UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Technical Paper No. 44, Series B

Hydraulics of Closed Conduit Spillways

Part XI. Tests Using Air

by

Fred W. Blaisdell and George G. Hebaus
Hydraulic Engineers, USDA, ARS

January 1966

Study conducted by

UNITED STATES DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE
SOIL AND WATER CONSERVATION RESEARCH DIVISION

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ABSTRACT

The use of air instead of water to evaluate the full flow entrance loss coefficients and pressure coefficients for closed conduit spillways is the subject of this paper.

The paper explains that air cannot be used as a substitute for water when the spillway is only part full, gives reasons for using air instead of water, presents background information, compares the water and air equations, develops the compressible flow equations required to analyze the data, and describes the test apparatus and procedure. Verification tests show that identical results can be obtained using either air or water.

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NOMENCLATURE

a	subscript denoting the surface of the headpool, atmosphere, or air
a	coefficient in Eq. XI-40; the friction pressure at point e, in pounds per square foot
a	coefficient in Eq. XI-69b; the centerline velocity, in feet per second
A	barrel area, in square feet
A_e	spillway entrance area, in square feet
A_o	spillway outlet area, in square feet
A_r	area of the riser or drop inlet, in square feet
A_1	area of the barrel just upstream from the flow-measuring orifice, in square feet
A_2	area of the flow-measuring orifice, in square feet
b	coefficient in Eq. XI-40; the rate of friction loss, in pounds per square foot
b	coefficient in Eq. XI-69b
B	corrected barometer reading, in inches of mercury
B_u	uncorrected barometer reading, in inches of mercury
c_m	specific heat of the air-water vapor mixture, dimensionless
c_p	specific heat at constant pressure, dimensionless
c_{pm}	specific heat at constant pressure of the air-water vapor mixture, dimensionless
c_v	specific heat at constant volume, dimensionless
c_{vm}	specific heat at constant volume of the air-water vapor mixture, dimensionless
C_o	coefficient of discharge for the measuring orifice, dimensionless
D	spillway or barrel diameter (nominal), in feet
D_e	spillway or barrel diameter at its entrance, in feet
D_i	spillway or barrel diameter at point i, in feet
D_o	spillway or barrel diameter at its outlet, in feet
D_2	diameter of the flow-measuring orifice, in inches
e	subscript denoting conditions at the entrance of the spillway barrel

f	Darcy-Weisbach friction factor, dimensionless
g	acceleration due to gravity, in feet per second per second
h'	enthalpy, British thermal units per pound of air
h_{fi}	friction head at point i, in feet
h_{mi}	micromanometer pressure measurement for point i, in feet
h_{mr}	micromanometer reading of the pressure at the mid-height of the riser or drop inlet, in feet
h_{m1}	micromanometer reading of the pressure upstream of the measuring orifice, in feet
h_{m2}	micromanometer reading of the pressure drop across the measuring orifice, in feet
h_n	local pressure deviation from the friction grade line, in feet
h_{ni}	local pressure deviation from the friction grade line at point i, in feet
h_{0i}	micromanometer zero reading, in feet
h_{pi}	pressure head at point i, in feet
h_{vp}	velocity head in the barrel, in feet
H	head on crest, in feet
H_t	total head causing flow; the difference in elevation between the headpool surface and the point at which the hydraulic grade line pierces the plane of the spillway exit, in feet
i	subscript denoting a point in the closed conduit spillway
J	mechanical equivalent of heat = 778.2 foot-pounds per British thermal unit
k	ratio of the specific heat at constant pressure to the specific heat at constant volume for the air-water vapor mixture, dimensionless
K_e	entrance loss coefficient, dimensionless
K_o	outlet loss coefficient, dimensionless
ℓ	length of the conduit, in feet
ℓ_i	length from the upstream end of the barrel (point e) to point i, in feet
ℓ_o	length from the upstream end of the barrel (point e) to the outlet, in feet
m	subscript used to designate a mixture of dry air and water vapor
$\mathbb{M}_e$	Mach number at the barrel entrance; ratio of the velocity to the sonic velocity, dimensionless
N	number of observations

o	subscript ordinarily denoting the outlet of the closed conduit spillway
oi	subscript denoting uncorrected conditions at the outlet of the closed conduit spillway
p	pressure, in pounds per square foot
p_a	pressure in the headpool, in pounds per square foot
p_a	atmospheric pressure, in pounds per square foot
p_e	pressure of the friction grade line at the barrel entrance, in pounds per square foot
p_{fi}	friction grade line pressure at point i, in pounds per square foot
pi	subscript denoting the pressure head at point i
p_i	pressure at point i in the closed conduit spillway
p_{mi}	measured pressure at point i, in pounds per square foot
p_n	local pressure deviation from the friction grade line, in pounds per square foot
p_{ni}	local pressure deviation from the friction grade line at point i, in pounds per square foot; identical to Δp_i
p_o	pressure (corrected) at the spillway outlet, in pounds per square foot
p_{oi}	uncorrected pressure at the spillway outlet, in pounds per square foot
p_{pi}	pressure (corrected) at point i, in pounds per square foot
p_r	pressure at the mid-height of the riser or drop inlet, in pounds per square foot
p_v	vapor pressure of the air-water mixture, in pounds per square foot
p_{vd}	vapor pressure at the dry bulb temperature, in pounds per square foot
p_{vi}	velocity pressure at point i, in pounds per square foot
p_{vp}	velocity pressure in the barrel, in pounds per square foot
p_{vr}	velocity pressure in the riser or drop inlet, in pounds per square foot
p_w	pressure of saturated vapor, in pounds per square foot
p_1	pressure upstream of the measuring orifice, in pounds per square foot
p_2	pressure downstream of the measuring orifice, in pounds per square foot
Δp_i	difference between the corrected observed pressure and the friction grade line pressure at point i; $\Delta p_i = p_{pi} - p_{fi}$, in pounds per square foot
Δp_{ni}	difference in pressure between point i in the drop inlet and the atmosphere, in pounds per square foot

Q	discharge, in cubic feet per second
r	relative humidity, dimensionless
r	subscript denoting the riser or drop inlet
r_o	radius of the pipe, in feet
r_p	distance from the centerline to the point where v_p is measured, in feet
R	gas constant, in feet per degree Rankine
R_m	gas constant of the air-water vapor mixture, in feet per degree Rankine
$\mathbb{R}$	Reynolds number, dimensionless
$\mathbb{R}_e$	Reynolds number at the barrel entrance, point e, dimensionless
s	specific humidity, pounds of vapor per pound of air
t_a	atmospheric temperature in the vicinity of the spillway inlet, in degrees Fahrenheit
t_b	temperature at the barometer, in degrees Fahrenheit
t_d	dry bulb temperature, in degrees Fahrenheit
t_m	temperature of the manometer fluid, in degrees Centigrade
t_o	temperature at the spillway outlet, in degrees Fahrenheit
t_w	wet bulb temperature, in degrees Fahrenheit
t_1	temperature just upstream from the measuring orifice, in degrees Fahrenheit
T	absolute temperature, in degrees Rankine
T_a	atmospheric temperature in the vicinity of the spillway inlet, in degrees Rankine
T_d	dry bulb temperature, in degrees Rankine
T_o	temperature at the spillway outlet, in degrees Rankine
T'_o	temperature at the spillway outlet, in degrees Kelvin
T_r	riser or drop inlet temperature, in degrees Rankine
T_w	wet bulb temperature, in degrees Rankine
T_1	temperature just upstream from the measuring orifice, in degrees Rankine
v	specific volume, in cubic feet per pound
v	subscript denoting vapor

vd	subscript denoting vapor at the temperature of the dry bulb
v_e	specific volume of air at the barrel entrance, in cubic feet per pound
v_o	specific volume of air at the barrel outlet, in cubic feet per pound
v_p	local velocity in the barrel, in feet per second
V	velocity in the barrel, in feet per second
V_a	velocity in the headpool, in feet per second
V_e	velocity at the barrel entrance, in feet per second
V_i	velocity at point i, in feet per second
V_o	velocity at the spillway outlet, in feet per second
V_{oi}	uncorrected velocity at the spillway outlet, in feet per second
V_p	velocity in the conduit, in feet per second
V_r	velocity in the riser or drop inlet, in feet per second
$\forall$	volume rate of flow, in cubic feet per second
w	specific weight of water, in pounds per cubic foot
wv	subscript used to designate water vapor
W	(actual) weight rate of flow, in pounds per second
W_t	theoretical weight rate of flow, in pounds per second
y	distance from the pipe wall, in feet
Y	expansion factor for compressible fluids, dimensionless
z_i	elevation of point i, in feet
Z	difference in elevation between the inlet crest or conduit invert at inlet and centerline of outlet, in feet
γ	specific weight, in pounds per cubic foot
γ_a	specific weight of vapor-laden air in the headpool upstream of the spillway entrance, in pounds per cubic foot
γ_a	specific weight of atmospheric air, in pounds per cubic foot
γ_{ad}	specific weight of dry air, in pounds per cubic foot
γ_e	specific weight of air at the barrel entrance, in pounds per cubic foot

γ_i	specific weight of air at point i, in pounds per cubic foot
γ_r	specific weight of air at the mid-height of the riser or drop inlet, in pounds per cubic foot
γ_o	specific weight (corrected) of air at the spillway outlet, in pounds per cubic foot
γ_{oi}	uncorrected specific weight of air at the spillway outlet, in pounds per cubic foot
γ_w	specific weight of the micromanometer fluid, in pounds per cubic foot
γ_{wv}	specific weight of water vapor required to saturate one cubic foot of air, in pounds per cubic foot
γ_1	specific weight of air upstream of the measuring orifice, in pounds per cubic foot
ν_e	kinematic viscosity at the barrel entrance, point e, in square feet per second
μ_e	absolute or dynamic viscosity at the barrel entrance, point e, in pound-seconds per square foot
Σ	mathematical symbol indicating "summation of"
0	subscript denoting a zero reading
1	subscript denoting a point just upstream from the measuring orifice
2	subscript denoting a point just downstream from the measuring orifice

HYDRAULICS OF CLOSED CONDUIT SPILLWAYS

FOREWORD

This technical paper is one of a series on the hydraulics of closed conduit spillways. Part I, giving the theory, symbols, and bibliography, appeared originally in 1952 as Technical Paper No. 12-B. It was revised in 1958. Parts II to VI, describing the hydraulic performance and presenting discharge coefficients for five forms of the closed conduit spillway, and Part VII, discussing vortices and their effect on the spillway capacity, appeared as Technical Paper No. 18-B. Parts VIII and IX, reporting tests on models of specific field structures and on field structures themselves, appeared as Technical Paper No. 19-B. Part X, reporting the development of the hood inlet, appeared as Technical Paper No. 20-B in April 1958. The present paper, Part XI of the series, discusses the use of air for tests of closed conduit spillways.

Part XI

Tests Using Air*

PRELIMINARY CONSIDERATIONS

Some of those items which should be considered before deciding whether it is desirable to substitute air for water as the test fluid will be mentioned before the use of air for tests of closed conduit spillways is discussed.

Range of Flows for which Air may be Substituted for Water

The most serious limitation in the use of air is that air tests are valid only when the conduit is completely full of a single fluid. This means that water must be used to determine the spillway characteristics when the spillway contains both water and air. Both water and air are in the spillway for weir flow, orifice flow, short tube flow, slug flow, and mixture flow. Therefore, if air is used in testing, water must be used also. On the contrary, the use of water alone is sufficient to define all the spillway characteristics and coefficients. It is apparent from these comments that strong arguments must be forthcoming if air is to be used for test purposes.

The head-discharge curves of Fig. I-5 and the illustrations of Fig. I-1 presented in Part I of this series of technical bulletins [XI-10]± will be used to show the range over which it is possible to substitute air for water.

In general, air cannot be substituted for water when there is a free surface in the spillway. Fig. I-1 shows that there is a free surface somewhere within the spillway for weir control at the entrance, for

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*Agricultural Research Service Report No. 41-304-111.

Acknowledgment: Harvey J. Johnson, hydraulic engineer, formerly USDA, ARS, assisted in the initial development of the test methods, designed the apparatus, and initially calibrated the flow-measuring orifices.

±Numbers in brackets refer to Bibliography listed on p. 47.

orifice control, and for short tube control. Water alone is used for tests when these types of control exist. Air might be substituted for water if the form of the free surface were known and a fixed boundary placed at the water surface. However, this procedure is somewhat academic for the experimental design program conducted on closed conduit spillways. A further limitation on the use of air for weir, orifice, or short tube control is that the flowing water may entrain air. The use of air alone cannot duplicate this flow condition.

Vortices, as they exist in closed conduit spillways, require a free surface. Water must be used to determine the vortex potential of a spillway. Water must also be used to evaluate the effectiveness of anti-vortex devices.

A very definite restriction on the use of air exists during two-phase flow—when both air and water are carried through the spillway. Two-phase flow frequently occurs for that portion of the weir control curve which lies a short distance to the left of the intersection of the weir and pipe curves of Fig. I-5. This flow is described in Part I of the closed conduit spillway report series [XI-10] on page 9 under the heading Appearance of the Flow and on pages 10 and 11 under the heading Intermediate Flow Conditions.

Air can be substituted for water only for those tests which cover the pipe flow portion of the head-discharge curve of Fig. I-5.

Reason for the Use of Air

Air is used for the full flow tests because preliminary examination showed that, compared with water, the experimental apparatus would be simpler, changes in the model could be made more easily, and the preparations for and conduct of each test would require considerably less time. A further advantage, discovered during the tests, is that the precision of the air tests is higher than for the water tests.

Additional apparatus was required to expedite the tests on the closed conduit spillway. The new apparatus could have been a duplicate of the water apparatus already in successful use (the fourth test setup described in Part V under the heading APPARATUS AND PROCEDURE [XI-11, pp. 27-28]). Or it could have been an apparatus of an entirely new design using air, if the limitations in the use of air could be tolerated. An examination of the test program showed that it could logically be broken up into a study of free-surface and two-phase flow phenomena, to be conducted using water, and a simultaneous study of full-flow phenomena, which might more easily be made using air.

A careful comparison was made between water and air techniques from the standpoint of the physical requirements of the apparatus and its operating characteristics. These considerations are discussed along with other comparisons made possible by subsequent experience with an air model.

The water apparatus occupies two floor levels and would require at least one additional floor if special constant level tanks had not been installed. A large reservoir is required to hold the supply of water treated with rust preventative and maintain it at room temperature. The channel in which the drop inlet is located has to be quite large to provide satisfactory approach conditions. Heavy supports for the channel are therefore required. In contrast, the air apparatus can be located on a single floor using a fan to suck air through the spillway. The room itself can serve both as the approach to the drop inlet and as the "storage reservoir," thus eliminating the need to build these two large appurtenances. Support is required only for the spillway itself, since its contents are weightless for all practical purposes. The experimental apparatus is consequently simpler for air than for water.

To change the slope of the barrel when water is used, it is necessary to separate the barrel from the approach channel, set the desired slope, and insert a new watertight connection with the approach channel. When air is used, the barrel can be left in a permanent position and the effect of different slopes obtained by changing the angle between the inlet and the barrel—something which has to be done for the water model also in addition to changing the barrel slope. Changes in the inlet are easier to make in the air model because modeling clay is adequate to seal and hold the change in place instead of the screws and cement required to sustain the higher water pressures. Another simplification is that the time-consuming determination of piezometer zeros is eliminated when air is the model fluid. Because model changes are easier and faster when air is used, much more time can be devoted to testing.

The test program calls for a large number of generalized tests to determine the full-flow loss coefficients for the drop inlet and pressure coefficients for the horizontal plate, end walls, and side walls of the drop inlet. Initially, pressures were to be measured at nearly 100 points in the drop inlet and barrel. If the test fluid were water, the problem of bleeding each line before each test would be formidable. There would also be the ever-present possibility of random vortices admitting air to the pressure lines and causing undetected errors. With air as the test fluid and the pressure lines also full of air, the tedious and time-consuming bleeding would be unnecessary. The errors due to air becoming trapped in the pressure tubing would be eliminated also. These practical laboratory conditions alone are sufficient to warrant the substitution of air for water as the test fluid.

It was found that fewer air tests than water tests were required on each modification of the drop inlet to satisfactorily evaluate the loss and pressure coefficients. Due to natural fluctuations, eight to ten runs with water are required to obtain good averages of the coefficients. The smaller variation between the air coefficients computed for different runs permits a two-thirds reduction in the number of runs required to obtain satisfactory averages.

The Reynolds number covered a very narrow range for the water tests so that any effect of Reynolds number was hidden in the natural experimental fluctuations. The Reynolds number for the air tests covered a wider range and its effect on the coefficients was readily apparent.

The practical advantages of using air are seen to be sufficient to overcome the restriction that the use of air is limited to full pipe flow. Experience has shown the soundness of the decision to use air to evaluate the loss and pressure coefficients.

Previous Use of Air

Some of the experiences of others who have substituted air for water for tests of hydraulic structures will be mentioned. No thorough search of the literature has been attempted; the appended bibliography lists only papers that were readily available to the authors.

According to Theodor von Karman [XI-36] the analogy between two-dimensional open channel flow in water and in air was first presented by Emile Jouguet. Publications referred to by Jouguet in a 1920 article [XI-19] indicate that he was aware of this analogy shortly after the beginning of the 20th century. In the 1930's, Dimitri Riabouchinsky extended the theory [XI-28]. These efforts were apparently directed to the use of water to simulate air flow.

The earliest comparison of water and air tests to come to the attention of the authors is that reported by H. F. Schmidt in 1930 [XI-34]. Schmidt made a study of ship condenser scoops using both water and air. He reports: "The tests with water . . . check with the tests run with air to a degree which was within the limits of the error of observation." His range of air velocities was from 100 to 350 feet per second.

Air was used to test hydraulic machines in the 1930's. Quinones reported water and air tests of pumps. These tests were conducted at Rensselaer Polytechnic Institute and were reported in 1934 [XI-26]. The writings of C. Keller [XI-21, XI-22, and XI-23] describe the successful use of aerodynamic laboratories for tests of hydraulic machinery by the Swiss firm Escher Wyss. American firms, such as the Newport News Shipbuilding and Drydock Company, also use air to test hydraulic machinery.

The first reported substitution of air for water in the field of civil engineering was made at the State University of Iowa. Rouse [XI-32] made the initial report and cited some of the advantages of using air. Appel [XI-6, discussion] extends Rouse's comments, elicits confidence in the substitution of air for water, and cites a number of experiments performed at the State University of Iowa.

A general article on the use of air for testing hydraulic models was presented by Ball in 1952 [XI-6]. Ball's ". . . paper was written from the hydraulic point of view for engineers who are fearful of using compressible fluid data for solving problems relating to incompressible flow. . . . It is intended to encourage the use of air tests. . . ." He lists a number of successful applications of air to different types of hydraulic problems.

An interesting French substitution of air for water is reported by G. Remenieras [XI-27] and P. Bourguignon [XI-13]. Remenieras' article gives the criteria for the use of air to determine the capacity of a power tunnel while Bourguignon's article presents values of the friction factor based on both air and water tests. Along this same line, laboratory experiments using both water and air to determine pipe friction were made by Hablützel [XI-16] at the Cantonal Technical College, Winterthur, Switzerland.

Although it is generally considered that free surface flows cannot be simulated using air, there are exceptions to this general statement. M. Kahan and S. Hâncu [XI-20] cite the use in Romania of very small scale (1/1000 to 1/5000) aerodynamic models of rivers and hydrotechnical works. They also discuss movable bed aerodynamic models. The free surface of the flow is represented by a rigid wall. Rouse, Siao, and Nagaratnam [XI-33, p. 926] also used this method in a study of the hydraulic jump; they fitted a rigid plate to the shape of the surface of the hydraulic jump so turbulence measurements could be made using air. For tests of a valve, Ball [XI-6, p. 832] found it necessary to install an additional piezometer to correct for the fact that the air tests represented a submerged condition whereas the water flow would be into free air. It is thus apparent that free surface water flows can sometimes be studied using air as the fluid.

Studies of gates have been made by the U. S. Bureau of Reclamation. Simmons [XI-35] used air alone to determine the hydraulic downpull on gates. Some of these tests involved free discharge downstream of the gate. Ball [XI-7] studied the pressures and the cavitation potential in the vicinity of gate slots using both water and air. Excellent agreement was obtained where comparisons could be made.

A study of these papers shows that air can be successfully substituted for water to make many tests of hydraulic structures and hydraulic machinery. Conversely, water can be substituted for air to make aerodynamic tests.

EQUATIONS

The equations required to determine the entrance loss and pressure coefficients, and to evaluate the physical quantities entering into these equations are presented. An example of the solution of these equations using both desk and digital computers is given.

Comparison of Water and Air Equations

The objective of the experiment using air is the determination of the entrance loss and pressure coefficients for various forms and proportions of closed conduit spillways. Equations for these coefficients will be developed from basic considerations. Throughout the development, the terms applying to incompressible (water) flow will be compared with those applying to compressible (air) flow. Reference will be made to Part I of this report series [XI-10] where such reference will facilitate the explanation. Evaluation of the various quantities entering into the equations will be presented under the heading Evaluation of Quantities. Only the basic equations required to determine the coefficients for water and air will be compared in this section.

Entrance Loss Coefficient

The equation for full flow through closed conduit spillways can be developed from the Bernoulli theorem. The Bernoulli equation, written between the surface of the headpool (point a) and the unsubmerged exit of the closed conduit spillway (point o), is, for water,

$$\frac{V_a^2}{2g} + \frac{p_a}{w} + H_t = K_o \frac{V_o^2}{2g} + \frac{p_o}{w} + K_e \frac{V_o^2}{2g} + \ldots + f \frac{\ell}{D} \frac{V_o^2}{2g} \qquad \text{(XI-1)}$$

where V_a and V_o are the velocities in the headpool and at the spillway outlet in feet per second, g is the acceleration due to gravity in feet per second per second, p_a and p_o are the pressures in the headpool and at the spillway outlet in pounds per square foot, w is the unit weight of water in pounds per cubic foot, H_t is the total head causing flow—the difference in elevation between the headpool water surface and the point at which the hydraulic grade line pierces the plane of the spillway exit—in feet, K_e is the dimensionless entrance loss coefficient, K_o is the dimensionless outlet loss coefficient, f is the dimensionless Darcy-Weisbach friction factor, ℓ is the length of the conduit in feet, and D is the diameter of the conduit in feet. The ellipses in Eq. XI-1 indicate that if there are other sources of energy loss, terms for these losses must be added to the right side of the equation. These additional sources of energy loss might be the friction loss in the drop inlet or bends in the barrel. Additional information on the terms in Eq. XI-1 will be found in Part I, pages 5 to 6.

The velocity in the headpool V_a is so low that it is assumed to be zero. The first term of Eq. XI-1 thus can be dropped.

(For water, p_a and p_o are both equal to the atmospheric pressure and cancel from Eq. XI-1. Making this substitution, noting that V_o is identical to V_p, and considering the comments of the preceding paragraph, Eq. XI-1 becomes identical to Eq. I-4.)

No term for friction loss in the drop inlet is included in Eq. XI-1 because this loss is so small that it can be neglected in the usual case.

All terms of Eq. XI-1 are expressed in feet of water. For the flow of air, it is more convenient to express the terms in pounds per square foot because the specific weight changes as the air passes through the spillway. The units of Eq. XI-1 can be changed to pounds per square foot if each term is multiplied by the specific weight of water w Dropping the first term and multiplying by w, Eq. XI-1 becomes

$$\left[p_a + wH_t = K_o w \frac{V_o^2}{2g} + p_o + K_e w \frac{V_o^2}{2g} + \ldots + f \frac{\ell}{D} w \frac{V_o^2}{2g} \right]_{\text{water}} \qquad \text{(XI-2)}$$

Each term in Eq. XI-2, which is valid for water, will be explained and compared with the corresponding term for air.

A fundamental difference between the water and air models of the closed conduit spillway is the source of the force which causes the flow. Flow in the water model is caused by the gravity force wH_t whereas flow in the air model is caused by the force $(p_a - p_o)$ developed by a blower. For the water model, the force $(p_a - p_o)$ is zero and for the air model the force $\gamma_a H_t$ is zero, where γ_a, the specific weight of atmospheric air, is substituted for the specific weight of water w. Since the spillway is not concerned with whether the force causing flow is developed by gravity or by a pump, the terms

$$\left[p_a - p_o + wH_t \right]_{\text{water}} = \left[wH_t \right]_{\text{water}} \qquad \text{(XI-3)}$$

for water correspond to

$$\left[p_a - p_o + \gamma_a H_t\right]_{air} = \left[p_a - p_o\right]_{air} \qquad \text{(XI-4)}$$

for air.

The reasoning behind Eqs. XI-3 and XI-4 will be explained in greater detail. There is a vertical drop of H_t through the water model. The force of gravity, acting through this drop, provides wH_t pounds per square foot to cause flow in the water model. Because the air model is horizontal, H_t is zero and there is no gravity force to cause flow. But a blower is provided to suck air through the air model so that atmospheric pressure p_a exists upstream of the spillway inlet and less than atmospheric pressure p_o exists at the spillway outlet. The difference in pressure, $(p_a - p_o)$ pounds per square foot, is the force which causes flow through the air model. For the water model there is atmospheric pressure at both the inlet and the outlet, so $(p_a - p_o)$ is zero for the water model. The force which causes flow in the water and air models is thus seen to derive from a different source. The source of the force causing flow is not important. What is important is that there must be a force to cause flow and that the researcher must be able to evaluate the force term in the flow equation.

The outlet loss coefficient K_o is assumed to be 1 for closed conduit spillways. Any errors resulting from this assumption are accumulated in K_e because K_e represents a residual loss after all specifically assigned losses are accounted for. The exit loss coefficient is dimensionless and has an identical numerical value for both water and air flows.

The term $wV_o^2/2g$ is the specific weight of water multiplied by the velocity head at the spillway outlet. The corresponding term for air is $\gamma_o V_o^2/2g$ where γ_o is the specific weight of air at the spillway outlet and $V_o^2/2g$ is the velocity head at the spillway outlet. Thus the term

$$\left[w \frac{V_o^2}{2g}\right]_{water} \qquad \text{(XI-5)}$$

for the water model corresponds to

$$\left[\gamma_o \frac{V_o^2}{2g}\right]_{air} \qquad \text{(XI-6)}$$

for the air model. Because water is incompressible, w is a constant. However, because air is compressible, γ_o is not a constant. In the air model γ_o varies with V_o. For example, to increase the flow and V_o, the blower must decrease the pressure at the barrel exit (point o). As a result, the air will expand and γ_o will decrease.

The entrance loss term in Eq. XI-2, $K_e wV_o^2/2g$, is correct for the water model because water is incompressible and the velocity V_o is constant at all points along the barrel; for water, the velocity at the barrel entrance V_e is the same as the velocity at the barrel outlet V_o. This is not true for air because the pressure drops, the air expands, and the velocity increases with distance along the barrel. Conditions at the barrel entrance (point e) determine the entrance loss. Therefore, the entrance loss term for air is

$$K_e \gamma_e \frac{V_e^{\,2}}{2g} \qquad \text{(XI-7)}$$

However, when computing the experimental data it is more convenient to use the conditions at the barrel outlet. The specific weight of air at the barrel entrance γ_e and the velocity at the barrel entrance V_e can be related to the specific weight and velocity at the barrel outlet through the equation of state for a perfect gas,

$$pv = RT \qquad \text{(XI-8)}$$

where p is the absolute pressure in pounds per square foot, v is the specific volume in cubic feet per pound, R is the gas constant in feet per degree Rankine, and T is the absolute temperature in degrees Rankine. Isothermal conditions are assumed to exist along the spillway barrel, that is, between point e and point o; it will be assumed that the amount of heat employed in doing useful work—moving the fluid through the barrel—is equal to the heat transmitted through the conduit walls and absorbed by the gas. Since the gas will be at less than atmospheric pressure and at less than ambient temperature because it expands as it is drawn through the spillway, this assumption is valid as a first approximation. This means that T is constant along the barrel and that the product RT in Eq. XI-8 is also constant at all points along the barrel. Therefore

$$p_e v_e = p_o v_o = RT = \text{constant} \qquad \text{(XI-9)}$$

where the subscripts e and o refer to the barrel entrance and outlet. Since $v = 1/\gamma$,

$$\frac{p_e}{\gamma_e} = \frac{p_o}{\gamma_o} \qquad \text{(XI-10)}$$

and

$$\gamma_e = \frac{p_e}{p_o} \gamma_o \qquad \text{(XI-11)}$$

This is the substitution for γ_e in Eq. XI-7.

The substitution for V_e in Eq. XI-7 will now be derived. The velocity V in the barrel in feet per second is equal to the volume rate of flow Ꝟ in cubic feet per second divided by the barrel area A in square feet; $V = \text{Ꝟ}/A$ or $\text{Ꝟ} = AV$. Also, the volume rate of flow Ꝟ is equal to the product of the weight rate of flow W in pounds per second and the specific volume v in cubic feet per pound; $\text{Ꝟ} = Wv$ or $v = \text{Ꝟ}/W$. Substituting these values into Eq. XI-8 and rearranging,

$$pV = WRT/A \qquad \text{(XI-12)}$$

Since A and W as well as R and T are constant at all points along the barrel,

$$p_e V_e = p_o V_o = WRT/A = \text{constant} \qquad \text{(XI-13)}$$

and

$$V_e = \frac{p_o}{p_e} V_o \tag{XI-14}$$

Substituting Eqs. XI-11 and XI-14 into Eq. XI-7 and reducing gives

$$\left[K_e \gamma_o \frac{p_o}{p_e} \frac{V_o^{\,2}}{2g} \right]_{air} \tag{XI-15}$$

for the air model, which corresponds to

$$\left[K_e \, w \frac{V_o^{\,2}}{2g} \right]_{water} \tag{XI-16}$$

for the water model. The only difference between the incompressible (water) Eq. XI-16 and the compressible (air) Eq. XI-15 is the correction for the difference in specific weights at the entrance and outlet of the barrel when the fluid is compressible.

The friction loss term in Eq. XI-2 is the last one to be compared. This term represents the loss in head or pressure in the conduit due to friction alone. It cannot be evaluated by simply measuring the local pressures at the two ends of the barrel because the pressures at the entrance and in the upstream portion of the barrel are affected by the entrance. Therefore, in conducting experiments with either water or air, the rate of friction energy loss must be determined downstream of the region affected by the entrance. The rate of friction energy loss—the slope of the friction grade line—so determined is projected to the barrel entrance. This is so the pressure at the barrel entrance p_e can be computed as if there had been only friction losses—so that the energy losses caused by friction can be separated from the losses caused by the entrance. The pressure at the barrel outlet—a point on the friction grade line—is p_o. The difference $(p_e - p_o)$ is the loss in pressure along the barrel caused by friction. Therefore, the friction loss term in Eq. XI-2,

$$\left[f \frac{\ell}{D} w \frac{V_o^{\,2}}{2g} \right]_{water} = \left[p_e - p_o \right]_{water} \tag{XI-17}$$

for water, corresponds to

$$\left[p_e - p_o \right]_{air} \tag{XI-18}$$

for air.

Substituting in the rearrangement of Eq. XI-2 for water,

$$\left[w H_t = w \frac{V_o^2}{2g} + K_e w \frac{V_o^2}{2g} + \ldots + f \frac{\ell}{D} w \frac{V_o^2}{2g} \right]_{water} \qquad \text{(XI-2a)}$$

or

$$\left[w H_t = w \frac{V_o^2}{2g} + K_e w \frac{V_o^2}{2g} + \ldots + p_e - p_o \right]_{water} \qquad \text{(XI-2b)}$$

the values for air given by Eqs. XI-4, XI-6, XI-15, and XI-18, the corresponding equation for air is obtained.

$$\left[p_a - p_o = \gamma_o \frac{V_o^2}{2g} + K_e \gamma_o \frac{p_o}{p_e} \frac{V_o^2}{2g} + \ldots + p_e - p_o \right]_{air} \qquad \text{(XI-19)}$$

If Eqs. XI-2b and XI-19 are solved for V_o and multiplied by the barrel area A, equations for the discharge of the spillway will be obtained.

An objective of the experiments is to determine the entrance loss coefficient K_e. Solution of Eqs. XI-2a, XI-2b, and XI-19 for K_e gives

$$K_e = \left[\frac{H_t}{V_o^2/2g} - 1 - f \frac{\ell}{D} \right]_{water} \qquad \text{(XI-20a)}$$

or

$$K_e = \left[\frac{H_t}{V_o^2/2g} - 1 - \frac{p_e - p_o}{w V_o^2/2g} \right]_{water} \qquad \text{(XI-20b)}$$

for water and

$$K_e = \left[\left(\frac{p_a - p_o}{\gamma_o V_o^2/2g} - 1 - \frac{p_e - p_o}{\gamma_o V_o^2/2g} \right) \frac{p_e}{p_o} \right]_{air} \qquad \text{(XI-21a)}$$

or

$$K_e = \left[\left(\frac{p_a - p_e}{\gamma_o V_o^2/2g} - 1 \right) \frac{p_e}{p_o} \right]_{air} \qquad \text{(XI-21b)}$$

for air. In Eqs. XI-20 and XI-21, identical values of K_e are obtained regardless of whether a compressible fluid (air, for example) or an incompressible fluid (water) is used to make the determination. Conversely, the value of K_e computed from Eqs. XI-21 using data obtained on the air model may be used in Eq. I-5 [XI-10] to determine the capacity of a geometrically similar closed conduit spillway in which the fluid is water.

Pressure Coefficients

Pressure coefficients are required for both the hydraulic and structural design of closed conduit spillway drop inlets and barrels. The equations used to evaluate these coefficients will be given for water and then modified for use with air.

Barrel Pressure Coefficients. The barrel pressure coefficient has been derived and its meaning and use explained in Part I [XI-10], pages 11 to 14. In Eq. I-13, h_n and h_{vp} are expressed in feet of water. Multiplying the numerator and denominator by w makes it possible to express the pressures p_n and p_{vp} in pounds per square foot. The ratios h_n/h_{vp} and p_n/p_{vp} are dimensionless and have identical values for any particular point i along the barrel. Therefore, it makes no difference whether the pressures are measured in feet of water or pounds per square foot. However, the latter units are more convenient to use when the fluid is air.

Eq. I-12, expressed in pounds per square foot at point i, is

$$\left[w\,h_{ni} = w\,h_{pi} + w\,z_i + w\,h_{fi}\right]_{water} \qquad \text{(XI-22a)}$$

or

$$\left[p_{ni} = p_{pi} + w\,z_i + p_{fi}\right]_{water} \qquad \text{(XI-22b)}$$

Each term of Eq. XI-22b, which applies to water, will be explained and compared with a corresponding term for air.

The explanation of p_n for either water or air is identical to the explanation of h_n which follows Eq. I-12 in Part I. Its value is obtained from Eq. XI-22b.

The pressure term p_{pi} is the piezometric pressure at point i. It is measured by piezometers and water manometers in both the water and air models and is converted to pounds per square foot.

The elevation of point i, z_i, is zero for the horizontal air model. For the water model, z_i is the difference in elevation between the outlet centerline and the piezometer at point i.

The term p_{fi} is the friction grade line pressure at point i. Since point i is upstream of the outlet, p_{fi} is negative.

When these values for air are substituted for the water values in Eq. XI-22b, the air equation becomes

$$\left[p_{ni} = p_{pi} + p_{fi}\right]_{air} \qquad \text{(XI-23)}$$

The denominator for h_n in Eq. I-13 is p_{vp}, the velocity pressure in the barrel in pounds per square foot. For water, this is constant along the barrel. Therefore, for water,

$$\left[p_{vp} = p_{vi} = w\frac{V_i^2}{2g} = w\frac{V_o^2}{2g}\right]_{water} \tag{XI-24}$$

For air, the velocity pressure varies along the barrel. The velocity pressure at point i, p_{vi}, is taken as the denominator for the air model. This velocity pressure at point i in terms of the conditions at the spillway outlet is obtained from Eqs. XI-11 and XI-14 by substituting the subscript i or pi for the subscript e. Therefore, for air

$$\left[p_{vi} = \gamma_i\frac{V_i^2}{2g} = \gamma_o\frac{p_o}{p_{pi}}\frac{V_o^2}{2g}\right]_{air} \tag{XI-25}$$

The equations for the pressure coefficients along the barrel therefore are

$$\left[\frac{p_{ni}}{p_{vi}} = \frac{p_{pi} + w z_i}{w V_o^2/2g} + f\frac{\ell_i}{D}\right]_{water} \tag{XI-26}$$

for water and

$$\left[\frac{p_{ni}}{p_{vi}} = \frac{p_{pi} + p_{fi}}{\gamma_o\dfrac{p_o}{p_{pi}}\dfrac{V_o^2}{2g}}\right]_{air} \tag{XI-27}$$

for air. The only significant differences between these equations are the elevation term in Eq. XI-26, wz_i, which does not appear in Eq. XI-27 because the barrel is horizontal, and the correction for compressibility in the denominator of Eq. XI-27.

Drop Inlet Pressure Coefficients. Pressure coefficients for the drop inlet p_{ni}/p_{vr} are obtained differently than are the pressure coefficients for the barrel.

A major difference is that friction losses are neglected in the drop inlet because they are small.

A second difference is that the pressures are related to the velocity head or velocity pressure in the riser p_{vr}. For water

$$\left[p_{vr} = w\frac{V_r^2}{2g} = w\frac{(Q/A_r)^2}{2g}\right]_{water} \tag{XI-28}$$

where Q is the discharge in cubic feet per second, A_r is the drop inlet area in square feet and V_r is the velocity in the drop inlet in feet per second. The corresponding equation for air is

$$\left[p_{vr} = \gamma_r \frac{V_r^2}{2g} = \frac{(W/A_r)^2}{\gamma_r 2g} \right]_{air} \tag{XI-29}$$

where W is the discharge in pounds per second and γ_r is the specific weight of air in the drop inlet in pounds per cubic foot.

The symbol Δp_{ni} denotes the difference between the measured pressure at point i, p_{pi}, and the pressure at the same elevation in the headpool. For water, the headpool pressure at the elevation of point i is $w(Z - z_i + H) + p_a$ pounds per square foot. For air, the inlet is laid on its side, the values of γ_a and $(Z - z_i + H)$ are small, their product is so small it can be neglected, and the headpool pressure at the elevation of point i is taken as p_a. The drop inlet pressure coefficients thus become

$$\left[\frac{\Delta p_{ni}}{p_{vr}} = \frac{p_{pi} - [w(Z - z_i + H) + p_a]}{w(Q/A_r)^2/2g} \right]_{water} \tag{XI-30}$$

for water and

$$\left[\frac{\Delta p_{ni}}{p_{vr}} = \frac{p_{pi} - p_a}{(W/A_r)^2/\gamma_r 2g} \right]_{air} \tag{XI-31}$$

for air. The difference between these equations is the result of considering the static pressure at the piezometer elevation for the water model and correcting the specific weight for compressibility for the air model.

Evaluation of Quantities

The quantities such as specific weight, velocity, discharge, and pressure used to solve Eq. XI-21b for the entrance loss coefficient and Eqs. XI-27 and XI-31 for the pressure coefficients must be evaluated. Only that information required to evaluate the air quantities will be presented.

Dimensions

The dimensions of the structure which must be measured are:

1. The diameter, in inches, of the flow-measuring orifice D_2
2. The diameter, in feet, of the
   - a. barrel (nominal) D
   - b. barrel at its outlet D_o
   - c. barrel at its entrance D_e
   - d. barrel at each piezometer D_i

3. The length, in feet, from the upstream end of the barrel (point e) to the
    a. outlet ℓ_o
    b. location of each piezometer ℓ_i
4. The cross-sectional area, in square feet, of the
    a. drop inlet or riser A_r
    b. barrel at the spillway outlet A_o
    c. barrel just upstream from the flow-measuring orifice A_1
    d. flow-measuring orifice A_2

Temperatures

Some temperatures are observed; others are computed. Observed temperatures are measured with mercury thermometers in Centigrade or Fahrenheit degrees. Most of the temperatures must be converted to absolute temperatures for use in the gas equations. The conversion equations are:

$$\text{degrees Rankine } (^\circ\text{R}) = \text{degrees Fahrenheit } (^\circ\text{F}) + 459.7. \tag{XI-32}$$

$$\text{degrees Kelvin } (^\circ\text{K}) = \text{degrees Centigrade } (^\circ\text{C}) + 273.2 \tag{XI-33}$$

The atmospheric temperature T_a is measured to 0.1° R in the vicinity of the closed conduit spillway inlet with a mercury thermometer having 0.2° F graduations.

The manometer fluid temperature t_m is estimated to 0.1° C with a mercury thermometer having 1° C graduations.

The barometer temperature t_b is read to 1° F from an attached thermometer having 2° F graduations.

The spillway outlet temperature T_o (°R) or T'_o (°K) is measured by a thermometer whose bulb is inserted into the barrel in the vicinity of the outlet. The temperature is read to 0.1° F from a scale having 0.2° F graduations.

The dry bulb temperature t_d or T_d and the wet bulb temperature t_w or T_w of an aspirator psychrometer are read to 0.5° F from scales having 1° F graduations.

The drop inlet or riser temperature T_r is lower than the atmospheric temperature. It is computed from the equation

$$T_r = T_a \left(\frac{p_r}{p_a}\right)^{\frac{k-1}{k}} \tag{XI-34}$$

on the assumption that the air expands adiabatically as it passes from the "headpool" into the drop inlet.

Pressures

Those pressures which are observed are measured by a mercury barometer or by a water micromanometer. Other pressures are computed.

The atmospheric pressure p_a is measured in the room containing the closed conduit spillway. The bulb of the barometer is at the elevation of the barrel.

The height of the mercury barometer column B_u is read by vernier to 0.01 inch. An attached thermometer is read to 1° F to give the barometer temperature t_b. A temperature correction table is furnished by the manufacturer to correct the observed reading to the standard 62° F temperature for the barometer scale and 32° F temperature for the mercury. The table is prepared for a latitude of 45°—the latitude of Minneapolis, Minnesota, where the experiments were performed.

The equation for the corrected barometer reading B, developed from the table to facilitate its use by a digital computer, is

$$B = B_u - (1.72727 - 2.63636\,B_u) \times 10^{-3} - (90.91\,B_u t_b - 18.18\,t_b) \times 10^{-6} \qquad \text{(XI-35)}$$

The conversion factor from inches of mercury to pounds per square foot is 70.73 [XI-18, p. 1934]. Therefore

$$p_a = 70.73\,B \qquad \text{(XI-36)}$$

Piezometric pressures at points i in the closed conduit spillway p_{mi} are measured by a water micromanometer. The micromanometer is read by vernier to 0.001 foot of water. The micromanometer zero reading h_{oi} is subtracted from the height of the water column for each pressure measurement h_{mi} to give the observed pressure head in feet of water. This is multiplied by the micromanometer fluid specific weight γ_w to convert the pressure to pounds per square foot. In mathematical symbols, this reads $(h_{mi} - h_{oi})\gamma_w$. Since one leg of the micromanometer is open to the atmosphere, the atmospheric pressure p_a is added so the pressure will be in absolute units. Therefore

$$p_{mi} = p_a + (h_{mi} - h_{oi})\,\gamma_w \qquad \text{(XI-37)}$$

pounds per square foot absolute.

Corrected piezometric pressures at points i in the barrel p_{pi} are required because the barrel is not of exactly uniform diameter. This is accomplished by adding algebraically to the observed pressure p_{mi} a correction based on the velocity pressure at the point under consideration p_{vi} and the fourth power of the ratio D_i/D_o. The corrected observed pressure is

$$p_{pi} = p_{mi} + \left(1 - \frac{D_i^4}{D_o^4}\right) p_{vi} \qquad \text{(XI-38)}$$

pounds per square foot absolute. The terms $(1 - D_i^4/D_o^4)$ are constants for the experimental apparatus.

The velocity pressure at each barrel piezometer p_{vi} related to conditions at the spillway outlet can be obtained from Eq. XI-15 by dropping K_e and substituting the subscript i for the subscript e.

This gives

$$p_{vi} = \gamma_{oi} \frac{p_{oi}}{p_i} \frac{V_{oi}^2}{2g} \tag{XI-39}$$

pounds per square foot absolute.

The pressure at the outlet p_{oi} is the value of p_{pi} at ℓ_o from the barrel entrance. In Eq. XI-38, $D_i = D_o$ from which $p_{oi} = p_{pi}$.

The computed barrel pressure p_{fi} is obtained from the equation

$$p_{fi} = a + b\ell_i \tag{XI-40}$$

pounds per square foot which represents the equation for the pressures p_{pi} in the barrel downstream of the region of influence of entrance disturbances. It is the equation of the friction grade line—the hydraulic grade line beyond the range of entrance effects. The constants a and b are determined by least squares methods using the equations

$$a = \frac{\Sigma \ell_i^2 \ \Sigma p_{pi} - \Sigma \ell_i \ \Sigma \ell_i p_{pi}}{N \Sigma \ell_i^2 - (\Sigma \ell_i)^2} \tag{XI-41}$$

and

$$b = \frac{N \Sigma \ell_i p_{pi} - \Sigma \ell_i \ \Sigma p_{pi}}{N \Sigma \ell_i^2 - (\Sigma \ell_i)^2} \tag{XI-42}$$

where N is the number of observations. Because of the effect of entrance disturbances on the friction grade line, piezometers closer than 20 D to the entrance were not used when solving Eqs. XI-41 and XI-42.

The barrel outlet pressure p_o is the Eq. XI-40 value of p_{fi} at the point where $\ell_i = \ell_o$.

The barrel entrance pressure p_e is the Eq. XI-40 value of p_{fi} at the point where $\ell_i = 0$. Solution of Eq. XI-40 at $\ell_i = 0$ shows that

$$p_e = a \tag{XI-43}$$

pounds per square foot absolute.

The barrel pressure difference Δp_i is the difference between the corrected observed pressure p_{pi} computed by Eq. XI-38 and the friction grade line pressure for the same point p_{fi} computed by Eq. XI-40. In equation form,

$$\Delta p_i = p_{pi} - p_{fi} \tag{XI-44}$$

pounds per square foot absolute.

The drop inlet or riser pressure difference Δp_{ni} is the difference in pressure between point i in the drop inlet and the atmosphere. Since the two micromanometer legs are exposed to pressures in the atmosphere and at point i, the micromanometer reading gives Δp_{ni} directly in feet of water. The equation is

$$\Delta p_{ni} = (h_{oi} - h_{mi})\,\gamma_w \tag{XI-45}$$

pounds per square foot absolute.

The velocity pressure in the drop inlet or riser p_{vr} is

$$p_{vr} = \frac{(W/A_r)^2}{2g\,\gamma_r} \tag{XI-46}$$

pounds per square foot absolute.

The pressure upstream of the measuring orifice p_1 is measured by the micromanometer. Its equation is

$$p_1 = p_a + (h_{m1} - h_{01})\,\gamma_w \tag{XI-47}$$

pounds per square foot absolute.

The pressure downstream of the measuring orifice p_2 is the sum of p_1 and the drop in pressure across the orifice measured by the micromanometer. Its equation is

$$p_2 = p_1 + (h_{m2} - h_{02})\,\gamma_w \tag{XI-48}$$

pounds per square foot absolute.

The pressure of saturated vapor p_w is given by the Marks equation [XI-17] as

$$\log p_w = 12.67371 - \frac{4873.7}{T_w} - 4.051 \times 10^{-3}\, T_w + 1.393 \times 10^{-6}\, T_w^{\,2} \tag{XI-49}$$

where p_w is in pounds per square foot.

A comparison was made of the values of p_w computed using Eq. XI-49 with values listed in tables published by Marks' [XI-8, p. 4-83, Table 1] and Marvin [XI-24, pp. 24-32, Table II]. The comparison shows that within the 50° F to 80° F range of temperatures likely to occur during the tests, the agreement with Marks' table is within 0.1 per cent and the agreement with Marvin's table is within 0.9 per cent.

The vapor pressure of the air-water vapor mixture p_v is given by Marks' [XI-8, p. 4-83, Eq. (1)] as

$$p_v = p_w - \frac{p_a\,(t_d - t_w)}{2700} \tag{XI-50}$$

pounds per square foot.

The vapor pressure at the dry bulb temperature p_{vd} is given by Eq. XI-49 when the subscript vd is substituted for the subscript w.

The pressure at the mid-height of the drop inlet p_r is given by Eq. XI-37 when the subscript r is substituted for the subscript i.

Specific Weights

The specific weight (weight per cubic foot) of the fluid is required at a number of points in the experimental setup.

The specific weight of the manometer fluid γ_w is the specific weight of water, since the manometer fluid was distilled water to which 0.2 per cent of Aerosol OT was added to reduce the surface tension and a little red food dye was added to make the fluid readily visible. The specific weight of the fluid (water) was obtained from U. S. Bureau of Standards Circular No. 19, "Standard Density and Volumetric Tables" [XI-3]. An equation was developed from Table 34 because the experimental data were to be analyzed by a digital computer. The equation is

$$\begin{aligned}\gamma_w &= 62.5059 - 0.01800\,(t_m - 4) - 127 \times 10^{-6}\,(t_m - 4)^2 + 186 \times 10^{-9}\,(t_m - 4)^3 \\ &= 62.5759 - 0.01698\,t_m - 129 \times 10^{-6}\,t_m^{\,2} + 186 \times 10^{-9}\,t_m^{\,3}\end{aligned} \tag{XI-51}$$

pounds per cubic foot. This equation gives values of γ_w to within 0.3 per cent of the table values for temperatures between 0° C and 100° C.

The specific weight of vapor-laden air in the headpool upstream of the spillway entrance γ_a is given by Marks' [XI-8, p. 4-83, Eq. (7)] as

$$\gamma_a = \frac{p_a - 0.38\,p_v}{R_m\,T_a} \tag{XI-52}$$

pounds per cubic foot.

The uncorrected specific weight of air at the spillway outlet γ_{oi} is obtained from conditions in the headpool (point a) and the equation of state for a perfect gas (Eq. XI-8) with the substitution of $1/\gamma$ for v (as used in Eq. XI-10),

$$\frac{p_a}{\gamma_a T_a} = R = \text{constant} = \frac{p_{oi}}{\gamma_{oi}\,T_o} \tag{XI-53}$$

Solving for γ_{oi}, the equation is

$$\gamma_{oi} = \gamma_a \frac{p_{oi}}{p_a} \frac{T_a}{T_o} \tag{XI-54}$$

pounds per cubic foot.

The <u>specific weight of air at any point i in the barrel</u> γ_i is given by the equation

$$\gamma_i = \frac{p_i}{p_{oi}} \gamma_{oi} \tag{XI-55}$$

pounds per square foot. This relation is similar to that given by Eq. XI-54 except for the temperature ratio, which becomes 1 for the isothermal flow assumed in the barrel.

The <u>corrected specific weight of air at the spillway outlet</u> γ_o, assuming that the temperature T_o remains unchanged, is obtained from Eq. XI-55 when the subscript o is substituted for the subscript i so

$$\gamma_o = \frac{p_o}{p_{oi}} \gamma_{oi} \tag{XI-56}$$

pounds per cubic foot. This correction is necessary to adjust conditions to those given by the least squares equation, Eq. XI-40.

The <u>specific weight of air at the barrel entrance</u> γ_e is obtained from Eq. XI-56 by substituting the subscript e for the subscript o and the subscript o for the subscript oi.

The <u>specific weight of air at the mid-height of the drop inlet</u> γ_r is obtained from Eq. XI-54 by substituting the subscript r for the subscripts oi and o.

The <u>specific weight of air upstream of the measuring orifice</u> γ_1 is obtained from Eq. XI-54 by substituting the subscript 1 for the subscript oi. In solving this equation, T_1 is assumed to be equal to T_o.

The <u>specific weight of dry air</u> γ_{ad} is given by Marks' [XI-8, p. 4-83, Eq. (5)] as

$$\gamma_{ad} = \frac{1}{53.30} \frac{p_a - p_v}{T_a} = 0.01876 \frac{p_a - p_v}{T_a} \tag{XI-57}$$

pounds per cubic foot.

The <u>specific weight of water vapor required to saturate one cubic foot of air</u> γ_{wv} is obtained from Marks' [XI-8, p. 4-83, Eqs. (4), (5), and (6)] as

$$\gamma_{wv} = \frac{1}{85.81} \frac{p_v}{T_a} = 0.01165 \frac{p_v}{T_a} \tag{XI-58}$$

pounds per cubic foot.

Velocities

The velocity at a number of points in the spillway is needed to compute the velocity pressures at these points.

The uncorrected velocity at the spillway outlet V_{oi} is

$$V_{oi} = \frac{W}{\gamma_{oi} A_o} \tag{XI-59}$$

feet per second.

The velocity at any point i in the barrel V_i is

$$V_i = \frac{p_{oi}}{p_i} V_{oi} \tag{XI-60}$$

feet per second. This correction is necessary because the pressure drops, the air expands, and the velocity increases as air flows along the barrel.

The corrected velocity at the spillway outlet V_o is obtained from Eq. XI-60 by substituting the subscript o for the subscript i.

The velocity at the barrel entrance V_e is obtained from Eq. XI-60 by substituting the subscript e for the subscript i and the subscript o for the subscript oi.

Gas Properties

Some properties of the air-water vapor mixture are required to solve the equations. Equations will be given only for those properties necessary to solve the air-water vapor equations presented herein.

Those properties of air and water vapor necessary for use in the mixture equations were obtained from Marks' [XI-8, p. 4-20, Table 23]. They are listed in Table XI-1 for room temperature. When using the symbols given in Table XI-1 in equations, the subscript a will be added to designate air, the subscript wv will be added to designate water vapor, and the subscript m will be added to designate the air-water vapor mixture.

Values of k and R for the mixture are constant throughout the system. This means that values computed for atmospheric conditions can be used throughout the spillway.

The ratio of the specific heat at constant pressure to the specific heat at constant volume for the air-water vapor mixture k is

$$k = \frac{c_p}{c_v} \tag{XI-61}$$

TABLE XI-1

PROPERTIES OF GASES

Gas	Specific Heat		Ratio of Specific Heats	Gas Constant
	c_p	c_v	$k = c_p/c_v$	R
	Btu/lb			ft-lb/lb/°R
Air	0.241	0.1725	1.397	53.30
Water Vapor	0.46	0.36	1.278	85.81

The specific heat of the air-water vapor mixture c_m is given by Marks' [XI-8, p. 4-11] as

$$c_m = \frac{\gamma_{ad}\, c_a + r\, \gamma_{wv}\, c_{wv}}{\gamma_{ad} + r\, \gamma_{wv}} \qquad \text{(XI-62)}$$

British thermal units per pound. Values of c_{pm} and c_{vm} are computed from Eq. XI-62. These values are substituted in Eq. XI-61 to obtain the value of k for the air-water vapor mixture.

The relative humidity of the air r is given by Marks' [XI-8, p. 4-83, Eq. (2)] as

$$r = \frac{p_v}{p_{vd}} \qquad \text{(XI-63)}$$

This ratio is dimensionless.

The gas constant of the air-water vapor mixture R_m is given by Allen and Bursley [XI-1, p. 19, Eq. 23] as

$$R_m = J\,(c_{pm} - c_{vm}) = 778.2\,(c_{pm} - c_{vm}) \qquad \text{(XI-64)}$$

foot-pounds per pound of gas mixture per degree Rankine. In Eq. XI-64, J is the mechanical equivalent of heat. It is equal to 778.2 foot-pounds and is equivalent to 1 British thermal unit.

Acceleration Due to Gravity

The acceleration due to gravity g at Minneapolis, Minnesota, where the experiments were made, was taken from the Handbook of Chemistry and Physics [XI-18, p. 2167]. Its value is 32.172 feet per second per second.

Rate of Flow*

The weight rate of flow of air W is measured by orifices at the spillway outlet. It is computed by the equation given by Daugherty and Ingersoll [XI-14, p. 150, Eq. 7.40]:

$$W = C_o Y A_2 \sqrt{2g \,{}_1 \frac{p_1 - p_2}{1 - (D_2/D_1)^4}} \qquad \text{(XI-65)}$$

Expansion Factor

The expansion factor for compressible fluids Y for square-edged orifices as given by Daugherty and Ingersoll [XI-14, p. 152] is

$$C_o = 0.672 - 0.032\,D_2 \qquad \text{(XI-66)}$$

Orifice Coefficient*

The coefficient of discharge for the measuring orifice C_o is given by the equation

$$Y = 1 - \left[0.41 + 0.35\left(\frac{D_2}{D_1}\right)^4\right]\left(\frac{p_1 - p_2}{k p_1}\right) \qquad \text{(XI-67)}$$

where C_o is dimensionless. An equation is given for C_o because it is easier for the digital computer to solve an equation than to look up table values for C_o. The equation is based on only two values of D_2—2.000 and 2.375 inches. The approach pipe has a nominal diameter of 3 inches. Corner taps are used. The measuring orifices are in a stainless steel Merriam multiple orifice plate numbered 8167.

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[*] Initially the equation [XI-14, p. 150, Eq. 7.38]

$$W = C_o A_2 \sqrt{2g \frac{k}{k - 1} p_1 \gamma_1 \left(\frac{p_2}{p_1}\right)^{2/k} \frac{1 - (p_2/p_1)^{(k-1)/k}}{1 - (A_2/A_1)^2 (p_2/p_1)^{2/k}}}$$

was used to determine the weight rate of flow of air. The expansion factor Y is missing from this equation. The effect of expansion at the vena contracta was accounted for by using a coefficient that varied with p_2/p_1. The value of C_o thus determined was

$$C_o = 0.6395 - 0.0200\,D_2 + 0.38\left(1 - \frac{p_2}{p_1}\right)$$

When analyzing the closed conduit spillway data, it was found that the plots of the entrance loss coefficients against Reynolds number showed a slight discontinuity when the data obtained using the 2-inch orifice to determine the rate of flow were compared with the 2.375-inch orifice data. This discontinuity was largely or entirely eliminated when the equations presented in the text were used.

Because the differences between the results computed using the two methods are small, the data computed using the footnote equations were not recomputed. The footnote equations were used for Series A-1 through A-397. All data obtained subsequent to Series A-397 were computed using the equations presented in the text.

The calibration was made using a 1/8-inch Pitot cylinder to traverse the pipe. The Pitot cylinder was located 66 pipe diameters from the pipe entrance and the orifice plate was 140 pipe diameters from the pipe entrance. Fig. XI-1 shows the Pitot cylinder, the adapter to support it in the pipe, and the scale to determine the Pitot cylinder orifice position. The Pitot cylinder orifice was traversed across the pipe diameter. Total pressures were measured at ten predetermined positions. The pipe cross section was divided into 5 equal concentric areas as is shown in Fig. XI-2. The total pressure was measured at the midpoint of the annuli on both sides of the pipe centerline. The Pitot cylinder constant was assumed to be 1.00. The static pressure at the Pitot cylinder was computed by projecting the least squares fit of pressure measurements observed at piezometers located 17 D, 33 D, 49 D, and 65 D from the pipe entrance. The difference between the total and static pressures at the Pitot cylinder is the velocity pressure. The velocity at each of the 10 positions of the Pitot orifice was computed from the equation

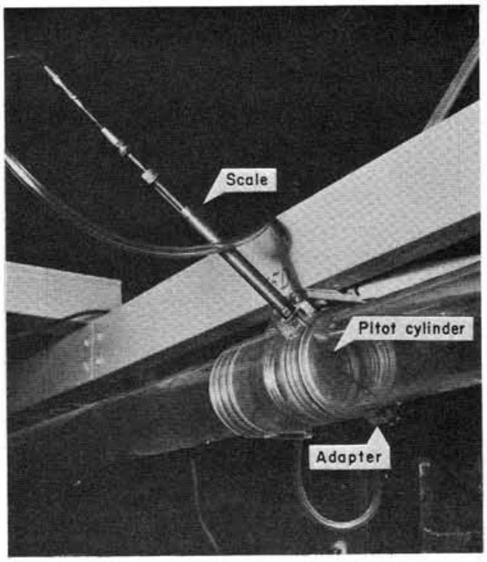


Fig. XI-1 - Pitot Cylinder in Position for Measuring the Velocity Distribution in the Pipe During the Orifice Meter Calibration.

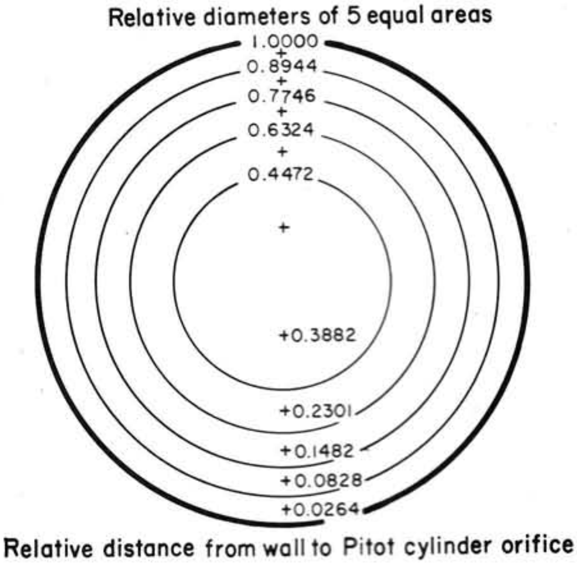


Fig. XI-2 - Location of the Pitot Cylinder Orifice Across the Pipe for Calibration of the Measuring Orifice.

$$V = \sqrt{2g\,\frac{p}{\gamma}} \qquad \text{(XI-68)}$$

In this equation, p is the velocity pressure and γ is the specific weight of air at the Pitot cylinder computed from Eq. XI-54 by substituting the static pressure at the Pitot cylinder for p_{oi}.

The logarithm of the velocity was plotted against the logarithm of the relative distance from the pipe centerline. An example is shown in Fig. XI-3. Two velocities were

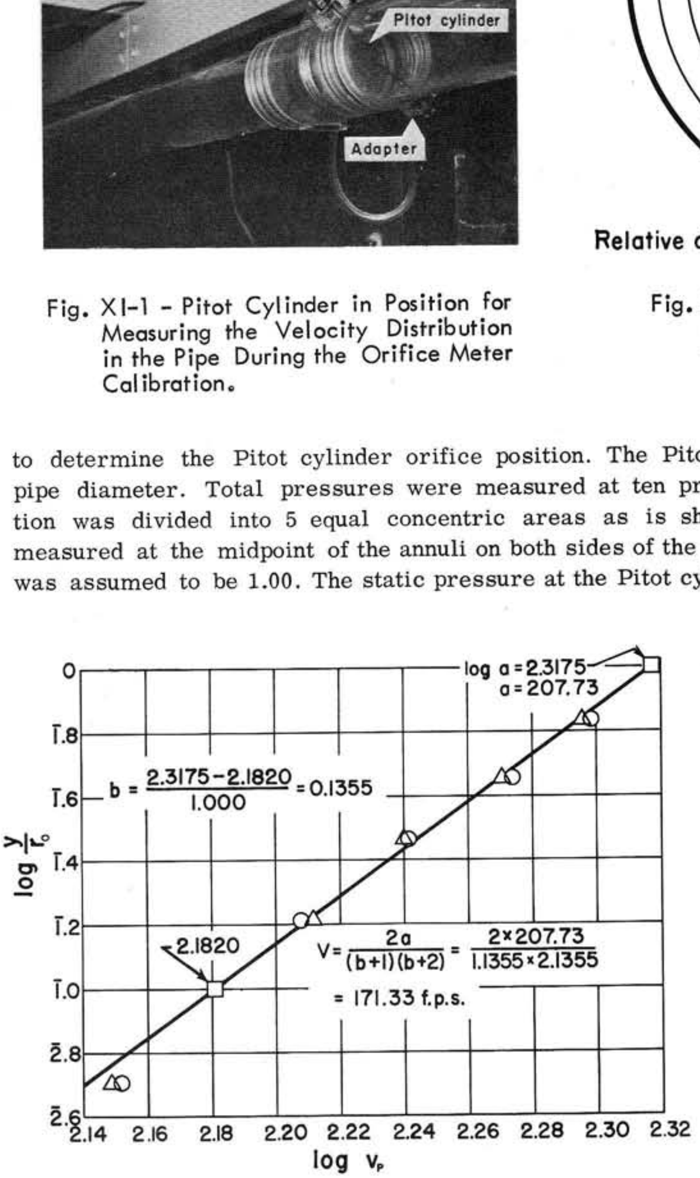


Fig. XI-3 - Plot of the Velocity Against the Relative Distance from the Pipe Centerline, Orifice Calibration Run 64.

obtained for each relative distance from the pipe centerline. The velocities measured on opposite sides of the centerline are identified by different symbols. A straight line of best fit was drawn through the data. The intercept of this line with the pipe centerline and at a relative radius of 0.1 ($\log y/r_o = -1$) from the pipe wall were read from the plot and used to compute the average velocity of flow in the following manner.

The form of the equation of the line in Fig. XI-3 is

$$\log v_p = \log a + b \log \frac{y}{r_o} \tag{XI-69a}$$

or

$$v_p = a \left(\frac{y}{r_o} \right)^b \tag{XI-69b}$$

where v_p is the local velocity in the barrel in feet per second, y is the distance from the pipe wall, r_o is the radius of the pipe, a is the centerline velocity in feet per second and b is the slope of the line in Fig. XI-3.

The discharge through the barrel is obtained by integrating the local velocities across the barrel. The discharge is also equal to the average velocity V in feet per second multiplied by the barrel area A in square feet. This equality is

$$A\,V = \int_0^{r_o} 2\pi\, r_p\, v_p\, dr_p \tag{XI-70}$$

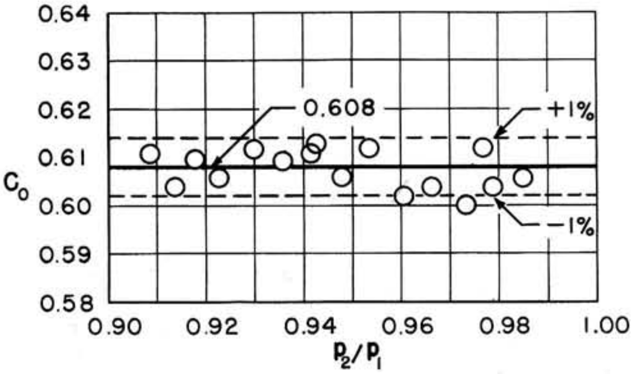
where r_p is the distance in feet from the centerline to the point where v_p is measured. Since $y = r_o - r_p$, $dr = -dy$, and v_p is obtained from Eq. XI-69b, Eq. XI-70 can be written

$$A\,V = \frac{2\pi\, a}{r_o^{\,b}} \int_{r_o}^{o} (r_o - y)\, y^b\, (-dy) \tag{XI-71}$$

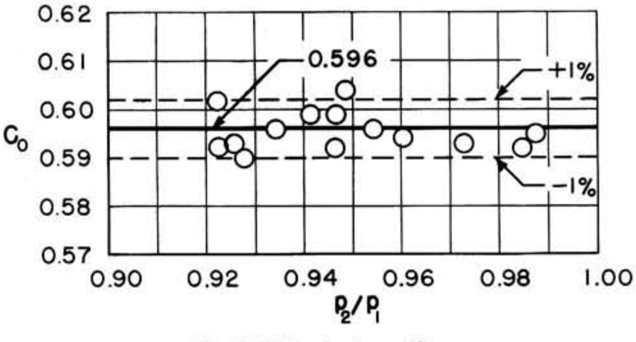
Integrating and solving for the average velocity,

$$V = \frac{2a}{(b+1)(b+2)} \tag{XI-72}$$

feet per second.



(a) 2.000-inch orifice



(b) 2.375-inch orifice

Fig. XI-4 - Measuring Orifice Discharge Coefficients Plotted Against the Ratio of Corner Tap Pressures.

The average velocity in feet per second is multiplied by the specific weight of air at the Pitot tube location in pounds per cubic foot and the pipe area in square feet to obtain the actual weight rate of flow W in pounds per second. The theoretical weight rate of flow W_t is computed from Eqs. XI-65 and XI-66 assuming that C_o is 1.

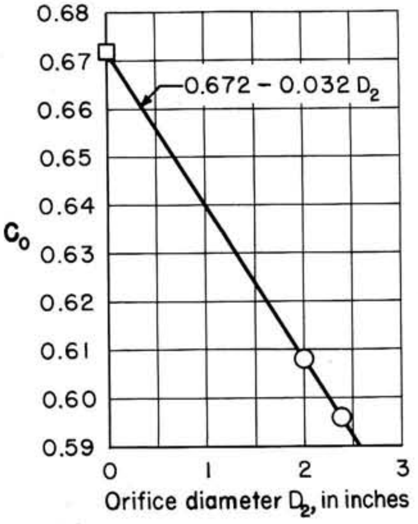


Fig. XI-5 - Measuring Orifice Coefficient Plotted Against the Orifice Diameter.

The value of the discharge coefficient is

$$C_o = \frac{W}{W_t} \tag{XI-73}$$

Values of the coefficient of discharge C_o for the 2.000- and 2.375-inch orifices are plotted in Fig. XI-4 against the ratio of the pressure drop across the orifice p_2/p_1. Lines drawn in Fig. XI-4 show that, with two exceptions, the 24 data points are within 1 per cent of the coefficients computed by Eq. XI-67.

Fig. XI-5 is the plot which gives the relationship between the coefficients and the orifice diameter.

As a check on the measuring orifice calibration tests, the Darcy-Weisbach friction factor f was computed from Eqs. XI-74 and XI-75, the Reynolds number $\mathbb{R}$ was computed from Eq. XI-76, and this information was plotted on Rouse's f - $\mathbb{R}$ diagram [XI-31, p. 211, Fig. 111]. Since the plastic pipe was smooth and it had been washed just prior to the calibration tests, the friction factor should fall close to the "smooth" curve if the results are to agree with those obtained by others. The results of this comparison are shown in Fig. XI-6. The good agreement of the data with the "smooth" curve is an indication that the pressure and velocity measurements are satisfactory.

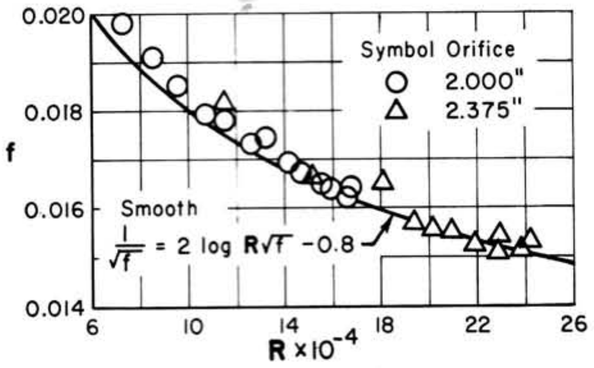


Fig. XI-6 - Comparison of the Pipe Friction Factor Obtained from the Measuring Orifice Calibration with the Curve for Smooth Pipe.

Friction Factor

The Darcy-Weisbach friction factor f is obtained from the equation

$$f = \left(f \frac{\ell}{D}\right) \frac{D_o}{\ell_o} \tag{XI-74}$$

where the quantity within the parentheses is obtained from an equation given by Binder [XI-9, vol. I, p. 63, Eq. 3-7] by rearranging and converting from natural logarithms to common logarithms. Thus,

$$f \frac{\ell}{D} = \frac{p_e g}{V_e^{2} \gamma_e} \left[1 - \left(\frac{p_o}{p_e} \right)^{2} \right] - 4.6052 \log \frac{p_e}{p_o} \tag{XI-75}$$

In the case of water, the hydraulic or pressure grade line is straight if the only losses are those due to fluid friction. In the case of air, the pressure loss along the barrel causes the air to expand and the velocity to increase with a conversion of pressure energy to kinetic energy so that the pressure grade line is not straight.

The error involved in using a straight-line relationship instead of the correct curved-line relationship has been tested over the range of conditions anticipated during the closed conduit spillway experiments. The maximum error resulting from using the simpler straight-line relationship was found to be on the order of 0.01 per cent—a negligible magnitude.

Reynolds Number

The Reynolds number at the barrel entrance $\mathbb{R}_e$ is

$$\mathbb{R}_e = \frac{V_e D_e}{\nu_e} \qquad \text{(XI-76)}$$

where ν_e is the kinematic viscosity at the barrel entrance.

Viscosity

Both the kinematic viscosity and the dynamic viscosity are required to solve the equations.

The kinematic viscosity at the barrel entrance ν_e is

$$\nu_e = \frac{\mu_e g}{\gamma_e} \qquad \text{(XI-77)}$$

square feet per second.

The absolute or dynamic viscosity at the barrel entrance μ_e is given by Pankhurst and Holder [XI-25, p. 643] as

$$\mu_e = 3.059 \times 10^{-8} \frac{(T'_o)^{3/2}}{T'_o + 114} \qquad \text{(XI-78)}$$

pound-seconds per square foot.

Example

Now that all the equations required for the analysis of a test using air have been presented, it is appropriate to present an example of the solution. The example is worked out in Tables XI-2 and XI-3.

Column 1 of Table XI-2 lists the quantities for which a value is desired. Column 2 lists the source of the values listed in columns 3, 4, and 5. The entry "obs." in column 2 indicates that the columns 3, 4,

TABLE XI-2

EXAMPLE OF COMPUTATION

Series A-378, Run 1

$D_o = 0.2493$ $D_e = 0.2511$ $h_{oi} = 2.860$ $A_o = 0.04882$ $A_1 = 0.04989$ $A_r = 0.0945$

Quantity	Source	Value		
		Desk	Key	Encoder
(1)	(2)	(3)	(4)	(5)
t_w	obs.	59.0	59.000	59.000
T_w	XI-32	518.7		
p_w	XI-49	35.58		
B	obs.	28.55	28.544	28.544
p_a	XI-35	2019.34		
t_d	obs.	77.0	77.000	77.000
T_d	XI-32	536.7		
p_v	XI-50	22.12		
p_{vd}	XI-49	66.06		
r	XI-63	.335		
t_a	obs.	78.2	78.200	78.200
T_a	XI-32	537.9		
γ_{ad}	XI-57	.06965		
γ_{wv}	XI-58	.00048		
c_{pm}	XI-62	.2415		
c_{vm}	XI-62	.1729		
k	XI-61	1.397		
R_m	XI-64	53.38		
γ_a	XI-52	.07004		
t_o, t_1	obs.	76.2	76.200	76.200
T_o, T_1	XI-32	535.9		
t_m	obs.	23.0	23.000	23.000
γ_w	XI-51	62.119		
h_o	obs.	2.860	2.860	2.859
h_{m1}	obs.	1.474	1.474	1.475
p_1	XI-47	1933.24		
h_{m2}	obs.	1.097	1.097	1.098
p_2	XI-48	1823.72		
p_2/p_1	---	.94335	.943	.943
γ_1	XI-54	.06730		
D_2	obs.	2.375	2.375	2.375
A_2	---	.03076		
$(A_2/A_1)^2$	---	.38014		
C_o	XI-67	.596		
W	XI-65	.4958	.496	.496

Quantity	Source	Value		
		Desk	Key	Encoder
(1)	(2)	(3)	(4)	(5)
p_o	XI-40	1922.63		
γ_o	XI-56	.06693		
V_o	XI-60	151.72		
$\gamma_o V_o^2/2g$	---	23.944		
K_e	XI-21b	.793		
f	XI-73	.0163	.016	.016
$\underline{R}_e$	XI-76	207609	207940	207879
h_{mr}	obs.	2.688		
p_r	XI-47	2008.66		
T_r	XI-34	537.1		
γ_r	XI-35	.06977		

Piezometer	h_{mi}	p_{pi}	$\Delta p_{ni}/p_{vr}$		
			Desk	Key	Encoder
(6)	(7)	(8)	(9)	(10)	(11)
Source:	obs.	XI-47	XI-31	XI-31	XI-31
1	2.688	2008.66	-1.742	-1.738	-1.720
2	2.680	2008.16	-1.823	-1.818	-1.806
3	2.662	2007.04	-2.006	-2.000	-1.987
4	2.615	2004.12	-2.482	-2.475	-2.465
5	2.580	2001.95	-2.836	-2.829	-2.819
etc.					

TABLE XI-3

EXAMPLE OF HYDRAULIC GRADE LINE COMPUTATION

Series A-378, Run 1

$h_{oi} = 2.860$ Subscript o = subscript 137 D

Quantity	Source	Barrel piezometer location i										
		D/2 top	D/2 bot.	17 D	33 D	49 D	65 D	81 D	97 D	113 D	129 D	137 D
h_{mi}	obs.	1.767	2.183	2.076	1.970	1.874	1.767	1.663	1.563	1.441	1.357	1.301
p_{mi}	XI-37	1951.44	1977.29	1970.64	1964.05	1958.09	1951.44	1944.98	1938.77	1931.19	1925.98	1922.50
p_{mi}/p_o	---	1.01505	1.02850	1.02504	1.02161	1.01851	1.01505	1.01169	1.00846	1.00452	1.00181	1.00000
γ_{oi}	XI-54											.06693
V_{oi}	XI-59											151.12
p_{vi}	XI-39	23.40	23.10	23.17	23.25	23.32	23.40	23.48	23.56	23.65	23.71	23.76
$1 - \frac{D_i^4}{D_o^4}$	obs.	-.0283	-.0283	-.0216	-.0188	-.0188	-.0121	+.0053	-.0054	+.0238	+.0013	.0000
p_{pi}	XI-38	1950.78	1976.64	1970.14	1963.61	1957.65	1951.16	1945.10	1938.64	1931.75	1926.01	1922.50
ℓ_i	obs.	.125	.125	4.26	8.26	12.26	16.26	20.27	24.27	28.28	32.29	34.29
		$N = 8$		$\Sigma \ell_i = 176.18$		$\Sigma \ell_i^2 = 4501.0352$		$\Sigma p_{pi} = 15536.42$		$\Sigma \ell_i p_{pi} = 341167.317$		
a	XI-41			$a = 1976.92$								
b	XI-42								$b = -1.5834$			
p_{fi}	XI-40	1976.72	1976.72	1970.17	1963.84	1957.51	1951.17	1944.82	1938.48	1932.14	1925.79	1922.63
$\Delta p_i = p_{ni}$	XI-44	-25.94	-.08	-.03	-.23	+.14	-.01	+.28	+.16	-.39	+.22	-.13
p_{ni}/p_{vi}	XI-27 Desk	-1.109	-.003	-.001	-.010	+.006	-.000	+.012	+.007	-.016	+.009	-.005
do.	Key	-1.107	-.004	-.002	-.010	+.005	-.000	+.011	+.006	-.016	+.008	-.005
do.	Encoder	-1.109	-.005	-.002	-.009	+.005	-.001	+.013	+.005	-.017	+.009	-.005

and 5 figures were observed during the experiment. The point of observation is identified in the section of the report describing the apparatus. The other entries in column 2 list the number of the equation used to obtain the entries in columns 3, 4, and 5. The values for use in the respective equations are obtained from appropriate values listed previously in columns 3, 4, and 5.

After determining W in Table XI-2, it is necessary to defer further computation until p_o and p_e have been evaluated. This computation is carried out in Table XI-3. The explanation of the first two columns is identical to that for columns 1 and 2 in Table XI-2. The remaining columns represent data obtained at the various piezometers along the barrel.

Values of p_{ni}/p_{vi} in Table XI-3 for piezometers 33 D to 137 D should be zero. The deviation from zero is an indication of how well the pressures computed using the least squares equation agree with the observed pressures. Any significant deviation from zero is an indication of poor experimental data, a reason to investigate possible sources of the error, and a reason to suspect the quality of the results obtained for that particular test. Values of p_{ni}/p_{vi} near the barrel entrance are affected by entrance conditions and should not be expected to equal zero. They are required for design purposes and so are computed.

The computations in Table XI-2 are resumed after Table XI-3 has been completed.

A section has been added to Table XI-2 to show how the drop inlet pressure coefficients are computed. For convenience of listing, the computations are carried out horizontally for each piezometer. The previous explanations should make obvious the procedure employed.

The results of the computations made by three different methods are compared in Tables XI-2 and XI-3. A desk calculator was used for one set of computations. The same data was also solved with a Control Data 160-A[∞] computer using two different methods of punching the input tapes. For the "Key" column, the punched input tape was prepared manually using a key punch. For the "Encoder" column, the input tape was produced semi-automatically during the experiment by reading the point gage through an encoder.

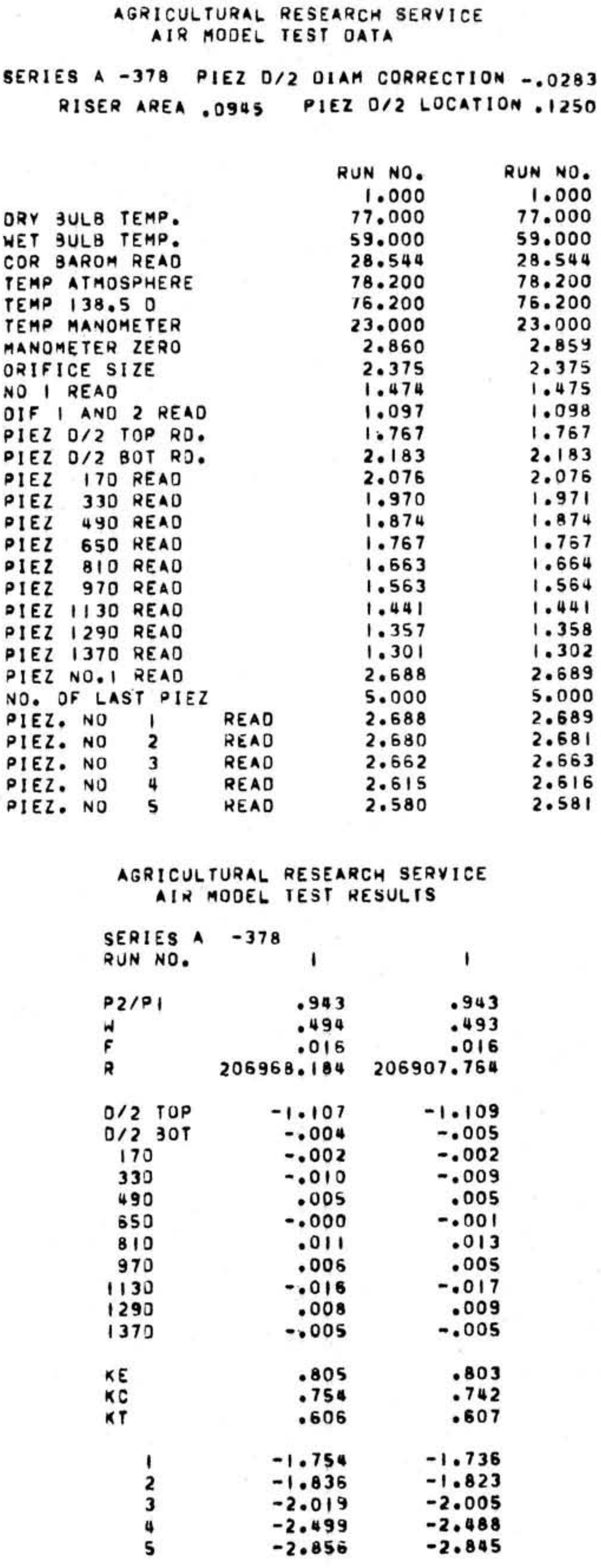
The digital computer input and output for both tape punching methods are printed out in the form shown in Fig. XI-7. The "Key" and "Encoder" values listed in Tables XI-2 and XI-3 are taken from Fig. XI-7. The comparison shows that, within the limits of experimental precision, identical results are obtained for all methods of computation.

The explanation of the differences in the values shown in the "Key" and "Encoder" columns of Tables XI-2 and XI-3 follow. Because of the gear train between the point gage and the encoder, the encoder readings must be multiplied by 0.6141 to obtain the corresponding point gage reading. Repeated checks have shown that the average encoder error that can be expected is one encoder unit or about 0.0006 foot with a maximum error of two encoder units or about 0.0012 foot. Therefore, encoder errors of 0.001 foot are not unexpected. However, this is well within the limits of experimental precision obtainable with the air apparatus. The "Key" and "Encoder" columns of Tables XI-2 and XI-3 thus indicate the differences in the computed values that can be attributed to the encoder.

TEST APPARATUS AND PROCEDURE

The apparatus developed for the air tests of the closed conduit spillway will be described. Emphasis will be given to the features which differ from those used in the water tests. The test procedure will be explained and the experience gained in the operation and maintenance of the air apparatus will be mentioned.

[∞] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.



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          AGRICULTURAL RESEARCH SERVICE
             AIR MODEL TEST DATA

SERIES A -378  PIEZ D/2 DIAM CORRECTION -.0283
     RISER AREA .0945   PIEZ D/2 LOCATION .1250


                              RUN NO.      RUN NO.
                               1.000        1.000
DRY BULB TEMP.                77.000       77.000
WET BULB TEMP.                59.000       59.000
COR BAROM READ                28.544       28.544
TEMP ATMOSPHERE               78.200       78.200
TEMP 138.5 D                  76.200       76.200
TEMP MANOMETER                23.000       23.000
MANOMETER ZERO                 2.860        2.859
ORIFICE SIZE                   2.375        2.375
NO 1 READ                      1.474        1.475
DIF 1 AND 2 READ               1.097        1.098
PIEZ D/2 TOP RD.               1.767        1.767
PIEZ D/2 BOT RD.               2.183        2.183
PIEZ  170 READ                 2.076        2.076
PIEZ  330 READ                 1.970        1.971
PIEZ  490 READ                 1.874        1.874
PIEZ  650 READ                 1.767        1.767
PIEZ  810 READ                 1.663        1.664
PIEZ  970 READ                 1.563        1.564
PIEZ 1130 READ                 1.441        1.441
PIEZ 1290 READ                 1.357        1.358
PIEZ 1370 READ                 1.301        1.302
PIEZ NO.1 READ                 2.688        2.689
NO. OF LAST PIEZ               5.000        5.000
PIEZ. NO   1    READ           2.688        2.689
PIEZ. NO   2    READ           2.680        2.681
PIEZ. NO   3    READ           2.662        2.663
PIEZ. NO   4    READ           2.615        2.616
PIEZ. NO   5    READ           2.580        2.581


          AGRICULTURAL RESEARCH SERVICE
             AIR MODEL TEST RESULTS

     SERIES A   -378
     RUN NO.           1            1

     P2/P1          .943         .943
     W              .494         .493
     F              .016         .016
     R        206968.184   206907.764

     D/2 TOP      -1.107       -1.109
     D/2 BOT       -.004        -.005
      170          -.002        -.002
      330          -.010        -.009
      490           .005         .005
      650          -.000        -.001
      810           .011         .013
      970           .006         .005
     1130          -.016        -.017
     1290           .008         .009
     1370          -.005        -.005

     KE             .805         .803
     KC             .754         .742
     KT             .606         .607

        1         -1.754       -1.736
        2         -1.836       -1.823
        3         -2.019       -2.005
        4         -2.499       -2.488
        5         -2.856       -2.845
```

Fig. XI-7 - Example of Digital Computer Printout

Test Apparatus

There are three major parts of the test apparatus: the closed conduit spillway, the blower, and the instrumentation. A separate section will be devoted to each.

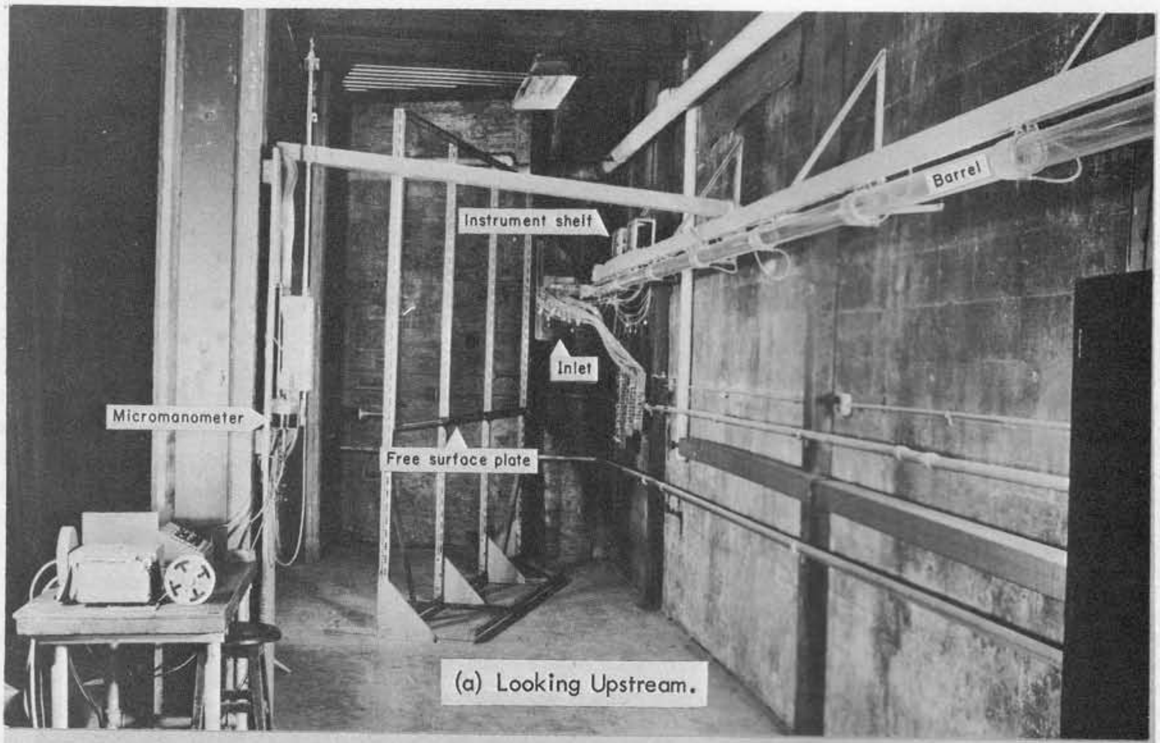
Closed Conduit Spillway

The barrel of the closed conduit spillway is located along a wall of the laboratory as shown in Fig. XI-8. Since it is immersed in the fluid—air—there is no requirement that the inlet be vertical. For convenience, the spillway is laid on its side with the barrel centerline about 7 feet above the floor. This locates the spillway about midway between the floor and the ceiling and provides equal access of the air to both sides of the inlet. Brackets attached to the wall at 8-foot intervals support a 3- by 1.5-inch steel channel. The channel centerline is 18 inches from the wall. The barrel is attached to the channel at 4-foot intervals.

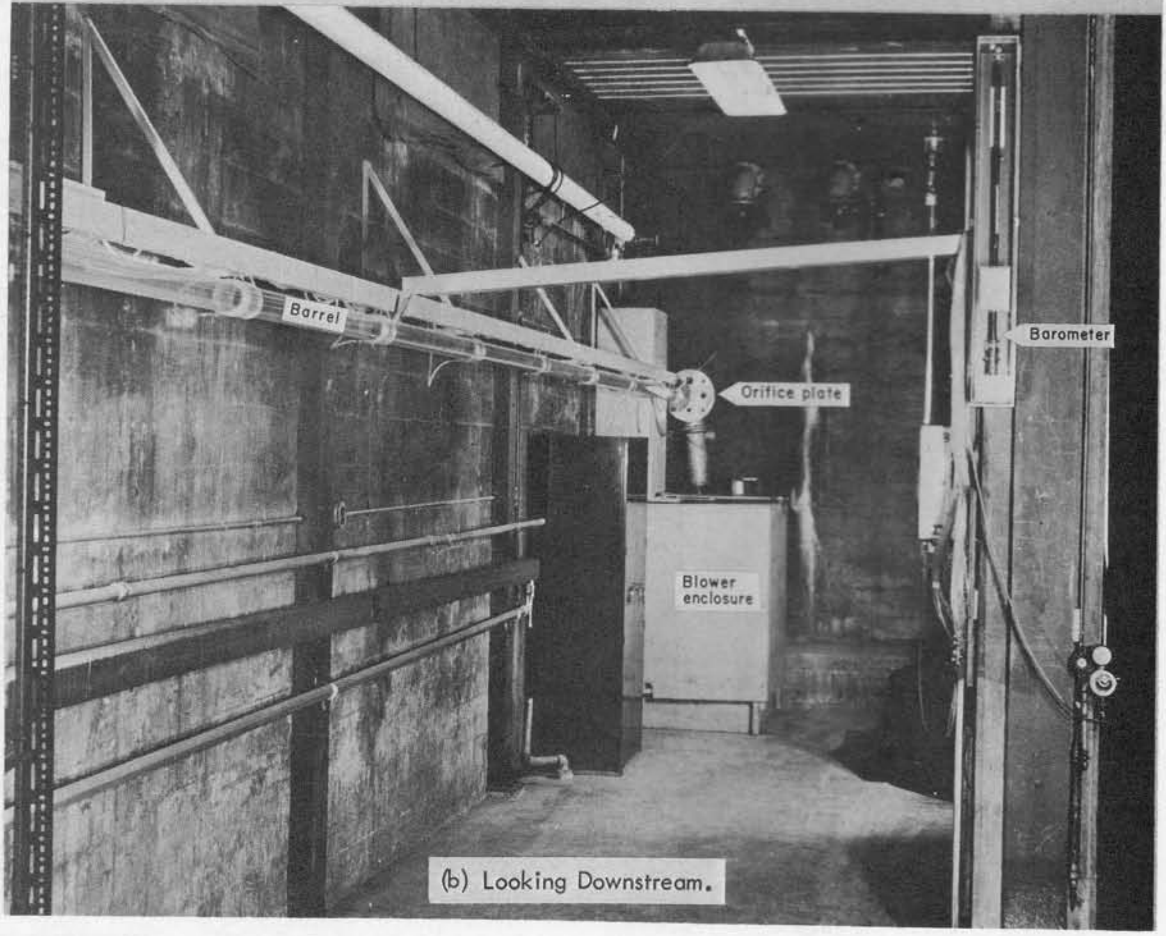
The barrel mounting is permanent. Different barrel slopes are simulated by changing the angle between the barrel and the inlet. This means that only the inlet need be changed and that there is no need to change the barrel position.

The barrel is a transparent cast acrylic tube with a 3-inch inside diameter by 3-1/4-inch outside diameter. The permanent installation begins 6 inches or 2 D (2 pipe diameters) from the inlet so a stub can be attached to each inlet. The permanent barrel installation consists of 8 lengths of pipe 48 inches or 16 D long and one length 24 inches or 8 D long.

Four piezometer holes are located at the pipe quadrants 3 inches or 1 D from the downstream end of each pipe length. The piezometer holes are 1/16 inch in diameter. They were drilled in a milling machine to insure that they were exactly perpendicular to the pipe wall. The holes were carefully deburred to a 1/64-inch radius using a specially made tool and jig after which they were inspected with the aid of a magnifying glass. Four holes are used to reduce dependence on one hole and increase the reliability of the measurements.



(a) Looking Upstream.



(b) Looking Downstream.

Fig. XI-8 - Air Apparatus.

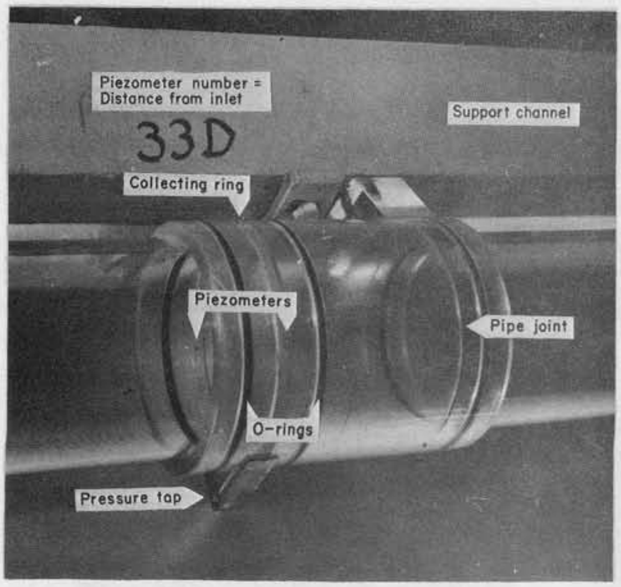


Fig. XI-9 - Pipe Coupling and Piezometer Collecting Groove.

The pipe sections are coupled using a 3-1/4-inch inside diameter by 3-3/4-inch outside diameter transparent acrylic tube. The coupling is shown in Fig. XI-9. O-ring grooves are cut into the coupling on either side of the pipe joint. The coupling is extended to beyond the piezometer location where a third O-ring groove is cut. A collecting groove is cut in the coupling at the location of the piezometers so that all four piezometers feed into the single collecting groove. This collecting groove is tapped so the pressure can be conveyed to a point of measurement. All O-ring grooves are individually fitted to the pipe to compensate for variations in the pipe diameter and insure a tight fit. A tapped lug is cemented to each coupling for attachment to the support channel. The barrel is supported at each joint.

The barrel is extended 6 inches or 2 D to a pair of acrylic flanges between which is located a plate having four measuring orifices as is shown in Fig. XI-10. Rubber gaskets 1/16-inch thick seal against leakage between the flanges and the orifice plate. The inside diameters of these gaskets are made 4 inches to provide an annular space between the ends of the pipe and the orifice plate for the transmission of the upstream and downstream orifice plate pressures. A pressure-collecting groove in the flange and a tap to the groove permit a connection to the manometer.

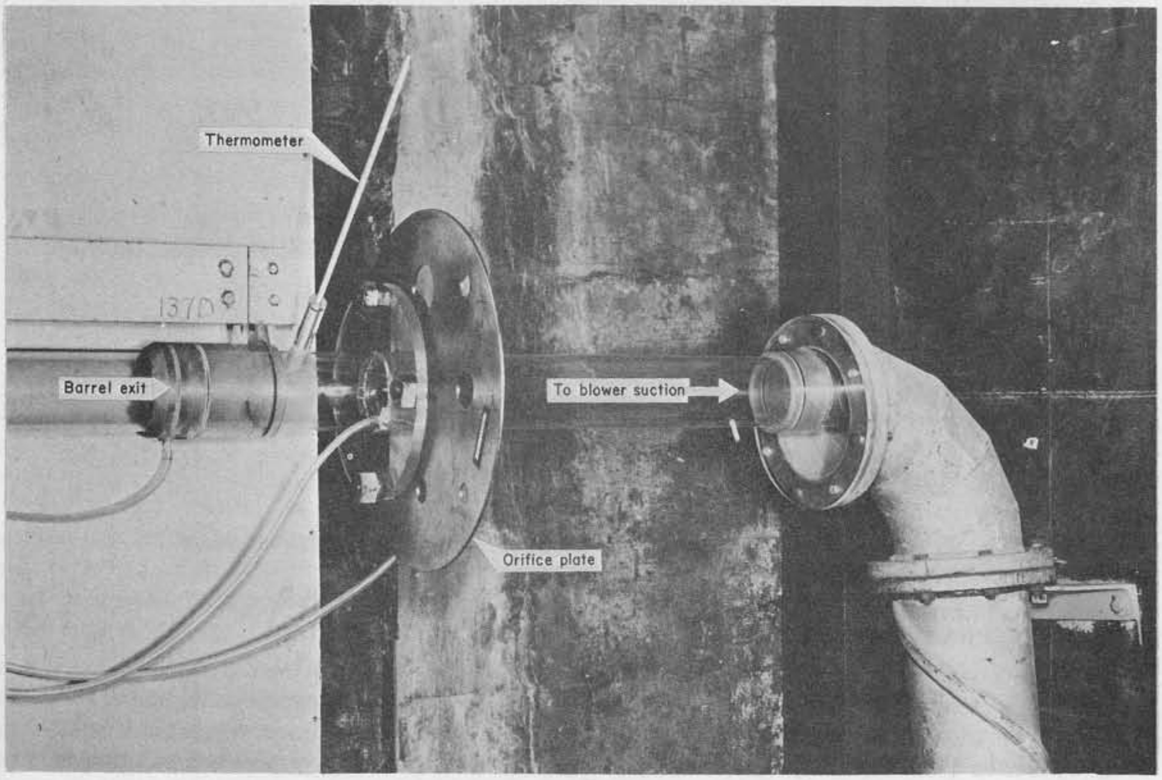


Fig. XI-10 - Barrel Exit and Orifice Plate.

The barrel extension downstream from the orifice plate is 25 inches or 8-1/3 diameters long. It projects through a coupling into the 6-inch steel pipe, shown in Fig. XI-10, which in turn discharges into the 10-inch blower suction line.

The vertical transparent acrylic plate shown in Fig. XI-8a is provided at the inlet end of the barrel to simulate a free surface. This plate is 12 feet long by 6 feet high. The horizontal centerline of the free surface plate coincides with the barrel centerline. The plate is mounted on punched galvanized angle supports. The assembly can be skidded on the floor to center it longitudinally over the various inlets. It also can be skidded transversely when it is desired to simulate different heights of the free surface.

Blower

The blower is an Ingersoll-Rand Type "G" motor blower. The 15-hp. motor has a speed of 3500 r.p.m. The capacity of the blower is 1800 cubic feet per minute at a pressure of 1-1/4 pounds per square inch or 34.5 inches of water.

The blower was operated to suck the air through the closed conduit spillway. A sheet metal gate valve in the blower discharge pipe is used to control the flow rate.

A problem encountered with the blower was noise control. Before installation, a sound level of 106 decibels was measured close to the blower and 83 decibels 20 feet from the blower. After installation and soundproofing, the sound level near the blower was 97 decibels and was 92 decibels 18 feet from the blower. The "before" readings were taken in a much less confined space than the "after" readings. In this connection Marks' states [XI-8, p. 12-155], "The sound level established in a room by a noise source is higher than that which the same source would produce in a free space. . . ." The implication is that the measured "before" sound level is lower than it would have been if the measurement had been made after the blower had been installed but before the soundproofing had been applied.

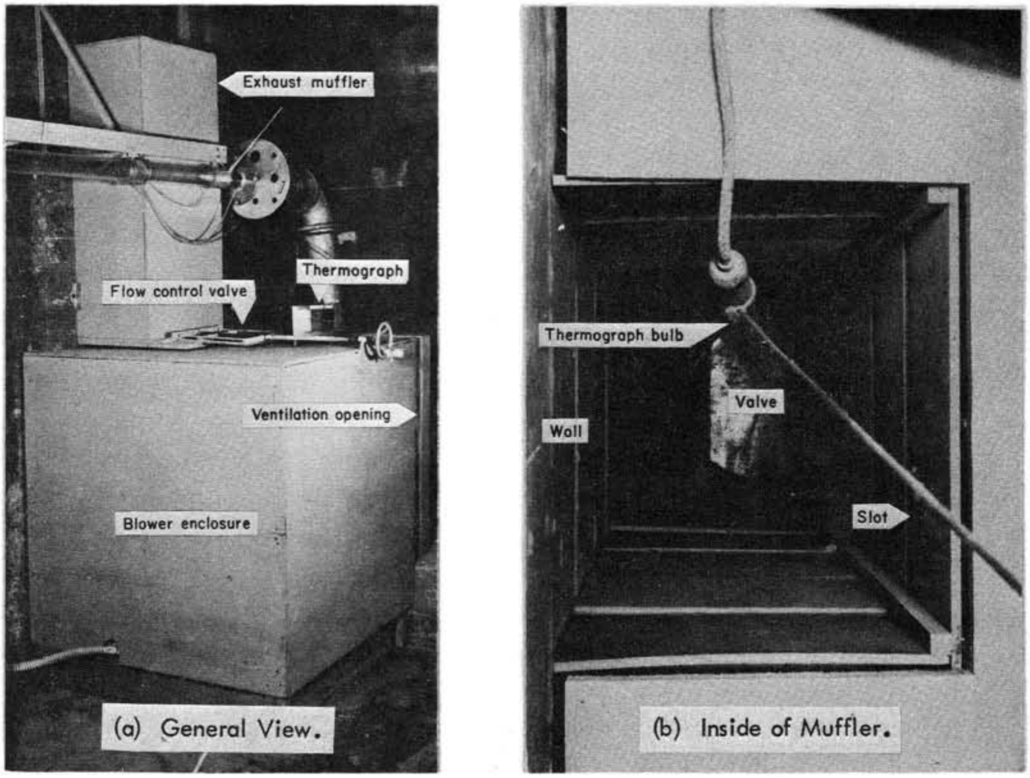
Marks' [XI-8, p. 12-153, Table 2] describes typical sound levels as follows:

	Decibels	
	120	Threshold of feeling, thunder
Deafening	110	Nearby riveter
	100	Boiler factory
Very loud	90	Noisy factory
	80	Noisy office
Loud	70	Average street noise
	60	Noisy home
Moderate	50	Average office, average conversation
	40	Private office
Faint	30	Quiet conversation
	20	Whisper
Very faint	10	Threshold of audibility, soundproof room

The noise level of the blower is seen to be "very loud."

Before installation of the soundproofing the noise was uncomfortable and conversation in the vicinity of the blower was almost impossible. After installation of the soundproofing the noise was not uncomfortable and conversation became readily possible. Some of this improvement can be attributed to the reduction in the sound pressure level. However, the major improvement seems to be due to the absorption of the higher and more objectionable frequencies. In this connection Marks' says [XI-8, p. 12-153], ". . . two noise sources, each capable of producing a sound level of 90 db, together produce a sound level of only 93 db. Conversely, in a composite noise produced by two noise sources, the complete quieting of one of these will produce only 3 db reduction in the measured sound level (corresponding to approximately 20 per cent reduction in the subjective loudness)." It appears that the soundproofing reduced the "subjective loudness" percentage much more than it did the sound pressure percentage. In any case, a satisfactory result was achieved.

This satisfactory sound control was achieved by three means: (1) The blower was mounted on sound-absorbent rubber and a flexible rubber connection was used in the suction pipe; (2) the blower and motor were completely enclosed in a plywood box lined with 3-1/2-inch-thick rock wool insulation, except for a ventilation space; and (3) a muffler was provided in the blower exhaust line. The enclosure and muffler are shown in Fig. XI-11.



(a) General View.

(b) Inside of Muffler.

Fig. XI-11 - Blower Soundproofing.

The plywood box shown in Fig. XI-11a is 4 feet 0 inches wide, 4 feet 9 inches high, and 4 feet 8 inches long. A 4-inch-wide opening in one side and the top provides a slot for the escape of heat produced by the motor.

The exhaust muffler is a 3-sided plywood box 24 inches long by 16 inches deep placed with the open side against the concrete building wall. Its inside dimensions are 12 by 10 inches. The height is 4 feet 0 inches. Fig. XI-11b shows the inside of the muffler. Horizontal baffles 6 inches wide extend around the inside of the muffler at 6-inch vertical intervals. The outside walls of these spaces are covered with rock wool insulation. Five-inch-wide pieces of plywood are nailed to the horizontal baffles so that the muffler has 1-inch-wide horizontal slots opening to the chambers in the walls. This effectively reduces the noise of the exhaust.

Instrumentation

Each of the special instruments used to obtain data and control the experiments will be described.

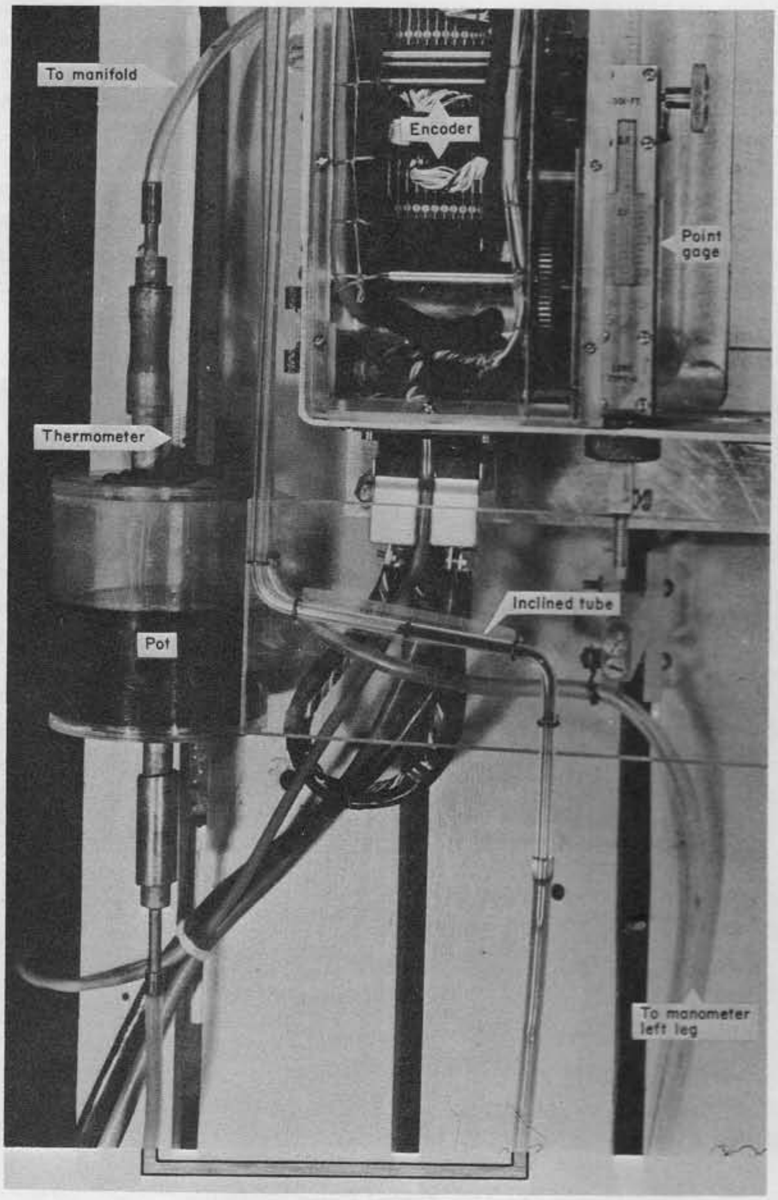


Fig. XI-12 - Micromanometer.

Barometer. The barometer which can be seen in Fig. XI-8b is a "Princo" Fortin-type mercury barometer manufactured by the Precision Thermometer and Instrument Company. The mercury reservoir is located at the elevation of the closed conduit spillway barrel centerline.

Microbarograph. A No. 5-800 microbarograph manufactured by the Instruments Corporation is located on an instrument shelf just above the barrel entrance in order to detect changes in the barometric pressure that might occur during an experiment. The instrument shelf is identified in Fig. XI-8a.

Psychrometer. A model HA/2 hand-aspirated psychrometer manufactured by Julian P. Friez and Sons, Inc., is used to determine the relative humidity. It was modified so that aspiration is provided by low-pressure air from the laboratory compressed air system instead of from the hand bulb pump provided by the manufacturer. The psychrometer is located just over the barrel entrance on the instrument shelf.

Hygrothermograph. A No. 5-594 hygrothermograph manufactured by the Belfort Instrument Company is located on the instrument shelf with the psychrometer and microbarograph to detect changes in the relative humidity and atmospheric temperature that might occur during an experiment.

Thermometers. The temperature of the atmosphere at the inlet is measured by a mercury thermometer located on the instrument shelf near the spillway entrance. This thermometer has 0.2° F graduations.

The temperature at the barrel exit and at the orifice is measured by a similar thermometer which is shown in Fig. XI-10. This thermometer is located 4-1/2 inches upstream of the orifice. It is also 4-1/2 inches downstream of the piezometers at 137 D which are considered the barrel outlet. The thermometer bulb is in a recess 1/2 inch in diameter by 1 inch long drilled through the pipe wall into the thermometer support which is cemented to the pipe. An O-ring prevents leakage around the thermometer.

The temperature of the micromanometer fluid is measured by the thermometer shown in Fig. XI-12. The thermometer bulb is immersed in the manometer reservoir. A seal around the thermometer prevents leakage of pressure from the pot. This thermometer has 1° C graduations.

Distance Thermograph. The bulb of a distance thermograph is located in the blower exhaust duct. This is very useful in determining when stable conditions are reached and experimental observations can safely begin. The thermograph and its bulb can be seen in Figs. XI-11a and XI-11b, respectively.

Micromanometer. The micromanometer for measuring the pressures in the drop inlet and along the barrel is shown in Fig. XI-12. It was assembled at the laboratory. (The encoder shown in Fig. XI-12 is used to convert point gage settings to electrical contacts. A description of the encoder and its associated tape-punching equipment is given in reference XI-12.)

The micromanometer consists of a reservoir or pot 3-3/4 inches in inside diameter which is connected by flexible tubing to an inclined tube mounted on a McIntyre point gage. The inclined acrylic tube has a 1/8-inch inside diameter. To increase its sensitivity, the tube slopes at about 8° from the horizontal as shown in Fig. XI-13. The graduations shown in Fig. XI-13 are about 1/12 inch apart and represent 0.001 foot of water pressure. It was difficult to repeat readings to within 0.01 foot with distilled water in the tube. However, the addition of 0.2 per cent by weight of Aerosol OT to the water made it possible to repeat readings to 0.001 foot. The addition of red food dye makes the meniscus readily visible.

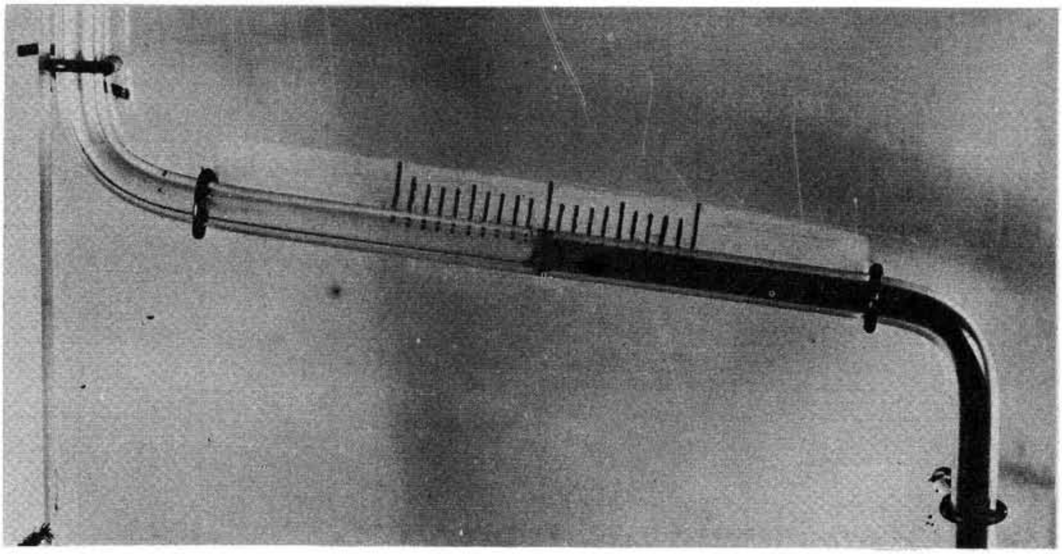


Fig. XI-13 - Micromanometer Meniscus.

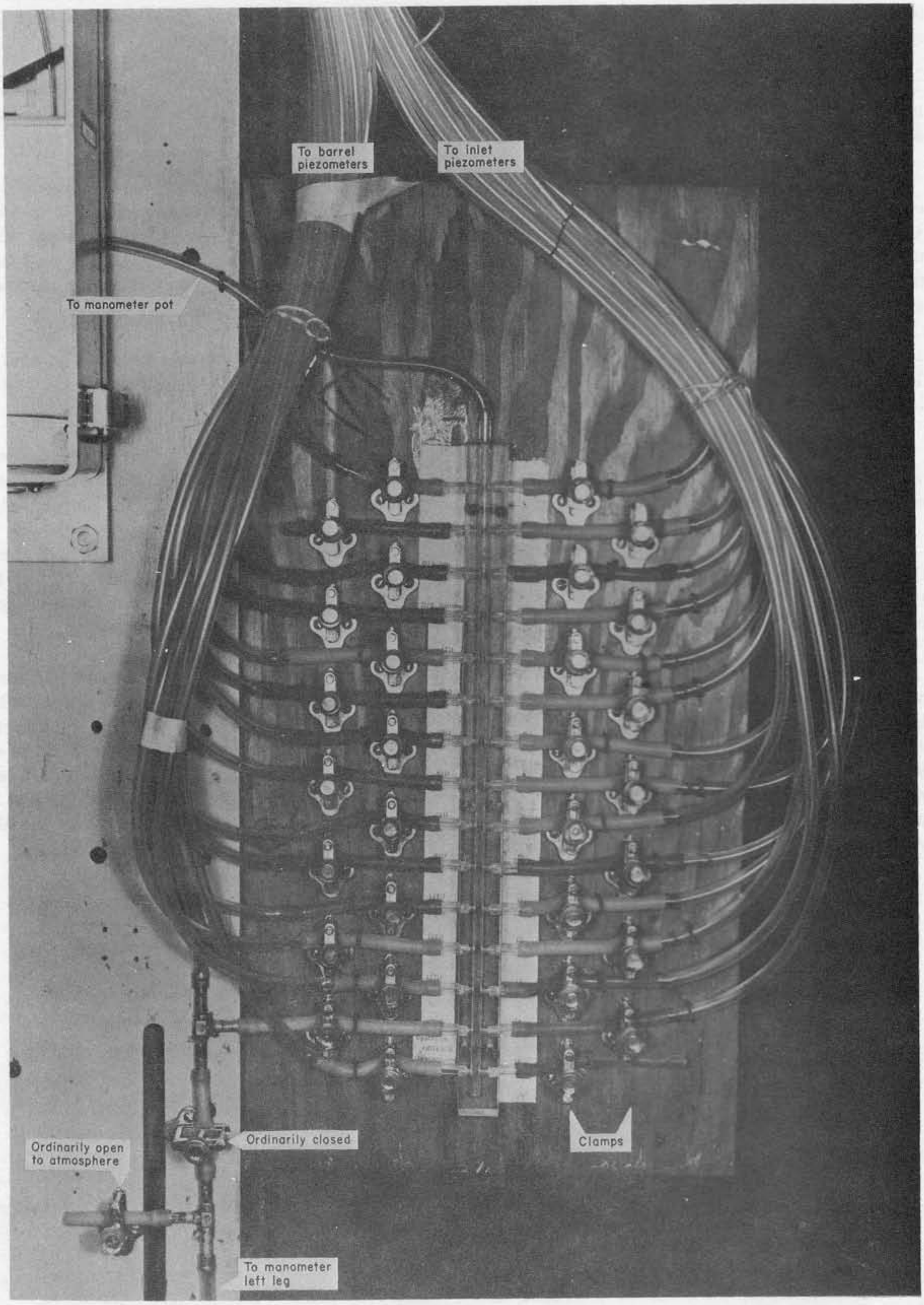


Fig. XI-14 - Pressure Manifold.

The micromanometer is used as a nul balance instrument. That is, the point gage is read only after it has been adjusted so that the meniscus is at a mark scribed on the tubing. This mark barely can be seen under the center graduation of Fig. XI-13 because the meniscus coincides with it. If there are no changes in the volume of the flexible tubing due to changes in pressure, then the level in the manometer pot is at its initial level and the difference between the zero and final readings of the point gage is the pressure in feet of water. The area of the pot is purposely made relatively large to minimize surface level variations due to volume changes in the connecting 3/16-inch inside diameter by 5/16-inch outside diameter vinyl tubing.

A single micromanometer is used for all pressure readings. This made necessary the manifold shown in Fig. XI-14. A single flexible tube connects the micromanometer to the manifold. Flexible tubing connected to each piezometer also terminates in this manifold. Fisher Scientific Company No. 5-847 Castaloy-R hosecock clamps are used to close all tubes except the one leading to the desired piezometer. Originally the clamp was applied to the 3/16-inch inside diameter vinyl tubing. Repeated clamping caused holes to develop in the 1/16-inch-thick walls so the tubing under the clamp was replaced with gum rubber tubing.

Test Procedure

Waiting Period

Before making any experimental observations it is necessary to let the blower warm up with the flow control valve set to give the approximate desired rate of flow. If this precaution were not taken, rate of flow changes would occur and pressure readings would drift during the course of a test.

Fig. XI-15 shows that the temperature in the blower exhaust rises to 30° F or more above the ambient temperature. Notes explain the changes that occur in the exhaust temperature.

When the blower is first started up, a minimum waiting period of 30 minutes is required to insure that the system has reached equilibrium. Between runs, where only the flow control valve setting is changed, a minimum waiting period of 10 minutes is sufficient. The distance thermograph recording is used to determine when stable conditions have been reached.

Observations

Observations are begun after stabilized flow conditions are achieved. Initially, the psychrometer, barometer, and all thermometers were read at the beginning and end of each run. Also, the atmospheric and barrel outlet thermometers were read at 15-minute intervals during a run and average readings were used in subsequent computations. In mid-1963, conversion to semi-automatic recording of the observations directly on punched tape in a form acceptable to the digital computer [XI-12] and the consequent elimination of pencil data recording made it desirable to use initial observations only. The potential errors that might result from single readings will be investigated later in this technical paper. The remaining observations are made using the micromanometer to read, successively, the zero reading, the orifice pressures, the pressures along the barrel, and the pressures in the inlet. The time required to take a complete set of observations has ranged from 5 minutes when a single drop inlet piezometer was read to 120 minutes when 98 piezometers were read.

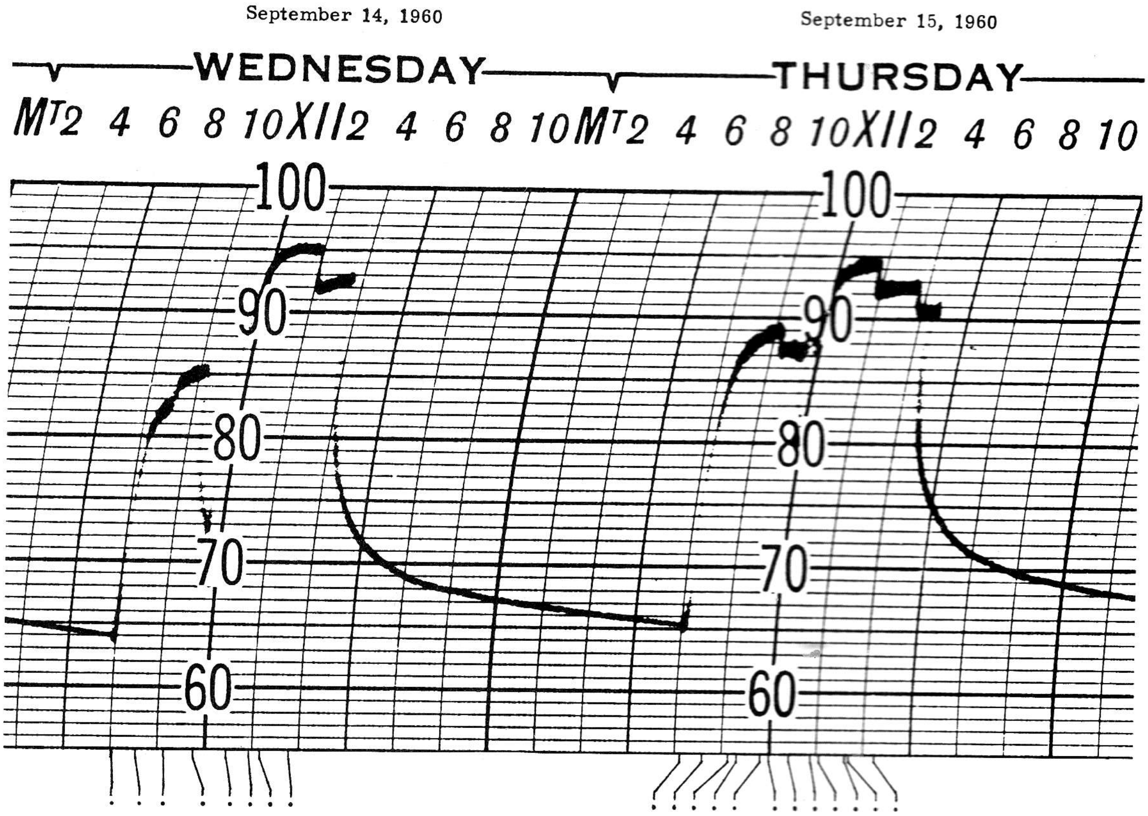
A check of the distance thermograph, hygrothermograph, and microbarograph charts indicates if and when important changes have taken place during a run.

Drift in Observations

Inspection of the recorder charts shows that the following changes have occurred in the maximum 2-hour period required to complete a set of observations:

Barometric pressure	0.20 inch of mercury
Temperature	8° F
Relative humidity	32 per cent

No changes this large have ever occurred during a test; they represent possible but not necessarily maximum variations that might occur.



Time	History of Operation
8:00	Blower turned on
9:05	Series A-45, Run 7, begin
10:15	Series A-45, Run 7, end Blower turned off; inlet change
11:20	Blower turned on
12:45	Series A-46, Run 1, begin
1:45	Series A-46, Run 1, end, flow decreased
2:15	Series A-46, Run 2, begin
3:23	Series A-46, Run 2, end, blower turned off
8:05	Blower turned on
9:00	Series A-46, Run 3, begin
10:10	Series A-46, Run 3, end, flow decreased
10:30	Series A-46, Run 4, begin
11:30	Series A-46, Run 4, end, blower turned off Orifice size increased
11:55	Blower turned on, maximum flow
12:40	Series A-46, Run 5, begin
1:40	Series A-46, Run 5, end, flow decreased
2:00	Series A-46, Run 6, begin
3:15	Series A-46, Run 6, end, flow decreased
3:25	Series A-46, Run 7, begin
4:20	Series A-46, Run 7, end, blower turned off

Fig. XI-15 - Blower Exhaust Temperature.

Large rates of change of barometric pressures are shown in Fig. XI-16. A long period of rapid drop in pressure began about midnight on January 18, 1963. The change between 6 p.m. and 8 p.m. on January 19 was 0.18 inch. The greatest change recorded occurred in a 25-minute period beginning at about 5:30 a.m. on August 3, 1960. The change was 0.20 inch. However, there was no net change between 2 a.m. and 8 a.m.

Temperature and relative humidity changes are usually inversely related and may be a result of several causes. Opening or closing the outside doors has a major effect. Operation of the unit heaters also affects the temperature and relative humidity.

The maximum ranges of temperature and relative humidity experienced are shown in Fig. XI-17 and the causes are identified therein. On May 11, 1961, the outside door was opened at about 8 a.m. on what apparently was a warm, dry day. In any case, the temperature rose somewhat during the day and the relative humidity dropped 39 per cent, with 30 per cent of this change occurring during the first hour. The record for May 26, 1961, shows an unexplained drop of 32 per cent in the relative humidity in 30 minutes with no change in the temperature. The record for December 17, 1962, shows the maximum observed temperature increase of 8° F accompanied by a 23 per cent drop in the relative humidity. It seems likely that these changes may have resulted from setting the unit heater thermostats to give a higher room temperature.

The ordinary effects of intermittent unit heater operation are shown in Fig. XI-18.

The effects of opening or closing the outside door are shown in Fig. XI-19. The room in which the air apparatus is located is used by others who may open and close the doors to admit supplies and equipment, or for other reasons. These door changes can occur without warning and without the air apparatus observer being aware of them until the readings are affected.

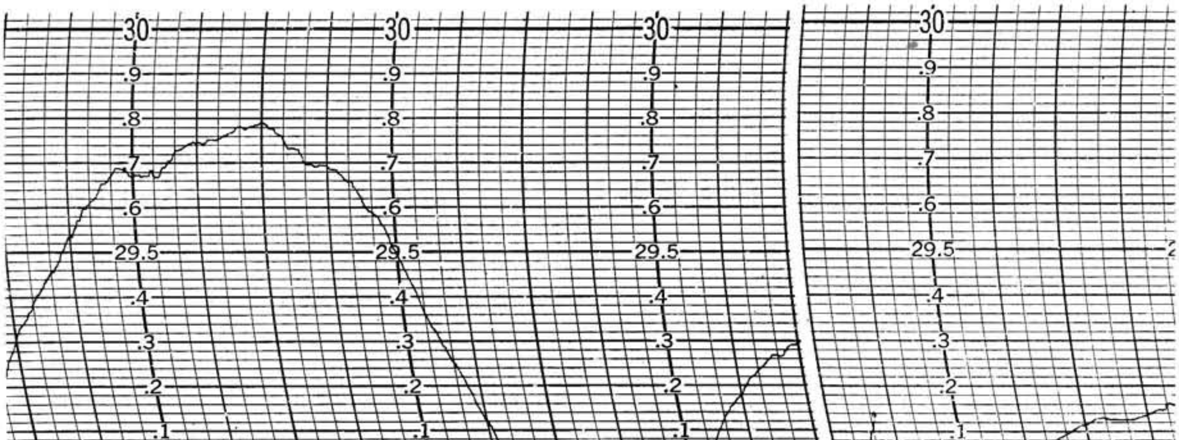
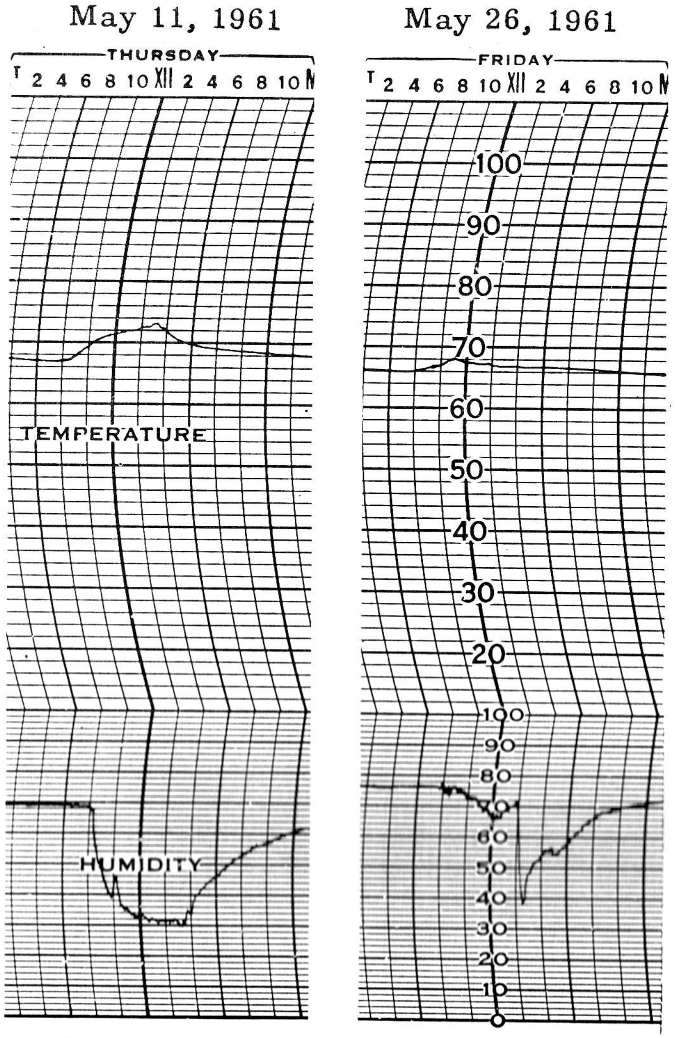


Fig. XI-16 - Barometric Pressure Changes.



Outside door opened

Reason for change is unknown

Unit heater fan probably turned up

Fig. XI-17 - Range of Temperature and Relative Humidity.

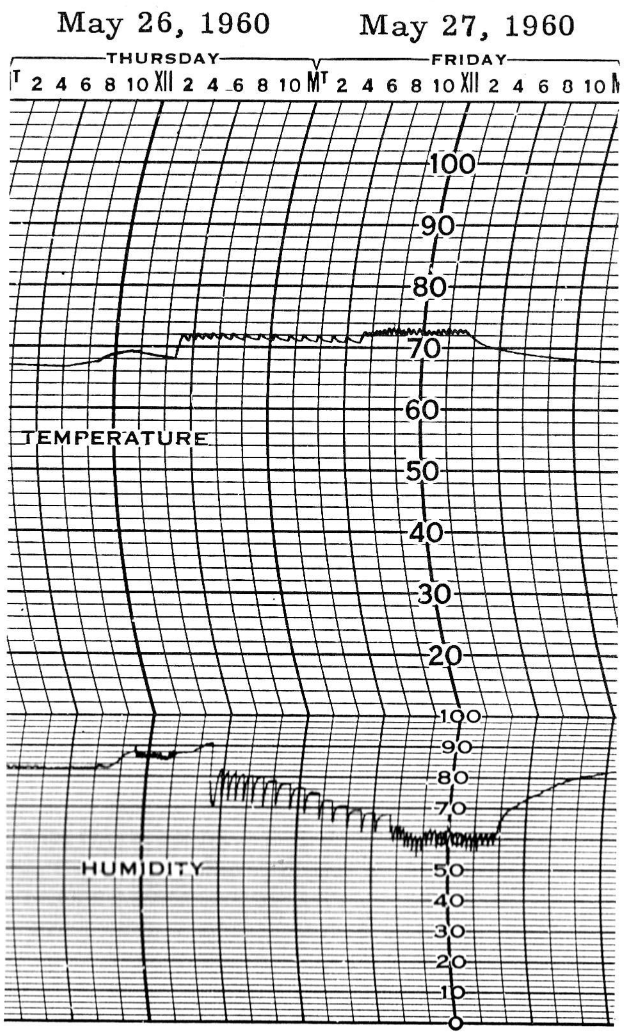
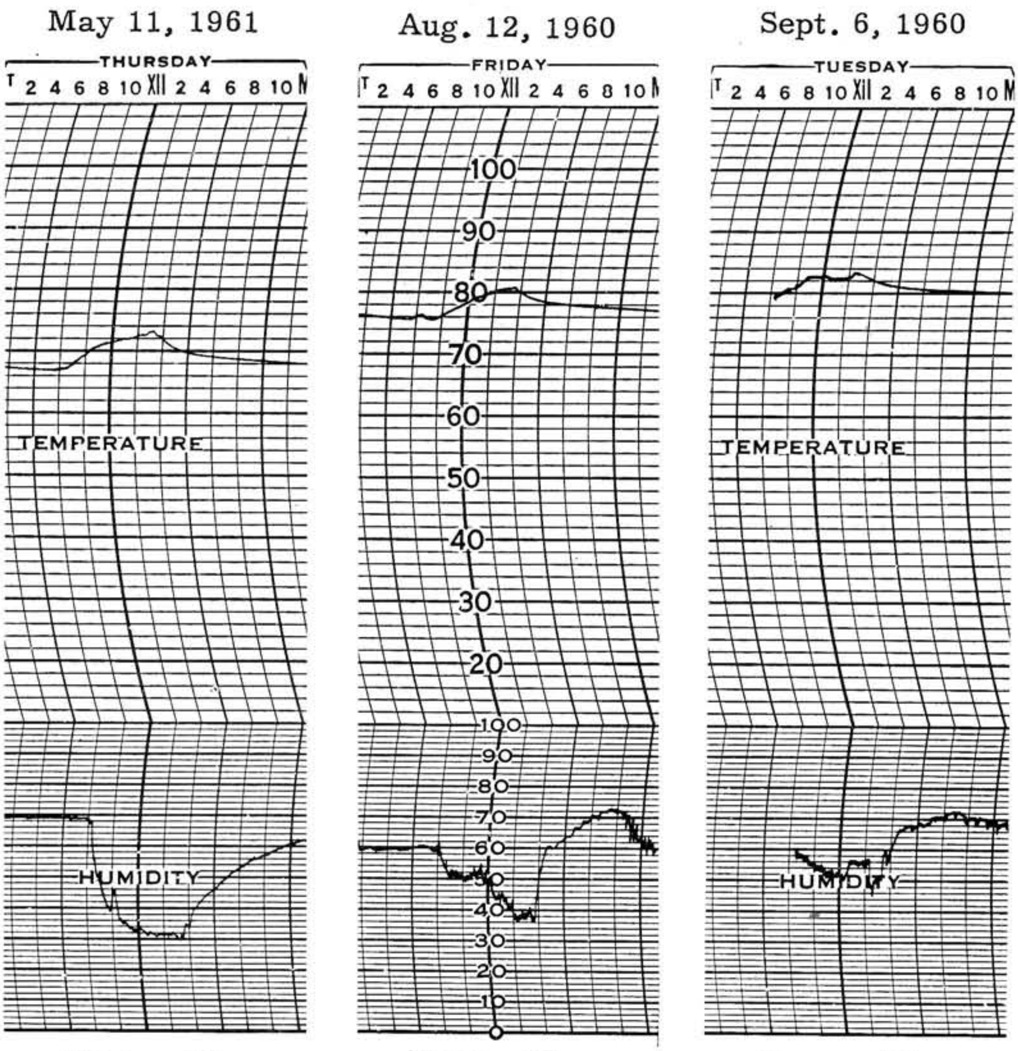


Fig. XI-18 - Effect of Unit Heater Operation.



Door	Time
Opened	8:00±

Door	Time
Closed	3:45±

Door	Time
Closed	12:15±
Opened	2:15±
Closed	2:30±

Fig. XI-19 - Effect of Opening and Closing Outside Door.

The charts of Figs. XI-16 to XI-19 show that the effects of changes in barometric pressure, temperature, and relative humidity must be evaluated and tolerable limits set to insure satisfactory precision of the experimental results. The effect of these changes on the experimental results is shown in Table XI-4.

Only changes in the entrance loss and pressure coefficients are of importance from a practical standpoint. Furthermore, changes beyond the second decimal place are outside the limit of precision of the experiments. The maximum changes in the coefficients resulting from the maximum probable changes in the barometric pressure, atmospheric temperature, and relative humidity shown in Table XI-4 are seen to amount to a maximum of only two units in the third decimal place. This is an insignificant change.

The conclusion to be derived from this discussion is that the maximum probable changes in the environment in the vicinity of the air apparatus will have no practical effect on the experimental results.

It therefore appears that any environmental changes that occur after a reading is taken and recorded at the beginning of a run will not affect the results. This permits the observer to make a single observation of the environment and punch it on the computer input tape at the time the observation is made and assures the observer that it will not be necessary to check or correct the observation as a result of environmental changes that may occur during the experiment.

Precautions

Some of the precautions necessary to insure dependable experimental data will be presented. Most of these precautions must be exercised during the experiments. However, the first point to be discussed will show that when computing the experimental results it is necessary to use the thermodynamic equations developed herein instead of the simpler hydrodynamic equations.

TABLE XI-4

EFFECT ON RESULTS OF CHANGES IN

BAROMETRIC PRESSURE, TEMPERATURE, AND RELATIVE HUMIDITY

AGRICULTURAL RESEARCH SERVICE
AIR MODEL TEST RESULTS

SERIES A -378

RUN NO.	1	Error $\times 10^3$	1	Error $\times 10^3$	1	Error $\times 10^3$	1	Error $\times 10^3$	1	Error $\times 10^3$
P2/P1	.943	0	.942	-1	.943	0	.943	0	.943	0
W	.496	0	.494	-2	.500	+4	.494	-2	.499	+3
F	.016	0	.016	0	.016	0	.016	0	.016	0
R	207911.676		207112.737		212057.223		207228.996		211542.540	
D/2 TOP	-1.097	0	-1.098	-1	-1.097	0	-1.097	0	-1.097	0
D/2 BOT	-.003	0	-.003	0	-.003	0	-.003	0	-.003	0
170	-.002	0	-.002	0	-.002	0	-.002	0	-.002	0
330	-.009	0	-.009	0	-.009	0	-.009	0	-.009	0
490	.005	0	.005	0	.005	0	.005	0	.005	0
650	-.001	0	-.001	0	-.001	0	-.001	0	-.001	0
810	.012	0	.012	0	.012	0	.012	0	.012	0
970	.006	0	.006	0	.006	0	.006	0	.006	0
1130	-.016	0	-.016	0	-.016	0	-.016	0	-.016	0
1290	.009	0	.009	0	.009	0	.009	0	.009	0
1370	-.006	0	-.006	0	-.006	0	-.006	0	-.006	0
KE	.787	0	.787	0	.787	0	.787	0	.787	0
KC	.725	0	.726	+1	.725	0	.725	0	.725	0
KT	.596	0	.596	0	.596	0	.596	0	.596	0
1	-1.725	0	-1.726	-1	-1.725	0	-1.725	0	-1.725	0
2	-1.806	0	-1.807	-1	-1.806	0	-1.806	0	-1.806	0
3	-1.992	0	-1.993	-1	-1.992	0	-1.992	0	-1.992	0
4	-2.470	0	-2.472	-2	-2.470	0	-2.470	0	-2.470	0
5	-2.824	0	-2.826	-2	-2.824	0	-2.824	0	-2.824	0
Input change	a		b		c		d		e	

Input change:
a. None
b. Barometric pressure decreased 0.20 inches of mercury
c. Atmospheric temperature decreased 8 °F
d. Relative humidity increased 30 percent
e. Atmospheric temperature decreased 8 °F and relative humidity increased 30 percent

Comparisons of Incompressible, Isothermal, and Adiabatic Equations of Flow. Comparisons of the incompressible, isothermal, and adiabatic conditions of flow are made for the rate of friction loss in horizontal pipes that covers the range of pressure drops along the pipe that is possible with the experimental apparatus in use. These comparisons are made for initial Mach numbers $\mathbb{M}_e$ that cover the possible range, where the Mach number is the ratio of the actual velocity to the acoustic velocity. The equations used for computing the friction loss are those presented by Binder [XI-9, p. 64, Eq. 3-13; p. 63, Eq. 3-9; p. 67, Eq. 3-19].

The results are presented in Table XI-5. It is apparent that little difference in the results is obtained if either isothermal or adiabatic conditions are assumed; an error in the initial assumption would not cause a significant error in the results. However, a large and significant error will result if the simpler incompressible (hydrodynamic) equations are used. These errors could be as large as 23 per cent.

It is obvious that thermodynamic equations must be used to avoid serious errors in the results.

TABLE XI-5

COMPARISON OF GAS EQUATIONS

p_2/p_1	$\underline{M}_e$	$f\ \ell/D$			Incompressible / Isothermal	Adiabatic / Isothermal
		Incompressible	Isothermal	Adiabatic		
0.99	0.05	5.72	5.66	5.70	1.011	1.007
	0.1	1.43	1.40	1.41	1.021	1.007
	0.2	.358	.335	.337	1.069	1.006
	0.3	.159	.137	.139	1.161	1.014
0.95	0.05	28.6	27.8	27.9	1.029	1.004
	0.1	7.15	6.87	6.90	1.041	1.004
	0.2	1.79	1.64	1.66	1.091	1.012
	0.3	.795	.673	.681	1.181	1.012
0.90	0.05	57.2	54.1	54.2	1.057	1.002
	0.1	14.3	13.4	13.4	1.067	1.000
	0.2	3.58	3.18	3.20	1.126	1.006
	0.3	1.59	1.29	1.31	1.232	1.016

Effect of Water Vapor. Water vapor in the air can affect the results in two ways. First, the enthalpy (the sum of the internal and external energies) is different for a mixture of air and water vapor than it is for dry air alone. The magnitude of this difference is shown in Table XI-6 to be up to 3 per cent for the range of pressures and relative humidities encountered under the conditions at the air apparatus site. This difference is felt to be sufficient to warrant the inclusion of corrections for the water vapor content when the computations are made. The equations developed previously therefore include the effect of water vapor.

The second important effect of water vapor is that condensation may occur, particularly under conditions of large pressure drops and high humidities. Condensation is a change of state from water vapor to liquid water. The energy changes involved are not taken into consideration in this analysis. Therefore, the equations presented herein become invalid if there is condensation.

TABLE XI-6

EFFECT OF WATER VAPOR

t_a = 75.0° F T_a = 534.7° R (Eq. XI-32) p_a = 29.0 in. Hg k = 1.396 (k − 1)/k = 0.284

Quantity	Units	Source						
r	percent	Assumed	0	50	60	70	80	90
Δt	°F	[XI-24, pp. 62-66, Table VII]	29.0	12.5	9.8	7.0	4.5	2.2
t_w	°F	$t_a - \Delta t$	46.0	62.5	65.2	68.0	70.5	72.8
Dew point	°F	[XI-24, pp. 24-32, Table II]	<-25.	55.	60.	65.	68.	72.
p_v	in. Hg	[XI-24, pp. 24-32, Table II]	.000	.432	.517	.616	.684	.783
s	lb. vapor/lb. air	[XI-8, p. 4-83, Eq. 4]	.0000	.0094	.0113	.0135	.0150	.0173
h'_{ma}	Btu/lb. air	[XI-8, p. 4-84, Eqs. 8 & 9]	18.000	28.293	30.374	32.782	34.425	36.944
	p/p_a = 0.99:	T_2 = 533.2° R (Eq. XI-34)			t_2 = 73.5° F (Eq. XI-32)			
h'_{m2}	Btu/lb. air	[XI-8, p. 4-84, Eqs. 8 & 9]	17.640	27.927	30.006	32.414	34.055	36.572
$\Delta h'_m$	Btu/lb. air	$h'_{ma} - h'_{m2}$	.360	.366	.368	.368	.370	.372
Moist/dry	---	$\Delta h'_m / \Delta h'_{m\,(r\,=\,0)}$	1.000	1.017	1.022	1.025	1.028	1.033
	p/p_a = 0.95:	T_2 = 526.9° R (Eq. XI-34)			t_2 = 67.2° F (Eq. XI-32)			
h'_{m2}	Btu/lb. air	[XI-8, p. 4-84, Eqs. 8 & 9]	16.128	26.389	28.463	30.864	32.502*	35.012*
$\Delta h'_m$	Btu/lb. air	$h'_{ma} - h'_{m2}$	1.872	1.904	1.911	1.918	1.923*	1.932*
Moist/dry	---	$\Delta h'_m / \Delta h'_{m\,(r\,=\,0)}$	1.000	1.017	1.021	1.025	1.027*	1.032*
	p/p_a = 0.90:	T_2 = 518.9° R (Eq. XI-34)			t_2 = 59.2° F (Eq. XI-32)			
h'_{m2}	Btu/lb. air	[XI-8, p. 4-84, Eqs. 8 & 9]	14.208	24.436	26.503*	28.897*	30.529*	33.031*
$\Delta h'_m$	Btu/lb. air	$h'_{ma} - h'_{m2}$	3.792	3.857	3.871*	3.885*	3.896*	3.913*
Moist/dry	---	$\Delta h'_m / \Delta h'_{m\,(r\,=\,0)}$	1.000	1.017	1.021*	1.025*	1.027*	1.032*

---

* Fictitious because of condensation; t_2 is below the temperature of the dew point.

Condensation is indicated for several of the conditions shown in Table XI-6 when the relative humidity is in excess of 50 per cent. It is therefore necessary for the observer to be alert to the possibility of condensation and either suspend the tests or control the environment to prevent condensation. Condensation is likely to first appear in low pressure regions downstream of the measuring orifice or just inside the barrel entrance.

Dust. Atmospheric dust collects in the closed conduit spillway. The spillway must be watched carefully for evidence of dust accumulation.

Dust uniformly deposited on the walls would change the pipe friction loss. But this would have no effect on the entrance and pressure coefficients because friction is eliminated in the analysis. However, accumulations of dust around the piezometers are known to affect the readings. These accumulations are greater in the downstream part of the barrel than in the upstream part. The observer must check continuously for evidence of dust accumulation and periodically disassemble and wash the spillway.

Leaks. Leaks in a water apparatus are easy to detect and may not seriously affect the results. In contrast, leaks in an air apparatus are hard to detect and uncertainty as to their magnitude leads to uncertainty as to their effect. The observer must periodically check for leaks, particularly in the piezometer-to-manometer lines.

Leaks around the O-rings can be detected by dripping water around the couplings and observing if it is sucked into the joint.

Leaks in the pressure system can be detected and localized by setting a deflection on the micromanometer and clamping off a section of the system. If the micromanometer deflection changes, then there is a leak somewhere within the clamped-off section. The rapidity of the micromanometer deflection change indicates the seriousness of the leak. The most frequent leaks have been found in the manifolds or in the tubing under the clamps.

Comparison of Water and Air Tests

The first air tests were made primarily to check the air analytical methods, there being little doubt that identical results would be obtained using either water or air if the air analysis was made correctly.

Some differences were found between the entrance loss and pressure coefficients obtained on the water and air tests for the first two inlets. However, the agreement was close enough to show the correctness of the analytical methods.

To obtain a better check of the agreement between the water and air coefficients, the air apparatus was modified to accept a two-way drop inlet that had already been tested using water. With the modifications made, it is possible to compare only the inlet crest loss coefficient and pressure coefficients in the drop inlet. The comparison is made in Table XI-7. The agreement between the water and the air experiments is well within the limits of experimental precision.

No further formal check of the agreement of the water and air tests was attempted because the previous check showed the expected agreement with the theoretical predictions. Subsequent tests on the water apparatus and on the air apparatus were made to evaluate different spillway properties. Therefore, only occasional tests were performed on spillways that were sufficiently similar to permit quantitative comparisons of the results. A search of the available results shows only three comparisons that can be made. These are for two-way drop inlets 1 D (1 pipe diameter) wide and 1.5 D, 3 D, and 5 D long [XI-15]. The barrel entrance was square-edged and the barrel slope 0.20. The wall thickness was 0.444 D for the water tests and 0.5 D for the air tests. The anti-vortex plate was 0.8 D above the crest for the water tests and 0.812 D for the air tests. The overhang of the anti-vortex plate outside the drop inlet was 1.5 D for both tests. Because of the important effects of plate height

TABLE XI-7

COMPARISON OF THE COEFFICIENTS OBTAINED ON THE SAME DROP INLET USING BOTH WATER AND AIR

Fluid	K_c	Pressure Coefficient				
		1	2	3	4	5
Water	1.14	2.14	4.01	3.97	0.33	0.37
Air	1.20	2.20	3.99	3.90	0.27	0.30

K_c represents the loss between the headpool and the mid-height of the drop inlet.

Piezometer 1 is at the mid-height of the drop inlet.

Piezometer 2 is on the inside rounding of the crest.

Piezometer 3 is on the flat portion of the crest.

Piezometer 4 is in the anti-vortex plate over the center of the drop inlet.

Piezometer 5 is in the anti-vortex plate directly over piezometer 3.

and wall thickness on the crest loss coefficient, the comparison will be for the barrel entrance loss coefficients where the effects of these variations are minimized. The average barrel entrance loss coefficients obtained are:

Drop inlet length	1.5 D	3 D	5 D
Coefficient from water tests	0.65	0.48	0.39
Coefficient from air tests	0.65	0.48	0.41

Such comparisons as are available are presented and show that identical results are obtained using either air or water as the test fluid when a valid substitution of one for the other can be made.

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P. 19, Eq. 23, equation for gas constant.

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A curve shows very good comparison of air and water tests of a pump. Air tests do not reproduce cavitation. Power required for air tests is so small that errors in measurement preclude determining the efficiency. Errors due to viscosity and elasticity are insignificant.

[XI-3] Anonymous. "Standard Density and Volumetric Tables." U. S. Department of Commerce, Circular of the Bureau of Standards, No. 19. Washington: Government Printing Office, 6th Edition, October 31, 1924.

P. 50, Table 34.—Weight of 1 cubic foot of water.

[XI-4] Anonymous. "The Aerodynamic Testing of Centrifugal Pumps and Water Turbines." Engineering (London), Vol. CXLVII (147), No. 3811, pp. 93-96, January 27, 1939.

Compressibility is of small importance if the changes in pressure and temperature are small and the velocity of flow is small compared with the velocity of sound. The models must have geometric similarity and close equality of Reynolds numbers, although a discrepancy of Reynolds numbers does not affect the reliability of the results when a correcting coefficient is introduced. Both pressure and suction are used to test turbines. Vacuums are apparently only about 100 mm. (4 in.) of water.

[XI-5] Anonymous. "Combined Aerodynamic Research for All Turbo-Machines." Escher Wyss News, Vol. 17/18, 1944/45, pp. 173-174.

Wet and dry steam, gas, water, or air can be simulated by air tests. Steam turbines, water turbines, pumps, and valves can be investigated.

[XI-6] Ball, James W. "Model Tests Using Low Velocity Air." Transactions, American Society of Civil Engineers, Vol. 117, 1952, pp. 821-838.

Low air velocities range up to about 250 feet per second or about 25 percent of the sonic velocity. They yield, for all practical purposes, the same results as hydraulic tests. The hydraulic equation can be used for an intake orifice if the pressure differential is less than 1 foot of water. Fig. 2 shows the error introduced by using a hydraulic instead of an aerodynamic equation for an intake orifice.

Advantages of low velocity air testing: (p. 822) "1. The low density of air minimizes the structural requirements of the test facilities. 2. Power requirements to circulate the test fluid are comparatively low. 3. Absolute fluid tightness is not essential but more easily attained. The wetting problem is nonexistent, permitting use of wide variety of materials. 4. The atmosphere serves both as a supply reservoir and a catch basin. 5. Test procedure is usually greatly simplified but requires certain types of more highly developed and sensitive instruments. 6. Reynolds numbers can be made about the same for either air or water in a given model. Use of a larger model to test at a higher Reynolds number might be advantageous in some cases. 7. The relationships for noncompressible fluids can be applied with negligible error if the air velocities are kept below certain values . . ."

Disadvantages are: ". . .it appears that air could not be used to replace a liquid where effects of compressibility, cavitation, and gravity effects are predominating factors. This is not always the case, but it is necessary to be sufficiently familiar with the dynamics of gaseous flow in order to recognize when such studies are applicable."

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[XI-8] Baumeister, Theodore. (Marks') Mechanical Engineers' Handbook. New York: McGraw-Hill Book Company, Inc., Sixth Edition, 1958.

P. 4-11, equation for specific heat of mixtures.

P. 4-20, Table 23. Properties of Gases

P. 4-83, Eq. (1), equation for vapor pressure of air-water mixture.

Eq. (2), equation for relative humidity.

Eq. (4), equation for specific humidity.

Eq. (5), equation for specific weight of dry air.

Eq. (6), equation for vapor density.

Eq. (7), equation for specific weight of vapor-laden air.

Table 1. Vapor Pressure of Water

Pp. 12-150 to 157, sound and noise.

P. 12-153, Table 2. Typical Sound Levels

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Vol. I, p. 64, Eq. 3-13, equation for $f\ell/D$ assuming incompressible flow.

Vol. I, p. 67, Eq. 3-19, equation for $f\ell/D$ assuming adiabatic flow.

[XI-10] Blaisdell, Fred W. Hydraulics of Closed Conduit Spillways. Part I. Theory and Its Application. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Paper No. 12, Series B, Revised February 1958.

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"Apparently opposed to these advantages are factors stemming from the three major characteristics of liquids as distinguished from gases: the relatively high elastic modulus, the tendency to become discontinuous when the vapor pressure of the liquid is reached, and the ability to maintain a free surface. It would therefore seem that air could not replace water for experimental purposes under conditions involving the effects of compressibility, cavitation, or gravitational attraction. Such, however, is not entirely the case . . . . air may undergo velocity changes of several hundred feet per second without the influence of its compressibility becoming apparent . . ."

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of the approaching stream, check with the tests run with air to a degree which was within the limits of the error of observation.

"That the tests conducted with water should check with those run with air simply verifies the mathematical relationships which apply to scoops or divergent tubes, since it will be observed in the various formulas presented in the theoretical discussion that all the expressions for head contain no factors which are dependent upon the medium employed, as long as the head is expressed in feet of the same fluid.

"Strictly speaking, from a scientific standpoint, there are factors which should be taken into consideration, such as the scale effect and the variation in kinematic viscosity between water and air. As far as the writer has been able to observe from his experience with pumps and blowers, these do not influence the results to a practical degree within the limits of size which would ever be required."

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Technical Paper No. 44, Series B
St. Anthony Falls Hydraulic Laboratory

HYDRAULICS OF CLOSED CONDUIT SPILLWAYS. PART XI. TESTS USING AIR, by Fred W. Blaisdell and George G. Hebaus. January 1966. 52 pages incl. 19 illus.

Air instead of water is used to evaluate the full flow entrance loss coefficients and pressure coefficients for closed conduit spillways. The paper explains that air cannot be used as a substitute for water when the spillway is only part full, gives reasons for using air instead of water, presents background information, compares the water and air equations, develops the compressible flow equations required to analyze the data, and describes the test apparatus and procedure. Verification tests show that identical results can be obtained using either air or water.

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1. Testing with Air
2. Air Tests
3. Fluid Flow
4. Spillways, Closed Conduit
5. Culverts

I. Title
II. Blaisdell, Fred W.
III. Hebaus, George G.
IV. St. Anthony Falls Hydraulic Laboratory

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5. Culverts

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IV. St. Anthony Falls Hydraulic Laboratory

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