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PREDICTION OF DISSOLVED GAS TRANSFER IN SPILLWAY AND OUTLET WORKS STILLING BASIN FLOWS

BY

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ABSTRACT

An empirical model developed from field data collected at 24 different structures is presented. The model predicts oxygen and nitrogen transfer to and from flows through hydraulic structure energy dissipators and thus may be used to evaluate a structure's potential for reaeration and dissolved gas supersaturation development. The model may be applied to many types of spillway and outlet works stilling basins. Considered in the analysis are the velocity, cross sectional shape, and orientation of flow entering the basin; stilling basin length, width, depth, and shape; and tailwater depth. An example application is included.

INTRODUCTION

Because of concern about both reaeration and dissolved gas supersaturation, it is desirable to be able to predict how particular hydraulic structures operating under specific conditions will change the dissolved gas content of the flow. A predictive ability could be applied to existing facilities and could 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. Typically each structure draws water from different elevations in a density stratified reservoir. Because resulting dissolved gas levels depend in part on the structure through which the flow passes, the magnitude of the discharge, the initial dissolved gas levels, and the water temperature, considerable operating flexibility with respect to dissolved gas may exist with multiple structure use. To establish operating criteria for each structure based on actual measurement of resulting dissolved gas levels may be difficult. Not only are there a great number of structures that would have to be calibrated but each one can operate over a wide range of discharges. The 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, frequently operate over their full discharge range. Other structures, such as spillways, rarely 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 which could yield operating criteria and allow preparation for possible consequences.

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 that has a significant fishery. If a stream is tranquil, supersaturated dissolved gas levels created by a release might extend many miles downstream. With high levels of supersaturation, serious negative impacts to the zoologic community could result. 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.

A predictive analysis would have application at both ends of the dissolved gas problem (evaluating the potential for increasing depleted dissolved oxygen levels or predicting excessive dissolved gas levels). Oxygen is active in various biological processes, while nitrogen and argon are inactive. That is, while nitrogen and argon levels may remain constant at values set by the physical conditions of the flow, dissolved oxygen levels may be changing as a result of chemical or 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 decay of organic material. Thus, if water is withdrawn from the reservoir, it may be low in dissolved oxygen and yet may conceivably be high in dissolved nitrogen. The analysis of this specific release could include evaluation of both oxygen reaeration and nitrogen supersaturation. This analysis is appropriate for both evaluations.

Two predictive models have been developed either by or for the U.S. Army Corps of Engineers (Roesner and Norton, 1971, Wilhelms and Smith, 1981). Each Corps model was developed for a specific generic structure type. The Roesner and Norton model is for low-head, run-of-the-river structures, with gate-controlled ogee spillways. The Wilhelms and Smith model is for gated-conduit outlet works. These models are clearly defined and easily applied for the specific structure type. However, they cannot be generally applied to structures whose configuration varies from those on which the analysis is based. The model presented in this paper is intended to have a more generalized application. This model is based on field data collected at 24 different structures. Structures ranged from open chute hydraulic jump basins to flip buckets and plunge pools and from hollow-jet valve to fixed-cone valve to slide-gate-controlled outlet works basins. Forty-nine different operating conditions have been monitored. Field data used were obtained from Austin, Heller, and Johnson (1974), Seattle Marine Laboratories (1974), Pacific Northwest Region, Bureau of Reclamation (1973), and various unpublished sources. Typically reservoir water surface elevation, reservoir water temperature, reservoir dissolved oxygen, reservoir dissolved nitrogen and argon, structure discharge, structure operating arrangement (what gates and valves are being used), tailwater elevation, final water temperature, final dissolved oxygen, final dissolved nitrogen and argon, and barometric pressure were monitored. Combined, these data were considered to provide an adequate base from which the predictive analysis could be developed.

ANALYSIS

Noting that the rate of gas transfer either to or from a water parcel is governed by Fickian diffusion, the rate of gas transfer is described by the equation:

$$dC(t) = K[C_s - C(t)]\ dt \tag{1}$$

where $C(t)$ is the existing dissolved gas concentration and C_s is the saturated gas concentration. K is a constant coefficient for the particular flow and gas transfer conditions. If C_s is assumed a constant for a particular hydraulic structure, Eq. 1 may be manipulated and then integrated with respect to time (t) to obtain:

$$\ln[C(t) - C_s] + A_1 = -Kt + A_2 \tag{2}$$

where A_1 and A_2 are constants of integration. By combining the constants A_1 and A_2 into B and taking the inverse natural log, it is found that

$$C(t) - Cs = e^{-Kt+B} \tag{3}$$

If it is recognized that when $t = 0$, $C(t) = C_I$ (where C_I is the dissolved gas level in the water entering the structure from the reservoir), the equation can be written in its final form of:

$$C(t) = C_s + (C_I - C_s)e^{-Kt} \tag{4}$$

It should be noted that $C(t)$, C_s, and C_I are absolute dissolved gas concentrations measured in milligrams per liter of water.

Eq. 4 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 operation 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. The value of C_I is thus treated as a constant whose value equals either a known or assumed level. The other three parameters (C_s, t, and K) depend on the structure, the operating condition, the water temperature, and the barometric pressure. Efforts were therefore directed at evaluating C_s, t, and K.

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 the water temperature and the absolute pressure on the water. Through selective withdrawal, the water temperature is basically a function of the reservoir temperature distribution, the reservoir withdrawal location, and the discharge. The absolute pressure on the flow in the stilling basin is a function of the barometric pressure and the submergence of the flow with entrained air within the stilling basin pool. Barometric pressure is controlled by the elevation at which the structure is located with minor influences due to atmospheric conditions. The effects caused by atmospheric or weather fluctuations 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 was assumed and barometric pressures were computed. The pressure due to submergence depends on the flow and the basin geometry. Typically the flow with entrained air plunges into the basin, penetrates to the basin floor, and is deflected downstream to the end of the basin where it is deflected toward the surface (Fig. 1). Throughout the flow passage, the flow is also undergoing turbulent diffusion. Consequently, the mean submergence pressure that the flow is exposed to varies with location. Prediction of an average flow depth for individual discharges and structures would be a difficult task. It was recognized that free jet diffusion is linear, and, thus, typically the flow would expand upward from the basin floor to the water surface. This would result in a triangular flow pattern with the average depth being two-thirds of the total water depth in the basin. With this in mind and noting the complexity of the flow, the two-thirds depth was selected as representative of an average submergence. This evaluation is very approximate, but it is thought to be nearly as accurate as values that could be obtained through a more detailed analysis. In general, the findings of this study indicate that the two-thirds assumption is reasonable. One exception is in cases where the flow does not penetrate to the floor of the basin. In these cases applications indicate that it is appropriate to evaluate the average submergence as two-thirds of the average maximum penetration depth.

C_s for a particular stilling basin and operating condition is evaluated by summing the two-thirds depth with the barometric pressure to obtain the average absolute pressure on the flow. This average pressure is then used to adjust the standard atmospheric pressure saturation concentration, as presented by Weiss (1970), for the particular gas of interest and the particular water temperature. The saturation concentration is directly proportional to the absolute pressure on the water. This pressure adjusted saturation concentration is C_s.

The next parameter from Eq. 4 to be considered is t, the length of time that the flow with entrained air is under pressure in the stilling basin, and thus the length of time over which substantial quantities of gas are being dissolved into the flow. t may be limited either by the basin geometry or by the characteristics of the inflowing jet. A basin that is substantially smaller than a free dissipation pool or a free hydraulic jump basin or a basin that has excessive or oversized energy dissipation baffle piers will prematurely force the air-water flow to the surface. The result would be a substantial reduction in the value of t from the value that corresponds to a free dissipation of the jet. However, it appears that in most cases, basins are sized for a large maximum discharge and are designed for a relatively unforced energy dissipation. Consequently, in most cases the value of t is

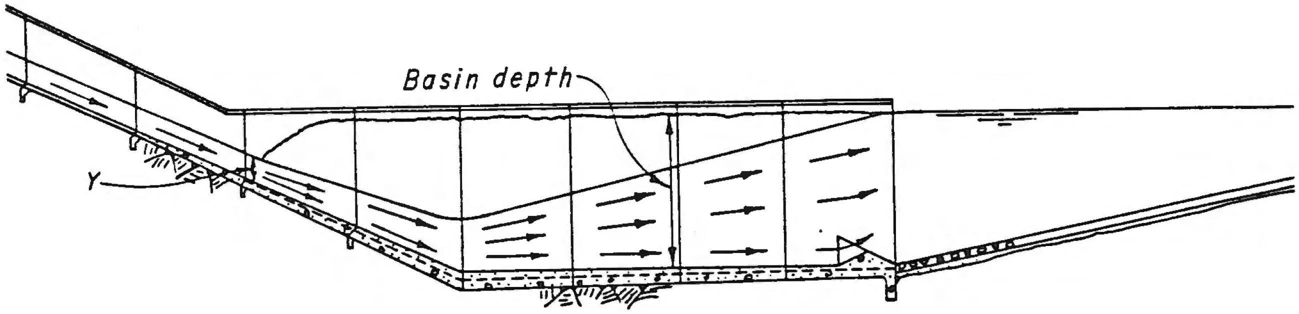

Fig. 1: Typical stilling basin flow.

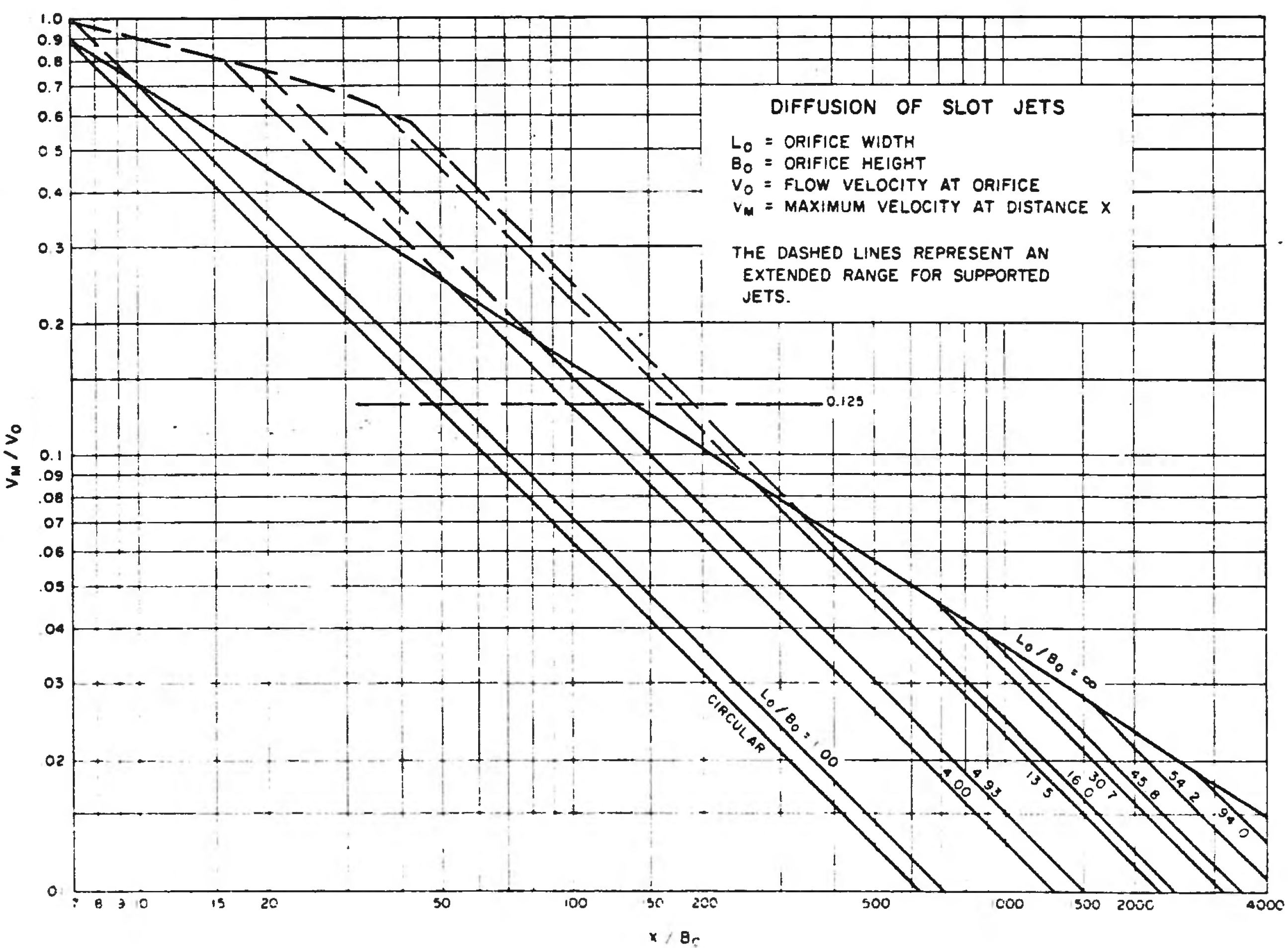

Fig. 2: Diffusion of slot jets.

limited by the characteristics of the inflowing jet. Parameter analysis indicates that the term YV, where Y is the vertical thickness of the jet (jet thickness/cosine of angle of penetration), and V is the average jet velocity; is representative of the jet's potential submergence time. The term YV will be referred to as t* throughout the remainder of this report. It should be noted that the term YV parallels the jet diffusion findings of Yevjevich (1965) and Henry (1950), Fig. 2, which show the path length to be a function of the initial jet velocity and the initial jet thickness and width. In general, the term t* is used in this analysis as a representative evaluation of t. It is noted that this is not an exact evaluation, and that correction coefficients are included in a multiplier (0.04) and in the K value used in the Kt exponent. This is discussed in more detail later in the analysis and in the example application. Note that this evaluation of t has the dimensions length^2/time. For this analysis, the dimensions ft^2/s should be used.

The remaining term to be evaluated in Eq. 4 is K, the gas transfer coefficient. K depends only on the hydraulic action in the basin. Attempts to find a predictive procedure that could be used to evaluate K resulted in the curves shown on Fig. 3. To obtain these curves, the field data were manipulated into various parameters until the desired results were found. From Fig. 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; it relates the amount of energy in the flow to the path length over which the energy is dissipated. 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 value of X obtained from Fig. 2 for the appropriate initial jet conditions and for a Vm/Vo value of 0.125. The 0.125 path length was selected because field data indicated that it yields K prediction that is consistent from structure to structure. 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. For complex jet and basin geometry shapes evaluation of the shear perimeter is a judgment factor and is probably best handled by individual consideration. 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.

It should be noted that the analysis, as it has been developed, is largely empirical. Prototype data were used extensively to evaluate the coefficients that were 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. Any analysis of these flow conditions would be quite involved and the resulting accuracy would be questionable. Consequently, the terms C_s, t*, and K were

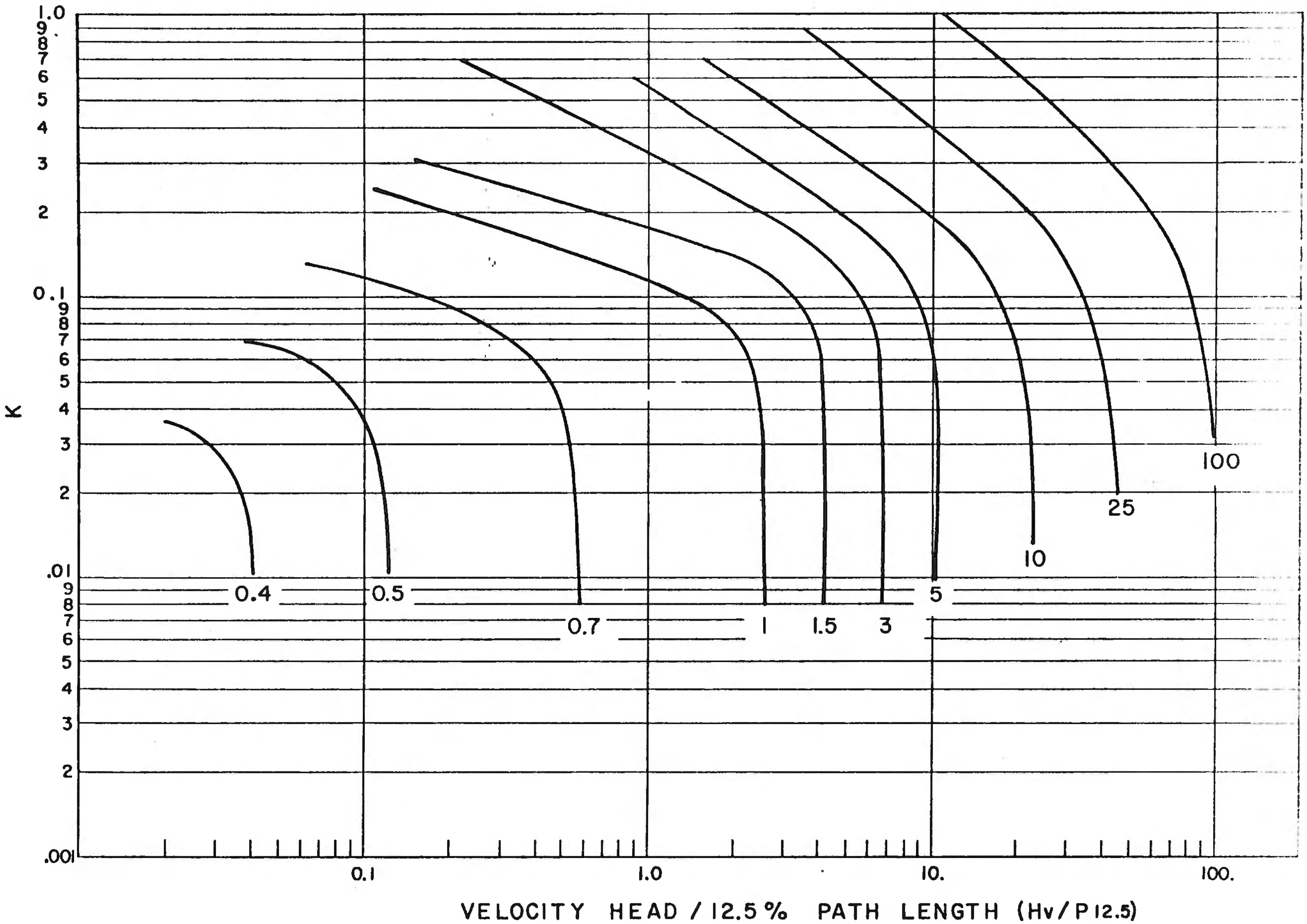

Fig. 3: K prediction curves.

evaluated as bulk descriptive parameters for the specific energy dissipation structure and for the specific operating condition. It is recognized that this evaluation of these parameters is substantially different than the conventional. Comparison to other gas transfer analyses and coefficients is thus limited. It is intended that in the future, work will be done to further refine these terms. However, it should be noted that the present coefficients do have a rational basis and are representative of, and do give, insight into the significance of the physical parameters.

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, releases were exposed only briefly to the air and free air entrainment either into the jet or the stilling basin flow was minimal. And yet, in some instances, these structures were among the worst in creating supersaturated conditions. Therefore, it should be assumed that if any air is entrained by the operating structure, the quantity of air will not be a limiting factor with respect to the dissolved gas levels created.

EXAMPLE APPLICATION

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 (C_I) = 14.85 mg/l

Also, the information in Fig. 4 is known. In addition, initial observations yield:

Available head (H_v) = 319 feet
Initial velocity = 143.3 ft/s
Angle of penetration = 51°
Flow width (L_o) = 450 feet
Basin depth = 85 feet

All of the above are straightforward evaluations except for path length. H_v is the difference between reservoir and tailwater surface elevations and assumes no losses. The initial velocity is a conversion of the velocity head H_v into a velocity. The angle of penetration and the flow width are dictated by the orientation of the spillway invert and the gate widths, respectively.

C_s for nitrogen, the basin's potential dissolved nitrogen saturation concentration is found as:

$$C_s = \frac{[734 \text{ mm Hg} + \frac{2}{3}(85 \text{ ft } H_2O)\ (304.8 \text{ mm/ft})/(13.55 \text{ mm } H_2O/\text{mm Hg})]\ (13.98 \text{ mg/l/atmosphere})}{760 \text{ mm Hg/atmosphere}}$$

$$= 36.95 \text{ mg/l}$$

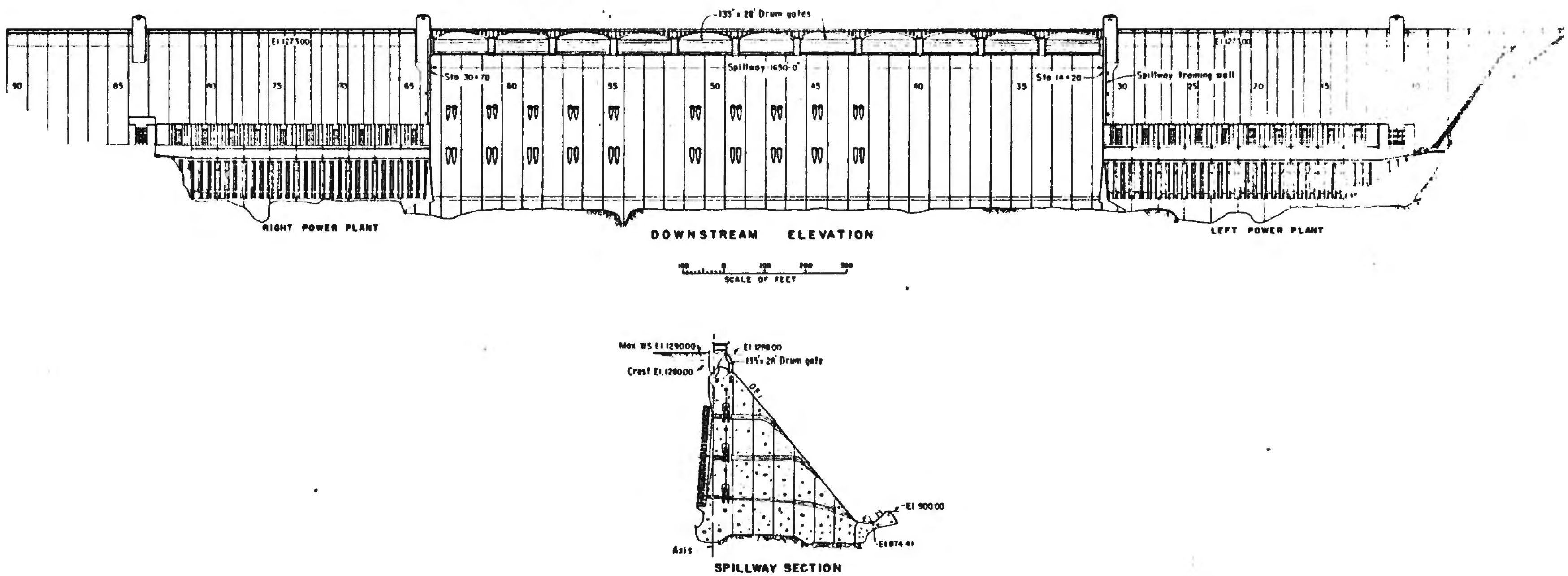

Fig. 4: Grand Coulee Dam.

To evaluate t

Flow cross sectional area = 89.32 ft^2
B_o = 89.32 ft^2/450 ft = 0.198 foot
Y = 0.198 ft/cos 51° = 0.315 foot
$t^* = YV = (0.315\text{ ft})(143.3\text{ ft/s}) = 45.1\text{ ft}^2/\text{s}$

To evaluate K

$Lo/Bo = 450\text{ ft}/0.198\text{ ft} = 2273$
$P_{0.125} = (190)(Bo) = (190)(0.198\text{ ft}) = 37.6\text{ ft}$
$H_v/P = 319\text{ ft}/37.6\text{ ft} = 8.48$

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

K = 0.11 from Fig. 3

Substitution in Eq. 4 then yields:

$$C(t) = 36.95 + (14.85-36.95)e^{-(0.04)(45.1)(0.11)} = 18.83\text{ mg/l } N_2$$

$$\frac{18.83\text{ mg/l}}{13.98\text{ mg/l}} = 135\text{ percent} = \text{resulting dissolved nitrogen saturation percentage}$$

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