft/s}$$

This is less than (15.3 ft/s/2) or 7.65 ft/s, so the 7.65 ft/s should be used.

The time (t_{flow}) is then the path length divided by this average velocity.

$$t_{flow} = 95 \text{ ft}/25.1 \text{ ft/s} = 3.78 \text{ seconds}$$

The smaller of the two computed times is the one that is applicable to the problem. For this particular case t_{flow} = 3.78 seconds is the applicable time interval.

The final term, K, to be evaluated is found through the use of figure 3. To apply figure 3, two parameters must be computed. H_V/P is the ratio of the velocity head to the appropriate flow path length. If the time interval used is based on basin retention time (t_{flow}), the basin flow path length (X) is used as P. If, however, the smaller time results from the consideration of the bubble rise time ($t_{0.696}$) then the flow path length (X_A) to be used is less than the basin flow path length (X).

For the Yellowtail Afterbay Dam sample problem, the time based on the basin retention time applies because it is the smaller, and so the initially determined path length of 95 feet is used. H_V/P is, therefore,

$$H_V/P = 28\ \text{ft}/95\ \text{ft} = 0.295$$

For the application of figure 3, the second parameter that must be evaluated is a ratio of the shear perimeter length of the jet to the cross-sectional area of the jet. For this problem the shear perimeter is the jet width plus the jet height for each side or

$$\text{Shear perimeter} = 8\ \text{ft} + 3.48\ \text{ft} + 3.48\ \text{ft} = 14.96\ \text{feet}$$

The cross-sectional area (A_{flow}) has already been found to be 27.8 ft^2. Thus, the ratio is:

$$\text{Shear perimeter}/A_{flow} = 14.96\ \text{ft}/27.8\ \text{ft}^2 = 0.538\ \text{ft}^{-1}$$

Note that this term is not dimensionless. If the curves of figure 3 are then referred to, the value of K is 0.100. All the terms may now be substituted into equation (11) and the resulting dissolved nitrogen level (not corrected for barometric pressure) is determined.

$$C\ (t) = 27.43 + (21.53 - 27.43)\ e^{-(0.100)(3.78)} = 23.39\ \text{mg/l}$$

If this is then divided by the saturation concentration from figure 1, the percent nitrogen saturation is obtained.

$$C\ (t) = 23.39/20.7 \times 100 = 113 \text{ percent}$$

The actual observed N_2 value was also 113 percent. As with the evaluation of the 20.7 mg/l concentration used above, the resulting dissolved nitrogen concentration [C(t)] has not been adjusted for barometric pressure. To obtain a predicted absolute concentration, multiply the predicted percentage by an adjusted absolute concentration.

$$(1.13)\ (677/760)\ (20.7) = 20.84 \text{ mg/l of } N_2$$

Now if dissolved oxygen is considered, it is known that:

$$C_I = (0.85)\ (12.9) = 10.97 \text{ mg/l}$$

where 12.9 mg/l is the saturation concentration of oxygen at 4.4° C from figure 1. It is also known that:

$$C_s = \frac{677\text{mm Hg} + \frac{2}{3}(22 \text{ ft of } H_2O)\ \dfrac{304.8\text{mm/ft}}{13.55\text{mm } H_2O/\text{mm Hg}}}{760\ \dfrac{\text{mm Hg}}{\text{atmosphere}}}\ (12.9 \text{ mg/l/atmosphere})$$

$$= 17.09 \text{ mg/l}$$

$$t = 3.78 \text{ seconds}$$

$$K = 0.100$$

All of which follows from the nitrogen calculations above. Applying equation (11), it can be found that:

$$C(t) = 17.09 + (10.97 - 17.09)\ e^{-(0.100)(3.78)} = 12.90 \text{ mg/l}$$

The percent oxygen saturation calculated is:

$$(100)\ 12.90/12.9 = 100 \text{ percent}$$

The actual observed O_2 value was also 100 percent.

An approximation of the percent total dissolved gas would be:

$$(100)(23.39 + 12.9)/(20.7 + 12.9) = 108 \text{ percent}$$

This, of course, considers only nitrogen and oxygen, but it should be realized that the two together comprise over 99 percent of the total dissolved gas.

Example 2

Grand Coulee spillway; gates 4, 5, and 6 operating

Discharge = 12,800 ft^3/s

Reservoir water surface elevation = 1274 feet

Tailwater surface elevation = 955 feet

Water temperature = 23.5° C

Barometric pressure = 734 mm Hg

Reservoir dissolved nitrogen = 116 percent

Reservoir dissolved oxygen = 107 percent

Also, the information in figures 6 and 7 is known. In addition, initial observations yield:

Velocity head = 319 feet

Velocity = 143.3 ft/s

Angle of penetration = 51°

Flow width = 450 feet

Path length = 164 feet

Basin depth = 85 feet

All of the above were found in the same manner as before except for the path length. Because there is no distinct stilling basin pool, no distinct flow limits could be directly observed. One could, however,

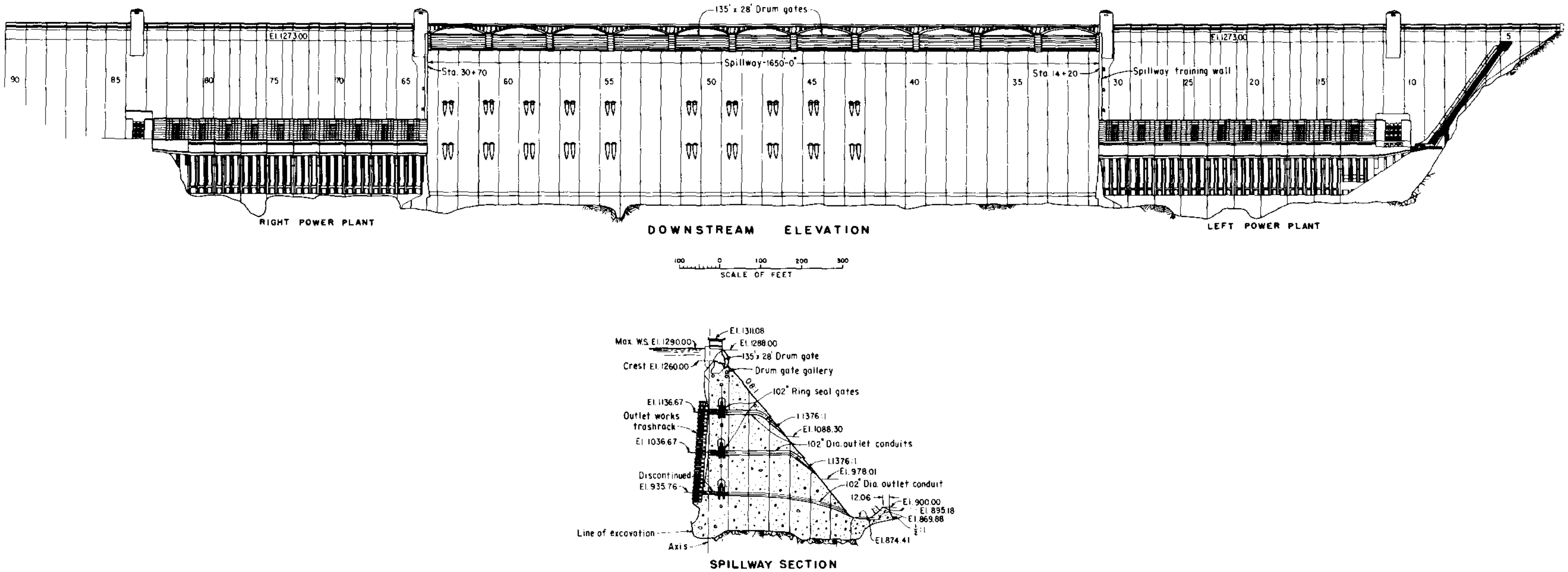


Figure 6. Grand Coulee Dam - Elevation view and section.

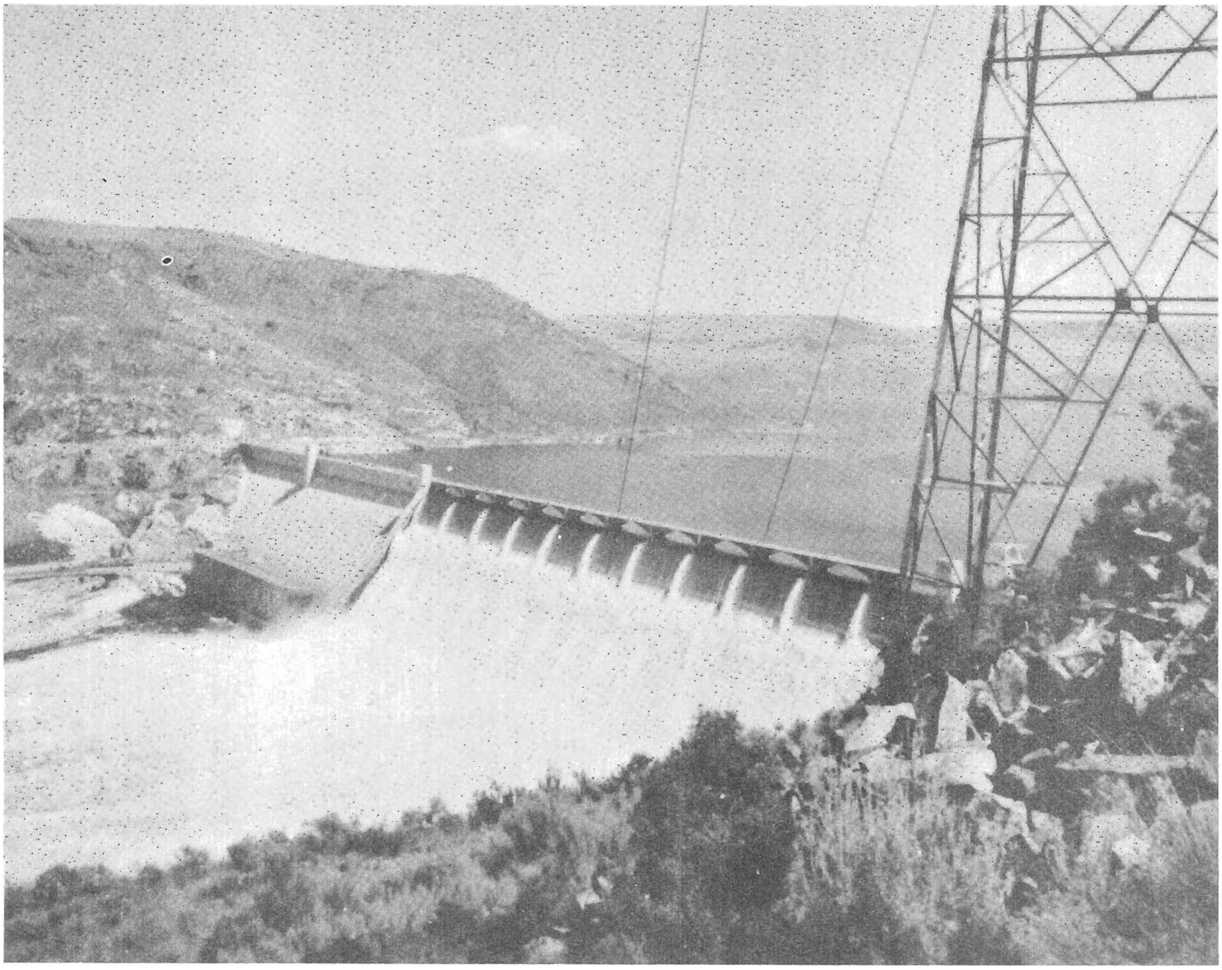


Figure 7. Grand Coulee Dam. Photo 222-116-42513

hypothesize that the flow would penetrate to the roller bucket where it would be deflected towards the surface. Because of the very large basin depth, it could be expected that gas would continue to be dissolved as the jet rises. The path length was intuitively selected as 1-1/2 times the length along the spillway from the tailwater surface to the bucket (or the distance shown as a dashed line in fig. 6).

$$(1.5)(85/\sin 51°) = 164 \text{ feet}$$

The analysis follows:

$$C_I = (1.16)(13.9 \text{ mg/l}) = 16.12 \text{ mg/l}$$

The 13.9 mg/l is obtained from figure 1.

$$C_s = \frac{734\text{mm Hg} + \frac{2}{3}(85 \text{ ft } H_2O)(304.8\text{mm/ft})/(13.55\text{mm } H_2O/\text{mm Hg})}{760\text{mm Hg/atmosphere}}(\text{mg/l/atmosphere})$$

$$= 36.74 \text{ mg/l}$$

To evaluate $t_{0.696}$

$$A_{flow} = 89.32 \text{ ft}^2$$

$$B_o = 89.32 \text{ ft}^2/450 \text{ ft} = 0.198 \text{ foot}$$

$$Y = 0.198 \text{ ft}/\cos 51° = 0.315 \text{ foot}$$

$$Y/0.696 = 0.315 \text{ ft}/0.696 \text{ ft/s} = 0.453 \text{ second}$$

To evaluate t_{flow}

$$X/B_o = 164\ \text{ft}/0.198\ \text{ft} = 828$$

$$L_o/B_o = 450\ \text{ft}/0.198\ \text{ft} = 2{,}270$$

$$V_m/V_o = 0.0413 \text{ from figure 2}$$

$$V_m = 0.0413\ (143.3\ \text{ft/s}) = 5.9\ \text{ft/s}$$

$$V_x = \frac{143.3\ \text{ft/s} + 5.9\ \text{ft/s}/2}{2} = 73.1\ \text{ft/s}$$

$$t_{flow} = (164\ \text{ft}/73.1\ \text{ft/s}) = 2.24 \text{ seconds}$$

The time interval computed using the terminal bubble velocity ($t_{0.696}$) is the smaller and, therefore, applies. This being the case, a modified flow path length (X_A) must be computed for use in the prediction of K. To do this, a linear deceleration is assumed and the ratio of the two times ($t_{0.696}/t_{flow}$) is multiplied by the velocity drop over flow path length, X, (143.3-2.95) to obtain the velocity drop over the $t_{0.696}$ distance. The average velocity along the effective path is then computed by averaging the velocities at the beginning and end of the path. This average velocity multiplied by $t_{0.696}$ would yield the effective path length. The velocity drop over the effective path (X_A) is:

$$(0.453\ \text{s}/2.24\ \text{s})(143.3\ \text{ft/s}-2.95\ \text{ft/s}) = 28.4\ \text{ft/s}$$

X_A is, therefore:

$$X_A = \frac{143.3 \text{ ft/s} + 114.9 \text{ ft/s}}{2} (0.453 \text{ s}) = 58.5 \text{ feet}$$

To evaluate K

$$H_V/P = 319 \text{ ft}/58.5 \text{ ft} = 5.4$$

$$\text{Shear perimeter}/A_{flow} = 450.4 \text{ ft}/89.32 \text{ ft}^2 = 5.043 \text{ ft}^{-1}$$

$$K = 1.87 \text{ from figure 3}$$

Substitution in equation (11) then yields:

$$C\ (t) = 36.74 + (16.12\text{-}36.74)e^{-(1.87)(0.453)} = 27.90 \text{ mg/l}$$

$$\frac{27.90 \text{ mg/l}}{13.9 \text{ mg/l}} = 201 \text{ percent} = \text{resulting dissolved nitrogen saturation percentage}$$

$$(2.01)(734/760)(13.9) = 26.98 \text{ mg/l} = C(t) \text{ corrected for barometric pressure}$$

Likewise, when dissolved oxygen is considered, it is known that:

$$C_I = (1.07)(8.6 \text{ mg/l}) = 9.20 \text{ mg/l}$$

where the 8.6 mg/1 comes from figure 1

$$C_s = \left(\frac{734\text{mm Hg} + \frac{2}{3}(85\text{ ft }H_2O)\left(304.8\text{mm/ft}\Big/13.55\frac{\text{mm }H_2O}{\text{mm Hg}}\right)}{760\text{ mm Hg/atmosphere}}\right)(8.6\text{ mg/1/atmosphere})$$

$$= 22.73\text{ mg/1}$$

$K = 1.87$ $t = 0.453$ second

So

$$C(t) = 22.73 + (9.20-22.73)e^{-(1.87)(0.453)} = 16.93\text{ mg/1}$$

$16.93/8.6 = 197$ percent = resulting dissolved oxygen percentage

When this operating condition was observed in the prototype, the powerplant was also operating. Thus, dissolved gas levels taken downstream represented the combined effect of the two releases. Data indicate that no increase in the dissolved gas content of the flow occurs when the flow passes through the turbines. The powerplant discharges were, therefore, considered to have a dissolved gas level equal to that at the penstock intake level of the reservoir. The powerplant releases diluted the dissolved gas concentrations from the spillway. A computation was carried out and the dissolved nitrogen level created by this spillway flow was found to be 199 percent. No downstream dissolved oxygen data were available for comparison.

Example 3

Fontenelle spillway

Discharge = 750 ft^3/s

Water temperature = 19.6° C

Barometric pressure = 597 mm Hg

Reservoir water surface elevation = 6507 feet

Tailwater surface elevation = 6397 feet

C_I = 103 percent for N_2

99 percent for O_2

Manipulation of the above, along with the information in figures 8 and 9 yield:

H_v = 90 feet   Velocity = 76.1 ft/s

Basin depth = 43 feet

Angle of penetration = 25°

Chute width = 50 feet

Path length = 190 feet

It should be observed that for this particular problem the velocity head (H_v) was not evaluated as the difference between the reservoir and tailwater surface elevations. As can be seen in figure 9, the

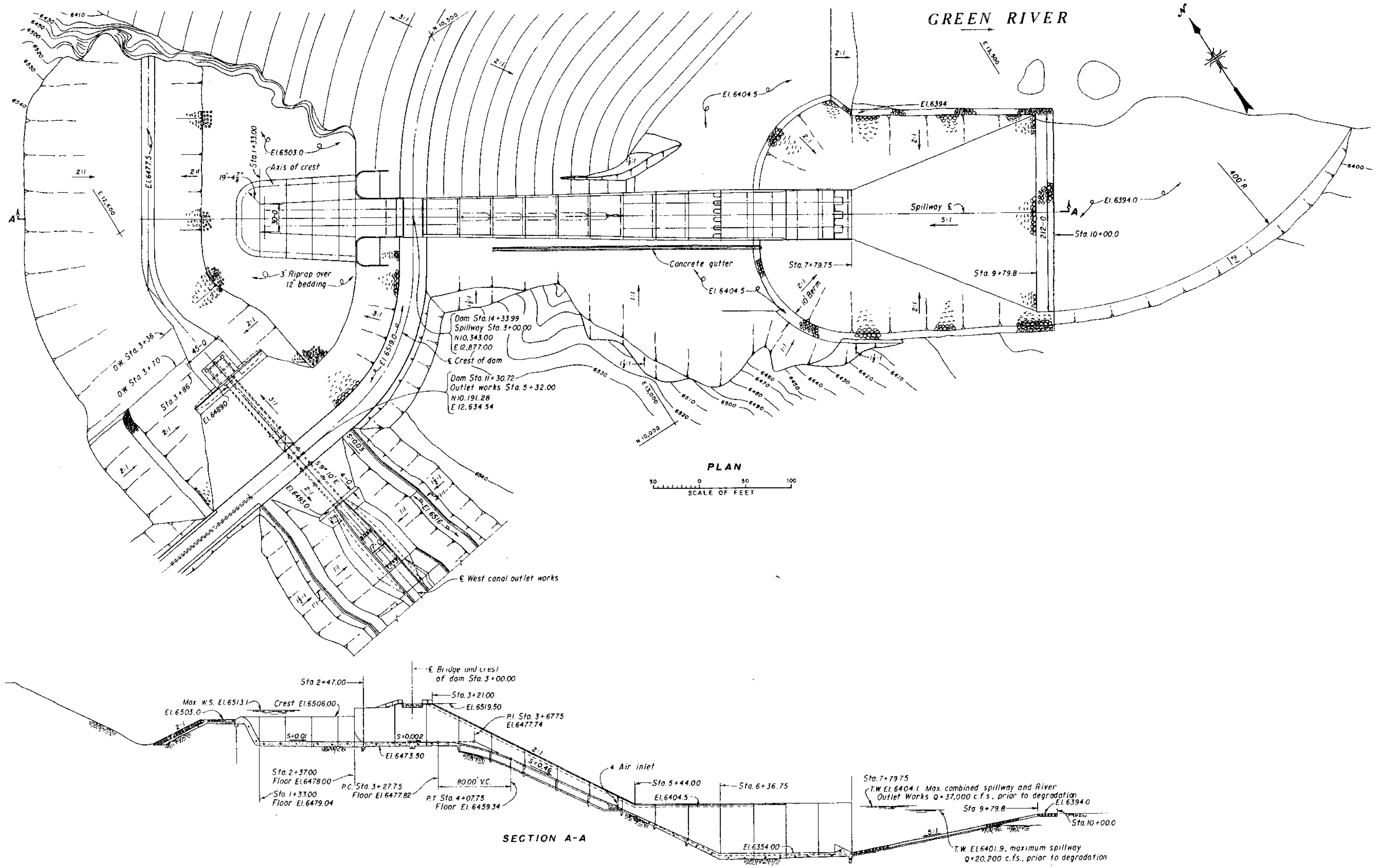


Figure 8. Fontenelle spillway - Plan and profile

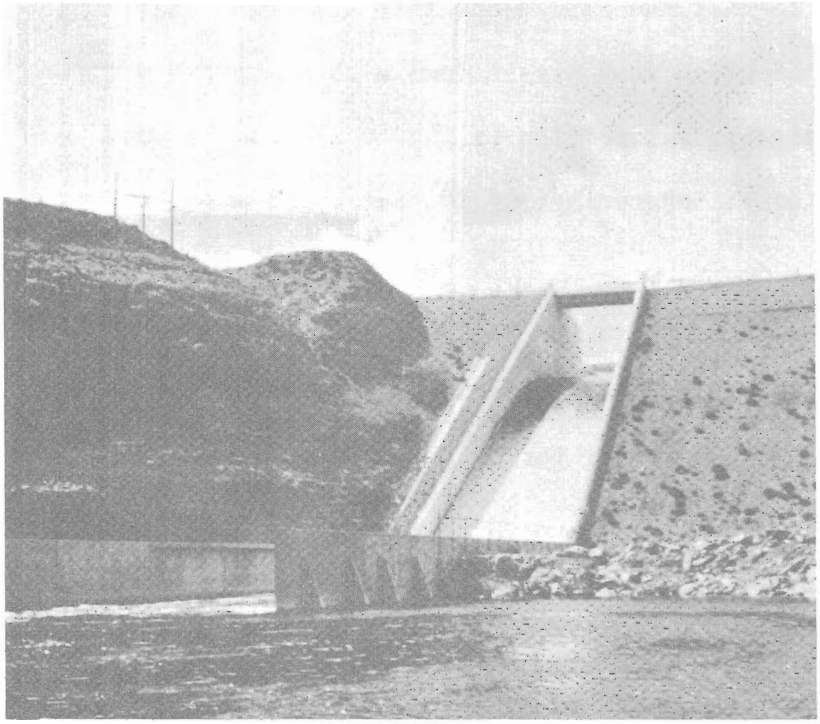


Photo H-1755-2

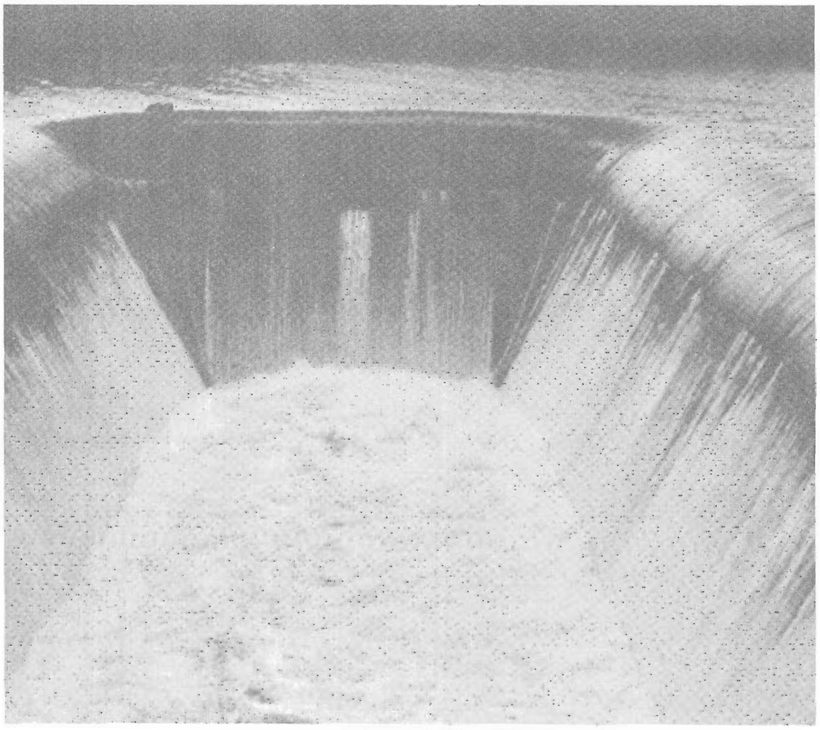


Photo H-1755-3

Figure 9. Fontenelle spillway.

spillway is designed so that the flow drops into a trough, goes through a hydraulic jump, and then passes down a chute to the stilling basin. Thus, a significant portion of the total head is lost. It appears that the loss is approximately 20 feet. The calculations then follow:

$$C_I = (1.03)(14.90) = 15.35 \text{ mg/l for } N_2$$
$$(0.99)(9.15) = 9.06 \text{ mg/l for } O_2$$

The 14.9 and 9.15 values come from figure 1

$$C_s = \left[\frac{(597 + (2/3)(43)(304.8/13.55))}{760}\right](14.9) = 24.35 \text{ mg/l for } N_2$$
$$= 14.95 \text{ mg/l for } O_2$$

To evaluate $t_{0.696}$

$$A_{flow} = 750/76.1 = 9.855 \text{ ft}^2$$
$$B_o = 9.885/50 = 0.1971 \text{ feet}$$
$$Y = 0.1971 \text{ ft}/\cos 25° = 0.2174 \text{ feet}$$
$$t_{0.696} = 0.2174/0.696 = 0.312 \text{ second}$$

To evaluate t_{flow}

$$X/B_o = 190/0.1971 = 964$$
$$L_o/B_o = 50/0.1971 = 254$$

$$V_m/V_o = 0.0377 \text{ from figure 2}$$

$$V_x = (76.1 + 2.87/2)/2 = 38.8 \text{ ft/s}$$

Computation of the average flow velocity at the end of the basin, based on discharge and basin cross-sectional area, yields:

$$V_{avg} = (750)/(43)(50) = 0.35 \text{ ft/s}$$

0.35 ft/s is less than 1.43 ft/s (2.87/2), so the latter would be used.

$$t_{flow} = 190/38.8 = 4.90 \text{ seconds}$$

The time interval based on the terminal bubble size ($t_{0.696}$) is the smaller, so it should be used in the remaining analysis.

To evaluate K the path length is modified.

$$(0.312/4.90)(76.1 - 2.87/2) = 4.75 = \text{velocity drop over path}$$

$$[(76.1 + 76.1 - 4.75)/2]\ (0.312) = 23.0 \text{ feet} = X_A$$

$$H_V/P = 90/23.0 = 3.91$$

$$\text{Shear perimeter/area} = 50/9.855 = 5.07 \text{ ft}^{-1}$$

Where a chute is connected to a stilling basin, and the basin has the same width as the chute, the shear perimeter is equal to the chute width.

Now, from figure 3, K = 0.75.

So

$$C(t) = 24.35 + (15.35 - 24.35)e^{-(0.75)(0.312)} = 17.23 \text{ mg/l for } N_2$$

$$14.95 + (9.06 - 14.95)e^{-(0.75)(0.312)} = 10.29 \text{ mg/l for } O_2$$

$$17.23/14.9 = 116 \text{ percent for } N_2$$

$$10.29/9.15 = 112 \text{ percent for } O_2$$

This results in predicted dissolved gas levels (adjusted for barometric pressure) of:

$$(1.16)(597/760)(14.9) = 13.58 \text{ mg/l of } N_2$$

$$(1.12)(597/760)(9.15) = 8.05 \text{ mg/l of } O_2$$

The observed dissolved nitrogen and oxygen levels were 116 and 108 percent, respectively.

Example 4

Navajo auxiliary outlet

Along with figures 10 and 11, the following information is known:

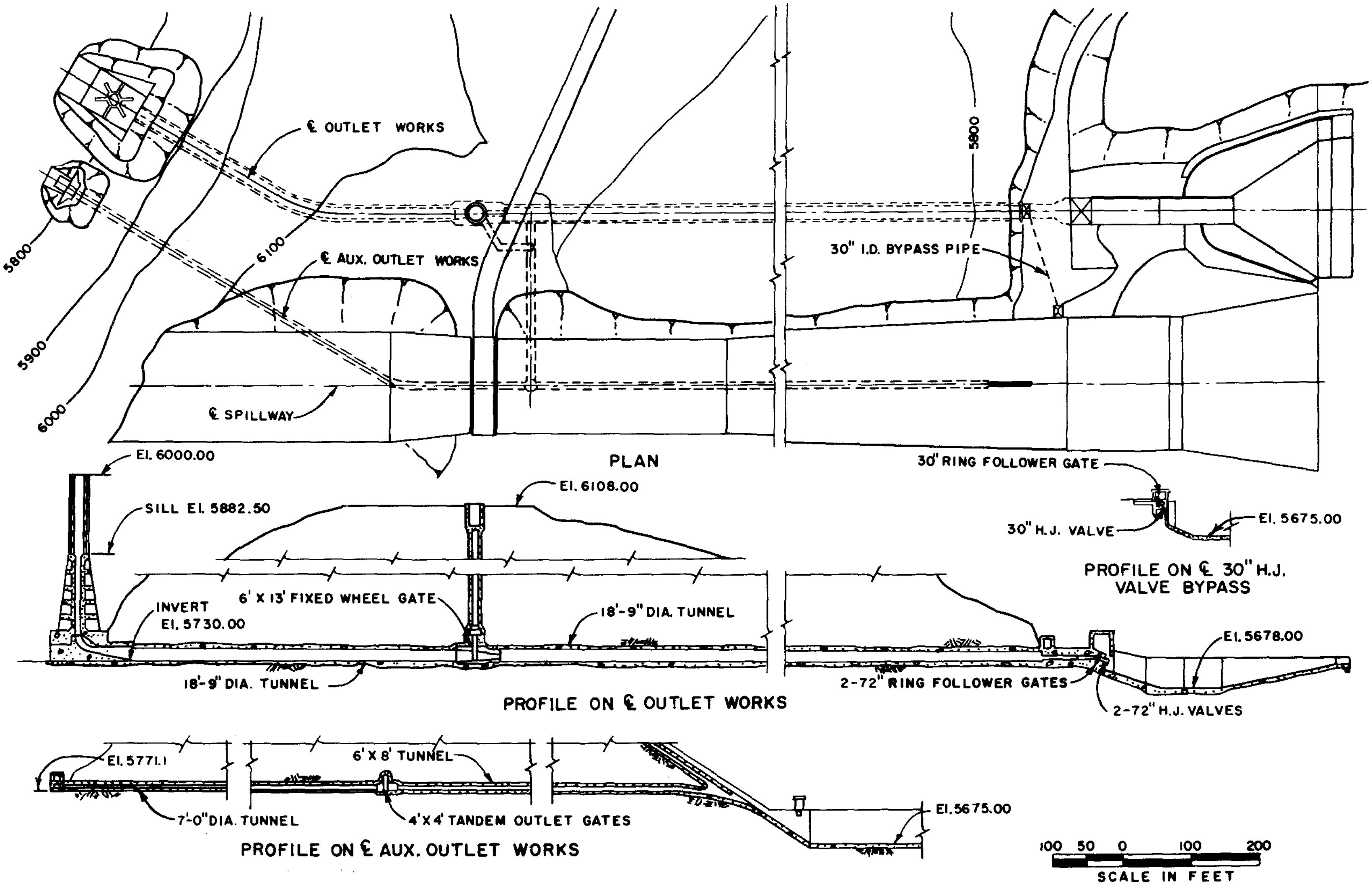


Figure 10. Navajo Dam outlet works - Plan and profile.

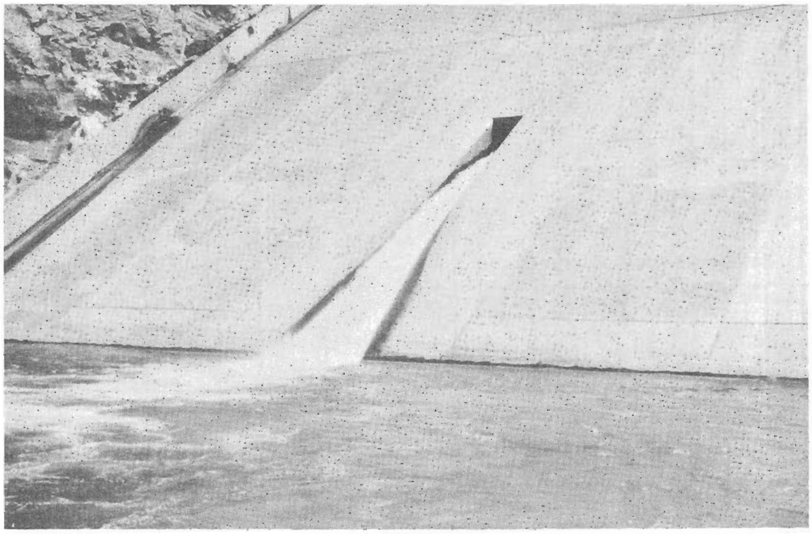


Figure 11. Navajo auxiliary outlet at 1,000 ft^3/s.
Photo P711-D-74128

Water temperature, °C	6.1	6.1	6.1	5.4
Barometric pressure, mm Hg	610	610	610	617
C_I, percent O_2	85	85	85	85
C_I, percent N_2	105	105	105	105
Reservoir water surface elevation	6085	6085	6085	6020
Tailwater surface elevation	5712	5712	5712	5712
Discharge, ft^3/s	400	800	1,600	1,000

From the known information, the following values were calculated:

H_v (feet)	373	373	323	308
V_o (ft/s)	155	155	155	141
L_o (feet)	6	6	6	6
X (feet)	180	180	180	180

Basin water depth (feet)	37	37	37	37
C_I, mg/l, N_2	20.79	20.79	20.79	22.21
O_2	10.50	10.50	10.50	10.67
C_s, mg/l, N_2	30.35	30.35	30.35	31.00
O_2	18.93	18.93	18.93	19.24
A_{flow} (ft^2)	2.58	5.16	10.32	7.09
B_o (feet)	0.430	0.860	1.72	1.18
Y (feet)	0.519	1.037	2.075	1.423
$t_{0.696}$ (second)	0.746	1.49	2.98	2.04
X/B_o	419	209	105	153
L_o/B_o	13.95	6.98	3.49	5.08
V_m/V_o	0.055	0.080	0.115	0.100
V_m (ft/s)	8.52	12.40	17.82	14.10
t_{flow} (seconds)	2.26	2.23	2.20	2.43
Applicable time (seconds)	0.746	1.49	2.20	2.04
X_A (feet)	97.1	156.9	180.0	172.9
H_V/P	3.84	2.38	2.07	2.16
Shear perimeter/A_{flow}	2.66	1.50	0.915	1.18
K	2.90	2.85	4.2	3.25
Kt	2.15	4.25	9.24	6.63
e^{-Kt}	0.1153	0.0143	0.0001	0.0013
C(t), percent N_2	148	153	153	154
O_2	145	152	153	153

Observed C(t), percent N_2	147	155	158	125
percent O_2	130	132	135	130

The differences between predicted and measured values of nitrogen supersaturation for the 1,000-ft^3/s discharge might be explained as measurement error. There is an observed tendency for gas at high supersaturation levels to escape from the sample.

The differences between predicted and measured levels of dissolved oxygen might be caused by heavy organic loading, though this could not be proven without measurement of BOD.

Example 5

Granby spillway

The following information is available along with that in figures 12 and 13:

Discharge = 638 ft^3/s

Reservoir water surface elevation = 8260

Tailwater surface elevation = 8050

Barometric pressure = 563 mm Hg

Water temperature = 14.8° C

C_I, percent N_2 = 110 percent

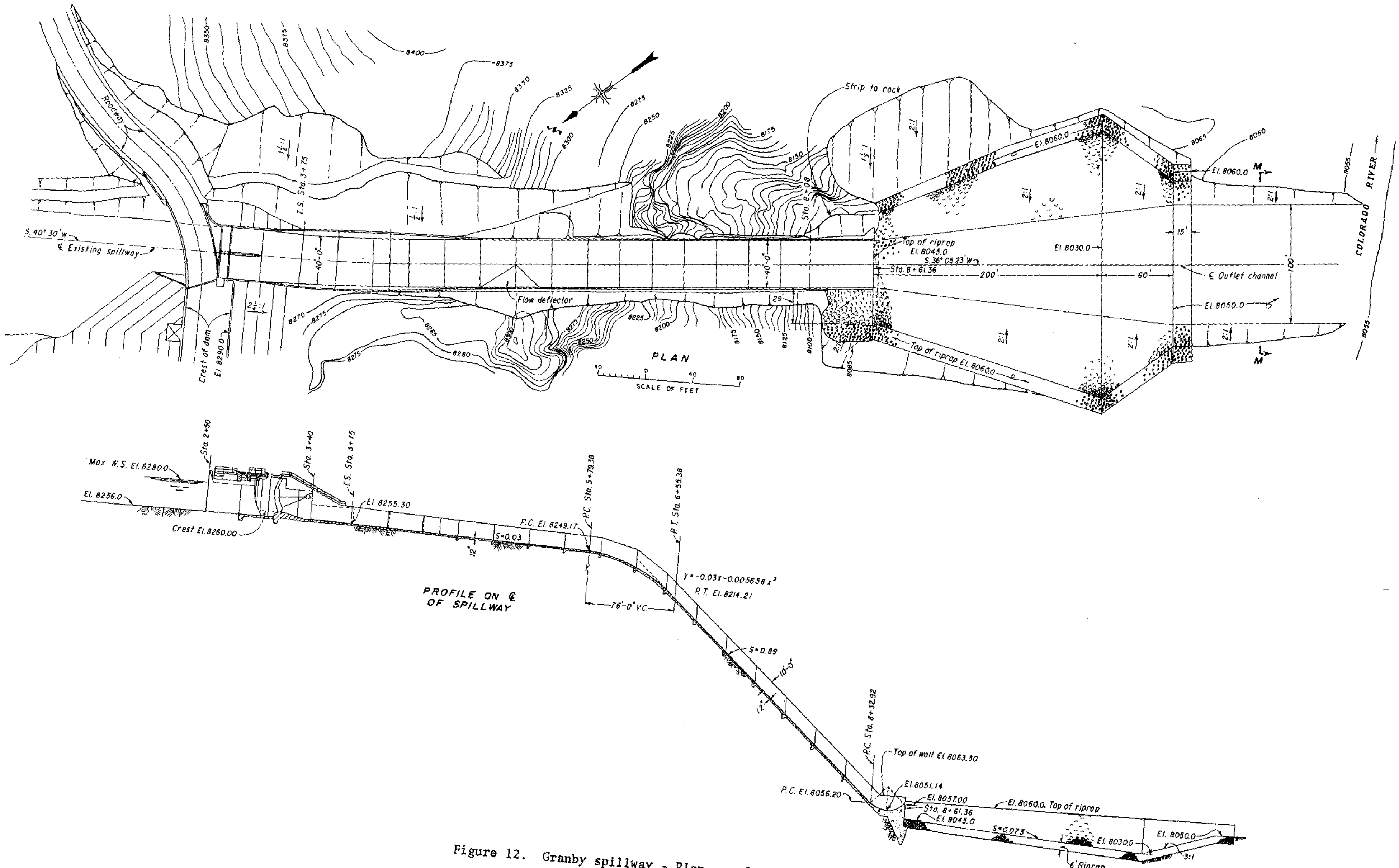


Figure 12. Granby spillway - Plan, profile, and sections.

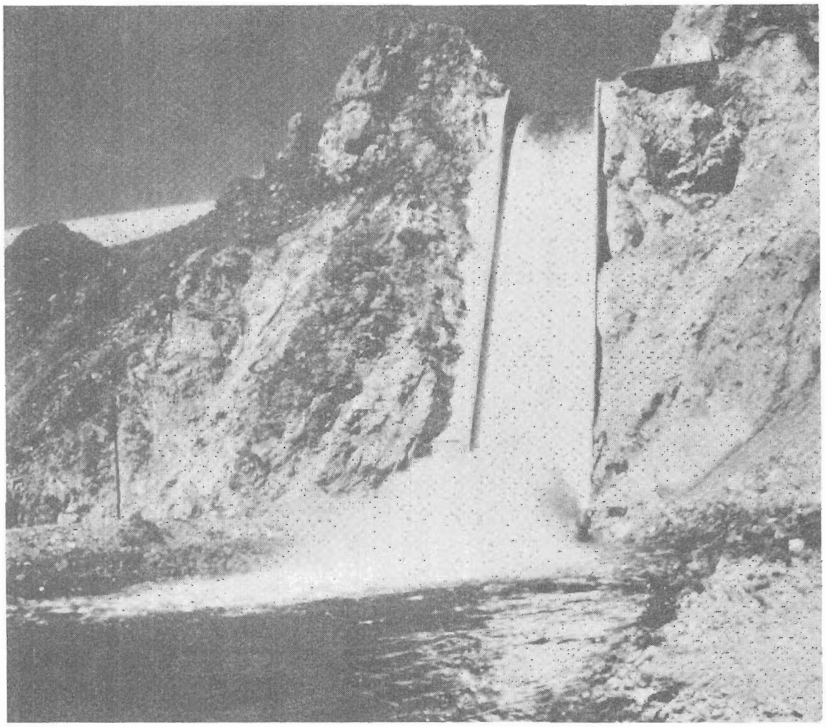


Photo H-1755-1

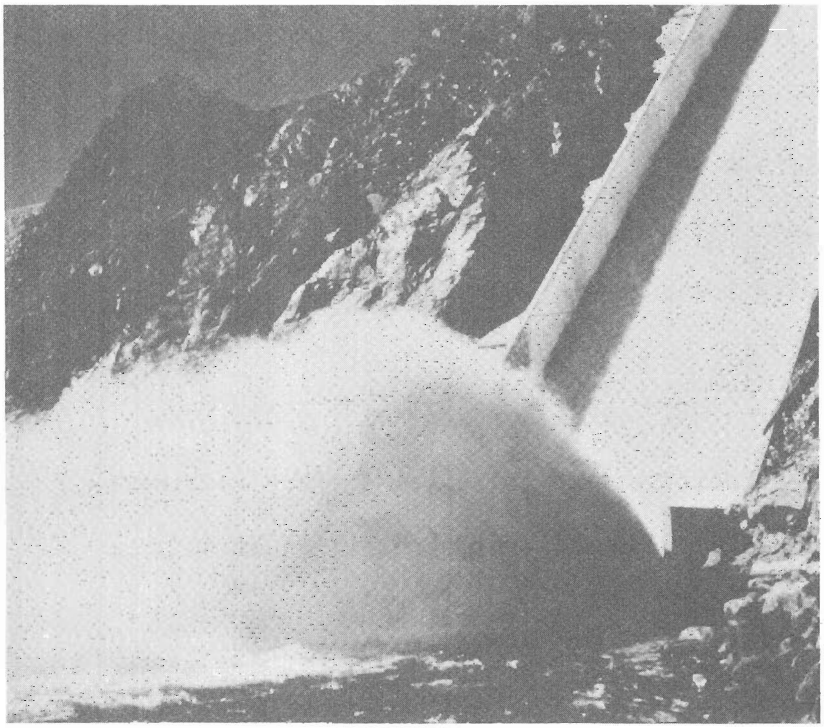


Photo H-1755-4

Figure 13. Granby spillway.

The following analysis would then result:

H_v = 210 feet with the last 7 feet a free drop

V_o = 116.2 ft/s

V at the release point from the flip bucket would be 114.3 ft/s

Angle of release = 45° upward

Basin water depth = 15 feet

X = 50 feet

L_o = 40 feet

C_I, N_2 = (1.1)(16.3) = 17.93 mg/1 N_2

$$C_s, N_2 = \left[\frac{563 + (15)(2/3)(304.8/13.55)}{760}\right](16.3) = 16.90 \text{ mg/1 } N_2$$

Since the jet passes through a free trajectory before it penetrates the stilling basin pool, a computation must be carried out to find the angle of penetration. At the release point the vertical and horizontal components of the velocity are both equal to 80.85 ft/s or (114.3) (sin 45°). This would also be the value of the horizontal component of the velocity at the tailwater surface.

The total velocity head at the tailwater surface is 210 feet. The vertical component of the velocity at the tailwater surface is, therefore, 83.59 ft/s. This results in an angle of penetration of 46°.

To evaluate $t_{0.696}$

$$A_{flow} = 638/116.2 = 5.49 \text{ ft}^2$$

$$B_o = 0.1373 \text{ feet}$$

$$Y = 0.1974 \text{ feet}$$

$$t_{0.696} = 0.284 \text{ seconds}$$

To evaluate t_{flow}

$$X/B_o = 50/0.1373 = 365$$

$$L_o/B_o = 291$$

$$V_m/V_o = 0.07$$

$$t_{flow} = 0.831 \text{ second}$$

and to evaluate K

$$X_A = 27.57 \text{ feet}$$

$$H_v/P = 210/27.57 = 7.62$$

$$\text{Shear perimeter}/A_{flow} = 80.3/5.49 = 14.625 \text{ ft}^{-1}$$

Because this is a free jet penetrating the stilling basin pool, the shear perimeter is the total perimeter of the jet (40 + 40 + 0.137 + 0.137 = 80.27). When figure 3 is referred to, K is found to be 0.175. Thus:

$$C(t) = 16.90 + (17.93 - 16.90)e^{-(0.175)(0.2839)}$$

$$= 17.88 = 109 \text{ percent } N_2$$

The barometric pressure adjusted concentration is (17.88)(563/760) or 13.25 mg/l. The actual observed concentration was 103 percent. Although the analysis did not closely predict the actual percentage, it should be noted that the analysis does correctly indicate a reduction in the dissolved gas level. This type of structure, with a free jet falling into a pool where the depth may not be exactly known, in many cases could result in an erroneous prediction.

REFERENCES

[1] Roesner, L. A., and Norton, W. R., "A Nitrogen Gas (N_2) Model for the Lower Columbia River," Final Report, Water Resources Engineers, Inc., January 1971

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[3] "Dissolved Gas Supersaturation, Grand Coulee Dam Project 1973," Seattle Marine Laboratories, January 1974.

[4] "Dissolved Gas Survey," Pacific Northwest Region, Bureau of Reclamation, December 1973.

[5] Yevdjevich, V. M., "Diffusion of Slot Jets with Finite Orifice Length - Width Ratios," Colorado State University Hydraulics Paper No. 2, December 1965.

[6] Henry, H. R., Discussion of "Diffusion of Submerged Jets," Paper No. 2409, Transactions of the American Society of Civil Engineers, Vol. 115, pp 687-694, 1950.

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 380-68) 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, 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 I

QUANTITIES AND UNITS OF SPACE

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

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
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
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^5	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	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 exactly	Celsius or Kelvin degrees (change)*
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 831-907

ABSTRACT

Various hydraulic structures including spillways and outlet works affect the dissolved gas content of the flow. Depending on the structure and conditions, the structures may: (1) aerate flows depleted in dissolved gas, (2) create supersaturated dissolved gas levels in the flow, or (3) reduce supersaturation levels in the flow. An analysis is presented which may be used to predict the effect of a wide variety of hydraulic structures on the dissolved gas content of the flow. Parameters considered include dissolved gas levels in the flow upstream from the structure; water temperature; barometric pressure; velocity, shape, and orientation of the flow entering the stilling basin; stilling basin geometry; and tailwater depth. The analysis is developed from prototype data. Included are several example applications with detailed descriptions of the procedures involved. (6 ref)

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Gr-8-75
Johnson, P. L.
PREDICTION OF DISSOLVED GAS AT HYDRAULIC STRUCTURES
Bur Reclam Rep GR-8-75, Div Gen Res, July 1975, Bureau of Reclamation, Denver, 67 p, 13 figs, 1 tab, 6 ref

DESCRIPTORS--/ applied research/ dissolved gases/ *reaeration/ hydraulic structures/ *spillways/ *outlet works/ *forecasting/ operations research/ future planning (projected)/ design criteria/ *supersaturation

COSATI Field/Group 8H

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