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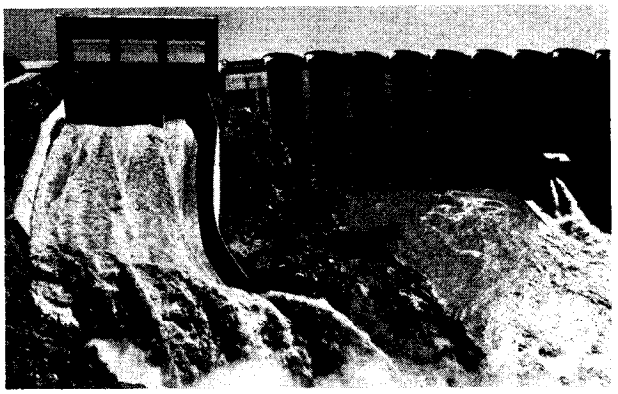

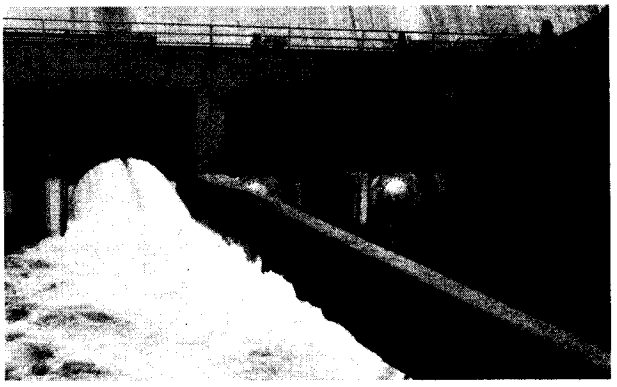

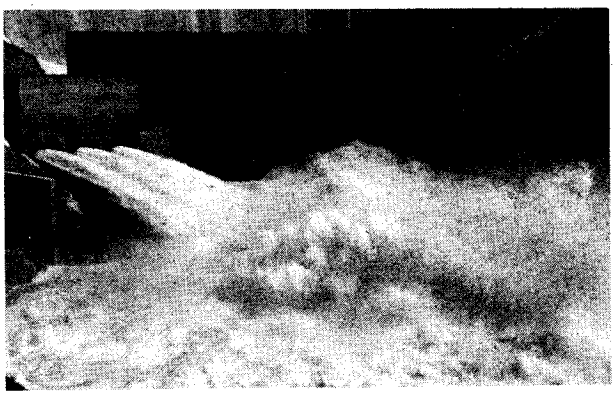

AIR-WATER FLOW IN HYDRAULIC STRUCTURES

UNITED STATES DEPARTMENT OF THE INTERIOR

WATER AND POWER RESOURCES SERVICE

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16. ABSTRACT

The purpose of this report is to summarize the work that has been completed on air-entrainment and air-demand in both open- and closed-conduit flows. The intent was to produce a concise reference source from which design manuals, monographs, and charts for specific applications could be prepared. Areas that need additional research have been identified. The report was prepared from available reference material. In several areas, data from several references have been combined to produce generalized curves. Includes 64 figs., 74 ref,. 3 app., and 155 pp.

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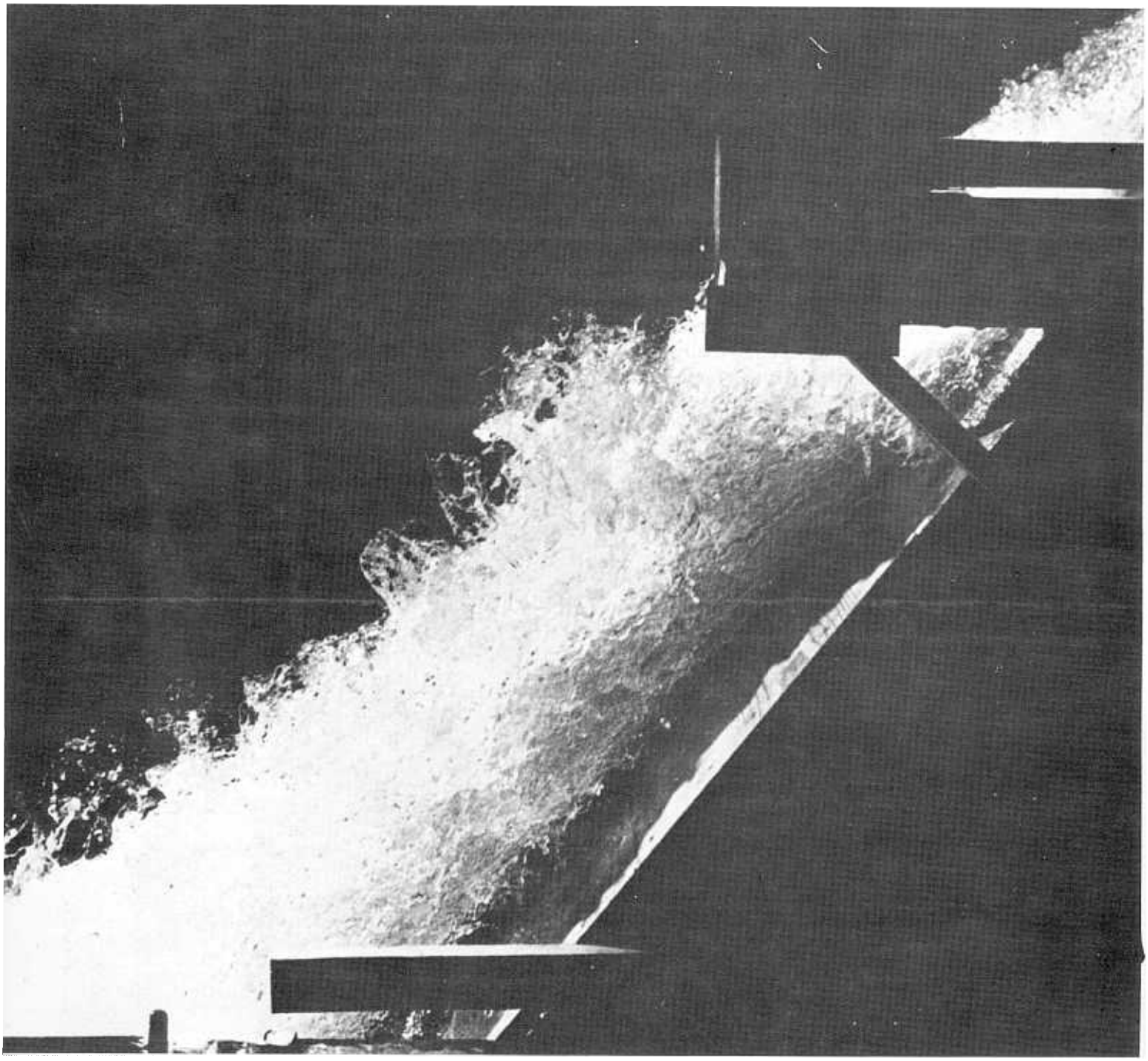

FRONTISPIECE.—*High velocity jet from a slide gate. P801-D-79275*

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Preface

The material assembled in this report is the result of studies extending over many years by a large number of engineers. Ellis Picket at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi, supplied a reference list dealing with air-water problems. Personnel of the Water and Power Resources Service E&R Center, Water Conveyance Branch made their files and drawing on air design criteria in pipelines available for publication in this report. Prior to publication, the report was reviewed by Ellis Pickett and Ted Albrecht with the U.S. Army Engineers; and by engineers in the Dams, Mechanical, and Water Conveyance Branches, E&R Center, Water and Power Resources Service. The many constructive comments by these individuals and the assistance of Richard Walters who provided continuity and technical editing is greatly appreciated.

Letter Symbols and Quantities

Symbol	Quantity
A	Cross sectional area of water prism
A_a	Cross sectional area of airflow passage
A_c	Cross sectional area of air core in a vertical shaft
A_d	Cross sectional area of conduit
A_o	Orifice area
A_p	Cross sectional area of penstock
A_v	Cross sectional area of vent
a	Ratio of bubble terminal velocity in turbulent flow to terminal velocity in still water
a_0	Mean air distribution function
a_1	Mean air distribution constant
B	Width of rectangular chute
b	Width of flow channel
b_n	Nappe width
b_s	Empirical coefficient accounting for sand grain roughness
C	Air concentration
C_a	Actual air concentration
C_b	Drag coefficient on a bubble
C_d	Discharge coefficient based on 100 percent gate opening
C_f	Local loss coefficient
C_l	Air concentration at $d_t/2$
C_m	Air concentration measured by a pitot tube sampler
C_o	Orifice discharge coefficient
C_s	Drag coefficient on a sphere
C_t	Air concentration at the bottom of the mixing zone
$\overline{C}$	Mean air concentration
c	Waterhammer wave celerity
D	Conduit diameter
D_b	Smaller dimension of a rectangular conduit
D_d	Diameter of water drop
D_e	Equivalent bubble diameter
D_s	Larger dimension of a rectangular conduit
d	Flow depth
d_b	Bulked flow depth
d_e	Deflector height
d_n	Nappe thickness
d_o	Orifice diameter
d_t	Total depth of underlying and air free zones
d_{95}	Bubble diameter for which 95 percent of the air, by volume, is contained in bubbles of this diameter or smaller
E	Relative width of the frequency spectrum
exp	Napierian logarithm equal to 2.71828, approximately
f	Darcy-Weisbach friction factor
G	Gate opening
G_g	Mass velocity of gas
G_l	Mass velocity of liquid
g	Gravitational constant (acceleration)
H	Hydraulic radius of prototype air vent
H_f	Fall height of a water jet
H_m	Head across orifice
H_n	Net head across turbine
H_o	Distance from channel invert to energy grade line
H_t	Total potential and kinetic energy
h	Mean wave height
h_a	Height of airflow passage
h_f	Distance from inlet to the water level in the vertical shaft
h_l	Head loss per unit length
h_m	Head across manometer
h_w	Allowable head rise in penstock
K_e	Entrance loss
K_s	Singular (form) loss
k	Von Karman universal constant equal to 0.4
k_r	Coefficient of roughness
k_s	Sand grain roughness

LETTER SYMBOLS and QUANTITIES—Continued

Symbol	Quantity
L	Length of conduit or vent
L_c	Distance to start of self-aeration
L_r	Prototype to model scale ratio
L_s	Distance between stiffener rings
M	Unit mass
M_o	Maximum difference in elevation between a wave crest and the mean water level
m	Air concentration distribution coefficient
N	Safety factor
n	Manning's roughness coefficient
n_v	Velocity distribution power-law coefficient
P	Energy dissipated
P_g	Normal distribution function
P_h	Probability that the wave height is equal to given height
P_w	Probability that the water surface is equal to or greater than the given elevation
p	Pressure intensity
p_a	Allowable internal pressure
p_{atm}	Atmospheric pressure
p_c	Collapse pressure
p_{in}	Internal pressure
p_n	Nappe perimeter
Q	Discharge
Q_a	Volume flowrate of air
Q_c	Critical discharge
Q_r	Discharge from reservoir
Q_w	Volume flowrate of water
q	Unit discharge
q_a	Insufflation rate of air per unit surface area
R	Bubble radius
R_b	Equivalent bubble radius
R_c	Radius of curvature of the bubble cap
R_j	Thickness of annular jet
r	Water jet radius
r_s	Relative roughness of conduit (rugosity to diameter ratio)
S	Submergence depth
S_o	Pipe slope
S_f	Slope of energy grade line
s	Root-mean-square value of wave height distribution
s_w	Root-mean-square value of water surface distribution
T	Top width of flow passage
t	Pipe wall thickness
U	Free stream velocity
U_d	Velocity of water drop relative to air velocity
U_j	Water jet velocity
u	Local air velocity
V	Mean flow velocity
V_f	Terminal velocity of bubbles in turbulent flow
V_i	Nappe velocity at impact
V_m	Minimum velocity required to entrain air
V_o	Maximum water surface velocity
V_s	Terminal velocity of bubbles in slug flow
V_t	Terminal velocity of bubbles in still water
W	Wetted perimeter
x	Distance from start of boundary layer growth
y	Distance normal to channel bottom (flow depth)
y_a	Distance from water surface
y_c	Conjugate depth
y_e	Effective depth
y_k	Critical depth
y'	Normal distance to the bottom of the mixing zone
z	Elevation

LETTER SYMBOLS and QUANTITIES—Continued

Symbol		Quantity
α	alpha	Angle chute invert makes with horizontal
β	beta	Ratio of volumetric airflow rate to waterflow rate
γ	gamma	Specific force of water
δ	delta	Boundary layer thickness
ϵ	epsilon	Mass transfer coefficient of bubbles
ζ	zeta	Air concentration distribution constant
η	eta	Normalized wave height
θ	theta	Void fraction
$\varkappa$	kappa	Gas constant
λ	lambda	Density ratio
μ	mu	Dynamic viscosity
μ_a		Dynamic viscosity of air
μ_w		Dynamic viscosity of water
ν	nu	Kinematic viscosity
ν_f		Water viscosity
π	pi	Ratio of the circumference of any circle to its radius, 3.14159...
ϱ	rho	Density
ϱ_a		Air density
ϱ_w		Water density
ϱ_g		Gas density
ϱ_l		Liquid density
ϱ_m		Density of manometer fluid
σ	sigma	Interfacial surface tension
τ_o	tau	Wall shear stress
τ_j		Shear stress at water jet
υ_{atm}	upsilon	Specific volume of air at atmospheric pressure
υ_*		Shear velocity
ψ	psi	Multicomponent flow parameter
ω	omega	Volume of gas bubble
ω_a		Volume of air
ω_w		Volume of water
∞		Infinity

Symbol	Quantity		
E	Eötvös number	=	$\frac{\gamma D^2}{\sigma}$
E_u	Euler number	=	$\frac{\Delta p}{\varrho V^2}$
F	Froude number	=	$\frac{V}{(gD)^{1/2}}$
P	Prandtl velocity ratio	=	$\frac{V}{(\tau_o/\varrho)^{1/2}}$
P_o	Poiseuille number	=	$\frac{h_a^2\,(dp/dx)}{2\,\mu V}$
R	Reynolds number	=	$\frac{VD}{\nu}$
R_x	Distance Reynolds number	=	$\frac{Vx}{\nu}$
W	Weber number	=	$\frac{V}{(\sigma/\varrho D)^{1/2}}$

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FIGURES—Continued

APPENDIX

Introduction

In many engineering projects a strong interaction developes between the water flowing through a structure and the air which is adjacent to the moving water. Sometimes the interaction produces beneficial effects. However, more often than not, the effects are not beneficial and the remedial action required to reduce the effects can be costly.

Cases in which air-water interaction develop include:

- Open channels with fast flowing water that require depths adequate to contain the air which is entrained within the water
- Morning-glory spillways that must have a capacity to convey the design flood and its entrained air
- Vertical shafts that entrain large quantities of air at small water discharges
- Measuring weirs that need adequate ventilation to prevent false readings and to eliminate surging
- Outlet gates that require adequate aeration to prevent the development of low pressures—which can lead to cavitation damage
- Emergency gates at penstock entrances that require ventilation to prevent excessive negative internal pressures during draining or emergency gate closures
- Sag pipes (inverted siphons)[1] that can be damaged due to blowback of entrained air
- Long pipelines that require air release and vacuum relief valves

From these cases it is noted that air-water flows can be generalized into three basic flow types:

1. Air-water flows in open channels,
2. Air-water flows in closed conduits, and
3. Free-fall water flows.

The first type usually is called *air-entraining* flow because air is entrained into the water mass. The second basic flow type generally is referred to as *air-demand*. The term *air-demand* is both misleading and technically incorrect, since an air vent does not demand air any more than an open valve demands water. However, since the term has been in common use for over 20 years, efforts to improve the nomenclature seem rather futile. The third type is referred also to as *air-entraining flow*.

[1] "siphon, inverted—A pipe line crossing over a depression or under a highway, railroad, canal, etc. The term is common but inappropriate, as no siphonic action is involved. The suggested term, *sag pipe*, is very expressive and appropriate." *Nomenclature for Hydraulics*, Comm. on Hyd. Str., Hyd. Div., ASCE, 1962.

Purpose and Application

The purpose of this report is to summarize the work that has been done on *air-entrainment* and *air-demand* regarding the most recent theories and to suggest ways in which the results can be applied to design. The intent was to produce a concise reference of material from which design manuals, nomographs, and charts for specific applications could be prepared.

Although many generalizations of the data can be made, some types of flow conditions that are encountered in practice can be treated only by individual studies with physical models. These cases are identified when they occur.

Additional studies are needed in many areas. Some of the most critical areas requiring further research include the following:

- Effects of turbulence and air concentration on bubble dynamics
- Fluid dynamics in the developing aeration regime of free-surface flow
- Effects of hydraulic and conduit properties on probabilistic description of water surface in free-surface, high-velocity flow
- Effect of pressure gradients on air flow in partially-filled, closed conduits
- Bubble motion in closed-conduit flows for conduit slopes exceeding 45-degrees
- Effects of ambient pressure levels on cavitation characteristics of gates and valves discharging into a closed conduit
- Interaction between the air and a free jet

Summary and Conclusions

Methods have been developed to predict the mean air concentration and the concentration distribution with open channel flow. A new description of the free water surface in high velocity flow is proposed which more accurately represents actual conditions in high velocity flow. The effect of air entrainment on the performance of a stilling basin can be estimated using a bulked flow concept. A computer program (app. II) is presented with which the mean air concentration in steep chutes and spillways can be estimated.

With exception of a falling-water surface and decreasing flow in pipelines, closed conduit flows require model studies. When properly conducted and analyzed, model studies will yield accurate data for estimating air-flow rates. Experimental methods are discussed. A computer program (app. III) is presented which can be used to predict the airflow rate with a falling-water surface. Design charts are presented for sizing air relief valves and vacuum valves on pipelines.

The airflow rate in vertical shafts was found to be extremely dependent upon the flow conditions at the shaft inlet. Equations are included for estimating the airflow rate having various inlet conditions.

Factors influencing the airflow rate around free falling jets are discussed. This area is identified as one needing additional research. Equations are presented from which the air entraining characteristics of a jet entering a pool can be estimated.

Open Channel Flow

INTRODUCTION

In observing flow in a chute or on an overflow spillway, one normally observes a region of clear water where the water enters the chute or spillway. Then—at some distance downstream—the water suddenly takes on a milky apperance. Lane [46] suggested that the "white water" begins when the turbulent boundary layer from the floor intersects the water surface. The validity of this assumption has been verified by many researchers. The cases in which the boundary layer creates the air entrainment are referred normally to as *self-aerated* flows. However, this is not the only way in which air entrainment can begin on chutes and spillways. The American Society of Civil Engineers Task Committee on Air Entrainment in Open Channels [5][2] has summarized tests in which air entrainment is generated by the boundary layer on the side walls of chutes. They also reported tests in which air entrainment was observed downstream of piers on overflow spillways. This latter case is the result of the flow rolling over on itself as it expands after passing through the opening between the piers. Levi [49] reported on longitudinal vortices on spillway faces. These vortices can entrain air if they intersect the water surface. All of these forms of air entrainment are apparent in figure 1.

Air entrainment implies a process by which air enters into a body of water. Normally, the appearance of "white water" is considered to be synonmous with entrainment. This is not always true. For instance, if the water surface is rough enough and moving at a sufficiently high velocity, the surface will appear to be white even though the water volume contains no air. The whiteness of the water is caused by the large number of reflections coming from different angles off the rapidly moving highly irregular surface (refer to frontispiece). For high water velocities, one's eye does not respond rapidly enough to observe each individual reflection. Instead, these individual reflections blur into a fuzzy mass which appears white. High speed photography of "white water" demonstrates this effect very well. This leads one to the obvious conclusion that a flow could conceivably appear frothy but actually does not entrain any air! With air in the water, reflections also come from the surface of the bubbles. These reflections produce the same impression

[2]Numbers in brackets refer to the bibliography.

of "white water" as the water surface reflections.

Experiments have shown that flow in channels with mild slopes do not entrain air even though the boundary layer intersects the water surface. Thus, some degree of turbulence must be exceeded for the entrainment process to begin.

The turbulence causes the water surface to become irregular enough to trap bubbles of air. These bubbles of air are then diffused downward into the body of water if the vertical water velocities induced by the turbulence in the flow are larger than the terminal velocities of the bubbles. The *terminal velocity* V_t of a bubble is defined as the rate of rise of a bubble in a liquid in which the effects of turbulence, walls, other bubbles, and acceleration are negligible. The interaction of the terminal velocities of bubbles and the turbulence are considered in the following section.

BUBBLE DYNAMICS

Terminal Velocity of a Single Bubble in Still Water.

In still water, surface tension is the predominant effect on the shape of very small bubbles. Therefore, small bubbles tend to be perfect spheres. The motion of these bubbles through a fluid can be described by a balance between the buoyant forces and the viscous forces. However, as the bubbles become larger, surface tension effects become small with respect to shear forces. The shape of these larger bubbles can be approximated by a spherical cap having an included angle of about 100 degrees and an unstable relatively flat base (fig. 2). Because different effects predominate at different bubble diameters, one can expect the correlation between the bubble size and its terminal velocity to vary as the bubble diameter varies. Haberman and Morton [26] have experimentally determined the terminal velocity as a function of the bubble size (fig. 3).

Assuming the bubble to be a rigid sphere, the terminal velocity V_t of small bubbles can be written as

$$V_t=\frac{2}{9}\left\{\frac{R^2g\,[1-(\varrho_g/\varrho_w)]}{\nu_f}\right\} \tag{1}$$

where

g = gravitational constant (acceleration), 9.81 m/s^2
R = bubble radius, mm
ν_f = water kinematic viscosity, 1.5×10^{-6} m^2/s at 10 °C
ϱ_w = water density, 1000 kg/m^3 at 10 °C
ϱ_g = air density, 1.29 kg/m^3 at 10 °C

This also is known as Stokes' solution.[3] Substituting the respective values for air, water, and gravity into equation 1 gives the terminal velocity of a small air bubble in meters per second as

$$V_t=1.45\,R^2 \tag{2}$$

Theoretically, this relation is valid only for bubble radii R smaller than 0.068 mm.

For bubble radii between 0.068 and 0.40 mm, the empirical relation

$$V_t=0.625\,R^2 \tag{3}$$

fits the data.

With bubble radii between 0.40 and 10 mm, the terminal velocity is about equal to 0.25 m/s. As the bubble diameter increases from 0.4 to

[3]G.G. Stokes was the first investigator to analytically determine the drag on a slowly moving sphere in a viscous fluid falling as a result of its mass relative to the fluid mass.

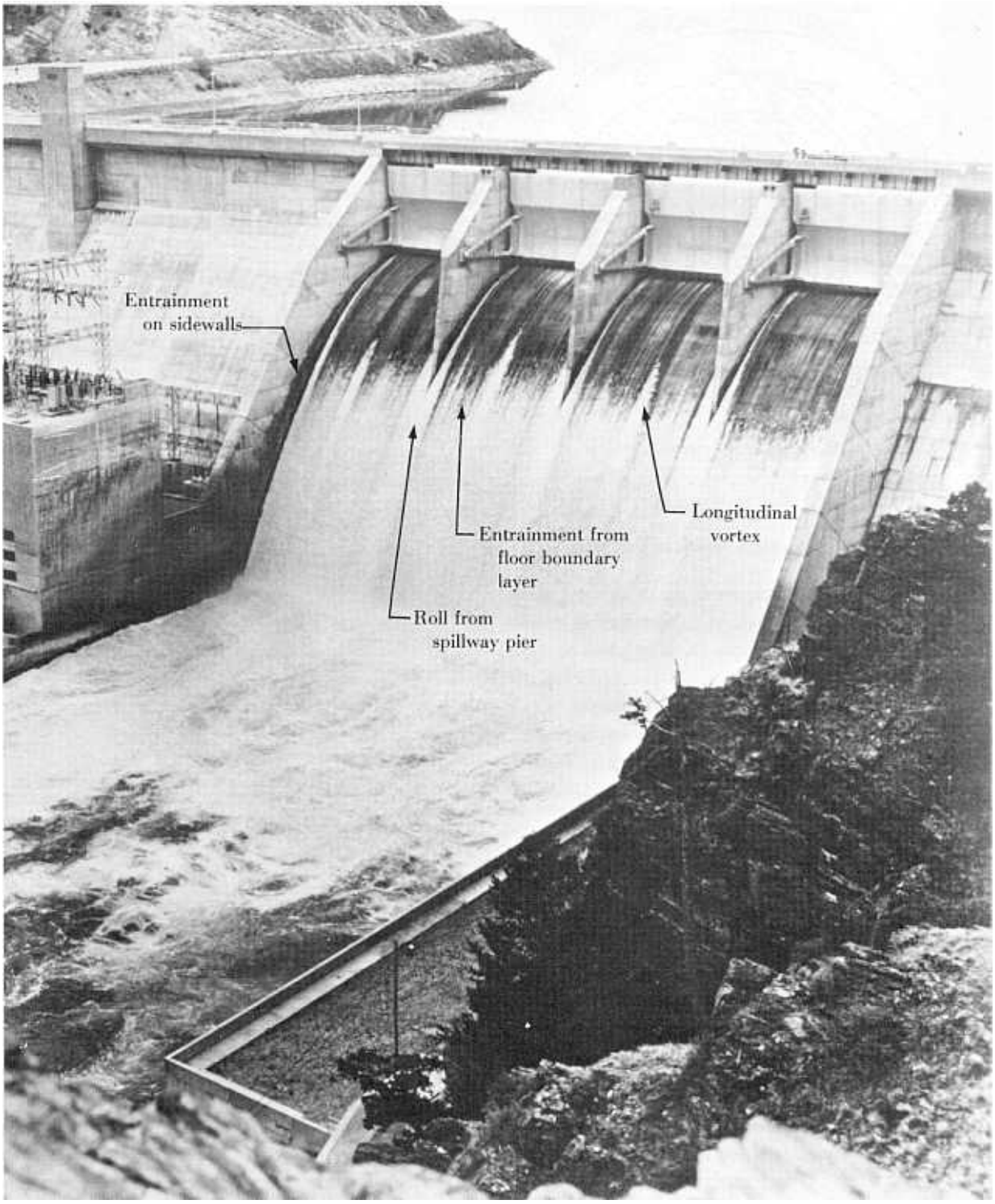


FIGURE 1.—*Forms of air entrainment on a spillway*—Canyon Ferry Dam, Montana. *P801-D-79276*

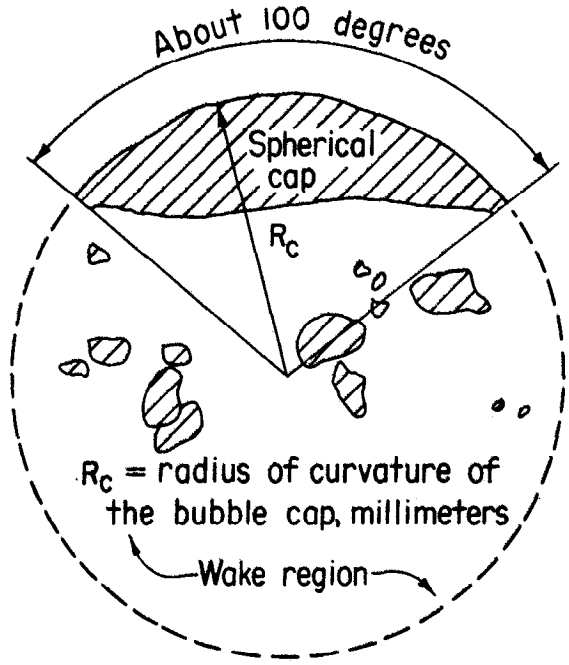


FIGURE 2.—*Large gas bubble in a liquid.*

10 mm, its form changes from a sphere to a spherical segment. When the diameter is about 2 mm, an instability in the bubble path can be observed. This instability gives the bubbles an irregular or spiral trajectory. Comolet [17] argues that in this region both buoyant and surface tension forces are significant with respect to inertial forces, and proposes the equation

$$V_t=\left(1.04\, gR_b+\frac{1.07\sigma}{\varrho_w R_b}\right)^{1/2}, m/s \qquad (4)$$

where

R_b = the radius of a sphere whose volume equals the volume of the gas bubble, mm

$$=\left(\frac{3\omega}{4\pi}\right)^{1/3}$$

g = gravitational constant = 9.81 m/s²

σ = interfacial surface tension

σ = 0.0728 N/m for air-water

ϱ_w = water density = 988 kg/m³

ω = volume of gas bubble, mm³

Using the above values for various constants gives

$$V_t=[0.01R_b+(0.079/R_b)]^{1/2} \qquad (5)$$

For bubbles larger than 10 mm, the terminal velocity is only a function of the ratio between the buoyant and inertial forces. Davies and Taylor [18] show the terminal velocity is

$$V_t=\frac{2}{3}(gR_c)^{1/2} \qquad (6)$$

where R_c is the radius of curvature of the bubble cap.

Using this relation and the spherical segment geometry of figure 2, the terminal velocity in terms of an equivalent radius can be shown to be equal to

$$V_t=(gR_b)^{1/2} \qquad (7)$$

or

$$V_t=0.10\,R_b^{1/2} \qquad (8)$$

for R_b in millimeters and V_t in meters per second.

This equation approaches Comolet's relation (eq. 4) asymptotically when the bubble radius becomes large.

Bubble Size in Shear Flows

The mean bubble size in flowing water or in mechanically agitated systems is determined primarily by the shearing stresses within the fluid. This effect can be visualized by examining the two extreme conditions. Assume that very small bubbles are introduced into a turbulent flow. As the bubbles rise, they tend to form into a mass or agglomerate because of entrainment in each other's wake. As the individual bubbles touch they coalesce to form a

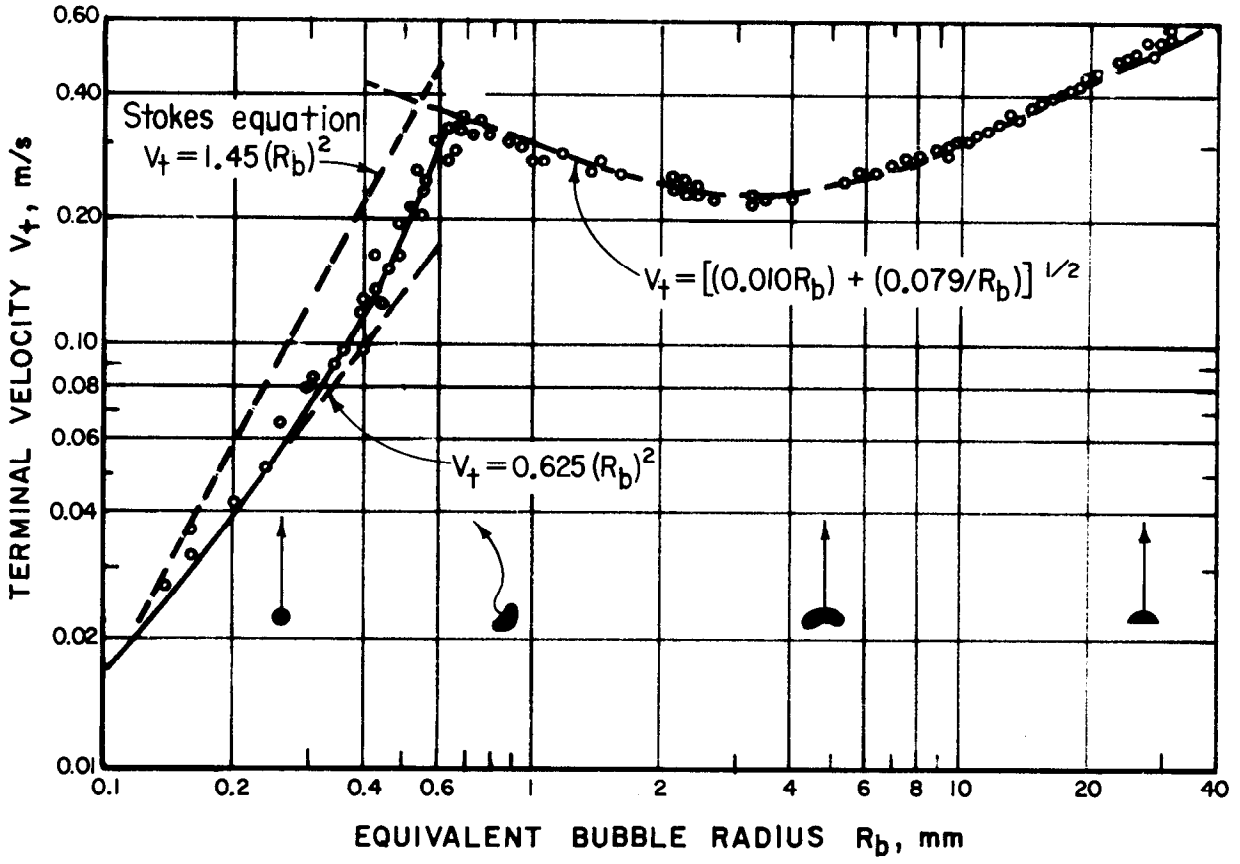


FIGURE 3.—*Terminal velocity of air bubbles in filtered or distilled water as a function of bubble size, Haberman and Morton [26].*

larger bubble. This process continues until larger and larger bubbles are formed.

At the other extreme, assume that a very large bubble is introduced into a turbulent flow. The turbulence of the flow field introduces shear stresses which tends to tear or fracture the bubble into smaller and smaller bubbles.

Due to the simultaneous action of agglomeration and fracture, it can be inferred that some critical bubble size is reached which represents a balance between surface tension forces and fluid stresses. This relation is expressed through a suitably defined Weber number W. The only equation available for estimating the critical bubble size was developed by Hinze [35]. The equation is

$$d_{95} = 0.725 \left[\left(\frac{\sigma}{\varrho_w}\right)^3 \left(\frac{M}{P}\right)^2\right]^{1/5} \tag{9}$$

where

d_{95} = bubble diameter for which 95 percent of the air, by volume, is contained in bubbles of this diameter or smaller

P/M = rate of energy dissipation per unit mass

ϱ_w = fluid density

σ = interfacial surface tension

The rate of energy dissipation per unit mass for flow in pipes can be estimated in the following manner; Rouse [59] showed that the rate of energy dissipation in a length of conduit L is given by

$$P=Q\gamma h_l \tag{10}$$

where

Q=discharge
h_l=head loss through a length of conduit L
γ=specific force of fluid

The unit mass is given by

$$M=\varrho_w AL=\frac{\varrho_f Q L}{V} \tag{11}$$

where

A=cross sectional area of conduit
V=mean flow velocity

Therefore, for flow in conduits, the rate of energy dissipation per unit mass is given by

$$\frac{P}{M}=\frac{gh_lV}{L}=gS_fV \tag{12}$$

where S_f=slope of energy grade line=h_l/L

Substitution of the rate of energy dissipation per unit mass of equation 12, into 9 gives

$$d_{95}=0.725\left[\left(\frac{\sigma}{\varrho_w}\right)^3\left(\frac{1}{gS_fV}\right)^2\right]^{1/5} \tag{13}$$

In dimensionless terms equation 13 can be written as

$$\frac{d_{95}}{D}=0.658\left[\left(\frac{\sigma}{\gamma D^2}\right)^3\left(\frac{D^5g}{Q^2}\right)\left(\frac{1}{S_f}\right)^2\right]^{1/5} \tag{14}$$

where D=conduit diameter

The first dimensionless ratio $\gamma D^2/\sigma$ is known as the Bond, Eotvös or Laplace number. The second ratio D^5g/Q^2 is another form of the Froude number $V/(gD)^{1/2}$. Additional information concerning the mean concentration distribution of the bubbles and the direction of their motion in nonhorizontal flows can be found in this chapter (Design Parameters —*Air distribution in the mixing zone*) and in the following chapter (Flow in Partially Filled Conduits—Analytic Estimates).

Terminal Velocity of Bubbles in Turbulent Flow

Even though a bubble diameter can be determined for turbulent flow from equation 14, the terminal velocity of these bubbles cannot be determined simply from figure 3. The figure can be used only to estimate the terminal velocity of single bubbles in still water. Both turbulence and the presence of other bubbles modify the terminal velocity shown on figure 3.

As with sediment particles, turbulence tends to keep the air bubbles in suspension. Thus, the effect of turbulence is to reduce the terminal velocity of the bubbles. If V_t is the terminal velocity of bubbles in still water, then V_f is the terminal velocity in a turbulent flow. Their relation can be expressed as

$$V_f=aV_t \tag{15}$$

where a is an empirically determined variable.

Haindl [28] determined the relation between the variable a and a form of the Froude number F applicable to annular jumps. By making appropriate assumptions, the Froude numbers were converted to equivalent quantities of the dimensionless discharge parameter. The relation between the variable a and the dimensionless discharge parameter is given on figure 4.

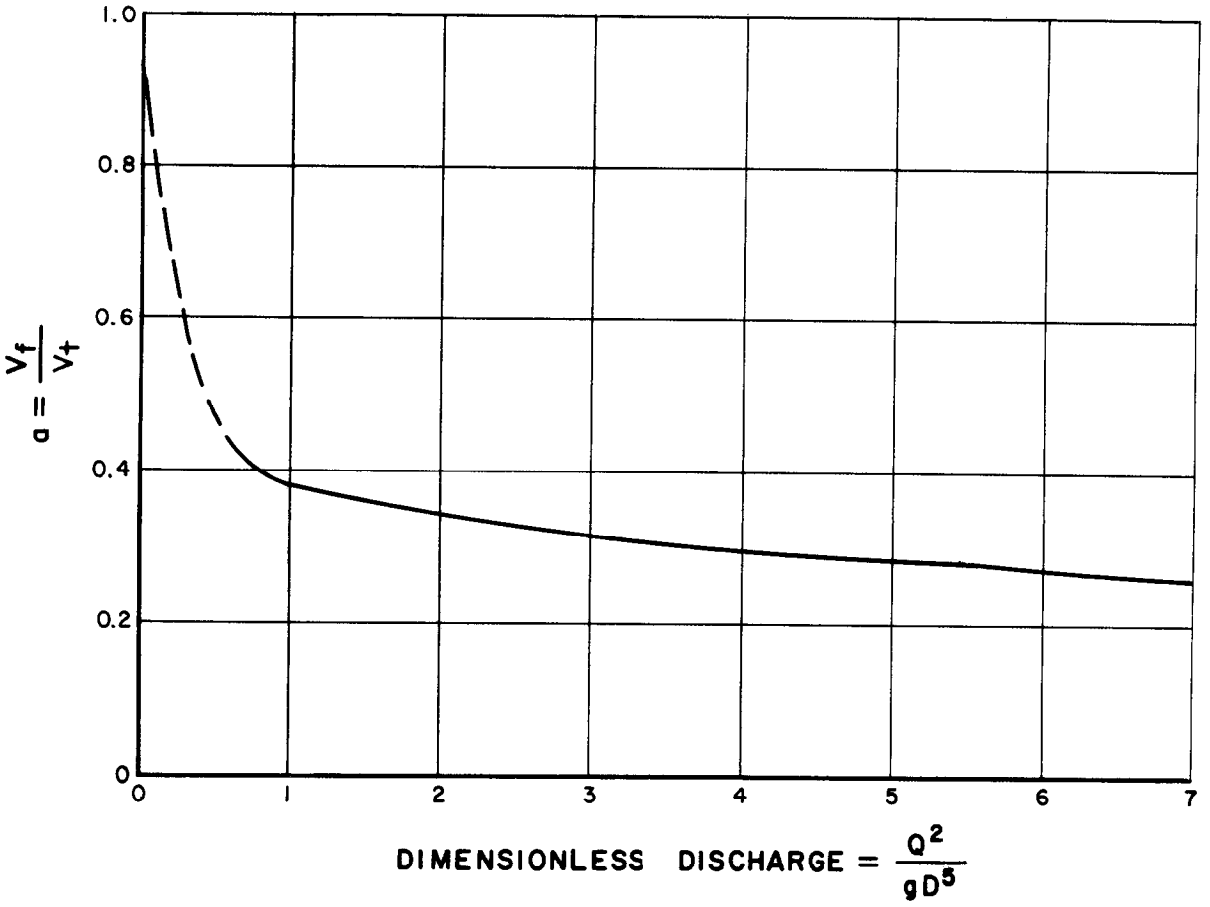


FIGURE 4.—*Terminal velocity of bubbles in turbulent flow.*

The effect of turbulence on the bubbles can be visualized by considering the buoyant and the turbulent diffusion forces acting on the bubbles. The bubbles tend to move upward because of buoyancy. Whereas turbulence tends to move bubbles from areas of high concentration into areas of low concentration. The balance between mass flow rates caused by these two forces is given—normal to the channel bed by

$$CV_f = \varepsilon \frac{dC}{dy} \tag{16}$$

where

C = local air concentration
V_f = terminal velocity of bubbles in turbulent flow
y = vertical direction
ε = mass transfer coefficient of bubbles

If a functional relation could be obtained for V_f and ε, then the air concentration as a function of depth could be determined.

References could not be found that indicate the magnitude of the effect of air concentration on the terminal velocity of a bubble. Further

research into the effects of turbulence and air concentration on air bubble dynamics definitely is needed.

VERTICAL AND LONGITUDINAL FLOW STRUCTURE

The vertical structure of the flow in open channels with highly turbulent flows can be divided into four zones, Killen [41] and Killen and Anderson ([42], fig. 5). These are:

1. An upper zone of flying drops of water,
2. A mixing zone where the water surface is continuous,
3. An underlying zone where air bubbles are diffused within the water body, and
4. An air free zone.

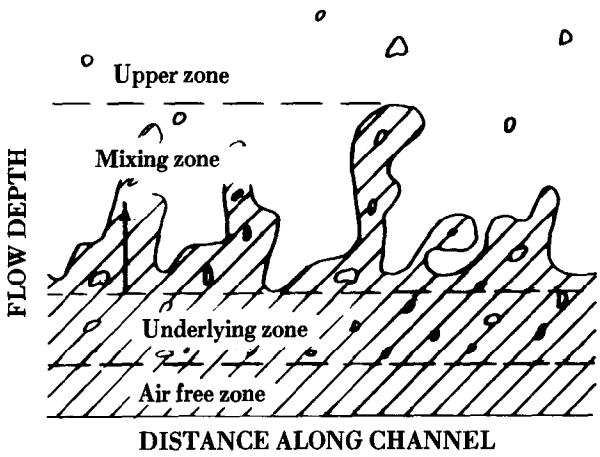


FIGURE 5.—*Structure of open channel flow, Killen and Anderson [42].*

The *upper zone* consists of water particles that have been ejected from the mixing zone. These particles can rise a considerable distance above the mean water surface. Normally, this region is neglected in engineering considerations since its mass is small.

The *mixing zone* consists of a region of surface waves having random amplitudes and frequencies. A knowledge of the characteristics in the mixing zone is extremely important since all air ingested into the main body of the water or released from the flow must pass through this zone. Also, the maximum wave heights that occur in the mixing zone determine the height of the open channel sidewalls if overtopping is to be prevented.

The *underlying zone* is a region into which the waves do not penetrate. The air concentration at any depth in this zone is determined by the number of air bubbles and their size. The primary factor influencing the air concentration distribution is the turbulence intensity distribution throughout the flow. Using turbulent boundary layer theories, it has been possible to develop correlations for the air concentration distribution in this zone. However, the problem has not been solved completely since the air bubbles tend to inhibit the turbulence. The interrelations between air concentrations, bubble size distribution, and turbulence intensities have not been determined yet.

An *air-free zone* exists only in that section of the channel where aeration is still developing. In most practical applications, the boundary between the air free zone and the underlying zone cannot be determined accurately. At the interface, the air concentration has a very small value and the rate of change in concentration with depth is small. Halbron et al., [31] noted extremely fine bubbles which could not be detected near the bottom of their channel by the air concentration measuring apparatus; this indicates that the location of the interface may in fact be a function of the sensitivity of the measuring instrument.

In addition to defining the flow structure in a vertical plane, it also is possible to identify flow regimes in a longitudinal direction for flow in a wide channel. Here, a wide channel is defined as one in which the chanel width is greater than five times the flow depth. Borman [11] identifies three distinct regions in self-aerating flows in wide channels. They are:

1. A regime of no air entrainment where the turbulent boundary layer has not reached the water surface,
2. A regime of developing air entrainment in which the air concentration profiles are not constant with distance, and
3. A regime of fully developed air entrainment in which the air concentration profiles are constant with distance.

Keller, Lai, and Wood [39] divide Bormann's middle regime into two sections. The first is a region where the aeration is developing, but the air has not reached the bottom of the chute. The second is a region where the air has reached the bottom of the chute, but the air concentration profile continues to vary with distance (fig. 6).

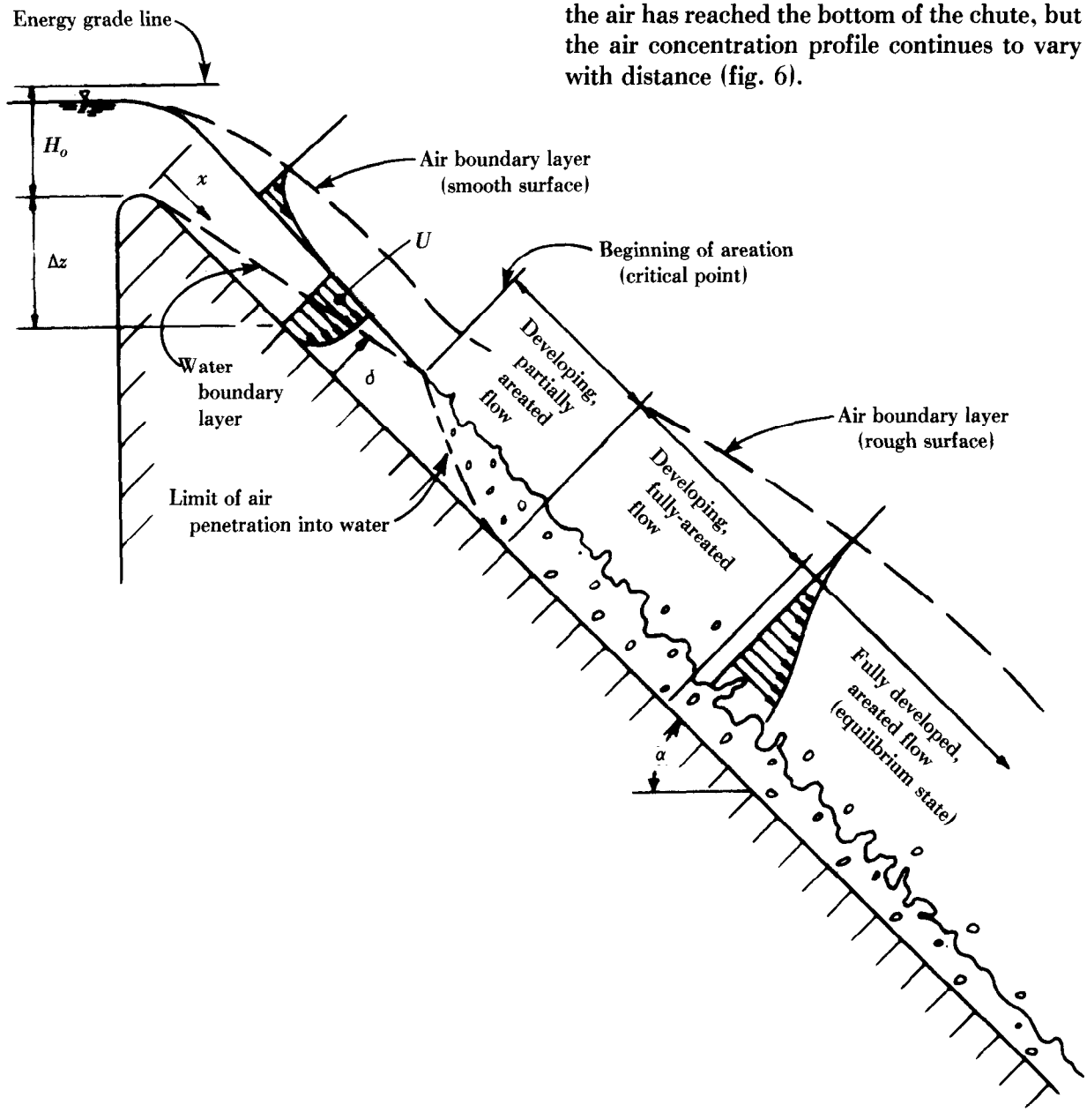


FIGURE 6.—*Air entraining flow regimes in open channel flow.*

DESIGN PARAMETERS

From an engineering viewpoint, the significant parameters in the design of a conveyance structure are:

- Distance to the beginning of aeration
- Distance to fully develop aerated flow
- Mean air concentration in the flow
- Flow depth of the aerated flow
- Water and air velocities in the aerated flow

The results of investigations concerning these parameters are presented in the following sections.

Location of Beginning of Aeration

The point at which "white water" begins in a wide channel generally is accepted to be the location where the turbulence effects generated at the channel floor first reach the water surface. Many different investigators have proposed equations for the location of this so-called "critical point." Many of the early predictions were rather poor. However, as the understanding of boundary layer growth over smooth and rough surfaces has improved, predictions of the "critical point" location also have improved. Although some questions concerning the theory still exist, present methods yield results that are sufficiently accurate for engineering purposes.

Typical examples of early correlations for the boundary layer thickness δ are those by Annemuller [4] who gave

$$\frac{\delta}{x}=0.01 \tag{17}$$

where x=distance from start of boundary layer growth,

Hickox [34] who gave

$$L_c=14.7\,q^{0.53} \tag{18}$$

where

L_c=distance to start of self-aeration
q=unit discharge, cubic feet per second per foot of width,

and Beta et. al., [10] who recommended values of

$$\frac{\delta}{x} \text{ between } 0.016 \text{ and } 0.01.$$

Schlichting [63] applied the results of measurements made in a pipe directly to a flat plate and found that the boundary layer thickness was given by

$$\frac{\delta}{x}=0.37\left(\frac{Ux}{\nu_f}\right)^{-0.2} \tag{19}$$

where

x=distance measured from the chute entrance
U=free stream velocity
δ=distance from the boundary at which the velocity equals 99 percent of U
ν_f=kinematic viscosity of water

The free stream velocity is

$$U=[2g(\Delta z+H_o-d\cos\alpha)]^{1/2} \tag{20}$$

where

d=water depth of computational point
g=gravitational constant (acceleration)
H_o=total head on crest
Δz=difference in elevation from crest to computational point
α=angle channel makes with horizontal

Equation 19 is also the expression used by Rouse [59] for flow over smooth surface. In

analyzing the results of Bauer [8], Halbronn [30] showed that the value of the coefficient for open channel flow should be equal to 0.16 instead of 0.37.

Equation 19 neglects two important considerations:

1. The surface can be hydraulically rough, and
2. Intermittent turbulence is present at a distance of up to 1.2δ from the channel floor.

A hydraulically rough surface is one in which

$$\frac{v_* k_s}{\nu_f} \geq 70 \tag{21}$$

where

k_s = equivalent sand grain roughness
ϱ_w = water density
τ_o = wall shear stress
v_* = shear velocity $= (\tau_o/\varrho_w)^{1/2}$

If the surface is rough, then the effect of the roughness height must be included in the computations.

The second consideration means that "white water" generally will occur before the boundary layer, as previously defined, actually reaches the water surface. Bormann [11] circumvented this difficulty by redefining the boundary layer thickness. Keller and Rastogi [40] recognized the same problem. Their point of incipient air entrainment also occurs at a location which lies somewhat above the previously defined boundary layer thickness. Thus, these methods account for the intermittant turbulence that occurs outside the conventionally defined boundary layer thickness.

Bormann [11] used a rather novel method of determining the "critical point." Bormann's method involves the simultaneous solution of equations relating local loss coefficient C_f, boundary layer thickness δ, and the distance Reynolds number $\mathbf{R}_x$. In Bormann's scheme the local loss coefficient can be viewed as a parametric term through which the other parameters are related. The appealing aspect of this approach is that it can be compared with the presently available equations for flow over smooth and rough boundaries.

The correlations relating the boundary layer thickness δ and the local loss coefficient C_f are

$$\frac{1}{C_f^{1/2}} = 3.85 \log \left(\frac{\delta U}{\nu} C_f\right)^{1/2} + 3.67 \tag{22}$$

for hydraulically smooth surfaces, and

$$\frac{1}{C_f^{1/2}} = 3.85 \log \left(\frac{\delta}{k_s}\right) + 6.45 \tag{23}$$

for hydraulically rough surfaces.

The correlation between distance Reynolds number and the local loss coefficient was determined empirically from

$$C_f = \frac{b_s}{(\log \mathbf{R}_x)^{2.38}} \tag{24}$$

where $\mathbf{R}_x$ = distance Reynolds number $= \frac{Ux}{\nu}$

The b_s value (fig. 7) can be approximated by

$$b_s = 0.32 + 8.15\, k_s^{0.47} \tag{25}$$

where

b_s = empirical coefficient accounting for sand grain roughness
k_s = equivalent sand grain roughness, mm

Alternatively, the value of b_s can be approximated by

$$b_s = 0.66\, k_s^{0.23} \tag{26}$$

For this approximation, the sand grain roughness must be equal to or greater than 0.01 mm; any smaller values represent a smooth surface.

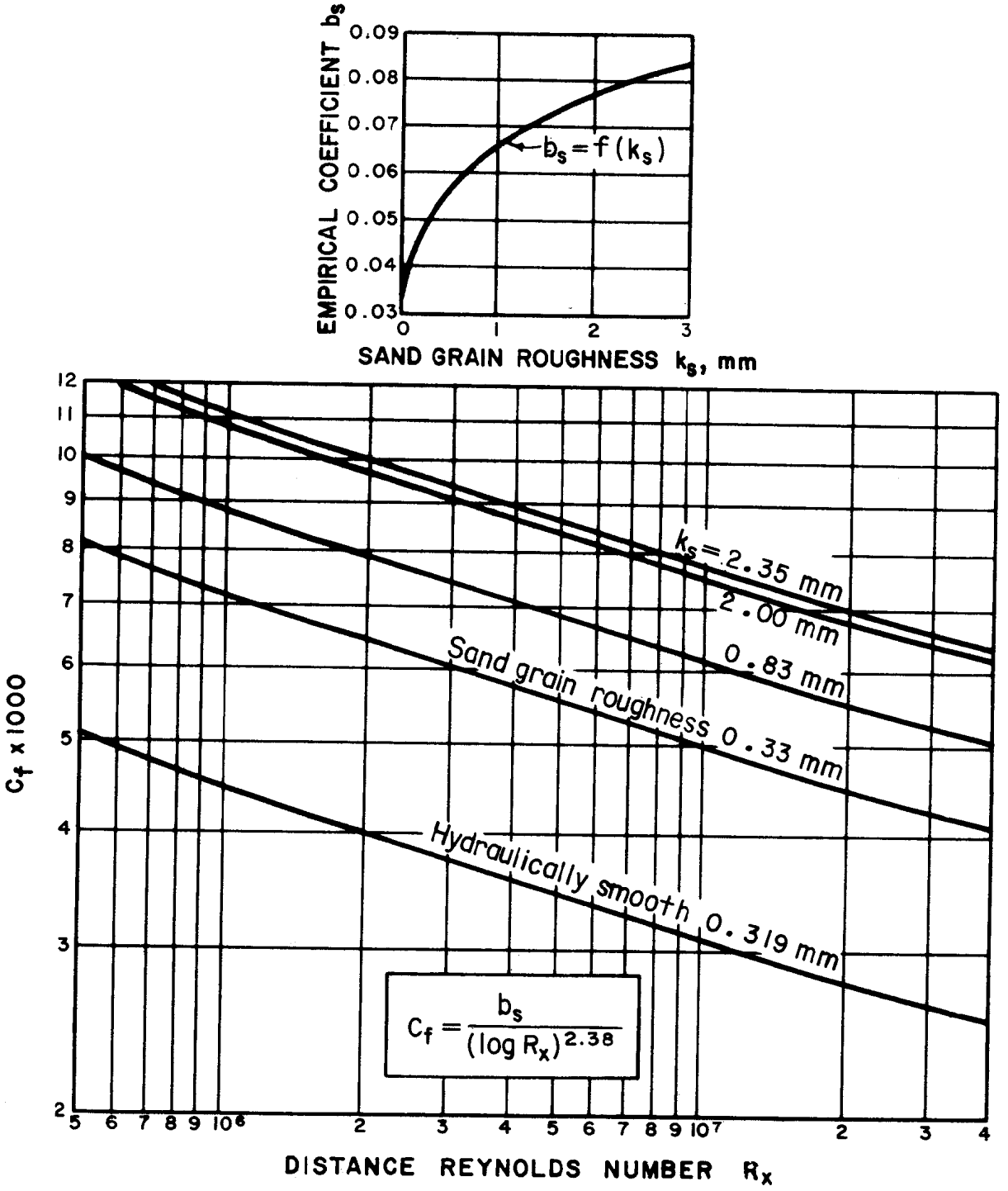


FIGURE 7.—*Experimentally determined local loss coefficient C_f, Bormann [11].*

To solve these equations it is necessary to use the following trial and error procedure.

a. Determine the energy grade line elevation H_o where y_k equals the critical depth from

$$H_o=1.5\ (y_k)^{1/2}\ =1.5\left(\frac{q^2}{g}\right)^{1/3} \qquad (27)$$

b. Estimate the water depth d at a given distance x from the entrance

c. Calculate the freestream velocity U from

$$U=[2g(H_o x+\sin\alpha-d\cos\alpha)]^{1/2} \qquad (29)$$

d. Determine the local loss coefficient C_f as a function of the boundary layer thickness δ using equations 22 or 23 as appropriate. In these equations the flow depth assumed in b. is used for the boundary layer thickness.

e. Calculate the local loss coefficient as a function of distance Reynolds number from equation 24 where the distance Reynolds number is defined as

$$\mathbf{R}_x=\frac{Ux}{\nu}=\frac{U^3}{2g\,\nu\sin\alpha} \qquad (30)$$

f. Repeat steps b. through e. with revised values of depth until the same values are obtained for the local loss coefficients in equations 22 or 23 and 24.

As an example, this procedure was applied to a surface having a sand grain roughness k_s which corresponds to a float finish concrete surface. This finish is equivalent to a Manning's roughness coefficient of 0.013. The results are presented in a set of design curves shown on figure 8. Similar curves can be prepared for other values of Manning's coefficients.

Finally, the latest development in calculating the distance to the point of air entrainment is by Keller and Rastogi [40]. Their method involves integrating the equations of motion using a finite element scheme. The calculated velocity profiles agree very well with the experimentally determined values. However, their studies have not been put into a form that is useful for designers.

Location of Fully Aerated Flow

The location at which the flow becomes fully aerated has not been studied. Straub and Lamb [67] show that a constant air concentration distribution can be achieved, but the distance required for its development is not specified. Bormann [11] measured the location of the air-water interface, but not the concentration profile. For Bormann's results one can imply that the length of the developing aeration regime is of the same order as the length of the developing boundary layer regime.

Keller, Lai, and Wood [39] indicate that the length of the developing aeration region can be defined in terms of the air concentration. In their definition, the length of the developing region is at least as long as the distance from the "critical point" to a location where a 5-percent air concentration has reached middepth of the total flow depth. The data by Straub and Lamb [67] show that this criterion is inadequate.

The length of the developing aeration regime cannot be determined analytically. This is one area in which additional research could be pursued gainfully.

Air Concentration Profiles

Definition of concentration.—The conventional definition of concentration is the quantity—usually measured by volume—of a material A either dissolved or suspended in another material B. Thus, if material A is air and material B is water, air concentration would be the volume of air in a given volume of water.

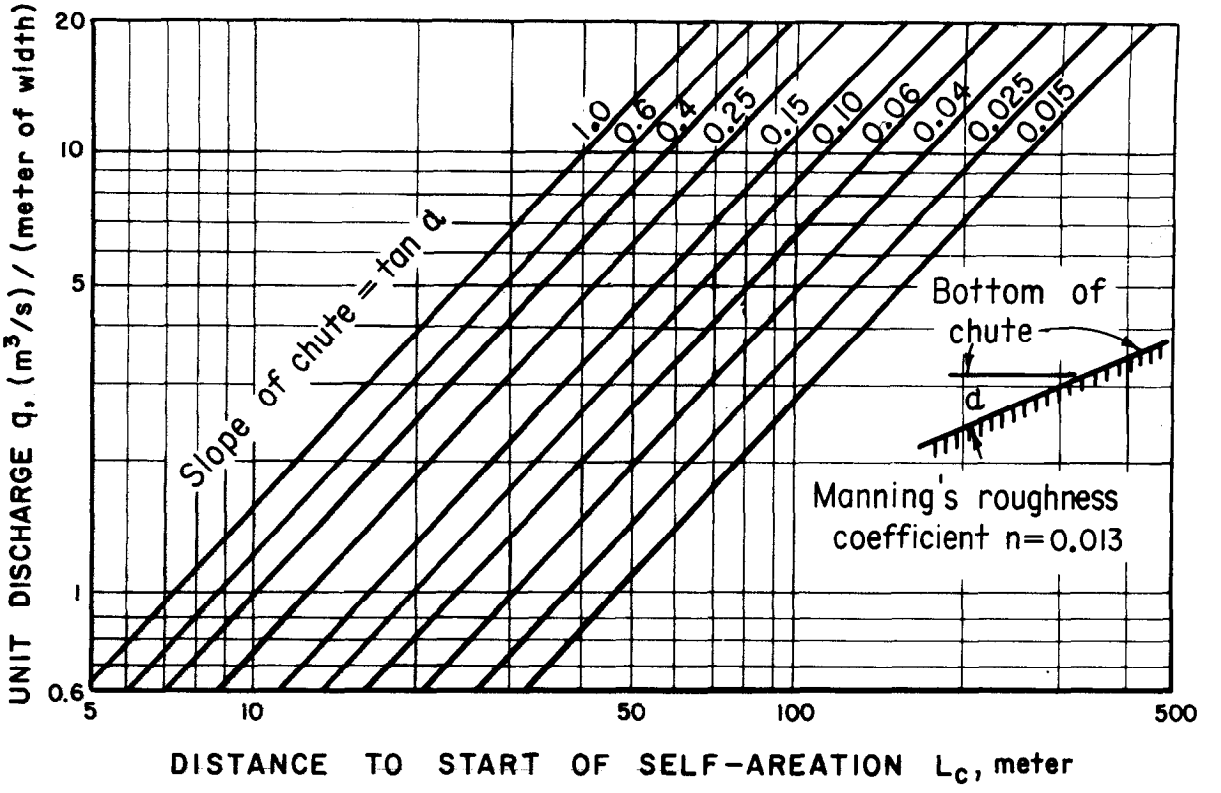


FIGURE 8.—*Location of inception of air entrainment.*

However, when the amount of suspended material becomes large, the reference volume is the sum of the volume of material B and the volume of material A. In this case the average air concentration $\overline{C}$ is given by

$$\overline{C} = \frac{\omega_a}{\omega_a + \omega_w} \tag{31}$$

where

ω_a = volume of air
ω_w = volume of water

This latter definition of concentration is used throughout this report.

The concentration also can be expressed in terms of volumetric flow rates as

$$\overline{C} = \frac{Q_a}{Q_a + Q_w} = \frac{\beta}{\beta + 1} \tag{32}$$

where

Q = discharge
$\beta = Q_a / Q_w$

The early method of measuring the concentration of air-water flows used a pitot-tube-type sampler developed by Viparelli [72]. This type of device gives accurate results in the *underlying zone* (fig. 4). However, in the *mixing zone*, the sampler records not only air in water, but also the air between the waves. Therefore, the measurements indicate air concentrations that are too large in the mixing zone. It should be noted that in some cases the total air discharge and not air concentration is desired. For instance, in closed conduit flow, the total air discharge is required for proper vent sizing. In this case, the pitot tube sampler would yield the desired air flow quantities in all four air flow zones.

Killen and Anderson [42] showed that the air concentration—as indicated by a pitot tube sampler—is related to the actual air concentration in the water by

$$C_a = \frac{C_m - 1 + P_w}{P_w} \tag{33}$$

where

C_a = actual air concentration in percent of volume
C_m = air concentration measured by a pitot tube sampler
P_w = probability that the water surface is equal to or greater than the given elevation (refer to the following sec.—*Air distribution in the mixing zone)*

The water surface probability in equation 33 can be measured with electrical probes described by Killen [41]. He also reported on an electrical device that measures the actual air concentration directly.

Almost all references to air concentration in the bibliography include values for the amount of air between the waves. Therefore, values for the amount of air in flowing water generally are excessive. Unless noted otherwise, the term "air concentration" refers only to the amount of air actually entrained in water.

Air distribution in the mixing zone.—Many investigators have observed that measured air concentration distribution obeys one law in the *mixing zone* and another in the *underlying zone*. Apparently, these two laws were discovered by Anderson [2] who examined the results of a large number of experiments.

Investigators reasoned that in the *mixing zone* the air concentration should follow a Gaussian law of normal probability, since this is also the law for the wave height distribution. They found the relation is given by

$$\frac{dC_m}{dy} = \frac{2(1-C_t)}{h\pi^{1/2}} \exp\left[-\left(\frac{y'}{h}\right)^2\right] \tag{34}$$

where

C_m = air concentration (including the air between the waves) at any elevation in percent of total volume
C_t = air concentration at the bottom of the mixing zone
h = mean wave height $= 2^{1/2}s$
s = standard deviation of the wave height distribution
y = distance normal to the channel bottom
y' = distance normal to the bottom of the mixing zone, figure 5

The integral form of the equation is

$$\frac{1-C_m}{1-C_t} = \frac{2}{\pi^{1/2}} \int_{y'}^{\infty} \exp\left[-\left(\frac{y'}{h}\right)^2 d\left(\frac{y'}{h}\right)\right] \tag{35}$$

This equation is almost identical to the cumulative Gaussian or normal distribution function

$$P_g = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\eta} \exp\left(-\frac{\eta^2}{2}\right) d\eta \tag{36}$$

where $\eta = y'/s$

The air distribution equation, equation 35, includes a factor of 2 because the relation applies to positive values of y'; whereas equation 36 applies to both positive and negative values

of y'. By reversing the limits of integration in equation 36, it can be shown that

$$\frac{1}{(2\pi)^{1/2}} \int_{\eta}^{\infty} \exp\left(-\frac{\eta^2}{2}\right) d\eta = 1 - P_g \qquad (37)$$

Combining equation 35 with equation 37 gives

$$\frac{1-C_m}{1-C_t} = 2(1-P_g) \qquad (38)$$

Values of the normal distribution function P_g can be found in statistics texts. A graphical representation of the normal distribution function and the air concentration distribution is given in figure 9.

The actual air concentration in the waves is a function of the wave height probability and the air concentration at the bottom of the mixing zone. The relation is given by

$$C_a = \frac{P_w - 2(1-C_t)(1-P_g)}{P_w} \qquad (39)$$

For the wave height distribution given in this chapter (Design Parameters—Water Surface Location), a family of curves can be derived for the actual air concentration distribution in the *mixing zone* (fig.10). The maximum upper limit of these curves is discussed in the following subsection *Mean air concentration.*

These distributions are valid for both the developing and the fully developed aerated flow regimes. They can be used for the determination of the air concentration at any elevation if the standard deviation of wave height distribution and the air concentration at the bottom of the mixing zone are known. Unfortunately, these parameters can neither be predicted in the developing aerated flow regime nor in the fully developed aerated flow regime. Therefore, the equations only can be used to fit experimental data. Additional research is needed in this area.

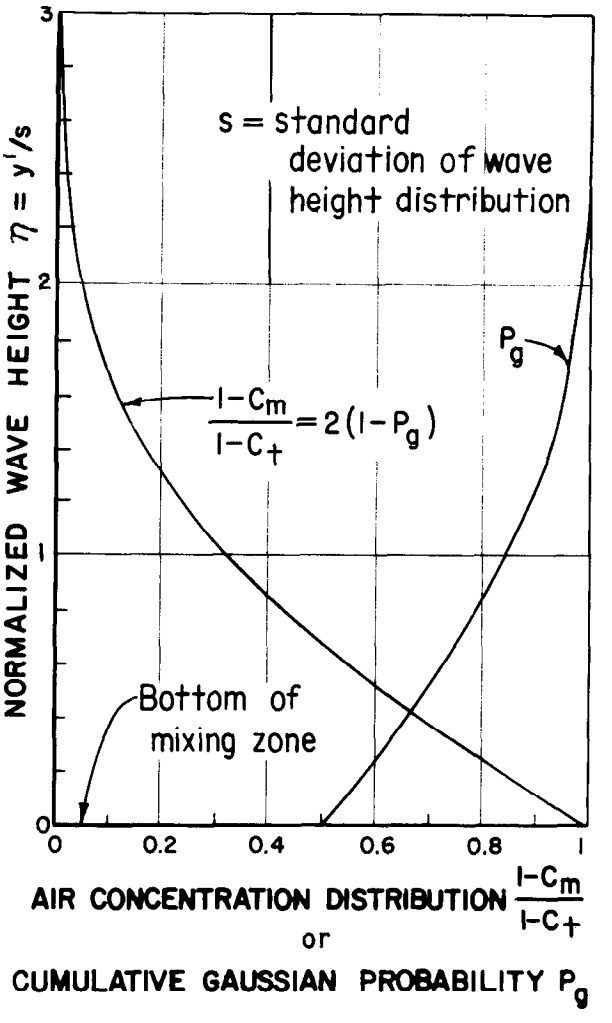


FIGURE 9.—*Cumulative Gaussian probability and measured air concentration distributions in the mixing zone.*

Air distribution in the underlying zone.—The *underlying zone* consists of a region into which waves do not penetrate. Straub and Anderson [66] were successful in deriving an equation that describes air distribution in this zone (also refer to Streeter [68]).

They defined the bubble mass transfer coefficient ε as

$$\varepsilon = \zeta k(\tau_o/\varrho_l)^{1/2}\left(\frac{d_t - y}{d_t}\right)y \qquad (40)$$

where

d_t = total depth of underlying and air free zones
k = Von Karman universal constant equal to 0.4
ζ = air concentration distribution constant
ϱ_l = liquid density
τ_o = wall shear stress

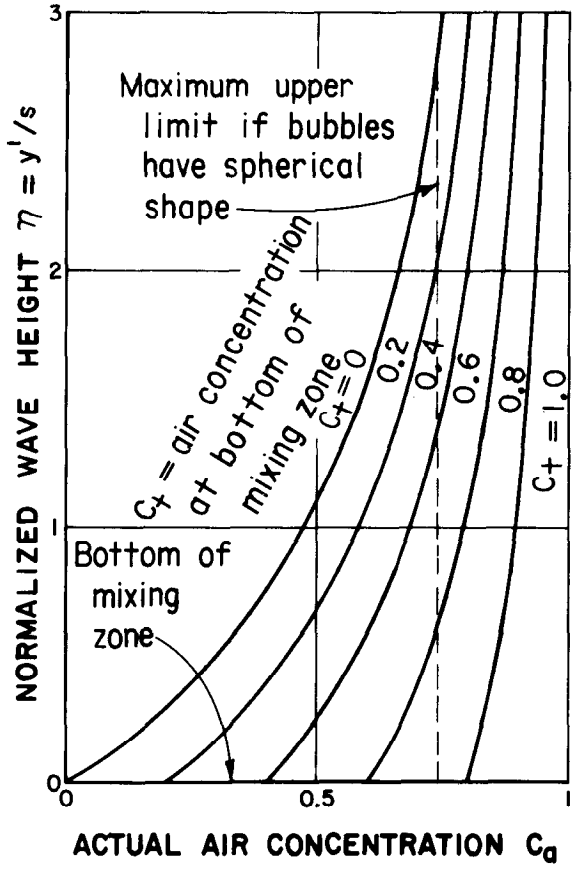


FIGURE 10.—*Actual air concentration distribution in the mixing zone.*

This relation makes ε equal to zero at both the channel floor and at the interface between the *mixing zone* and the *underlying zone*. Actually, the expression is not valid at the interface since air is transported across the boundary. However, by substituting equation 40 for the mass transfer coefficient ε into equation 16—and assuming the terminal velocity of bubbles is constant—upon integration one obtains

$$C = C_1 \left(\frac{y}{d_t - y}\right)^m \tag{41}$$

where $m = \dfrac{V_f}{\zeta k(\tau_o/\varrho_l)^{1/2}} = \dfrac{V_f}{\zeta k v_*}$

C = local air concentration
C_1 = air concentration at $d_t/2$
v_* = shear velocity $= (\tau_o/\varrho_l)^{1/2}$

This equation fits the data well for fully developed aerated flows by properly selecting C_1, d_t, and m (fig. 11). The measured air concentration distribution in the *mixing zone* given by equation 38 also will give good results. The satisfactory fit of the data with these two equations implies that turbulent diffusion and buoyancy are the two most important factors affecting the determination of the air concentration distribution in the fully developed aerated flow zone.

In the developing aerated flow regime, equation 41 is not valid. In the developing aeration regime two conditions must be considered. The first condition is where air is being insufflated into the flow. For this case, the governing equation is

$$q_a = \varepsilon \frac{dC}{dy} - CV_f \tag{42}$$

where q_a = insufflation rate of air per unit surface area

The other condition is that of excess air being present in the water. In this condition, air is released from the flow until an equilibrium state is reached. Equation 42 also is valid for this condition except the sign q_a will be negative which indicates that air is leaving the water.

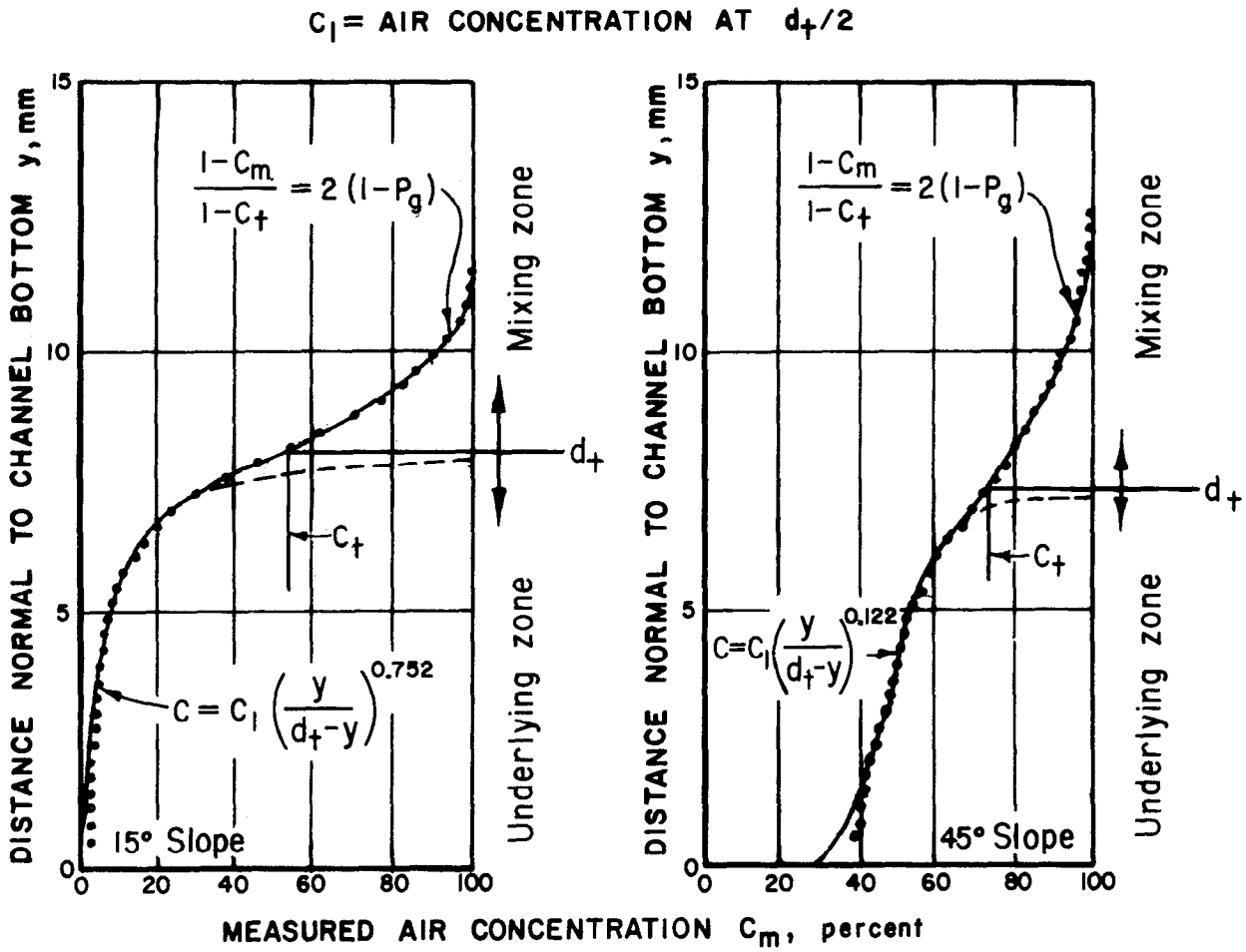


FIGURE 11.—*Air concentration distributions of channel flow on steep slopes, Straub and Anderson [66].*

Killen [41] measured air concentration distributions for the first condition of air insufflation. However, no one has developed equations for the observed distribution. This is another area needing additional research.

Mean air concentration.—The mean air concentration for the entire flow stream is defined by

$$\overline{C} = \frac{1}{d_m}\int_o^{d_m} C_a\, dy \qquad (43)$$

The depth d_m represents some upper bound for the water surface. Straub and Anderson [66] define the depth as representing that point where the measured air concentration is 0.99. A more reasonable reference depth would be the depth which is exceeded by only 1 percent of the waves.

The air concentration C_a in equation 43 is the actual air concentration and does not include air moving between the waves (in this chap., Design Parameters—*Definition of concentration).* However, all the published data were measured with a pitot-tube-type sampler and, thus, include the interwave air motions in the *mixing zone.* The mean air concentration $\overline{C}$ based on the actual air concentration C_a distribution can be estimated by the following

reasoning. The upper limit of the air concentration can be approximated by assuming the bubbles to be spherical. If thay retain a spherical shape, Gardner [23] showed that the air concentration for the bubbles packed in their most dense configuration is about 75 percent. The upper limit for the Straub and Anderson data [66] is about 84 percent. Thus their data are roughly 12 percent too high.

Since the air concentration is obtained from an integration of the local air concentration distribution, buoyancy and turbulent diffusion must be the most significant parameters which influence the mean concentration for any flow. The buoyant forces are governed primarily by the bubble size. With respect to turbulence, Hinze [35] indicates that bubbles tend to be broken up by both viscous shear forces and turbulent shear forces. This tendency to be broken up is resisted by interfacial tensile forces. For high enough degrees of turbulence, the viscous shear forces are insignificant with respect to the turbulent shear forces. With solid boundaries the significant parameter defining the turbulent shear forces is the wall shear stress, τ_o.

The following presents the development of an empirical equation to predict the mean air concentration in the fully developed aerated flow zone. The development is based upon the classical methods of dimensional analysis.

Assuming that buoyancy and turbulent diffusion are significant, it is possible to express the volume flow of air Q_a as a function of:

- Gravity
- Turbulent shear stress
- Interfacial forces
- Fluid properties of both air and water
- Characteristic flow dimensions

The expression is

$$Q_a = f(V, b, d, g, \mu_a, \mu_w, \varrho_a, \varrho_w, \sigma, \tau_o) \qquad (44)$$

where

Q_a = volume flow of air, m^3/s
V = water velocity, m/s
b = width of flow channel, m
d = water depth, m
g = gravitational constant (acceleration) = 9.81 m/s^2
μ = dynamic viscosity, $N \cdot s/m^2$
ϱ = density, kg/m^3
σ = interfacial surface tension, N/m
τ_o = wall shear stress, Pa
$f(\ )$ = denotes "a function of"

Subscripts a and w refer to air and water, respectively.

Using V, d, and ϱ_w as the repeating variables results in the following dimensionless parameters.

$$\frac{Q_a}{V^2} = f\left(\frac{\tau_o}{V^2\varrho_w}, \frac{\sigma}{V^2 d\varrho_w}, \frac{\varrho_a}{\varrho_w}, \frac{\mu_a}{\mu_w}, \frac{\mu_w}{Vd\varrho_w}, \frac{b}{d}, \frac{gd}{V^2}\right) \qquad (45)$$

By examining the magnitude of these dimensionless terms and transforming some of them, it is possible to develop parameters that should be used for correlating the available model and prototype data. For instance, the dependent parameter can be written as

$$\frac{Q_a}{Vd^2} = \frac{Q_a}{Vdb}\left(\frac{b}{d}\right) = \frac{Q_a}{Q_w}\left(\frac{b}{d}\right) \qquad (46)$$

Since

$$\beta = \frac{Q_a}{Q_w} \quad \text{and} \quad \overline{C} = \frac{\beta}{\beta + 1}$$

by definition, the mean concentration is also a function of the same dimensionless terms given above.

The first independent parameters in the parenthesis of equation 47 can be written as

$$\frac{1}{\mathbf{P}^2} = \frac{\tau_o}{V^2 \varrho_w}$$

where $\mathbf{P}$=Prandtl velocity ratio$=\frac{V}{(\tau_o/\varrho_w)^{1/2}}$

The Prandtl velocity ratio represents the ratio of the inertial force to the wall shear force.

For the condition of uniform flow on a wide, steep chute, the wall shear stress τ_o is given by

$$\tau_o = \gamma d \sin \alpha \qquad (47)$$

where

d=flow depth
α=angle chute invert makes with horizontal
γ=specific force of fluid

substituting this into the Prandtl velocity ratio P gives

$$\frac{\tau_o}{V^2 \varrho_w} = \frac{\gamma d \sin \alpha}{V^2 \varrho_w} = \frac{g d \sin \alpha}{V^2} = \frac{\sin \alpha}{\mathbf{F}^2} \qquad (48)$$

where $\mathbf{F}$=Froude number $=\frac{V}{(gd)^{1/2}}$

Thus for uniform flow on wide, steep chutes, the parameters $\sin \alpha/\mathbf{F}^2$ represents the ratio of turbulent shear forces to the inertial forces.

The tensile force parameter, $\sigma/(V^2 d \varrho_w)$, is simply the reciprocal of the Weber number squared

$$\frac{\sigma}{V^2 d \varrho_w} = \frac{1}{\mathbf{W}^2} \qquad (49)$$

where $\mathbf{W}$=Weber number $=\frac{V}{(\sigma/\varrho_w d)^{1/2}}$

The Weber number represents the ratio of the inertial forces to the interfacial tensile forces. The surface tension is only a function of temperature (fig. 12)

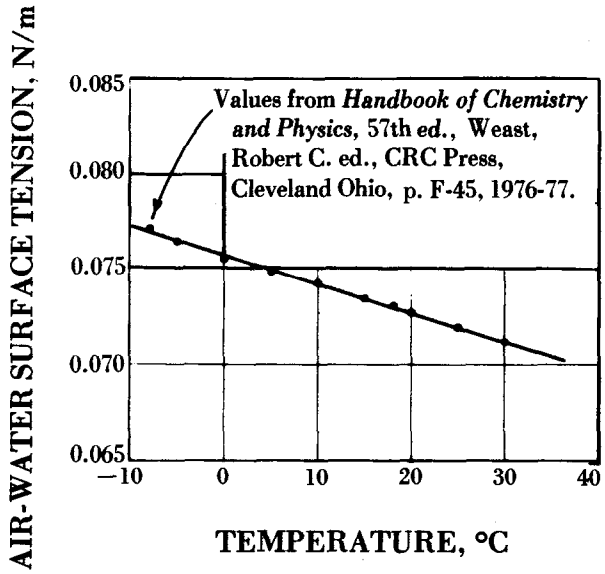


FIGURE 12.—*Interfacial surface tension.*

The bubble size is determined by the ratio of turbulent shear forces to the interfacial tensile forces. In terms of the previously developed parameters, the ratio is

$$\frac{g d \sin \alpha}{V^2} \left(\frac{V^2 d \varrho_w}{\sigma}\right) \qquad (50)$$

Reducing this ratio to the first power of V and generalizing results in

$$\frac{(\sin \alpha)^{1/2} \mathbf{W}}{\mathbf{F}} \qquad (51)$$

The ratio of viscous forces to inertial forces can be written as

$$\frac{\mu_w}{V d \varrho_w} = \frac{\nu}{V d} = \frac{1}{\mathbf{R}} \qquad (52)$$

where **R**=Reynolds number

The use of channel width b and flow depth d in the list of variables implies the use of a rectangular cross section. More generality can be obtained by the use of the hydraulic radius as the significant length parameter. The hydraulic radius is defined by

$$H=A/W \tag{53}$$

where

A=cross sectional area of water prism
W=wetted perimeter

With the exception of the Froude number, the hydraulic radius seems to be the most appropriate characteristic length to correlate air entrainment for any cross sectional shape.

The effective depth is the characteristic length to be used with the Froude number. The effective depth y_e is defined as

$$y_e=A/B$$

where

A=cross sectional area of water prism
B=top width of water prism

By using the above transformations, the mean air concentration can be written as

$$\overline{C}=f\left(\frac{(\sin\alpha)^{1/2}\mathbf{W}}{\mathbf{F}},\ \mathbf{W},\ \frac{\varrho_a}{\varrho_w},\ \frac{\mu_a}{\mu_w},\ \mathbf{R},\ \mathbf{F}\right) \tag{54}$$

Equation 54 represents a seven-dimensional surface. Determining relations between all the variables is practically impossible. However, the problem can be made simpler by neglecting those independent variables which have either a small range of values or a negligible effect on the mean air concentration. For example, the tensile force varies less than 10 percent over the temperature range normally existing in the field and laboratory (fig. 12). Therefore, the tensile force parameters, **W**, of equation 49 can be neglected.

Neglecting the tensile force parameter does not mean that the ratio of the turbulent shear to interfacial tensile force parameter also can be neglected. This latter ratio, which governs the bubble diameter, must be retained.

For flows that are turbulent enough to entrain air naturally, the dynamic pressure forces determine the size of the largest air bubbles. These dynamic forces are a result of changes in velocity over distances that are about the same scale as the diameter of the bubble. For typical flows on spillways and in steep chutes the dynamic forces predominate over the viscous forces. Therefore, the dimensionless terms involving viscosity are not significant with respect to the magnitude of the other terms.

Finally, the dimensionless density ratio varies almost linearly from 0.0012 at 4 °C to 0.0011 at 30 °C. Therefore, this term also can be considered as unimportant for the temperature range that is typical in hydraulic structures.

The reduced form of equation 54 is

$$\overline{C}=f\left(\frac{(\sin\alpha)^{1/2}\mathbf{W}}{\mathbf{F}},\ \mathbf{F}\right) \tag{55}$$

This equation represents a three-dimensional surface which can be defined from experimental and field investigations. The Straub and Anderson [66] data from model studies and data from prototype studies of Michels and Lovely [54] as well as Thorsky et. al., [70] were used to determine the functional relations between the mean air concentration $\overline{C}$, Froude number **F**, and turbulent-interfacial tension force ratio.

The variation of the mean concentration as a function of Froude number was determined

from the model data. For this correlation the turbulent-interfacial tension force ratio was approximately constant. With mean air concentrations less than 0.6, the correlation had the form

$$\overline{C} = a_o + a_1 F \tag{56}$$

where a_o is a function of the turbulent to interfacial tension force ratio.

The values of a_1 for turbulent to interfacial tension force ratios of 0.166, 0.114, and 0.085 are 0.0469, 0.0486, and 0.0556, respectively. Although the value of a_1 apparently increases as the turbulent to interfacial tension force ratio decreases, the data are insufficient to support the conclusion. Therefore, a_1 was taken to be equal to the mean of the values or 0.050.

The function a_o was determined from both the model data and tests on prototype chutes and spillways. The prototype values correspond with the initiation of air entrainment. The values of a_o were determined from the equation

$$a_o = \overline{C} - 0.05F \tag{57}$$

The curve

$$a_o = -\frac{(\sin \alpha)^{1/2} W}{63F} \tag{58}$$

approximately fits the data (fig. 13).

Therefore, the mean air concentration correlation is given by

$$\overline{C} = 0.05F - \frac{(\sin \alpha)^{1/2} W}{63F} \tag{59}$$

for

$$0 \leqslant \overline{C} \leqslant 0.6$$

If $\overline{C}$ is greater than 0.6, the air concentration values must be taken from the empirical curves on figure 14.

With the exception of the spillway data, the Froude and Weber numbers were calculated using the relation for normal depth without aeration. The model tests correspond with fully developed aerated flow.

In the absence of any better information, these curves also can be used to estimate the mean air concentration in developing flow. For this case, the Froude and Weber numbers are calculated from the depth and velocity values that result from the gradually varied flow computations without considering aeration of the flow.

The use of these curves are illustrated by an example.

- **Example**

  Given a rectangular chute 15 meters wide, calculate the development of the air entrainment along the length of the chute. The discharge is 20 m^3/s. The channel is built on a 1:3 slope and has a Manning's n value of 0.0100.

  The computer program **HFWS** (app. II) was used to compute the water surface profile and the mean air concentrations (fig. 15). The program can be used with either drawdown or backwater curves for rectangular, trapezoidal, circular, and transitional cross sections.

Water Surface Location

One of the first concepts that developed in self-entraining flows was bulking. With this concept, the air was considered to be evenly distributed throughout the flow. As a result, the depth of the mixture was increased by a predictable amount (fig. 16). The relation is given by

$$\frac{d_b}{d} = \frac{1}{1 - \overline{C}} \tag{60}$$

where

d = flow depth (without aeration)

d_b = bulked flow depth

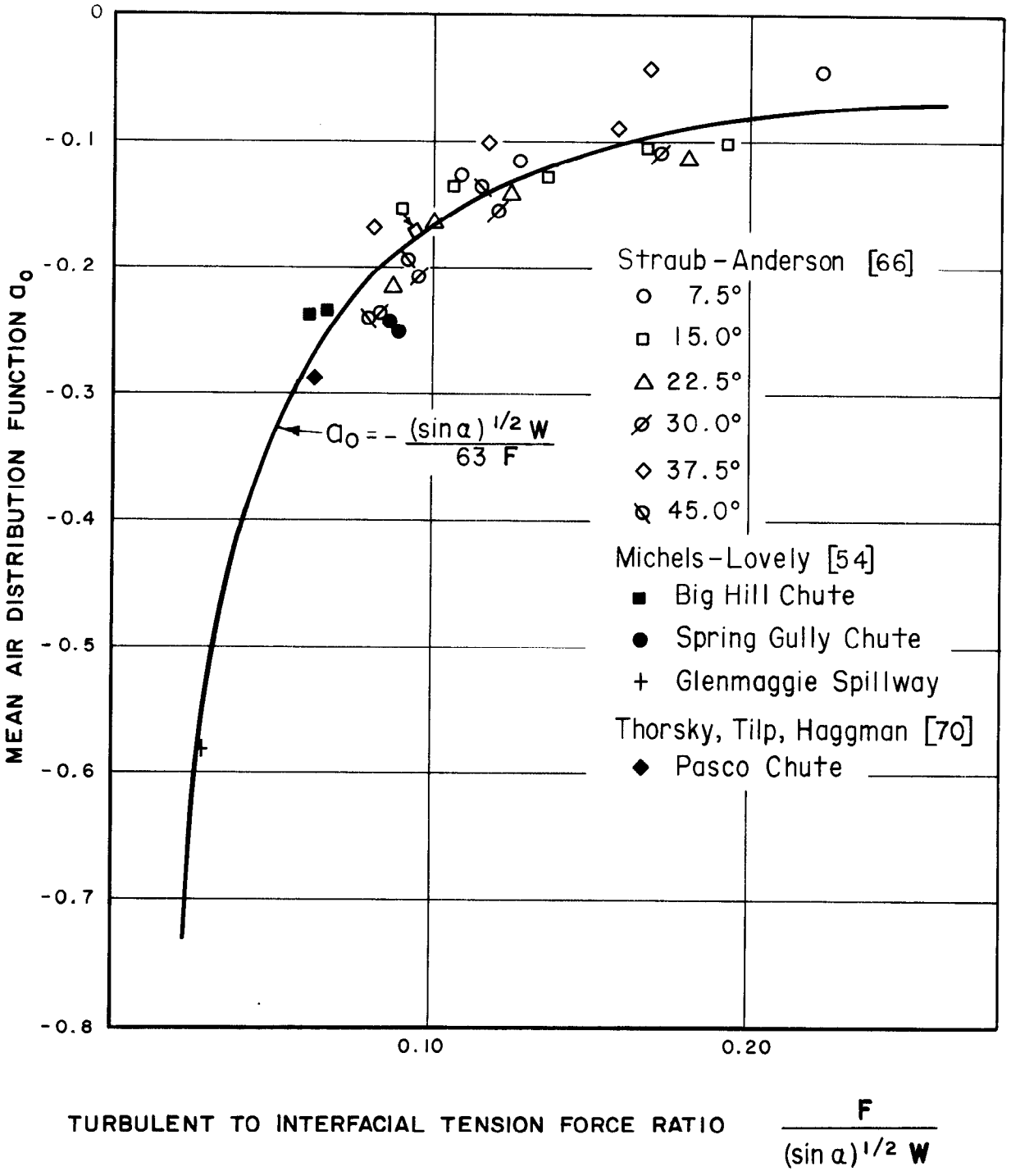


FIGURE 13.—*Air entrainment coefficient.*

g = gravitational constant
V = mean flow velocity
W = weber number = $V/(\sigma/\rho y_e)^{1/2}$
y_e = effective depth
α = angle chute invert makes with horizontal
ρ = density of water
σ = interfacial surface tension

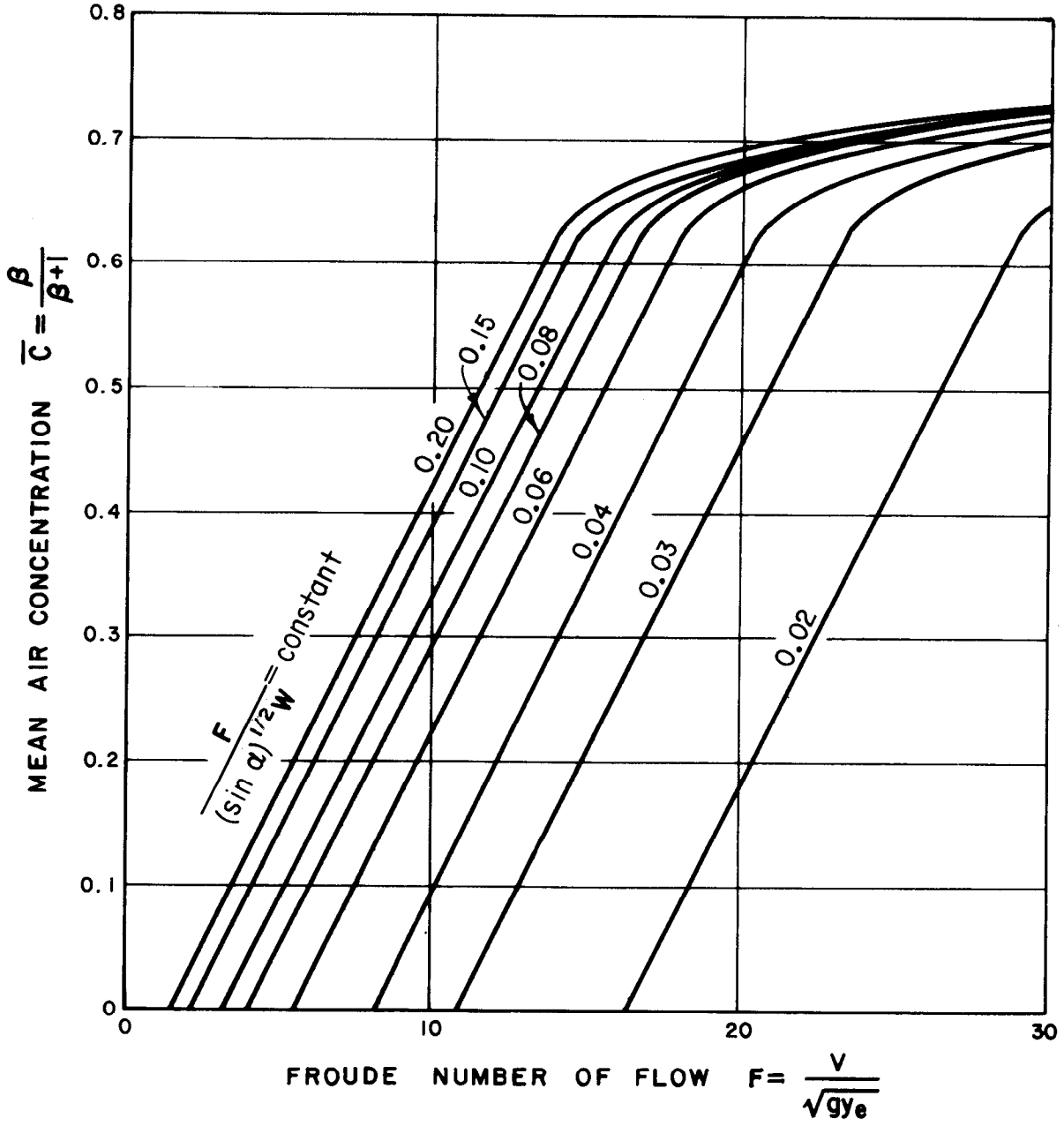


FIGURE 14.—*Air entrainment in open channel flow.*

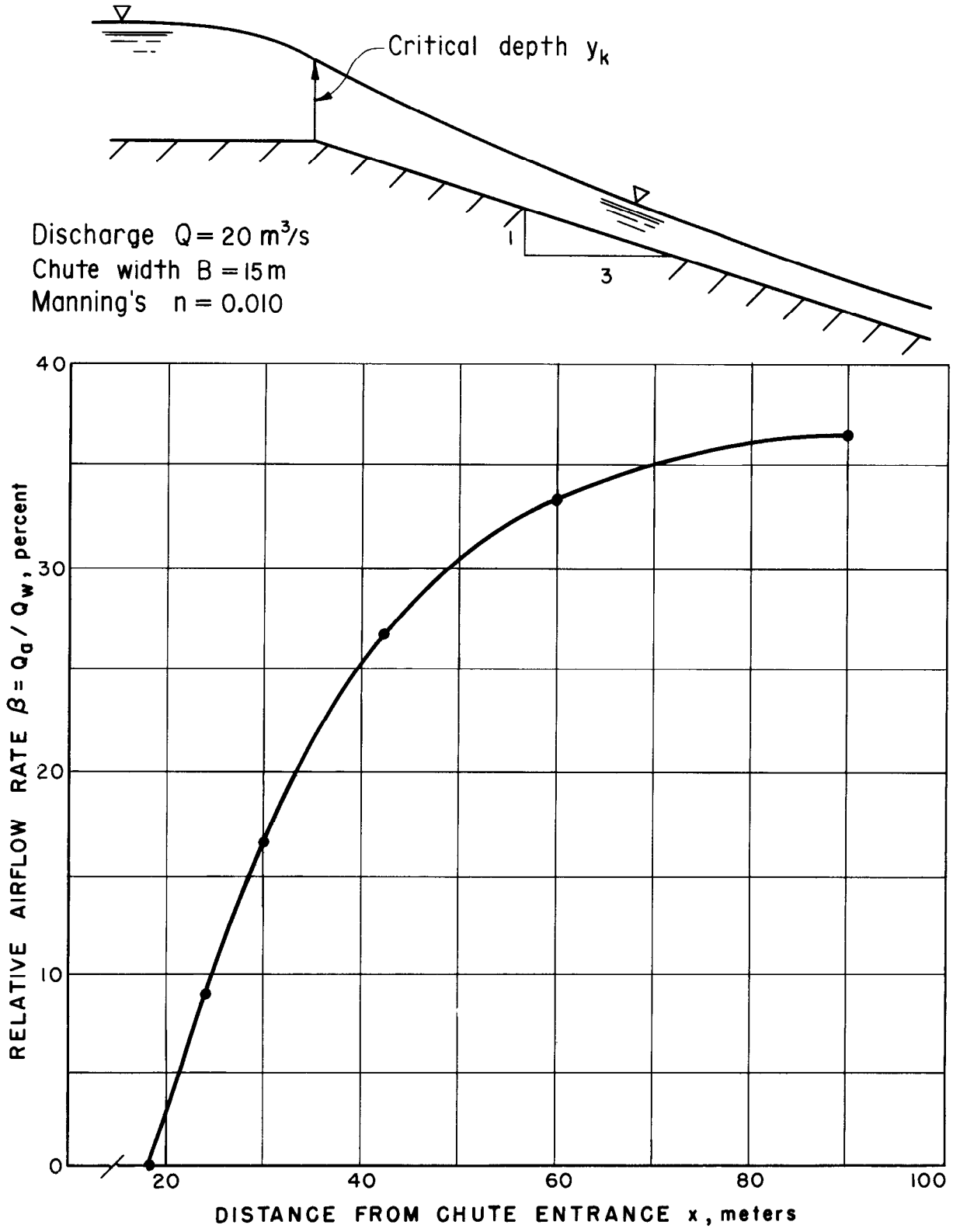
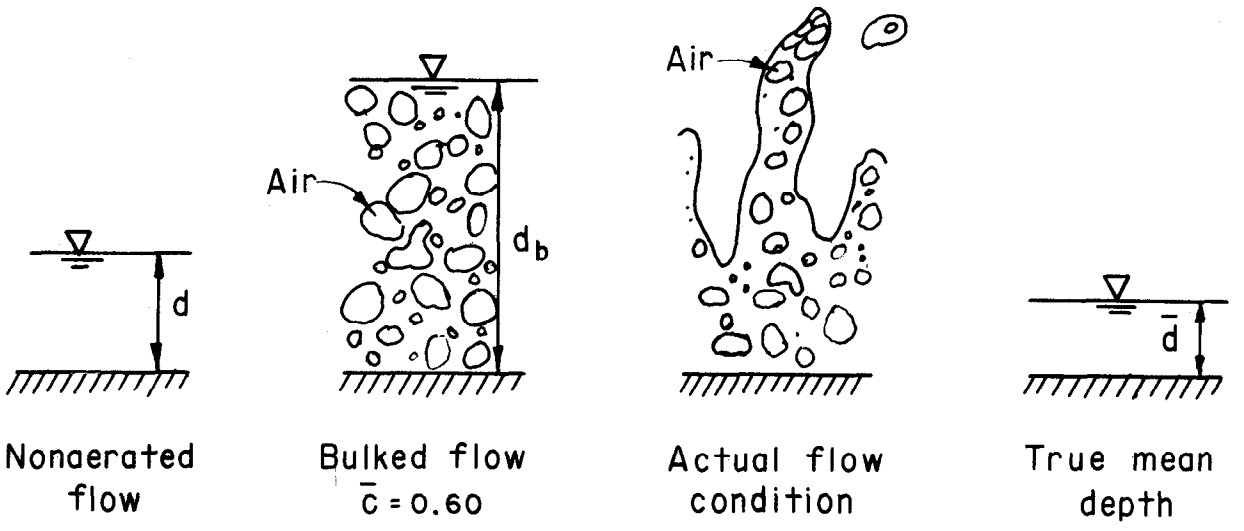


FIGURE 15.—*Example of air entrainment in chutes.*



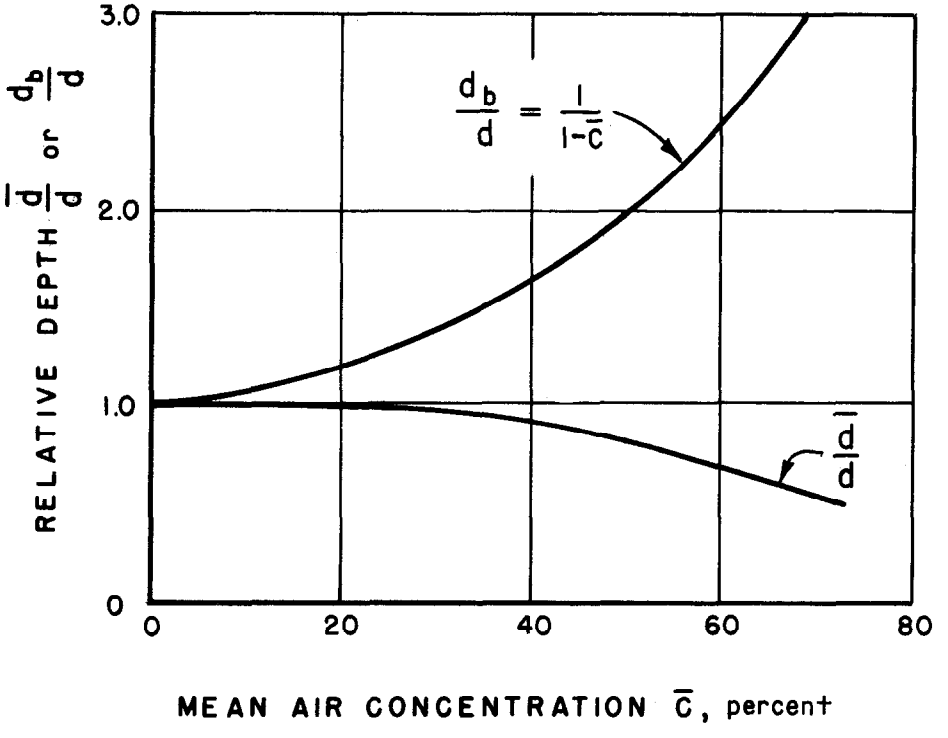


FIGURE 16.—*Definitions of aerated flow depth.*

For chutes having rectangular cross sections, equation 60 can be written as

$$\overline{C} = 1 - \frac{VdB}{Vd_bB} \tag{61}$$

where

B = width of rectangular chute
V = velocity of air-water mixture

Thomas [69] used the bulked depth concept indirectly to determine the air content on the Kittitas chute[4]. He measured the bulked depth (with some difficulty), total waterflow and the velocity of the air-water mixture. The velocity of the air-water mixture was determined by the salt velocity method. Thomas measured d_b, V, and Q. He calculated the air concentrations using equation 61 by setting

$$Q = VdB \tag{62}$$

The determination of airflow rates by this method raises two questions that need to be considered in some detail. These are:

1. Does the air content influence the flow velocity and hence, the true mean depth?
2. How accurate are the measurements of the bulked flow depth?

Straub and Anderson [66] found that the depth of the flow actually decreases as the air concentration increases above a value of 25 percent (fig. 17). In other words, as the air concentration increases, the flow velocity increases. For instance, at the 74-percent air concentration, the flow velocity is about 1.8 times the nonaerated flow velocity. Therefore, the Standard Step Method and Manning's equation can be used to estimate the true depth up to air concentrations of about 25 percent. For higher concentrations the values must be adjusted by figure 16.

The bulked flow depth virtually is impossible to measure accurately because the surface is highly turbulent (note frontispiece). Thomas [69] noted the following:

> "The choppy water surface and the large amount of spray rendered it difficult to determine where the point of the gage should be to give a reading that would be indicative of the actual depth of flow. The surface conditions also made it difficult to observe the point of the gage. The depth of flow was considered to be at the base of the loosely flying spray and drops of water. The top of the main portion of the flow included numerous small waves or rollers. The vibration of the point gage was relied upon more than visual observation to insure that the point was at relatively the same position in the flow for successive readings."

The practical difficulties of determining accurate measurements indicate a need to reexamine the actual flow conditions (fig. 16). A careful consideration of actual flow conditions, such as the frontispiece and the preceeding note, reveals that the entire concept of a bulked flow depth is a poor representation of reality. Thus, other means of describing the location of the water surface should be considered.

Water surface fluctuations that occur in open channels can be described by several methods. Longuet-Higgins [50], in studies of ocean waves, based his analysis on a probability distribution of wave heights. He defined a wave height as the difference in elevation between a crest (maximum) and its succeeding trough (minimum). Relatively good correlations were

[4]The Kittitas chute is the common name given to describe the Main Canal - Sta. 1146+30 (feet) Wasteway in the Kittitas Division, Yakima Project - Washington. The care with which the tests were conceived and executed have made them a valuable reference source—even up to the present time.

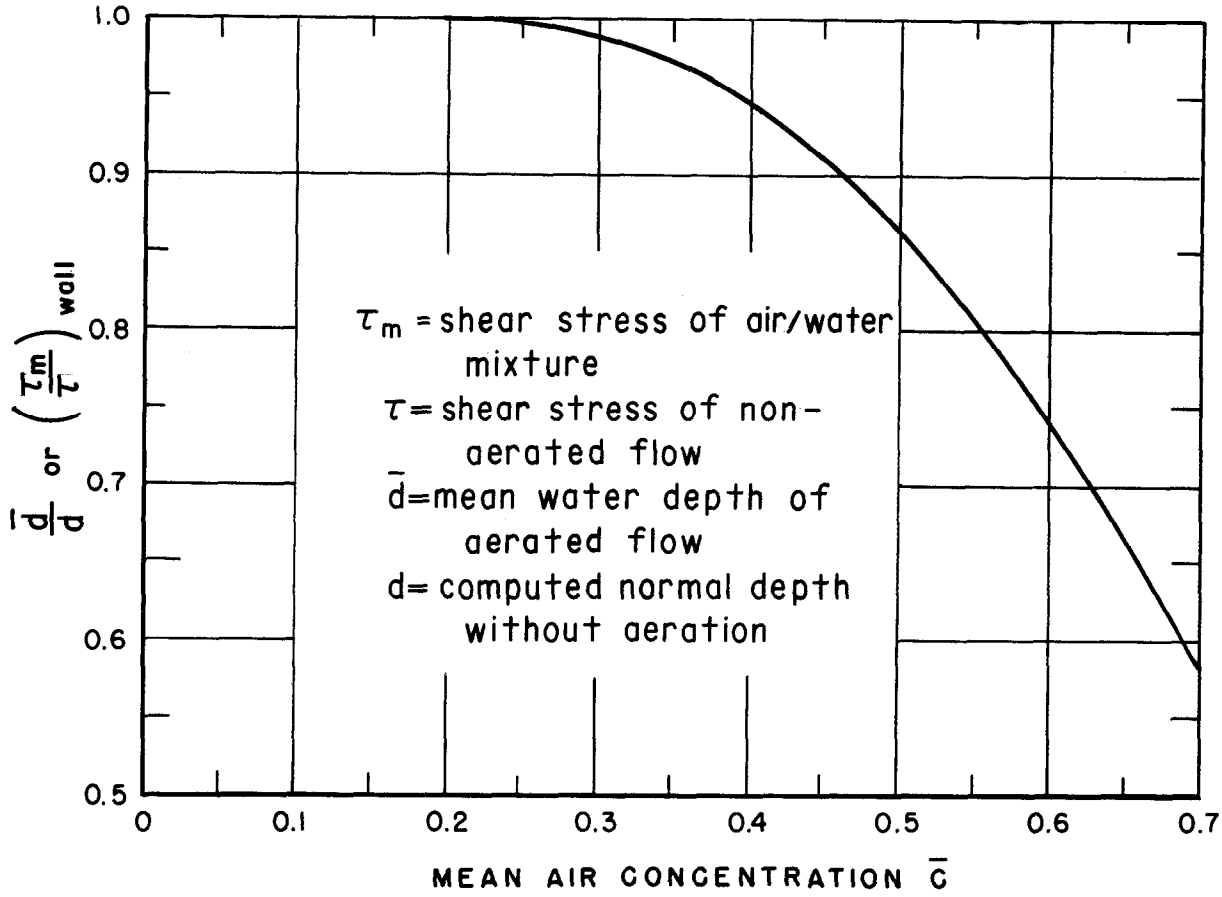


FIGURE 17.—*Relation of aerated to nonareated flow depth.*

obtained between the data and a Rayleigh probability density function. This function can be written as:

$$P_h = \eta \exp -(\eta^2/2) \qquad (63)$$

where

η = normalized wave height = M_o/s
M_o = wave height amplitude, (half crest to trough distance)
s = root-mean-square value of the wave height amplitudes
P_h = probability that the wave height is equal to the given height

Cartwright and Longuet-Higgins [13] used another description of the fluctuating water surface. They based their analysis on the maximum difference on elevation between a wave crest and the mean level of the water surface for a given wave period. These differences can be normalized by dividing them by the root-mean-square value of the water surface fluctuation about the mean water surface elevation. Since a crest can occur at an elevation below the mean water surface, the dimensionless crest elevations can have negative values. The specific shape of the distribution depends upon the relative width of the frequency spectrum E. This parameter defines a series of probability distributions that range from a Rayleigh to a Gaussian distribution (fig. 18). The value of the parameter E for ocean waves is about 0.6

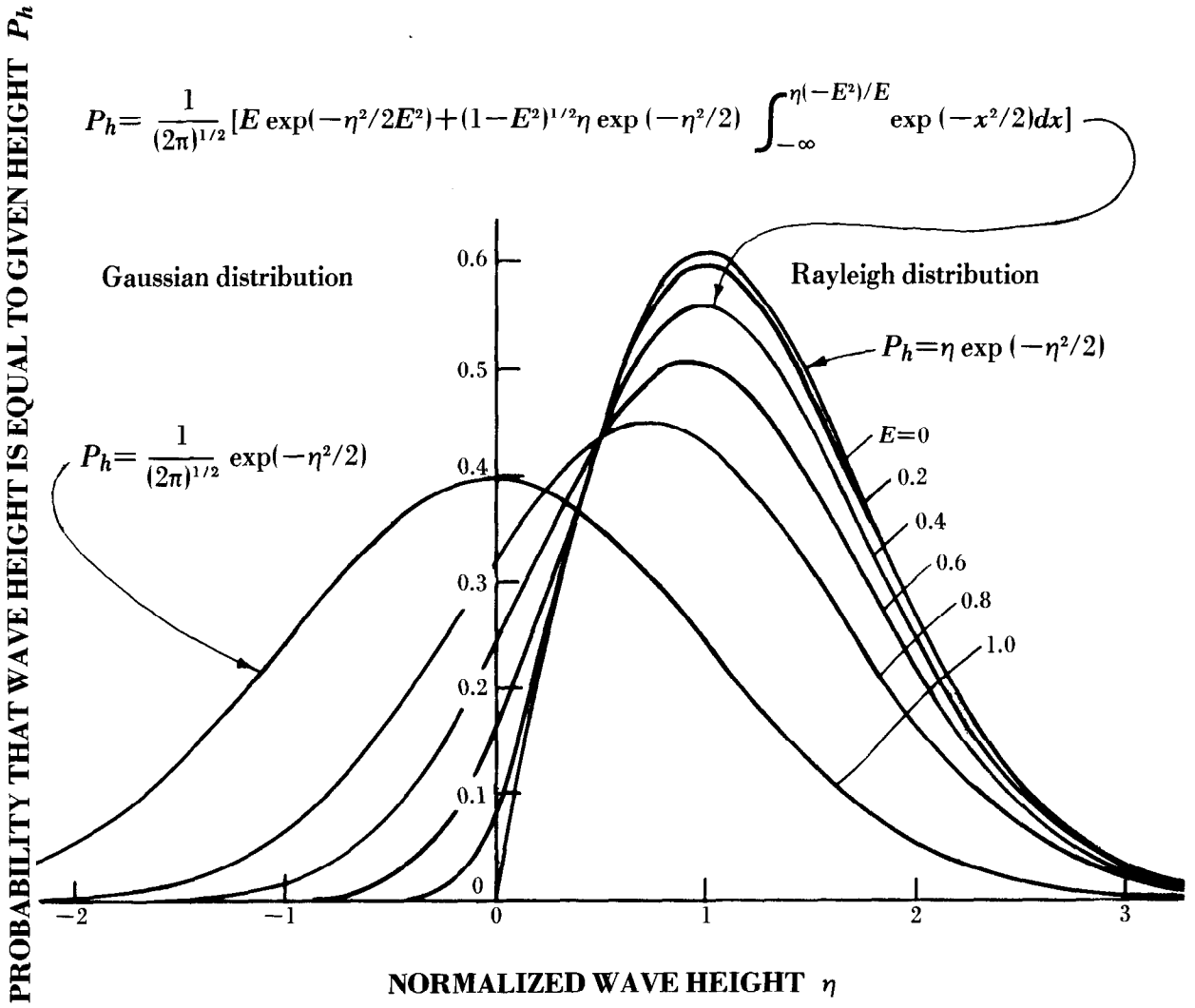


FIGURE 18.—*Probability density distribution for different values of the width of the energy spectrum.*

A third method of describing the water surface fluctuations is not based upon a definition of wave heights. Instead, the difference between the instantaneous water surface and the mean value of the water surface is used. This probabilistic description of the water surface is probably the most useful in hydraulic structures since designers require a knowledge of the mean flow depth and a measure of how frequently the water surface exceeds some specified elevation above the mean depth.

Unfortunately, very little research has been concerned with a probabilistic description of the water surface in open channel flow. Preliminary investigations in the laboratory indicate that the distribution of the water surface in fully developed, rough, open-channel flow is nearly Gaussian. If the distribution is Gaussian, a plot of the cumulative probability distribution versus flow depth will be a straight line on arithmetric probability paper (fig. 19). A wave depth probe of the type described by

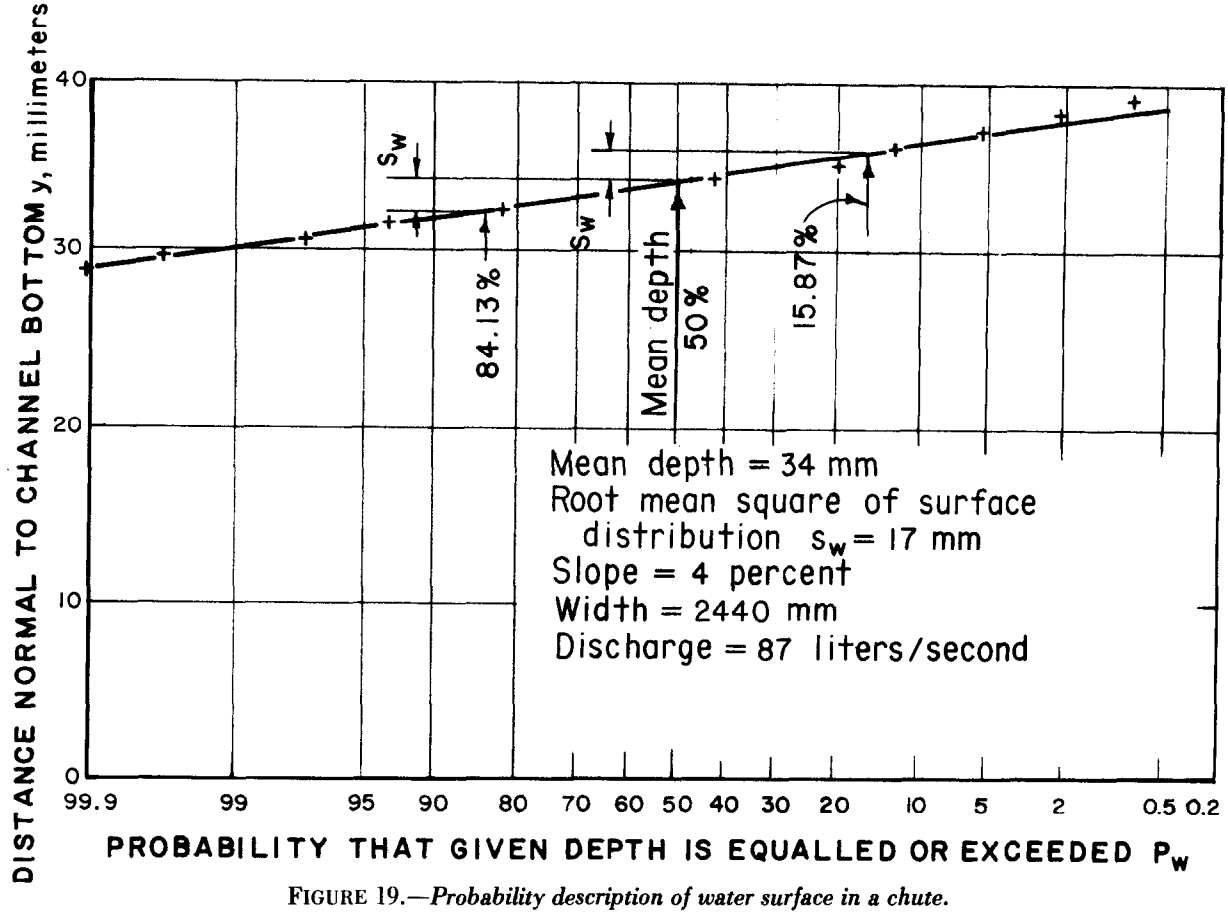


FIGURE 19.—*Probability description of water surface in a chute.*

Killen [41] or the circuitry given in appendix I can be used to measure the cumulative probability directly. The root-mean-square value of the water surface fluctuation can be read from the plot. The root-mean-square value is the difference between the depth having an 84.13-percent probability and the mean depth (50% probability). Alternatively, the mean depth and the 15.87-percent probable depth can be used.

Effect of Air Entrained Flow on Stilling Basin Performance

The effect of air entrained flow on the performance of stilling basins has been considered for many years. Gumensky [25] concluded that for all practical purposes the conjugate depth of the hydraulic jump could be determined from nonaerated flow equations. Rajaratnam [57] followed with some investigations that indicated a significant effect might be produced by the air entrainment. However, later studies by Herbrand [33] showed that the coefficients used in Rajaratnam's equations produced too large an effect on the result and that they were not necessary. Therefore, in rectangular channels the conjugate depth y_c can be calculated with sufficient accuracy from

$$y_c=0.5y_1(\sqrt{8F^2+1}-1) \tag{64}$$

where the depths and Froude numbers are calculated with the appropriate bulked flow depths (fig. 16).

Closed Conduit Flow

CLASSIFICATION OF FLOW

The conventional term for the concurrent flow of air and water is *two-phase* flow. Here, *phase* refers to one of the states of matter (gas, liquid, or solid). Technically the term two-phase flow should be reserved to describe the motion of a substance which is present in two of its phases, such as a flow of ice and water. The word *multicomponent* is a better description of flows which do not consist of the same chemical substance, such as air and water. If both components move in the same direction, the flow is termed *concurrent flow.* If the components move in opposite directions, the flow is *countercurrent.*

Closed conduit flow can be classified according to the type of pattern that develops. The flow patterns which develop depend upon the airflow rate relative to the waterflow rate and the slope of the conduit. For example, the flow patterns in horizontal conduits have been defined by Baker [7], (fig. 20). The correlation can be applied to other gases and liquids by substituting appropriate quantities into the following parameters:

G_g = mass velocity of gas, kg/(m^2·s)
G_l = mass velocity of liquid, kg/(m^2·s)
$\lambda = [(\varrho_g/\varrho_a)(\varrho_l/\varrho_w)]^{1/2}$
μ = dynamic viscosity, Pa·s
ϱ_g = gas density, kg/m^3
ϱ_a = air density (at 101.3 kPa and 20 °C) = 1.20 kg/m^3
ϱ_l = liquid density, kg/m^3
ϱ_w = water (at 101.3 kPa and 20 °C) = 988 kg/m^3
σ = interfacial surface tension, N/m
σ_{aw} = air-water surface tension (at 101.3 kPa and 20 °C) = 0.0728 N/m
$\psi = (\varrho_w/\varrho_l)[\mu(\varrho_w/\varrho_l)^2]^{1/3}$, Pa$^{1/3}$·s$^{1/3}$

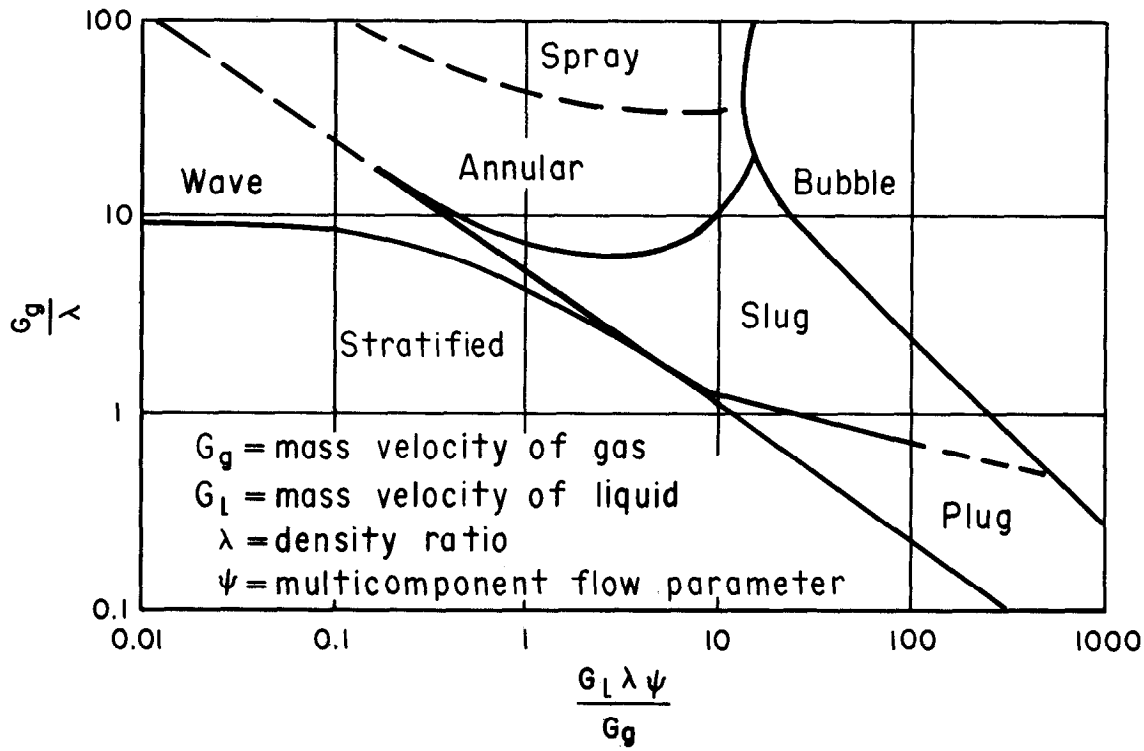


FIGURE 20.—*Flow patterns in horizontal pipes, Baker [7].*

These various flow patterns were described by Alves [1] according to the physical appearance of the flow as follows (fig. 21):

- **Bubble flow.**—The air forms in bubbles at the upper surface of the pipe. The bubble and water velocities are about equal. If the bubbles are dispersed through the water, the flow is called "froth flow."
- **Plug flow.**—For increased airflow rates the air bubbles coalesce with plugs of air and water alternately flowing along the top of the pipe.
- **Stratified flow.**—A distinct horizontal interface separates the air and waterflows.
- **Wave flow.**—As the airflow rate is increased, surface waves appear on the stratified flow interface.
- **Slug flow.**—Wave amplitudes are large enough to seal the conduit. The wave forms a frothy slug where it touches the roof of the conduit. This slug travels with a higher velocity than the average liquid velocity.
- **Annular flow.**—For greater airflow rates the water flows as a film on the wall of the pipe, while the air flows in a high-speed core down the axis of the pipe.
- **Spray flow.**—For very great airflow rates the annular film is stripped from the pipe walls and is carried in the air as entrained droplets.

A similar set of flow pattern descriptions exist for vertical flows. They are:

- **Bubble flow.**—The air is distributed in the water as spherical or spherical cap bubbles which are small with respect to the conduit diameter.

- **Slug flow.**—As the air flow increases, alternate slugs[5] of air and water move up the pipe. The transition from bubble flow to slug flow is shown on figure 22. This transition occurs when the bubble diameter is about one-half the conduit diameter.

If the vertical conduit is rectangular instead of cylindrical, the appropriate relation for slug flow is given by Wallis [73] as

$$\frac{V_s}{V_t} = \left(0.325+0.184\ \frac{D_s}{D_b}\right)\left(\frac{D_e}{D_s}\right)^{-1/2} \qquad (65)$$

where

D_s = larger dimension of a rectangular conduit
D_b = smaller dimension of a rectangular conduit
D_e = bubble diameter
V_s = terminal velocity of air bubbles in slug flow
V_t = terminal velocity of air bubbles in still water

With respect to the flow quantities, Martin [52] found that the transition from bubbly to slug flow occurs at a void fraction somewhere between 19 and 23 percent.

The void fraction θ is the average volumetric concentration in a length of pipe (assuming uniform flow) and expressed as

$$\theta = \frac{\omega_w}{AL} \qquad (66)$$

where

ω_w = volume of water
A = cross sectional area of conduit
L = length of conduit over which the volume ω_w is determined

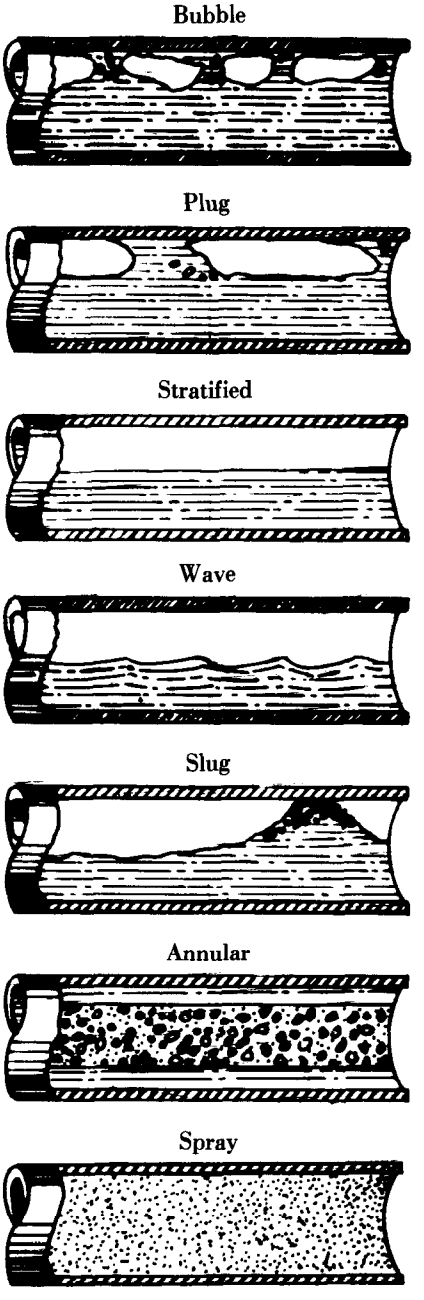


FIGURE 21.—*Flow pattern sketches, Alves [1].*

[5]It is not clear whether the term slug refers to a slug of air or a slug of water. The air bubble could be called a slug due to its bullet or slug shaped form. The water could be called a slug due to its similarity in form to the terrestrial gastropod in horizontal flows or due to its impact properties in vertical flow. The author prefers the reference to slugs of air.

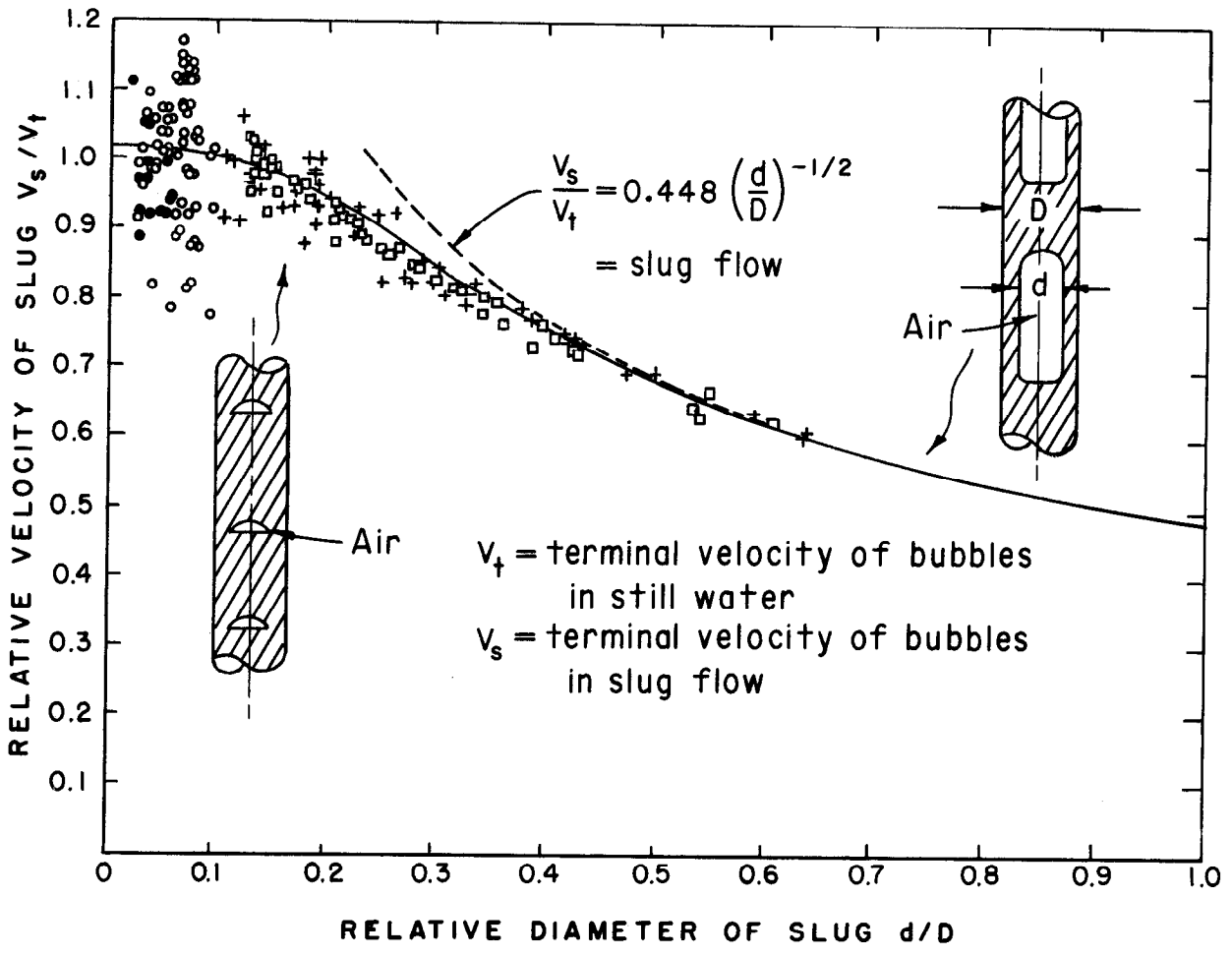


FIGURE 22.—*Effect of conduit diameter on terminal velocity of a bubble, Collins [16].*

- **Froth flow.**—As the airflow increases, the slugs break up into a turbulent disordered pattern of air and water.

The annular and spray flow patterns are identical in both vertical and horizontal pipes.

In hydraulic structures, the conduits may also be placed on a slope. The additional complexities in the flow patterns caused by slope will be discussed later.

From a designer's viewpoint, air-water flows in closed conduits can be classified into four general categories. Each category may contain only one or a combination of the flow patterns enumerated previously. These categories are:

1. Flow in partially filled conduits,
2. Flow having a hydraulic jump that fills the conduit,
3. Flow from control devices, and
4. Falling water surface.

Each category listed above is considered in detail in the following subsections.

In addition to the four categories of flow, two others are considered separately. These are:

- Flow in pipelines and siphons
- Flow in vertical shafts

The pipelines and siphons require special consideration because of their length. Vertical shafts present special problems because of the various types of flow which can exist in the shaft.

FLOW IN PARTIALLY FILLED CONDUITS

Model Predictions

Flow in a partially filled conduit can be thought of as open-channel flow in a closed conduit. The air flows through the passage which is formed above the water surface.

The total volume flow of air, which enters at the upstream end of the air passage, equals the sum of the air that is insufflated into the flow and that which flows above the water surface as a result of the air-water shear forces. The quantity of air insufflated into the flow can be estimated from equation 59. The quantity of air that flows above the water surface is a function of the waterflow properties and the pressure drop in the air vent. This can be expressed as

$$Q_a = f(L, V, g, p, y_e, \varrho_w) \qquad (67)$$

where

A = cross sectional area of water prism
g = gravitional constant (acceleration)
L = conduit length
p = pressure intensity
Q_a = total airflow rate
T = top width of flow passage
V = mean water velocity
y_e = effective depth = A/T
ϱ_w = water density

Applying dimensional analysis to equation 67 with y_e, V, and ϱ_w as the repeating variables gives

$$\frac{Q_a}{Q_w} = f\left(\frac{L}{y_e}, \frac{1}{F^2}, \frac{p/\gamma}{V^2/2g}\right) \qquad (68)$$

where

F = Froude number
Q_w = waterflow rate
γ = specific force of water

The interrelation between these parameters can be found for a specific geometry through the use of model studies.

There are many literature references that indicate model predictions often underestimate in the quantity of air which actually flows in prototype structures. However, very careful model tests in which all air- and waterflow passages were modeled in their entirety have shown good agreement between model and prototype measurements.

For instance, Sikora [65] showed that the airflow rates could be accurately predicted from model studies. His tests were with three geometrically similar models having scales of 1:1, 1:2, and 1:4 (fig. 23). The pressure values on the figure refer to the difference between atmospheric pressure and the air pressure at the upstream end of the waterflow passage.

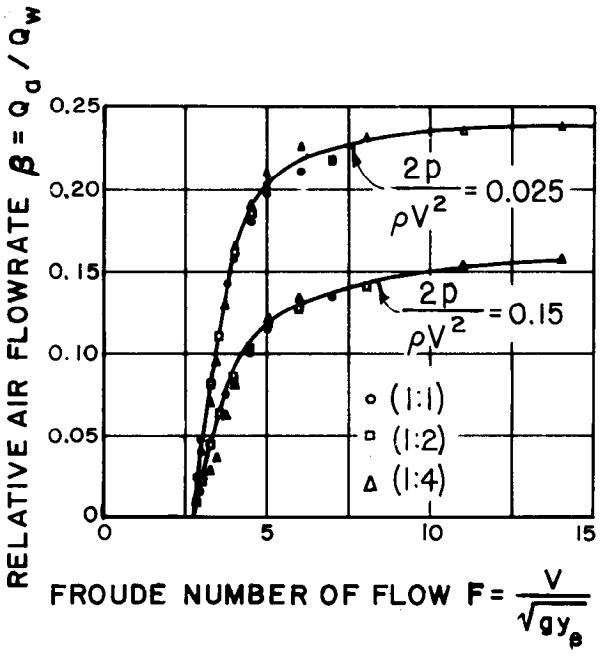


FIGURE 23.—*Influence of air pressure in conduit in airflow rate, Sikora [65].*

Harshbarger, Vigander, and Hecker [32] conducted 1:20 scale model and prototype tests of a gated tunnel discharge. Free-surface flow

existed in the tunnel for all discharges. A scale effect was not detectable in their investigations.

These studies clearly indicate that for estimating airflow rates using models, it is necessary to accurately reproduce the entire airflow passage above the water surface. In those cases where air enters the water conduit through a vent, two options are available for measuring the airflow rates. The options depend upon whether or not the air vent has been designed.

Air vent not designed.—If the air vent design has not been determined, it is necessary to measure the airflow rate while controlling the air pressure at the upstream end of the water conduit. These tests must be performed for a series of flow depths and flow rates in the water conduit.

The upstream air pressures can be controlled by incorporating an air pump into the airflow measuring device. To be applicable for all possible designs, the pressure should be varied over the maximum possible range. The lowest end of the range corresponds with the condition of no airflow through the vent. The upper end of the range is achieved when the upstream air pressure is equal to the atmospheric pressure.

A good example of this procedure is the work by Sikora [65] who developed a set of curves for the airflow in the horizontal leg of morning-glory spillway (fig. 24).

Once the family of curves for the airflow rates has been experimentally determined it is possible to investigate the effect of adding various size air vents to the structure. This is done by first developing an expression for the air vent characteristics in terms of the dimensionless parameters on figure 24.

For air velocities less than 100 m/s and values of $fL/4H \geq 4$, the volume flowrate Q_a through a vent can be expressed as

$$Q_a = A_v \left\{ 2g \frac{(\varrho_w/\varrho_a)[(p_{atm}/\gamma)-(p_1/\gamma)+\Delta z(\varrho_a/\varrho_w)]}{\sum K_s + fL/4H} \right\}^{1/2} \tag{69}$$

where

A_v = cross sectional area of vent
f = Darcy-Weisbach friction factor
g = gravitational constant (acceleration)
H = hydraulic radius of prototype air vent
K_e = entrance loss
K_s = singular (form) loss in vent, the greatest of which is the entrance loss $K_e = 0.5$
L = vent length
p_1 = pressure at vent exit
p_{atm} = atmospheric pressure
Δz = difference between vent intake and vent exit elevations
γ = specific force of water
ϱ_a = air density
ϱ_w = water density

Volume flowrate of water can be expressed as

$$Q_w = A\left[2g\left(\frac{V^2}{2g}\right)\right]^{1/2} \tag{70}$$

where

A = cross sectional area of water prism
V = mean waterflow velocity in conduit

Using these two expressions, the dimensionless airflow rate β can be expressed as

$$\beta = \frac{Q_a}{Q_w} = \frac{A_v}{A}\left\{\frac{\varrho_w/\varrho_a}{\sum K_s + fL/4H}\left[\frac{(p_{atm}/\gamma)-(p_1/\gamma)}{V^2/2g}\right]\right\}^{1/2} \tag{71}$$

when $\Delta z \frac{\varrho_a}{\varrho_w}$ is negligible.

The first ratio inside the brackets is a function of the fluid properties, the singular losses, and the flow geometry. The second ratio is in the form of a pressure factor or Euler number. By using this equation, the characteristics of a given vent can be plotted on the dimensionless airflow curves (fig. 24). The intersection points

A = cross sectional area of water prism
A_d = cross sectional area of conduit
d_e = deflector height
F = Froude number = $\frac{V}{\sqrt{gy_e}}$
ρ = air density
g = gravitational constant
p = pressure at end of air vent
Δp = pressure drop across vent
Q_a = volume flowrate of air
Q_w = volume flowrate of water
V = mean flow velocity
y_e = effective depth

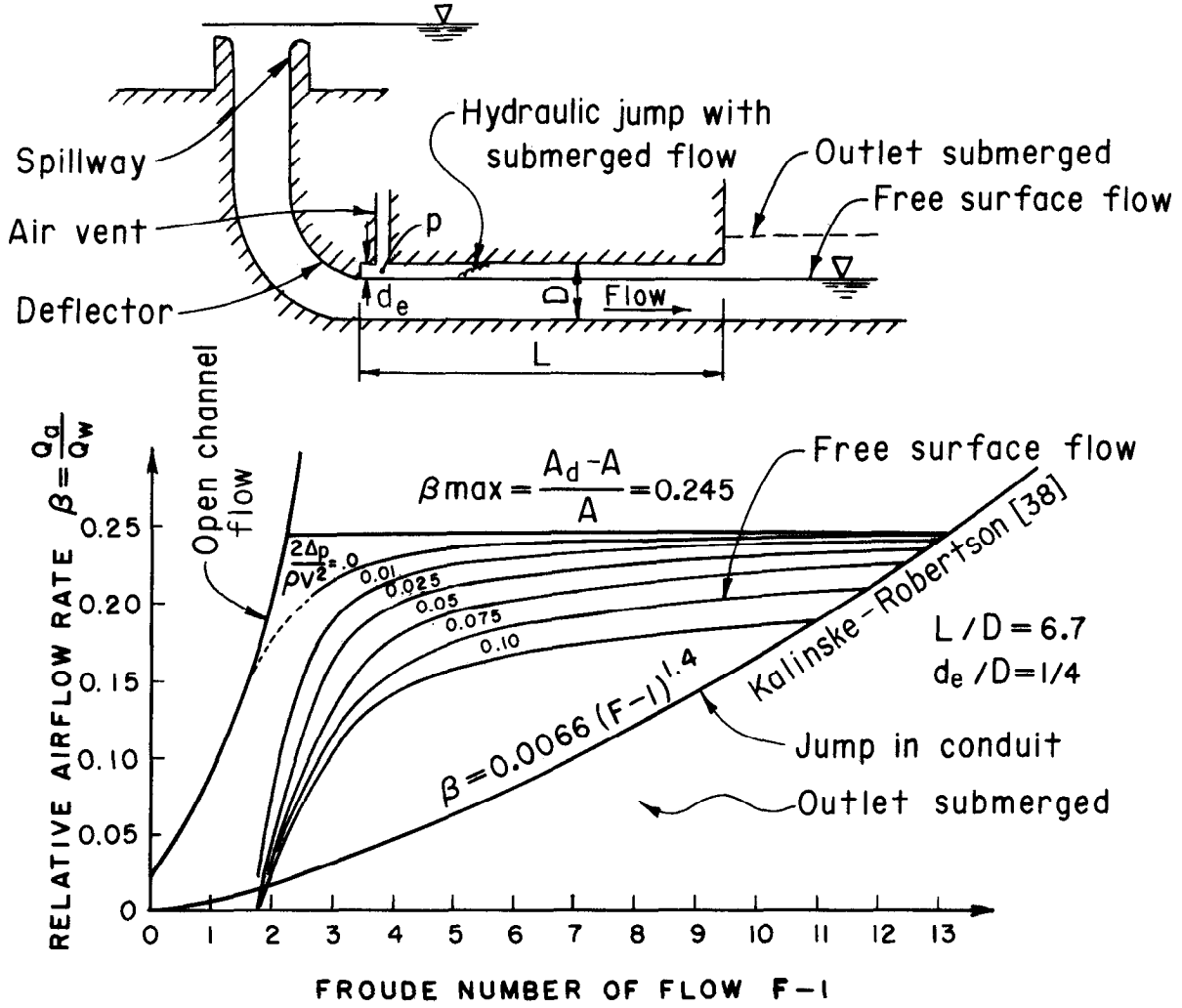


FIGURE 24.—*Model tests on a spillway, Sikora [65].*

of the two sets of curves gives the pressures and airflow rates for a given set of air vent parameters. If the resulting values are not satisfactory, another set of vent characteristics is chosen and the process repeated.

Air vent designed.—For some studies the design of the air vent is available. In these cases it is necessary to calculate the total loss for the vent and to simulate this loss in the model air vent. The loss for the prototype and the model must include both frictional and form losses. Normally, the air vent velocities are kept low enough so that incompressible loss coefficients are valid. The model air vent is simulated correctly when the loss coefficients in the model and prototype vents are made equal. If devices such as nozzles or orifices are installed into the model air vent for flow measurement purposes, the loss across them must be included in computing the total model air vent loss coefficient. In the case of an orifice, its loss coefficient often constitutes the entire loss for the model air vent. It is possible to express the required orifice size as

$$A_o = \frac{A_v}{C_o L_r^2 \left(1 + \sum K_s + fL/4H\right)^{1/2}} \qquad (72)$$

where

A_o = orifice area
A_v = prototype air vent area
C_o = orifice discharge coefficient
f = Darcy-Weisbach factor for prototype air vent
H = hydraulic radius of prototype air vent
K_s = singular losses (including entrance, bends, and changes in area)
L = length of prototype air vent
L_r = prototype to model scale ratio

If the orifice is placed on the end of the model air vent pipe, its discharge coefficient is obtained from figure 25.

Analytic Estimates

In many instances, model tests for predicting the airflow rates have not been performed. For these cases, the airflow rates often can be estimated closely enough by an approximate method. For this estimation three rather gross assumptions must be made, namely:

1. The amount of air flowing through the vent is a function of only the air insufflated into the flow and the air that is induced to flow by the moving water boundary,
2. The amount of air insufflated into the flow can be predicted by open channel flow equations, and
3. The air motion above the water surface is determined solely by the boundary layer δ thickness at the most downstream conduit location.

These assumptions neglect the fact that air actually can enter from the downstream end of the conduit. Schlichting [63] showed that with Couette-Poiseuille[6] flow in the laminar region, a flow reversal occurs when

$$\mathbf{P}_o = \frac{h_a^2}{2\mu V_o}\left(\frac{dp}{dx}\right) \leqslant -1 \qquad (73)$$

[6]The dimensionless parameter $\mathbf{P}_o$ is known as the Poiseuille number. Its primary use is in the laminar fluid friction field. For example, in a round circular pipe, the Poiseuille number is equal to 32. In this case the pipe diameter is substituted for the height of the airflow passage in equation 73. Couette flow exists between two parallel walls when one wall is moving and the other is stationary. The motion is due solely to the shear field created by the relative movement of the two walls. Couette flow has no pressure gradient in the direction of flow. Couette-Poiseuille flow describes a Couette type flow having a longitudinal pressure gradient. Turbulent Couette-Poiseuille flow should describe the air motion above a moving water surface in a closed conduit.

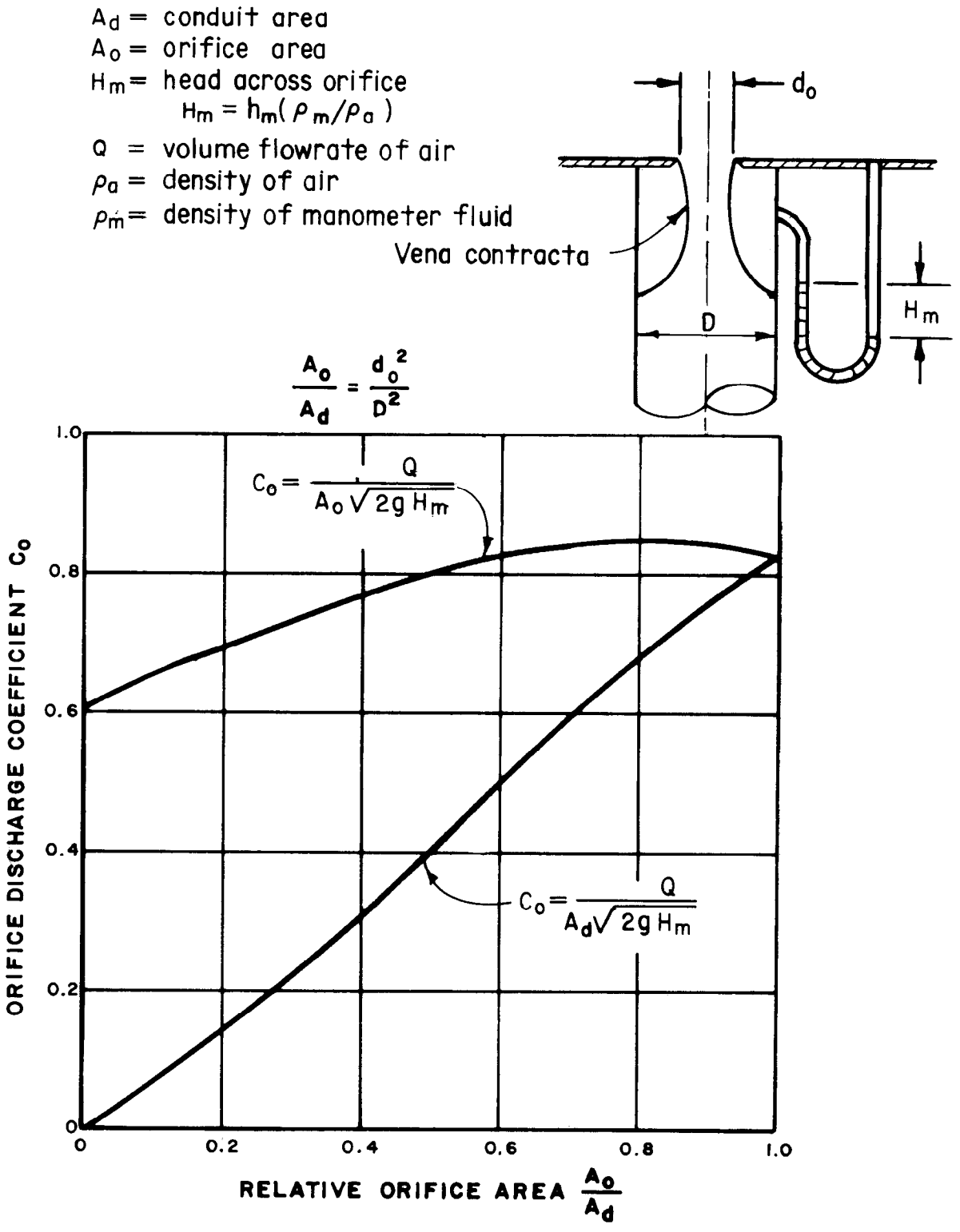


FIGURE 25.—*Discharge coefficients for orifice at end of pipe.*

where

h_a = height of airflow passage
dp/dx = pressure gradient in the air
V_o = maximum water surface velocity
μ = dynamic viscosity of air

Leutheusser and Chu [48] have investigated Couette flow in the turbulent region. Insufficient tests have been made to determine the magnitude of the dimensionless parameter P_o for the turbulent Couette-Poiseuille flow. However, some laboratory tests indicate that with turbulence, reverse flow begins when

$$P_o \approx -1000 \tag{74}$$

The amount of air flowing above the water surface can be visualized by considering a boundary layer which increases in thickness from a value of zero at a gate, to a maximum value at the end of the conduit (fig. 26). The growth of a turbulent boundary layer that is induced by a moving rough boundary has not been studied. As a first approximation it is assumed that

$$\delta = 0.01x \tag{75}$$

where

δ = boundary layer thickness
x = distance from gate

The velocity distribution within the boundary layer is assumed to obey a power law of the order:

$$u = V_o\left(\frac{y_a}{\delta}\right)^{1/n_v} \tag{76}$$

where

n_v = velocity distribution power law coefficient
u = local air velocity
V_o = maximum water surface velocity
y_a = distance from the water surface
δ = boundary layer thickness

The value of the coefficient n_v varies between 10 for flow over smooth surfaces to 5.4 for flow over rough surfaces when the Reynolds number is about 10^6. Normally n_v is assumed to be equal to 7. This approach is similar to that used by Campbell and Guyton [12] except they assumed the boundary layer always coincided with the roof of the conduit.

The boundary layer entrains the maximum amount of air at the extreme downstream location in the conduit. To maintain continuity, flow at upstream locations consists of boundary layer flow plus some mean flow (fig. 26). The air velocity at the water surface must be equal to the water velocity. Therefore, at the upstream locations, the air velocity above the water surface may have a larger magnitude than that at the water surface. Careful laboratory experiments by Ghetti [24] of the Vaiont Dam (Italy) gated outlets show that the maximum air velocity near the water surface at the vent can be as much as four times the water velocity.

For some flow conditions the boundary layer will reach the roof of the conduit. When this happens the roof will begin to retard the flow. If the water surface and the roof of the conduit had equal roughness values, the maximum flow rate would be given by turbulent plane Couette flow. For this case the maximum airflow rate Q_m is

$$Q_m = \frac{A_a V_o}{2} \tag{77}$$

where

A_a = cross sectional area of airflow passage (rectangular)
V_o = maximum water surface velocity

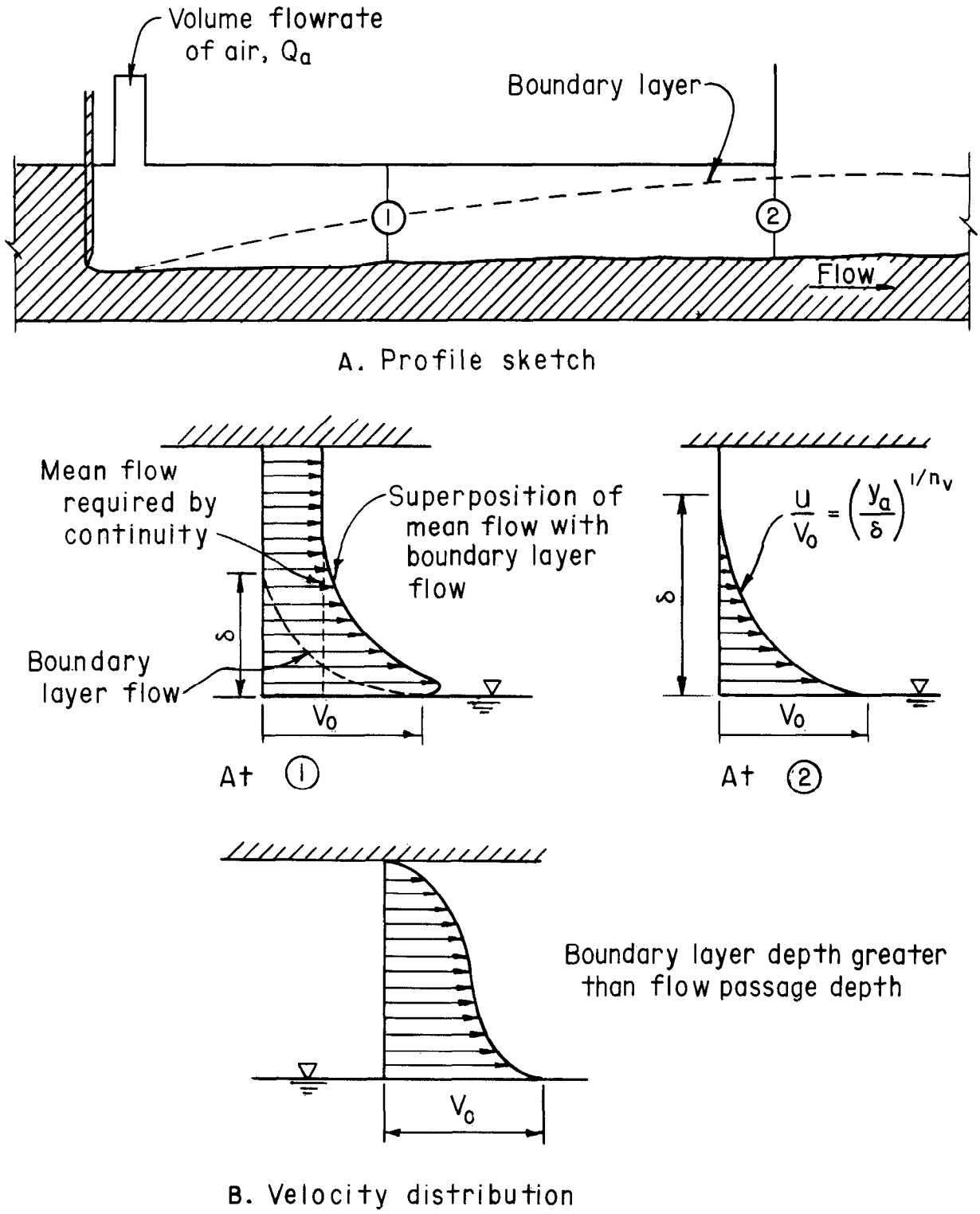


FIGURE 26.—Airflow above water surface.

Actually the roughness of the water surface is greater than that of the conduit roof. This increased roughness will produce higher air velocities near the water surface which result in airflow rates greater than those given by equation 77. Sikora [65] reasoned that the mean air velocity could not exceed the mean water velocity. This leads to the expression for the maximum possible airflow rate in a closed conduit, which is

$$\left(\frac{Q_a}{Q_w}\right)_{max} = \frac{A_d}{A} - 1 \qquad (78)$$

where

A_d = cross sectional area of conduit
A = maximum cross sectional area of water prism

Application of equation 78 without regard to the boundary layer thickness will result in excessively large values of the airflow rates. However, for design purposes, this approach may be satisfactory since the resulting air vent will be oversized.

FLOW HAVING A HYDRAULIC JUMP THAT FILLS THE CONDUIT

Kalinske and Robertson [38] studied the special case of two-layer flow in which a hydraulic jump fills the conduit. From dimensional analysis and model studies, they determined that the amount of air entrained by the jump is given by

$$\frac{Q_a}{Q_w} = 0.0066\,(\mathrm{F}-1)^{1.4} \qquad (79)$$

where F = Froude number upstream of the hydraulic jump.

In a circular pipe the Froude number can be calculated conveniently from the flow depth y using

$$\mathrm{F} = \frac{V}{(gy_e)^{1/2}} \qquad (80)$$

where

A = cross sectional area of water prism
D = conduit diameter
T = top width of flow passage $= 2[y(D-y)]^{1/2}$
g = gravitational constant (acceleration)
V = mean flow velocity
y_e = effective depth $= A/T$
y = flow depth

Equation 79 is good only if all air entrained is passed downstream. Prototype tests—for which a hydraulic jump formed in the conduit and in which the conduit velocities were large enough to convey all the entrained air out of the conduit—confirm the experimentally derived curve (fig. 27).

If the conduit is horizontal or sloping upward in the direction of flow then all the entrained air will move with the flow. However, if the conduit slopes downward in the direction of flow air bubbles can either move upstream or downstream relative to the pipe wall.

The direction of movement taken by the bubbles can be examined by considering the relative magnitudes of the buoyant and drag forces upon a stationary bubble in the flow (fig. 28). For example, the bubble will move perpendicular to the pipe axis only when the upstream component of the buoyant force vector equals the drag force component. This can be written as

$$(\varrho_w - \varrho_g)\frac{\pi D_e^3}{6}(gS_o) = C_b\frac{\pi D_e^2}{4}\left(\frac{\varrho_w V^2}{2}\right) \qquad (81)$$

where

C_b = drag coefficient on bubble
D_e = equivalent bubble diameter
S_o = pipe slope = sin α

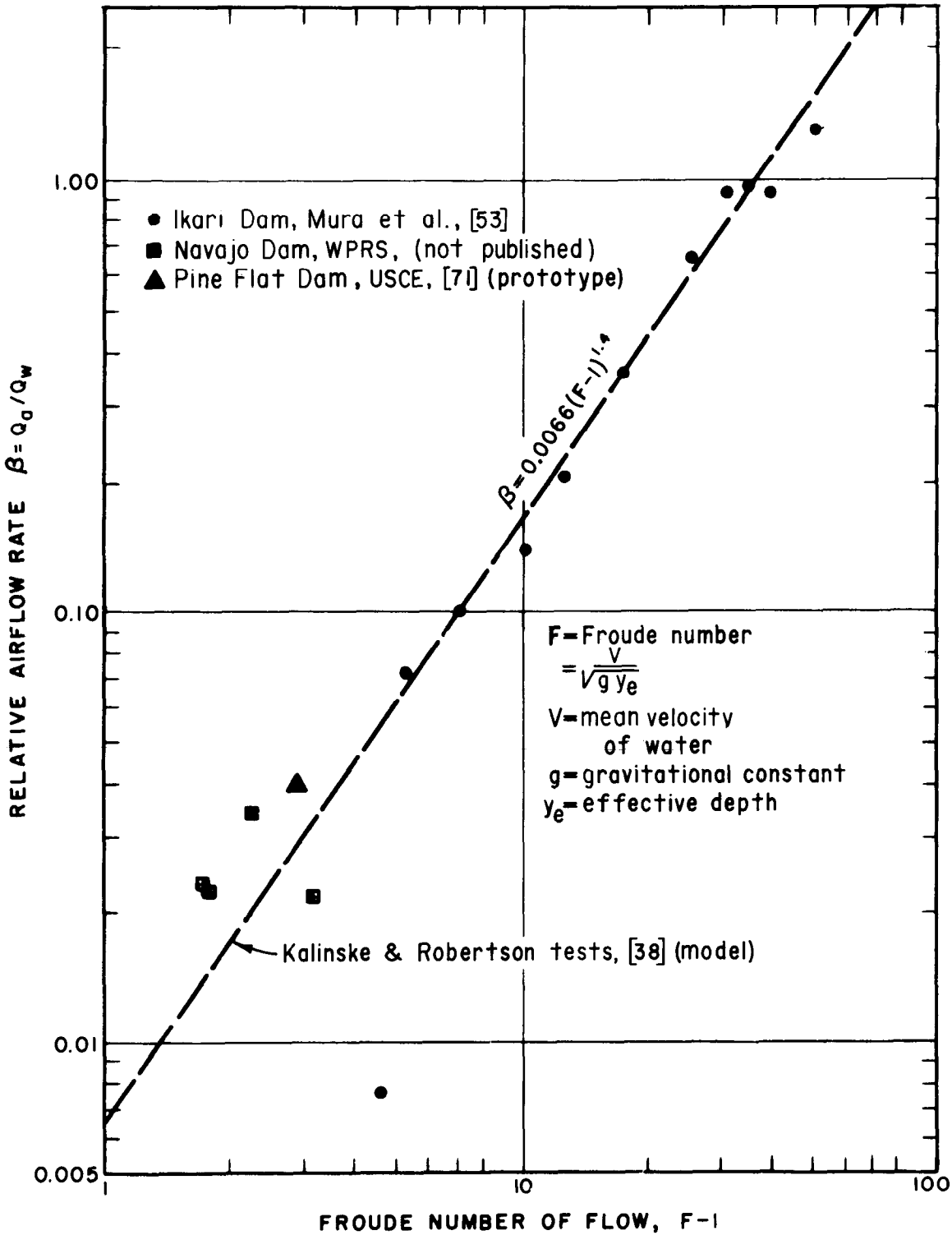


FIGURE 27.—*Air entrainment with hydraulic jump closing conduit.*

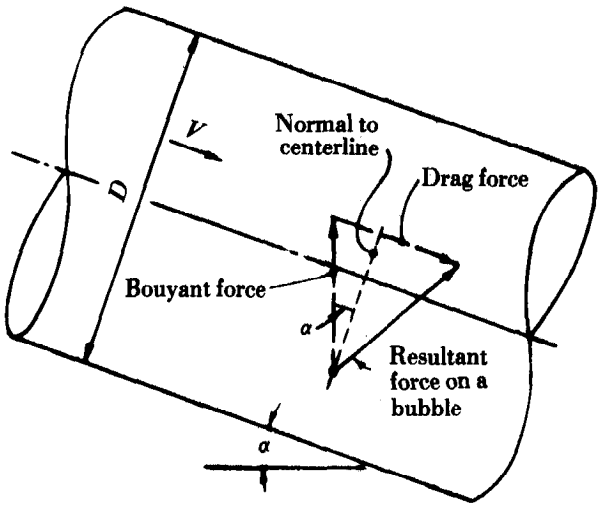


FIGURE 28.—*Forces on a stationary bubble.*

Rearranging terms and dividing by the conduit diameter gives

$$\frac{V^2}{gD} = \frac{4}{3}\left[1-(\varrho_g/\varrho_w)\right]\frac{D_e}{D}\left(\frac{S_o}{C_b}\right) \qquad (82)$$

or

$$\frac{Q_c^2}{gD^5} = \frac{\pi^2}{12}\left[1-(\varrho_g/\varrho_w)\right]\frac{D_e}{D}\left(\frac{S_o}{C_b}\right) \qquad (83)$$

where

Q_c = critical discharge needed to carry bubbles with the flow
D = conduit diameter

This relation shows that the critical discharge for bubble motion is a function of the effective bubble diameter D_e, the densities, ϱ, the drag coefficient C_d of the bubble, and the pipe slope S_o. Unfortunately, the drag coefficient and effective bubble diameter can not be predicted for flow in a pipe. Therefore, the techniques of dimensional analysis must be used to determine the significant parameters for correlations.

As was shown under Design Parameters—*Mean air concentration*, the effective bubble diameter is a function of the interfacial surface tension and the friction slope. In terms of dimensionless parameters, the critical discharge required to move the bubbles can be expressed as

$$\frac{Q_c^2}{gD^5} = f\left(\frac{\gamma D^2}{\sigma}, S_f, S_o, C_b\right) \qquad (84)$$

The parameter $\frac{\gamma D^2}{\sigma}$ is designated frequently as the Eötvös number E.

Kalinske and Bliss [37] found relatively good correlations for the initiation of bubble movement by using only the pipe slope S_o and the Eötvös number. Data by Colgate [15] also fits their curves relatively well (fig. 29).

Additional studies are required to define the bubble motion curve (fig. 29) for slopes greater than 45 degrees. Martin [52] showed that a stationary air pocket forms when the dimensionless discharge Q_w^2/gD^5 is equal to 0.30 for vertically downward flow. Therefore, the increasing trend of the curve in figure 29 probably does not continue past the 45-degree slope.

As the bubbles travel downstream in sloping conduits, they tend to rise to the top of the conduit and form large pockets of air. Runge and Wallis [61] discovered that the rise velocity of these pockets is greater in sloping conduits than it is in vertical conduits (fig. 30). For a specific range of discharge, a flow condition can exist whereby bubbles will move downstream and form into pockets that move against the flow in an upstream direction.

Sailer [62] investigated prototype cases in which large air pockets moved against the flow with sufficient violence to completely destroy reinforced concrete platforms. The reverse flow region has been delineated on figure 29 using the data of Colgate [15] and the slug-flow curve of figure 30. The five structures pointed out by Sailer as having experienced blowbacks are indicated by crosses on figure 29. It is noted that

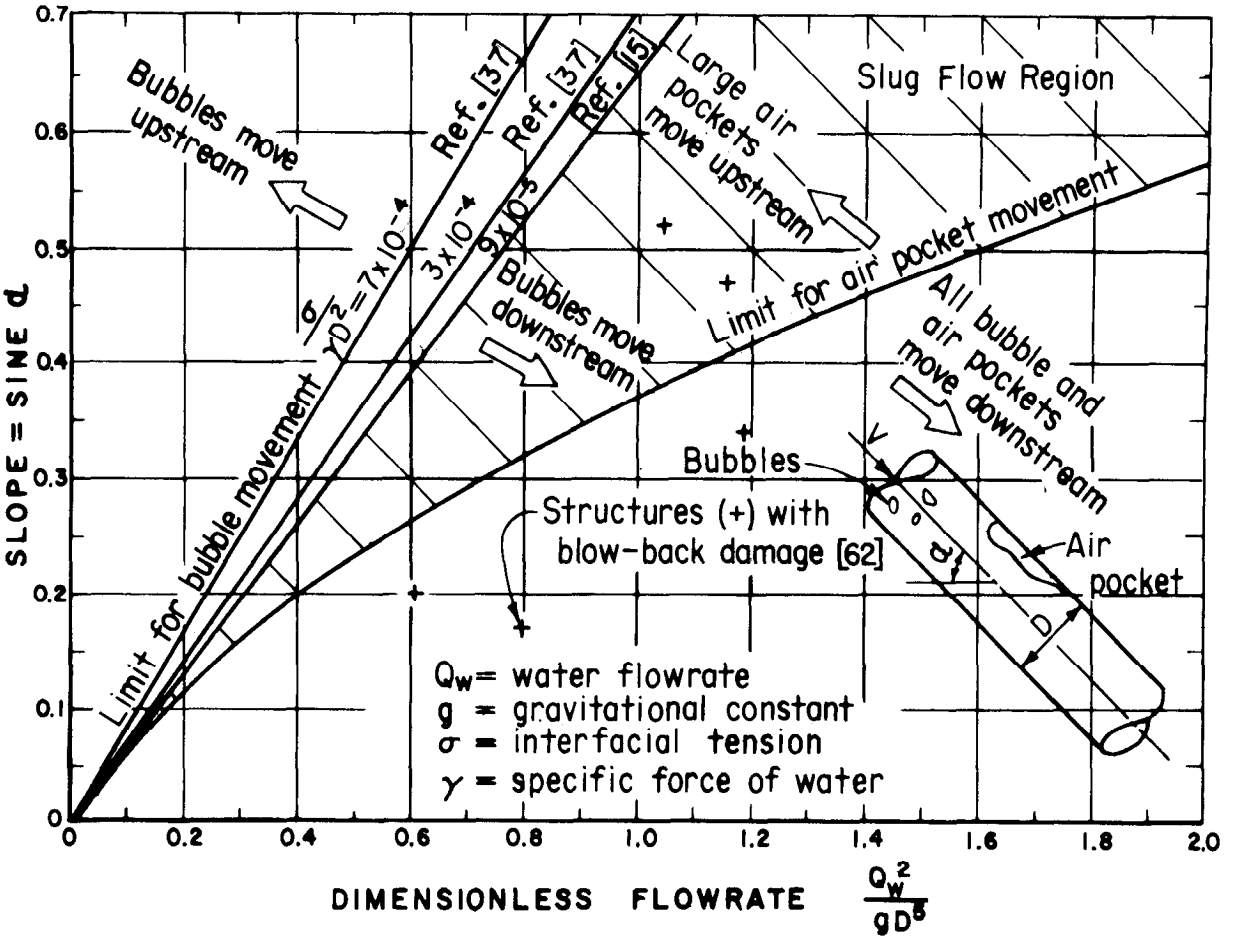


FIGURE 29.—*Bubble motion in closed conduits flowing full.*

two of these structures lie within the blowback zone at design discharge. The other three must pass through the blowback zone in coming up to the design discharge. For pipe slopes less than 0.1, the width of the blowback zone is so small that problems normally are not experienced.

FLOWS FROM CONTROL DEVICES

Flows from control devices refer to cases in which the primary cause of the air demand is due to the waterflow conditions at a control device. Two types of flow control devices that will be considered are gates and valves. These devices also induce air movement in open channel flows. However, in unconfined flows the water movement does not cause low pressures which must be relieved by air vents.

A distinction is made in the field of hydraulic machinery between valves and gates even though both serve as flow control in a closed conduit. A valve is a device in which the controlling element is located within the flow (fig. 31). A gate is a device in which the controlling element is out of the flow when it is not controlling and which moves transverse to the flow when controlling (fig. 31). The jets from gates are different than those from valves; therefore, the two cases are considered separately.

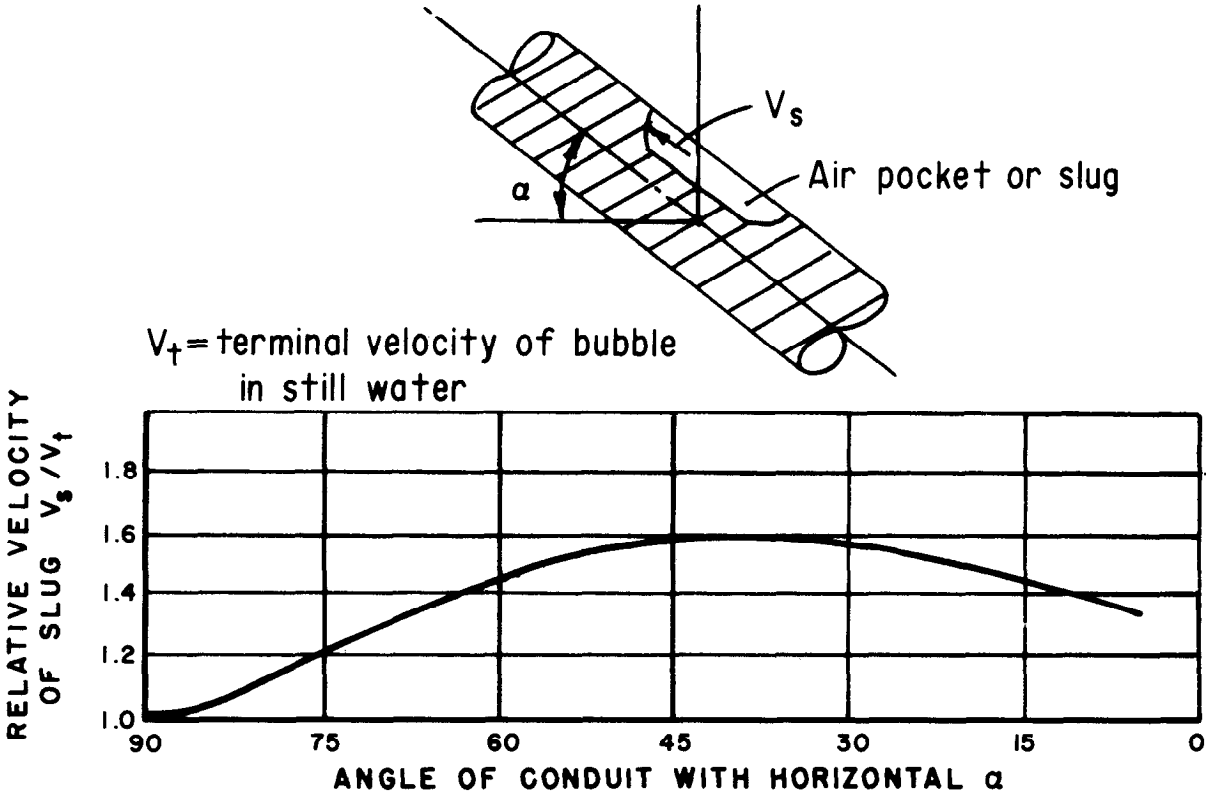


FIGURE 30.—*Slug flow in inclined pipes, Runge and Wallis [61].*

Flows From Valves

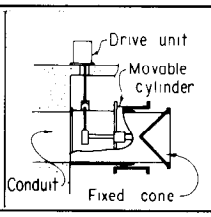
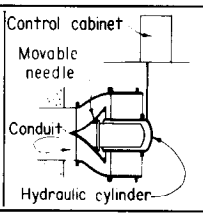
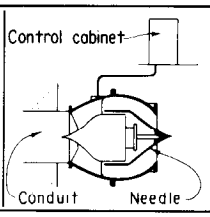
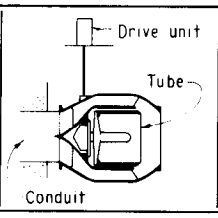
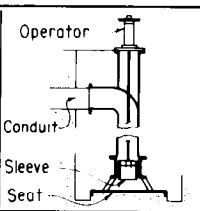
Around the beginning of the 20th century, many outlet valves were placed on or near the upstream faces of the dams. Nearly all were severely damaged by cavitation erosion. Since a satisfactory method could not be found to reduce or eliminate the damage at all gate positions, the operating ranges of these valves were severely restricted. Because of this limitation, the location of the throttling valves was shifted to the downstream side of the dam. Present practice is to avoid placement of throttling valves within the conduit. Nevertheless, from time to time it is necessary to place the valves within the conduits. This is especially true when the downstream conduit is a tunnel—when spray could cause icing problems—and when a flow control station is placed in a pipeline.

If stratified or wave flow exists downstream of the valve, air is induced to move by a relatively low water velocity acting over a large surface area. However, if the flow from the valve impinges on the downstream conduit walls, the airflow is induced by high velocity waterjet acting over a relatively small surface area. In this case, the significant airflow parameters are the:

- Kinetic energy of the waterflow,
- Gate opening, and
- Air pressure at some characteristic location.

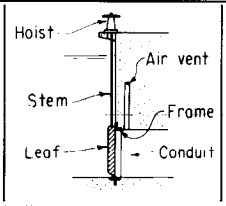
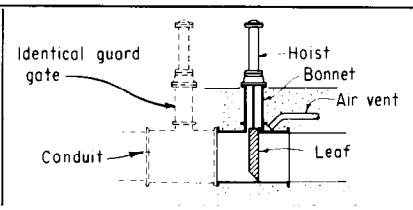
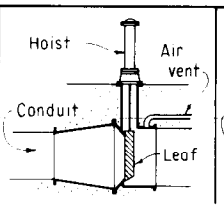
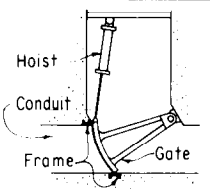
Parameters such as length of conduit downstream of the valve and the Froude numbers of the downstream flows are obviously of lesser importance.

THROTTLING VALVES

SERVICE CLASSIFICATION	FIXED-CONE VALVE	HOLLOW-JET VALVE	NEEDLE VALVE	TUBE VALVE	SLEEVE VALVE
SCHEMATIC DIAGRAM FLOW DIRECTION →					
Maximum head (approximate)	300 m	300 m	300* m	90 m	75* m
Discharge coefficient (a)	0.85	0.70	0.45 To 0.60	0.50 To 0.55	0.80
Submerged operation	Yes (1)	No (1)	No	Yes	Yes (1)
Throttling limitations	None	Avoid very small discharge	None	None	None
Spray	Very heavy (2)	Moderate	Small	Moderate (1)	None
Leakage	None	None	None	None	None
Nominal size range, diameter (b)	200- to 2740-mm	760- to 2740-mm	250 to 2440-mm	910- to 2440-mm	310- to 610-mm*
Availability	Commercial standard (3)	Special design	Special design	Special design	Special design
Maintenance required	Paint	Paint	Paint (1)	Paint	Paint
COMMENTS AND NOTES:	(1) Air-venting required. (2) Spray rating will change to moderate if a downstream hood is added. (3) Valves are not "stock" items but standard commercial designs are available.	(1) Submergence to centerline of valve is permissible.	(1) If water operation is used, disassembly at 3 to 5 year intervals for removing scale deposits is usually unecessary.	(1) Spray is heavest at openings of less than 35%. At the larger openings the rating would be better than moderate.	(1) Valve is designed for use only in fully submerged conditions. (2) Larger sizes seem feasible and will probably be developed.

(a) Coefficients are approximate and may vary somewhat with specific designs.
(b) Size ranges shown are representative, and are not limiting.

THROTTLING GATES

SERVICE CLASSIFICATION	UNBONNETED SLIDE GATE	BONNETED SLIDE GATES: "HIGH PRESSURE" TYPE	BONNETED SLIDE GATES: STREAMLINED TYPE	JET-FLOW GATE	TOP-SEAL RADIAL GATE
SCHEMATIC DIAGRAM FLOW DIRECTION →					
Maximum head (approximate)	25 m	60 m	150* m	150* m	60-75 m
Discharge coefficient (a)	0.6 To 0.8	0.95	0.97	0.80 To 0.84	0.95
Submerged operation	No	No	Yes (1)	Yes (1)	No
Throttling limitations	Avoid very small discharge	Avoid very small discharge	Avoid very small discharge	None	None
Spray	Minimum	Minimum	Minimum	Small	Minimum
Leakage	Small	Small	Small	None	Small to moderate
Nominal size range (b)	3660-wide & 3660-mm high	1830-wide & 2740-mm high	3050- to 6100-mm high	250- to 3050-mm dia.	4570-wide & 9140-mm high
Availability	Commercial standard (1)	Special design	Special design	Special design	Special design
Maintenance required	Paint	Paint	Paint (2)	Paint	Paint-seals (1)
COMMENTS AND NOTES:	(1) Gates are readily available from several commercial sources. They are not an "off-the-shelf" item, however.		(1) Air vents required (2) Use of stainless steel surfaced fluidways, will reduce painting requirements and cavitation damage hazard.	(1) Air vents required	(1) Seal replacement in 5-15 years is probable depending on design and use.

(a) Coefficients are approximate and may vary somewhat with specific designs.
(b) Size ranges shown are representative, and are not limiting

FIGURE 31.—*Valve and gate data, Kohler [44].*

Colgate [14] made model studies of airflows in valves having a fixed-cone.[7] His results were given in terms of gate opening and discharge. Transforming these values into the appropriate dimensionless parameters results in good correlations for all conditions that were tested (fig. 32). In this case, the kinetic energy of the flow is proportional to the total upstream head. Thus

$$\frac{Q_a}{Q_w} = f\left(G, \frac{\Delta p/\gamma}{H_t}\right) \tag{85}$$

where

G = gate opening in percent
H_t = total potential and kinetic energy (upstream)
$\Delta p/\gamma$ = differential between atmospheric pressure and air pressure at end of vent
γ = specific force of water

Once curves like those presented in figure 32 are developed, it is possible to determine the airflow rates through any air vent that is connected to the structure by using equation [71]. To perform the determination, equation 71 is plotted on figure 31. The intersections of the two sets of curves give the airflow rates for any particular vent.

Flows From Gates

At small gate openings, a considerable amount of spray is produced by flow which impinges in gate slots. This spray induces considerably more air movement than that produced by stratified or wave flow. In a sense, the effect of spray in producing air movement is similar to that of flow from valves. However, with spray the jet does not impinge on the walls of the downstream conduit; therefore, a seal does not form.

The significant parameters for flow with spray are the same as those for flow from valves; i.e.,

- Gate opening,
- A reference air pressure, and
- The total upstream energy.

Model studies can be used to obtain estimates of the airflow rates which can be expected when spray is present.

As the gate opening increases, the amount of spray decreases. Typically, spray is not significant for openings greater than 10 or 20 percent. The exact percentage depends upon the design of the gate. For the larger openings, the airflow rate is controlled by the two-layer flow relations. That is, the significant parameters are:

- Length of conduit,
- Froude number of the flow, and
- Air pressure at some reference location.

For jet-flow gates a point is reached—as the gate opening increases above some value—where the flow impinges on the downstream conduit. Typically this occurs at a 50- to 60-percent opening. With impinging flow, the airflow rate is correlated with the parameters used for flow from fixed-cone valves. For this type of flow, the length to diameter ratio of the conduit is significant only if the downstream conduit length is less than the distance to the impingement point or if the adverse pressure gradient is large.

FALLING WATER SURFACE

A falling water surface in a closed conduit induces airflow in the conduit. This flow is analogous to that induced by a piston in a cylinder; the water corresponds to the piston. A typical example of this type of flow occurs during an emergency closure of the intake gate to a penstock (fig. 33). As the gate closes, water flowing into the penstock from the reservoir is

[7] The fixed-cone valve is also called a Howell-Bunger valve after its inventors.

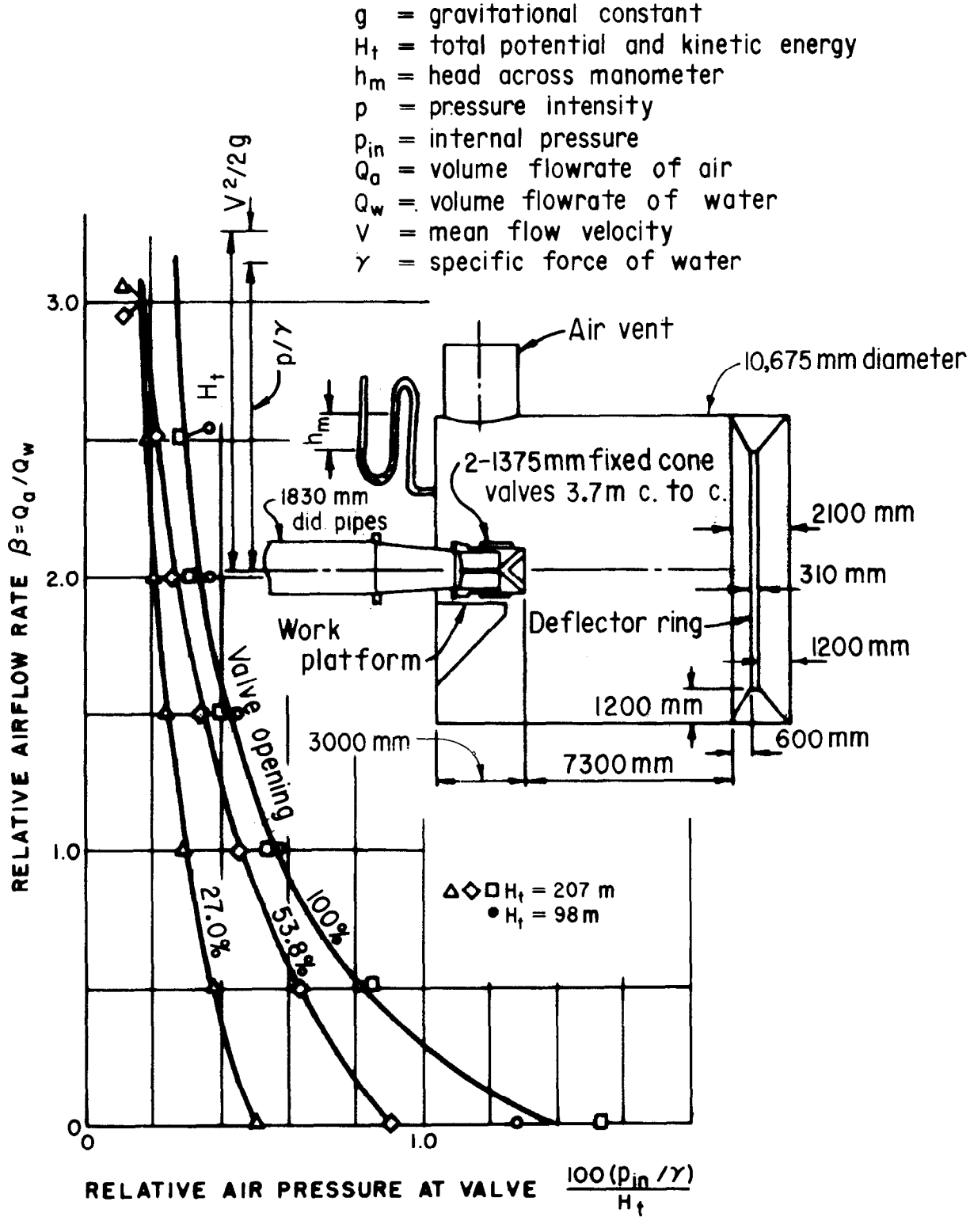
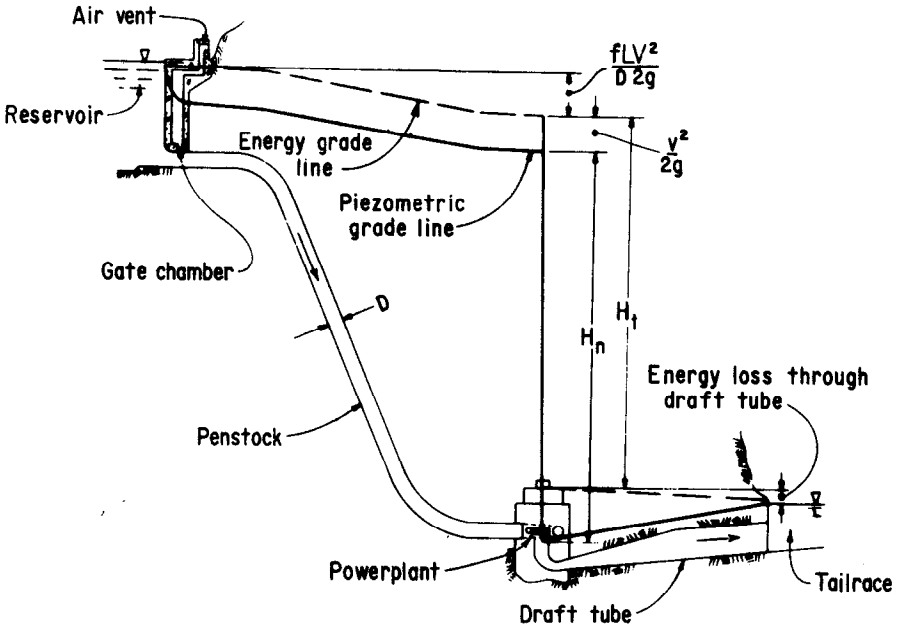
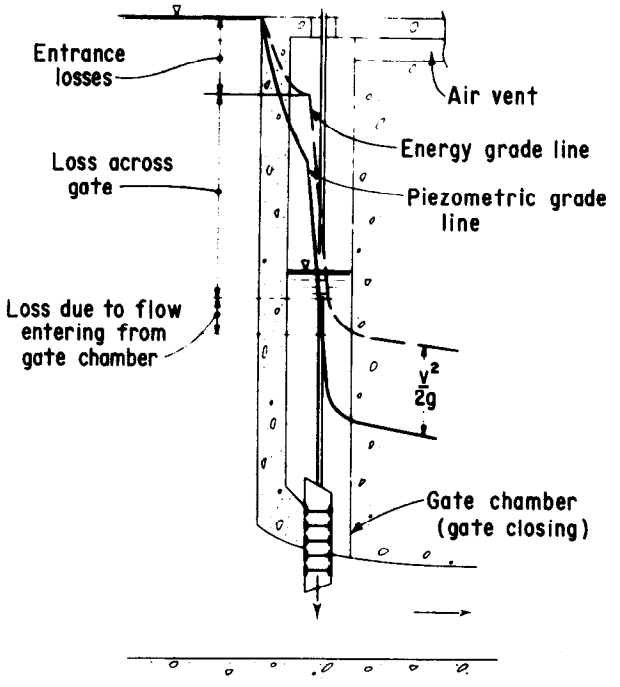


FIGURE 32.—*Airflow rate for two 1375-mm fixed-cone (Howell-Bunger) valves.*



a. ENERGY AND PIEZOMETRIC GRADE LINES IN PENSTOCK AND DRAFT TUBE



b. ENERGY AND PIEZOMETRIC GRADE LINES AT INTAKE STRUCTURE

FIGURE 33.—*Falling water surface.*

gradually stopped. However, water in the penstock continues to flow through the turbine in the powerplant. Eventually the gate becomes fully closed. For water to continue flowing from the penstock, air must be allowed to enter the system through a vent located just downstream from the intake gate.

The airflow and waterflow relations—through the penstock and gate chamber—can be simulated analytically by the appropriate mathematical model, Falvey [22]. This model, based upon momentum and continuity equations, yields the airflow rates, etc., as a function of time.

With relatively long penstocks; i.e., length to diameter ratios exceeding 30, the maximum airflow rate occurs slightly after the emergency gate closes completely. The magnitude of the airflow rate is equal approximately to the penstock discharge prior to the start of the gate closure. These observations provide "rules of thumb" which can be used for the design of the air vent structures on dams. The computer program presented in appendix III should be run if a time history of the air-water flow relation is required or if shorter penstocks are being analyzed. This program is a generalized version of the original program and includes typical turbine characteristics.

Good correlations have been found between the computer model calculations and prototype measurements (fig. 34).

AIR VENT DESIGN CRITERIA FOR CLOSED CONDUITS

Purpose

The design of air vents for closed conduits requires careful consideration. The preliminary step is to decide the purpose that the vent is to perform. For instance, air vents can permit air to enter a structure to prevent collapse or to prevent the formation of low pressures within the flowing water which could lead to cavitation and its possible attendant damage. Conversely, air vents can permit air to escape from a structure. In this case the purpose is to bleed air from a conduit prior to operation.

Location

The next step is to locate the vent properly. General rules cannot be delineated for all cases other than the vent usually is placed where the pressure in the conduit is the lowest. For instance, in gates the appropriate location is immediately downstream of the gate (fig. 31B). For valves the air vent is upstream from the point where the water jet impinges on the conduit walls (fig. 32). In some cases the location must be determined by intuition or carefully conducted model studies.

Maximum Airflow Rate

After the vent is located, the maximum airflow rate through the vent must be estimated. This estimate should be based upon a consideration of the various types of flow which are possible in the water conduit. The previous sections have presented in detail some methods of estimating the maximum airflow rates for specific types of closed conduit flows.

Structural Considerations

The pressure drop across the air vent causes a reduced pressure in the penstock and gate structure. Each part of the structure which is subjected to reduced pressure should be analyzed to determine if it will withstand the imposed loads.

Physiological Effects

The effects of noise produced by high air velocities as well as the structural integrity must

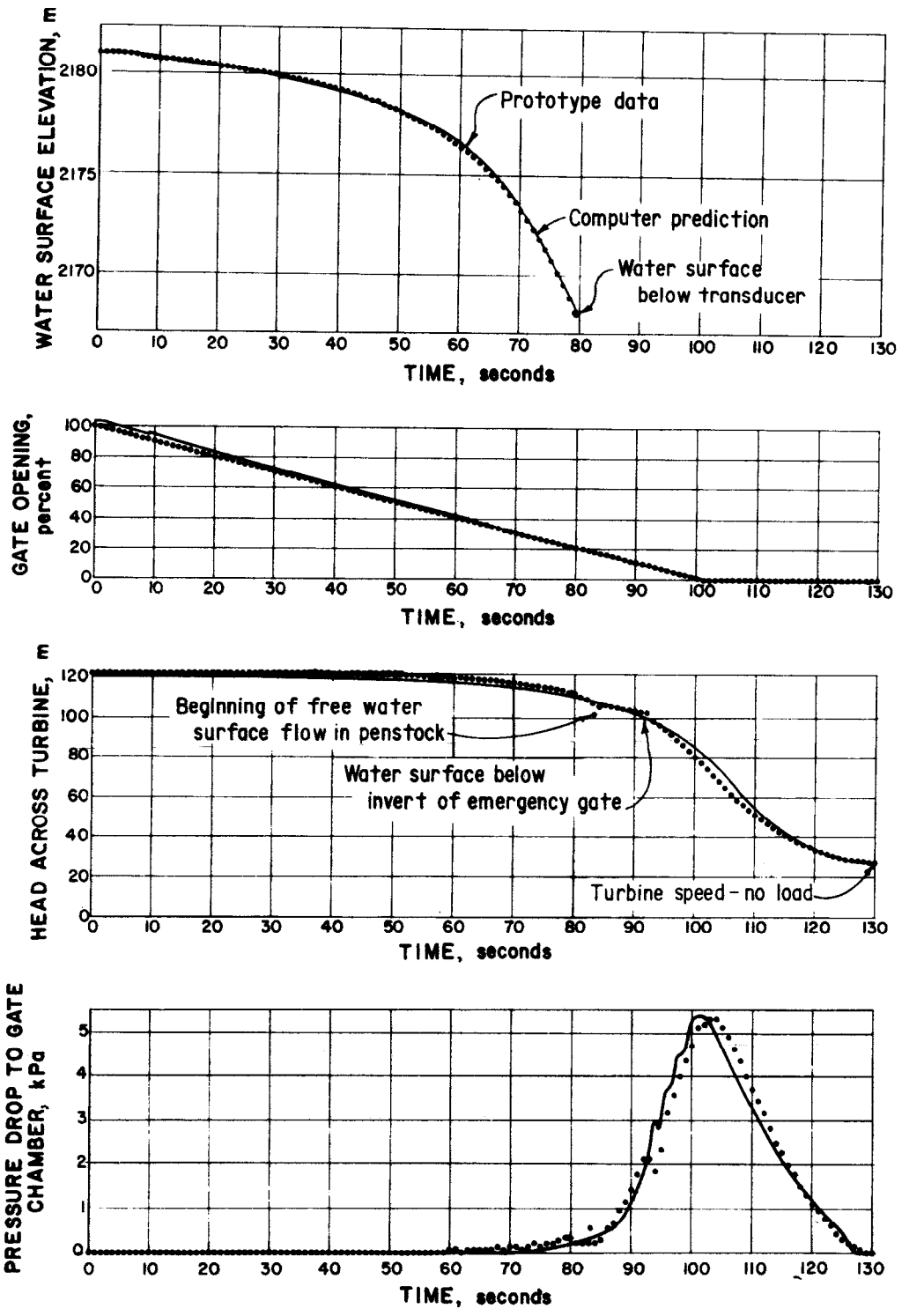


FIGURE 34.—*Comparison of field data with computer prediction.*

be considered in the design of air vents. The limiting air velocity—with respect to noise—in a vent has been established (by the Water and Power Resources Service) to be about 30 m/s. Above this velocity an objectionable whistling sound occurs. The intensity of the sound and not its mere presence is the governing factor. For instance, ear protection is required for exposure times greater than eight hours and pressure levels above 85 dB (decibels) Beranek and Miller [9].[8] For pressure levels above 135 dB, ear protection is required for any exposure time.

Field measurements 5 meters from an air vent having an 80-m/s velocity produced sound level intensities of 105 dB. With this sound intensity, ear protection is required for exposure times exceeding 7 minutes. Since sound level intensities increase by the 6th to 8th power of velocity Davies and Williams [19], a 200-m/s air velocity would have produced a sound level intensity between 128 and 136 dB which is damaging to the ears for any exposure time. Based upon this limited result, a 90-m/s flow velocity appears to be a good value to use as a design criterion for air vents that operate for a short duration. If the air will flow through the vent for extended periods, the upper limit on the air velocity should be restricted to the 30-m/s value.

[8] *Construction Safety Standards*, Water and Power Resources Services, pp. 27-28, rev. 1979. The standard states * * *. Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown below when measured on the A-scale of a standard Type II sound level meter at a slow response.

Duration per day, hours	*Sound level, dBA, slow response*
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

Safety of Personnel

Another design consideration concerns the safety of personnel in the vicinity of the vent when it is operating. Generally, personnel barriers should be placed around vents at locations where the air velocities exceed 15 m/s. This will prevent personnel and loose objects from being swept either through the air vent or held on the air vent louvers.

Freeze Protection

In areas where the vents operate in cold weather for prolonged periods, the vents should be protected from freezing. Icing occurs when supercooled air passes through the louvers and screens at the vent intake. In some cases ice buildup was sufficient to completely block the flow area (fig. 35). Icing protection includes using heating elements on the louvers, rerouting the vent to place the intake in a warm portion of the structure, or redesign of the intake to eliminate ice buildup areas.

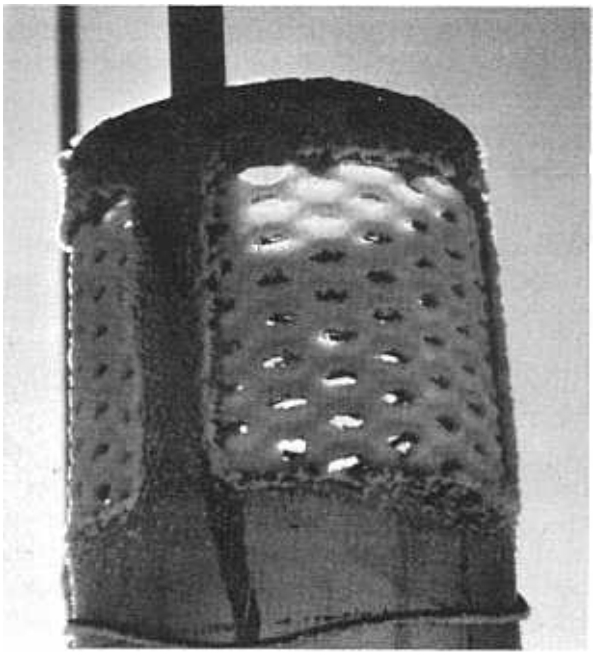
Cavitation Damage

The pressure downstream of gates discharging into conduits should be prevented from becoming too low. If the pressure does drop excessively, cavitation damage may result during prolonged periods of operation. Unfortunately, general guidelines concerning minimum acceptable pressures cannot be given. Each gate or valve design has its own particular characteristics. Some designs are more susceptible to cavitation damage than others. Research studies are needed to define minimum pressure values for the different classes of gates and valves.

Water Column Separation

If the pressure in the water column reaches vapor pressure of the water a possibility exists

A.—*View of the vent pipe installed to provide air for a square slide gate in an outlet works. Initial installation had a cap which required removal after frost plugged the screen. P801-D-79278*



B.—*Closeup view of the screen for a vent pipe after removal of the cap. P801-D-79277*

FIGURE 35.—*Air vent, Shadow Mountain Dam, Colorado-Big Thompson Project, Colorado.*

that the column will separate. Depending upon the geometry of the conduit, the separation can occur at either one location or at several locations. If water column separation is indicated, special waterhammer computations should be performed to determine the overpressures when the water columns rejoin.

AIR VENT DESIGN CRITERIA FOR PIPELINES

Introduction

Flow in long pipelines presents a separate class of considerations from those already discussed. One of the reasons for the new set of considerations is the fact that the pipeline profile normally follows the ground surface topography vary closely. This causes intermediate high locations which provide an opportunity for the collection of air pockets. To assure trouble-free pipeline operation, details of alinement, location, and sizing of vent structures must be considered.

There are essentially four main categories of pipelines. They are:

1. Gravity pipelines in which the water flows from a higher elevation to a lower one through the effect of gravity (fig. 36A).
2. Sagpipes (inverted siphons)[9] in which the flow from one canal to another is passed under a road or across a valley (fig. 36B).
3. Pump lifts in which the water flows from a low elevation to a higher one through pump action (fig. 36C).
4. Siphons in which some portion of the pipe is designed to operate at subatmospheric pressures (fig. 36D). This type of structure is used frequently to prevent water from the upper reservoir from passing back through the pump if a loss of electrical power occurs.

[9]See footnote 1.

Gravity systems, figures 36A and B, normally have different alinement problems than pumping systems (fig. 36C and D); therefore, the two are considered separately.

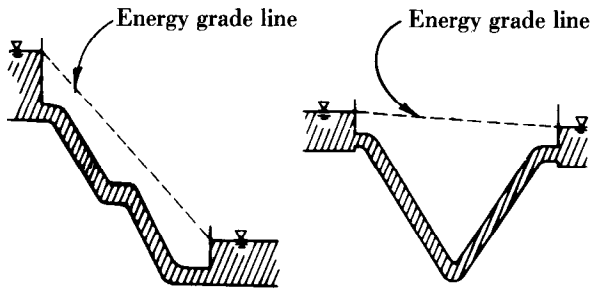


FIGURE 36.—*Pipeline configurations.*

Gravity Systems

A vertical section through a typical gravity system is shown on figure 37. The same type of layout also applies to sag pipes if the open vent structures are replaced by canal sections. Two types of summit configurations are depicted. In one case the intermediate summit is above the downstream vent structure. This forms a pool upstream of the summit at the no-flow condition. In the other case, the intermediate summit is below the downstream vent structure. Therefore, it is submerged by the pool which forms at the no-flow condition.

To prevent difficulties during startup operations, certain criteria should be followed regarding both the vertical and horizontal alinement at the upstream vent structure and at intermediate summits whose elevations lie above the downstream open vent structure.

Vertical alinement criteria.—The pipe invert should be placed on a uniform slope between the vent or summit and the adjacent downstream pool. If this cannot be achieved then the pipe should be placed on continuingly steeper slopes so that during filling the flow continues to accelerate to the pool level. If the flow were allowed to decelerate, the water depth in a circular pipe could gradually increase until the pipe was about 82 percent full. At this depth the flow could become unstable, alternating between full conduit flow and the 82-percent depth.

At less than design discharge, the flow downstream of nonsubmerged summits passes from free-surface to closed-conduit flow. An air-entraining hydraulic jump always forms when the flow makes this transition. The entrained air can form large air pockets under certain circumstances which move against the direction of flow. This condition is commonly referred to as blowback (refer to previous section—Flow Having a Hydraulic Jump That Fills the Conduit).

If the alinement cannot be planned to avoid either operating in or passing through the blowback region delineated in figure 29, then the pipe diameter should be altered to avoid the region.

Some attempts have been made to collect the large air bubbles which form on the crown of the pipe and lead them away from the pipeline (fig. 38). In the example, the flow conditions never entered the blowback flow region. Therefore, the complicated air collection

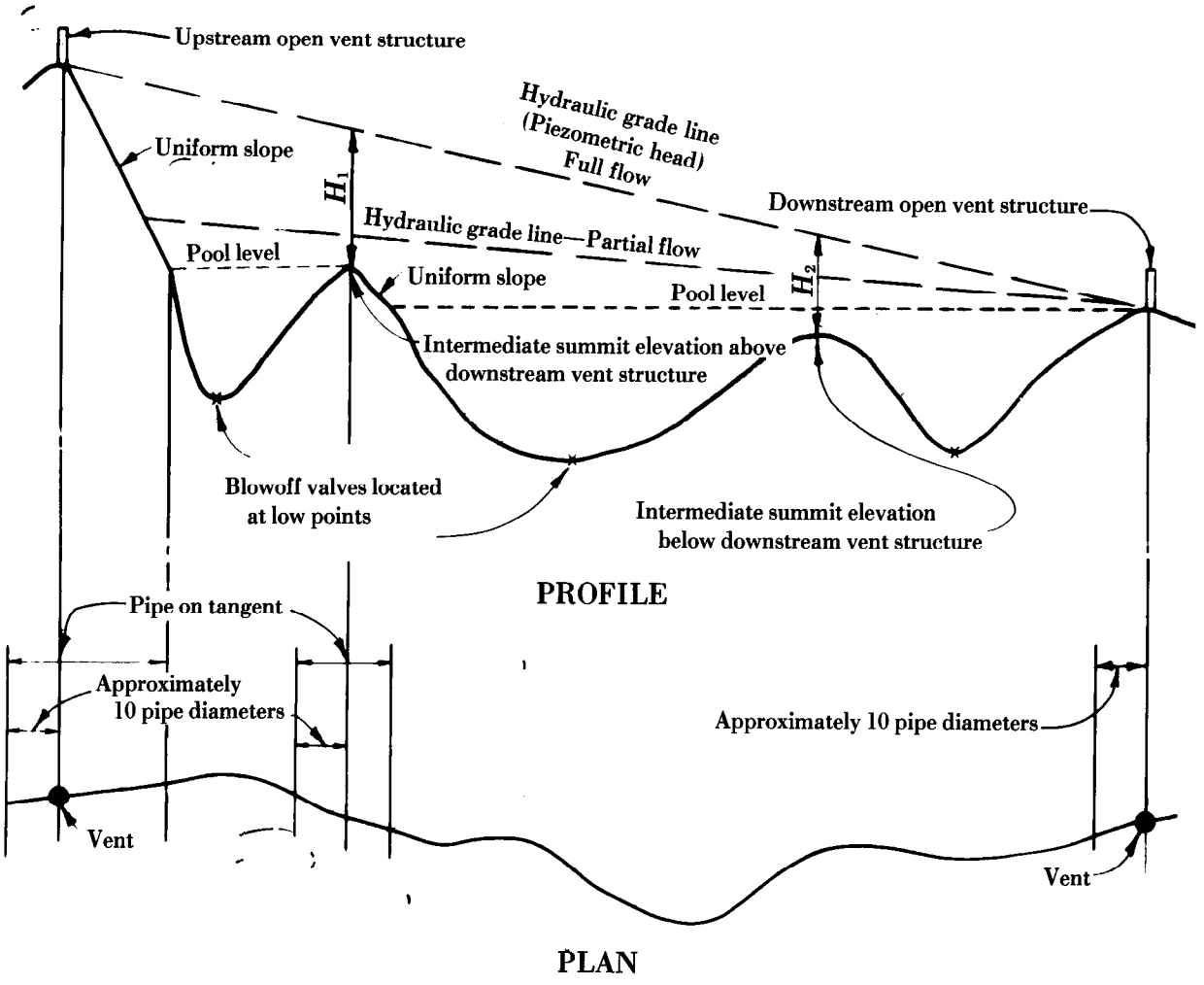


FIGURE 37.—*Plan and profile of a gravity pipeline.*

system was not needed. If flow had entered the blowback region, this structure probably would not have worked. Colgate [15] found that an unsteady flow condition develops when large air bubbles are bled from a pipeline with too small a vent. To minimize the unsteady flow it is necessary for the vent diameter to equal the pipeline diameter. The design of antiblowback structures like the type shown on figure 38 should not be attempted without hydraulic model studies.

Horizontal alinement criteria.—At the open vent structures and at the intermediate summits higher than the downstream vent, the pipe should not contain bends for 10 pipe diameters upstream of the location. In addition bends should be avoided in the section between the vent on the summit and the adjacent downstream pool. These criteria prevent transverse waves from being formed on the free water surface which can exist downstream of the vent or summit at partial flows. These transverse waves could roll over with enough amplitude to intermittently seal the pipeline.

Vent location.—The type of air release structure to be used at a summit is determined by the

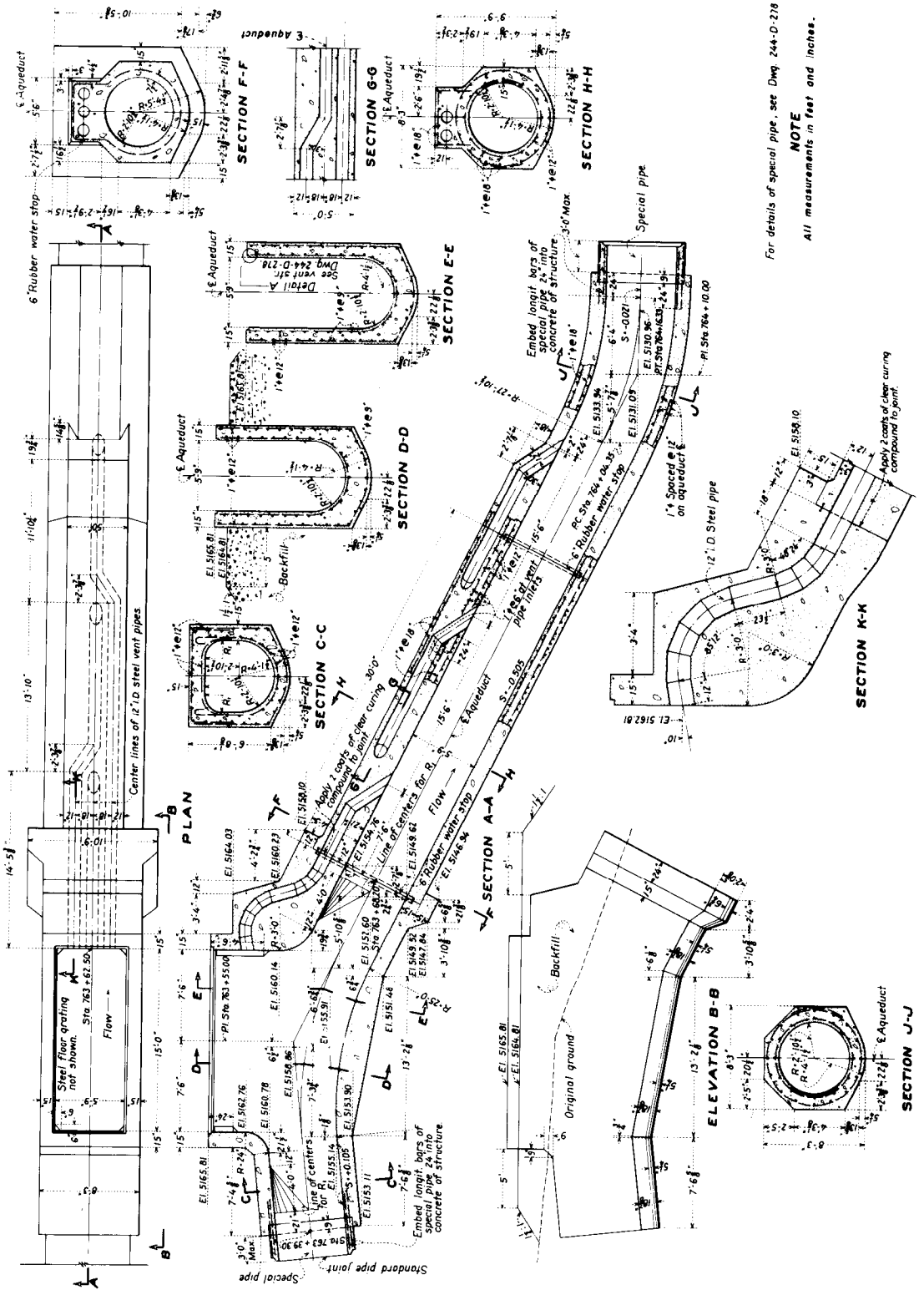


FIGURE 38.—*Vent structure.* 244-D-799

distance from the pipe invert to the hydraulic grade line at the summit. For summits higher than the downstream vent, an open vent is desirable. The maximum allowable vent height is determined from topographic, aesthetic, and economic considerations. Normally, open vents at intermediate summits are not feasible if the distance to the hydraulic grade line H_1 exceeds 6 to 10 meters.

For summits lower than the downstream vent, the type of air release structure is more difficult to determine. If the distance to the hydraulic grade line H_2 is less than about 6 meters, an open vent should be used. However, if the distance exceeds 6 meters an air valve installation should be used (fig. 39). Since mechanical air valves tend to chatter and spit water if their operating pressures are too low, the top of the air valve should be set at least 3 meters below the pool level.

To provide desirable operating characteristics at all discharges, vents also are required at locations other than at the intermediate summits. If the water velocities are of sufficient magnitude to carry air bubbles with the flow, then vents are needed downstream of changes from negative to positive pipe slopes. Without the vents the air slugs, which collect on the crown of the pipe, will attain very high velocities in areas with large positive slopes. These slugs can damage the vent structures at intermediate locations, at downstream connecting canals, and can cause slamming of air valves. These vents should be located less than 30 meters downstream from the negative to positive pipe slope change. If the distance from the intersection of the pool with the negative slope and the proposed vent exceeds $20D$, where D is the conduit diameter, then the vent should be placed at the greater of the two distances (fig. 40). The criterion for the vent type is the same as for vents placed at intermediate summits below the downstream vent structure. If the distance between the upstream and downstream vent structures is very great,

FIGURE 39.—*Typical irrigation system air valve installation. P801-D-79279*

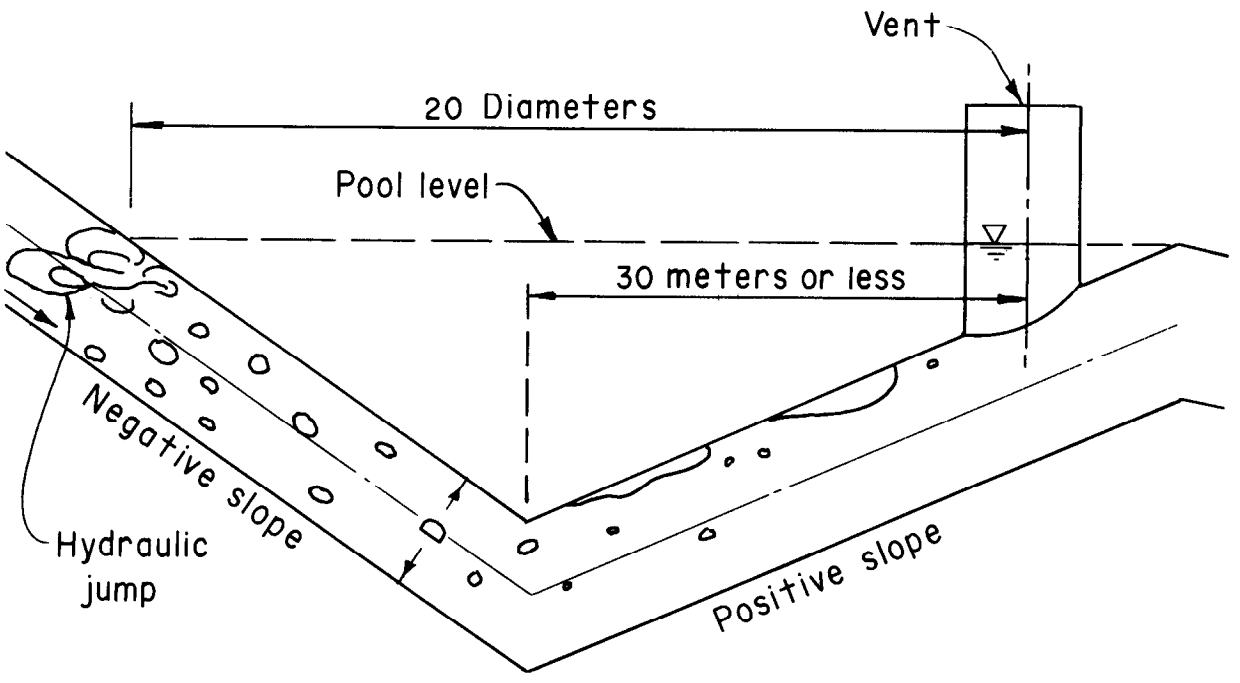


FIGURE 40.—*Vent location at changes in pipe slope.*

Lescovich [47] recommends that air valves be placed every 500 to 1000 meters along descending, horizontal, or ascending stretches that have no intermediate summits.

Pumping Systems

All intermediate summits are potential locations for the collection of air pockets. If these pockets begin to develop, the hydraulic gradient downstream of the summit will equal approximately the pipe slope in the area where the air pocket has formed. For a pipe slope greater than the full-flow hydraulic gradient, the air pocket will require a greater head differential to produce a given discharge. Conversely, for a constant head differential, the presence of the air pocket will result in decreased discharges. The limiting condition is a complete blockage of flow. In pumping systems this blockage is known as *air binding* [58]. With air binding the shutoff head of the pump will have been reached (fig. 41). One obvious solution to the problem of air collection at summits is to provided air release valves or vent structures at these locations. Another solution is to aline the pipeline so that all intermediate summits are eliminated.

Vent Structure Design Considerations

Vent structures have three primary purposes:

1. Evacuation of air during filling,
2. Removal of air during operation, and
3. Prevent pipe collapse during draining.

Each is considered in detail. The size of the vent and the piping connecting the vent to the pipeline is determined by the purpose for which the vent is installed.

Evacuation of air during filling.—The filling rate of pipelines usually is set at 5 to 15 percent

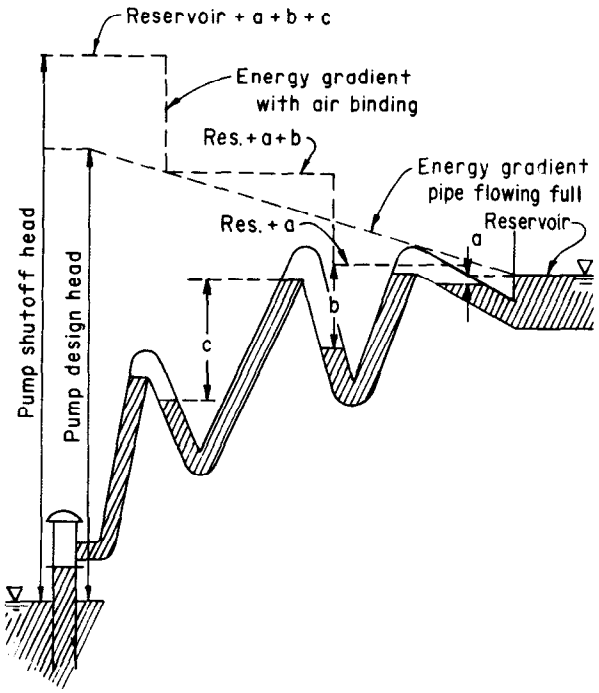


FIGURE 41.—*Air binding in a pipeline.*

of the design discharge. The actual rate is governed by the maximum waterhammer pressures that the pipeline and valves can withstand. These pressures are generated when the water column in the penstock reaches the air release valve. Based on waterhammer considerations the filling rate of pipelines can be computed from

$$Q_a=\frac{gA_p\Delta h_w}{c} \tag{86}$$

where

Q_a = penstock filling rate equals airflow rate through vent
A_p = cross sectional area of penstock
c = celerity of waterhammer wave in penstock
g = gravitational constant (acceleration)
h_w = allowable head rise in penstock due to waterhammer pressures

Lescovich [47] indicated that large orifice air valves should be used to permit air escape during filling (fig. 42). In this case a large orifice refers to diameters greater than 25 millimeters. This type of air valve is designed to remain closed after the pipeline is filled. Thus, they cannot be used to release small amounts of air that accumulate during operation. These valves will open immediately when the pipeline pressure drops below atmospheric. This allows air to reenter the pipeline and prevents a vacuum from forming.

Normally, air velocities discharging from an air valve should not exceed 30 m/s. The primary reason for limiting the velocity is to prevent the air valve from being blown shut. Some air valves are designed to eliminate this problem.

With the 30-m/s velocity limitation, the air can be considered to be incompressible. The equation for the airflow rate is

$$Q_a=A_oC_o\left(\frac{2\Delta p}{\varrho_a}\right)^{1/2} \tag{87}$$

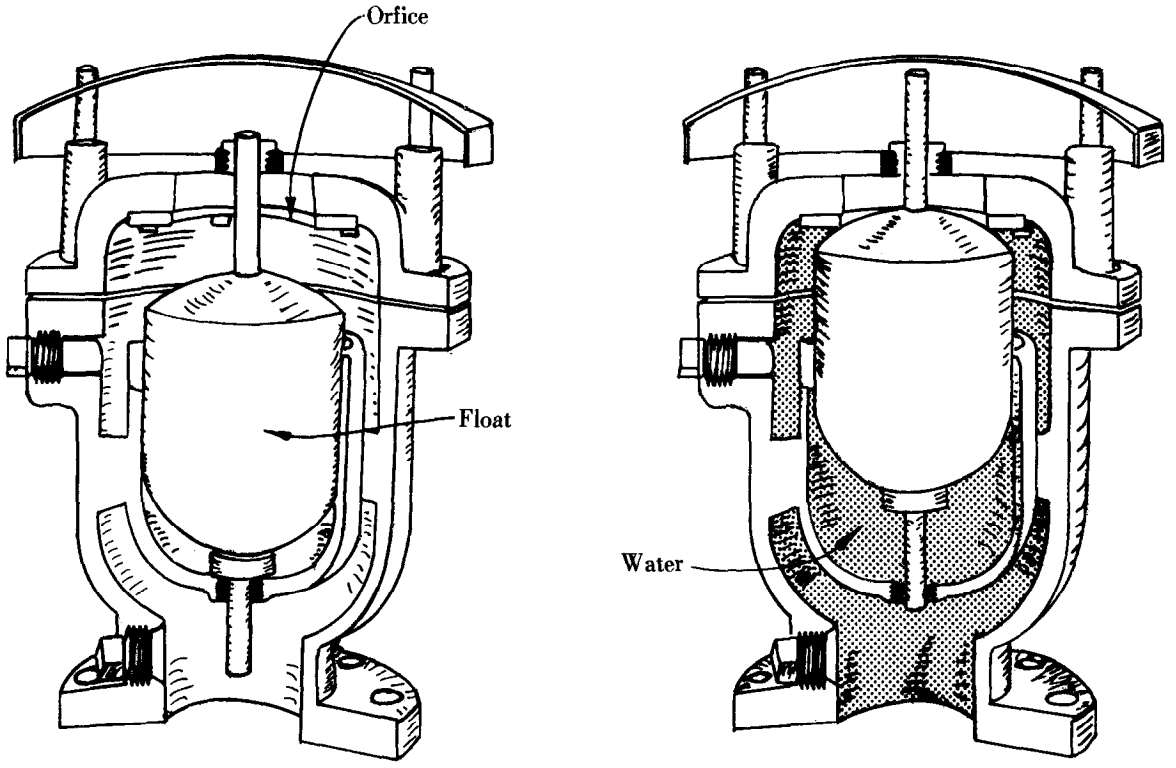
where

A_o = orifice area, m^2
C_o = orifice coefficient ≈ 0.6
Δp = pressure differential across the orifice, kPa
ϱ_a = air density (at 20 °C and a pressure of 101.3 kPa, $\varrho_a=1.204$ kg/m^3)

From this equation, performance curves for large-orifice air valves can be derived (fig. 43).

If the desired capacity cannot be achieved with a single air valve, the valves can be placed in clusters—up to four valves—on a single vent pipe from the pipeline.

Removal of air during operation.—Two types of structures are used to remove air during operation. These are an open-vent structure and small-orifice air valves. In either case the connection to the pipeline must be large enough



A.—Lowered position - Float allows air to flow into or out of pipeline

B.—Raised position - Air cannot enter or leave pipeline

FIGURE 42.—*Large-orfice air valve.*

to collect the slugs and bubbles of air which are traveling on the crown of the pipeline.

Colgate [15] investigated the sizing criteria for open-vent structures. He found that if the collection port was too small, portions of large air slugs would pass by the vent. To trap all the air it was necessary for the diameter of the collection port to be equal to the pipe diameter. Additional tests were made to investigate the size of the vent structure itself. It was found that if the air vent diameter was less than the pipeline diameter, an unsteady flow was established in the vent as large air bubbles exited from the vent. This unsteady flow pumped air back into the pipeline. To minimize pumping it was necessary to make the vent diameter equal to the pipeline diameter.

Colgate [15] concluded that the collection and evacuation of air from a pipeline can be best accomplished by a vertical air vent which is connected directly to the pipeline. The diameter of the vent should be at least equal to the diameter of the pipeline. From access considerations, the minimum vent diameter usually is set at about 1 meter. Removal of air is promoted if the pipe slope immediately downstream of the vent is made steep enough to cause the air bubbles to return upstream. Figure 29 can be used to determine the required slope for a given discharge.

For the case in which the hydraulic grade line is too far above the pipeline to economically install an open vent, air valves are used to remove the air. Investigations concerning the design of

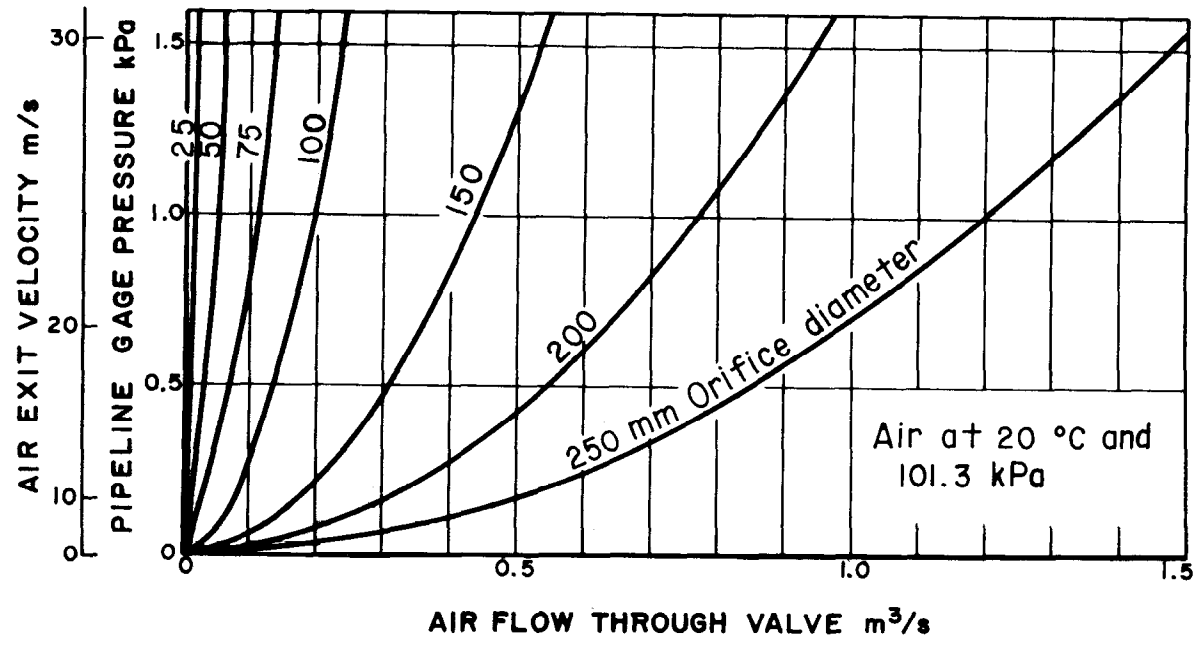


FIGURE 43.—*Performance curves for large-orfice air release valves.*

a collector have not been performed. Based upon the design of open vents it can be assumed that the diameter of the collector should be at least equal to that of the pipeline. The height of the collector also should be one pipeline diameter. In many cases, manholes in the pipeline can serve as collectors.

To release air from pipelines under high pressures, small-diameter orifice installations are used (fig. 44). The small orifice assures that the opening force of the float is not exceeded by the closing force whose magnitude is equal to the internal gage pipe pressures times the orifice area. The volume flow of air relation through an orifice with a back pressure is given by

$$Q_a = 460 A_o [(p_{in}/p_{atm})^{0.2857} - 1]^{1/2} \qquad (88)$$

for

$$\frac{p_{atm}}{p_{in}} > 0.53$$

and

$$Q_a = 11.8 A_o [p_{in}(p_{in}/p_{atm})^{0.7143}]^{1/2} \qquad (89)$$

for

$$\frac{p_{atm}}{p_{in}} \leqslant 0.53$$

These equations are presented as performance curves (fig. 45).

To prevent the air valves from freezing, frequently they are placed in concrete structures located below the frost line (fig. 46). In this case it is necessary to provide adequate ventilation into or out of the structure. The required ventilation area is based upon a 2.5-m/s maximum air velocity through the gross area of a fixed louver vent. If wire mesh screen is used, the maximum air velocity is 6.6 m/s through the gross area of the screen.

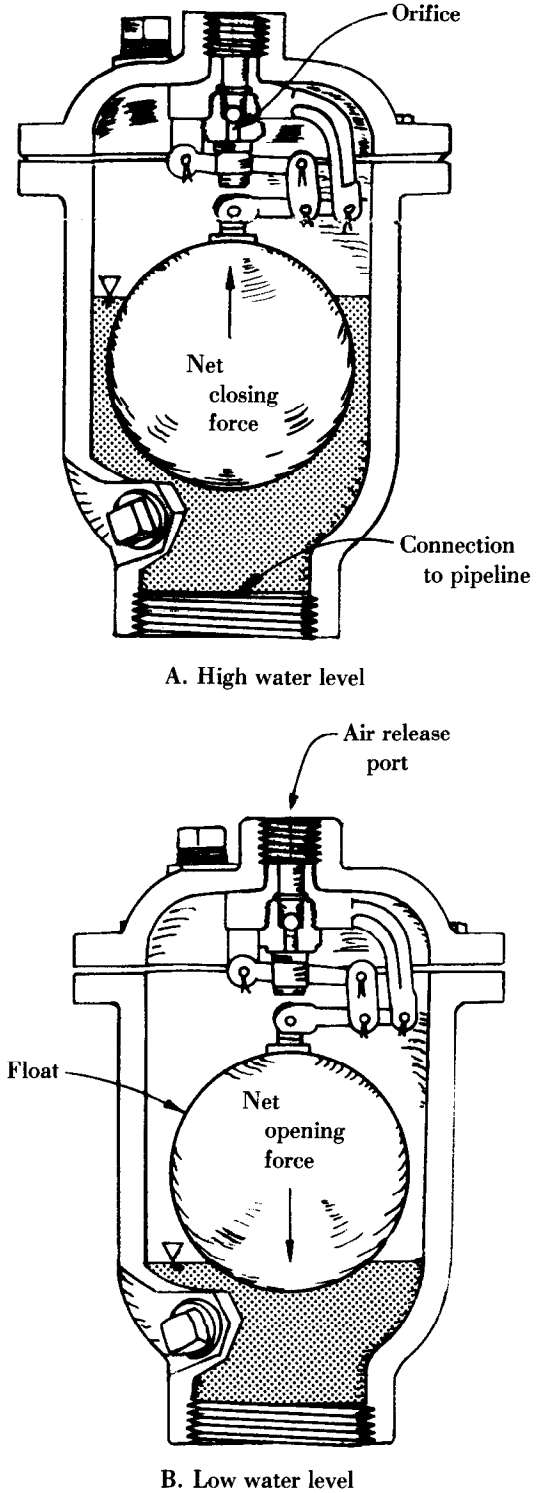


FIGURE 44.—*Typical small-orifice air release valve.*

Prevent pipe collapse during draining.— The venting criteria discussed thus far are based upon the need to remove air from the pipeline. In several instances above-ground steel pipelines have collapsed because vacuum formed during rapid draining operations or because of breaks in the pipeline. Parmakian [56] developed criteria for the size and location of air valves to be placed in steel pipelines to protect them against collapse.

On steel pipes, the collapse pressure can be estimated from (Parmakian [56])

$$p_c = 3.5\times10^8\left(\frac{t}{D}\right)^3 = p_{atm} - (p_{in})_{abs} = -(p_{in})_{gage} \tag{90}$$

where

D = conduit diameter, mm
p_{atm} = atmospheric pressure, kPa
p_c = collapse pressure, kPa
p_{in} = internal absolute or gage pressure, kPa
t = pipewall thickness, mm

With stiffener rings, the appropriate equation is

$$p_c = \frac{5.1\times10^8(t/D)^{2.5}}{(L_s/D)} \tag{91}$$

where L_s = distance between stiffener rings.

These two equations are presented graphically in figure 47.

Applying a safety factor N to the internal collapse pressure p_c gives the allowable internal pressure p_a as

$$p_a = p_{atm} - \frac{p_c}{N} \tag{92}$$

If the ratio of the internal to atmospheric pressure is greater than 0.53 then the volume

flow of air into the pipeline through an orifice is given by

$$Q_a = C_d A_o \left(\frac{p_{in}}{p_{atm}}\right)^{\frac{1}{\varkappa}} \left\{ \frac{2p_{in}}{2\varrho_{atm}} \left(\frac{\varkappa}{\varkappa+1}\right) \left[1-\left(\frac{p_{in}}{p_{atm}}\right)^{\frac{\varkappa-1}{\varkappa}}\right] \right\}^{\frac{1}{2}} \quad (93)$$

If the ratio is equal to or less than 0.53 then the airflow rate into the pipeline through an orifice is given by

$$Q_a = C_d A_o \left(\frac{2}{\varkappa+1}\right)^{\frac{1}{\varkappa-1}} \left[\frac{2p_{atm}}{\varrho_{atm}} \left(\frac{\varkappa}{1+\varkappa}\right)\right]^{1/2} \quad (94)$$

Using

$C_d = 0.6$
$p_{atm} = 101.3$ kPa
$\varkappa = 1.4$
$\varrho_{atm} = 1.20$ kg/m^3

in equations 93 and 94 results in

$$Q_a = 460 A_o \left(\frac{p_{in}}{p_{atm}}\right)^{0.715} \left[1-\left(\frac{p_{in}}{p_{atm}}\right)^{0.286}\right]^{1/2} \quad (95)$$

for

$$\frac{p_{in}}{p_{atm}} > 0.53$$

and

$$Q_a = 119 A_o \quad (96)$$

for

$$\frac{p_{in}}{p_{atm}} \leqslant 0.53$$

where

A_o = orifice area, m^2
Q_a = airflow area, m^3/s

These equations are presented as performance curves for various size vacuum relief valves (fig. 48).

Parmakian presented an alternate method of determining the required air vent size in terms of a dimensionless ratio. The ratio is in the form of an Euler number and is given by

$$\left(\frac{\Delta V^2}{C_o^2\, p_{atm}\, \upsilon_{atm}}\right)^{1/4} = \frac{1}{C_o^{1/2}\, \mathrm{E}_u^{1/4}} \quad (97)$$

where

C_o = orifice discharge coefficient
E_u = Euler number $= p_{atm}/\varrho_a V^2$
p_{atm} = atmospheric pressure
ΔV = change in water velocity approaching and leaving air vent
ϱ_a = density of air at standard atmospheric pressure
υ_{atm} = specific volume of air at atmospheric pressure

The pressure and specific volume of the atmosphere are both functions of elevation (fig. 49). This alternate method results in the required air vent orifice diameter as a function of the pipeline diameter (fig. 50).

Normally, air valves are placed at the crests in the pipeline profile and at locations where the pipeline begins a steep downward slope.

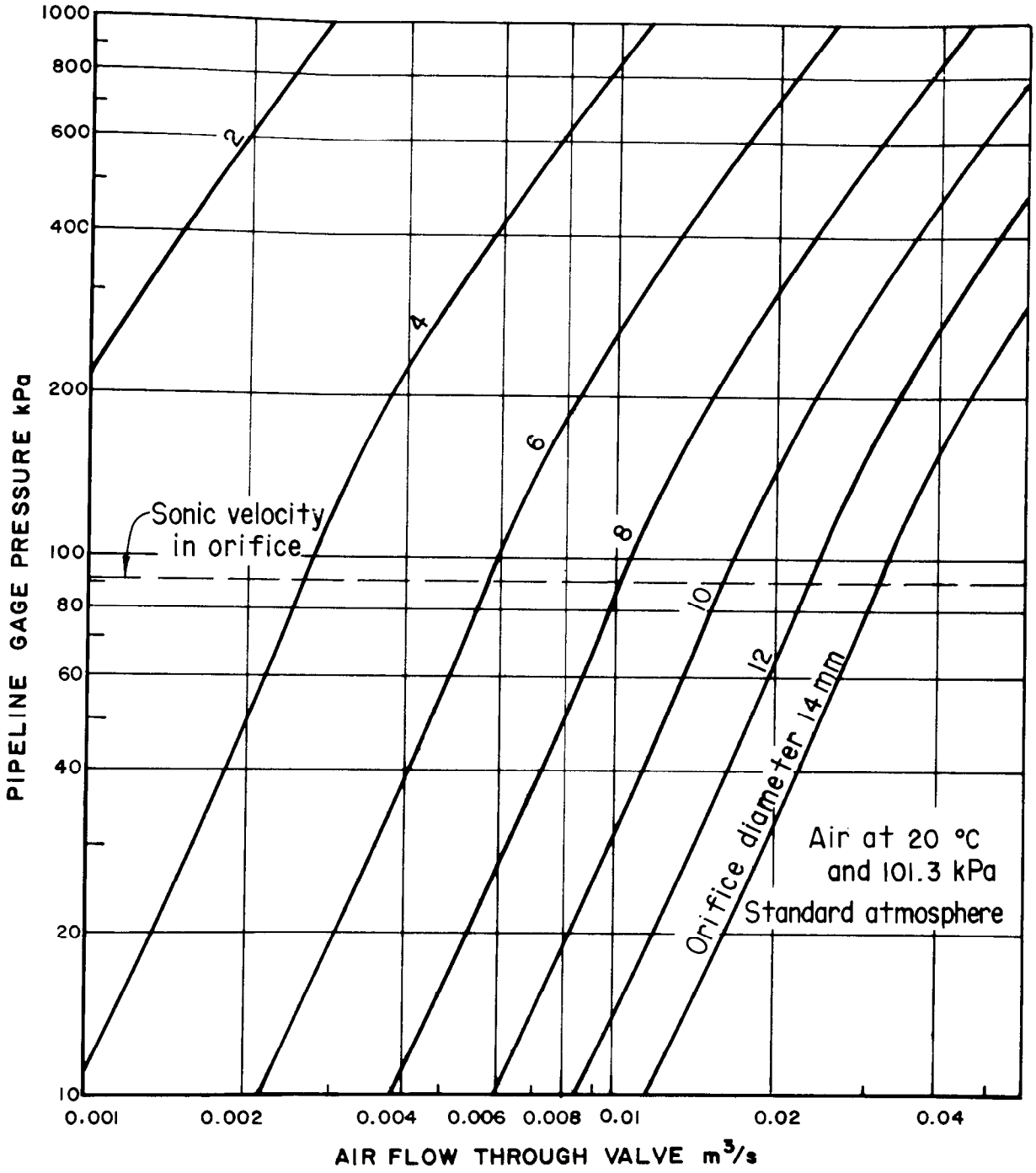


FIGURE 45.—*Performance curves for small-orifice air release valves.*

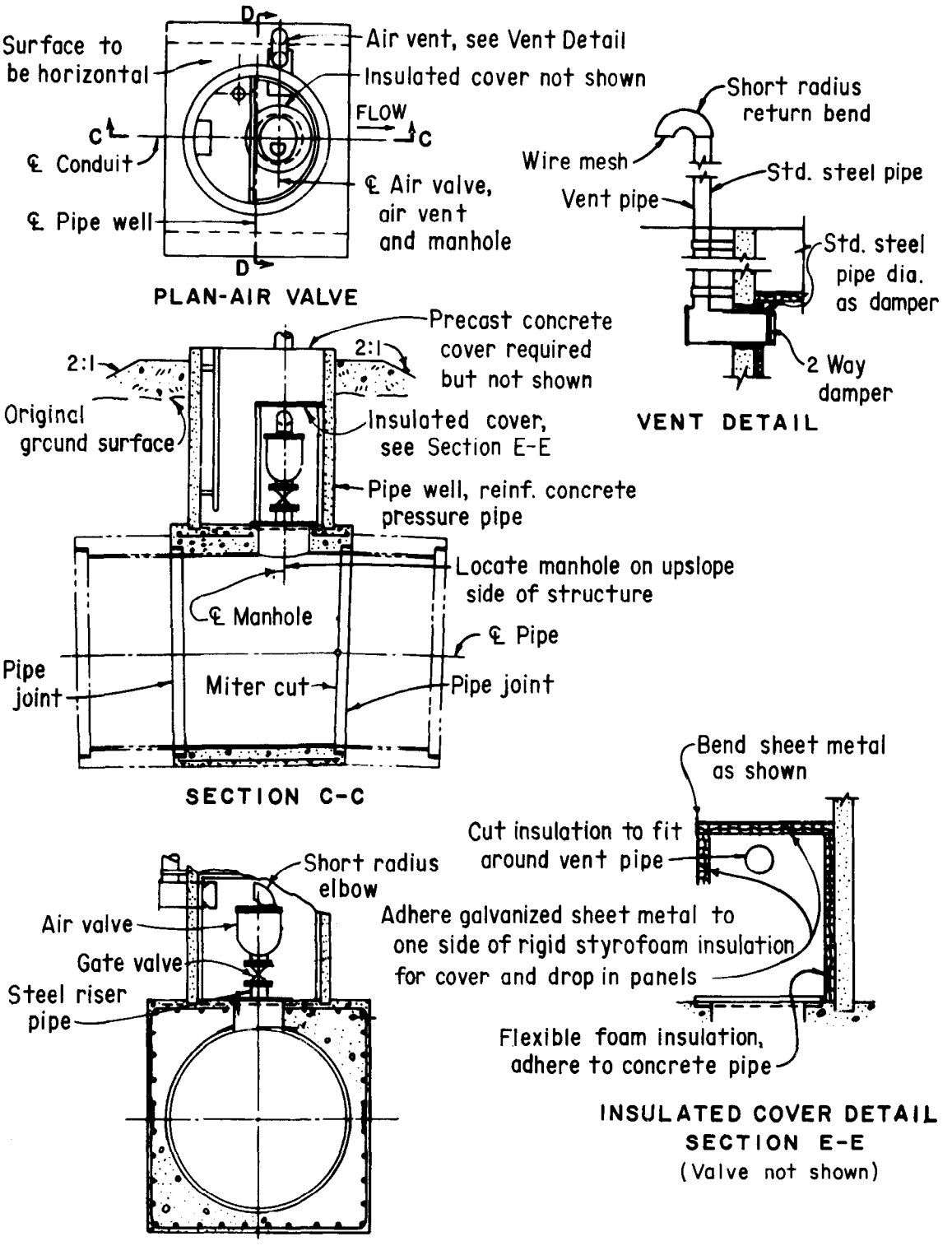


FIGURE 46.—*Typical frost protection installation.*

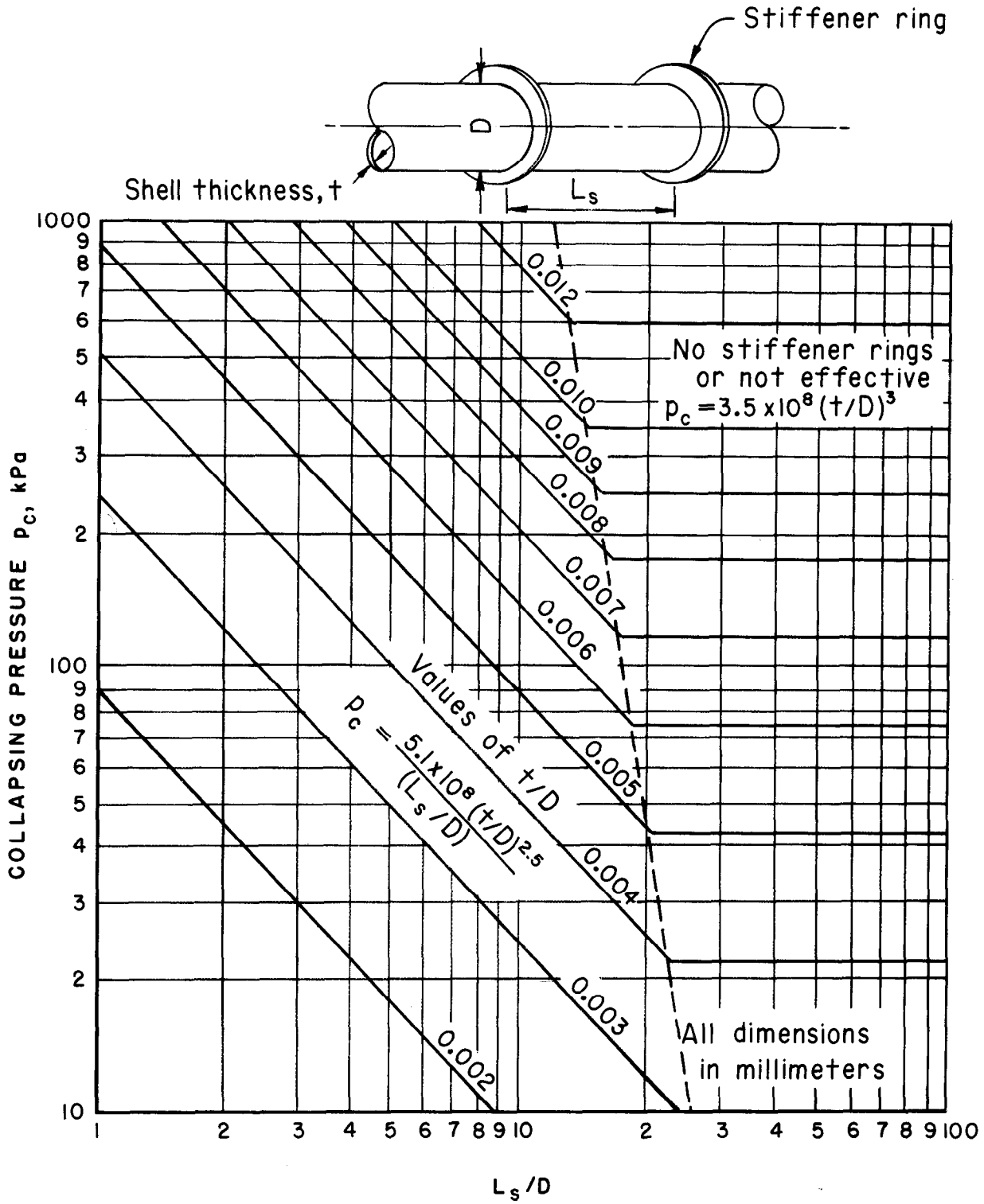


FIGURE 47.—*Collapsing pressure of a steel pipe with stiffener rings.*

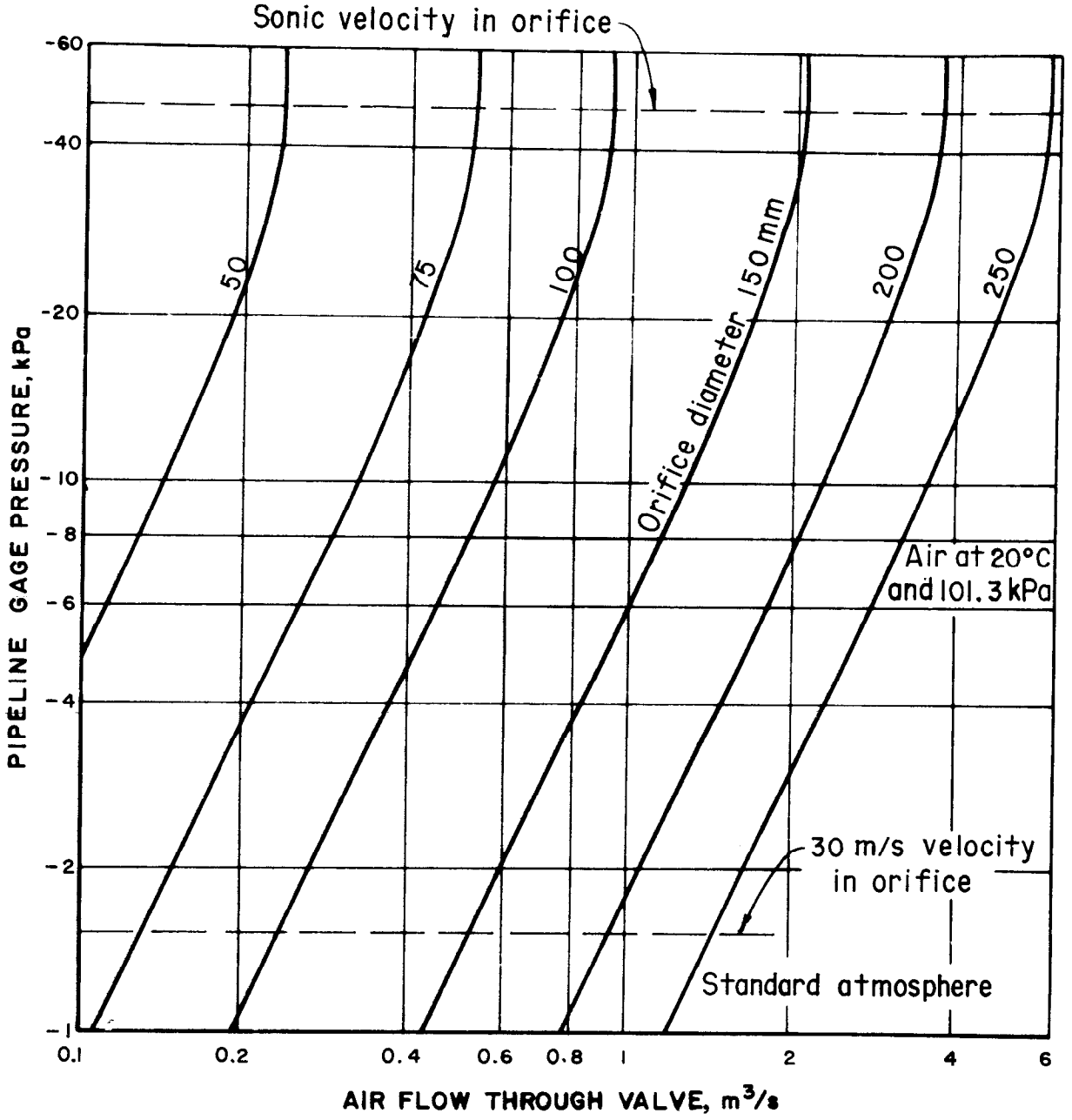


FIGURE 48.—*Performance curves for large-orifice vacuum relief valves.*

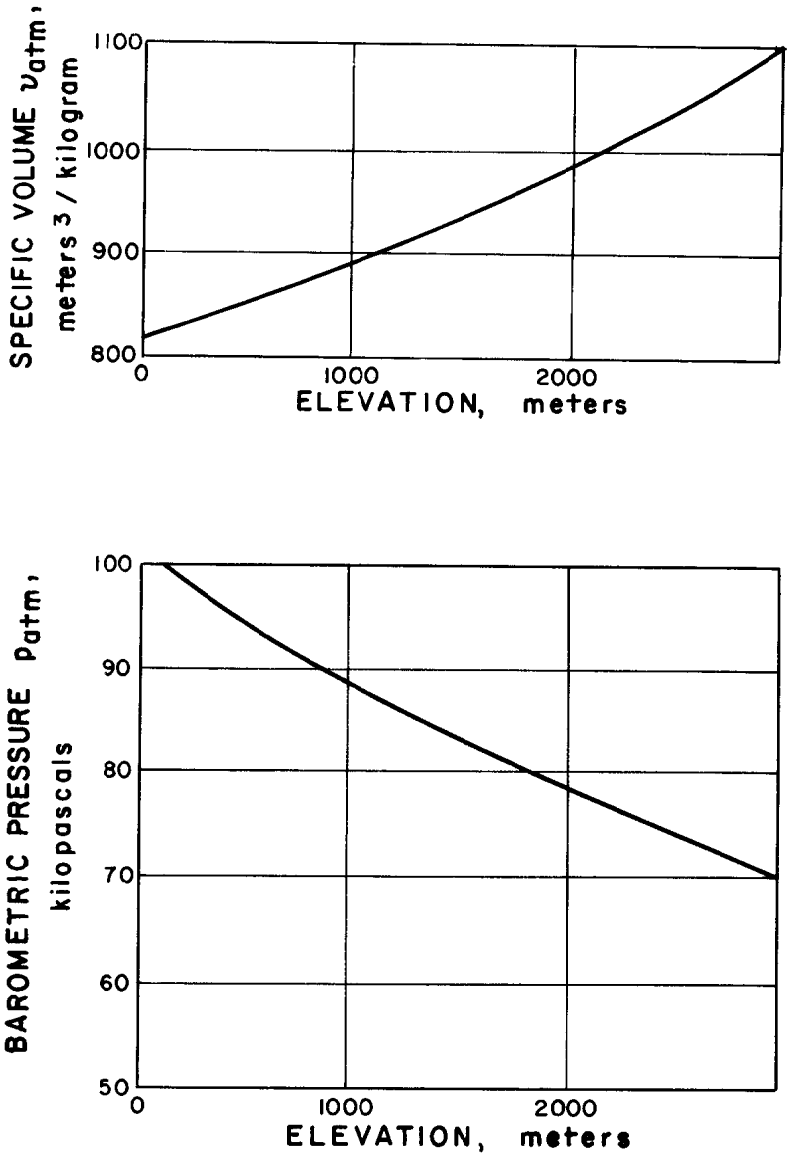


FIGURE 49.—*Specific volume and barometric pressure of air as a function of elevation.*

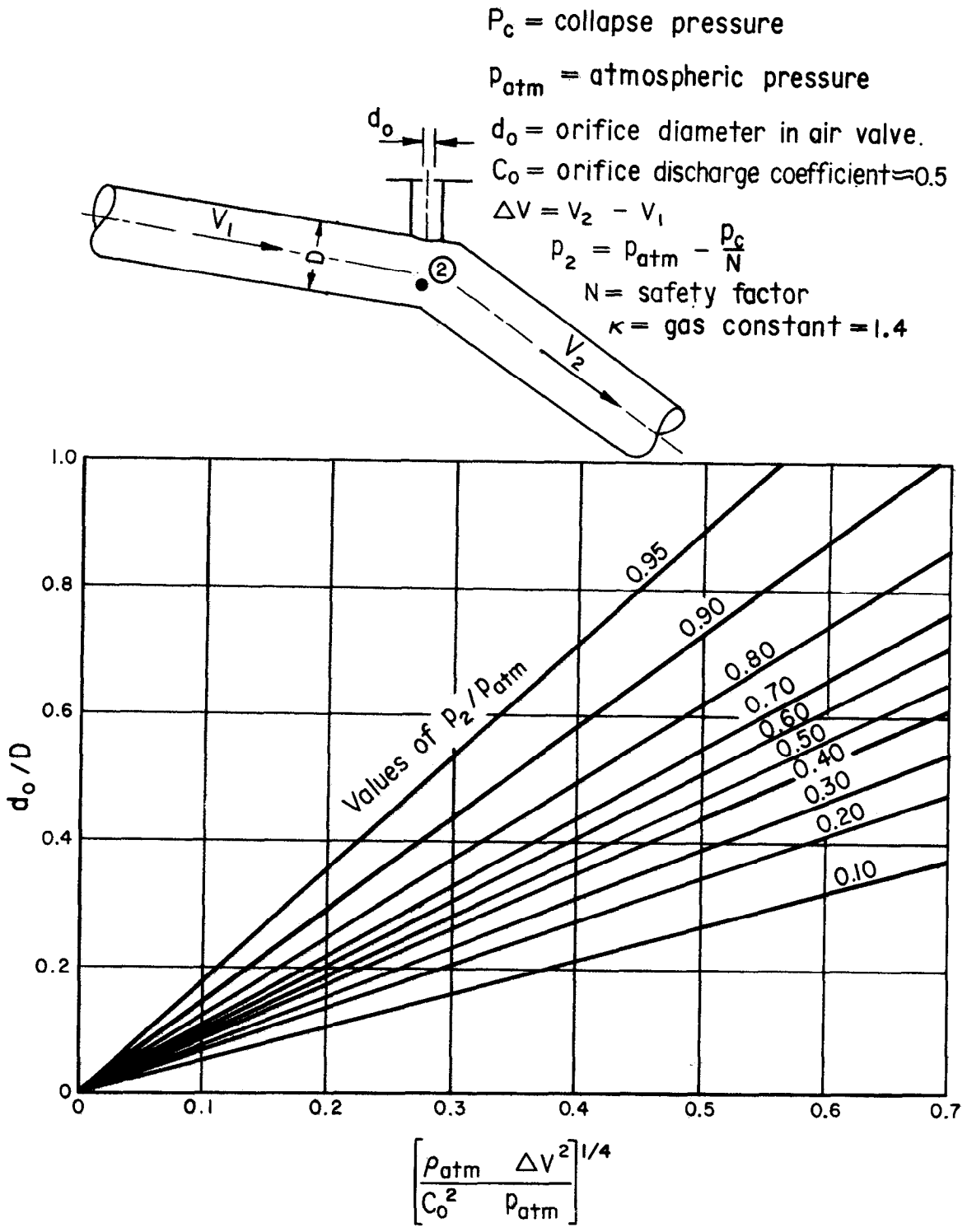


FIGURE 50.—*Required air relief orifice diameter to prevent collapse of steel pipelines.*

FLOWS IN VERTICAL SHAFTS

Classification of Airflows

Three types of hydraulic structures that use a vertical shaft to convey water from one elevation to another are:

- Spillways
- Intakes
- Drop shafts

The air entrainment properties of these structures are important since at certain flowrates explosive air blowbacks are possible (fig. 51). Often extensive studies are necessary to design vent structures to remove the air which is entrained in the vertical shaft Anderson [3] and Babb [6].

The amount of air entrained in the shaft is strongly dependent upon the type of flow into the shaft and upon the water level in the shaft. The inlet flow can vary from radial to tangential with flow entering around the circumference of the shaft. Typical types of inlet structures (fig. 52) are:

- Circular weirs
- Vortex inlets
- Radius elbows

The effect of water surface (reservoir) elevation at the entrance to a shaft can be examined by considering the discharge characteristics of a vertical shaft spillway (fig. 53). For low water surface levels the discharge is proportional to the three-halves power of the total head on the crest. The flow in the shaft clings to the walls in

FIGURE 51.—*Observed air blowback in morning glory spillway at Owyhee Dam, Oregon. P801-D-79280*

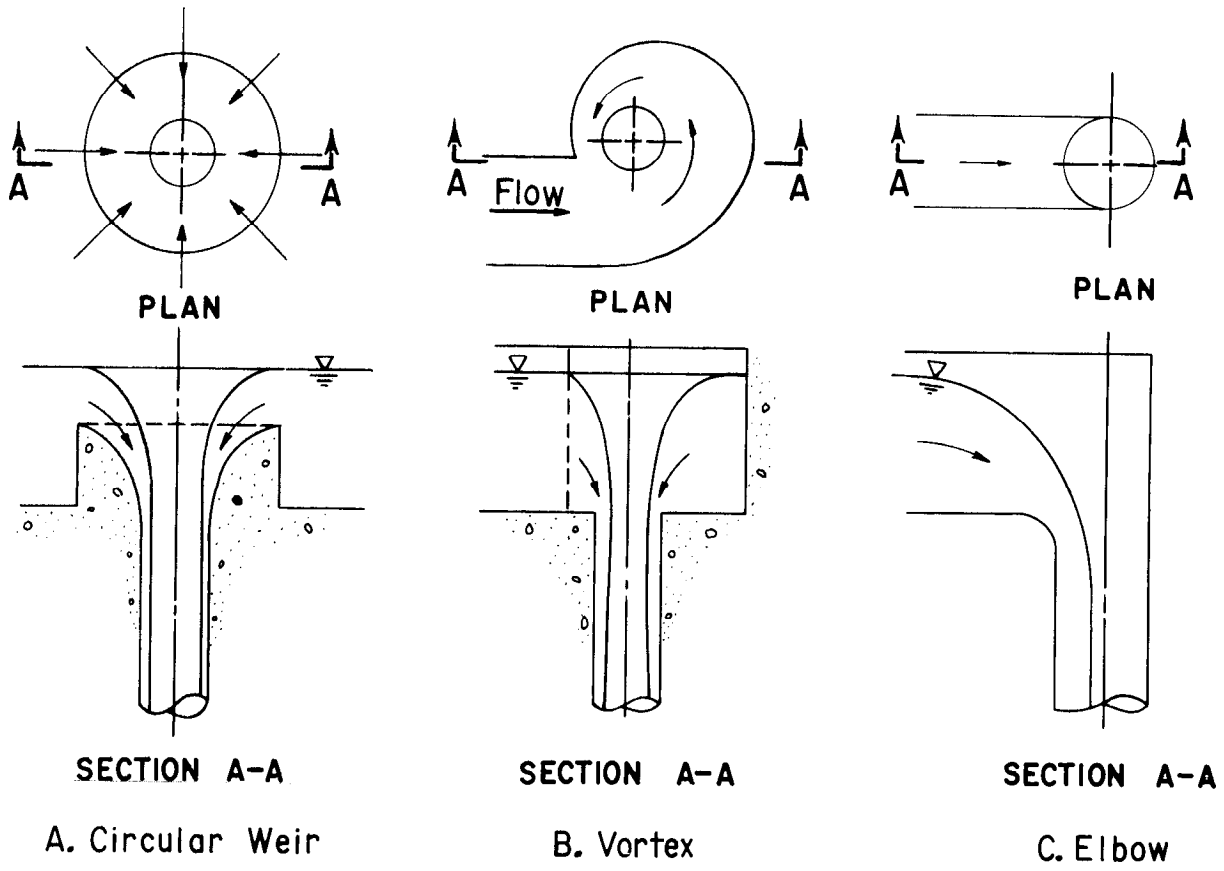


FIGURE 52.—*Typical types of vertical shaft inlet structures.*

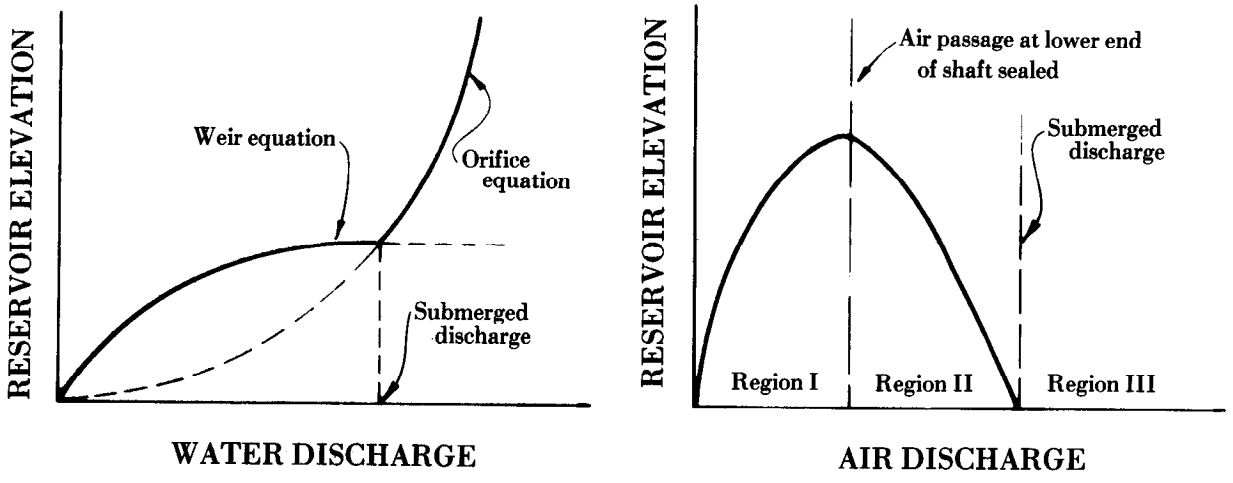


FIGURE 53.—*Vertical shaft spillway discharge characteristics.*

a relatively thin sheet. The volume flow rate of air is determined primarily by the shear action of the air-water interface and by entrainment into the mass of the water. This type of flow has been designated as region I on figure 53. As the water discharge increases with increasing reservoir elevation, a point is reached when the sheet of water is sufficiently thick to completely fill the upper end of the conduit. This water discharge separates region I from region II type flows.

Region II type flows are characterized by an annular hydraulic jump. Further increases in reservoir elevation merely cause the location of the jump to move upward in the vertical shaft. When the jump reaches a point near the top of the shaft, the flow is said to become submerged.

For reservoir elevations in excess of that required to produce the submerged water flow, all inflow of air to the shaft ceases. The discharge for this flow range is proportional to the one-half power of total energy over the crest.

If the bottom of the shaft is always submerged, then a region I type flow will not develop. Instead, the air motion will be described by a region II type flow up to the point when the vertical shaft is submerged.

The airflow rates discussed above should not be confused with those that are present in the portions of the structure downstream of the vertical shaft. The methods discussed in this chapter—Flow in Partially Filled Conduits—should be used to analyze the flow of air in the horizontal sections of vertical shaft spillways and similar structures. Mussalli and Carstens [55] studied surging problems that develop as the horizontal conduit seals [fig. 21 (5)]. However, they did not develop any air entrainment criteria for the vertical shaft.

Region I Airflow Rates

The airflow rate down the vertical shaft can be calculated by assuming:

a. The water flow on the shaft walls is similar to open chanel flow, and
b. The lower end of the shaft is open to the atmosphere.

If the inlet is not designed to keep the water flow attached to the wall, the airflow rate cannot be calculated.

Several methods are available to estimate the airflow rate when the water forms in a sheet on the walls. For instance, the air insufflated into the flow can be estimated from equation 59 using open channel flow relations. The amount of air flowing on the core of the pipe can be determined from

$$Q_a = V_o A_c \tag{98}$$

where

A_c = cross sectional of air in core
V_o = maximum water velocity in vertical shaft

Hack [27] recommends that the total airflow be determined from

$$Q_a = 0.35 + 16.1\,\overline{C}^{2.88} \tag{99}$$

where $\overline{C}$ = mean air concentration
The mean air concentration is estimated from

$$\overline{C} = \{1 + [4(1 - e^{k_r(\mathbf{F}_o^{4/3} - \mathbf{F}^{4/3})})]^{-1}\}^{-1} \tag{100}$$

where

D = conduit diameter
$\mathbf{F}$ = Froude number at end of shaft
$\mathbf{F}_o$ = Froude number at point where boundary layer intersects water surface
$k_r = 1.8\, r_s + 0.0108$
k_s = equivalent sand grain roughness
r_s = relative roughness $= k_s/D$

The point where the boundary layer intersects the water surface is found through the application of equations 27 through 30.

Region II Airflow Rates

Various investigators have studied the entrainment of air by an annular jet.

Haindl [29] found that the air entrainment obeys a law very similar to that found by Kalinske and Robertson [38] for a hydraulic jump in a conduit. The relation is

$$\beta=\frac{Q_a}{Q_w}=0.02\,(\mathrm{F}-1)^{0.86} \tag{101}$$

where F=Froude number

$$\mathrm{F}=\frac{Q_w}{R_j D\,[1-(R_j/D)](gR_j)^{1/2}} \tag{102}$$

D=outside jet diameter (conduit diameter)
g=gravitational constant (acceleration)
Q_a=volume flowrate of air
Q_w=volume flowrate of water
R_j=thickness of annular jet

Kleinschroth [43] found a correlation for flows in vertical shafts having a vortex inlet. The relation is

$$\beta=0.022\left(\frac{h_f}{D}\right)^{3/5} \tag{103}$$

where
h_f=distance from the inlet to the water level in the vertical shaft
D=shaft diameter

Reverse Airflow in a Vertical Shaft

All the preceeding relations assume that the waterflow rates are sufficient to remove all the entrained air from the system. Martin [51] showed that slug flow begins when the dimensionless airflow β exceeds 0.223. It was shown earlier that these slugs move up the shaft for

$$\frac{Q^2}{gD^5}<0.3 \tag{104}$$

Therefore, for dimensionless water flow ratios less than 0.3, the airflow quantities given by equations 101 and 103 are too large. In addition, it is possible that blowback will occur in the shaft.

Submergence

The water depth which causes a vertical shaft to flow submerged has been determined only for the case of radial inflow. Jain, Raju, and Garde [36] determined that the submergence at which airflow down the shaft ceases is given by

$$\frac{S}{D}=0.47\,\mathrm{F}^{1/2} \tag{105}$$

where
D=shaft diameter
$\mathrm{F}=V/(gD)^{1/2}$
g=gravitational constant (acceleration)
S=submergence depth
V=mean water velocity in shaft flowing full

For a vortex inlet or for approach flow having some circulation, the required submergence would be greater than that given by equation 105.

Free Falling Water Jets

Free falling water jets have important aeration effects in the case of unconfined flow discharging from gates and valves. Three main areas of concern are:

1. Jet characteristics,
2. Airflow around the jet, and
3. Air entraining characteristics as a falling jet enters a pool of water.

Each of these subtopics will be considered in detail.

Jet Characteristics

Dodu [20] and Rouse et. al., [60] have shown that the jet characteristics are a function of the conduit geometry and flow dynamics upstream from the point where the jet begins. For instance, a laminar jet exiting from a carefully shaped orifice connected to a large tank of quiescent water can have such a smooth surface that the jet appears to be made of glass. If the water surface in the tank is disturbed, however, waves will form on the surface of the jet. For turbulent flow, the jet always disintegrates somewhere along its length if it is allowed to travel far enough. However, the distance to the point at which the breakup occurs is controlled by the turbulent intensity within the jet. By changing the flow geometry upstream of the jet, its turbulent intensity is varied.

It should be emphasize that the breakup of the jet is caused primarily by turbulence internal to the jet and only secondarily by the action of the air into which the jet discharges [60]. Tests by Schuster [64] in which a jet discharged into a vacuum show exactly the same jet texture and breakup characteristics as observed by Dodu [20] of a jet discharging into air. From this, one can conclude that physical models should accurately predict the spread and energy content of prototype jets if the turbulent intensity in the model is similar to that in the prototype.

When comparing model and prototype jets near their origin, the prototype jet apparently is surrounded by much more spray than the model (fig. 54A). This difference is due partially to the time scale relations between the two jets. The prototype represents, in essence, a high-speed photograph of the model. The many small drops in the model (fig. 54A) appear as a frothy spray when photographed at a much faster camera speed.

The effect of the air on the jet becomes significant only after the jet atomizes into individual drops.

In the region far from the origin of the jets, their trajectory is affected by air resistance and a large portion of the stream falls vertically downward as spray (fig. 54B).

Hinze [35] studied the breakup of individual falling drops. His results have been replotted in the form of Weber and Reynolds number relations (fig. 55). Here the Weber number is defined as

$$W^2=\frac{U_d^2 D_d}{\sigma/\varrho_f} \tag{106}$$

where

D_d=diameter of water drop
U_d=velocity of water drop relative to air velocity
ϱ_f=water (drop) density
σ=interfacial surface tension

The Reynolds number is defined as

$$R=\frac{U_d D_d}{\nu} \tag{107}$$

where ν=kinematic viscosity of the drop

From figure 55 and fall velocity equation for a rigid sphere, it is possible to estimate the maximum stable drop diameter as about 0.4 mm. The fall velocity of spheres can be determined from a form of the Stokes equation (eq. 1). The relationship is

$$V=\left\{\frac{4}{3}[(\varrho_w/\varrho_a)-1]\frac{gD_d}{C_s}\right\}^{1/2} \tag{108}$$

where C_s drag coefficient of a sphere

The drag coefficients of spheres can be found in fluid mechanics texts [59].

The maximum stable drop diameter usually is not observed in nature because the larger free falling drops have some survival time associated with them. As small drops atomize they pass from a spherical shape to a torus with an attached hollow bag-shaped film. As this bag bursts, the entire torus breaks up. A certain time is required for this process to take place. Komabayasi et al., [45] found that drops of 7-and 5-millimeter diameters took 10 and 200 seconds, respectively, to break up. Thus, a 7-mm-diameter-drop would have to fall more than 85 meters at a terminal velocity of 8.5 m/s to breakup into smaller drops. A distance of more than 1300 meters would be required for the 5-m-diameter drop to breakup at a terminal fall velocity of 6.7 m/s.

Airflow Around the Jet

The airflow around a jet depends primarily upon the velocity of the jet and roughness of the jet. Dodu [20] found that the velocity distribution in the air around the jet was approximately logarithmic up until the point where the jet breaks up. The velocity distribution should follow a law expressed by

$$\frac{U_j-u}{v_*}=f\left(\frac{y_a-r}{\delta}\right) \tag{109}$$

where

r = water jet radius
U_j = water jet velocity
u = air velocity at a point located y_a distance from the jet centerline
y_a = distance from water surface
δ = boundary layer thickness
v_* = shear velocity = $(\tau_j/\varrho_a)^{1/2}$
ϱ_a = air density
τ_j = shear stress at water jet

The functional relation should be very similar to that for flow over a flat plate as studied by Bormann [11] (fig. 56).

Unfortunately, data are not presently available that will allow the computation of the shear velocity and boundary layer thickness in the air surrounding a jet for a given jet geometry and flow rate.

Air Entraining Characteristics as a Falling Jet Enters a Pool

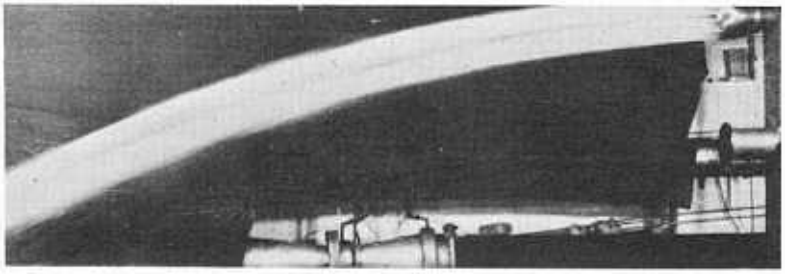
Ervine and Elsawy [21] studied the air entrained by a rectangular jet falling into an open pool. They developed an empirical relation that predicts the relative quantity of air taken into the water by the jet. The relation is

$$\beta = \frac{Q_a}{Q_w} = 0.26 \frac{b_n}{p_n} \left(\frac{H_f}{d_n}\right)^{0.446} \left(1 - \frac{V_m}{V_i}\right) \quad (110)$$

where

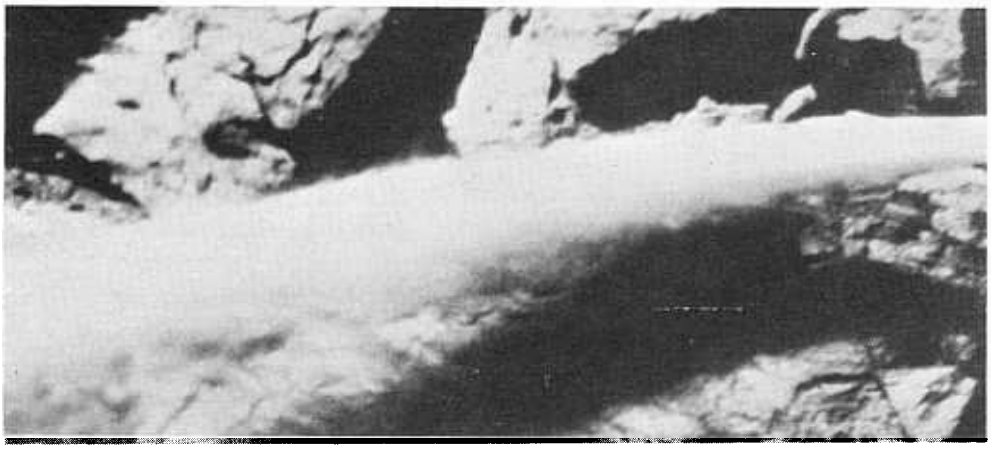
b_n = nappe width
d_n = nappe thickness
H_f = fall height of a waterjet
p_n = nappe perimeter
Q_a = volume flow of air
Q_w = volume flow of water
V_i = nappe velocity at impact
V_m = minimum velocity required to entrain air = 1.1 m/s

Model



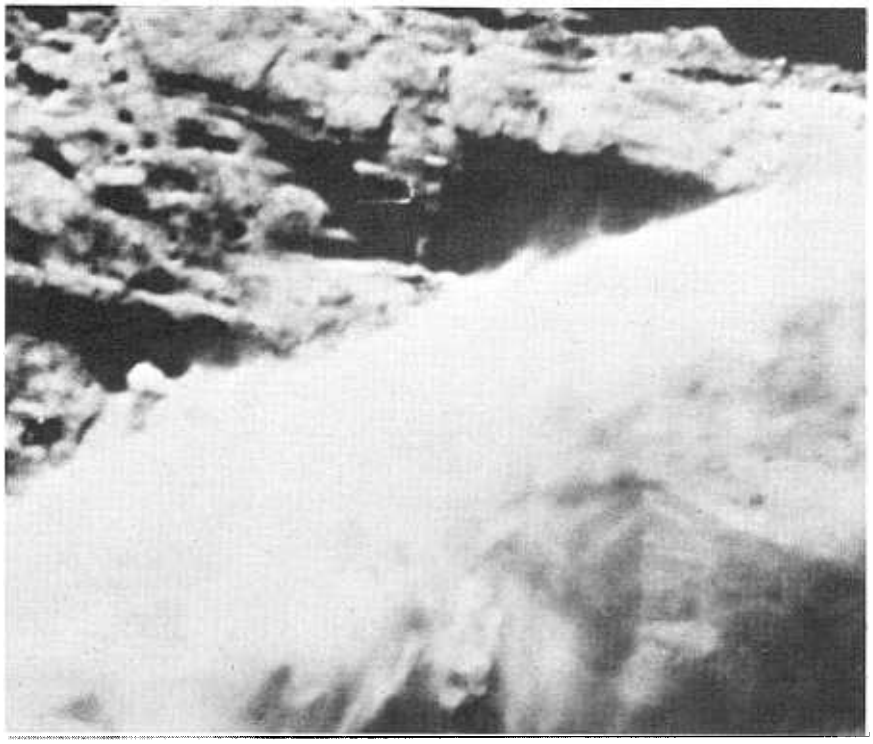
Valve fully open.

Prototype



A.-Jet characteristics near the valve.

Prototype



B.-Jet characteristics far from the valve.

FIGURE 54.—*Breakup of a water jet from a hollow-jet valve. P801-D-79281*

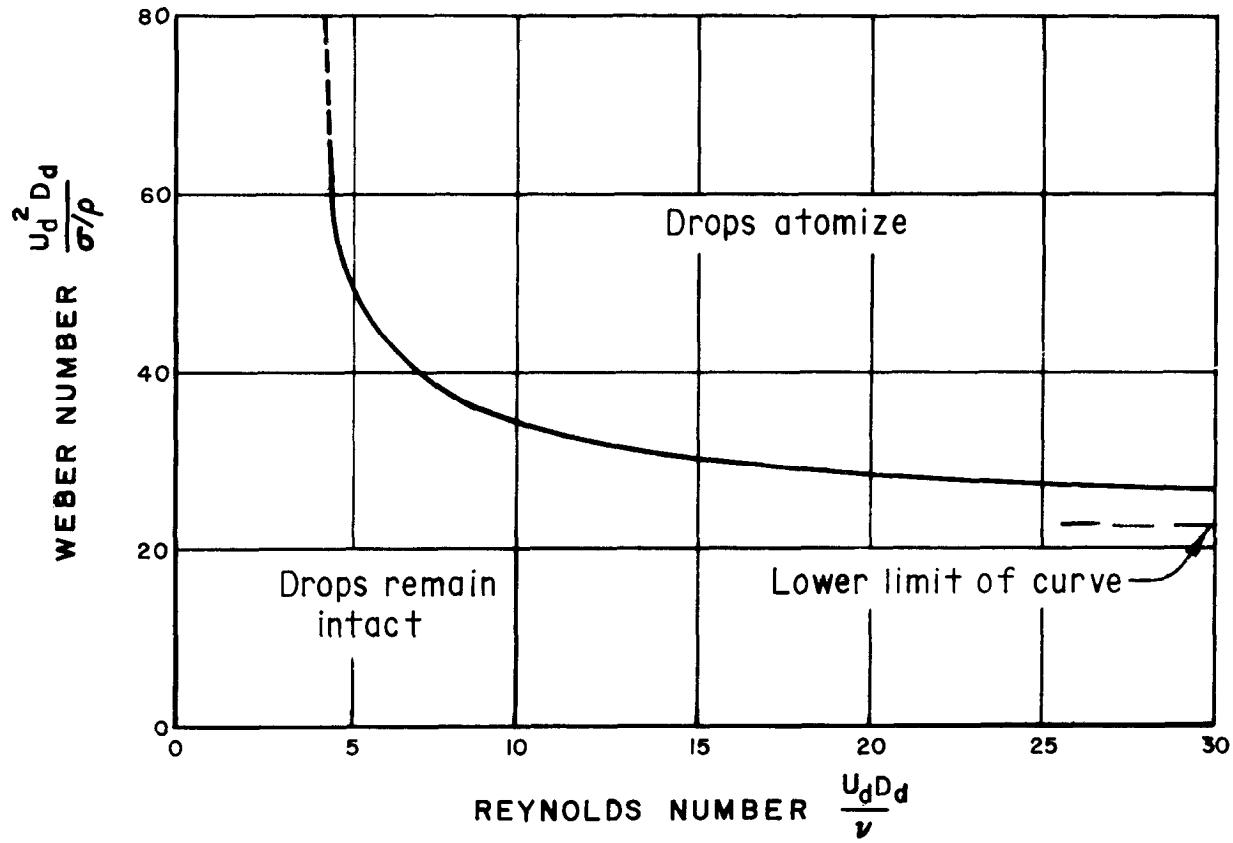


FIGURE 55.—*Water drop breakup.*

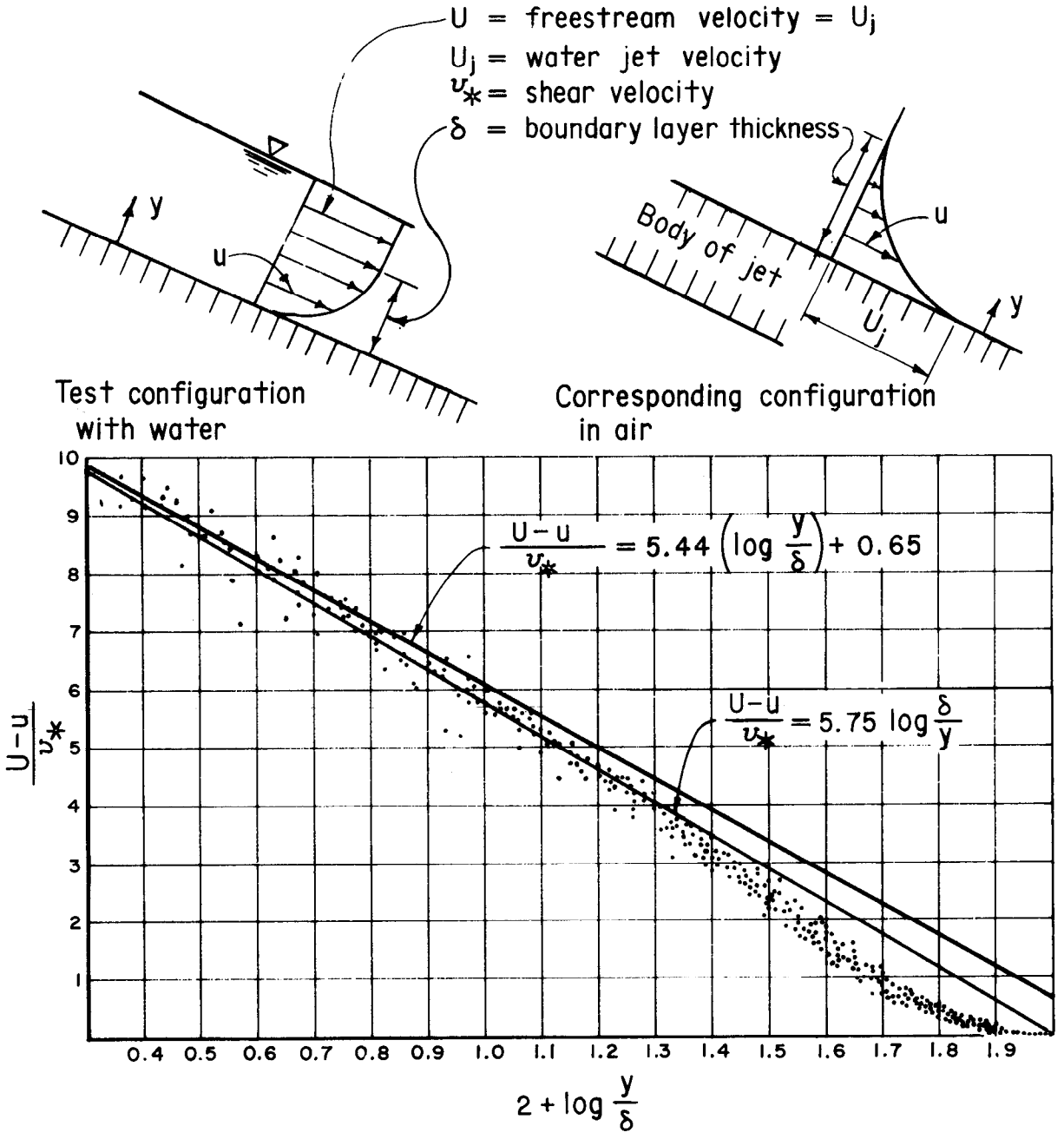


FIGURE 56.—*Velocity distribution for flow over a flat plate, Bormann [11].*

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[74] Wisner, P., "Air Demand and Pulsatory Pressures in Bottom Outlets," High Velocity Flow Symposium, Bangalore, India, 1967.

Appendix

I - Probability Depth Probe

II - Mean Air Concentration, Free Surface Flow, Computer Program

III - Air Demand, Falling Water Surface, Computer Program

Appendix I - Probability Depth Probe

A water surface probe was developed by Killen [41] at the St. Anthony Falls Hydraulic laboratory (University of Minnesota) which permits a direct determination of the probability that the water surface is greater than or equal to a given elevation. The original probe circuitry has been modernized to function with operational amplifiers (fig. I-1).

Experiments showed that a probe consisting of two parallel wires separated by a short distance exhibited a temperature drift when the probe was removed from the water. By connecting one wire to a metal point gage and the other to an electrode in the body of water, the drift was eliminated (fig. I-2).

The electronics, battery, and controls are conveniently mounted in a utility box (fig. I-3).

The following steps are necessary to put the unit in operation:

- Zero integrating voltmeter with zero control on box (within about 5 millivolts acceptable)
- Set gain control on box for 10 volts when probe is shorted (in water). Note reading on digital voltmeter.
- Repeat steps one and two (if necessary repeat twice).
- Take reading. Voltage read should indicate percentage of the probe shorted (i.e., in water).

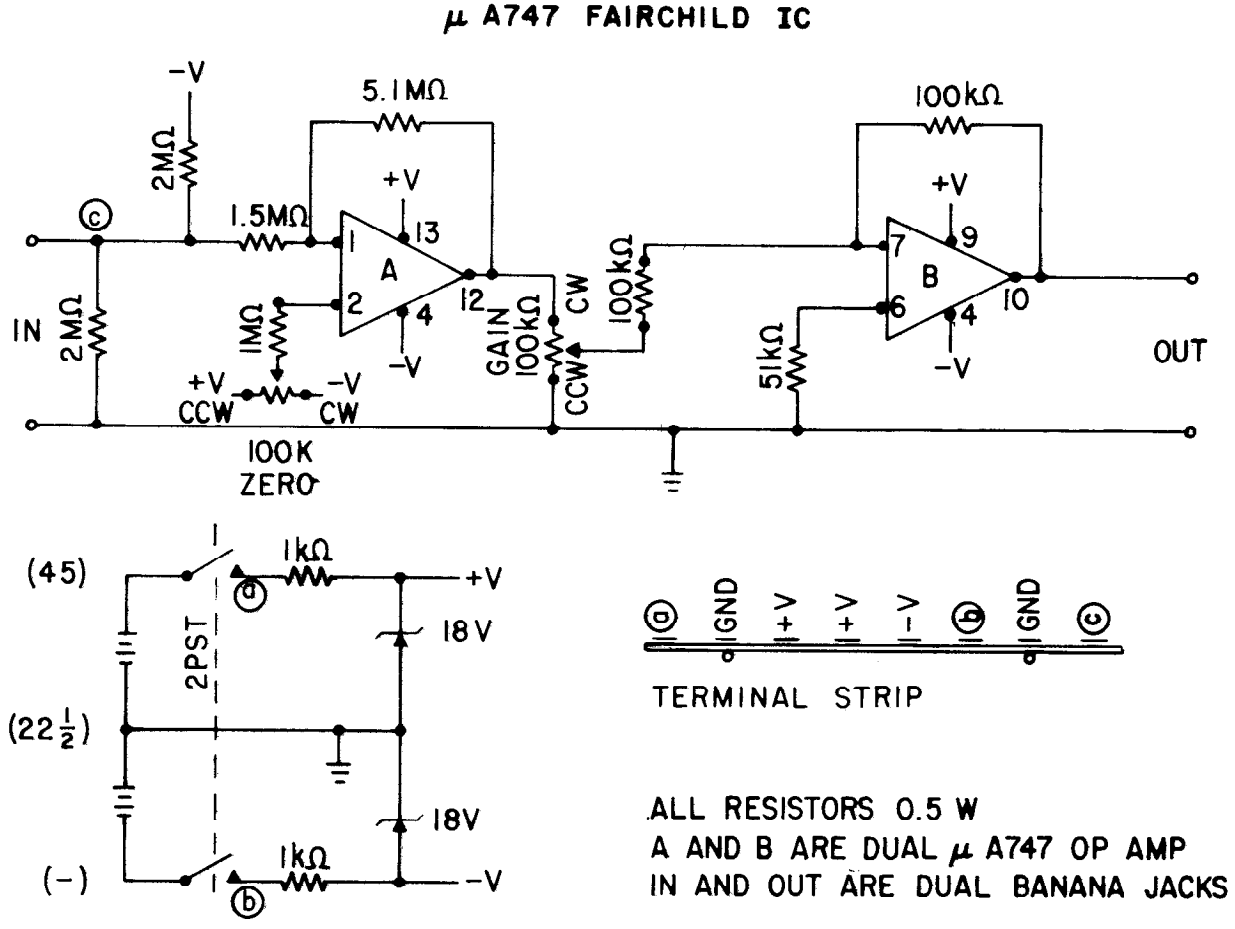


FIGURE I-1.—*Electronics schematic.*

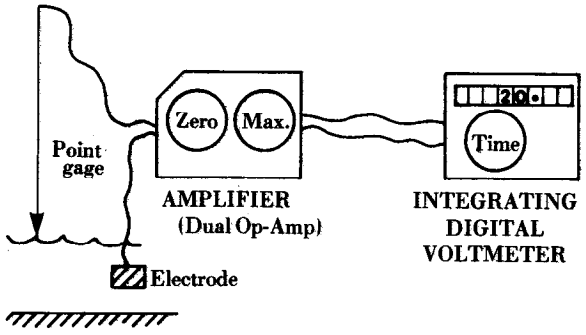


FIGURE 1-2.—*Probe schematic.*

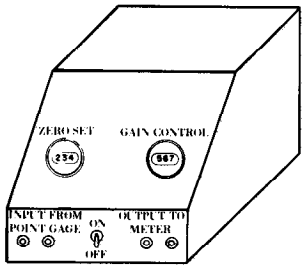


FIGURE I-3.—*Controls in utility box.*

Appendix II - Mean Air Concentration, Free Surface Flow, Computer Program

A detailed description of the computer program input is given in the program listing. The program was written to read the input data from a file called **HSPWY**.

An example of the input format and its output is presented at the end of the computer listing.

```
      PROGRAM HFWS

 1              PROGRAM HFWS(HSPWY=/80,OUTPUT,TAPE2=HSPWY,TAPE3=OUTPUT)
                COMMON A,B,HR,W,SS,R,IS,PI,ELINV,SB,ELC,R1,T,G,JIC
                DIMENSION TITL(10)
           C
 5         C      THIS PROGRAM COMPUTES THE AMOUNT OF AIR INSUFFLATED INTO OPEN
           C      CHANNEL FLOW.  THE CHANNEL CAN HAVE A TRAPEZOIDAL, CIRCULAR, OR
           C      A TRANSITIONAL CROSS SECTION.  THE PROGRAM IS GOOD FOR RESERVOIR,
           C      DRAWDOWN,AND BACKWATER CURVES.  IF A HYDRAULIC JUMP FORMS IN
           C      THE CIRCULAR OR TRANSITION SECTIONS, THE AIR CONTENT OF THE
10         C      WATER IS COMPUTED WITH EQUATIONS GIVEN BY KALINSKI AND
           C      ROBERTSON. A KINETIC ENERGY CORRECTION FACTOR OF 1.1 IS APPLIED
           C      TO EVERY STATION .
           C
           C
15         C      THE PROGRAM ALSO CHECKS FOR THE FORMATION OF DAMAGING
           C      CAVITATION.  IF A POTENTIAL FOR DAMAGE EXISTS, THE
           C      PROGRAM INDICATES THE SITE AND THE HEIGHT OF THE
           C      OFFSET.  IT IS ASSUMED THAT THE OFFSETS ARE INTO THE
           C      FLOW.
20         C
           C
           C      THE REQUIRED INPUT IS ;
           C      1) DISCHARGE,INITIAL DEPTH, RUGOSITY, DIRECTION OF
           C      COMPUTATION, METRIC, INITIAL BOTTOM SLOPE (DISTANCE VERTICAL
25         C      TO DISTANCE HORIZONTAL).
           C
           C      TYPICAL RUGOSITIES
           C      ------------------
           C      CONCRETE 0.3-3.0 MM
30         C      STEEL      0.05  MM
           C      TUBING    0.0015 MM
           C
           C      DIRECTION OF COMPUTATION
           C      ------------------------
35         C      UPSTREAM   0
           C      DOWNSTREAM 1
           C
           C      DIMENSIONAL UNITS
           C      -----------------
40         C      METRIC   0
           C      ENGLISH  1
           C
           C      2) THE TITLE, CENTERED IN A FIELD OF 60 CHARACTERS
           C
45         C
           C
           C      3) THE NUMBER OF STATIONS
           C
           C
50         C      4) THREE DESCRIPTION CARDS ARE REQUIRED FOR EACH STATION.
           C      THESE CONSIST OF THE FOLLOWING;
           C
           C      CARD 1
           C      ------
55         C      SHAPE OF CROSS SECTION
           C      I=0-RECTANGULAR OR TRAPEZOIDAL
           C      I=1-CIRCULAR
           C      I=2-TRANSITION
           C
60         C      SLOPE OF CROSS SECTION AT TRANSITION
           C      IS=1-SECTION VERTICAL
           C      IS=2-SECTION NORMAL TO FLOOR
           C
           C
```

```
      PROGRAM HFWS

C     CARD 2. IS ONE OF THE FOLLOWING;
C     -------
C
C     A) RECTANGULAR OR TRAPEZOIDAL
C     STATION, INVERT ELEVATION, BOTTOM WIDTH,
C     CHANNEL SIDE SLOPE (DISTANCE HORIZONTAL TO UNITY
C     VERTICAL).
C
C
C     B)  CIRCULAR SECTION
C     STATION, INVERT ELEVATION, RADIUS OF
C     CIRCULAR SECTION.
C
C
C     C)  TRANSITION SECTION
C     THE TRANSITION SECTION IS ESSENTIALLY A SQUARE
C     WITH CIRCULAR FILLETS IN THE FOUR CORNERS AND
C     A CENTER SUPPORT WALL.  THE DATA TO DESCRIBE THIS
C     SECTION INCLUDES;
C
C     THE STATION, INVERT ELEVATION,
C     WIDTH OF SECTION, RADIUS OF UPPER FILLETS,
C     (IF NOT CLOSED CONDUIT FLOW, SET EQUAL TO ZERO),
C     ELEVATION OF CENTERLINE OF UPPER RADIUS POINT,
C     (IF NOT CLOSED CONDUIT FLOW, SET EQUAL TO ZERO),
C     RADIUS OF LOWER FILLETS, THICKNESS OF SUPPORT
C     WALL.
C
C
C     CARD 3
C     ------
C     THE TRANSITION LOSS FACTOR,  THE BEND LOSS
C     FACTOR, THE BEND RADIUS, THE BEND ANGLE.
C
C     THE HEAD LOSS DUE TO TRANSITIONS IS EQUAL TO THE
C     THE TRANSITION LOSS FACTOR TIMES THE DIFFERENCE
C     IN UPSTREAM AND DOWNSTREAM VELOCITY HEADS.
C
C     THE HEAD LOSS DUE TO° VERTICAL BENDS IS EQUAL TO THE BEND
C     LOSS FACTOR TIMES ONE HALF THE SUM OF THE UPSTREAM
C     AND DOWNSTREAM KINETIC ENERGIES.
C
C     THE BEND ANGLE IS EQUAL TO THE INCLUDED ANGLE OF
C     OF THE VERTICAL CURVE, IN RADIANS, BETWEEN STATIONS.
C     IF THE VERTICAL RADIUS OF CURVATURE VARIES FROM
C     ONE STATION TO ANOTHER, ADJUST THE BEND ANGLE
C     SO THAT THE RUN BETWEEN THE STATIONS IS EQUAL
C     TO THE BEND ANGLE*ABS(BEND RADIUS)
C
C     IF THE INVERT MOVES AWAY FROM THE FLOW, THE SIGN OF THE
C     VERTICAL RADIUS OF CURVATURE IS NEGATIVE.  IF THE SECTION
C     BETWEEN STATIONS IS STRAIGHT, SET THE VERTICAL RADIUS OF
C     CURVATURE EQUAL TO 0.
C
C     ================================================================
C
C     THE INPUT IS READ WITH A FREE FORMAT.  THIS MEANS THAT
C     THE DATA FOR EACH CARD MUST BE ON A SINGLE LINE AND
C     SEPARATED BY ONE OR MORE BLANKS, OR BY A COMMA OR A
C     SLASH, EITHER OF WHICH MAY BE PRECEEDED OR FOLLOWED BY
C     ANY NUMBER OF BLANKS.  BLANKS ARE NOT ALLOWED AS
C     SUBSTITUTES FOR ZERO.  A DECIMAL POINT
C     OMITTED FROM A REAL CONSTANT IS ASSUMED TO OCCUR TO
C     THE RIGHT OF THE RIGHTMOST DIGIT OF THE MANTISSA.
C     EXTRANEOUS DATA ON A CARD WILL BE READ ON
```

```
      PROGRAM HFWS

130           C     SUBSEQUENT READ COMMANDS.  THIS WILL RESULT IN
              C     *ERROR DATA INPUT*DIAGNOSTICS.
              C
              C
              C     THE INITIAL DEPTH MUST BE AT LEAST 0.5 PERCENT LARGER
135           C     OR SMALLER THAN THE CRITICAL DEPTH TO INITIATE THE
              C     COMPUTATIONS.
              C
              C     THE AIR CONTENT IS COMPUTED FROM
              C
140           C     C= 0.05*F-SQRT(SINE(ALPHA))*W/(61*F)
              C
              C     WHERE  F= V/SQRT(G*Y(EFF))
              C            W= V/SQRT(SIGMA/RHO*HR)
              C            HR= HYDRAULIC RADIUS
145           C            SIGMA= INTERFACIAL TENSION
              C            RHO= DENSITY OF WATER
              C            G= ACCELERATION OF GRAVITY
              C            Y(EFF)= EFFECTIVE DEPTH
              C                  = AREA/TOP WIDTH OF WATER PRISM
150           C     THE AIR RATIO IS DEFINED AS BETA= Q(AIR)/Q(WATER)= C/(1-C)
              C
              C     IF A HYDRAULIC JUMP FORMS IN THE CONDUIT,
              C
              C            BETA= 0.0066*(F-1.)**1.4
155           C
              C
              C
              C     ================================================================
              C
160           C     INITIALIZATION OF DATA
              C
                  1 S= -0.1
                    V= 0.0
                    HV= 0.
165                 ELINV= 0.
                    STA= 0.
                    EGL= 0.
                    F= 0.
                    TOTAL= 0.0
170                 BETA= 0.0
                    PI= 3.1415926
                    JIC= 0
                    K= 0
                    NL= 1
175                 DIA= 0.
                    DT= 0.
              C
              C     INPUT OF FLOW DATA
              C
180                 READ (2,*) Q,DN,RUG,NCURV,MET,SB
                    IF(MET.EQ.0)RUG=RUG/1000.
                    IF(EOF(2))2,3
                  2 CALL EXIT
                  3 G= 9.807
185                 IF(MET.EQ.1)G= 32.2
                    VIS= 1.4E-05
                    IF(MET.EQ.0)VIS= 1.3E-06
                    DNO= DN
                    READ(2,4)(TITL(I),I=1,10)
190                 FORMAT(10A6)
                    READ (2,*) NS
              C
              C     LOOP WHICH INCREMENTS THE STATIONS
              C
```

```
      PROGRAM HFWS

195                 CHECK= EGL
                    DO 68 NT=1,NS
                      SAVE=STA
                      STORE=S
                      STORE1=ELINV
200                   EGL= CHECK
                      HIDE1=HV
                      IF(NT.NE.2)GO TO 14
                C
                C     COMPUTATION OF HYDRAULIC PROPERTIES OF FIRST STATION
205             C
                      IF(BENDR.EQ.0.) GO TO 5
                C
                C     HYDROSTATIC DEPTH WITH BEND
                      D= DN/SQRT(1.0+SB*SB)+2.0*HV*DN/BENDR
210                   GO TO 6
                C
                C     HYDROSTATIC DEPTH WITHOUT BEND
                    5 D= DN/SQRT(1.0+SB*SB)
                    6 TOTAL= ELINV+D+HV
215             C
                C     WRITE STATEMENTS FOR TITLES
                C
                      WRITE(3,7)(TITL(I),I=1,10)
                    7 FORMAT(1H1,28X,10A6/28X,20H--------------------
220                  +         40H---------------------------------------- //)
                      IF(MET.EQ.1)WRITE(3,8)Q,DN,RUG,CN
                    8 FORMAT(19X,3HQ =,F7.1,4H CFS,3X,15HINITIAL DEPTH =,F6.2,
                     +         3H FT,3X,10HRUGOSITY =, F8.6,3H FT,3X,3HN =,F6.4//)
                      IF(MET.EQ.1)WRITE (3,9)
225                   9 FORMAT(66X,6HENERGY,33X,5HDEPTH/
                     +         47H STATION    INVERT ELEV    SLOPE      DEPTH     VEL
                     +         42HOCITY     PIEZ     GRADE LINE  Q AIR/Q WATER,
                     +         27H   PROFILE   NORMAL   CRITICAL /
                     +         4X,2HFT,9X,2HFT,20X,2HFT,6X,6HFT/SEC,6X,2HFT,9X,2HFT,
230                  +         32X,2HFT,7X,2HFT/)
                      IF(MET.EQ.0)RUG= RUG*1000.
                      IF(MET.EQ.0)WRITE(3,10)Q,DN,RUG,CN
                      IF(MET.EQ.0)RUG= RUG/1000.
                   10 FORMAT(19X,3HQ =,F9.3,4H CMS,3X,15HINITIAL DEPTH =,F6.3,
235                  +         2H M,3X,10HRUGOSITY =,F8.4,3H MM,3X,3HN =,F6.4//)
                      IF(MET.EQ.0)WRITE (3,11)
                   11 FORMAT(66X,6HENERGY,33X,5HDEPTH/
                     +         47H STATION    INVERT ELEV    SLOPE      DEPTH     VEL
                     +         42HOCITY     PIEZ     GRADE LINE  Q AIR/Q WATER,
240                  +         27H   PROFILE   NORMAL   CRITICAL /
                     +         3X,2H M,10X,2H M,19X,2H M,6X,6H M/SEC,6X,2H M,9X,2H M,
                     +         33X,1HM,8X,1HM/)
                      WRITE (3,12) STA,ELINV,SB,DN,V,D,TOTAL,BETA,AN,M,YN,YC
                   12 FORMAT (1X,F7.2,F12.3,F10.4,F10.3,F11.3,F9.3,3X,F10.3,F12.3
245                  +         ,9X,A1,I1,1X,F9.3,F9.3/)
                      IF(SIG.GT.SIG1.AND.SIG.GT.SIGR)GO TO 14
                      IF(SIG1.GT.SIGR.AND.SIG1.GT.SIG)GO TO 13
                      WRITE(3,64)
                      GO TO 14
250                13 IF(MET.EQ.1)WRITE(3,66)HO,NSL
                      IF(MET.EQ.0)WRITE(3,67)HO,NSL
                   14 ILOOP= (NL-1)/21-K
                      IF(ILOOP.NE.1)GO TO 15
                      K= K+1
255                   WRITE(3,7)(TITL(I),I=1,10)
                      IF(MET.EQ.1)WRITE(3,9)
                      IF(MET.EQ.0)WRITE(3,11)
                   15 READ (2,*) I,IS
                      IF(EOF(2))71,16
```

```
      PROGRAM HFWS

260               16    IF (I-1) 17,18,19
                  C
                  C       RECTANGULAR OR TRAPEZOIDAL CHANNELS
                  17    READ (2,*) STA,ELINV,W,SS
                        READ (2,*) TLF,BLF,BENDR,BENDA
265                     CALL TRAP(DN)
                        GO TO 22
                  C
                  C       CIRCULAR CONDUITS
                  18    READ (2,*) STA,ELINV,R
270                     READ (2,*) TLF,BLF,BENDR,BENDA
                        DIA= 1.99999*R
                        CALL CIRC(DIA)
                        GO TO 22
                  C
275               C       CIRCULAR TO RECTANGULAR TRANSITIONS
                  19    READ (2,*) STA,ELINV,W,R,ELC,R1,T
                        READ (2,*) TLF,BLF,BENDR,BENDA
                        IF(ELC.LT.ELINV)GO TO 20
                        SB= (ELINV-STORE1)/ABS(SAVE-STA)
280                     IF(NCURV.EQ.1)SB= -SB
                        WMIN= (W-T)/2.
                        IF(R.GE.WMIN.AND.IS.EQ.1)DT= 0.99999*(ELC-ELINV+SQRT(
                       +R*(W-T)-0.25*(W-T)*(W-T)))
                        IF(R.GE.WMIN.AND.IS.EQ.2)DT= 0.99999*((ELC-ELINV)*SQRT(SB*SB
285                    +1.)+SQRT(R*(W-T)-0.25*(W-T)*(W-T)))
                        IF(R.LT.WMIN.AND.IS.EQ.1)DT= 0.99999*((ELC-ELINV)+R)
                        IF(R.LT.WMIN.AND.IS.EQ.2)DT= 0.99999*((ELC-ELINV)*SQRT(SB*SB
                       +1.)+R)
                        GO TO 21
290               20    DT= DN
                  21    CALL TRANS(DT)
                  C
                  C       USING EQ 4-13 FROM OPEN CHANNEL FLOW BY HENDERSON,
                  C       MACMILLAN, 1970.  THIS IS THE COLEBROOK EQUATION.
295               C
                  22    REY= 4.*HR*(Q/A)/VIS
                        FRICO= 0.
                        DO 23 N=1,20
                          FRICT= -2.*ALOG10(RUG/(12.*HR)+2.5*FRICO/REY)
300                       IF(ABS(1.-FRICO/FRICT).LE.0.01)GO TO 24
                          FRICO= FRICT
                  23    CONTINUE
                  24    IF(MET.EQ.0)CN=(HR**0.166667)/(SQRT(8.*G)*FRICT)
                        IF(MET.EQ.1)CN=(HR**0.166667)*1.49/(SQRT(8.*G)*FRICT)
305               C
                  C       COMPUTATION OF BOTTOM SLOPE
                  C
                        IF(NT.EQ.1)GO TO 25
                        SB= (ELINV-STORE1)/ABS(SAVE-STA)
310                     IF(NCURV.EQ.1)SB= -SB
                  C
                  C       CHECK FOR MAXIMUM DISCHARGE IN CLOSED CONDUITS
                  C
                  25    IF(I.EQ.0)GO TO 26
315                     QMAX= A*SQRT(ABS(SB))*HR**0.66667/CN
                        IF(MET.EQ.1)QMAX= 1.49*QMAX
                  C
                  C       COMPUTATION OF CRITICAL DEPTH BY NEWTONS METHOD
                  C
320               26    DY= DN/2.
                        YC= DN
                        DO 31 NN=1,25
                          IF(I-1)27,28,29
                  27      CALL TRAP(YC)
```

```
      PROGRAM HFWS

325                     DBDY= 2.*SS
                        GO TO 30
                28      CALL CIRC(YC)
                        DBDY= (DIA-2.*YC)/SQRT(YC*DIA-YC*YC)
                        GO TO 30
330             29      CALL TRANS(YC)
                        DBDY= 0.
                30      VC= Q/A
                        HVC= VC*VC/(2.*G)
                        HVCK= A/(2.*B)
335                     DHVC= HVC-HVCK
                        IF(ABS(DHVC/HVCK).LE.0.001)GO TO 32
                        DFDY= DBDY*HVCK/B-0.5*(1.+2.*B*HVC/A)
                        YCO= YC
                        YC= YC-DHVC/DFDY
340                     IF(YC.LE.0.)YC=ABS(YC)
                        IF(I.EQ.1.AND.YC.GT.DIA)YC= (YCO+DIA)/2.
                        IF(I.EQ.2.AND.YC.GT.DT)YC= (YCO+DT)/2.
                31    CONTINUE
              C
345           C       COMPUTATION OF NORMAL DEPTH BY NEWTONS METHOD
              C
                32    IF(I.EQ.0.AND.SB.GE.0.)GO TO 33
                      IF(SB.GT.0..AND.QMAX.GT.Q)GO TO 33
                      YN= 1000.
350                   IF(SB.LT.0.)YN= -1000.
                      GO TO 41
                33    DY= -DN/2.
                      YN= ABS(DN)
                      DO 40 NN=1,25
355                     IF(I-1)34,35,36
                34      CALL TRAP(YN)
                        GO TO 37
                35      CALL CIRC(YN)
                        GO TO 37
360             36      CALL TRANS(YN)
              C
              C         USING EQ 4-13 FROM OPEN CHANNEL FLOW BY HENDERSON,
              C         MACMILLAN, 1970.  THIS IS THE COLEBROOK EQUATION.
              C
365             37      REY= 4.*HR*(Q/A)/VIS
                        FRICO= 0.
                        DO 38 N=1,20
                          FRICT= -2.*ALOG10(RUG/(12.*HR)+2.5*FRICO/REY)
                          IF(ABS(1.-FRICO/FRICT).LE.0.01)GO TO 39
370                       FRICO= FRICT
                38      CONTINUE
                39      IF(MET.EQ.0)CN=(HR**0.166667)/(SQRT(8.*G)*FRICT)
                        IF(MET.EQ.1)CN=(HR**0.166667)*1.49/(SQRT(8.*G)*FRICT)
                        QM= A*SQRT(SB)*HR**0.66667/CN
375                     IF(MET.EQ.1)QM=1.49*QM
                        DHDY= HR/YN-2.*HR/(B+2.*YN)
                        FUN= Q-QM
                        IF(ABS(FUN/Q).LE.0.001)GO TO 41
                        DFDY= -B*QM/A-2.*QM*DHDY/(3.*HR)
380                     YNO= YN
                        YN= YN-FUN/DFDY
                        IF(YN.LE.0.)YN=ABS(DY)
                        IF(I.EQ.1.AND.YN.GT.DIA)YN= (DIA+YNO)/2.
                        IF(I.EQ.2.AND.YN.GT.DT)YN= (DT+YNO)/2.
385             40    CONTINUE
              C
              C       DETERMINATION OF PROFILE TYPE
              C
                41    IF(YN.LT.YC)GO TO 42
```

```
      PROGRAM HFWS

390                   IF(YN.EQ.YC)GO TO 43
                      IF(SB.EQ.0.)GO TO 44
                      IF(SB.LT.0.)GO TO 45
                C
                C     MILD SLOPE
395             C
                      AN= 1HM
                      IF(DN.GE.YN)M=1
                      IF(DN.LT.YN.AND.DN.GT.YC)M=2
                      IF(DN.LE.YC)M=3
400                   GO TO 46
                C
                C     STEEP SLOPE
                C
                   42 AN=1HS
405                   IF(DN.GE.YC)M=1
                      IF(DN.GT.YN.AND.DN.LT.YC)M=2
                      IF(DN.LE.YN)M=3
                      GO TO 46
                C
410             C     CRITICAL SLOPE
                C
                   43 AN= 1HC
                      IF(DN.GE.YN)M=1
                      IF(DN.LT.YN)M=3
415                   GO TO 46
                C
                C     HORIZONTAL
                C
                   44 AN= 1HH
420                   IF(DN.GE.YC)M=2
                      IF(DN.LT.YC)M=3
                      GO TO 46
                C
                C     ADVERSE
425             C
                   45 AN= 1HA
                      IF(DN.GE.YC)M=2
                      IF(DN.LT.YC)M=3
                C
430             C     COMPUTATIONAL LOOP TO DETERMINE WATER DEPTH
                C
                C
                   46 DO 60 J=1,100
                C
435             C
                C       COMPUTATION OF HYDRAULIC PROPERTIES
                C
                        IF (I-1) 47,48,49
                C
440             C       HYDRAULIC PROPERTIES FOR RECTANGULAR SECTION
                C
                   47   CALL TRAP(DN)
                        FRUD= F
                C
445             C       NOTE THE FROUDE NUMBER IS NOT CORRECTED FOR SLOPE
                C       AND ENERGY CORRECTION FACTOR
                        F=(Q/A)/(SQRT(G*A/B))
                        IF(NT.EQ.1)GO TO 50
                        CKFRUD= (FRUD-1.)/(F-1.)
450                     GO TO 50
                C
                C       HYDRAULIC PROPERTIES FOR CIRCULAR SECTION
                C
                   48   CALL CIRC(DN)
```

```
      PROGRAM HFWS

455                     IF(JIC.EQ.1)GO TO 69
                        FRUD= F
                        F=(Q/A)/(SQRT(G*A/B))
                        IF(NT.EQ.1)GO TO 50
                        CKFRUD= (FRUD-1.)/(F-1.)
460                     GO TO 50
               C
               C        HYDRAULIC PROPERTIES IN TRANSITION
               C
                  49    CALL TRANS(DN)
465                     IF(JIC.EQ.1)GO TO 69
                        FRUD= F
                        F=(Q/A)/(SQRT(G*A/B))
                        IF(NT.EQ.1)GO TO 50
                        CKFRUD= (FRUD-1.)/(F-1.)
470            C
               C        COMPUTATION OF DEPTH BY STANDARD STEP METHOD
               C
                  50    V=Q/A
                        HV= 1.1*V*V/(2.*G)
475            C
               C        COMPUTATION OF MANNINGS N VALUE FROM THE RUGOSITY
               C        USING EQ 4-13 FROM OPEN CHANNEL FLOW BY HENDERSON,
               C        MACMILLAN, 1970.  THIS IS THE COLEBROOK EQUATION.
               C
480                     REY= 4.*HR*(Q/A)/VIS
                        FRICO= 0.
                        DO 51 N=1,20
                          FRICT= -2.*ALOG10(RUG/(12.*HR)+2.5*FRICO/REY)
                          IF(ABS(1.-FRICO/FRICT).LE.0.01)GO TO 52
485                       FRICO= FRICT
                  51    CONTINUE
                  52    IF(MET.EQ.0)CN=(HR**0.166667)/(SQRT(8.*G)*FRICT)
                        IF(MET.EQ.1)CN=(HR**0.166667)*1.49/(SQRT(8.*G)*FRICT)
               C
490            C        1.1 IS THE KINETIC ENERGY CORRECTION FACTOR
               C
                        HT= TLF*ABS(HV-HIDE1)
                        HB=BLF*(HV+HIDE1)/2.0
                        S=(CN*CN*V*V)/(HR**1.3333)
495                     D= DN/SQRT(1.0+SB*SB)
                        IF(MET.EQ.1)S=S/2.208
               C
               C        NT= 1 IS THE CONDITION FOR THE FIRST STATION
               C
500                     IF(NT.EQ.1)DYDX= (SB-S)/(1.-F*F)
                        IF(NT.EQ.1)CHECK= ELINV+HV+DN/SQRT(1.+SB*SB)
                        IF(NT.EQ.1)GO TO 63
                        AVGS=(STORE+S)/2.0
                        IF(BENDR.NE.0.)GO TO 53
505            C
               C        COMPUTATION OF HEAD LOSS WITHOUT BENDS
               C
                        RUN= SQRT((STA-SAVE)*(STA-SAVE)+(STORE1-ELINV)*(STORE1-ELINV)
                     +  )
510                     HF=RUN*AVGS
                        SUM=HF+HT+HB
                        GO TO 54
               C
               C        COMPUTATION OF HEAD LOSS WITH BENDS
515            C
                  53    RUN= BENDA*ABS(BENDR)
                        HF= RUN*AVGS
                        SUM= HF+HT+HB
                        D= DN / SQRT(1.0+SB*SB)+2.0*HV*DN / BENDR
```

```
      PROGRAM HFWS

520           C
              C          COMPUTATION OF ENERGY GRADE LINE
              C
                 54      TOTAL=ELINV+D+HV
                         CHECK= EGL+SUM
525                      IF(NCURV.EQ.1)CHECK= EGL-SUM
              C
              C          DETERMINATION OF FLOW DEPTH USING NEWTONS METHOD
              C
                         EGLCK= TOTAL-CHECK
530                      DTDY= 1./SQRT(1.+SB*SB)-2.*HV*B/A
                         DCDY= 2.*(HF+HB+HT)*B/A+4.*HF*B*B/
                         (3.*HR*(B+2.*DN)*(B+2.*DN))
                         IF(NCURV.EQ.1)DCDY= -DCDY
                         DEDY= DTDY+DCDY
535                      DINC= EGLCK/DEDY
              C
              C          CHECK TO ENSURE THAT NEWTONS METHOD DOES NOT CAUSE A
              C          JUMP ACROSS NORMAL DEPTH IF COMPUTATIONS ARE PROCEEDING
              C          TOWARD THE NORMAL DEPTH.
540           C
                         IF(AN.EQ.1HM.AND.NCURV.EQ.0)GO TO 55
                         IF(AN.EQ.1HS.AND.NCURV.EQ.1)GO TO 56
                         GO TO 58
                 55      IF(M.EQ.3)GO TO 58
545                      IF(ABS(DINC).GT.ABS(DN-YN))GO TO 57
                         GO TO 58
                 56      IF(M.EQ.1)GO TO 58
                         IF(ABS(DINC).GT.ABS(DN-YN))GO TO 57
                         GO TO 58
550              57      DINC= ABS(DN-YN)*DINC/(ABS(DINC)*2.)
              C
                 58      DN= DN-DINC
                         IF(DN.LE.0.)DN= (DN+DINC)/2.
              C
555           C          CHECK ON THE ACCURACY OF COMPUTATIONS
              C
                         PCTEL= 100.*((TOTAL-CHECK)/(ABS(STORE1-ELINV)+D+HV))
                         IF(CKFRUD.LT.0.0)GO TO 73
                         IF(ABS(PCTEL).LT.0.01)GO TO 59
560                      GO TO 60
              C
              C          COMPUTATION OF AIR CONTENT WITH OPEN CHANNEL FLOW
              C
                 59      IF(SB.LE.0.)C=0.
565                      IF(SB.LE.0.)GO TO 61
                         ALPHA= ATAN(SB)
                         W= 100.*V/SQRT(0.74/HR)
                         IF(MET.EQ.1)W= V/SQRT(0.00257/HR)
                         C= 0.05*F-SQRT(SIN(ALPHA))*W/(63.*F)
570                      IF(C.LT.0.)C= 0.
                         IF(C.GE.0.74)C= 0.74
                         BETA= C/(1.-C)
                         GO TO 61
                 60    CONTINUE
575              61    IF(J.GE.100)GO TO 73
              C
              C        WRITE OUTPUT
              C
                       WRITE (3,12) STA,ELINV,SB,DN,V,D,CHECK,BETA,AN,M,YN,YC
580                    NL= NL+1
              C
              C        CHECK ON SPACING OF STATIONS
              C        (THIS KEEPS ERROR IN DEPTH TO LESS THAN 1-PERCENT)
              C
```

```
      PROGRAM HFWS

585                   DYDX= (SB-S)/(1.-F*F)
                      IF(DYDX.LE.1.E-10)GO TO 63
                      ERRY= 100.*0.5*(RUN/DNO)*(RUN/DNO)*ABS((SB-STORE)/(
                     +(1.-FRUDO*FRUDO)*(1.-FRUDO*FRUDO))*(10./3.*STORE-3.*(SB-STORE)*
                     +FRUDO*FRUDO/(1.-FRUDO*FRUDO)))
590                   IF(ERRY.LT.1.0)GO TO 63
                      DX= RUN/2.
                      WRITE(3,62)ERRY,DX
                   62 FORMAT(15X,22HERROR IN DEPTH EXCEEDS ,F4.0,9H PERCENT,  ,
                     +          4X,42HPLEASE ADD INTERMEDIATE STATIONS WITH DX = ,F6.0)
595                   NL= NL+1
               C
               C      CHECK ON CAVITATION FORMATION
               C
                   63 DNO= DN
600                   FRUDO= F
                      PABS= 33.9*(1.-ELINV/145400.)**5.255-0.39
                      IF(MET.EQ.0)PABS=10.33*(1.-ELINV/44303)**5.255-0.13
                      SIG= 2.*G*(PABS+D)/(V*V)
                      SIG1= 0.061*(V*DN/VIS)**0.196
605                   SIGR= 32.*G*CN*CN/HR**0.33333
                      IF(MET.EQ.1)SIGR= SIGR/2.208
                      IF(SIG.GT.SIG1.AND.SIG.GT.SIGR)GO TO 68
               C      CAVITATION OF BOUNDARY ROUGHNESS
               C
610                   IF(SIG1.GT.SIGR.AND.SIG1.GT.SIG)GO TO 65
                      WRITE(3,64)
                   64 FORMAT(25X,38HSURFACE SUFFICIENTLY ROUGH TO CAVITATE /)
                      NL= NL+1
                      GO TO 68
615            C
               C      ASSUME BOUNDARY LAYER THICKNESS = FLOW DEPTH
               C      CIRCULAR ARC ASSUMPTION
                   65 HO= 10800.*DN*(SIG**2.91)*(VIS/(V*DN))**0.776
               C
620            C      CHECK THAN KEEP OFFSETS GREATER TO OR EQUAL
               C      TO THE RUGOSITY.
                      IF(RUG.GE.HO)HO= RUG
               C                        °
               C      COMPUTATION OF REQUIRED CHAMFER
625                   ALPHA= 18.762*SIG
                      NSL= INT(1./TAND(ALPHA))+1
                      IF(MET.EQ.1)HO= 12.*HO
                      IF(NT.EQ.1)GO TO 68
                      IF(MET.EQ.1)WRITE(3,66)HO,NSL
630                66 FORMAT(16X,41HCAVITATION WILL OCCUR FOR OFFSETS GREATER,
                     +          5H THAN,F6.2,4H IN, ,3X,
                     +          4H1 TO,I3,18H CHAMFERS REQUIRED/)
                      IF(MET.EQ.0)WRITE(3,67)HO,NSL
                   67 FORMAT(18X,41HCAVITATION WILL OCCUR FOR OFFSETS GREATER,
635                  +          5H THAN,F7.3,4H M,  ,3X,
                     +          4H1 TO,I3,18H CHAMFERS REQUIRED/)
                      NL= NL+1
                   68 CONTINUE
               C
640            C     NORMAL TERMINATION OF PROGRAM
               C
                      GO TO 1
               C
               C     ABNORMAL TERMINATION OF PROGRAM
645            C
               C
               C     COMPUTATION OF AIR CONTENT WITH A HYDRAULIC JUMP
               C
                   69 IF(F.GT.0.)BETA= 0.0066*(F-1.)**1.4
```

```
      PROGRAM HFWS

650                IF(F.LE.0.)BETA=0.
                   WRITE (3,70) STA,BETA
                70 FORMAT (1X,F10.3,10X,29H HYDRAULIC JUMP FILLS CONDUIT,
                  +         4X,6HBETA= ,F5.2)
                   GO TO 76
655           C
              C    INSUFFICIENT DATA
              C
                71 WRITE (3,72) STA
                72 FORMAT(40X,35HINSUFFICIENT DATA. LAST STATION WAS ,F8.0)
660                GO TO 76
              C
              C    IMPOSSIBLE FLOW CONDITION SPECIFIED
              C
                73 WRITE(3,74)
665             74 FORMAT(1H0,43X,30HENERGY BALANCE WAS NOT REACHED/
                  +         38X,41HSEVERAL CONDITIONS CAN CAUSE THIS PROBLEM//
                  +         38X,40HCURVILINEAR FLOW MAY HAVE CAUSED PROBLEM/33X
                  +         ,50HOR YOU MAY HAVE SPECIFIED AN IMPOSSIBLE CONDITION.//
                  +         33X,
670               +         50HPLEASE REVIEW YOUR NORMAL DEPTH AND CRITICAL DEPTH /
                  +         36X,41HCOMPUTATIONS AS WELL AS THE PROFILE TYPE. //
                  +         28X,40HALSO, CHECK INPUT DATA FILE FOR MISSING
                  +         21HOR INCORRECT ENTRIES. //)
                   FTEST= Q*Q*B/(G*A*A*A)
675                WRITE(3,75)STA,DN,AVGS,FTEST,YC,YN
                75 FORMAT(20X,5HSTA =,F7.2,9H  DEPTH =,F8.4,20H  AVG SLOPE OF EGL =,
                  +         ,F8.5,13H  FROUDE NO =,F6.2/47X,16HCRITICAL DEPTH =,F8.3/
                  +         47X,14HNORMAL DEPTH =,F8.3)
                76 CONTINUE
680                END


   SUBROUTINE TRAP

  1                SUBROUTINE TRAP(DN)
              C
              C    HYDRAULIC PROPERTIES OF TRAPEZOIDAL SECTIONS
              C
  5                COMMON A,B,HR,W,SS,R,IS,PI,ELINV,SB,ELC,R1,T,G,JIC
                   A=W*DN+SS*DN*DN
                   B= W+2.*SS*DN
                   HR= A/(W+2.0*SQRT(DN*DN+((SS*DN)*(SS*DN))))
                   RETURN
 10                END


   SUBROUTINE CIRC

  1                SUBROUTINE CIRC(DN)
              C
              C    HYDRAULIC PROPERTIES OF CIRCULAR SECTIONS
              C
  5                COMMON A,B,HR,W,SS,R,IS,PI,ELINV,SB,ELC,R1,T,G,JIC
                   IF (DN-R) 1,2,3
              C
              C    LESS THAN HALF FULL
              C
```

SUBROUTINE CIRC

```
10                1 ROOT= SQRT(R*R-(R-Dn)*(R-DN))
                    TERM=ROOT/(R-DN)
                    ANGLE= ATAN(TERM)
                    A=((R*R)*ANGLE)-((R-DN)*ROOT)
                    HR=A/(R*2.0*ANGLE)
15                  B= 2.*ROOT
                    RETURN
              C
              C     EXACTLY HALF FULL
              C
20                2 A=(PI*R*R)/2.0
                    B= 2.*R
                    HR=R/2.0
                    RETURN
              C
25            C     GREATER THAN HALF FULL
              C
                  3 IF(DN.GT.2.*R)GO TO 5
                    IF(DN.EQ.2.*R)GO TO 4
                    ROOT= SQRT(R*R-(DN-R)*(DN-R))
30                  TERM=ROOT/(DN-R)
                    ANGLE= ATAN(TERM)
                    A=(PI*R*R)-((R*R*ANGLE)-((DN-R)*ROOT))
                    B= 2.*ROOT
                    HR=A/((2.0*PI*R)-(R*2.0*ANGLE))
35                  RETURN
              C
              C     EXACTLY FULL
              C
                  4 A= PI*R*R
40                  B= 0.
                    HR= R/2.
                    RETURN
              C
              C     FLOW FILLS CONDUIT
45            C
                  5 JIC= 1
                    RETURN
                    END
```

SUBROUTINE TRANS

```
 1                  SUBROUTINE TRANS(DN)
              C
              C     HYDRAULIC PROPERTIES OF CIRCULAR TO RECTANGULAR
              C     SECTIONS WITH AND WITHOUT DIVIDER WALLS
 5            C
                    COMMON A,B,HR,W,SS,R,IS,PI,ELINV,SB,ELC,R1,T,G,JIC
                    SEC= (1.-PI/4.)
                    IF(ELC.LE.ELINV)GO TO 3
                    DELV= ELC-ELINV
10                  IF(IS.EQ.1)GO TO 1
              C
              C     SECTION NORMAL TO FLOOR
              C
                    DELV= (ELC-ELINV)*SQRT(SB*SB+1.)
15                  DIFF1= DN-DELV
                    GO TO 2
              C
              C     SECTION VERTICAL
              C
```

```
      SUBROUTINE TRANS
   20       1 DN= DN*SQRT(SB*SB+1.)
              DIFF1=DN-DELV
            2 IF (DIFF1.GT.0.)GO TO 7
            C
            C     EQUAL TO OR LESS THAN THE DEPTH OF THE RECTANGULAR SECTION
   25       C
            3 IF(DN.LT.R1)GO TO 5
              A= DN*(W-T)-2.*SEC*R1*R1
              B= W-T
              IF(T.GT.0.)GO TO 4
   30         HR= A/(W+2.*DN-4.*SEC*R1)
              RETURN
            C
            C     WITH DIVIDER WALL
            C
   35       4 HR= A/(W-T+4.*DN-4.*SEC*R1)
              RETURN
            C
            C     EQUAL TO OR LESS THAN DEPTH OF RADIUS IN THE BOTTOM CORNER OF
            C     TRANSITION
   40       C
            5 ROOT= SQRT(2.*DN*R1-DN*DN)
              TERM=ROOT/(R1-DN)
              ANGLE= ATAN(TERM)
              A= R1*R1*ANGLE-ROOT*(R1-DN)+(W-2.*R1-T)*DN
   45         B= W-T-2.*R1+2.*SQRT(R1*R1-(R1-DN)*(R1-DN))
              IF(T.GT.0.)GO TO 6
              HR=A/(W-2.0*R1+2.0*R1*ANGLE)
              RETURN
            C
   50       C
            C     WITH DIVIDER WALL
            6 HR=A/(W-2.0*R1+2.0*R1*ANGLE-T+2.0*DN)
              RETURN
            C
   55       C     GREATER THAN THE DEPTH OF THE RECTANGULAR SECTION
            C
            7 IF(R-DIFF1) 12,9,8
            8 ROOT= SQRT(R*R-DIFF1*DIFF1)
              ARG2= DIFF1/ROOT
   60         PHI1= ATAN (ARG2)
              TW= W-2.0*R
              IF(TW.GE.T)GO TO 10
            C
            C     CHECK WITH UPPER RADIUS GREATER THAN HALF WIDTH OF SECTION
   65       C     OR WITH RADIUS POINT INSIDE CENTER PIER
            C
              DEPTH= SQRT(R*(W-T)-0.25*(W-T)*(W-T))
              IF(DIFF1.GT.DEPTH)GO TO 12
              GO TO 10
   70       C
            C     FLOW DEPTH EQUAL CONDUIT DEPTH
            C
            9 PHI1= PI/2.
              ROOT= 0.
   75       C
            C     COMPUTATION OF AREA AND TOP WIDTH OF WATER SURFACE
           10 A= DN*(W-T)-DIFF1*(W-TW)-2.*SEC*R1*R1+R*R*PHI1 +
             +ROOT*DIFF1
              B= TW+2.*ROOT
   80         IF(T.EQ.0.)GO TO 11
              HR= A/(W-4.*SEC*R1-T+2.*(DN-DIFF1)+2.*DN +
             +2.0*R*PHI1)
              RETURN
           11 HR= A/(W-4.*SEC*R1+2.*(DN-DIFF1)+2.*R*PHI1)
```

```
      SUBROUTINE TRANS

 85                 RETURN
                C
                C       FLOW FILLS CONDUIT
                C
                   12 JIC= 1
 90                 A= DN*(W-T)-DEPTH*(W-TW)-2.*SEC*R1*R1+R*R*PHI1+ROOT*DEPTH
                    B=0.
                    IF(T.EQ.0.)GO TO 13
                    HR= A/(W-4.*SEC*R1-T+2.*(DN-DEPTH)+2.*DN+2.*R*PHI1)
                    RETURN
 95                 13 HR= A/(W-4.*SEC*R1+2.*(DN-DEPTH)+2.*R*PHI1)
                    RETURN
                    END
```

EXAMPLE - WATER SURFACE PROFILE

Q = 20.000 CMS INITIAL DEPTH = .563 M RUGOSITY = 1.7000 MM N = .0142

STATION M	INVERT ELEV M	SLOPE	DEPTH M	VELOCITY M/SEC	PIEZ M	ENERGY GRADE LINE M	Q AIR/Q WATER	PROFILE	DEPTH NORMAL M	DEPTH CRITICAL M
0.00	100.000	.3333	.563	2.368	.534	100.849	0.000	S2	.126	.566
.72	99.760	.3333	.369	3.618	.350	100.844	0.000	S2	.126	.566
1.39	99.538	.3338	.316	4.215	.300	100.834	0.000	S2	.126	.566
2.62	99.127	.3333	.264	5.042	.251	100.804	0.000	S2	.126	.566
5.13	98.289	.3333	.213	6.254	.202	100.684	0.000	S2	.126	.566
11.59	96.136	.3332	.164	8.132	.156	100.000	0.000	S2	.126	.566
18.03	93.989	.3333	.146	9.147	.138	98.819	0.000	S2	.126	.566
24.22	91.927	.3333	.138	9.695	.130	97.329	0.000	S2	.126	.566
37.45	87.515	.3334	.130	10.228	.124	93.507	.033	S2	.126	.566
60.69	79.771	.3333	.128	10.420	.121	85.982	.056	S2	.126	.566
75.67	74.778	.3333	.128	10.417	.121	80.985	.055	S2	.126	.566

DATA FILE – HSPWY

```
20.,0.563,0.01,1,0,0.33333
11
0,1
0.,100.,15.,0.
0.,0.,0.,0.
0,1
0.720,99.76,15.,0.
0.,0.,0.,0.
0,1
1.385,99.538,15.,0.
0.,0.,0.,0.
0,1
2.618,99.127,15.,0.
0.,0.,0.,0.
0,1
5.132,98.289,15.,0.
0.,0.,0.,0.
0,1
11.593,96.136,15.,0.
0.,0.,0.,0.
0,1
18.034,93.989,15.,0.
0.,0.,0.,0.
0,1
24.22,91.927,15.,0.
0.,0.,0.,0.
0,1
37.454,87.515,15.,0.
0.,0.,0.,0.
0,1
60.687,79.771,15.,0.
0.,0.,0.,0.
0,1
75.667,74.778,15.,0.
0.,0.,0.,0.
```

Appendix III - Air Demand, Falling Water Surface, Computer Program

INTRODUCTION

The original version of the falling water surface computer program[1] contained simplifications that could have led to significant errors in the flow simulation. The present program was modified to represent more realistically the flow conditions at the gate and to include a better representation of the hydraulic turbine characteristics. The complicated prototype geometry is input into the program through the use of a few parameters which approximate the actual geometry.

JUNCTION ENERGY EQUATIONS

The original study[1] assumed that the relation between the flow from the reservoir and gate chamber could be described by the junction flow equations for a pipe tee. A more realistic flow description—considering the varying area created by the closing gate—would be the formation of a submerged hydraulic jump downstream from the gate (fig. III-1).

Writing the momentum equation in the horizontal direction on the prism of water between points V and P gives:

$$\frac{p_V}{\gamma} = \frac{2A_G}{(A_P+A_G)}\left[\left(\frac{p_P}{\gamma}\right)\frac{(A_G+A_P)}{2A_G}\right] + \frac{2A_P}{A_G}\frac{V_P^2}{2g} - \frac{2}{C_c G_P}\frac{A_P^2}{A_G^2}\frac{V_V^2}{2g} \quad (1)$$

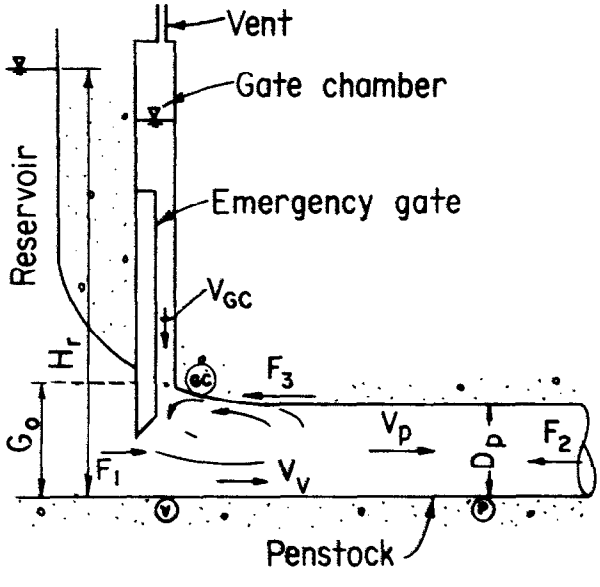
where

$$V_V = \frac{Q_R}{G_P A_G C_c} \text{ and } V_P = \frac{Q_P}{A_P}, \text{ figure III-1}$$

The contraction coefficient C_c is related to the discharge coefficient C_d through [59]

$$C_c = \frac{(C_d/G_P)^2(G/H_r)}{2} + \frac{(C_d/G_P)^4(G/H_r)^2+4(C_d/G_P)^2}{2} \quad (2)$$

[1] H. T. Falvey, *Air Vent Computations, Morrow Point Dam*, Hydraulic Laboratory Report HYD-584, Bureau of Reclamation, Denver, Colorado, 39 p., 1968.



A_P = penstock area
A_G = total area of gate opening
C_c = contraction coefficient
C_d = discharge coefficient
D_P = penstock diameter
D_3 = Discharge diameter of runner
F_1 = upstream force
F_2 = penstock force
F_3 = force of walls on jump
G = partial gate opening
G_o = full gate opening
$G_P = (G/G_o)$ = percent gate opening
g = gravitational constant (acceleration)
H_r = reservoir head on gate
K_t = turbine loss coefficient
p_{GC} = pressure at lower end of gate chamber
p_P = penstock pressure
p_V = pressure at vena contracta
Q = discharge
Q_P = penstock discharge
Q_R = reservoir discharge
Q_{11} = specific discharge through a turbine
V_{GC} = velocity in gate chamber
V_P = penstock velocity
V_V = velocity at vena contracta
W = gate width
γ = specific force of water
$\pi = 3.14159...$

The forces F are defined as

$$F_1 = \gamma(p_V/\gamma - G_o/2)\, A_G$$
$$F_2 = \gamma(p_V/\gamma - D_P/2)\, A_P$$
$$F_3 = \frac{\gamma}{2}[(p_V/\gamma + p_P/\gamma)(A_G - A_P) + (D_P A_P - G_o A_G)]$$

The velocities V are defined as

$$V_V = Q_R/(C_c G_o W) = Q_R/(C_c\, G_P\, A_G)$$
$$V_P = Q_P/A_P$$

FIGURE III-1.—*Definition sketch at penstock intake.*

The discharge coefficient in equation 2 is based on the area of the fully open gate.

If the kinetic energy in the submerged hydraulic jump is assumed small, the pressure at the lower end of the gate chamber is given by

$$\frac{p_{GC}}{\gamma} = \frac{p_V}{\gamma} - D_P \tag{3}$$

When all water has drained from the gate chamber, but the gate is still submerged, the pressure at point P is given by

$$\frac{p_P}{\gamma} = \frac{Q_R^2}{gGC_c^2\, A_G\, A_P} + \frac{2}{\pi}\left(\frac{p_V}{\gamma}\right)^2 \frac{1}{D_P} - \frac{2V_P^2}{2g} + \frac{D_P}{2} \tag{4}$$

The pressure at point V, which is also the water depth at that point, is determined from the air volume in the penstock and assuming a 1:7 slope for the free water surface of the hydraulic jump.

If the hydraulic jump is not submerged, the pressure at V is given by

$$\frac{p_V}{\gamma} = C_c A_G G \tag{5}$$

TURBINE CHARACTERISTICS

The head loss coefficient across the turbine was arbitrarily assumed constant in the original study.[2] The validity of the assumption is investigated in the following paragraphs.

The energy loss across the turbine is given by

$$h_d = K_t \frac{V_P^2}{2g} \tag{6}$$

The loss coefficient K_t can be written

$$K_t = \frac{2gh_d}{V_P^2} \tag{7a}$$

or

$$K_t = \frac{\pi^2 g}{8} \left(\frac{D_P}{D_3}^4\right) \left(\frac{D_3^2\sqrt{h_d}}{Q}\right)^2 \tag{7b}$$

where D_3 is a characteristic dimension of the turbine runner.

The quantity $\frac{Q}{D_3^2\sqrt{h_d}}$ is a basic parameter used in describing the turbine characteristics. The quantity is known as the specific discharge and usually is written Q_{11}. The subscripts signify the discharge from a one-meter-diameter runner having a one-meter head across the turbine runner. Thus, the loss coefficient also can be written:

$$K_t = \frac{\pi^2 g}{8} \left(\frac{D_P}{D_3}\right)^4 \left(\frac{1}{Q_{11}}\right)^2 \tag{8}$$

The discharge through a turbine is dependent upon the head across the unit, runner speed, and wicket gate opening. The runner speed and head across the unit are described by a dimensionless parameter known as ϕ (phi) defined by

$$\phi = \frac{\pi D_3 n}{60\sqrt{2gh_d}} \tag{9}$$

where n is the rotational speed in revolutions per minute.

Typical turbine characteristic curves for a runner having a specific speed[3] of about 230 show that the specific discharge is not significantly affected by changes in the rotational speed (fig. III-2). The maximum change in specific discharge between the maximum efficiency and the runaway condition at a constant gate opening amounts to about 3 percent. The corresponding change in the loss coefficient is about 6 percent.

Loss coefficient curves can be prepared for any turbine runner. These curves will be a function of the wicket gates opening and the phi value (fig. III-3).

If the generator unit remains connected to the electrical system during a closure of the emergency gate, the turbine will operate at a constant speed. The condition with the turbine at synchronous speed but with no flow is called *motoring*.[4] During motoring the turbine will develop a head in the penstock. The magnitude of this head must be input into the computer program. For reaction turbines the magnitude

---

[2]Ibid.

[3]The specific speed of a turbine is given by

$$n_s = \frac{n(P_d)^{1/2}}{(h_d)^{5/4}}$$

where

h_d = turbine head, m
n = rotational speed, r/min
P_d = turbine power output, kW

[4]Power requirements for motoring can be minimized by depressing the water surface in the draft tube. This is used for either power factor adjustment or for spinning reserve. During an emergency, depression of the water surface in the draft tube cannot be assumed to occur.

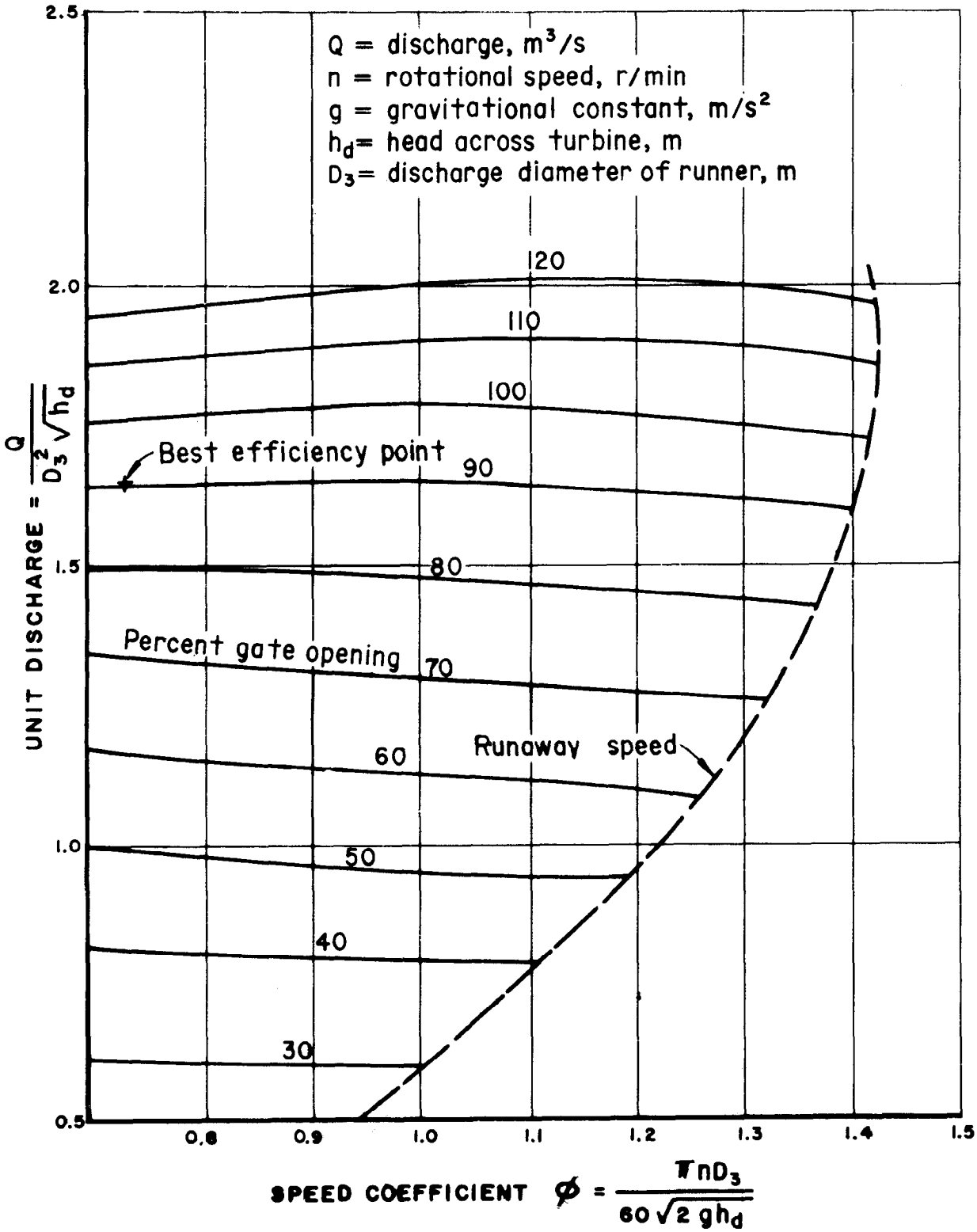


FIGURE III-2.—*Typical turbine characteristics of runner specific speed 230 in m-kW units.*

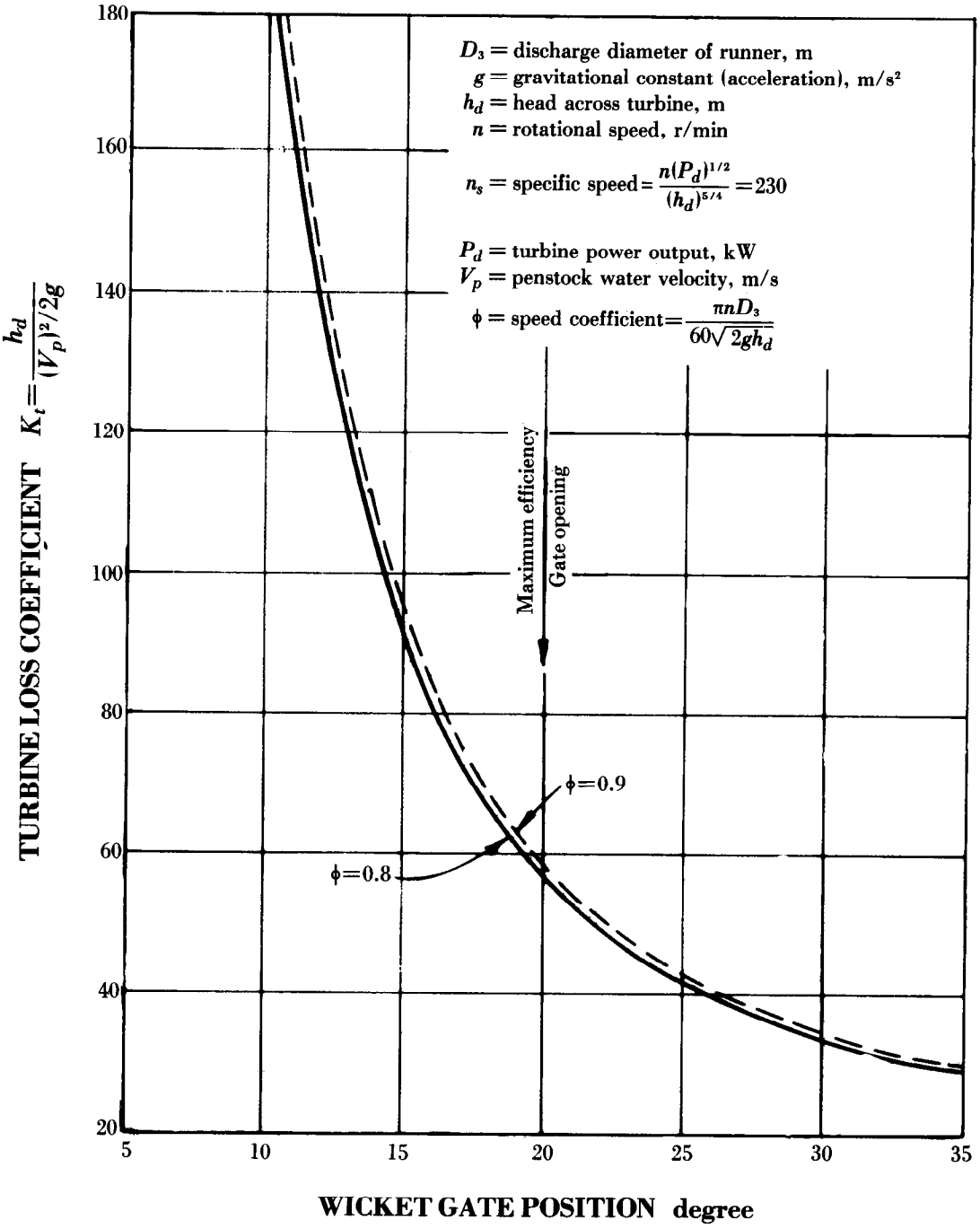


FIGURE III-3.—*Turbine loss coefficient.*

of the motoring head is about 20-to 25-percent of the turbine net head.

GEOMETRY

The two most significant geometric effects which must be calculated for free surface flow in the penstock are the air volume in the penstock and the water surface area as a function of water surface elevation.

The actual variation of the air volume in the penstock is a complicated function due to the circular section of the penstock and vertical bends. The air volume must be computed as a function of elevation for enough points to define the prototype curve. Two straight lines are fitted through the prototype values (fig. III-4). The coefficients of these two straight lines are input into the program.

A similar procedure is used for the water surface area as a function of elevation. However, the prototype curve is fitted with a sine wave and a vertical line instead of two straight lines (fig. III-5).

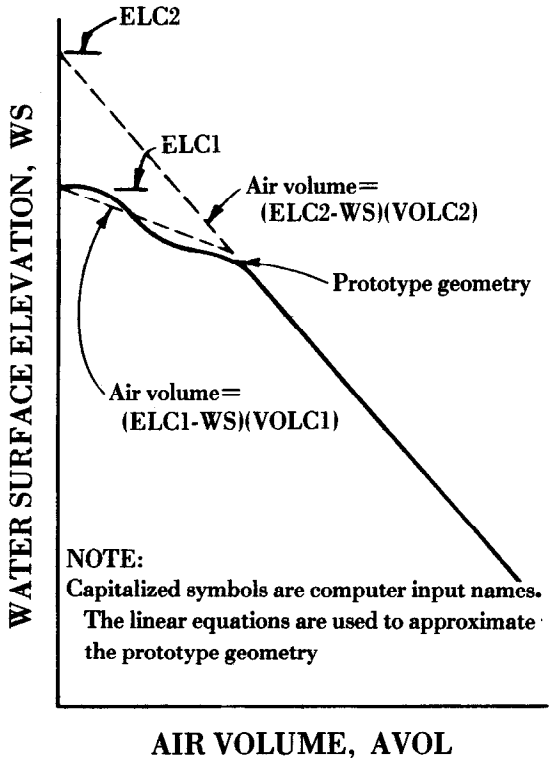


FIGURE III-4.—*Air volume in penstock.*

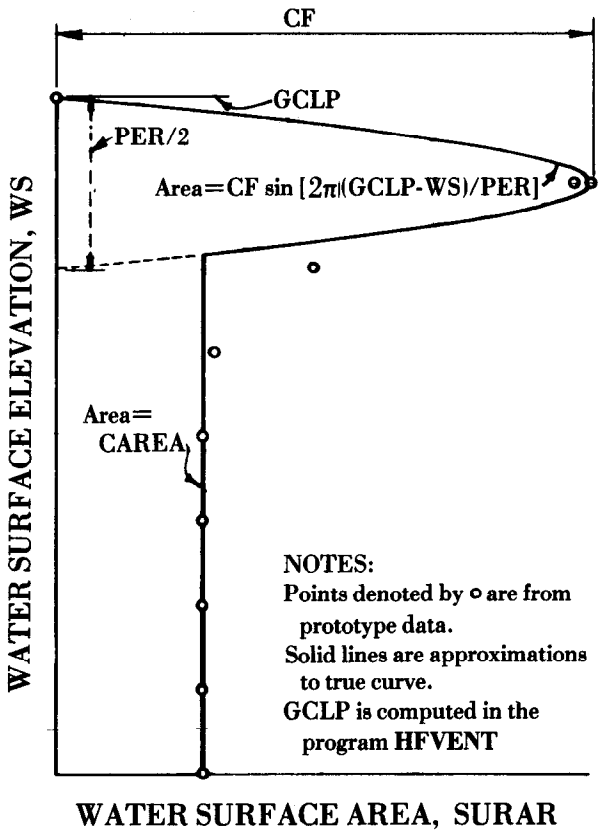


FIGURE III-5.—*Water surface area.*

PROGRAM HFVENT

```
      PROGRAM HFVENT(INPUT=65,OUTPUT=65,TAPE3=OUTPUT)
C     COMPUTATION OF AIR FLOW INTO GATE CHAMBER DURING AN EMERGENCY
C     CLOSURE OF GATES FOR THE PENSTOCK INTAKE STRUCTURE
C
      REAL MACHA,MACHGA,NVENTS
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),J,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
      DIMENSION QGA(50),AR(50),AP(50),AS(50),AGC(50),
     +VIN(50),VOUT(50),PA(50),PGA(50),CA(50),ERTAGC(50),
     +RHOAG(50),SPVOL(50),DX(50),DY(50),
     +CKB(50),X(50),Y(50),VP(50),VGC(50),DPL(50),DVC(50),JCT(50)
      WRITE(3,1)
    1 FORMAT(1H1,//)
C
C     INPUT DATA
C     ==========================================================
C
C
C     COMPUTATION CONTROLS
C     --------------------
C
C     SYSTEM OF UNITS
C     METRIC, SET METRIC = 1
C     ENGLISH, SET METRIC = 0
      METRIC= 1
C
C     INITIAL TIME
      T(1)= 0.
C
C     TIME INTERVAL BETWEEN CALCULATIONS (SEC)
      DELT= 1.
C
C     MAXIMUM TIME WHICH IS TO BE CALCULATED (SEC)
      TMAX= 40.
C
C     THE TITLE AND AIR VENT DESCRIPTION ARE INPUT IN THE
C     FORMAT STATEMENTS.  THEY CAN CONTAIN UP TO 60 CHARACTERS
C     EACH.  BOTH DESCRIPTIONS MUST BE CENTERED IN THE FIELD.
    2 FORMAT(6X,60H                          MORROW POINT DAM
     +         )
    3 FORMAT(6X,60H                  ONE 840MM BY 915MM AIR VENT
     +         )
C
C
C     WATER FLOW QUANTITIES
C     ---------------------
C
C     TURBINE LOSS COEFFICIENT
      TLOSS= 111.2
C
C     TYPE OF TURBINE OPERATION DURING CLOSURE
C     (IF UNIT RUNS AT CONSTANT SPEED, SET NSPEED = 1.
C     IF THE CIRCUIT BREAKERS ARE OPEN SO THAT
C     THE SPEED CAN VARY, SET NSPEED = 0.  BOTH
C     OF THESE  TYPES OF OPERATION ASSUME A BLOCKED
C     GATE OPERATION.)
      NSPEED = 1
C
C     HEAD DEVELOPED BY TURBINE DURING MOTORING
C     (SPEED NO LOAD)
      HMOTOR= 27.5
C
```

```
      PROGRAM HFVENT

C     GATE CLOSING RATE (PERCENT/SEC)
      GCR= 0.9901
C
C     DARCY-WIESBACH FRICTION FACTOR IN PENSTOCK
      FP= 0.009
C
C     SINGULAR LOSS BETWEEN UPPER AND LOWER GATE CHAMBER
      EK= 0.3
C
C     AIR FLOW QUANTITIES
C     -------------------
C
C     TEMPERATURE
      TEMP= 4.5
C
C     ATMOSPHERIC PRESSURE (PSI OR KPA)
      PATM= 77.6
C
C     INCOMPRESSIBLE FRICTION FACTOR FOR THE AIR FLOW IN
C     THE DUCT (FL/D)
      FRICT= 0.93
C
C     COMPRESSIBLE DISCHARGE COEFFICIENT OF AIR
C     AT DUCT INLET
      CINC= 0.5
C
C     GEOMETRY
C     --------
C
C     RESERVOIR WATER LEVEL
      RES= 2181.64
C
C     TAIL WATER LEVEL
      TW= 2059.23
C
C     ELEVATION UPPER GATE CHAMBER TO LOWER GATE CHAMBER
      UGCLGC= 2168.04
C
C     ELEVATION INVERT AT GATE
      ZP= 2155.93
C
C     ELEVATION OF TOP OF GATE CHAMBER
      TGC= 2183.89
C
C     AREA UPPER GATE CHAMBER
      AU= 13.80
C
C     AREA LOWER GATE CHAMBER
      AD= 4.33
C
C     AREA GATE
      AG= 20.64
C
C     CROSS-SECTIONAL AREA OF EACH AIR VENT
      AVENT= 0.766
C
C     NUMBER OF VENTS
      NVENTS= 1.
C
C     CONSTANTS WHICH DESCRIBE THE VOLUME OF THE
C     ------------------------------------------
C     PENSTOCK AS A FUNCTION OF THE WATER SURFACE
C     SEE THE DOCUMENTATION FOR THE DEFINITION OF
C     THESE CONSTANTS
      VOLC1= 46.16
      VOLC2= 13.3
```

```
      PROGRAM HFVENT

                  ELC1= 2155.93
                  ELC2= 2170.21
135           C
              C     PENSTOCK LENGTH
                  PL= 143.56
              C
              C     PENSTOCK LENGTH AS A FUNCTION OF WATER SURFACE PARAMETER
140               PENLEN= 2016.48
              C
              C     PENSTOCK DIAMETER
                  DP= 4.12
              C
145           C     HEIGHT OF GATE
                  SO= 5.01
              C
              C     HYDRAULIC DIAMETER OF LOWER GATE CHAMBER
                  HYDDIA= 1.41
150           C
              C     CONSTANTS WHICH DESCRIBE THE FREE WATER SURFACE AREA
              C     ---------------------------------------------------
              C     IN THE PENSTOCK.  SEE THE DOCUMENTATION FOR THE
              C     DEFINITION OF THESE CONSTANTS
155               CF= 48.83
                  PER= 8.23
                  CAREA= 13.5
              C
              C     END OF INPUT DATA
160           C     ================================================================
              C
              C     COMPUTED CONSTANTS
              C
                  PI= 3.14159
165               K= INT((TMAX-T(1))/(40.*DELT))+1
                  GRAV= 32.2
                  GASCTE= 53.3
                  PTOHD= 2.30769
                  VAPOR= PTOHD*0.0256*10.**(0.0162*TEMP)
170               AGCCTE= 144.
                  ACURAC= .01
                  PGCINC= 0.01
                  ABSTEM= TEMP+459.67
                  RHOA= AGCCTE*PATM/(GASCTE*ABSTEM)
175               CD= 0.9303
                  IF(METRIC.EQ.0)GO TO 4
                  GASCTE= 287.
                  PTOHD= 0.000102
                  VAPOR= PTOHD*.582*10.**(0.0292*TEMP+3.)
180               AGCCTE= 1000.
                  PATM= PATM*AGCCTE
                  ACURAC= 0.003
                  PGCINC= 50.
                  GRAV= 9.807
185               ABSTEM= TEMP+273.15
                  RHOA= PATM/(GASCTE*ABSTEM
                4 ABSPGC = PATM
                  AREAP= PI*DP*DP/4.
                  HEAD= RES-TW
190               PGD= 1.
                  BH= SO/(RES-ZP)
                  CC= (CD*CD*BH+SQRT(CD**4*BH**2+4.*CD**2))/2.
                  CONST= TLOSS-1.+FP*PL/DP+(AREAP/(AG*CD))**2-4.*ARE*D*AREAP/(
                 +(AG+AREAP)*CC*PGD*AG)+4.*AREAP/(AG+AREAP)
195               QR= AREAP*SQRT(2.*GRAV*HEAD/CONST)
                  VHP= (QR/AREAP)**2./(2.*GRAV)
                  VHR= VHP
                  PR= RES-ZP-VHR*(AREAP/AG/CD)**2
```

```
      PROGRAM HFVENT

                  WS= ZP+PR
  200             PP= PR+2.*AG/(AG+AREAP)*(2./CC*VHR*(AREAP/AG)**2-2.*VHP*AREAP/AG)
                  WSREF = WS
                  HCOL= WSREF-UGCLGC
                  GCLP= ZP+DP
                  GCLL= UGCLGC- GCLP
  205             QP = QR
                  QGC = 0.
                  AVOLRE= (TGC-WS)*AU
                  WTAIR = RHOA * AVOLRE
                  AVOL= AVOLRE
  210             PIN = PATM
                  PGC = PTOHD*PATM
                  CONST = PATM / RHOA**1.4
                  CKA= 0.
                  JFIRST= 1
  215             DELTIM= 0.
                  JCK= 1
                  NT= 1
                  IF(NSPEED.EQ.0)HMOTOR= 0.
                  SLOSS= 1.-HMOTOR/(TLOSS*VHP)
  220             PVAPOR= VAPOR-PGC
            C
            C     ------------------------------------------------------------------
            C
            C     SIGNIFICANCE OF JFIRST
  225       C     1 - FIRST TIME THRU MAIN LOOP
            C     2 - SECOND TIME THRU MAIN LOOP,
            C     WATER SURFACE IN UPPER GATE CHAMBER
            C     3 - LAST TIME INCREMENT IN UPPER GATE CHAMBER
            C     4 - FIRST TIME INCREMENT IN LOWER GATE CHAMBER
  230       C     5 - WATER SURFACE IN LOWER GATE CHAMBER
            C     6 - LAST TIME INCREMENT IN LOWER GATE CHAMBER
            C     7 - FIRST TIME INCREMENT IN PENSTOCK
            C     8 - WATER SURFACE IN PENSTOCK
            C     9 - WATER  ELEVATION LESS THAN TAIL WATER SURFACE
  235       C     ELEVATION
            C     10 - VAPOR PRESSURE FORMED AT GATE
            C     11 - SONIC VELOCITY IN AIR VENT
            C
            C     ==================================================================
  240       C
            C     *** COMPUTATIONS IN MAIN LOOP ***
                  DO 48 NTIM=1,K
                    IF(NTIM.GE.2)NT= 2
                    IF(NTIM.LE.1)GO TO 5
  245       C
            C       DATA INITIALIZATION FOR SUBSEQUENT PASSES THRU MAIN LOOP
                    T(1)= T(41)
                    QGA(1)= QGA(41)
                    AR(1)= AR(41)
  250               AP(1)= AP(41)
                    VP(1)= VP(41)
                    VGC(1)= VGC(41)
                    X(1)= X(41)
                    Y(1)= Y(41)
  255               AS(1)= AS(41)
                    AGC(1)= AGC(41)
                    VIN(1)= VIN(41)
                    VOUT(1)= VOUT(41)
                    PGA(1)= PGA(41)
  260               CA(1)= CA(41)
                    ENRTAP(1)= ENRTAP(41)
                    ERTAGC(1)= ERTAGC(41)
                    DPL(1)= DPL(41)
                    DVC(1)= DVC(41)
```

```
      PROGRAM HFVENT

265                 PA(1)= PA(41)
                    MACHA(1)= MACHA(41)
                    MACHGA(1)= MACHGA(41)
                    RHOAG(1)= RHOAG(41)
                    SPVOL(1)= SPVOL(41)
270                 WTFLA(1)= WTFLA(41)
                    CKB(1)= CKB(41)
                    P3(1)= P3(41)
                    JCT(1)= JCT(41)
              C
275           C     COMPUTATIONAL LOOP FOR 40 TIME INCREMENTS
              C
                  5 DO 25 M=NT,41
                      J= M
                      JN= J-1
280                   IF(NTIM.EQ.2.AND.J.LE.3)GO TO 6
                      GO TO 7
                  6   JM2= J+38
                      IF(J.GE.3)JM2= J-2
                      JM1= J+39
285                   IF(J.GE.2)JM1= J-1
              C
              C       TRIAL DETERMINATION OF WATER SURFACE
              C
                  7   IF(JFIRST.EQ.1) GO TO 19
290                   IF(JFIRST.GE.6) GO TO 10
                      IF(JFIRST.GE.3)GO TO 8
                      IF(J.LE.4)GO TO 17
                      WSTEST= AS(J-2)-(5.*VGC(JN)+VGC(J-2)+DELT*FUNCT2(Y(JN),
                     +VP(JN),VGC(JN)))*DELT/3.
295                   GO TO 9
                  8   IF(JFIRST.EQ.3) WSTEST= AS(JN)-(DELT-DELTIM)*VGC(JN)*AU/AD
                      IF(JFIRST.EQ.3)GO TO 9
                      WSTEST= AS(JN)-DELT*(VGC(JN)+DELT*FUNCT2(Y(JN),VP(JN),
                     +VGC(JN))/2.)
300                   IF(JFIRST.EQ.4)WSTEST= AS(JN)-(DELT+DELTIM)*VGC(JN)
                  9   IF(WSTEST.LE.GCLP)GO TO 10
                      IF(WSTEST.LE.UGCLGC)GO TO 14
                      GO TO 17
              C
305           C       WATER SURFACE IN PENSTOCK
              C
                 10   IF(JFIRST.EQ.6)GO TO 11
                      IF(JFIRST.EQ.7)GO TO 12
                      IF(JFIRST.EQ.8)GO TO 13
310           C       LAST INCREMENT BEFORE PENSTOCK FLOW
                      VOLGC= (AS(JN)-GCLP)
                      IF(J.GE.3)JM2= J-2
                      TOUT= T(JN)+VOLGC*2./(VGC(JN)+VGC(JM2))
                      IF(JFIRST.EQ.4) TOUT= T(JN)+VOLGC*2.*AU/(AD*(VGC(JN)+VGC(JM2))
315                  +)
                      IF(TOUT.GE.(T(JN)+DELT))TOUT= T(JN)+VOLGC/VGC(JN)
                      VEL2= VGC(JN)+FUNCT2(Y(JN),VP(JN),VGC(JN))*
                     +(TOUT-T(JN))
                      IF(JFIRST.EQ.4)DELT= DELT+DELTIM
320                   DELTIM= VOLGC*2./(VEL2+VGC(JN))
                      IF(DELTIM.GT.DELT)GO TO 17
                      IF(DELTIM.LE.0.)DELTIM= TOUT-T(JN)
                      JFIRST= 6
                      CALL DE2(X,Y,VP,VGC,T,DELTIM,JN)
325                   AS(J)= UGCLGC-Y(J)
                      IF(AS(J).LT.GCLP)AS(J)=GCLP
                      WS= AS(J)
                      X(J) = 0.
                      CALL AMACH(CINC,FRICT,AVENT,DELTIM,PGCINC,WTAIR,CONST,
330                  +CKA)
```

```
      PROGRAM HFVENT

            C          TIME INCREMENT AS WATER ENTERS PENSTOCK
                       GO TO 20
               11      DELT= DELT-DELTIM
                       JFIRST= 7
335                    GO TO 13
               12      DELT= DELT+DELTIM
                       JFIRST= 8
               13      CALL DE1(X,VP,DELT)
                       AS(J)= WS
340                    GO TO 18
            C
            C          WATER SURFACE IN LOWER GATE CHAMBER
            C
               14      IF(JFIRST.EQ.3)GO TO 15
345                    IF(JFIRST.EQ.4)GO TO 16
                       IF(JFIRST.EQ.5)GO TO 17
            C          LAST INCREMENT IN UPPER GATE CHAMBER
                       VOLGC= (AS(JN)-UGCLGC)
                       TOUT= T(JN)+VOLGC/VGC(JN)
350                    VEL2= VGC(JN)+FUNCT2(Y(JN),VP(JN),VGC(JN))*
                 +     (TOUT-T(JN))
                       DELTIM= VOLGC*2./(VEL2+VGC(JN))
                       JFIRST= 3
                       CALL DE2(X,Y,VP,VGC,T,DELTIM,JN)
355                    AS(J)= WSREF-Y(J)
                       WS= AS(J)
                       CALL AMACH(CINC,FRICT,AVENT,DELTIM,PGCINC,WTAIR,CONST,
                 +     CKA)
                       GO TO 20
360         C          TIME INCREMENT AS WATER ENTERS LOWER GATE CHAMBER
               15      DELT= DELT-DELTIM
                       JFIRST= 4
                       WSREF= UGCLGC
                       JCK=2
365                    GO TO 17
               16      DELT= (DELT+DELTIM)
                       JFIRST= 5
            C
            C          WATER SURFACE IN UPPER OR LOWER GATE CHAMBER
370         C
               17      CALL DE2(X,Y,VP,VGC,T,DELT,JN)
                       AS(J)= WSREF-Y(J)
                       WS= AS(J)
            C
375         C          DETERMINATION OF AIR FLOW RATE IN VENT
            C
               18      CALL AMACH(CINC,FRICT,AVENT,DELT,PGCINC,WTAIR,CONST,
                 +     CKA)
                       IF(JFIRST.GE.7)P3(J)= PTOHD*(ABSPGC-PATM)
380                    GO TO 20
            C
            C          ASSIMILATION OF RESULTS FOR FIRST TIME THRU
            C
               19      QGA(1)= QGC
385                    AR(1)= QR
                       AP(1)= QP
                       VP(1)= AP(1)/AREAP
                       VGC(1)= 0.
                       X(1)= 0.
390                    Y(1)= 0.
                       DX(1)= 0.
                       DY(1)= 0.
                       AS(1)= WS
                       AS(2)= WS
395                    AGC(1)=ABSPGC
                       IF(METRIC.EQ.1)AGC(1)= AGC(1)/AGCCTE
```

```
      PROGRAM HFVENT

                        VIN(1)= 0.
                        VOUT(1)= 0.
                        ENRTAP(1)= FUNCT1(VP(1),VGC(1),T(1))
400                     ERTAGC(1)= FUNCT2(Y(1),VP(1),VGC(1))
                        DVC(1)= P3(1)+DP
                        PGA(1)= PGO
                        CA(1)= CD
                        PA(1)= PP
405                     MACHA(1)=  0.
                        MACHGA(1)= 0.
                        RHOAG(1)= RHOA
                        SPVOL(1)=  1./RHOA
                        WTFLA(1)=  0.
410                     CKB(1)=    0.
                        JCT(1)= JCK
                        VOLR= 0.
                        JFIRST= 2
                        DPL(1)= TLOSS*SLOSS*(AP(1)/(.785*DP*DP))**2./(2.*GRAV)+HMOTOR
415                     GO TO 25
              C
              C         ASSIMILATION OF RESULTS FOR REMAINING TIME INCREMENTS
              C
                 20     CALL Q(QGC,VP,VGC)
420                     QGA(J)= QGC
                        PCHECK= ABS(P3(J)-PVAPOR)
                        IF(PCHECK.LE.0.0001)JFIRST=10
                        IF(JFIRST.EQ.10)GO TO 26
                        IF(JFIRST.EQ.11)GO TO 26
425                     IF(WS.LE.TW.OR.QP.LT.0.)JFIRST= 9
                        IF(JFIRST.EQ.9)GO TO 26
                        AR(J)= QR
                        AP(J)= QP
                        AGC(J)=ABSPGC
430                     IF(METRIC.EQ.1)AGC(J)= AGC(J)/AGCCTE
                        IF(JFIRST.GE.7) GO TO 21
                        ENRTAP(J)= FUNCT1(VP(J),VGC(J),T(J))
                        ERTAGC(J)= FUNCT2(Y(J),VP(J),VGC(J))
                        IF(JFIRST.GE.4)ERTAGC(J)= ERTAGC(J)*(GCLP-WS)/GRAV
435                     GO TO 22
                 21     ENRTAP(J)= FUNCT3(X(J),VP(J),T(J))
                        ERTAGC(J)= 0.
                 22     WTAIR= WTAIR+(WTFLA(JN)+WTFLA(J))*DELT/2.
                        IF(JFIRST.EQ.3.OR.JFIRST.EQ.6)WTAIR= WTAIR+(WTFLA(JN)
440                +   +WTFLA(J))*(DELTIM-DELT)/2.
                        RHOAG(J)= WTAIR/AVOL
                        SPVOL(J)= 1./RHOAG(J)
                        VOLR= VOLR+(QR+AR(JN))*DELT/2.
                        IF(JCK.LT.4)VOLR= 0.
445                     DPL(J)= TLOSS*SLOSS*(AP(J)/(.785*DP*DP))**2./(2.*GRAV)+HMOTOR
                        DVC(J)= PR
                        PGA(J)= PGO
                        PA(J)= PP
                        CA(J)= CD
450                     JCT(J)= JCK
                        DX(J)= DELX
                        DY(J)= DELY
                        VOUT(J)= MACHGA(J)*SQRT(GRAV*SPVOL(J)*1.4*AGC(J)*AGCCTE)
                        IF(METRIC.EQ.1)VOUT(J)= VOUT(J)/SQRT(GRAV)
455                     IF(PIN.GE.PATM)GO TO 23
                        VIN(J)= CVEL*SQRT(7.*GASCTE*GRAV*ABSTEM*
                   +    (1.-(PIN/PATM)**(2./7.)))
                        IF(METRIC.EQ.1)VIN(J)= VIN(J)/SQRT(GRAV)
                        IF(MACHA(J).LT.0.)VIN(J)= (-1.)*VIN(J)
460                     GO TO 24
                 23     VIN(J)= VOUT(J)
                 24     CKB(J)= CKA
```

```
      PROGRAM HFVENT

           25   CONTINUE
      C
      C         *** WRITE STATEMENTS FOR OUTPUT OF RESULTS ***
      C
           26   J= JN+1
                IF(JFIRST.EQ.10) J=J-1
                IF(JFIRST.EQ.11)J=J-1
                IF(JFIRST.EQ.9)J=J-1
                IF(METRIC.EQ.1)PATM= PATM/AGCCTE
      C
      C         FLOW QUANTITIES
      C
                IF(METRIC.EQ.1)GO TO 38
                WRITE(3,27)
                WRITE(3,2)
                WRITE(3,28)PATM,RHOA
                WRITE(3,3)
           27   FORMAT (1H1,8X,
             +          48H COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER D
             +          8HURING AN / 16X,
             +          40H EMERGENCY GATE CLOSURE IN THE PENSTOCK-  / 27X,
             +          18H INTAKE STRUCTURE  )
           28   FORMAT(//  8X,21H ATMOSPHERIC PRESSURE  ,14X,
             +          23H  SPECIFIC MASS OF AIR  / 13X
             +          , F6.2, 5H PSI ,
             +          ,23X,F6.4,11H LB/CU.FT.   //)
                WRITE(3,29)(T(N),PGA(N),CA(N),AR(N),QGA(N),AP(N),N=1,J)
           29   FORMAT(28X,15HFLOW QUANTITIES  //
             +          8X,
             +          34H TIME       GATE      COEFF         Q
             +          20H          Q          Q  / , 16X,
             +          49H OPENING    DISCH.    RESERVOIR   GATE    PENSTOCK /
             +          48X,8HCHAMBER  /
             +          8X,46H(SEC)      (0/0)                (CFS)      (CFS)
             +          9H     (CFS)  /
             +          (5X,F8.1,2X,F8.1,1X,F8.2,4X,F8.1,1X,F8.1,3X,F8.1))
                IF(JFIRST.EQ.10)WRITE(3,30)T(J+1)
           30   FORMAT(4X,F8.1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER )
                IF(JFIRST.EQ.11)WRITE(3,31)T(J+1)
           31   FORMAT(4X,F8.1,9X,23H SONIC VELOCITY IN VENT)
      C
      C         WATER PRESSURES
      C
                WRITE(3,27)
                WRITE(3,2)
                WRITE(3,28)PATM,RHOA
                WRITE(3,3)
                WRITE(3,32)(T(N),AS(N),DPL(N),P3(N),DVC(N),PA(N),N=1,J)
           32   FORMAT(28X,15HWATER PRESSURES //
             +          8X,
             +          45H TIME        WS        HEAD    END GATE    VENA
             +          12H    PENSTOCK /
             +          16X,40H   ELEV      ACROSS   CHAMBER   CONTRACTA /
             +          29X,4HUNIT /
             +          8X,46H(SEC)       (FT)       (FT)       (FT)       (FT)
             +          9H      (FT)  /
             +          (5X,F8.1,3X,F8.2,2X,F8.2,2X,F8.2,2X,F8.2,2X,F8.2))
                IF(JFIRST.EQ.10)WRITE(3,33)T(J+1)
           33   FORMAT(7X,F8.1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER )
                IF(JFIRST.EQ.11)WRITE(3,34)T(J+1)
           34   FORMAT(7X,F8.1,9X,23H SONIC VELOCITY IN VENT  )
      C
      C         AIR FLOW PROPERTIES
      C
                WRITE(3,27)
                WRITE(3,2)
```

```
      PROGRAM HFVENT

                      WRITE(3,28)PATM,RHOA
530                   WRITE(3,3)
                      WRITE(3,35)(T(N),V1N(N),VOUT(N),WTFLA(N),RHOAG(N),AGC(N),
                     + N=1,J)
                      IF(JFIRST.EQ.10)WRITE(3,33)T(J+1)
                      IF(JFIRST.EQ.11)WRITE(3,34)T(J+1)
535                35 FORMAT(24X,21H  AIR FLOW PROPERTIES   //
                     +          8X,
                     +          47H TIME      INLET    OUTLET   AIR FLOW  SPECIFIC
                     +          8H    GATE  /
                     +          16X,
540                  +          48H  AIR VEL   AIR VEL    RATE      MASS    CHAMBER /
                     +          48X,17HOF AIR   PRESSURE /
                     +          8X,50H(SEC)     (FT/SEC)  (FT/SEC) (LBM/SEC) (LB/CU FT)
                     +          7H (PSIA) /
                     +          (5X,F8.1,3X,F8.1,2X,F8.1,2X,F8.2,2X,F8.4,2X,F8.2))
545           C
              C       COMPUTATIONAL PROPERTIES
              C
                      WRITE(3,27)
                      WRITE(3,2)
550                   WRITE(3,28)PATM,RHOA
                      WRITE(3,3)
                      WRITE(3,36)(T(N),CKB(N),DY(N),DX(N),JCT(N),N=1,J)
                   36 FORMAT(24X,24HCOMPUTATIONAL PROPERTIES  //
                     +          14X,44HTIME    ACCURACY  INTEGRATION ERROR     FLOW  /
555                  +          20X,41H   GATE       GATE    PENSTOCK  CONDITION   /
                     +          20X,39H  CHAMBER   CHAMBER              (* SEE  /
                     +          20X,40H   PRESS                          LEGEND) /
                     +          12X,36H (SEC)     (PSI)      (FT)      (FT)  /
                     +          (10X,F8.1,2X,F8.3,3X,F8.4,2X,F8.4,4X,I4))
560                   IF(JFIRST.EQ.10)WRITE(3,33)T(J+1)
                      IF(JFIRST.EQ.11)WRITE(3,34)T(J+1)
                      IF(NTIM.EQ.K.OR.JFIRST.EQ.9)WRITE(3,37)
                   37 FORMAT(1H1,29X,6HLEGEND//
                     +          8X,49H* 1 WATER SURFACE IN UPPER GATE CHAMBER          /
565                  +          8X,49H  2 WATER SURFACE BELOW TOP OF GATE              /
                     +          8X,49H  3 WATER SURFACE JUST ENTERING PENSTOCK         /
                     +          8X,49H  4 HYDRAULIC JUMP FILLS PENSTOCK, GATE SUBMERGED/
                     +          8X,49H  5 HYDRAULIC JUMP FILLS PENSTOCK, GATE FREE FLOW/
                     +          8X,48H  6 WATER SURFACE IN PENSTOCK                    /)
570                   IF(NTIM.EQ.K.OR.JFIRST.EQ.9)GO TO 49
                      GO TO 48
              C
              C       METRIC WRITE STATEMENTS
              C
575                38 WRITE(3,27)
                      WRITE(3,2)
                      WRITE(3,39)PATM,RHOA
                      WRITE(3,3)
                      WRITE(3,40)(T(N),PGA(N),CA(N),AR(N),QGA(N),AP(N),N=1,J)
580                39 FORMAT(//  8X,21H ATMOSPHERIC PRESSURE  ,14X,
                     +          23H  SPECIFIC MASS OF AIR  / 13X
                     +          , F6.2, 5H KPA ,
                     +          ,23X,F6.4,11H KG/CU.M.     //)
                   40 FORMAT(28X,15HFLOW QUANTITIES  //
585                  +          8X,
                     +          34H TIME      GATE     COEFF         Q
                     +          20H          Q          Q  /, 16X,
                     +          49H OPENING    DISCH.   RESERVOIR   GATE    PENSTOCK /
                     +          48X,8HCHAMBER  /
590                  +          8X,46H(SEC)     (C/C)                (CMS)     (CMS)
                     +          9H    (CMS)  /
                     +          (5X,F8.1,2X,F8.1,1X,F8.2,4X,F8.3,1X,F8.3,3X,F8.3))
                      IF(JFIRST.EQ.10)WRITE(3,41)T(J+1)
                   41 FORMAT(4X,F8.1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER )
```

```
      PROGRAM HFVENT

595               IF(JFIRST.EQ.11)WRITE(3,42)T(J+1)
                42 FORMAT(4X,F8.1,9X,23H SONIC VELOCITY IN VENT)
             C
             C     WATER PRESSURES
             C
600               WRITE(3,27)
                  WRITE(3,2)
                  WRITE(3,39)PATM,RHOA
                  WRITE(3,3)
                  WRITE(3,43)(T(N),AS(N),DPL(N),P3(N),DVC(N),PA(N),N=1,J)
605             43 FORMAT(28X,15HWATER PRESSURES //
                 +          8X,
                 +          53H TIME        WS        HEAD    END GATE    VENA    PENS
                 +          4HTOCK /
                 +          16X,40H   ELEV      ACROSS   CHAMBER   CONTRACTA /
610              +          29X,4HUNIT /
                 +          8X,45H(SEC)       (M)        (M)        (M)        (M)
                 +          9H       (M)   /
                 +          (5X,F8.1,3X,F8.2,2X,F8.2,1X,F8.2,2X,F8.2,2X,F8.2))
                  IF(JFIRST.EQ.10)WRITE(3,44)T(J+1)
615             44 FORMAT(7X,F8.1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER )
                  IF(JFIRST.EQ.11)WRITE(3,45)T(J+1)
                45 FORMAT(7X,F8.1,9X,23H SONIC VELOCITY IN VENT  )
             C
             C     AIR FLOW PROPERTIES
620          C
                  WRITE(3,27)
                  WRITE(3,2)
                  WRITE(3,39)PATM,RHOA
                  WRITE(3,3)
625               WRITE(3,46)(T(N),VIN(N),VOUT(N),WTFLA(N),RHOAG(N),AGC(N),
                 + N=1,J)
                  IF(JFIRST.EQ.10)WRITE(3,44)T(J+1)
                  IF(JFIRST.EQ.11)WRITE(3,45)T(J+1)
                46 FORMAT(24X,21H  AIR FLOW PROPERTIES   //
630              +          8X,
                 +          47H TIME       INLET    OUTLET   AIR FLOW  SPECIFIC
                 +          9H    GATE /, 16X,
                 +          48H  AIR VEL   AIR VEL    RATE      MASS    CHAMBER /
                 +          48X,17HOF AIR   PRESSURE /
635              +          8X,48H(SEC)       (M/SEC)   (M/SEC)  (KG/SEC) (KG/CU M)
                 +          7H  (KPA)  /
                 +          (5X,F8.1,3X,F8.1,2X,F8.1,2X,F8.3,2X,F8.4,2X,F8.2))
             C
             C     COMPUTATIONAL PROPERTIES
640          C
                  WRITE(3,27)
                  WRITE(3,2)
                  WRITE(3,39)PATM,RHOA
                  WRITE(3,3)
645               WRITE(3,47)(T(N),CKB(N),DY(N),DX(N),JCT(N),N=1,J)
                47 FORMAT(24X,24HCOMPUTATIONAL PROPERTIES  //
                 +          14X,44HTIME    ACCURACY  INTEGRATION ERROR     FLOW  /
                 +          20X,41H   GATE       GATE    PENSTOCK  CONDITION   /
                 +          20X,39H  CHAMBER   CHAMBER              (*LAST  /
                 +          20X,40H   PRESS                           PAGE) /
650              +          12X,36H (SEC)      (PA)        (M)       (M)  /
                 +          (10X,F8.1,1X,F8.0,4X,F8.4,2X,F8.4,4X,I4))
                  IF(JFIRST.EQ.10)WRITE(3,44)T(J+1)
                  IF(JFIRST.EQ.11)WRITE(3,45)T(J+1)
655               IF(NTIM.EQ.K.OR.JFIRST.EQ.9)WRITE(3,37)
                  IF(NTIM.EQ.K.OR.JFIRST.EQ.9)GO TO 49
                  PATM= AGCCTE*PATM
                48 CONTINUE
                49 CALL EXIT
660                END
```

SUBROUTINE Q

```
      SUBROUTINE Q(QGC,VP,VGC)
C
C     THIS PROGRAM COMPUTES THE DISCHARGE THROUGH THE EMERGENCY
C     GATE AS A FUNCTION OF GATE OPENING, RESERVOIR ELEVATION,
C     DOWNSTREAM PRESSURE (FREE OR SUBMERGED), AND THE FREE
C     FLOW DISCHARGE COEFFICIENT.
C
      REAL MACHA,MACHGA,NVENTS
      DIMENSION VP(50),VGC(50)
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),N,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
      QP= VP(N)*AREAP
      IF(JFIRST.GT.6)GO TO 1
      QGC=VGC(N)*AU
      IF(JFIRST.GT.3)QGC= VGC(N)*AD
      GO TO 2
    1 QGC=0.
    2 QR= QP-QGC
      IF(JFIRST.GE.7)QR=AG*CD*SQRT(2.*GRAV*((RES-ZP)+PGC-PTOHD*PATM))
      IF(JCK.EQ.4)QR= AG*CD*SQRT(2.*GRAV*((RES-ZP)-PR+PGC-PTOHD*PATM))
      IF(JFIRST.GE.7.AND.QR.GE.QP)QR= QP
      IF(QR.LE.0.)QR=0.
      RETURN
      END
```

SUBROUTINE DE2

```
      SUBROUTINE DE2 (X,Y,VX,VY,U,DELT,N)
C
C     THIS PROGRAM SOLVES TWO DIFFERENTIAL EQUATIONS OF MOTION
C     SIMULTANEOUSLY.  THE TWO EQUATIONS ARE DEFINED BY FUNCT1
C     AND FUNCT2.  THE OUTPUTS ARE DISTANCE (X AND Y) AND
C     VELOCITY (VX AND VY).
C
C     FOR THE MATHEMATICS SEE ...LEVY,H.,BAGGOTT,E.A.,
C     NUMERICAL SOLUTIONS OF DIFFERENTIAL EQUATIONS,
C     DOVER PUBLICATIONS, P103, 1950.
C
      REAL MACHA,MACHGA,NVENTS
      DIMENSION X(50),Y(50),VX(50),VY(50),RKT(5),RKX(5),
     +RKY(5),RKVX(5),RKVY(5),F(5),G(5),U(50)
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),L,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
C
C     EACH TIME INTERVAL IS DIVIDED INTO FOUR EQUAL INCREMENTS.
C     THIS PORTION OF THE PROGRAM DETERMINES THE INITIAL VALUES
C     OF THE INTEGRAL FOR THE FIRST FOUR VALUES.  THAT IS,
C     TO (KNOWN)T1,T2,T3,AND T4.
C     THESE ARE DETERMINED USING KUTTA'S SIMPSON'S RULE
C
C
      RKX(1)= X(N)
```

```
      SUBROUTINE DE2

   30                 RKY(1)= Y(N)
                      RKVX(1)= VX(N)
                      RKVY(1)= VY(N)
                      IF(JFIRST.EQ.4)RKVY(1)= RKVY(1)*AU/AD
                      IF(JFIRST.EQ.4)RKY(1)= 0.
   35                 RKT(1)= T(N)
                      H= DELT/4.
                      F(1)= FUNCT1(RKVX(1),RKVY(1),RKT(1))
                      G(1)= FUNCT2(RKY(1),RKVX(1),RKVY(1))
                      DO 1 K=1,4
   40                   AK1= RKVX(K)*H
                        AL1= RKVY(K)*H
                        AM1= H*FUNCT1(RKVX(K),RKVY(K),RKT(K))
                        AP1= H*FUNCT2(RKY(K),RKVX(K),RKVY(K))
                        AK2= (RKVX(K)+AM1/2.)*H
   45                   AL2= (RKVY(K)+AP1/2.)*H
                        B1= RKY(K)+AL1/2.
                        C1= RKVX(K)+AM1/2.
                        D1= RKVY(K)+AP1/2.
                        E1= RKT(K)+H/2.
   50                   AM2 = FUNCT1(C1,D1,E1)*H
                        AP2 = FUNCT2(B1,C1,D1)*H
                        AK3= (RKVX(K)+AM2/2.)*H
                        AL3= (RKVY(K)+AP2/2.)*H
                        B2= RKY(K)+AL2/2.
   55                   C2= RKVX(K)+AM2/2.
                        D2= RKVY(K)+AP2/2.
                        E2= RKT(K)+H/2.
                        AM3 = FUNCT1(C2,D2,E2)*H
                        AP3 = FUNCT2(B2,C2,D2)*H
   60                   AK4= (RKVX(K)+AM3)*H
                        AL4= (RKVY(K)+AP3)*H
                        B3= RKY(K)+AL3
                        C3= RKVX(K)+AM3
                        D3= RKVY(K)+AP3
   65                   E3= RKT(K)+H
                        AM4 = FUNCT1(C3,D3,E3)*H
                        AP4 = FUNCT2(B3,C3,D3)*H
                        DELTX = (AK1+2.*AK2+2.*AK3+AK4)/6.
                        DELTY = (AL1+2.*AL2+2.*AL3+AL4)/6.
   70                   DELTVX= (AM1+2.*AM2+2.*AM3+AM4)/6.
                        DELTVY= (AP1+2.*AP2+2.*AP3+AP4)/6.
                        RKT(K+1)= RKT(K)+H
                        RKX(K+1)= RKX(K)+DELTX
                        RKY(K+1)= RKY(K)+DELTY
   75                   RKVX(K+1)= RKVX(K)+DELTVX
                        RKVY(K+1)= RKVY(K)+DELTVY
                        IF(JFIRST.EQ.6.AND.K.EQ.4)JCK= 3
                        F(K+1)= FUNCT1(RKVX(K+1),RKVY(K+1),RKT(K+1))
                        G(K+1)= FUNCT2(RKY(K+1),RKVX(K+1),RKVY(K+1))
   80                   IF(K.EQ.2)FSAV1= G(K+1)
                        IF(K.EQ.3)FSAV=G(K+1)
                    1 CONTINUE
                C
                C     CORRECTION OF INITIAL VALUES
   85           C
                      DELXS= 0.
                      DELYS= 0.
                      JCK= 2
                      CALL DELTD (F,DELF,DEL2F,DEL3F,DEL4F)
   90                 CALL DELTD (G,DELG,DEL2G,DEL3G,DEL4G)
                      RKVX(2)= RKVX(1)+H*(F(1)+DELF/2.-DEL2F/12.+DEL3F/24.-DEL4F/40.)
                      RKVY(2)= RKVY(1)+H*(G(1)+DELG/2.-DEL2G/12.+DEL3G/24.-DEL4G/40.)
                      RKX(2)= RKX(1)+H*(RKVX(1)+RKVX(2))/2.
                      RKY(2)= RKY(1)+H*(RKVY(1)+RKVY(2))/2.
```

SUBROUTINE DE2

```
                DO 2 J=1,3
                  F(J+1)= FUNCT1(RKVX(J+1),RKVY(J+1),RKT(J+1))
                  G(J+1)= FUNCT2(RKY(J+1),RKVX(J+1),RKVY(J+1))
                  RKVX(J+2)= RKVX(J)+(F(J+2)+4.*F(J+1)+F(J))*H/3.
                  RKVY(J+2)= RKVY(J)+(G(J+2)+4.*G(J+1)+G(J))*H/3.
                  RKX(J+2)= RKX(J)+(RKVX(J+2)+4.*RKVX(J+1)+RKVX(J))*H/3.
                  RKY(J+2)= RKY(J)+(RKVY(J+2)+4.*RKVY(J+1)+RKVY(J))*H/3.
                  IF(JFIRST.EQ.6.AND.J.EQ.3)JCK= 3
                  FC= FUNCT1(RKVX(J+2),RKVY(J+2),RKT(J+2))
                  GC= FUNCT2(RKY(J+2),RKVX(J+2),RKVY(J+2))
                  IF(J.EQ.1)FSAV1= GC
                  OLDX= RKX(J+2)
                  OLDY= RKY(J+2)
                  IF(J.EQ.2)FSAV= GC
                  RKVX(J+2)= RKVX(J+2)+(FC-F(J+2))*H/3.
                  RKVY(J+2)= RKVY(J+2)+(GC-G(J+2))*H/3.
                  RKX(J+2)= RKX(J+1)+H*(RKVX(J+2)+RKVX(J+1))/2.
                  RKY(J+2)= RKY(J+1)+H*(RKVY(J+2)+RKVY(J+1))/2.
                  DELX= ABS(OLDX-RKX(J+2))
                  DELY= ABS(OLDY-RKY(J+2))
                  IF(DELXS.GE.DELX)DELX= DELXS
                  IF(DELXS.GE.DELX)DELY= DELYS
                  F(J+2)= FC
                  G(J+2)= GC
                2 CONTINUE
C
C     VALUES AT END OF INTEGRATION PERIOD
C
                  VX(N+1)= RKVX(5)
                  VY(N+1)= RKVY(5)
                  X(N+1)= RKX(5)
                  Y(N+1)= RKY(5)
                  T(N+1)= T(N)+DELT
C
C     IF THE INTEGRATION ACCURACY IS EXCEEDED, THE
C     PREVIOUS VALUE OF VX AND OR VY IS USED TO
C     EXTRAPOLATE THE NEW VALUE OF X AND OR Y.
C
                  IF(DELX.LE.0.01)GO TO 3
                  VX(N+1)= VX(N)+DELT/(T(N)-T(N-1))*(VX(N)-VX(N-1))
                  P3(N+1)= P3(N)+DELT/(T(N)-T(N-1))*(P3(N)-P3(N-1))
                  X(N+1)= (VX(N)+VX(N+1))*DELT/2.+X(N)
                3 IF(DELY.LE.0.01)GO TO 4
                  VY(N+1)= VY(N)+DELT/(T(N)-T(N-1))*(VY(N)-VY(N-1))
                  P3(N+1)= P3(N)+DELT/(T(N)-T(N-1))*(P3(N)-P3(N-1))
                  Y(N+1)= (VY(N)+VY(N+1))*DELT/2.+Y(N)
C
C     END OF EXTRAPOLATION
C
                4 CKV= VY(N+1)
                  CKX= X(N+1)
                  RETURN
                  END
```

SUBROUTINE DELTD

```
      SUBROUTINE DELTD(A,B,E,D,DEL4)
C
C     THIS PROGRAM COMPUTES THE 4TH DIFFERENCE OF A SERIES
C     OF FIVE EQUALLY SPACED QUANTITIES
C
      REAL MACHA,MACHGA,NVENTS
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),J,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
      DIMENSION A(5),DEL(4),DEL2(3),DEL3(2)
      DO 1 I=1,4
    1 DEL(I)= A(I+1)-A(I)
      DO 2 K=1,3
    2 DEL2(K)= DEL(K+1)-DEL(K)
      DO 3 JK=1,2
    3 DEL3(JK)= DEL2(JK+1)-DEL2(JK)
      B= DEL(1)
      E= DEL2(1)
      D= DEL3(1)
      DEL4= DEL3(2)-DEL3(1)
      RETURN
      END
```

FUNCTION FUNCT1

```
      FUNCTION FUNCT1(CA,DA,EA)
C
C     THIS PROGRAM GIVES THE VALUE OF THE SECOND ORDER
C     DIFFERENTIAL EQUATION OF FLOW DISTANCE WITH RESPECT TO
C     TIME FOR THE WATER IN THE PENSTOCK.THE VALUE OF THE
C     DIFFERENTIAL IS FUNCT1.
C
      REAL MACHA,MACHGA,NVENTS
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),J,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
      PGO= 100.-GCR*EA
      CD= (1.049E-04)+(7.062E-03)*PGO-(5.830E-05)*PGO**2+(2.398E-06)
     +*PGO**3-(3.578E-08)*PGO**4+(1.987E-10)*PGO**5
      VHP= CA**2/(2.*GRAV)
      VHR= (CA-DA*AU/AREAP)**2/(2.*GRAV)
      IF(JFIRST.GE.4)VHR=(CA-DA*AD/AREAP)**2/(2.*GRAV)
      PR= RES-ZP-VHR*(AREAP/AG/CD)**2
      PGD= PGO/100.
      BH= PGD*SO/(RES-ZP)
      CC= (BH*(CD/PGD)**2+SQRT((CD/PGD)**4*BH**2+4.*(CD/PGD)**2))/2.
      PT= PR-DP
      PP= PR+2.*AG/(AG+AREAP)*(2./CC/PGD*VHR*(AREAP/AG)**2-2.*VHP*AREAP
     +/AG)
      PVAPOR= VAPOR-PTOHD*PATM
      IF(PT.GT.PVAPOR)GO TO 1
      PT= PVAPOR
    1 P3(J)= PT
      FUNCT1= GRAV/PL*(PP-VHP*(TLOSS*SLOSS-1.+FP*PL/DP)+ZP-TW-HMOTOR)
      RETURN
      END
```

FUNCTION FUNCT2

```
      FUNCTION FUNCT2(BB,CB,DB)
C
C     THIS PROGRAM GIVES THE VALUE OF THE SECOND ORDER
C     DIFFERENTIAL EQUATION OF DEPTH WITH RESPECT TO TIME
C     FOR THE WATER IN THE GATE CHAMBER.  THE VALUE OF THE
C     DIFFERENTIAL IS FUNCT2.
C
      REAL MACHA,MACHGA,NVENTS
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),J,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
      VHGC= DB**2/(2.*GRAV)
      VHR= (CB-DB*AU/AREAP)**2/(2.*GRAV)
      IF(JFIRST.GE.4)VHR= (CB-DB*AD/AREAP)**2/(2.*GRAV)
      PR= RES-ZP-VHR*(AREAP/AG/CD)**2
      PT= PR-DP
      PVAPOR= VAPOR-PTOHD*PATM
      IF(PT.GT.PVAPOR)GO TO 1
      PT= PVAPOR
    1 P3(J)= PT
      IF(JFIRST.GE.4)GO TO 2
C
C     WATER SURFACE IN UPPER GATE CHAMBER
C
      FUNCT2= GRAV/(HCOL-BB+GCLL*AU/AD)*(PGC-PTOHD*PATM-PT+HCOL-BB
     ++GCLL-VHGC*((1.+FP*GCLL/HYDDIA+EK)*(AU/AD)**2-1.)/2.)
      RETURN
C
C     WATER SURFACE IN LOWER GATE CHAMBER
C
    2 IF(JCK.EQ.3)GO TO 3
      FUNCT2= GRAV*((PGC-PTOHD*PATM-PT)/(GCLL-BB)+1.0-
     +VHGC*FP/HYDDIA)
      IF(DB.LT.0.)FUNCT2= GRAV*((PGC-PTOHD*PATM-PT)/(GCLL-BB)+1.0+
     +VHGC*FP/HYDDIA)
      RETURN
C
C     EXTRAPOLATION OF FUNCT2 TO ENTRANCE OF PENSTOCK
C     (ZERO LENGTH OF WATER COLUMN)  JCK=3 SIGNIFIES NO
C     MORE WATER IN GATE CHAMBER.
C
    3 FUNCT2= 2.*FSAV-FSAV1
      RETURN
      END
```

SUBROUTINE DE1

```
      SUBROUTINE DE1(X,VX,DELT)
C
C     THIS PROGRAM SOLVES THE DIFFERENTIAL EQUATION OF MOTION
C     FOR FLOW IN THE PENSTOCK WHEN THE WATER SURFACE IS IN THE
C     PENSTOCK.  THE OUTPUTS ARE DISTANCE(X) AND VELOCITY (VX).
C
      REAL MACHA,MACHGA,NVENTS
      DIMENSION X(50),VX(50),RX(5),RVX(5),RT(5),RF(5)
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),M,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
```

```
      SUBROUTINE DE1

     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
C
C     DETERMINATION OF INITIAL VALUES
C
      N= M-1
      RX(1)= X(N)
      RVX(1)= VX(N)
      RT(1)= T(N)
      H= DELT/4.
      RF(1)= FUNCT3(RX(1),RVX(1),RT(1))
      DO 1 K=1,4
        AK1= FUNCT3(RX(K),RVX(K),RT(K))*H
        A1= RX(K)+RVX(K)*H/2.+AK1*H/8.
        B1= RVX(K)+AK1/2.
        C1= RT(K)+H/2.
        AK2= FUNCT3(A1,B1,C1)*H
        B2= RVX(K)+AK2/2.
        AK3= FUNCT3(A1,B2,C1)*H
        A3= RX(K)+RVX(K)*H+AK3*H/2.
        B3= RVX(K)+AK3
        C3= RT(K)+H
        AK4= FUNCT3(A3,B3,C3)*H
        DELTX= H*(RVX(K)+(AK1+AK2+AK3)/6.)
        DELTVX= (AK1+2.*AK2+2.*AK3+AK4)/6.
        RX(K+1)= RX(K)+DELTX
        RVX(K+1)= RVX(K)+DELTVX
        RT(K+1)= RT(K)+H
        RF(K+1)= FUNCT3(RX(K+1),RVX(K+1),RT(K+1))
    1 CONTINUE
C
C     CORRECTION OF INITIAL VALUES
C
      DELY= 0.
      DELXS= 0.
      CALL DELTD(RVX,DELF,DEL2F,DEL3F,DEL4F)
      RX(2)= RX(1)+H*(RVX(1)+DELF/2.-DEL2F/12.+DEL3F/24.-DEL4F/40.)
      CALL DELTD(RF,DELF,DEL2F,DEL3F,DEL4F)
      RVX(2)= RVX(1)+H*(RF(1)+DELF/2.-DEL2F/12.+DEL3F/24.-DEL4F/40.)
      DO 2 J=1,3
        RF(J+1)= FUNCT3(RX(J+1),RVX(J+1),RT(J+1))
        RVX(J+2)= (RF(J+2)+4.*RF(J+1)+RF(J))*H/3.+RVX(J)
        OLDX= RX(J+2)
        RX(J+2)= (RVX(J+2)+4.*RVX(J+1)+RVX(J))*H/3.+RX(J)
        DELX= ABS(OLDX-RX(J+2))
        IF(DELXS.GE.DELX)DELX= DELXS
    2 CONTINUE
C
C     VALUES AT END OF INTEGRATION PERIOD
C
      VX(N+1)= RVX(5)
      X(N+1)= RX(5)
      CKX= X(N+1)
      CKV= VX(N+1)
      T(N+1)= T(N)+DELT
      RETURN
      END
```

FUNCTION FUNCT3

```
      FUNCTION FUNCT3(AC,BC,DC)
C
C     THIS PROGRAM GIVES THE VALUE OF THE SECOND ORDER
C     DIFFERENTIAL EQUATION OF FLOW DISTANCE WITH RESPECT
C     TO TIME FOR A FREE WATER SURFACE IN THE PENSTOCK.
C
      REAL MACHA,MACHGA,NVENTS
      COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
     +PP,P3(50),J,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
     +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
     +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
     +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
     +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
      JN= J-1
      VHP= BC**2/(2.*GRAV)
      PGO= 100.-GCR*DC
      IF(PGO.LE.0.)GO TO 1
      CD= (1.049E-04)+(7.062E-03)*PGO-(5.830E-05)*PGO**2+(2.398E-06)
     +*PGO**3-(3.578E-08)*PGO**4+(1.987E-10)*PGO**5
      PGD= PGO/100.
      BH= PGD*SO/(RES-ZP)
      CC= (BH*(CD/PGD)**2+SQRT((CD/PGD)**4*BH**2+4.*(CD/PGD)**2))/2.
      GO TO 2
    1 PGO= 0.
      CD= 0.
      PGD= 0.
      CC= .611
    2 HVC= SO*CC*PGD
      IF(WS.LE.ZP)GO TO 6
      AVOLCK= AC*AREAP-QR*(DC-T(JN))-VOLR
      IF(AVOLCK.LT.0.)AVOLCK= .1E-30
      CKWS= GCLP-AVOLCK/VOLC1
      IF(JCK.EQ.6)GO TO 6
      IF(JCK.EQ.5)GO TO 3
C
C     JUMP IN CONDUIT, GATE SUBMERGED
C
      DEPT= SQRT(AVOLCK/3.5/DP)
      PR= DP-DEPT
      QR= AG*CD*SQRT(2.*GRAV*((RES-ZP)-PR+PGC-PTOHD*PATM))
      IF(PR.LT.HVC)GO TO 3
      JCK= 4
      IF(PGD.LE.0.)GO TO 4
      PP= QR**2/(CC*PGD*AG*AREAP*GRAV)+PR*(DP-DEPT)/(2.*DP)-2.*VHP
     ++DP/2.+PGC-PTOHD*PATM
      GO TO 5
C
C     JUMP IN CONDUIT, GATE NOT SUBMERGED
C
    3 PR= HVC
      JCK=5
      IF(PGD.LE.0.)GO TO 4
      PP= (2.*CD**2*AG*(RES-ZP+PGC-PTOHD*PATM))/(PGD*CC*AREAP)
     ++PR*CC*AG*PGD/(2.*AREAP)-2.*VHP+DP/2.+PGC-PTOHD*PATM
      DEPT2= QR*QR/(16.1*DP*DP*CC*SO*PGD)+HVC*HVC-QP*QP/(16.1*DP*AREAP)
      IF(PP.LE.DP.AND.DEPT2.GT.0.)PP= SQRT(DEPT2)+PGC-PTOHD*PATM
      IF(DEPT2.LE.0.)GO TO 6
      GO TO 5
    4 PP= PR+PGC-PTOHD*PATM
    5 WS= ZP+PR
      IF(PP.LE.DP)WS= ZP+PP
      PL= WS-PENLEN
      IF(CKWS.LT.(ZP+PR).AND.JFIRST.EQ.8)GO TO 6
      FUNCT3= GRAV/PL*(PP-VHP*(TLOSS*SLOSS-1.+FP*PL/DP)+ZP-TW-HMOTOR)
      RETURN
C
```

FUNCTION FUNCT3

```
      C     WATER SURFACE BELOW GATE SEAT
      C
    6 QRTST= AG*CD*SQRT(2.*GRAV*(RES-ZP+PGC-PTOHD*PATM))
70    IF(QRTST.GT.QP)QRTST= QP
      JCK= 6
      DT= (DC-T(JN))
      IF(DT.LE.0.)GO TO 7
      DQRDT= (QR-QRTST)/DT
75    WS= ZP+DP-(AC*AREAP-(2.*QRTST-DQRDT*DT)*DT/2.-VOLR)/VOLC1
      IF(WS.LE.ELC1)WS= ELC2-(AC*AREAP-(2.*QRTST-DQRDT*DT)*DT/2.-
     +VOLR)/VOLC2
    7 IF(WS.GE.GCLP)GO TO 8
      PL= WS-PENLEN
80    SURAR= CF*SIN((GCLP-WS)/PER)
      IF(SURAR.LE.CAREA)SURAR= CAREA
    8 IF(ABS(GCLP-WS).LE.DP/4.)SURAR= AREAP
      VWS= (AREAP*BC-QRTST)/SURAR
      VHWS= VWS**2/(2.*GRAV)
85    IF(PGD.GT.0.) GO TO 9
      VHVC= 0.
      GO TO 10
    9 VHVC= (QRTST/(AG*CC))**2/(2.*GRAV)
   10 VHUS= SQRT(VHVC**2+VHWS**2)
90    FUNCT3= GRAV/PL*(PGC-PTOHD*PATM+WS-TW-HMOTOR+VHUS-VHP*
     +(TLOSS*SLOSS+FP*PL/DP))
      IF(WS.LT.ELC1)FUNCT3= GRAV/PL*(PGC-PTOHD*PATM-VHP*
     +(TLOSS*SLOSS+FP*PL/DP)+VHWS+WS-TW-HMOTOR)
      PP= PTOHD*(ABSPGC-PATM)
95    IF(WS.GE.ZP)PP= WS-ZP
      PR=HVC
      RETURN
      END
```

SUBROUTINE AMACH

```
1           SUBROUTINE AMACH(CINC,FRICT,AVENT,DELT,PGCINC,WTAIR,CONST,
           +CKA)
      C
      C     THIS PROGRAM GIVES THE AIR FLOW RATE IN THE AIR VENT AS A
5     C     FUNCTION OF THE WATER SURFACE ELEVATION.
      C
            REAL M1R,M1I,MACHIN,MACHGC
            REAL MACHA,MACHGA,NVENTS
            COMMON CD,CKV,ABSPGC,PATM,PGC,WSREF,HCOL,WS,QR,QP,GRAV,PTOHD,
10         +PP,P3(50),J,PL,FP,TLOSS,AU,AD,AREAP,AG,EK,GCR,PGO,JFIRST,WTFLA(50)
           +,MACHA(50),MACHGA(50),AVOL,PIN,CVEL,T(50),JCK,GCLP,RES,ZP,DP,TW,
           +UGCLGC,GCLL,HYDDIA,VOLC1,ELC1,VOLC2,ELC2,CF,PER,CAREA,HMOTOR,
           +NVENTS,TGC,ENRTAP(50),SO,VOLR,CKX,PR,FSAV,FSAV1,DELX,DELY
           +,ACURAC,ABSTEM,GASCTE,VAPOR,AGCCTE,SLOSS,METRIC,PENLEN
15          EQ(MACH)= (1.-MACH*MACH)/(1.4*MACH*MACH)+.8571*
           +ALOG((1.2*MACH*MACH)/(1.+.2*MACH*MACH))
            JN= J-1
            MACHIN= MACHA(JN)
            MACHGC= MACHGA(JN)
20          IF(ABS(MACHA(JN)).LE.0.0001)MACHIN=.0001
            IF(ABS(MACHGA(JN)).LE.0.0001)MACHGC=.0001
      C     SETS AIR FLOW DIRECTION INTO VENT
            CKSN= 1.
            IF(CKV.LT.0.)CKSN= -1.
25          IF(CKSN.LT.0.)MACHIN= CKSN*ABS(MACHIN)
            IF(CKSN.LT.0.)MACHGC= CKSN*ABS(MACHGC)
```

```
      SUBROUTINE AMACH

                      M1I= 0.50
                      CKASAV= 0.001
                      DM1I= -0.24999
30                C
                  C     COMPUTATION OF AIR VOLUME IN GATE CHAMBER AND PENSTOCK
                  C
                      RC= 1./(1.2)**3.5
                      OVER= 0
35                    AVOL= AU*(TGC-WS)
                      AVOLU= AU*(TGC-UGCLGC)
                      IF(WS.LE.UGCLGC)AVOL= AVOLU+(UGCLGC-WS)*AD
                      IF(WS.LE.GCLP)AVOL= AVOLU+AD*GCLL+(GCLP-WS)*VOLC1
                      IF(JFIRST.EQ.6)AVOL= AVOLU+(UGCLGC-GCLP)*AD
40                    IF(JCK.GE.4)AVOL= AVOLU+AD*GCLL+AREAP*CKX-VOLR-QR*DELT
                      IF(WS.LE.ELC1)AVOL= AVOLU+AD*GCLL+(ELC2-WS)*VOLC2
                  C
                  C     COMPUTATION OF THE PRESSURE RATIO,THE COMPRESSIBLE DISCHARGE
                  C     COEFFICIENT, THE REAL MACH NUMBER AT 1,AND THE AIR FLOW RATE
45                C     GIVEN THE IDEAL MACH NUMBER AT THE BEGINNING OF THE DUCT REGION
                  C
                      DO 14 NDO=1,30
                        R= 1./(1.+.2*M1I**2)**3.5
                        IF((R/RC).LE.1.)GO TO 1
50                C       COMPRESSIBLE DISCHARGE,COEFFICIENT
                        C= 1.-(1.-CINC)*(1.-.7*(CINC-.1)*(1./R-1.)/(1./RC-1.))
                        GO TO 2
                    1   C= 1.-(1.-CINC)*(1.-.7*(CINC-.1)-(.27+.1*CINC)*(1.-(R/RC)**2))
                    2   RADICL= 1.+.8*C*C*(M1I*M1I+.2*M1I*M1I*M1I*M1I)
55                      ROOT= SQRT(RADICL)
                  C       TRUE MACH NUMBER AT AIR VENT
                        M1R= SQRT((-1.+ROOT)/.4)
                        IF(ABS(M1R).LE.0.00001)M1R= .1E-10*CKSN
                        IF(CKSN.LT.0.)M1R= -1.*M1R
60                      MACHIN= M1R
                  C       ENTROPY INCREASE IN INLET REGION
                        ENT= (C*M1I/M1R)**7.
                        IF(ABS(M1I).LE.0.001)ENT=1.
                  C       STAGNATION PRESSURE AT END OF INLET
65                      PIN= ENT*PATM
                        IF(CKSN.LT.0.)PIN= ENT*PGCTRL
                  C       VELOCITY COEFFICIENT
                        CVEL= (M1R/M1I)**2/C
                  C       MASS FLOW RATE
70                      WTFLA(J)= AGCCTE/SQRT(ABSTEM*GASCTE/(1.4*GRAV))*AVENT*PATM*ENT*
                     +  M1R*NVENTS/(1.+.2*M1R**2)**3
                        IF(CKSN.LT.0.)WTFLA(J)=AGCCTE/SQRT(ABSTEM*GASCTE/(1.4*GRAV))*
                     +  AVENT*PGCTRL*ENT*CKSN*(1.+.2*M1R**2)**3
                        IF(METRIC.EQ.1)WTFLA(J)= WTFLA(J)/(AGCCTE*SQRT(GRAV))
75                C
                  C       COMPUTATION OF MACH NO. AT OUTLET OF AIR DUCT
                  C       CONSIDERING THE FRICTION LOSSES IN THE DUCT
                  C
                        FMAX= EQ(MACHIN)
80                      IF(FRICT.GT.FMAX)GO TO 5
                        MACHGC= MACHIN
                        CKM= -0.01
                        DM= MACHGC/2.
                        IF(DM.GE.0.5)DM= (1.-MACHGC)/2.
85                      EQRH= FMAX
                        EQLH= EQ(MACHGC)
                  C       THIS LOOP FINDS THE VALUE OF MACHGC
                        DO 4 K=1,35
                          EQLH= EQ(MACHGC)
90                        CK= EQRH-EQLH-FRICT
                          CALL NEWX(CK,CKM,MACHGC,DM)
                          IF(K.EQ.1)GO TO 3
```

```
      SUBROUTINE AMACH

                        T1= ABS(CK/FRICT)
                        IF(T1.LE.0.002)GO TO 12
 95                3     CKM= CK
                   4  CONTINUE
                      GO TO 12
                C
                C     COMPUTATION OF AIR FLOW RATE WITH MACH 1 AT DUCT OUTLET
100             C
                   5  MACHGC= 1.
                      MACHIN = 1.
                      DMIN= -0.25
                      C2= -0.01
105                   DO 6 N=1,30
                        EQRH= EQ(MACHIN)
                        C1= EQRH-FRICT
                        CALL NEWX(C1,C2,MACHIN,DMIN)
                        C2= C1
110                     T1= ABS(C1/FRICT)
                        IF(T1.LE.0.005)GO TO 7
                   6  CONTINUE
                   7  M1I= MACHIN
                      DMIN= -0.25
115                   C2= -0.01
                      M1I= 1.0
                      DO 10 MOON=1,30
                        R= 1./(1.+.2*M1I**2)**3.5
                        IF((R/RC).LE.1.)GO TO 8
120                     C= 1.-(1.-CINC)*(1.-.7*(CINC-.1)*(1./R-1.)/(1./RC-1.))
                        GO TO 9
                   8    C= 1.-(1.-CINC)*(1.-.7*(CINC-.1)-(.27+.1*CINC)*(1.-(R/RC)**2))
                   9    RADICL= 1.+.8*C**2*(M1I**2+.2*M1I**4)
                        ROOT= SQRT(RADICL)
125                     M1R= SQRT((-1.+ROOT)/.4)
                        C1= MACHIN-M1R
                        CALL NEWX(C1,C2,M1I,DMIN)
                        T1= ABS(C1/M1R)
                        IF(T1.LE.0.005)GO TO 11
130                10   CONTINUE
                   11   ENT= (C*M1I/M1R)**7.
                        PIN= ENT*PATM
                        CVEL= (M1R/M1I)**2/C
                        WTFLA(J)= AGCCTE/SQRT(ABSTEM*GASCTE/(1.4*GRAV))*AVENT*PATM*ENT*
135                   + M1R*NVENTS/(1.+.2*M1R**2)**3
                        IF(CKSN.LT.0.)WTFLA(J)=AGCCTE/SQRT(ABSTEM*GASCTE/(1.4*GRAV))*
                      + AVENT*PGCTRL**(1.+.2*M1R**2)**3
                        IF(METRIC.EQ.1)WTFLA(J)= WTFLA(J)/(AGCCTE*SQRT(GRAV))
                        JFIRST= 11
140                     GO TO 15
                C
                C     ADIABATIC EXPANSION OF AIR IN THE GATE CHAMBER GIVES THE GATE
                C     CHAMBER PRESSURE PGCTST
                C
145                12   RHOA= (2.*WTAIR+(WTFLA(JN)+WTFLA(J))*DELT)/(2.*AVOL)
                        PGCTST= CONST*RHOA**1.4
                        IF(JFIRST.EQ.4.OR.JFIRST.EQ.7)PGCTST= CONST*((WTAIR+WTFLA(J)*
                      + DELT)/AVOL)**1.4
                C
150             C     COMPUTATION OF PRESSURE AT END OF DUCT FLOW SECTION
                C
                      PGCTRL= PIN*MACHIN/MACHGC*SQRT(((1.+.2*MACHGC**2)/
                      + (1.+.2*MACHIN**2))**6)
                        IF(CKSN.LT.0.)PGCTRL= PATM/ENT*MACHIN/MACHGC*SQRT(((1.+.2*MACHGC
155                   + **2)/(1.+.2*MACHIN**2))**6)
                        CKA = PGCTRL - PGCTST
                        ABSPGC = (PGCTRL + PGCTST) / 2.
                        PGC = PTOHD*ABSPGC
```

SUBROUTINE AMACH

```
                    IF(ABS(CKA).LE.PGCINC)GO TO 15
160                 CALL NEWX(CKA,CKASAV,M1I,DM1I)
                    CKASAV= CKA
                    IF(M1I.GE.0.0.AND.CKV.GE.0.0)GO TO 13
                    IF(M1I.LT.0.0.AND.CKV.LT.0.0)GO TO 13
                    M1I= ABS(M1I)*CKSN/2.
165                 DM1I= DM1I/2.
                 13 IF(ABS(M1I).GE.1.238)M1I= 1.238*CKSN
                 14 CONTINUE
                    OVER= 1
                 15 MACHA(J)= M1R
170                 MACHGA(J)= MACHGC
                    IF(CKSN.LT.0.)MACHGA(J)= M1R
                    IF(CKSN.LT.0.)MACHA(J)= MACHGC
                    IF(OVER.EQ.1)WRITE(3,16)WS
                 16 FORMAT(1H1,19X,35HONE OR MORE LOOPS IN AMACH EXCEEDED /
175                +         30X,4HWS = ,F9.2)
                    RETURN
                    END
```

SUBROUTINE NEWX

```
 1                  SUBROUTINE NEWX(C1,C2,X,D)
                 C
                 C     THIS SUBROUTINE DETERMINES THE NEXT TRIAL VALUE OF X WHICH
                 C     SATISFIES A FUNCTION C= F(X).  IF THE CORRECT ROOT LIES
 5               C     BETWEEN THE OLD VALUE OF THE FUNCTION (C1) AND THAT VALUE
                 C     JUST COMPUTED (C2), THEN THE INCREMENT IS HALVED.  OTHERWISE,
                 C     X IS INCREMENTED BY D.  THE LOGIC OF THIS PROGRAM RESULTS
                 C     IN INCREASES OF C AS X INCREASES.  IF THE OPPOSITE IS TRUE
                 C     THEN D MUST BE MADE NEGATIVE IN THE CALLING ROUTINE.  IN
10               C     THE CALLING ROUTINE THE INITIAL VALUE OF C1 SHOULD BE EQUAL
                 C     TO ZERO.
                 C
                 C     C1= PREVIOUS VALUE OF FUNCTION
                 C     C2= VALUE OF FUNCTION JUST COMPUTED
15               C     X= INDEPENDENT VARIABLE
                 C     D= INCREMENT OF X
                 C
                       IF(C1.GT.0.)GO TO 2
                       IF(C2.LT.0.)GO TO 1
20                     D= D/2.
                       GO TO 3
                    1  X= X+D
                       RETURN
                    2  IF(C2.GT.0.)GO TO 3
25                     D= D/2.
                       GO TO 1
                    3  X= X-D
                       RETURN
                       END
```

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE MORROW POINT DAM

ATMOSPHERIC PRESSURE
77.60 KPA

SPECIFIC MASS OF AIR
.9738 KG/CU.M.

ONE 840MM BY 915MM AIR VENT
FLOW QUANTITIES

TIME	GATE OPENING	COEFF DISCH.	Q RESERVOIR	Q GATE CHAMBER	Q PENSTOCK
(SEC)	(O/O)		(CMS)	(CMS)	(CMS)
0.0	100.0	.93	61.845	0.000	61.845
1.0	99.0	.91	61.800	.045	61.845
2.0	98.0	.89	61.685	.160	61.845
3.0	97.0	.86	61.510	.335	61.845
4.0	96.0	.84	61.329	.515	61.844
5.0	95.0	.82	61.198	.646	61.844
6.0	94.1	.81	61.128	.715	61.843
7.0	93.1	.79	61.132	.711	61.843
8.0	92.1	.77	61.201	.642	61.843
9.0	91.1	.75	61.306	.537	61.842
10.0	90.1	.74	61.416	.426	61.842
11.0	89.1	.72	61.508	.333	61.841
12.0	88.1	.71	61.553	.288	61.840
13.0	87.1	.69	61.537	.301	61.839
14.0	86.1	.68	61.474	.362	61.836
15.0	85.1	.67	61.371	.462	61.834
16.0	84.2	.65	61.262	.568	61.831
17.0	83.2	.64	61.175	.652	61.827
18.0	82.2	.63	61.114	.710	61.824
19.0	81.2	.62	61.089	.731	61.821
20.0	80.2	.61	61.102	.715	61.817
21.0	79.2	.60	61.139	.675	61.813
22.0	78.2	.59	61.184	.625	61.809
23.0	77.2	.58	61.203	.602	61.805
24.0	76.2	.57	61.210	.590	61.800
25.0	75.2	.56	61.194	.601	61.795
26.0	74.3	.55	61.154	.635	61.790
27.0	73.3	.54	61.097	.686	61.784
28.0	72.3	.53	61.036	.741	61.777
29.0	71.3	.52	60.976	.794	61.770
30.0	70.3	.51	60.922	.841	61.763
31.0	69.3	.50	60.883	.872	61.755
32.0	68.3	.49	60.851	.897	61.747
33.0	67.3	.48	60.830	.909	61.739
34.0	66.3	.47	60.819	.911	61.730
35.0	65.3	.47	60.791	.929	61.720
36.0	64.4	.46	60.757	.953	61.710
37.0	63.4	.45	60.703	.996	61.699
38.0	62.4	.44	60.651	1.035	61.687
39.0	61.4	.43	60.595	1.079	61.674
40.0	60.4	.43	60.528	1.133	61.661

APPENDIX III

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE MORROW POINT DAM

ATMOSPHERIC PRESSURE
77.60 KPA

SPECIFIC MASS OF AIR
.9738 KG/CU.M.

ONE 840MM BY 915MM AIR VENT
WATER PRESSURES

TIME	WS ELEV	HEAD ACROSS UNIT	END GATE CHAMBER	VENA CONTRACTA	PENSTOCK
(SEC)	(M)	(M)	(M)	(M)	(M)
0.0	2181.11	122.10	21.06	25.18	24.55
1.0	2181.11	122.10	21.03	25.15	24.55
2.0	2181.10	122.10	21.01	25.13	24.55
3.0	2181.09	122.10	20.98	25.10	24.55
4.0	2181.05	122.10	20.96	25.08	24.55
5.0	2181.01	122.10	20.93	25.05	24.55
6.0	2180.96	122.10	20.90	25.02	24.55
7.0	2180.91	122.09	20.87	24.99	24.55
8.0	2180.86	122.09	20.84	24.96	24.54
9.0	2180.82	122.09	20.80	24.92	24.54
10.0	2180.78	122.09	20.76	24.88	24.54
11.0	2180.76	122.09	20.73	24.85	24.54
12.0	2180.73	122.09	20.69	24.81	24.54
13.0	2180.71	122.08	20.65	24.77	24.53
14.0	2180.69	122.07	20.61	24.73	24.52
15.0	2180.66	122.07	20.58	24.70	24.51
16.0	2180.62	122.06	20.54	24.66	24.51
17.0	2180.58	122.05	20.50	24.62	24.50
18.0	2180.53	122.04	20.47	24.59	24.48
19.0	2180.48	122.03	20.42	24.54	24.47
20.0	2180.42	122.02	20.38	24.50	24.46
21.0	2180.37	122.00	20.33	24.45	24.45
22.0	2180.33	121.99	20.28	24.40	24.44
23.0	2180.28	121.98	20.24	24.36	24.43
24.0	2180.24	121.96	20.19	24.31	24.41
25.0	2180.19	121.95	20.14	24.26	24.40
26.0	2180.15	121.93	20.09	24.21	24.38
27.0	2180.10	121.91	20.04	24.16	24.36
28.0	2180.05	121.89	19.98	24.10	24.34
29.0	2179.99	121.87	19.93	24.05	24.32
30.0	2179.94	121.85	19.87	23.99	24.30
31.0	2179.87	121.83	19.82	23.94	24.27
32.0	2179.81	121.80	19.75	23.87	24.25
33.0	2179.74	121.78	19.69	23.81	24.22
34.0	2179.68	121.75	19.62	23.74	24.19
35.0	2179.61	121.72	19.55	23.67	24.16
36.0	2179.54	121.69	19.48	23.60	24.13
37.0	2179.47	121.65	19.41	23.53	24.10
38.0	2179.40	121.62	19.33	23.45	24.06
39.0	2179.32	121.58	19.25	23.37	24.02
40.0	2179.24	121.54	19.17	23.29	23.98

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-
INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE
77.60 KPA

SPECIFIC MASS OF AIR
.9738 KG/CU.M.

ONE 840MM BY 915MM AIR VENT
AIR FLOW PROPERTIES

TIME	INLET AIR VEL	OUTLET AIR VEL	AIR FLOW RATE	SPECIFIC MASS OF AIR	GATE CHAMBER PRESSURE
(SEC)	(M/SEC)	(M/SEC)	(KG/SEC)	(KG/CU M)	(KPA)
0.0	0.0	0.0	0.000	.9738	77.60
1.0	.0	.0	.000	.9734	77.58
2.0	.3	.3	.243	.9741	77.62
3.0	.3	.3	.243	.9742	77.62
4.0	.6	.7	.547	.9737	77.59
5.0	.7	.8	.608	.9739	77.60
6.0	.8	1.0	.730	.9739	77.60
7.0	.8	.9	.669	.9739	77.60
8.0	.8	.9	.669	.9740	77.61
9.0	.6	.7	.486	.9741	77.61
10.0	.5	.6	.425	.9738	77.60
11.0	.4	.4	.304	.9737	77.59
12.0	.4	.4	.304	.9739	77.60
13.0	.3	.3	.243	.9736	77.59
14.0	.5	.6	.425	.9740	77.61
15.0	.4	.5	.365	.9739	77.60
16.0	.7	.8	.608	.9735	77.58
17.0	.7	.8	.608	.9738	77.60
18.0	.8	1.0	.730	.9738	77.60
19.0	.8	.9	.669	.9737	77.59
20.0	.8	1.0	.730	.9736	77.58
21.0	.7	.8	.608	.9734	77.57
22.0	.8	1.0	.730	.9741	77.62
23.0	.5	.6	.425	.9737	77.59
24.0	.8	1.0	.730	.9737	77.59
25.0	.5	.6	.425	.9737	77.59
26.0	.9	1.1	.790	.9739	77.60
27.0	.6	.7	.486	.9738	77.60
28.0	1.1	1.2	.912	.9738	77.60
29.0	.7	.8	.608	.9741	77.61
30.0	1.1	1.3	.973	.9739	77.60
31.0	.8	1.0	.730	.9742	77.62
32.0	1.1	1.3	.973	.9740	77.61
33.0	.8	1.0	.730	.9735	77.58
34.0	1.3	1.5	1.095	.9740	77.61
35.0	.8	.9	.669	.9738	77.60
36.0	1.4	1.6	1.216	.9742	77.62
37.0	.7	.8	.608	.9736	77.59
38.0	1.6	1.8	1.338	.9734	77.57
39.0	.8	1.0	.730	.9735	77.58
40.0	1.7	2.0	1.459	.9737	77.59

APPENDIX III

COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE MORROW POINT DAM

ATMOSPHERIC PRESSURE
77.60 KPA

SPECIFIC MASS OF AIR
.9738 KG/CU.M.

ONE 840MM BY 915MM AIR VENT
COMPUTATIONAL PROPERTIES

TIME	ACCURACY GATE CHAMBER PRESS	INTEGRATION ERROR GATE CHAMBER	PENSTOCK	FLOW CONDITION (*LAST PAGE)
(SEC)	(PA)	(M)	(M)	
0.0	0.	0.0000	0.0000	1
1.0	44.	.0000	.0000	2
2.0	-33.	.0000	.0000	2
3.0	-43.	.0000	.0000	2
4.0	16.	.0000	.0000	2
5.0	-7.	.0000	.0000	2
6.0	-9.	.0000	.0000	2
7.0	-6.	.0000	.0000	2
8.0	-22.	.0000	.0000	2
9.0	-26.	.0000	.0000	2
10.0	6.	.0000	.0000	2
11.0	11.	.0000	.0000	2
12.0	-4.	.0000	.0000	2
13.0	20.	.0000	.0000	2
14.0	-17.	.0000	.0000	2
15.0	-5.	.0000	.0000	2
16.0	34.	.0000	.0000	2
17.0	5.	.0000	.0000	2
18.0	-2.	.0000	.0000	2
19.0	11.	.0000	.0000	2
20.0	28.	.0000	.0000	2
21.0	49.	.0000	.0000	2
22.0	-34.	.0000	.0000	2
23.0	9.	.0000	.0000	2
24.0	11.	.0000	.0000	2
25.0	13.	.0000	.0000	2
26.0	-4.	.0000	.0000	2
27.0	6.	.0000	.0000	2
28.0	-4.	.0000	.0000	2
29.0	-27.	.0000	.0000	2
30.0	-14.	.0000	.0000	2
31.0	-45.	.0000	.0000	2
32.0	-24.	.0000	.0000	2
33.0	32.	.0000	.0000	2
34.0	-21.	.0000	.0000	2
35.0	7.	.0000	.0000	2
36.0	-46.	.0000	.0000	2
37.0	23.	.0000	.0000	2
38.0	47.	.0000	.0000	2
39.0	41.	.0000	.0000	2
40.0	5.	.0000	.0000	2

LEGEND

* 1 WATER SURFACE IN UPPER GATE CHAMBER
2 WATER SURFACE BELOW TOP OF GATE
3 WATER SURFACE JUST ENTERING PENSTOCK
4 HYDRAULIC JUMP FILLS PENSTOCK, GATE SUBMERGED
5 HYDRAULIC JUMP FILLS PENSTOCK, GATE FREE FLOW
6 WATER SURFACE IN PENSTOCK

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