UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

AIR VENT COMPUTATIONS
MORROW POINT DAM
COLORADO RIVER STORAGE PROJECT

Report No. HYD-584

HYDRAULICS BRANCH
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

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ABSTRACT

A computer program was written to determine the time-magnitude relationships of reduced pressures in the Morrow Point Dam inlet structure. The low pressures are formed during an emergency closure of the intake gates as water in the penstock drains through the turbine. The study was necessary to properly size the air vent system and to investigate the effect of various air vent dimensions on the reduced pressure. Consideration of design parameters, causes for air flow, and flow conditions within the air vent are discussed. The one-dimensional equations of gradually varying unsteady flow are given, and a computer program for their solution is presented in Fortran IV programming language. The program can be used for similar problems.

DESCRIPTORS--Air vents/Unsteady flow/Air demand/penstocks/computer programming/structures/Air/Velocity/Computation/Found/Reservoirs/Design criteria/Matematical analysis/Flow control/Adiabatic

IDENTIFIERS--Morrow Point Dam, Colo/Colorado River Storage Proj/Colorado/Water column separation
NOMENCLATURE

A = area, ft$^2$

C = discharge coefficient for compressible fluids
   = Q actual/Q ideal

C$_a$ = constant for atmospheric conditions of an isentropic flow process

C$_D$ = discharge coefficient through emergency gate

D$_f$ = friction loss factor

C$_p$ = specific heat with pressure held constant

C$_v$ = specific heat with volume held constant

C$_{vel}$ = velocity coefficient for compressible fluids
   = V actual/V ideal

D = conduit diameter, ft

H = length of water column in upper gate chamber under steady state conditions, ft

J = the mechanical equivalent of heat
   = 778.16 ft lbf/Btu

K = total energy loss factor

L = length, ft

M = Mach number = V$_{air}$/V$_{air}$ sonic

\[ \frac{V}{\sqrt{g v k p}} = \frac{V}{\sqrt{g k R T_R}} \approx \frac{V}{h g \sqrt{T_R}} \] (for air)

M$_I$ = ideal Mach number

Q = discharge, cfs

R = engineering gas constant
   = 53.29 ft lbf /lb °Rankine (for air)
\[ T_R = \text{temperature in degrees Rankine} \]
\[ = \text{degrees Fahrenheit} + 459.6 \]
\[ TW = \text{tailrace water surface elevation} \]
\[ V = \text{velocity, ft/sec} \]
\[ Vol = \text{volume of air, ft}^3 \]
\[ W = \text{air mass, lb}_m \]
\[ WS = \text{water surface elevation} \]
\[ Z = \text{reference elevation} \]
\[ f = \text{friction factor from a Moody diagram} \]
\[ g = \text{gravitational constant} \]
\[ = 32.2 \text{ ft lb}_m / \text{lb}_m \text{ sec}^2 \]
\[ h_L = \text{energy loss, ft} \]
\[ k = \text{isentropic flow constant} \]
\[ = 1.4 \text{ for air} \]
\[ p = \text{pressure, lb}_f / \text{in}^2 \text{ for air} \]
\[ = \text{pressure, lb}_f / \text{ft}^2 \text{ for water} \]
\[ r = \text{ratio of piezometric pressure in inlet region of air} \]
\[ \text{duct and stagnation pressure of atmosphere} \]
\[ = P_1 / P_0 \]
\[ r_c = \text{critical pressure ratio} \]
\[ s = \text{Entropy} \]
\[ t = \text{time, sec} \]
\[ v = \text{specific volume of air, ft}^3 / \text{lb}_m \]
\[ w = \text{mass flow rate of air, lb}_m / \text{sec} \]
\[ y = \text{distance between free water surface for steady state} \]
\[ \text{condition and free water surface at time } t, \text{ ft} \]
**Subscripts**

\textit{atm} = atmospheric

\textit{c} = compressible

\textit{e} = location where Mach number = 1.0 for airflow

\textit{g} = entrance to small gate chamber for waterflow

\textit{g} = emergency gate

\textit{GC} = gate chamber

\textit{i} = incompressible

\textit{p} = penstock

\textit{R} = reservoir side of gate chamber

\textit{res} = reservoir upstream from bellmouth entrance

\textit{T} = turbine

\textit{TW} = tailrace

\(0,1,2,3\) = refer to Figure 11 for waterflow

\(0,1,2,3\) = refer to Figure 12 for airflow

A bar over a value refers to an average value.
PURPOSE

The purpose of the study was to determine the magnitude of the reduced pressure in the Morrow Point Dam Powerplant intake gate structure as a function of time, to compute the maximum air velocities through the venting system, and to investigate the effect of the air vent dimensions on the reduced pressure in the penstock through the use of a digital computer program.

CONCLUSIONS

1. An individual 2-foot 9-inch by 3-foot air vent to each chamber prevents the pressure in the gate chamber and penstock from being less than 9.53 psia (pounds per square inch absolute) with an atmospheric pressure of 11.26 psi (pounds per square inch).

2. The maximum exit air velocity in the 2-foot 9-inch by 3-foot vent pipe is approximately 308 fps (feet per second).

3. The maximum inlet velocity 3 feet from the inlet to the 2-foot 9-inch by 3-foot air vent pipe is approximately 45 fps.

4. No water column separation occurs during the emergency closure.

APPLICATIONS

The analytical part of the study which is described by this report is complete. The computer program can be adapted for use on other geometrically similar installations by substituting appropriate values in all statements marked with an asterisk in the main program, in the subroutines, and in the function subprograms. If the other installations are not exactly geometrically similar, the program can still be used by re-writing the function subprograms. As with most mathematical models, the validity of curves presented in this report will not be definitely established until field tests have been performed. A time history of the gate chamber pressure and the percent gate opening during prototype operation would be sufficient to verify the accuracy of the computations presented in this report.

INTRODUCTION

Morrow Point Dam is one of three dams to be built on a 40-mile section of the Gunnison River in Colorado (Figure 1). The complex of dams, known as the Curecanti Unit, is primarily intended to develop water
storage and hydroelectric power generation potentials on the river. Other purposes of the Unit are irrigation, recreation, and flood control.

The power generation facilities at Morrow Point Dam will consist of two generators whose combined capacity is about 120,000 kilowatts (Figures 2 and 3). The hydraulic structures associated with the generators are a single intake structure, two penstocks, two underground hydraulic turbine units, and their draft tubes (Figures 4 through 6).

Under normal operating conditions with flow through the turbines, the intake gates are fully open and water stands in the intake gate chamber (Figures 7A and 7B). The standard procedure for stopping the flow through the penstocks is to close the wicket gates at the turbine and then to close the intake gates. This procedure keeps the penstocks filled with water and eliminates difficulties which are normally experienced when the penstocks must be filled. However, during emergency conditions, the intake gates could close and the wicket gates at the turbine remain open. For this case, the water level in the gate chamber would fall rapidly and eventually all of the water in the penstock would be discharged through the runaway turbine (Figure 7C). This rapid change in the water surface decreases the air pressure in the gate chamber and in the penstock. The formation of excessive subatmospheric pressures in these structures is prevented by admission of air to the system through vents located in the intake structure.

This study was initiated to assist in the determination of the air vent size required at Morrow Point Dam. The procedure which is outlined can be applied to the solution of other similar air vent problems.

BASIC CONSIDERATIONS

A. **Design Criteria**

In general, the following factors must be considered in the design of air vent systems:

1. The limiting subatmospheric pressure which can be tolerated in the structure to which the air vent is attached.

2. The economy of constructing large air vents into a relatively weak connecting structure versus small air vents connected to a strongly reinforced structure.

3. The maximum air velocity which can be tolerated within the air vent duct.
4. The maximum air velocities at the entrance to the air vent duct.

5. The overall effect of the quantity of air flowing through the vents on the flow of water through the system.

Normally, a water conveyance structure, such as a penstock, is designed for the maximum positive internal pressure which might be encountered during the lifetime of its operation. Such a design is also safe against collapse up to some critical negative (below atmospheric) internal pressure. However, if the internal pressure could fall below this critical value, the structure must then be designed to resist both large positive and negative internal forces. In practice the magnitude of the negative internal pressures is often reduced by admitting air into the structure through a venting system. Thus, the requirement of designing the structure to resist large negative pressures can be avoided. However, to achieve significant reductions in the magnitude of the negative pressure, the vents may have to be quite large. Therefore, the designer must weigh the cost of a structure that can withstand excessive negative pressures versus the cost of providing large air vents into the structure. In some cases, the construction of a stronger structure may be more economical than providing for large air vents.

Consideration of the maximum air velocity in the vent pipes is dictated primarily from physiological considerations. The limit on the air velocities in the air vents has been established by experience at about 300 fps and is generally considered to be that air velocity at which an objectionable whistling sound occurs. The intensity of the sound and not the mere presence of sound is the governing factor. For instance, if the sound has pressure levels greater than about 85 db (decibels), ear protection is recommended for exposure times greater than 8 hours.1/ For pressure levels greater than about 135 db, ear protection is recommended for any exposure time. A relationship between air velocities and sound pressure levels in air vents cannot be given unless the air vent configuration is accurately known. However, various studies indicate that the sound pressure levels for certain types of noise increase as the 6th to 8th power of the velocity.2/ Therefore, the noise levels could quickly become objectionable if the 300-fps limit is exceeded. In addition to limiting the velocities within the vent, it is desirable to limit air velocities in the vicinity of the air intake to about 60 fps so that personnel and loose objects will not be swept through the vents. Personnel barriers, placing the intake in inaccessible locations, and grills or screens over the air intake are used to reduce this hazard.

The quantity of air flowing through the vents could adversely affect the flow conditions in the system under certain circumstances. For instance, insufficient air flow into the gate chamber could result in the formation of a vapor pocket in the penstock with subsequent separation of the water column. The rejoining of the water column would create extremely high pressures and could damage the penstock and gate chamber. Grigg, et al/ have established that water column separation will not occur if the cross-sectional area of the flow passage in the lower part of the fully aerated gate chamber is greater than or equal to

\[
\frac{Q_p}{\sqrt{2g(P/\gamma)_{atm}}}
\]

If this criterion is not met, computations of the type described in this report must be performed to determine if water column separation will occur.

B. Criteria for Airflow

The quantity of air which flows through the air vent is determined by both the configuration of the air vent and the flow conditions in the structure to which the vent is connected. Typical examples of flow conditions which may occur in the connecting structure are: the formation of a hydraulic jump which seals off the conduit, spray downstream from a gate, high-velocity flow in a partially filled conduit and a falling water surface. Each of these conditions is described by its own characteristic air-water flow relationship. Due to the variety of possible flow conditions, compressibility of the fluid flow through the air vent, and the design considerations enumerated previously, an air vent which satisfies the many requirements cannot be accurately designed through the use of simple "rules of thumb." Instead, the designer should use hydraulic model studies4/ or, in a few specialized instances, mathematical models.

Of the various flow conditions which were enumerated, the only air-water flow relationships that can be expressed mathematically are for


the hydraulic jump in a conduit5/ and for a falling water surface. Even though an explicit relationship cannot be obtained for a falling water surface in a complex structure, this report indicates a means by which the implicit relationships can be evaluated to approximate the true air-water flow relationship.

C. Description of Computational Procedures

1. Quasi-steady State Solution

The system could be analyzed in several different manners depending upon the rate of change of the waterflow rate. For instance, if the rate of change of the discharge is small enough, the assumption of quasi-steady flow is valid. For this case, the flow at the end of each time increment would be treated as though it had reached a steady state condition. The solution would involve the repeated application of Bernoulli's equation and the continuity equation. The air inflow rate has an influence on the pressure terms in Bernoulli's equation and simultaneously the continuity equation has an influence on the air inflow rate. Therefore, the solution involves a trial and error computation to arrive at the final result for each time increment.

2. Consideration of Inertial Effects

If inertial effects are not small, the system can be analyzed as a surge-type problem. In this type of problem, two equations based on conservation of momentum are written to describe the flow in the penstock and in the gate chamber, respectively. The relationship between the two equations is established through consideration of the energy equation at the point where the gate chamber flow joins the penstock flow. For some specialized cases, these two nonlinear second order differential equations can be combined into one equation which can be solved numerically.6/ However, since a numerical method is generally used for solving the equation, a simpler procedure is to solve the two differential equations simultaneously by standard Runge-Kutta numerical methods.7/8/ After the water drains out of the gate chamber, the flow can be described by one relatively simple second order differential equation.

This type of computation generally falls under the heading of "Rigid Water Column Theory" and forms the basis for the computations described in this report.

3. Consideration of Compressibility Effects in the Water Columns

The previous method assumes that the water column is incompressible, which means pressure changes due to closure of the emergency gate are transmitted throughout the entire system instantaneously. Parmakian\(^9\) states that this assumption is satisfactory when the gate closure time, \(T\), is greater than \(L/1,000\), where \(L\) is the length of the water column. If \(T\) is less than \(L/1,000\), the effects of compressibility of the water column should be included in the analysis. The analysis which considers compressibility effects is known as "Elastic Water Column Theory." The mathematics is made more complex than the previous methods through the introduction of partial differential equations. Therefore, an examination of the necessity for considering an elastic water column can lead to simplifications in the analysis.

The Morrow Point Dam penstock is about 470 feet long, and the total gate closing time was assumed to be 60 seconds. Thus, \(T\) is about 120 times greater than \(L/1,000\) and the effects of compressibility in the water columns can be safely neglected.

D. Deviations from the Prototype

Various discrepancies frequently occur between a mathematical model and the prototype because of simplifying assumptions made in the mathematical model. If these deviations from actual conditions are minor, the mathematical model can still be expected to yield accurate results.

The simplifying assumptions used in the method of analysis described by this report which could cause discrepancies are:

a. Flow into the gate chamber along the upstream face of the partially open emergency gate is neglected.

b. The emergency gate closing rate is constant.

c. The loss coefficient across the turbine is constant.

The effect of these deviations was assumed to be minor. The validity of this assumption should be confirmed by prototype tests.

THE COMPUTER PROGRAM

A. General

The computer program determines quantities which satisfy the rigid water column flow equations. A general outline of the steps which the computer performs is shown in the flow chart (Figure 8). Basically, the program consists of two computational loops. The purpose of the major loop is to solve the two second-order, nonlinear differential equations simultaneously. Within the major loop, a secondary loop determines the airflow quantities through the vents. The program begins at the time corresponding to the inception of the emergency gate closure, computes the flow quantities for this time, increases the time by a fixed time increment and then repeats the computations. This procedure is continued until some preestablished time from inception of the gate closure has been reached. Then the program stops the computations. Only the major divisions of the program are discussed in the headings which follow, since details of the actual steps can be obtained from an examination of the program itself (written in FORTRAN), see Appendix.

B. Numerical Integration

The numerical integration is performed by the computer using the Runge-Kutta method in combination with "smoothing" or corrector equations. The Runge-Kutta method is actually a family of procedures for solving differential equations in which each procedure has its own characteristic degree of accuracy. The particular method used in this report consists of the following procedure (refer to Figure 9A):

The first approximation of the differential equation is a straight line whose slope is determined at the starting point.

The second approximation is a straight line passing through the starting point but whose slope is determined at the midpoint of the first approximation.

The slope for the third approximation is determined at the midpoint of the second approximation.

Finally, the slope of the fourth approximation is determined at the end point of the third approximation.

These four approximations result in four values of the differential equation at the end of the time interval, $\Delta t$, where $\Delta t$ is the time increment used in the integration. An average value is obtained by using Simpsons rule. The inherent error with this method is of the order $\Delta t^3$.

The simultaneous solution of two differential equations, \( g_1 \) and \( g_2 \), can be considered geometrically as the determination of a solution curve in three-dimensional space with coordinates \( x, y, \) and \( t \) (Figure 9B). The Runge-Kutta method of integration for this three-dimensional case is similar to that for the two-dimensional case described by one differential equation. At the end of the time interval \( \Delta t \), values of both \( \Delta x \) and \( \Delta y \) are determined for the two differential equations.

To insure the accuracy of the integration, short-time intervals were used. The values of \( x, y, v_x \) and \( v_y \) computed by the Runge-Kutta method were checked and corrected by assuming that the second-order time-derivatives could be expanded with a five-term Taylor series. For example, in this program the basic time increment for which values were desired was 1.0 second. To perform the integration this interval was broken into five equal intervals and the integration was performed using the Runge-Kutta method for each interval giving five values of \( x, y, v_x \) and \( v_y \). These values were then corrected using standard corrector equations which are based on a five-term Taylor series. A forward integration technique was used to extend the computations from the fifth value (the end of the fourth interval) to the end of the 1.0-second interval. This procedure resulted in water velocities which were correct to four places.

At the end of each time increment, the airflow rate through the vents is computed by solving simultaneously the compressible fluid flow equations for the airflow with the equation for the adiabatic expansion of air in the gate chamber. Although this computation changes the value of the pressure above the water surface in the gate chamber, the use of small time increments and the relatively slow rate of change of gate chamber pressure eliminates the need for repeating the integration.

C. Computation of Discharge Coefficient

The discharge coefficient for the intake gate is a function of both the gate opening and of the downstream conditions. If the water surface downstream from the gate is high enough to effect the discharge coefficient, the efflux is termed "submerged." For lesser water depths, the efflux is called "free." Unfortunately, the effect of submergence on the discharge coefficient of a slide gate located immediately downstream from the end of a bellmouth entrance is not presently available. Therefore, the discharge coefficients for a freely discharging slide gate were used in the program. The discharge coefficient curve was approximated with a fifth degree polynomial using a least squares fit (Figure 10).


12/ Falvey, H. T., Twin Buttes Auxiliary Regulating Gate, Report No. HYD-475, United States Bureau of Reclamation, Denver, Colorado.
The differential head across the gate was used to compute the discharge for the submerged condition. Whereas, the upstream head was used for the free-flow condition.

The emergency gate was assumed to have a linear rate of closure, going from wide open to fully closed in 1 minute. Thus, for each time interval, the percent gate opening was defined. The discharge coefficient which corresponded to a given gate opening was obtained from the polynomial expansion.

D. Computation of the Gate Chamber Pressure

As the water surface drops, the air in the gate chamber and penstock will expand adiabatically. This results in a decrease of the gate chamber pressure. The decreased gate chamber pressure in turn will increase the airflow rates through the air vents. The increased amount of air in the chamber will partially relieve the low pressure. This portion of the program was repeated until the pressure which created a certain airflow rate equaled the pressure formed by the adiabatic expansion of the previous air volume and of the air volume which flowed through the air vent.

E. Computation of the Mach Numbers in the Air Vent

Part of the computation of the gate chamber pressure involved computation of the airflow rate through the vent. Because the flow in the air vent is compressible, the Mach number of the flow into the vent is less than the Mach number of the flow out of the vent. The computer program computed the outlet Mach number based on a given value of the inlet Mach number. The inlet Mach number was determined from the airflow rate required to satisfy the gate chamber pressure.

F. Restrictions Imposed on the Computations

Since the flow equations were solved through successive approximations, maximum allowable error limits were imposed on the required accuracy of specific computations. These limits were as follows:

1. The pressure of the air in the gate chamber or penstock must be correct to within 0.01 psi of its true value.

2. The Mach number of the air entering the gate chamber must be with 0.1 percent of its true value as determined by the compressible flow equations.

These error limits result in a solution which converges rapidly. Smaller increments for the various steps increase the computation time
but do not significantly change the absolute values of the flow quantities. Therefore, these limits can be considered as an optimization of the required computational accuracy for a minimum computation time.

In addition to these restrictions, the computations will cease if vapor pressure is reached in the system since this is a condition which is not defined by the differential equations. Then too, the structure could be endangered if vapor pressures did form in the water columns.

To insure a unique solution at the very low airflow rates, the specific weight of the air in the gate chamber must be equal to or less than the specific weight of air at atmospheric pressure.

DEFINITION OF BASIC EQUATIONS

A. Discharge from Reservoir into Penstock

The flow rate from the reservoir into the penstock is a function of the reservoir elevation, the gate opening, and the pressure downstream from the gate. These quantities were related through the expression:

$$Q_R = A_g \cdot C_D \cdot \sqrt{2g} \cdot \sqrt{W_S \cdot res} - Z_p - \frac{P_R}{\gamma}$$ (1a)

for submerged flow and

$$Q_R = A_g \cdot C_D \cdot \sqrt{2g} \cdot \sqrt{W_S \cdot res} - Z_p + \frac{P_{\text{atm}}}{\gamma} - \frac{P_{\text{g}}}{\gamma}$$ (1b)

for free flow in the penstock

For these computations, a constant reservoir elevation of 7165.0 was assumed. The conduit invert elevation is 7073.25 and the conduit area at the upstream face of the gate is 222.13 square feet (13.52 x 16.43). The discharge coefficients were defined by a fifth degree polynomial which approximated the discharge curve, Figure 10.

B. Momentum Equation for Gate Chamber Flow

The gate chamber configuration was simplified by assuming that it consisted of two main parts, one having a large cross-sectional area and the other small (Figure 11). Equating the body forces and the gravitational forces on the water in the upper gate chamber with the inertia of the fluid gave:
Similarly equating body forces, gravitational forces, entrance drag forces and frictional forces in the lower gate chamber with the inertia of the fluid gave:

\[
P_0 A_1 - P_1 A_1 + \gamma (H - y_1) A_1 = \frac{\gamma (H - y_1)}{g} A_1 \frac{d^2 y_1}{dt^2}
\]  

(2)

Equations 1 and 2 are related to each other through the energy equation written at the junction of the upper and lower gate chambers:

\[
\frac{\gamma}{2g} \left( \frac{dy_1}{dt} \right)^2 + P_1 = \frac{\gamma}{2g} \left( \frac{dy_2}{dt} \right)^2 + P_2
\]  

(4)

Through the continuity equation:

\[
A_1 y_1 = A_2 y_2
\]  

(5)

Equations 2 through 4 can be combined into one equation which describes the flow out of the gate chamber:

\[
\frac{P_0}{\gamma} - \frac{P_3}{\gamma} + (H - y_1 + L_2) = \frac{1}{2g} \left[ \left( 1 + \frac{\gamma L_2}{D} + K_e \right) \left( \frac{A_1}{A_2} \right)^2 - 1 \right] \left( \frac{dy_1}{dt} \right)^2 = \frac{1}{g} \left[ H - y_1 + L_2 \left( \frac{A_1}{A_2} \right) \right] \frac{d^2 y_1}{dt^2}
\]  

(6)
If the water surface is in the lower gate chamber, the equation which corresponds with Equation 6 is:

\[
\frac{A}{A_3} \left( \frac{L_2 + H - y_2}{g} \right) \frac{d^2y_2}{dt^2} = \frac{P_0}{g} - \frac{P_3}{g} + (L_2 + H - y_2) \\
- \frac{fL}{D} \left( \frac{A}{A_3} \right) \frac{1}{2g} \left( \frac{dy_2}{dt} \right)^2
\]  

(7)

C. Momentum Equation for Penstock Flow

The momentum equation for the penstock flow can be written by equating body, frictional, and gravitational forces with inertia. This gives:

\[
\frac{P_p}{g} - \frac{P_4}{g} + Z_p - Z_{TW} - \frac{fL}{D} \frac{1}{2g} \left( \frac{dx}{dt} \right)^2 = \frac{L_p}{g} \frac{d^2x}{dt^2}
\]  

(8)

The pressure at the end of the penstock, \( P_4 \), can be expressed in terms of the tailrace water elevation through the Energy Equation:

\[
\frac{1}{2g} \left( \frac{dx}{dt} \right)^2 + \frac{P_4}{g} = \frac{K_t}{2g} \left( \frac{dx}{dt} \right)^2 + TW - Z_{TW}
\]  

(9)

The value for \( K_t \) is determined from the steady state conditions of flow through a runaway turbine. It is assumed that \( K_t \) is not a function of head across the turbine. For Morrow Point Dam, a maximum discharge of 5,530 cfs with a 405-foot head was used to compute \( K_t \) for the runaway condition. In Equation 9, the velocity head in the tailrace was neglected.

Substitution of \( P_4 \) from Equation 9 into Equation 8 yields the penstock momentum equation:

\[
\frac{P_p}{g} - \frac{K_t}{2g} - \left( \frac{dx}{dt} \right)^2 - TW + Z_p - \frac{fL}{D_p} \left( \frac{dx}{dt} \right)^2 = \frac{L_p}{g} \frac{d^2x}{dt^2}
\]  

(10)
If the free water surface is in the penstock, the length $L_p$ is the length of the water column in the penstock between the free water surface and the turbine.

D. Junction Energy Equations

The equation for the reservoir flow (Equation 1), the equation for the gate chamber flow (Equation 6 or Equation 7), and the penstock flow equation (Equation 10) are all related to each other through energy considerations at the junction of the gate chamber with the penstock.

The distribution of energy at a pipe branch or tee has been investigated by several researchers. The results of analytical computations were found to agree relatively well with experimental data. If the water enters the penstock from both the gate chamber and from the reservoir, the approximate relationship between the pressure immediately below the emergency gate and the penstock pressure is:

$$\frac{P_R}{\gamma} = \frac{V_p^2}{2g} + \frac{P_p}{\gamma} - \frac{V_R^2}{2g} + h_L \tag{11}$$

where

$$h_L = \left[ 1 - \left( \frac{Q_R}{Q_p} \right)^2 \right] \frac{V_p^2}{2g}$$

Similarly, the pressure in the gate chamber can be expressed by:

$$\frac{P_g}{\gamma} = \frac{P_p}{\gamma} + \frac{V_p^2}{2g} - \frac{V_R^2}{2g} - D_p + h_L \tag{12}$$

where

$$h_L = \left[ \frac{Q_{ac}}{Q_p} - 1 - \left( 2 - \frac{A_p}{A_3} \right) \left( \frac{Q_{ac}}{Q_p} \right) \right] \frac{V_p^2}{2g}$$


14/Gardel, A., Chambers D'Equilibre, F. Rouge and Cie, Lausanne, 1956, see also Perkins, F. E. et al, 1964, Hydro Power Plant Transients, Part III, Hydrodynamics Laboratory Report No. 71, Massachusetts Institute of Technology.
With free surface flow in the penstock the head loss across the junction is zero, as can be seen from Equation 11 when $Q_R = Q_p$.

E. Initial Conditions for the Differential Equations

To start the integration of Equations 6 and 10 certain initial conditions must be given. These conditions can be obtained by solving Equations 6 and 10 for the steady state condition ($d^2x/dt^2 = 0$ and $d^2y/dt^2 = 0$). Thus at time, $t = 0$, the initial conditions are:

$$x = 0; \quad dx/dt = 17.776 \text{ ft/sec}$$
$$y = 0; \quad dy/dt = 0$$

The initial conditions for Equation 7 were obtained by assuming conservation of momentum in the gate chamber and in the penstock as the flow left the upper gate chamber. This assumption makes $dx/dt$ and $dy/dt$ continuous functions. In this case $dy/dt$ must be referenced to the lower gate chamber.

F. Compressible Fluid Flow in the Air Vents

1. General - The differential equation of motion for compressible flow in a constant area duct when losses are considered is:

$$\frac{dp}{dL} + \frac{\gamma}{2} \frac{dM^2}{L} + \frac{\gamma}{2} \frac{M^2}{L} \frac{dT}{T} + \frac{dV}{pA} + \frac{\gamma}{2} \frac{M^2}{D} \frac{dx}{D} = 0$$

(Ref. 15, p 93.)

This equation can be solved if the flow is considered as being described by two separate flow regimes, an inlet flow regime and a duct flow regime (Figure 12A). For the inlet regime, the losses are primarily dependent upon form drag, and the effect of friction is neglected. In the duct regime, the losses are caused primarily by friction drag. Thus, the general differential equation is reduced to the following two simple differential equations:

With friction drag = 0,

$$\frac{dp}{dL} + \frac{\gamma}{2} \frac{dM^2}{L} + \frac{\gamma}{2} \frac{M^2}{L} \frac{dT}{T} = 0$$

(14)

With the form \( \text{drag} = 0 \),

\[
\frac{dp}{dx} + \frac{\gamma}{2} dM^2 + \frac{\gamma}{2} M^2 \frac{dT}{T} + \frac{\gamma}{2} \frac{M^2}{D} dx = 0
\]  

(15)

The solutions to these equations can be found in standard thermodynamic textbooks.\(^{15/16/17/}\) The most pertinent solutions using these equations are summarized and discussed in the following sections.

The solution of either equation is based on adiabatic (no heat transferred) flow in the air vent because both the length of the vents and the flow durations are short. Therefore, the amount of heat transfer which can take place is insignificant when compared with changes in air temperature. In addition, the air is assumed to obey the perfect or ideal gas laws. This means that the factor \( k \), in the equation,

\[
pv^k = \text{constant}
\]

remains constant. Actually, the factor \( k \) is a function of both temperature and pressure. However, for the temperature and pressure ranges which are experienced with air vent flows, the value of the factor is essentially constant.

2. Inlet flow - Computations of flow quantities in the inlet flow regime can be carried out in two distinct ways. First, the inlet flow regime can be considered as consisting of an accelerating zone followed by a decelerating zone, Figure 12A. The flow in the accelerating zone is characterized by varying area adiabatic flow with no change in entropy. The decelerating zone is characterized by constant area adiabatic flow in which changes in entropy are determined by integration of Equation 14. The drag term \( D_1 \) is defined as:

\[
D_1 = \frac{K}{2} \frac{P_m^2}{M_2^2} C_d A_2
\]

(17)

To integrate the equation, an expression giving the drag coefficient, \( C_d \), as a function of the Mach number is required. Often \( C_d \) is


assumed to be independent of the Mach number and is given the same value as it has with uncompressible flow (Ref. 15/, p 48). However, the validity of this assumption is somewhat questionable.

A second and probably the most accurate way of determining the inlet flow relations is to consider the entire region as being varying area adiabatic flow (Ref. 15/, p 120). The energy losses (or increases in entropy) are expressed through discharge and velocity coefficients which are determined experimentally.

Starting with an ideal discharge Mach number (no loss) at the end of the inlet region, the pressure ratio between the inlet and the stagnation pressure outside of the inlet is:

\[ r = \frac{p_1}{p_0} = \left(1 + \frac{K-1}{2} M_1^2 \right)^{\frac{k}{k-1}} \]  \hspace{1cm} (18)

With this pressure ratio, the compressible flow discharge coefficient can be obtained (Ref. 16/, p 100; Ref. 17/, p 337; and Ref. 18/).

For this computation, the equation:

\[ \frac{1-C}{1-C_{inc}} = 1 - 0.7(C_{inc} - 0.1) \left( \frac{1}{r} - 1 \right) \]  \hspace{1cm} (19)

from Reference 18 is probably the most useful. This expression is an empirical relationship in which the compressible discharge coefficient is computed from an experimentally determined value of the incompressible discharge coefficient. Equation 19 is valid for pressure ratios less than the critical pressure ratio:

\[ r_c = \frac{p_1}{p_0} = \left( \frac{K-1}{2} \right)^{\frac{k}{k-1}} \]  \hspace{1cm} (20)

For larger ratios the following empirical relationship must be used to determine the compressible discharge coefficient:

\[
\frac{1 - C}{1 - C_{inc}} = 1 - 0.7(C_{inc} - 0.1) - (0.27 + 0.1C_{inc})
\]

\[
\left[1 - \left(\frac{r}{r_e}\right)^2\right]^{2/3}
\]

(21)

When the compressible discharge coefficient has been determined, the true Mach number at the end of the inlet section can be obtained from:

\[
C = \frac{M_1}{M_{11}} \left[\frac{1 + \frac{K-1}{2} M_1^2}{1 + \frac{K-1}{2} M_{11}^2}\right]^{1/2}
\]

(22)

The velocity coefficient is given by:

\[
C_{vel} = \frac{M_1^2}{C M_{11}^2}
\]

(23)

From this the velocity at Point 1 is given by:

\[
V_1 = C_{vel} \sqrt{\frac{2kg RT_0}{k-1} \left[1 - \left(\frac{P_1}{P_0}\right)^{\frac{k-1}{k}}\right]}
\]

(24)

All of these relationships are required to compute the increase in entropy through the inlet region from the expression:

\[
\frac{\Delta S}{RT} = \left(\frac{C}{C_{vel}}\right)^{\frac{k}{k-1}}
\]

(25a)
With no external work, the entropy expression is also equal to the ratio of the stagnation pressures downstream and upstream from the intake. Thus:

\[ \frac{P_1}{P_0} = e^{\frac{\Delta S}{R}} \]  

(25b)

Finally the mass flow rate through the inlet in terms of the true Mach number at the end of the inlet region is:

\[ w = \frac{P_0 A}{\sqrt{\frac{RT_0}{kg}}} \left( e^{\frac{\Delta S}{R}} \right) \left( \frac{M_1}{1 + \frac{k-1}{2} M_1^2} \right)^{\frac{k+1}{k-1}} \]  

(26)

The various flow relationships expressed by Equations 18 through 26 are given in Figure 12B. The mass flow rate is shown for a vent area of 8.25 ft² (2.75 ft x 3.0 ft) and air temperatures of 40°F and 60°F. The 40°F curves were used in the computer program. A program to compute the values of Equations 18 through 26 is given in the Appendix.

3. Duct flow - The flow conditions in the remainder of the air vent are described by the equation for adiabatic flow in a constant area cross section in which the losses are caused by friction, Equation 15. The complete set of equations describing flow in this region are generally referred to as the Fanno Equations after an early investigator in this field. The effect of bends, changes in cross-sectional area, and other types of form losses can be simulated by expressing them in an equivalent length of air vent pipe. In this manner, an overall or equivalent friction coefficient for the air vent is obtained. The friction coefficient is defined as:

\[ C_f = \frac{fL}{D} \]  

(27)

Tables of the flow properties are available for the Fanno Flow relationships in which the inlet Mach number is the variable and the outlet Mach number is equal to 1.0. The tables are based on the
following equations; the pressure at the end of the duct in terms of the pressure at "l" is given by:

\[
\frac{P_1}{P_e} = \frac{1}{M_1} \left[ \frac{K + 1}{2(1 + \frac{K - 1}{2}M_1^2)} \right]^{\frac{1}{2}}
\]  

(28)

the friction factor is given by:

\[
\frac{fL_{\text{max}}}{D} = \frac{1 - M_1^2}{K M_1^2} + \frac{K + 1}{2K} \ln \left[ \frac{(K + 1) M_1^2}{2 \left(1 + \frac{K - 1}{2} M_1^2\right)} \right]
\]  

(29)

The pressure ratio, at the duct exit when the Mach number \( M_2 \) is not equal to 1.0, is given by:

\[
\frac{P_1}{P_2} = \left( \frac{P_1}{P_e} \right)_{M_1} \cdot \left( \frac{P_2}{P_e} \right)_{M_2}
\]  

(30)

The corresponding friction factor is given by:

\[
\frac{fL}{D} = \left( \frac{fL_{\text{max}}}{D} \right)_{M_1} - \left( \frac{fL_{\text{max}}}{D} \right)_{M_2}
\]  

(31)

4. Critical pressure ratio - Both experiments and the flow equations indicate that the flow rate reaches a maximum value for some given ratio of the inlet to outlet pressures. This ratio is known as the "critical pressure ratio." If the outlet pressure is decreased after the critical pressures ratio is reached, the flow rate does not increase, but remains constant. When the critical pressure ratio is obtained, then somewhere in the air vent a Mach number equal to unity (or a shock wave) has developed. At the critical pressure ratio with inlet flow, the shock wave forms at the location of the vena contracta. If however, a length of duct is placed downstream from the inlet and the critical
pressure ratio is maintained, then the shock wave can form at the exit of the duct instead of at the vena contracta.

For ideal flow through a frictionless nozzle, the value of the critical pressure ratio is 0.5283. However, the value of the critical pressure ratio is less than 0.5283 when friction losses or inlet losses are significant. The critical pressure ratio considering only friction losses for a specific Mach number at "1" can be obtained from Equations 20 and 28 using the relationship:

\[
\frac{P_e}{P_0} = \frac{P_1}{P_0} \cdot \frac{P_e}{P_1}
\]

The friction coefficient which corresponds to the specified Mach number at "1" is given by Equation 29.

If both friction and inlet losses are to be considered, then Equations 25b and 28 must be used in conjunction with Equation 32.

The critical pressure ratios with and without inlet loss for various lengths of air vent conduits are shown in Figure 13. The values given represent a shock wave forming at the end of the air vent. The asymptotic lines (dashed lines on the ordinate) represent a shock wave in the vena contracta of the inlet region. The curves are referenced to both the downstream stagnation pressure and the pressure at the duct exit. Normally the critical pressure ratio is referenced to the pressure at the duct exit and the inlet stagnation pressure.

G. Adiabatic Expansion in Gate Chamber

The adiabatic expansion of air in the gate chamber is based upon:

\[
yv^{1.4} = C_a
\]

The specific air volume, \( v \), is computed for each time increment from the equation:

\[
v_{t+\Delta t} = \frac{\text{Vol}_{t+\Delta t}}{\text{\( W_t + \Delta W \)}}
\]
where

\[ V_{t+\Delta t} = \text{air volume at end of time increment} \]
\[ W_t = \text{mass of air at beginning of increment} \]
\[ \Delta W = \frac{(W_t + W_{t+\Delta t}) \Delta t}{2} \]

\[ = \text{change in air mass during time interval from time = t to t+\Delta t} \]
\[ \bar{W} = \text{mass flow rate through the air vent} \]

The constant, \( C_a \), in Equation 33 is computed from known atmospheric conditions in the gate chamber at the steady state condition before the gate begins closing.

H. Gate Chamber and Penstock Volumes as a Function of Elevation

The air volume of the gate chamber and the penstock above any water surface elevation is a function of elevation. This function is a complicated algebraic expression. Therefore, to simplify the computation, the complicated expression is replaced with four linear equations. A plot of the volume as a function of elevation is given in Figure 14.

RESULTS OF COMPUTATIONS

The air vent configuration which was used in the final design consisted of a separate 2-foot 9-inch by 3-foot air vent to each gate chamber. With this design the maximum pressure drop in the gate chamber is 1.73 psi or 3.99 feet of water below atmospheric pressure, Figure 15A.

The maximum air velocity in the vent is 308 fps, Figure 15B. Assuming that the air flow approaches only from in front of the air vent, an air velocity of 101 fps will result at a point 2 feet distant from the air vent intake. At 3 feet, the air velocity is reduced to 45 fps. Therefore, personnel should be prevented from approaching nearer than about 4 feet from the intake to the air vent.

The minimum pressure in the penstock and gate chamber does not drop below the vapor pressure of the water, Figure 15C. Therefore, separation of the water column will not occur.
From the standpoints of pressure drop in the gate chamber, maximum air velocity, and flow conditions in the penstock, the air vent, as designed, is completely satisfactory.
Q. ENERGY AND PIEZOMETRIC GRADE LINES
IN PENSTOCK AND DRAFT TUBE

D. ENERGY AND PIEZOMETRIC GRADE LINES
AT INTAKE STRUCTURE
(STEADY STATE CONDITION)

C. ENERGY AND PIEZOMETRIC GRADE LINES
AT INTAKE STRUCTURE
(GATE CLOSING)

MORROW POINT DAM

ENERGY AND PIEZOMETRIC GRADE LINES
BEFORE AND DURING EMERGENCY GATE CLOSURE
FIGURE 8
REPORT HYD-584

FLOW CHART FOR AIR VENT COMPUTATIONS

MORROW POINT DAM
AIR VENT

READ BASIC VARIABLES AND TITLE
ASSIGN AND SAVE NEW INITIAL CONDITIONS
COMPUTE INITIAL CONDITIONS

FIRST TIME THRU LOOP?
NO
YES
SAVE INITIAL CONDITIONS

IS WON IN GATE CHAMBER?
NO
YES
SOLVE ONE DIFFERENTIAL EQUATION (FUNCT. 3)
SOLVE TWO SIMULTANEOUS DIFFERENTIAL EQUATIONS (FUNCT. 1 & FUNCT. 2)

COMPUTE AIR FLOW RATE AND GATE CHAMBER PRESSURE
COMPUTE DISCHARGE RATES
SAVE RESULTS

HAVE 4D VALVES BEEN SAVED?
NO
YES
WRITE RESULTS

HAS LOOP BEEN DONE TWICE?
NO
YES
\[ k_1 = h f'(t_0, x_0) \]
\[ k_2 = h f'(t_0 + h/2, x_0 + k_1/2) \]
\[ k_3 = h f'(t_0 + h/2, x_0 + k_2/2) \]
\[ k_4 = h f'(t_0 + h, x_0 + k_3) \]

\[ f'(t, x) = \text{Slope of the function } f(x, t) \text{ at the coordinates } x \text{ and } t. \]

A. GRAPHICAL REPRESENTATION OF A DIFFERENTIAL EQUATION BY THE RUNGE-KUTTA METHOD

B. GRAPHICAL REPRESENTATION OF THE SIMULTANEOUS SOLUTION OF 2-SECOND ORDER DIFFERENTIAL EQUATIONS

MORROW POINT DAM
AIR VENT

GRAPHICAL REPRESENTATION OF THE SOLUTION OF DIFFERENTIAL EQUATIONS
FIGURE 10
REPORT HYD-584

\[ C_0 = 1.049 \times 10^{-4} + 7.062 \times 10^{-3} G_0 \\
- 5.830 \times 10^{-5} G_0^2 + 2.398 \times 10^6 G_0^3 \\
- 3.578 \times 10^{-8} G_0^4 + 1.987 \times 10^{-10} G_0^5 \]

\[ \text{Discharge Coefficient} = \frac{Q}{A_g \sqrt{2gH}} \]

- DATA FROM MODEL STUDY, REF 11

\[ A_g = \text{Area Gate Open 100\%} \]
\[ H = \text{Upstream Head} \]
\[ Q = \text{Discharge} \]

MORROW POINT DAM AIR VENT

ASSUMED EMERGENCY GATE DISCHARGE COEFFICIENTS
Inlet conditions with losses taken from Fig. 12

No loss in inlet

With inlet loss

$\frac{P_{a}}{P_{o}}$ (No loss in inlet)

$\frac{P_{a}}{P_{o}}$ (With inlet loss)
MORROW POINT DAM AIR VENT

AIR VOLUME IN GATE CHAMBER AND PENSTOCK

Figure 14

Upper Gate Chamber:
\[ \text{VOL} = 106464.7 - 148.59 \times WS \]

Lower Gate Chamber:
\[ \text{VOL} = 7726.33 + (7113.3 - WS) \times 46.61 \]

Upper Penstock:
\[ \text{VOL} = 8900.90 + (7087.8 - WS) \times 496.9 \]

Lower Penstock:
\[ \text{VOL} = 16130.8 + (7073.25 - WS) \times 143.14 \]
MORROW POINT DAM AIR VENT
DEFINITION SKETCH FOR FLOW IN VICINITY OF INTAKE TO PENSTOCK
FIGURE 12

DEFINITION SKETCH FOR AIR VENT FLOW

G. FLOW RELATIONSHIPS IN THE INLET FLOW REGION

MORROW POINT DAM
AIR VENT
AIR VENT FLOW
Note: The circles denote computer generated values.
**UNITED STATES**  
**DEPARTMENT OF THE INTERIOR**  
Bureau of Reclamation

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### ELECTRONIC COMPUTER PROGRAM ABSTRACT

#### HEADER CARD

<table>
<thead>
<tr>
<th>DESCRIPTIVE NAME OF PROGRAM</th>
<th>AIRFLOW COMPUTATION, MORROW POINT DAM</th>
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<tr>
<td>AUTHOR</td>
<td>MALVEY</td>
<td>73</td>
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</tbody>
</table>

#### CARD 1

| PROGRAM STATUS          | 1 |
| DATE                    | 010167 |
| APPLICATION CODE        | 10 |
| COMPUTER                | 8000 |
| LANGUAGE                | FORTRAN |
| STORAGE REQUIRED        | 15000 |
| TYPE                    | 8 |

#### PURPOSE

| PURPOSE                      | 1 |
| COMPUTES FLOW QUANTITIES IN AIR, VENT AND PENS TOCK DURING AN EMERGENCY | 72 |
| GATE CLOSURE... INCLUDES COMPRENSIBLE FLOW EQUATIONS IN VENT... | 72 |

#### METHODS

| METHODS                      | 1 |
| SIMULTANEOUS SOLUTION OF TWO DIFFERENTIAL EQUATIONS USING RUNGE-KUTTA | 72 |
| METHOD OF NUMERICAL INTEGRATION | 72 |

#### LIMITATIONS

| LIMITATIONS                      | 1 |
| REGULATION OF AIRFLOW, MORROW POINT DAM | 72 |

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DUPLICATE THE FOLLOWING COLUMNS IN ALL CARDS. FILE NO. 714174

SEE REVERSE SIDE FOR INSTRUCTIONS FOR FILLING OUT THE ABSTRACT.
LIST OF SYMBOLS FOR PROGRAM TO COMPUTE AIRFLOW INTO GATE CHAMBER

A. Main Program

ABSPGC – Absolute pressure in the gate chamber (psia)
AD – Cross-sectional area of lower section in gate chamber (ft$^2$)
ADUCT – Array name for title
AG – Area of emergency gate (ft$^2$)
AGC – Array name to store ABSPGC
AP – Array name to store QP
AR – Array name to store QR
AREAP – Cross-sectional area of penstock (ft$^2$)
AS – Array name to store WS
AU – Cross-sectional area of upper section in gate chamber (ft$^2$)
AVENT – Cross-sectional area of the air vent (ft$^2$)
AVOL – Volume of air in gate chamber and penstock above the free water surface (ft$^3$)
AVOLRE – AVOL for steady state condition
C – Compressible discharge coefficient for air
CA – Array name for CD
CD – Emergency gate discharge coefficient
CINC – Incompressible discharge coefficient for air
CKA – Accuracy to which the gate chamber pressure has been computed (psi)
CKB – Array name for CKA
CONST – Constant for an isentropic process
DELT – Time increment for which computations are printed (sec)
DELTIM – Time interval from nearest second to time when water leaves upper section of gate chamber or time when water leaves lower section of gate chamber (sec)
EK – Loss factor between large and small sections of the gate chamber
ENRTAP – Inertia in penstock (ft/sec$^2$)
ERTAGC – Inertia in gate chamber (ft/sec$^2$)
FP – Friction factor in penstock
FRICT – Friction coefficient in air vent (Eq 27)
GCR – Time rate of emergency gate closure (%/sec)
HCOL – WSREF minus elevation of entrance to lower gate chamber (ft)
I – Counter
J – Counter
JFIRST – Integer to check for special conditions
JN – Counter
MACHA – Array name for MIR, see subroutine AMACH
MACHGA – Array name for MACHGC
MACHGC – Mach number at gate chamber end of air vent
MACHIN – Mach number at inlet end of air vent
MINC - Percent accuracy to which Mach number must be computed divided by 100
N - Counter
NLPS - Counter
NTIM - Counter
P3 - Pressure at lower end of small section of gate chamber (ft)
PA - Array name for PP
PATM - Atmospheric pressure (psi)
PGA - Array name for PGO
PGC - Gate chamber pressure (ft)
PCCINC - Accuracy to which gate chamber pressure must be computed (psi)
PGO - Percent emergency gate opening (%)
PIN - Pressure in inlet of air vent (psi)
PL - Length of water column in penstock (ft)
PP - Penstock pressure (ft)
QGA - Array name for QGC
QGC - Discharge from gate chamber (cfs)
QP - Discharge from penstock (cfs)
QR - Discharge through emergency gate (cfs)
SPVOL - Specific volume of air (ft³/lbm)
SPWTA - Specific weight of air (lbm/ft³)
SPWTAG - Array name for SPWTA
T - Elapsed time from beginning of gate closure for which output is printed (sec)
TLOSS - Loss factor across turbine
TOUT - Time at which water leaves large section of gate chamber or time at which water leaves small section of gate chamber (sec)
VEL2 - Velocity at which water leaves large section of gate chamber or velocity at which water leaves small section of gate chamber (ft/sec)
VGC - Velocity of the free water surface in the gate chamber (ft/sec)
VIN - Air velocity in inlet section of air vent (ft/sec)
VOLGC - Volume of water in gate chamber between last time increment and time water leaves the gate chamber (ft³)
VOUT - Air velocity in outlet section of air vent (ft/sec)
VP - Water velocity in penstock (ft/sec)
WS - Free water surface elevation in gate chamber or penstock
WSREF - Free water surface elevation in gate chamber for steady state condition
WSTEST - Dummy variable to check location of free water surface in gate chamber
WTAIR - Weight of air in gate chamber and penstock (lb)
WTFLA - Airflow rate through air vent (lbm/sec)
X - Distance particle of water moves in penstock after gate begins closing (ft)
Y - Distance water surface falls in gate chamber after gate begins closing (ft)
B. Subroutine Q

GATEZ - Elevation of bottom of emergency gate

All other symbols are defined in main program.

C. Subroutine DE2

All other variables are defined in the main program.

AI-3
AKI-4
ALI-4
AMI-4
API-4
BI-3
CI-3
DI-3
DELF
DEL2F
DEL3F
DEL4F
DEL G
DEL2G
DEL3G
DEL4GEI-3
F
FC
FL
G
GC
GL
RKT
RKVX
RKVY
RX
KY
H - Small increment of time which is one fifth as large as DELT
DEL X - Incremental change in X determined from the integration for time interval H
DELT VX - Incremental change in VX determined from the integration for time interval H
DELT Y - Incremental change in Y determined from the integration for time interval H
DELT VY - Incremental change in VY determined from the integration for time interval H
I
J - Counters
K
VX - VP in main program
VY - VGC in main program
D. Subroutine DELTD

DEL - Dummy variables used in computing the fourth difference
DEL2 - of a series of five quantities
DEL3 - DEL4 - The fourth difference
A - An array of five quantities

All other variables are defined in the main program.

E. Function FUNCTI

FUNCTI - The inertia of flow in the gate chamber (ft/sec²)
PT - The pressure at the lower end of the small section of
the gate chamber (ft)
PVAPOR - Vapor pressure of water (ft)
VHGC - Velocity head in the gate chamber (ft)
VHP - Velocity head in the penstock (ft)
VHR - Velocity head immediately downstream from the emergency gate
AA-X
BA-Y
CA-VX From Subroutine DE2
DA-VY
EA-T

All other variables are defined in the main program.

F. Function FUNCT2

FUNCT2 - The inertia of flow in the penstock (ft/sec²)
AB-X
BB-Y
CB-VX From Subroutine DE2
DB-VY
EB-T

All other variables are defined in the main program.

G. Subroutine DE1

AI
A3
AK1-4
BI-3
CI
C3
DELF
DEL2F
DEL3F
DEL4F
DELTX
F
FC
RF
RT
RVX
RX

H - Same definition as in Subroutine DE2
VX - VP in main program
K - counter

All other variables are defined in the main program.

H. Function FUNCT3

FUNCT3 - The inertia of flow in the penstock (ft/sec^2)
AC - X in the main program
BC - VP in the main program
DC - T in the main program
DQRDT - Time rate of change of QR (cfs/sec)
DWS - Difference between free water surface in penstock
       and tailwater elevation (ft)
GATEZ - Elevation of bottom of emergency gate
VHP - Velocity head in the penstock (ft)

All other variables are defined in the main program.

I. Subroutine AMACH

AVOLU - Air volume above elevation 7113
CK - Sum of all the terms in EQ 31
CKASAV - Dummy variable to save CK
CKM - Dummy variable to save CK
DCKDM - Derivative of CK with respect to MACHGC
DEQDM - Derivative of EQ with respect to MACH
DM1I - Incremental change in M1I

Ratio between stagnation pressure at end of inlet section
       in air vent and atmospheric pressure
EQ - Evaluation of EQ 29 for a given Mach number
DQLH - EQ with Mach number = MACHIN
EQRH - EQ with Mach number = MACHGC
JCK
JN
K
KK
MII - Ideal Mach number in inlet section of air vent
MIR - Real Mach number in inlet section of air vent
MACH - Dummy variable replacing given Mach number in the expression EQ
MACSAV - Dummy variable to save MACHIN
MM -
MOON -
N -
NDO -
NWP -

PGCTRL - Gate chamber pressure based on Mach numbers (psi)
PGCTST - Gate chamber pressure based on adiabatic expansion of air in gate chamber (psi)
PGCSAV - Dummy variable to save ABSPGC
PIN - Stagnation pressure at end of inlet region in air vent (psi)
R - Ratio between atmospheric pressure and pressure in inlet section of air vent
RADICL - Dummy variable used in computing MIR
RC - Critical pressure ratio in inlet section of air vent
RNLUP - Dummy variable
ROOT - Dummy variable used in computing MIR

All other variables are defined in the main program.

COMPUTER REQUIRED

The program conforms to USASI specifications for FORTRAN IV and is compatible with most computers using FORTRAN IV compilers. The program as written has been run on a Honeywell H-800 and a Control Data CDC 6400 computer.

RUNNING TIME

With the CDC 6400, 18 seconds of central processor time and 7 seconds input/output time are required. About 15,000 words of core memory are needed for the program.

With the Honeywell H-800, about 7 minutes of central processor time are required for compilation and execution. Of this time, 3 minutes are required for compilation. Core memory required is 7,378 words.
PREPARATION OF INPUT DATA

The input data consist of variables which the user will want to vary to determine their effect on the solution. These include:

- the time increment for which output is required
- atmospheric pressure
- specific weight of air
- cross-sectional area of air vent
- air vent friction factor
- emergency gate closing rate
- accuracy to which gate chamber pressure must be determined
- accuracy to which outlet Mach number must be determined for a given inlet Mach number
- title for the type of air vent studied

The first eight values of input data should be placed in Columns 1-64 of the first data card using an F8.4 format. The title should be placed in Columns 1-72 of the second data card using an 12A6 format. The title should be centered about Column 37 of the title card.

The deck should be stacked according to the following diagram:
COMPUTATION OF AIR FLOW INTO GATE CHAMBER DURING AN EMERGENCY CLOSURE OF GATES FOR THE PENSTOCK INTAKE STRUCTURE
MORROW POINT DAM

REAL MINC
REAL MACHA, MACHGA
COMMON CD, DELTVX, DELTVY, ABSPGC, PATM, PGC, WSREF, HCOL, WS, QR, QP,
1 PP, P3(50), J
2 PL, FP, TLOSS, AU, AD, AREAP, AG, EK
3 GCR, PGO, JFIRST,
4 WTFLA(50), MACHA(50), MACHGA(50)
5 AVOL, PIN, C
6 T(50), JCK
7 ENRTAP(50)
DIMENSION ADUCT(12), QGA(50), AR(50), AP(50), AS(50), AGC(50),
1 VINV(50), VNUT(50), PA(50), PGA(50), CA(50), ERTAGC(50),
2 SPWTA(50), SPVOL(50),
3 CBK(50), Y(50), VP(50), VGC(50)
1 READ(2, 2) DELT, PATM, SPWTA, AVENT, FRICT, GCR, PGCINC, MINC
2 FORMAT (8F8.4)
3 READ(2, 4) (ADUCT(I), I = 1, 12)
4 FORMAT (12A6)
WRITE(3, 111)
111 FORMAT (1H1, //)

INITIAL CONDITIONS

CD = .9303045
PL = 471.
FP = .009
TLOSS = 82.75
AU = 148.59
AD = 46.61
AREAP = 143.14
AG = 222.13
QR = AREAP*SORT(405, 644, 4/(TLOSS = 1*FP*PL/13.5+(AREAP/AG/CD)*2))
PP = 91.75-(QR/AG/CD)*3/64.4
QP = QR
QGC = 0.
WS = PP + 7023.25
WSREF = WS
HCOL = WSREF-7113.
AVOLRE = 1064647. - 148.59*WS
WTAIR = SPWTA - AVOLRE
AVOL = AVOLRE
CINC = .5
ABSPGC = PATM
PIN = PATM
MACHIN = 0.
MACHGC = 0.
PGC = 2.3*769*PATM
CONST = PATM / SPWTA*1.4
CKA = 0.
T(1) = 0.
EK = .8
JFIRST = 1
DELTIM = 0.
NTIM = 0.
COMPUTATIONS IN MAIN LOOP

40 NTIM = NTIM + 1
J = NTIM - 1
NLPS = NTIM + 40 - J
IF(NTIM, LE, 1) GO TO 45

SECOND TIME THRU

JFIRST = 2
T(1) = T(41)
QGA(1) = QGA(41)
AR(1) = AR(41)
AP(1) = AP(41)
VP(1) = VP(41)
VGC(1) = VGC(41)
X(1) = X(41)
Y(1) = Y(41)
AS(1) = AS(41)
AGC(1) = AGC(41)
VIN(1) = VIN(41)
VOUT(1) = VOUT(41)
PGA(1) = PGA(41)
CA(1) = CA(41)
ENRTAP(1) = ENRTAP(41)
ERTAGC(1) = ERTAGC(41)
PA(1) = PA(41)
MACHA(1) = MACHA(41)
MACHGA(1) = MACHGA(41)
SPWTAG(1) = SPWTAG(41)
SPVOL(1) = SPVOL(41)
WTFLA(1) = WTFLA(41)
CKB(1) = CKB(41)
P3(1) = P3(41)

45 J = J + 1
JN = J - 1
IF(JFIRST.EQ.1) GO TO 10
IF(JFIRST.EQ.6) GO TO 35
IF(J.LE.6) GO TO 30
WSTEST = AS(J-4) - 4.0 * DELT * (2.0 * VGC(J-1) - VGC(J-2) + 2.0 * VGC(J-3)) / 3.
IF(WSTEST.LE.7087.8) GO TO 35
IF(WSTEST.LE.7113.8) GO TO 37
GO TO 30

WATER SURFACE IN PENSTOCK

35 IF(JFIRST.EQ.6) GO TO 41
IF(JFIRST.EQ.7) GO TO 42
IF(JFIRST.EQ.8) GO TO 60
VOLGC = (AS(JN) - 7087.8)
TOUT = T(JN) + VOLGC/VGC(JN)
VEL2 = VGC(JN) + FUNCT2(X(JN), Y(JN), VP(JN), VGC(JN), T(JN))
1(TOUT) = T(JN)
DELTIM = (AS(JN) - 7087.8) * 2.0 * (VEL2 + VGC(JN))
T(IJ) = T(J-1) + DELTIM
CALL DE2(X, Y, VP, VGC, T, DELTIM, 2*N, JN)
JFIRST = 6
AS(J) = WSREF - Y(J)
WS = AS(J)
WSREF = AS(J)
X(J) = 0.
CALL AMACH(CINC, MINC, FRICT, AVENT, DELT, PGCINC, WTAIR, CONST, ICKA)
GO TO 7
41 DELT = DELT * DELT
JFIRST = 7
GO TO 60
42 DELT = DELT * DELT
JFIRST = 8
60 CALL DE1(X*VP*T*DELT*JN)
AS(J) = WS
GO TO 70

WATER SURFACE IN LOWER GATE CHAMBER

37 IF (JFIRST .EQ. 3) GO TO 38
   IF (JFIRST .EQ. 4) GO TO 39
   IF (JFIRST .EQ. 5) GO TO 30
VOLGC = (AS(JN) - 113.1)
TOUT = T(JN) + VOLGC/VGC(JN)
VEL2 = VGC(JN) + FUNCT2(X(JN), Y(JN), VP(JN), VGC(JN), T(JN))
1(TOUT-T(JN))
DELTIM = (AS(JN) - 113.1) * 2 * (VEL2/VGC(JN))
T(J) = T(J-1) + DELTIM
CALL DE2(X+Y+VP+VGC+T+DELT, JN+JN)
JFIRST = 3
AS(J) = WSREF - Y(J)
WS = AS(J)
CALL AMACH(CINC, MINC, FRICT, AVENT, DELT, PGCINC, WTAIR, CONST, ICKA)
GO TO 7
38 DELT = DELT * DELT
JFIRST = 4
GO TO 30
39 DELT = DELT * DELT
JFIRST = 5
GO TO 30
30 CALL DE2(X+Y+VP+VGC+T+DELT+JN+JN)
AS(J) = WSREF - Y(J)
WS = AS(J)
70 CALL AMACH(CINC, MINC, FRICT, AVENT, DELT, PGCINC, WTAIR, CONST, ICKA)
IF (JFIRST .GE. 7) P3(J) = 2.30769 * (ABSPGC-PATM)
GO TO 7

ASSIMILATION OF RESULTS

10 QGA(1) = QGC
AR(1) = QR
AP(1) = QR
VP(1) = AP(1)/143.14
VGC(1) = 0.
X(1) = 0.
Y(1) = 0.
AS(1) = WS
AS(2) = WS
AGC(1) = ABSPGC
VIN(1) = 0.
VOUT(1) = 0.
ENRTAP(J) = FUNCT1(X(J), Y(J), VP(J), VGC(J), T(J)) * PL/32.2 **(1)**
ERTAGC(J) = FUNCT2(X(J), Y(J), VP(J), VGC(J), T(J)) * (WSREF = 7113 + AU/1AD **25.2)** **(1)**/32.2
PGA(1) = PGO
CA(1) = CD
PA(1) = PP
MACHA(1) = 0.
MACHGA(1) = 0.
SPWTAG(1) = SPWTA
SPVOL(1) = VP(SWTA)
WTFLA(1) = 0.
CKB(1) = 0.
JFIRST = 2
6 GO TO 11
7 CALL Q(QGC, VP, VGC)
8 QGA(J) = QGC
IF(JFIRST.EQ.100) GO TO 55
AR(J) = QR
AP(J) = QP
AGC(J) = ABRPGC
IF(JFIRST.GE.7) GO TO 85
ENRTAP(J) = FUNCT1(X(J), Y(J), VP(J), VGC(J), T(J)) * PL/32.2 **(1)**
ERTAGC(J) = FUNCT2(X(J), Y(J), VP(J), VGC(J), T(J)) * (WS = 7113 + AU/1AD **25.2)** **(1)**/32.2
IF(WS.LE.7113.) ERTAGC(J) = FUNCT2(X(J), Y(J), VP(J), VGC(J), T(J)) **(1)**
1AD **25.2)** **(1)**/32.2
Go TO 80
85 ENRTAP(J) = FUNCT3(X(J), VP(J), T(J)) **(661618 - WS)/32.2
ERTAGC(J) = 0.
80 WTAIR = WTAIR + (WTFLA(JN) + WTFLA(J)) * DELT/2.
IF(JFIRST.EQ.3, OR. JFIRST.EQ.6) WTAIR = WTAIR + (WTFLA(JN) + WTFLA(J)) * DELT/2.
1+WTFLA(J) * DELT/2.
IF(JCK.EQ.3) WTAIR = WTAIR + (WTFLA(J) - WTFLA(JN)) * DELT/2.
SPWTAG(J) = WTAIR + AVOL
SPVOL(J) = 1.0 / SPWTAG(J)
PQA(J) = PGO
PA(J) = PP
CA(J) = CD
VOUT(J) = MACHA(J) * GRT(32.2 * SPVOL(J) + 1.4 * AGC(J) **144**) IF(AGC(J) .LE. PATM) GO TO 20
VIN(J) = C * 4449.4 * GRT(1.0 - (AGC(J) / PATM) ** (2. / 7.)) **(1)**
GO TO 21
20 VIN(J) = VOUT(J)
21 CKB(J) = CKQ
IF(JFIRST.EQ.100) GO TO 55
11 IF(J.LT.NLPS) GO TO 45
WRITE STATEMENTS FOR OUTPUT OF RESULTS
55 J = JN+1
IF(JFIRST.EQ.100) J = J-1
WRITE(3) PATM, SPWTAG, (ADUCT(I), I = 1, 12)
12 FORMAT (1H,1,8X,56H COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK = / 27X, 218H INTAKE STRUCTURE / 27X,18H MORROW POINT DAM / 8X,22H ATMOSPHERIC PRESSURE = / 19X, F6,2* SHP P 45, + 23X,F6.4, 11H LB/CU ft. / 12A6 //) WRITE (3,13) (T(N),QGA(N),AR(N),AP(N),AS(N),AGC(N),VIN(N),VOUT(N), 1N=1,J)
   IF (.FIRST.EQ.100) WRITE (3,120) T(J+1)
120 FORMAT (4X,F6,1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER)
13 FORMAT (5X,64H TIME Q Q Q WS GATE INLET OUTLET /5X,64H GATE RES PENSTOCK ELEV CHAMBER 2 AIR VEL AIR VEL /5X,64H CHAMBER 3 PRESS /5X,64H (SEC) (CFS) (CFS) (CFS)
   4 (PSIA) (FT/SEC) (FT/SEC) /,(4X,4F8,1,F8.2+1X,F8,3+2F8,1)) WRITE (3,13) PATM,SPWTA,(ADUCT(I),I=1,12)
   WRITE (3,14) (T(N),P3(N),PA(N),PGA(N),CA(N),ERTAGC(N),ENRTAP(N),N=1,12)
   IF (.FIRST.EQ.100) WRITE (3,100) T(J+1)
100 FORMAT (4X,F6,1,5X,38H VAPOR PRESSURE FORMED IN GATE CHAMBER)
14 FORMAT (8X,56H TIME PRESS PENSTOCK GATE COEFF INERTIAL T ERM 1MS /8X,56H AT 3 PRESS OPENING DISCH. GATE PENSTOC 2K /8X,32H (SEC) (FT) (FT) (0/0) /,(7X,F8,1+2F8,2+F8,1, 3F8,4,2F8,4))
   WRITE (3,12) PATM,SPWTA,(ADUCT(I),I=1,12)
   WRITE (3,15) (T(N),MACH(N),MACHGA(N),SPWTA(N),SPVOL(N),WTFLA(N), 1CKBN(N),N=1,J)
   IF (.FIRST.EQ.100) WRITE (3,100) T(J+1)
15 FORMAT (8X,56H TIME MACH NO,MACH NO SPECIFIC SPECIFIC AIR FLOW ACUR 1ACY /8X,56H AT AT WEIGHT VOLUME RATE OF PRES 2S /8X,56H INLET OUTLET OF AIR OF AIR CALC, 38X,56H (SEC) LB/CU FT CU FT/LB/MB/SEC (PSI) // 4(TX,FX,13F8,4,2F8,2,F8,4))
   WRITE (3,16) (QGA(J),AR(J),AP(J),VP(J),VGC(J),X(J),Y(J),AS(J), 1AGC(J),VIN(J),VOUT(J),PGA(J),CA(J),ENRTAP(J),ERTAGC(J), 2PA(J),MACH(J),MACHGA(J),SPWTA(J),SPVOL(J),WTFLA(J),CKB(J))
16 FORMAT (1H,1,9X,4E13.6)
   IF (.FIRST.EQ.100) GO TO 110
   IF (NTIM.LT.1) GO TO 40
110 CONTINUE
   GO TO 1
END
SUBROUTINE Q (QGC, VP, VGC)
REAL MACHA, MACHGA
DIMENSION VP (50), VGC (50)
COMMON CD, DELTVX, DELTVY, AG, SPGC, PATM, PGC, WSREF, HCOL, HS, QR, QP,
1PP, P3 (50), N
2PL, FP, TLOSS, AU, AD, AREAP, AG, EK
3GCR, PGO, JFIRST,
4WTFLA (50), MACHA (50), MACHGA (50)
5AVOL, PIN, C
6T (50), JCK
7ENRTAP (50)
QP = VP (N) * AREAP
2 IF (JFIRST .GT. 6) GO TO 3
QGC = VGC (N) * AU
IF (JFIRST .GT. 3) QGC = VGC (N) * AD
GO TO 4
3 QGC = 0.
4 QR = QP - QGC
IF (JFIRST .GE. 7) QR = AG * CD * SQRT (64.40 * (91.75 - PGC + 2.30769 * PATM))
GATEZ = 7073.25 + 13.5 * PGO / 100
IF (JFIRST .GE. 7 AND .NOT. GF .AND. WS .FORQGATEZ) QR = AG * CD * SQRT (64.40 * (91.75 - PP + PGC)
1-2.30769 * PATM))
RETURN
END
SUBROUTINE DE2 (X,Y,VX,VY,U,DELT,N,NT)
REAL MACHA,MACHGA
DIMENSION X(50),Y(50),VX(50),VY(50),RKT(5),RKX(5),RKY(5),F(5),G(5),U(50)
COMMON CD,DELT VX,DELT VY,ABS PG C, PAT M, PGC, HSREF, COL, WS, QR, QP,
PP,P3(50),IDUD
2,PL,FP,TLSS,AU,AD,ABEAP,AG,EK
3,GCR,PG0,JFIRST,
4WTFLA(50),MACHA(50),MACHGA(50)
5,A VOL,PIN,C
6+T(50),JCK
7+ENRTA P(50)
RKX(1) = X(N)
RK Y(1) = Y(N)
RK VX(1) = VX(N)
RK VY(1) = VY(N)
IF(JFIRST.EQ.4) RKVY(1) = RKVY(1)*AU/AD
RKT(1) = T(N)
H = DELT/5.
F(1) = FUNCT1(RK X(1),RK Y(1),RK VX(1),RK VY(1),RKT(1))
G(1) = FUNCT2(RK X(1),RK Y(1),RK VX(1),RK VY(1),RKT(1))
DO 100 K=1,N
AK1 = RK VX(K)*H
AL1 = RK VY(K)*H
AM1 = H*FUNCT1(RK X(K),RK Y(K),RK VX(K),RK VY(K),RKT(K))
AP1 = H*FUNCT2(RK X(K),RK Y(K),RK VX(K),RK VY(K),RKT(K))
AK2 = (RK VX(K)+AM1/2,H
AL2 = (RK VY(K)+AP1/2,H
AK3 = (RK VX(K)+AM2/2,H
AL3 = (RK VY(K)+AP2/2,H
AK4 = (RK VX(K)+AM3/2,H
AL4 = (RK VY(K)+AP3/2,H
DEL TX = (AK1+2.*AK2+2.*AK3+AK4)/6.
DEL T VY = (AL1+2.*AL2+2.*AL3+AL4)/6.
DELT VX = (AM1+2.*AM2+2.*AM3+AM4)/6.
DEL TVY = (AP1+2.*AP2+2.*AP3+AP4)/6.
N2100  CONTINUE

C
C  CORRECTION
C  OF
C  THE
C  INTEGRATION
C

CALL  DELTD  (F•DEL F•DEL 2F•DEL 3F•DEL 4F)
CALL  DELTD  (G•DEL G•DEL 2G•DEL 3G•DEL 4G)
RKX(2)= RKX(1)+H•(F(J)+DEL F/2+DEL 2F/12+DEL 3F/24+DEL 4F/40)
RKY(2)= RKY(1)+H•(G(J)+DEL G/2+DEL 2G/12+DEL 3G/24+DEL 4G/40)
RKX(J+2)= RKX(J+1)+H•(RKX(J)+RKX(J+2)/2)
RKY(J+2)= RKY(J+1)+H•(RKY(J)+RKY(J+2)/2)
DO 10  J=1,3
F(J+1)= FUNCTION(RKX(J),RKY(J),RKVX(J),RKVY(J),RK(T))
G(J+1)= FUNCTION(RKX(J),RKY(J),RKVX(J),RKVY(J),RK(T))
RKX(J+2)= RKX(J)+F(J+2)/2+F(J)/3
RKY(J+2)= RKY(J)+G(J+2)/2+G(J)/3
RKX(J+2)= RKX(J+1)+H•(RKX(J)+RKX(J+2)/2)
RKY(J+2)= RKY(J+1)+H•(RKY(J)+RKY(J+2)/2)
10  CONTINUE

C  FORWARD  INTEGRATION

VX(N+1)= RKX(4)+H•(2•F(5)+F(3)+2•F(2)+F(1))•F(2)
1+3•F(3)= 3•F(4))
VY(N+1)= RKY(4)+H•(2•G(5)+G(3)+2•G(2)+G(1))•G(2)
1+3•G(3)= 3•G(4))
X(N+1)= RKX(4)+H•(2•RKX(5)+VX(N+1)=2•RKX(4)+RKX(4))/3)
Y(N+1)= RKY(4)+H•(2•RKY(5)+VY(N+1)=2•RKY(5)+RKY(4))/3)
T(N+1)= T(N)+DEL T
FL= FUNCTION(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
GL= FUNCTION(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
VX(N+1)= RKX(4)+H•(F(4)+4•F(5)+FL)/3
VY(N+1)= RKY(4)+H•(G(4)+4•G(5)+GL)/3
X(N+1)= RKX(4)+H•(RKX(4)+4•RKX(5)+VX(N+1))/3
Y(N+1)= RKY(4)+H•(RKY(4)+4•RKY(5)+VY(N+1))/3
FL= FUNCTION(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
GL= FUNCTION(X(N+1),Y(N+1),VX(N+1),VY(N+1),T(N+1))
RETURN
END
SUBROUTINE DELTD(A, B, E, U, DEL4)
REAL MACHA, MACHGA
COMMON CD, DELTVX, DELTVY, AB3PGC, PATM, PGC, WSREF, COLWS, QR, GP,
1PP, P(50), J
2, PL, FP, TLOSS, AU, AD, AREAP, AG, EK
3, GCR, PGO, JFIRST,
4WFLA(50), MACHA(50), MACHGA(50)
5, AVOL, PIN, C
6, T(50), JC
7, ENRTAP(50)
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 = DEL1
E = DEL2(1)
D = DEL3(1)
DEL4 = DEL3(2) - DEL3(1)
RETURN
END
FUNCTION FUNCT1(AA, BA, CA, DA, EA)
REAL MACHA, MACHGA
COMMON CD, DELTVX, DELTVY, ABSPGC, PATM, PGC, WSREF, COL, WS, QR, QP,
1PP, P3(50), J
2*PL, FP, TLOSS, AU, AD, AREAP, AG, EK
3*GCR, PGO, JFIRST
4*WTFA(50), MACHA(50), MACHGA(50)
5*AVOL, PIN, C
6*T(50), JCK
7*ERNRAP(50)
PGO= 100.0*GCR*EA
IF(PGO .LE. 0.) GO TO 100
CD= (1.04E-04) + (7.062E-03 * PGO) * (5.830E-05) * PGO**2 + (2.395E-06) * PGO**3 + (1.987E-10) * PGO**4
GO TO 101
100
PGO= 0.0
CD= 0.
101
VHP = CA**2/64.4
VHGC = DA**2/64.4
IF(JFIRST .GE. 4) VHR = (CA - DA*AU/AAREAP)**2/64.4
PP = 91.75*VHP**2 + VHR**2
IF(DA .LT. 0.) PP = 91.75*VHP**2 + VHR**2
IF(PP .LT. 0.) PP = 91.75*VHP**2 + VHR**2
PT = PP + VHP**2/64.4
IF(PT .LT. 0.) PT = PP + VHP**2/64.4
VAPOR = 3.35*3.0769*PATM
IF(PT .GT. PVAPOR) GO TO 400
PT = PVAPOR
PP = PT + VHP**2/64.4
IF(PT .LT. 0.) PT = PP + VHP**2/64.4
400
RETURN
END
FUNCTION FUNCT2 (AB, BB, CB, DB, EB)
REAL MACHA, MACHG
COMMON CD, DELTVX, DELTVY, ABSPGC, PATM, PGC, WSREF, HCOL, WS, QR, QP,
1PP, P3(50), J
2PL, FP, TLoss, AU, AD, AREAP, AG, EK
3GCR, PGC, JFIRST,
4WTFLA (50), MACHA (50), MACHGA (50)
5AVOL, PIN, C
6T (50), VCK
7ENRTAP (50)
PT = P3(J)
VHP = CB**2/64.4
VHGC = DB**2/64.4
VHR = (CB - nB*AU/AREAP)**2/64.4
IF (JFIRST .GE. 4) VHR = (CB - DB*AD/AREAP)**2/64.4
PP = 91.75 - VHP**2/(1 - VHGC/VHP)**2
IF (DB .LT. 0.1) PP = 91.75 - VHP**2/(1.34*(ABS(AD/DB/AREAP/CB) - 18)**3.18**2
13010.34 + 1) * VHGP = (1 - (AREAP/AD)**2) * (AU/DB/AREAP/CB)
1**2 - VHGC = (AU/AD)**2 + 13.5
IF (JFIRST .GE. 4) PP = PP + VHP*(4,0DB*AU/AREAP - (2 - (AREAP/AD)**2) * (AU/DB/AREAP/CB)
10**2 - VHGC = (AU/AD)**2 + 13.5
PVAPOR = 35 - 2.30769*PATM
IF (PT.GT.PVAPOR) GO TO 400
PP = PT - VHP*(1.0 - DB/AREAP + (2 - (AREAP/AD)**2) * (AU/DB/AREAP/CB)
10**2 - VHGC = (AU/AD)**2 + 13.5
IF (JFIRST .GE. 4) PP = PT - VHP*(1.0 - DB/AREAP + (2 - (AREAP/AD)**2) * (AU/DB/AREAP/CB)
10**2 - VHGC = (AU/AD)**2 + 13.5
PVAPOR = 13.5 - 2.30769*PATM
RETURN
400 P3(J) = PP
IF (DB .LT. 0.1) GO TO 600
IF (JFIRST .GE. 4) GO TO 500
FUNCTION = 32.2/(HCOL - BB + 26.25*AU/AD) * (PGC - 2.30769*PATM + PT*HCOL
1 - BB + 26.25 - VHGC = (AU/AD)**2 + EK*(AU/AD)**2)
RETURN
500 FUNCTION = 32.2*AD/AU/(26.25 + HCOL - BB) * (PGC - 2.30769*PATM + 26.25 + HCOL
1 - BB - VHGC = (HCOL + 26.25 - BB)*FP/2.340*(AU/AD)**2 - PT
RETURN
600 FUNCTION = 32.2/(HCOL + BB + (AU/AD)*26.25) * (PGC - 2.30769*PATM + PT*HCOL
1 - BB + 26.25 - VHGC = (AU/AD)**2 - 2.1))
RETURN
END
SUBROUTINE DE1(X, VX, DELT, L)
REAL MACHA, MACHG
DIMENSION X(50), VX(50), RX(5), RVX(5), RT(5), RF(5), F(5), U(50)
COMMON CD, DELTVX, DELTVV, ABSPGC, PATM, PGC, WSREF, COL, WS, QR, RP,
1 PP, P3(50), NUT
2 PL, FP, TLOSS, AU, AD, AREAP, AG, EK
3 GCR, PGO, JFIRST
4 WTFLA(50), MACHA(50), MACHG(50)
5 AVOL, PIN, C
6 T(50), JCK
7 ENRTAP(50)
N = NUT + 1
RX(1) = X(N)
VX(1) = VX(N)
RT(1) = T(N)
H = DELT / 5.
RF(1) = FUNCT3(RX(1), RVX(1), RT(1))
DO 100 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.
C2 = RT(K) + H/2.
AK3 = FUNCT3(A2, B2, C2) * H
B3 = RVX(K) + AK3
C3 = RT(K) + H
AK4 = FUNCT3(A3, B3, C3) * H
DELTX = H * (RVX(K) + (AK1 + AK2 + AK3)/6.)/3.
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
100 RF(K+1) = FUNCT3(RX(K+1), RVX(K+1), RT(K+1))
CALL DELTD(RX, DELF, DEL2F, DEL3F, DEL4F)
RX(2) = RX(1) + H * (RVX(1) + DELF/2. + DEL2F/12. + DEL3F/24. + DEL4F/40.)/3.
CALL DELTD(RX, DELF, DEL2F, DEL3F, DEL4F)
RX(2) = RX(1) + H * (RF(1) + DELF/2. + DEL2F/12. + DEL3F/24. + DEL4F/40.)/3.
DO 10 J = 1, 3
RF(J+1) = FUNCT3(RX(J+1), RVX(J+1), RT(J+1))
RX(J+2) = (RF(J+2) + 4*RF(J+1) + RF(J))/H/3. + RVX(J)
10 WRITE(3, 20) (RT(I), RX(I), RVX(I), I = 1, 5)
20 FORMAT(F5.1, E10.3, F9.4)
RF(5) = FUNCT3(RX(5), RVX(5), RT(5))
RX(N+1) = RX(N) + H * (RF(5) + RF(1))/3. +
1 RF(5) + 3*RF(4) + 3*RF(3) + RF(2))/3.
X(N+1) = RX(N) + H * (2*RVX(5) + (RVX(3) + 2*RVX(2) + RVX(1))/3. +
1 RVX(5) - 3*RVX(4) + 3*RVX(3) - RVX(2))/3.
1 T(N+1) = T(N) + DELT
F = FUNCT3(X(N+1), VX(N+1), T(N+1))
RETURN
END
FUNCTION FUNCT3 (AC, BC, DC)
REAL MACHA, MACHGA
COMMON CD, DELTVX, DELTVY, ABSPGC, PATM, PGC, WSREF, HCOL, WS, QR, QP,
1PP, P3(50), J
2PL, FP, TLOSS, AU, AD, AREAP, AG, EK
3GCR, PGO, JFIRST
4WTFLA(50), MACHA(50), MACHGA(50)
5AVOL, PIN, C
6T(50), JCK
7ENRTAP(50)
JN= J
PGO = 100, GCR*DC
IF (PGO .LE. 0.) GO TO 100
CD = (1.049E-04 + 7.02E-03 + PGO * (5.830E-05 + PGO + 2*(2.398E-06))
10PGO**3 - (3.578E-08 + PGO**4 * (1.987E-10 + PGO**5))
GO TO 101
100 PGO = 0.
CD = 0.
101 QRST = AG*CD*SQRT(64.4* (91.75 + PGC - 2.30769*PATM))
GATEZ = 7073.25 + 13.5*PGO/100.
IF (WS .GT. GATEZ) QRST = AG*CD*SQRT(64.4* (91.75 + PP - PGC - 2.30769*PATM))
DT = (DC - T(JN))
IF (DT, LE. 0.) GO TO 1
DQRDT = (QR - QRST)/DT
WS = 7087.8 - (AC*AREAP*(2.0*QRST - DQRDT*DT)*DT/2.)/496.0
IF (WS .GE. 7087.8) WS = 7087.8
WS = 7073.25 - (AC*AREAP*(2.0*QRST - DQRDT*DT)*DT/2.)/1.7229.9
WS = 7073.25 - IF (WS. LE. 7073.25) WS = 7073.25 - PP = 2.30769*ABSPGC - PATM
IF (JFIRST .EQ. 7. AND. DT .LE. (1.E-30)) PPFRST = VHP*(TLOSS - 1. + FP*PL/113.5) - DWS - ENRTAP(JN)
IF (WS .GE. 7073.25) PP = (WS - 7073.25) + PPFRST/14.55 + 2.30769*(ABSPGC - 1*PATM)
FUNCT3 = 32.2/PL + PP - VHP*(TLOSS - 1. + FP*PL/13.5) + DWS
WRITE (3,2) WS, DQRDT, CD, FUNCT3, QRST, DT
2FORMAT (2E8.2, F8.4, 2E11.4, F8.4)
RETURN
END
SUBROUTINE AMACH 1/4

SUBROUTINE AMACH(CINC, MINC, FRIC, AVENT, DELT, PG, CINC, WTAIR, CONST, lCKA)
REAL MIR, M11, MACHIN, MACHGC, MACH, MINC, MACSAV
REAL MACHA, MACHGA
COMMON CD, DELTVX, DELTVY, ABDSPG, PARM, PG, WSMR, HCOL, WS, QR, QP,
1PP, P3, JT, PL, FP, TLnSS, AAD, ABEAP, AG, EK,
2GCR, PGO, JFIRST,
4WTLA(50), MACHA(50), MACHGA(50)
5, AVOL, PIN, C
6, T(50), JCK
7, ENRTAP(50)
EQ(MACH)= (1.+MACH**2)/(1.4*MACH**2)+.857*LOG((1.2*MACH**2)/
1(1.+2*MACH**2))
JN= J-1
MACHIN= MACHA(J-1)
MACHGC= MACHGA(J-1)
IF(MACHIN.LE.1.E-301) MACHIN= .0001
M1I=2., MACHIN
JCK= 1
DM1I= MACHIN/10.

COMPUTATION OF AIR VOLUME IN GATE CHAMBER AND PENSTOCK
RC= 1.)/(1.2)**3.5
AVOL= 1064647.-AU*WS
AVOLU= 1064647.-AU*7113.
IF(WS.LE.7113.) AVOL= AVOLU+(7113.-WS)*AD
IF(WS.LE.7087.8) AVOL= AVOLU+25.2*AD+(7087.8-WS)*496.9
IF(WS.LE.7073.25) AVOL= AVOLU+25.2*AD+7230.+ (7073.25-WS)0AREAP

COMPUTATION OF THE PRESSURE RATIO, THE COMPRESSIBLE DISCHARGE
COEFFICIENT, THE REAL MACH NUMBER AT 1, AND THE AIR FLOW RATE
GIVEN THE IDEAL MACH NUMBER AT THE BEGINNING OF THE DUCT REGION

NLUP= 1
PGCSAV= ABDSPG
DO 60 NDO=1,100
R= 1.)/(1.+2*M1I)**2)**3.5
IF(R/RC).LE.1.5)GO TO 21
C= 1.-.5*(1.-.28*(1.2R-1.5)/(1./RC-1.3))
GO TO 22

1 C= 1.-.5*(-.726.32*(1.-(R/RC)**2))
2 RADICL= 1.+8*C**2*(M1I**2+2*M1I**4)
ROOT= SQRT(RADICL)
MIR= SQRT((-1.+ROOT)/.4)
MACHIN= MIR
ENT= (CM1I/MIR)**.7
IF(M1I.LE.001)ENT= 1.
PIN= ENT*PARM
WTLA(4J)= 5.9285*AVENT*PATM*ENT*MIR/(1.+2*MIR**2)**3

COMPUTATION OF MACH NO. AT OUTLET OF AIR DUCT

216 IF(MACHIN .GT.0005) GO TO 1116
MACHGC= MACHIN
GO TO 97

23
SUBROUTINE AMACH 2/4

1116 EQRH = EQ (MACHIN)
     EQLH = EQ (MACHGC)
     CK = EQRH - EQLH - FRICT
     IF (CK) 403,97,401
401 MACHGC = MACHGC + .01
     IF (MACHGC) 404,404,405
403 MACHGC = MACHGC + .01
     IF (MACHGC = 1.) 405,280,280
404 MACHGC = (MACHGC + .01) / 2.
405 EQLH = EQ (MACHGC)
     CKM = EQRH - EQLH - FRICT
     DO 96 K = 1,100
     IF (CK) 407,97,406
406 IF (CKM) 55,97,409
407 IF (CKM) 408,97,55
408 MACHGC = MACHGC + .01
     IF (MACHGC = 1.) 410,280,280
409 MACHGC = MACHGC + .01
     IF (MACHGC) 411,411,410
411 MACHGC = (MACHGC + .01) / 2.
410 EQLH = EQ (MACHGC)
     CK = CKM
     CKM = EQRH - EQLH - FRICT
96 CONTINUE

COMPUTATION OF MACH OUT BY NEWTONS METHOD

55 CK = CKM
     IF (CK) 106,97,105
105 MACHGC = MACHGC + .01
     EQLH = EQ (MACHGC)
     CK = EQRH - EQLH - FRICT
106 DO 95 KK = 1,100
     IF (ABS (CK/EQRH) LE. MINC) GO TO 97
155 DCKDM = (1. - MACHGC**2) / (.7*MACHGC**3 + .14*MACHGC**5)
     MACHGC = MACHGC - CK * DCKDM
     IF (MACHGC.LE.0.) GO TO 203
     IF (MACHGC GT.1.) GO TO 280
     EQLH = EQ (MACHGC)
     CK = EQRH - EQLH - FRICT
95 CONTINUE
     GO TO 97

COMPUTATION OF AIR FLOW RATE WITH MACH 1 AT DUCT Outlet

280 MACHGC = 1.
     MACHIN = 0.
     DO 296 N = 1,100
     MACHIN = MACHIN + .05
     EQRH = EQ (MACHIN)
     IF (EQRH .FRICT) 262,87,296
262 MACHIN = MACHIN + .05
     IF (MACHIN.LE.0.) GO TO 203
     EQRH = EQ (MACHIN)
     DO 295 MM = 1,100
     IF (ABS (EQRH - FRICT).LE. MINC) GO TO 87
DEQDM = (1. - MACHIN**2) / (.7*MACHIN**3 + .14*MACHIN**5)
MACHIN = MACHIN - (EQRH - FRICT)/DEQDM*(1. -)
EQRH = EQ(MACHIN)
CONTINUE
CONTINUE
M1I = MACHIN**3
MACSAV = MACHIN
DO 2 MON:1,50
R = 1./((1.*+2.*M1I**2)**3.5)
IF((R/RC).LE.1.)GO TO 11
C = 1.-5.*(1.-28.*(1.*R-1.)/(1.*RC-1.))
GO TO 12
CONTINUE
2 RADICL = 1.+.8*(EQSAV**2*(M1I**2.*2.*M1I**0.4)
ROOT = SQRT(RADICL)
M1R = SQRT((-1.*ROOT)/4)
ENT = (C*M1I/M1R)**7,
PIN = ENT*PATM
WTFLA(J) = 5.*925.*(AVENT*PATM*ENT*M1R/(1.*+2.*M1R**0.2)**3
IF(ABS(M1R-MACSAV)*LE.*MINC)GO TO 97
M1I = M1I-MINC/2.
IF(M1R.LE.MACSAV)M1I=M1I+MINC
CONTINUE
ADIABATIC EXPANSION OF AIR IN THE GATE CHAMBER GIVES THE GATE CHAMBER PRESSURE PGCTST
PGCTST = (CONST*2.*WTAIR*WTFLA(JN)+WTFLA(J)*DELT)**1.4)/
(1.*AVOL)**1.4
IF(JCK.EQ.3)PGCTST = CONST*2.*WTAIR*WTFLA(J)*DELT)/AVOL)**1.4
COMPUTATION OF PRESSURE AT END OF DUCT FLOW SECTION
PGCTRL = PIN*MACHIN/MACHGC**SQRT(((1.*+2.*MACHGC)/
(1.*+2.*MACHGC))**6)
WRITE(3,1)R*C*M1R*M1I*ENT*WTFLA(J)*MACHIN*MACHGC
WRITE(3,4)PGCTST,PGCTRL,PIN,WTAIR,WTFLA(JN),AVOL,CONST
1 FORMAT(8F9.4)
4 FORMAT(3F9.4,E10.3,F9.4,E10.3,F9.4)
CKA = PGCTRL - PGCTST
ABSPGC = (PGCTRL + PGCTST) / 2.
PGC = 1.153645 * (PGCTRL + PGCTST)
IF(ABS(PGCTRL-PGCTST)*LE.*PGCINC)GO TO 28
IF(NDO,Eq.1)GO TO 50
IF(NLUP,Eq.2)GO TO 50
DM1I = CKA*DM1I/(CKASA-CKA)
50 IF(NDO,Eq.1.AND.CKA*LE.*0.)DM1I = (-1.)*M1I/2.
M1I = M1I+DM1I
IF(M1I.LE.(1.*E-30))GO TO 203
NLUP = 1
CKASA = CKA
GO TO 60
COMPUTATION WITH NEGATIVE MACH NUMBERS AT ENTRANCE OF DUCT SECTION
JCK = 3
SUBROUTINE AMACH 4/4

RNLUP = NLUP
M1I = MINC/RNLUP
NLUP = NLUP + 1
DM1I = M1I
60 CONTINUE
281 MACHA(J) = M1R
MACHGA(J) = MACHGC
RETURN
END
PROGRAM OUTPUT
COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK
INTAKE STRUCTURE
MORROW POINT DAM

ATMOSPHERIC PRESSURE
11.26 PSI

SPECIFIC WEIGHT OF AIR
.0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

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<th>Q RES (CFS)</th>
<th>Q PENSTOCK (CFS)</th>
<th>WS ELEV (FT/SEC)</th>
<th>GATE CHAMBER PRESS (PSIA)</th>
<th>INLET AIR VEL (FT/SEC)</th>
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### COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENSTOCK-INTAKE STRUCTURE MORROW POINT DAM

### ATMOSPHERIC PRESSURE

**11.26 PSI**

### SPECIFIC WEIGHT OF AIR

**0.0596 LB/CU.FT**

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

**ATMOSPHERIC PRESSURE**
11.26 PSI

**SPECIFIC WEIGHT OF AIR**
0.0596 LB/CU.FT.

**2FT-9IN. BY 3FT RECTANGULAR AIR DUCT**

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### COMPUTATION OF AIR FLOW INTO THE GATE CHAMBER DURING AN EMERGENCY GATE CLOSURE IN THE PENS TOCK INTAKE STRUCTURE

**MORROW POINT DAM**

**ATMOSPHERIC PRESSURE** 11.26 PSI

**SPECIFIC WEIGHT OF AIR** 0.0596 LB/CU.FT.

**2FT-9IN. BY 3FT RECTANGULAR AIR DUCT**

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

ATMOSPHERIC PRESSURE 11.26 PSI

SPECIFIC WEIGHT OF AIR .0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

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

ATMOSPHERIC PRESSURE
11.26 PSI

SPECIFIC WEIGHT OF AIR
0.0596 LB/CU.FT.

2FT-9IN. BY 3FT RECTANGULAR AIR DUCT

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LIST OF SYMBOLS FOR PROGRAM TO COMPUTE FLOW CONDITIONS IN INLET REGION OF AIR VENT

AREA - Area of Air vent (in²)
CINC - Incompressible discharge coefficient
CCOM - Compressible discharge coefficient
LEVEL - Velocity coefficient
EXPENT - Ratio of stagnation pressures
GASCON - Engineering gas constant for air \( \frac{\text{ft lb}_f}{\text{lb}_m \cdot R} \)
GRAV - Gravitational constant (ft/sec²)
K - Isentropic flow constant
MACH2I - Ideal Mach number at end of inlet region
MACH2R - Real Mach number at end of inlet region
MACHSQ - Dummy variable
R - Pressure ratio between atmosphere and end of inlet section
RCRIT - Reciprocal of critical pressure ratio
RC - Dummy variable
RR - Reciprocal of R
T - Temperature (°Rankine)
WTFLO - Mass flow rate of air (lb_m/sec)

COMPUTER REQUIRED

The program was written in FORTRAN II language for use in a GE time-sharing computer. The time required for compilation and execution was about 10 seconds.
FLOW CONDITIONS IN THE INLET REGION OF THE AIR VENT

FLOW DIAGRAM

READ VARIABLES

COMPUTE VALUES FOR EQUATIONS 18 THRU 26

WRITE RESULTS
PROGRAM LISTING

FLOW CONDITIONS IN THE INLET REGION OF THE AIR VENT
'PROGRAM TO COMPUTE FLOW CONDITIONS IN THE INLET REGION OF AN AIR VENT PIPE'

REAL K,MACH2I,MACHSQ,MACH2R
1 READ, AREA, K, T, GASC0N, GRAV, CINC, PATM
2 FORMAT(7F8.4)
3 RCRIT = ((K+1.)/2.)*(*K/(K-1.))
4 PRINT 4
5 FORMAT (24X,23H FLOW CONDITIONS IN THE /21X,13H INLET REGION,
6 +16H OF THE AIR DUCT /*1X,34H IDEAL MACH REAL MACHC0MP C0EFFC0MP
7 +26H C0EFF ENTR0PY AIR FL0 10H PRESSURE, 1IX,
8 +57H NUMBER DI0ERENCE VELOCITY EXP0NENT RATE,
9 +4X,6H RATI0/)
10 6 READ, MACH2I
11 C0NKE = (K-1.)/2.
12 R = (1.+C0NKE*MACH2I**2)**(K/(K-1.))
13 RC=RCRIT
14 CC0M = 1.- (1.-CINC)**(1.-1.7*(CINC-1.)*(27.+1.*CINC)**
15 + (1.-RC/R)**2)
16 IF(RCRIT-R)3,3
17 CC0M = 1.- (1.-CINC)**(1.-1.7*(CINC-1.)*(R-1.)/(RC-1.))
18 3 MACHSQ = (1.+SQRT(1.+2.*K-1.)*(CC0M*MACH2I)**2
19 +*(1.+K-1.)/2.*MACH2I**2)))/K-1.)
20 MACH2R = SQRT(MACHSQ)
21 CUEL = MACHSQ/CC0M*MACH2I**2)
22 EXPENT = (CC0M/CUEL)**(K/(K-1.))
23 W0FL0 = PATM*AREA/SQRT(GASC0N*T/(K*GRAV))**EXPENT*
24 +MACH2R/(1.+C0NKE*MACHSQ)**((K+1.)/(2.*K-1.))
25 RR = 1./R
26 PRINT 5, MACH2I, MACH2R, CC0M, CUEL, EXPENT, W0FL0, RR
27 5 FORMAT(1X,5E10.3,E10.4,E10.3)
28 G0 T0 6
29 $DATA
30 99, 1.4, 520, 53, 29, 32.2, 5, 11.26
31 1.29, 1.3
PROGRAM OUTPUT

FLOW CONDITIONS IN THE INLET REGION OF THE AIR VENT
## Flow Conditions in the Inlet Region of the Air Duct

### Ideal Mach Number

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### Temperature 40 °F

### Temperature 60 °F
CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-81.

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

Table I

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<td>Cubic feet</td>
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<td>Cubic meters</td>
</tr>
<tr>
<td>Cubic yards</td>
<td>0.000371</td>
<td>Cubic meters</td>
</tr>
<tr>
<td>CAPACITY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid ounces (U.S.)</td>
<td>29.5735</td>
<td>Cubic centimeters</td>
</tr>
<tr>
<td>Liquid pints (U.S.)</td>
<td>20.8234</td>
<td>Milliliters</td>
</tr>
<tr>
<td>Quarts (U.S.)</td>
<td>0.473176</td>
<td>Cubic decimeters</td>
</tr>
<tr>
<td>Gallons (U.S.)</td>
<td>3.785463</td>
<td>Liters</td>
</tr>
<tr>
<td>Gallons (U.K.)</td>
<td>4.54609</td>
<td>Cubic decimeters</td>
</tr>
<tr>
<td>Cubic feet</td>
<td>28.3168</td>
<td>Liters</td>
</tr>
<tr>
<td>Cubic yards</td>
<td>7.3452</td>
<td>Liters</td>
</tr>
<tr>
<td>Acre-feet</td>
<td>1.2335</td>
<td>Cubic meters</td>
</tr>
</tbody>
</table>

Table I (continued)

<table>
<thead>
<tr>
<th>QUANTITIES AND UNITS OF SPACE</th>
<th>Multiply By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallons (U.S.)</td>
<td>0.0378547</td>
<td>Cubic meters</td>
</tr>
<tr>
<td>Cubic feet</td>
<td>4.54609</td>
<td>Liters</td>
</tr>
<tr>
<td>Cubic yards</td>
<td>784.85</td>
<td>Liters</td>
</tr>
<tr>
<td>Acre-feet</td>
<td>1.2335</td>
<td>Cubic meters</td>
</tr>
</tbody>
</table>

The above table includes the following units of space:

- LENGTH
  - Mil.
  - Inches
  - Feet
  - Yards
  - Miles (statute)
- AREA
  - Square inches
  - Square feet
  - Square yards
  - Acres
  - Square miles (statute)
- VOLUME
  - Cubic inches
  - Cubic feet
  - Cubic yards
- CAPACITY
  - Fluid ounces (U.S.)
  - Liquid pints (U.S.)
  - Quarts (U.S.)
  - Gallons (U.S.)
  - Gallons (U.K.)
  - Cubic feet
  - Cubic yards
  - Acre-feet
### Table II

**QUANTITIES AND UNITS OF MECHANIC**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FORCE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ounces</td>
<td>1/16 pound (exact)</td>
<td>Pounds</td>
</tr>
<tr>
<td>Pounds per square inch</td>
<td>0.06944</td>
<td>Kilograms per square centimeter</td>
</tr>
<tr>
<td>Pounds per square foot</td>
<td>0.00694</td>
<td>Kilograms per square meter</td>
</tr>
<tr>
<td><strong>FREQUENCY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycles per second</td>
<td>1.0</td>
<td>Hertz</td>
</tr>
<tr>
<td><strong>FRICTION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newtons</td>
<td>1.0</td>
<td>Kilograms</td>
</tr>
<tr>
<td><strong>FUNDAMENTAL UNITS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meter</td>
<td>1.0</td>
<td>Meters</td>
</tr>
<tr>
<td>Second</td>
<td>1.0</td>
<td>Seconds</td>
</tr>
<tr>
<td>Kelvin</td>
<td>1.0</td>
<td>Kelvin</td>
</tr>
<tr>
<td><strong>FURTHER QUANTITIES AND UNITS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cubic feet per square foot per minute</td>
<td>304.8</td>
<td>Liters per square meter per day</td>
</tr>
<tr>
<td><strong>WORK AND ENERGY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horsepower</td>
<td>746.0</td>
<td>Watts</td>
</tr>
<tr>
<td>Foot-pounds per second</td>
<td>1.3556</td>
<td>Watts</td>
</tr>
<tr>
<td><strong>HEAT TRANSFER</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Btu / Min / Sq Ft C, thermal conductivity</td>
<td>1.442</td>
<td>Kilowatts/m2 deg C</td>
</tr>
<tr>
<td>Btu / Hr / Ft² / Deg F, thermal conductivity</td>
<td>0.396</td>
<td>Kilowatts/m² deg C</td>
</tr>
<tr>
<td>Foot-pounds per square inch (C, heat capacity)</td>
<td>2.041</td>
<td>Cal/deg C</td>
</tr>
<tr>
<td>Foot-pounds per second (Thermal diffusivity)</td>
<td>0.0875</td>
<td>Cal/sec</td>
</tr>
</tbody>
</table>

### Table III

**OTHER QUANTITIES AND UNITS**

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic feet per square foot per day</td>
<td>304.8</td>
<td>Liters per square meter per day</td>
</tr>
<tr>
<td>Pounds per square foot</td>
<td>0.8818</td>
<td>Kilograms per square meter</td>
</tr>
<tr>
<td>Square feet per second (Brick masonry)</td>
<td>0.009503</td>
<td>Square meters per second</td>
</tr>
<tr>
<td>Square feet per second (Cement)</td>
<td>0.009503</td>
<td>Square meters per second</td>
</tr>
<tr>
<td>Square feet per second (Concrete)</td>
<td>0.009503</td>
<td>Square meters per second</td>
</tr>
<tr>
<td>Square feet per second (Rammed earth)</td>
<td>0.009503</td>
<td>Square meters per second</td>
</tr>
<tr>
<td>Square feet per second (Tin)</td>
<td>0.009503</td>
<td>Square meters per second</td>
</tr>
<tr>
<td>Square feet per second (Wood)</td>
<td>0.009503</td>
<td>Square meters per second</td>
</tr>
<tr>
<td><strong>FUNDAMENTAL UNITS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot-pounds</td>
<td>1.3556</td>
<td>Watts</td>
</tr>
<tr>
<td><strong>FURTHER QUANTITIES AND UNITS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millimeters per cubic foot</td>
<td>28.3167</td>
<td>Millimeters per cubic meter</td>
</tr>
<tr>
<td>Millimeters per square foot</td>
<td>10.7928</td>
<td>Millimeters per square meter</td>
</tr>
<tr>
<td>Square feet per minute</td>
<td>10.064</td>
<td>Liters per square meter</td>
</tr>
<tr>
<td>Square feet per second</td>
<td>1.09666</td>
<td>Liters per square meter</td>
</tr>
</tbody>
</table>

---

**Notes:**
- Values are rounded to the nearest whole number.
- Units of energy are converted to their equivalent in Btu and metric units.
- Values for heat transfer are converted to their equivalent in kW/m²°C.
- Values for work and energy are converted to their equivalent in W and kW.
- Units for further quantities and units are standardized for ease of comparison.
ABSTRACT

A computer program was written to determine the time-magnitude relationships of reduced pressures in the Morrow Point Dam inlet structure. The low pressures are formed during an emergency closure of the intake gates as water in the penstock drains through the turbine. The study was necessary to properly size the air vent system and to investigate the effect of various air vent dimensions on the reduced pressure. Consideration of design parameters, causes for air flow, and flow conditions within the air vent are discussed. The one-dimensional equations of gradually varying unsteady flow are given, and a computer program for their solution is presented in Fortran IV programming language. The program can be used for similar problems.
AIR VENT COMPUTATIONS--MORROW POINT DAM--COLORADO RIVER STORAGE PROJECT. Bur Reclam Lab Rep Hyd-58h, Hydraul Br, July 1968. Bureau of Reclamation, Denver, 22 p, 15 fig, 7 tab, 17 ref, append

DESCRIPTORs--/ *vents/ *unsteady flow/ *air demand/ penstocks/ computer programming/ structures/ air/ velocity/ computation/ sound/ reservoirs/ design criteria/ mathematical analysis/ flow control/ adiabatic
IDENTIFIERS--/ Morrow Point Dam, Colo/ Colorado River Storage Proj/ Colorado/ water column separation