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IMPINGING JETS

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16. ABSTRACT

This report summarizes eight reports, selected from a review of literature on free jets striking solid boundaries. Numerous other reports found, were not directly related, but were about scour caused by a hydraulic jump or a roller bucket type spillway, but not a free jet. Nearly all eight reports are about small-scale tests that have been made with and without a water cushion. They relate the pressures to the velocity of the jet or height of fall or both. Several estimates for rate of velocity decrease, or excess pressure on a solid boundary are developed in these reports. These relationships were compared and one method is recommended for use in design procedures, which compares favorably with Water and Power Resources Service hydraulic model test data. The procedure will give conservative estimates of pressures unless the flow converges. Model tests are recommended whenever the geometry of the spillway causes the flow to converge.

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IMPINGING JETS

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ WATER AND POWER RESOURCES SERVICE

In May of 1981, the Secretary of the Interior approved changing the Water and Power Resources Service back to its former name, the Bureau of Reclamation. All references in this publication to the Water and Power Resources Service should be considered synonymous with the Bureau of Reclamation.

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GLOSSARY

b - Jet thickness
b_p - Distance at which $P = \frac{1}{2} P_m$
b_u - Radial distance at which $V = \frac{1}{2} V_m$
d - Nozzle or orifice diameter
c - Depth of water cushion
D - Jet width or $\sqrt{\frac{4Q}{\pi V}}$
e - Base of natural logarithms
g - Gravitational acceleration
H - Distance from nozzle to plate, or height of fall
H_c - Excess pressure without a water cushion
m - $0.225\ Q^{0.35}$
N_r - r/b_p
N_u - r/b_u
N_y - Y/b_p
P - Local excess pressure (above hydrostatic)
P_m - Maximum excess pressure
P_s - Stagnation pressure
P_w - Excess pressure on a wall or plate
Q - Discharge
r - Radial distance from jet axis or impact point
V - Velocity
V_m - Maximum velocity
V_o - Initial velocity
V_x - Velocity at any distance X
x - Distance from stagnation point to location of pressure measurement
X - Distance from nozzle along jet axis to location of pressure measurement
y - Distance from axis of jet to location of pressure measurement
y_c - Limit of the zone of flow establishment
y_s - Maximum depth at which equation ten is valid
y/b - Lateral distance per slot width
Y - Distance from center of impact parallel to plate, to location of pressure measurement

INTRODUCTION

A plunge basin can provide a simple, economical method of dissipating the energy from falling jets. These jets may be from gates and valves or from flip buckets and overflow spillways. A plunge basin is a deep pool into which a free jet of water falls. This jet enters the pool and its energy is dissipated by shearing action with the surrounding water and with the boundaries of the basin. The basin may be formed by the action of the jet falling on erodible material or it may be constructed as a lined or unlined structure from non-erodible material.

If the boundaries or dividing walls of the basin are near the point of the jet impact, high pressures and high forces will be developed. The forces created by the jets must be known so that structures can be designed properly to withstand these forces. These forces depend on the total head available (height of fall plus velocity head), the tailwater depth, the angle of entry into the basin, the size and shape of the basin, and the compactness of the jet. The compactness of a jet describes the turbulence in the jet and how much air has been mixed with the falling water. The physical characteristics of a jet change as it falls through the air. The jet is smooth and compact with negligible air in it when the height of fall is small. As the height of fall increases, the surface of the jet becomes rough and the jet spreads out and becomes mixed with air. Finally, the water breaks into discrete segments if the fall height is large. Pressures and forces are greatly reduced when the jets are broken into particles. Most large structures that create free surface jets that have fairly rough surfaces often fall as discrete particles. The stilling action in these basins is very complex; however, insight into these situations may be obtained by studying the results from small scale tests without a water cushion and direct impact of a jet on the water surface. Results of several small-scale model studies will be discussed and summarized in this report. Criteria summarized from these studies will be compared to existing data.

The dissipation of a free jet in a plunge pool is similar to a submerged jet in a confined basin. Both have (fig 1) a region of flow establishment, an established flow region (where the energy is diffused into the surrounding fluid) an impingement region, and a region very similar to a wall jet. The region of flow establishment is where the shearing action at the edge of the jet decreases the edge velocity, but does not affect the velocity near the center of the jet. The length of this region varies with the initial conditions of the jet entering the basin. The length of the flow establishment region for a round jet is about 6 diameters; however, it varies from 5 to 10 times the thickness of rectangular jets. The limit of this region is where the mixing zone penetrates the center of the jet. Beyond this limit, the velocity of the jet is decreased at the centerline and the energy of the jet is diffused into the surrounding fluid. This process continues until all the initial energy of the jet is dissipated, or until the influence of a boundary causes an impinging flow region. Without a boundary, the diffusion of the jet continues until its energy is dissipated into the surrounding fluid.

If a boundary is near the entry point of the jet, a region of increased pressure is formed. The pressure at the boundary may be nearly equal to the velocity head of the free jet if it is within the region of flow establishment. Pressures decrease rapidly with increasing radial distance from the axis of the jet. Flow around the impact point is radial if there are no walls to confine the flow. High shear stresses exist near the boundary, and negative pressures around the impingement point may exist. Negative pressures were observed during the tests performed by Cola [1][1] and Lencastre [2].

SUMMARY

This report compares the velocities and pressures at the boundaries of a basin caused by a free jet entering the basin. Some of the reports reviewed were for small-scale tests with and without water cushions.

Pressures at the boundaries were equal to the full stagnation pressure if the depth of the cushion was less than the depth of flow establishment. Beyond this depth boundary, pressures decrease rapidly as the depth of the water cushion increases. Most of the studies also show that the pressure decays nearly exponentially as the radial distance from the point of impact increases.

Several of the empirical criteria are summarized and compared with results from laboratory model tests. The comparison shows that the criteria selected give similar values to the results of the model tests.

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[1]Numbers in brackets refer to literature cited in the bibliography.

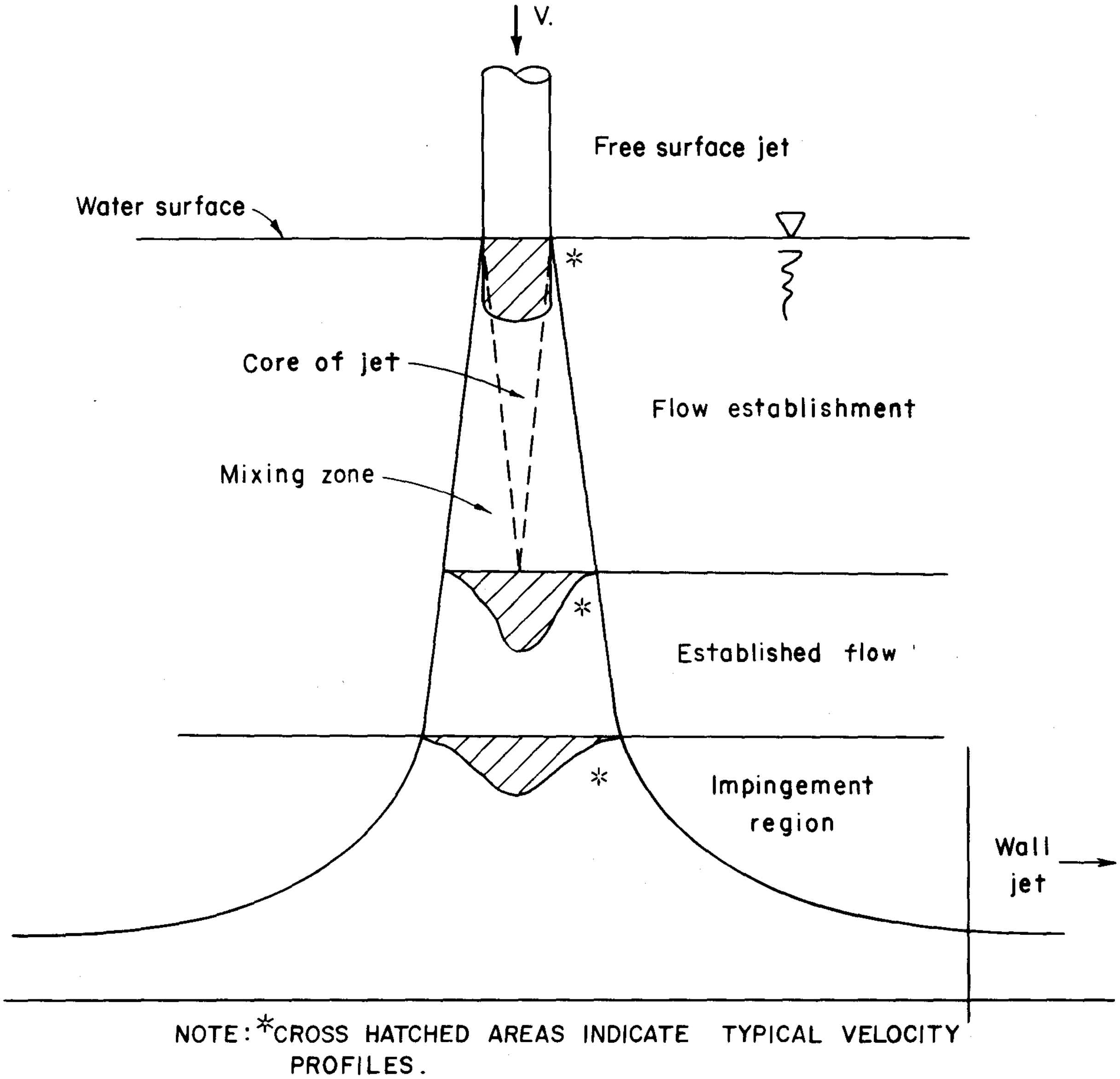

Figure 1.—Typical jet regions for submerged or free jets in a confined basin.

Several questions not answered by the studies cited are:

a. What is the effect of a nonvertical jet entering a basin?

b. How significant is the compactness of the jet entering the plunge basin? What is the amount of reduction in pressure due to jet disintegration?

c. Does entrained air in a jet reduce the pressure in a plunge basin?

d. What is the impact of a crossflow in a plunge basin, resulting from a powerplant or river outlet?

e. Can splitter piers or similar devices be used to reduce the impact pressures?

f. What is the effect of different stilling basin geometries?

Until the above questions can be answered, the relationships presented in this report will provide reasonable estimates for maximum pressures at the bottom of a plunge pool. However, if the jet is concentrated, like the Crystal spillway, higher pressures may result.

RESULTS OF PREVIOUS EXPERIMENTS

Circular Jets

Several tests have been reported for jets striking an unsubmerged plate (fig. 2). These tests without a water cushion result in maximum pressures and forces. The P_m (maximum pressure) is the equivalent to the stagnation pressure of the jet. A region around the center of the jet will have pressures equal to the stagnation pressure $P_s = V^2/2g$. The behavior of a jet plunging into a water cushion is similar to a free jet striking a plate. However, the velocities will decay more rapidly than the free jet and the excess pressures will decrease more rapidly.

In the results of a study [3] using a circular jet striking a flat plate, the nozzle diameter d varied from 6.4 to 23.4 mm and the height of the nozzle H varied from [redacted] to 65.7 times d. The velocity profile of the jet could be represented by:

21.2

$$\frac{V}{V_m} = e^{-0.693\, N_u^2} \qquad (1)$$

where:

V = Velocity
V_m = Maximum velocity at the cross section of flow from the nozzle
b_u = Radial distance at which $V = 1/2\ V_m$
r = Radial distance from jet axis or impact point
N_u = r/b_u
e = Base of natural logarithms

Beltaos and Rajaratnam [3] found that the above relationship was valid for values of $X/H \leq 0.95$ where X is the distance from the nozzle to the location of pressure measurement and H is the distance from the nozzle to the plate. Impingement of the jet occurs for values of X/H greater than 0.95. The velocity profiles are not similar in this region, and static pressures exceed the ambient pressures. Excess pressure distribution in this region is given by:

$$\frac{P}{P_m} = e^{-0.693\, N_r^2}$$

where:

P = Local excess pressure
P_m = Maximum excess pressure
b_p = Radius at which $P = P_m/2$
N_r = r/b_p

A very interesting result was obtained by plotting the excess pressure at the plate P_w as a function of r/H and the stagnation pressure P_S. The pressure at the plate (fig. 3) approaches the ambient at $r = 0.22\ H$.

The form of the curve is:

$$\frac{P_w}{P_s} = e^{-114\left(\frac{r}{H}\right)^2} \qquad (2)$$

which is similar to the other pressure relationship; that is, pressure decays exponentially away from the region of maximum pressure.

Two-dimensional flow

The effect of sidewalls on a two-dimensional flow was studied by Beltaos and Rajaratnam [4]. A definition sketch of impingement is shown (fig. 4), and the results are similar to those given

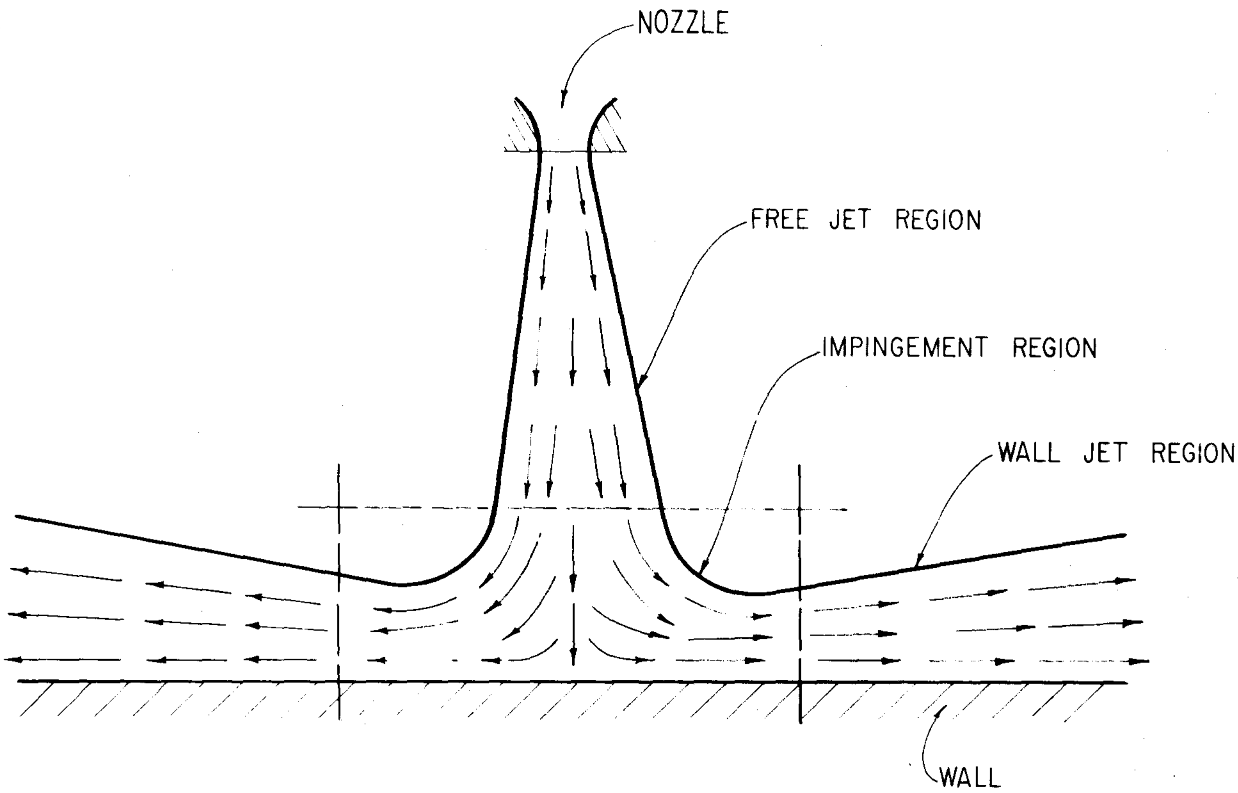

Figure 2.—Normal impingement of a jet on a flat plate.

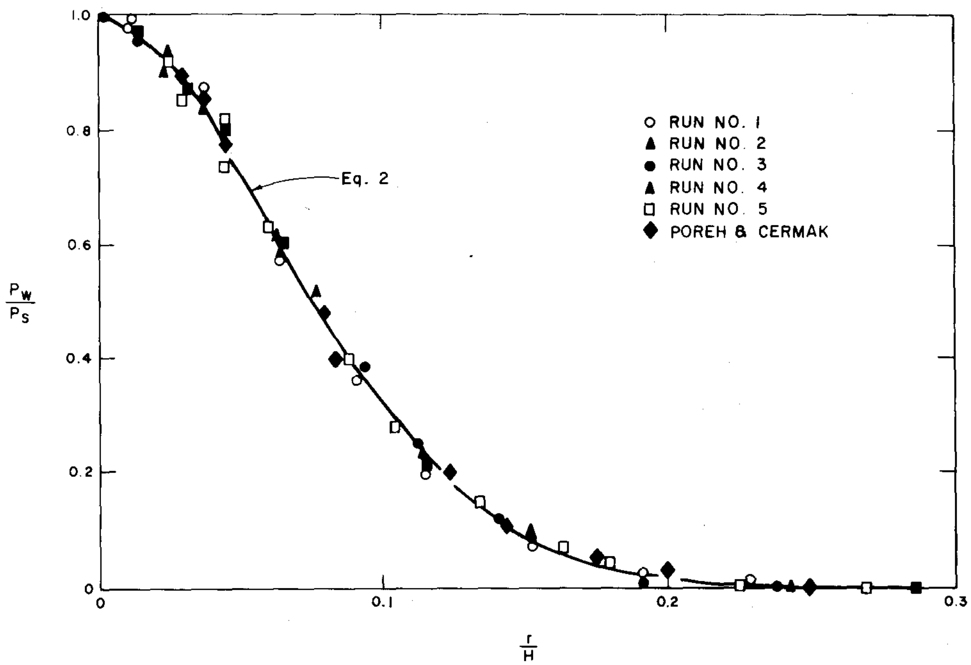

Figure 3.—Dimensionless pressures for jet impinging on a flat plate (Beltoas and Rajaratnam [3], Poreh and Cermak [9]).

by the same authors [3], except the coefficients of the equations are a different. Also, the influence of the plate where the jet impinges is felt at $X/H = 0.875$ instead of 0.95. The thickness of the slot is b. The pressure distribution in the impingement region is given by:

$$\frac{P}{P_m} = e^{-(0.834\,N_y)^2} = e^{-0.696\,N_y^2} \qquad (3)$$

Where:

$N_y = Y/b_p$

The influence of the confining plate is demonstrated in the relationship for the pressure at the plate:

$$\frac{P_w}{P_s} = e^{-38.5\left(\frac{Y}{H}\right)^2} \qquad (4)$$

Where:

Y = Distance from center point of impact parallel to plate to location of pressure measurement

The coefficient of the pressure relationship for two-dimensional flow is about 34 percent of that for a circular jet. This is also evident from a plot of the pressure at the plate (fig. 5) which shows that the excess pressure has decreased to ambient pressure at Y/H of about 0.35 instead of a value of 0.22 for a circular jet. This indicates that the pressure decay is less for a two-dimensional flow than for a circular jet.

Oblique Jets

Jets at an oblique angle to the floor are documented by Beltaos [5] for circular jets, and [6] for two-dimensional jets. The results indicated that the point of stagnation shifted but was not decreased in magnitude. Also, the pressure profiles near the stagnation point had an exponential decay away from the plane of symmetry for a circular jet. For the two-dimensional case, the pressure decay followed the exponential relationship for normal impingement up to a value of x/b_p of about 1.6, where x is the distance from the stagnation point to the location of pressure measurement and the point where the pressure is equal to $P_s/2$.

Submerged Jets

Albertson and others [7], in 1950, studied submerged jets from an orifice and the results were similar to those described previously for free jets. A zone of flow establishment and a zone of established flow were observed. The zone of flow establishment is a transition region that has a uniform velocity core surrounded by a rapidly decaying velocity toward the edge. The angle of divergence of the expanding cone is from 4 to 6° (fig. 1). The limit of the zone of flow establishment is where the uniform velocity core disappears. The velocity profile in the extablished flow region has a very nearly Gaussian distribution.

This profile gradually expands in width, and the maximum velocity decreases as the jet is diffused into the surrounding water. The experimental results indicated that the length of the zone of flow establishment was about 5.2 times the slot thickness for slot flow and 6.2 times the diameter of an orifice for orifice flow.

Beyond the zone of flow establishment, the velocity profiles followed:

Orifice flow:

$$\log \frac{V_x}{V_o}\frac{X}{d} = 0.79 - 33.0\,\frac{r^2}{X^2} \qquad (5)$$

Slot flow:

$$\log \frac{V_x}{V_o}\sqrt{\frac{X}{b}} = 0.36 - 1.84\,\frac{Y^2}{X^2} \qquad (6)$$

Where:

V_o = Initial velocity

Jets With a Water Cushion

The following results were obtained and velocities and pressures measured for several small-scale tests that used a water cushion.

A study was done by Cola [1] with a 1-m-wide, 0.0185-m-thick jet placed at the surface of a 0.82-m-deep basin. The jet velocities were varied from 1.8 to 4.8 m/s. The velocity distribution that was valid for 31.4 slot thicknesses below the fluid surface was the same as equation 6.

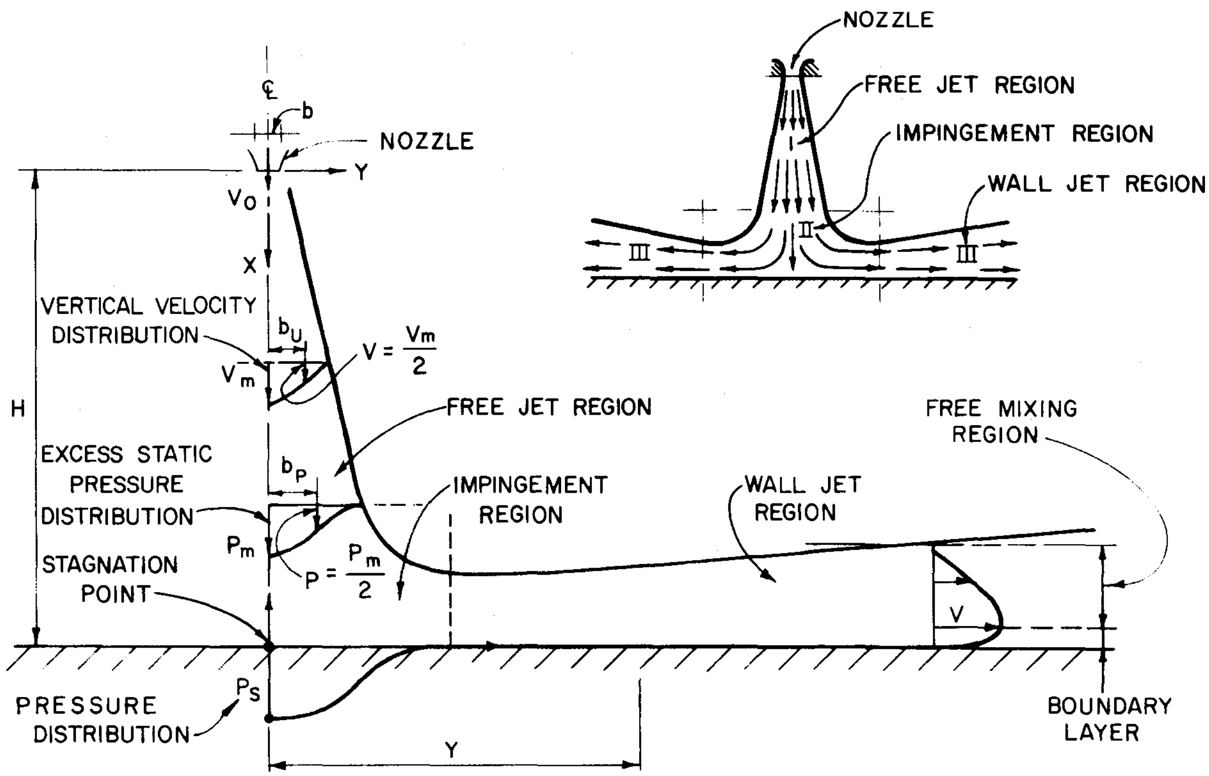

Figure 4.—Definition sketch of impingement [4].

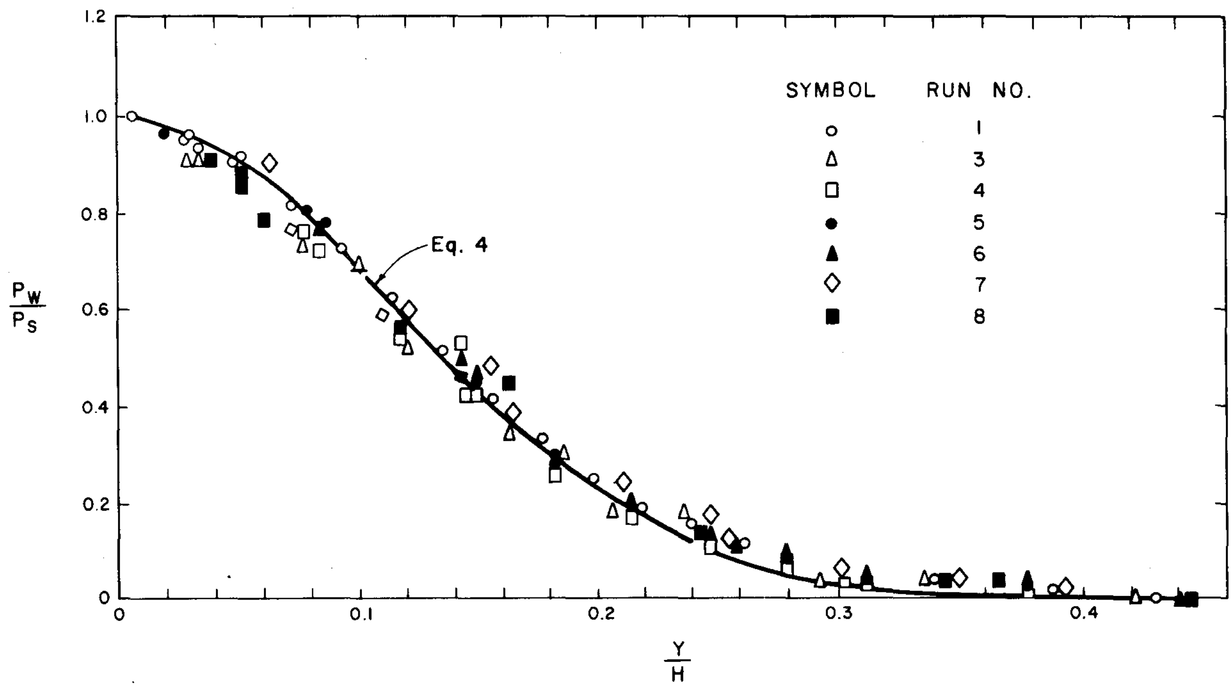

Figure 5.—Dimensionless pressures for a jet impinging on a flat plate [4].

Equation 6 was proposed by Albertson [7] for an infinite fluid, and Cola's data [1] followed it. The measured velocity profiles depart from equation 6 at about 13 b above the bottom. That is, the influence of the bottom plate increased the pressures at about 13 b from the lower boundary. Albertson's results indicated that the plate increased the pressure distribution about 13 slot diameters from the plate, which compares favorably.

Pressures above hydrostatic are shown (fig. 6) which have a maximum excess pressure of 0.147 $\rho\ V_o^2/2$. This distribution is similar to that for no water cushion. However, slight negative pressures were developed beyond Y/b of about ± 22. This may have been caused by the high velocities along the plate which decreased the local pressures, or by the fluid rebounding from the plate and creating a region of lower pressure.

A plot of the measured centerline velocities as a function of the distance along the centerline is very interesting. Figure 7 shows the velocity has not decreased for about 5 slot widths, then decays rapidly to about 0.4 V_o at a distance of 32 b and is about 0.2 V_o at 40 b. This implies that most of the energy has been dissipated by 40 slot thicknesses. However, the bottom was at 44 b and it may have influenced the results.

A series of tests was done at the National Civil Engineering Laboratory at Lisbon [2], where Lencastre used vertical jets of water 96- and 44-mm thick and the discharge varied from 66 to 0.138 m³/s per m. The heights of the jet above the bottom of the tank were 1140 and 660 mm. The velocity profiles were similar to those cited previously. The V_m (maximum velocity) (fig. 8) at any distance from the jet is described as a function of X/b, where b equals the slot thickness. This study shows that the velocity has decayed to 0.4 V_o at X/b of 5. This shows a much more rapid decay than that of Albertson's work for a submerged jet and may have been caused by high initial turbulence due to the jet passing through air before striking the water surface. One of the most interesting results from Lencastre's tests was the pressure distribution shown (fig. 9), which gives the excess pressure ratio as a function of the ratio Y/b. The flow is confined laterally on the upstream side of the vertical jet. The ratio of cushion depth c to slot width b varied from zero to 24.2. The asymmetrical shape of the pressure profile is caused by the water flowing downstream as shown. From these data the maximum pressures were less than 0.05 of the stagnation pressure for a water cushion depth of c = 24.2 times the slot width. The pressures are considerably less than were measured by Cola. Whether this difference was due to the influence of the cross flow or due to differences in experimental setup is yet to be resolved.

This series of tests had some results of dynamic pressure fluctuations on the bottom of the channel. The test conditions were for a fall height of 1140mm from a 44-mm slot discharging 0.138 m³/s per m. The following is a summary of the information given by Lencastre:

a. The pressure fluctuations at the point of impingement vary between zero and 2.8 times the mean pressure when the cushion is shallow, less than 11.4 times b.

b. Both amplitudes and frequencies decrease rapidly as the depth of the cushion increases.

c. At c/b of 30.2 the maximum pressure fluctuation is less than 0.6 of the mean pressure.

d. At c/b of 39.4 negligible pressure fluctuations exist.

e. The lateral distribution of pressure fluctuations also shows a sharp decrease with distance from the impingement point. At Y/b of 2.3 the pressure fluctuations are less than the mean pressure (H_c) and are negligible at Y/b of 4.5 for no cushion. The lateral pressure fluctuations decay more rapidly as the cushion increases. As an example, for c/b = 30.2, pressure fluctuations are about $0.6H_c$ at the center and less than $0.25H_c$ at Y/b of 2.3; where H_c is the excess pressure without a water cushion. Beyond the point Y/b = 2.3 pressure fluctuations were negligible.

f. The pressure fluctuations decreased more in the upstream direction than in the downstream direction for the same position Y and depth of water cushion.

g. In general, both pressure fluctuations and mean pressures on the basin floor were negligible for depths greater than 15 b. When the distance from a point to the impingement point exceeded 2 b, the pressures were less than 0.1 times the stagnation pressure. Negative pressures were observed along the bottom about 2 to 3 times the slot width both upstream and downstream from the point of

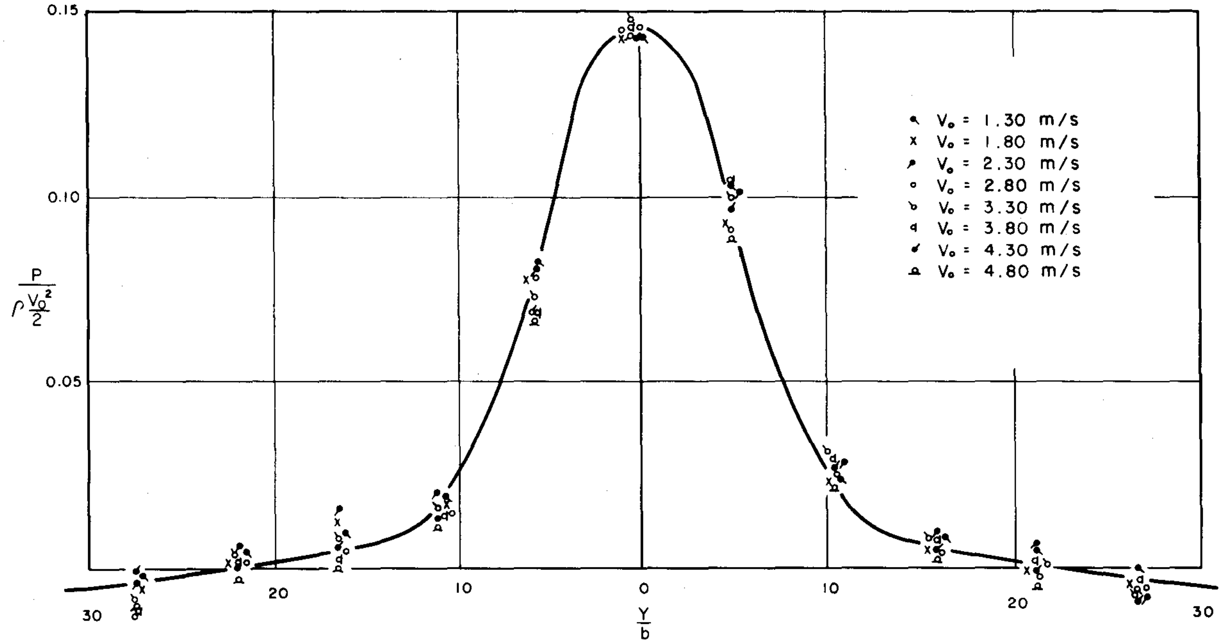

Figure 6.—Pressure distribution at the plate [1].

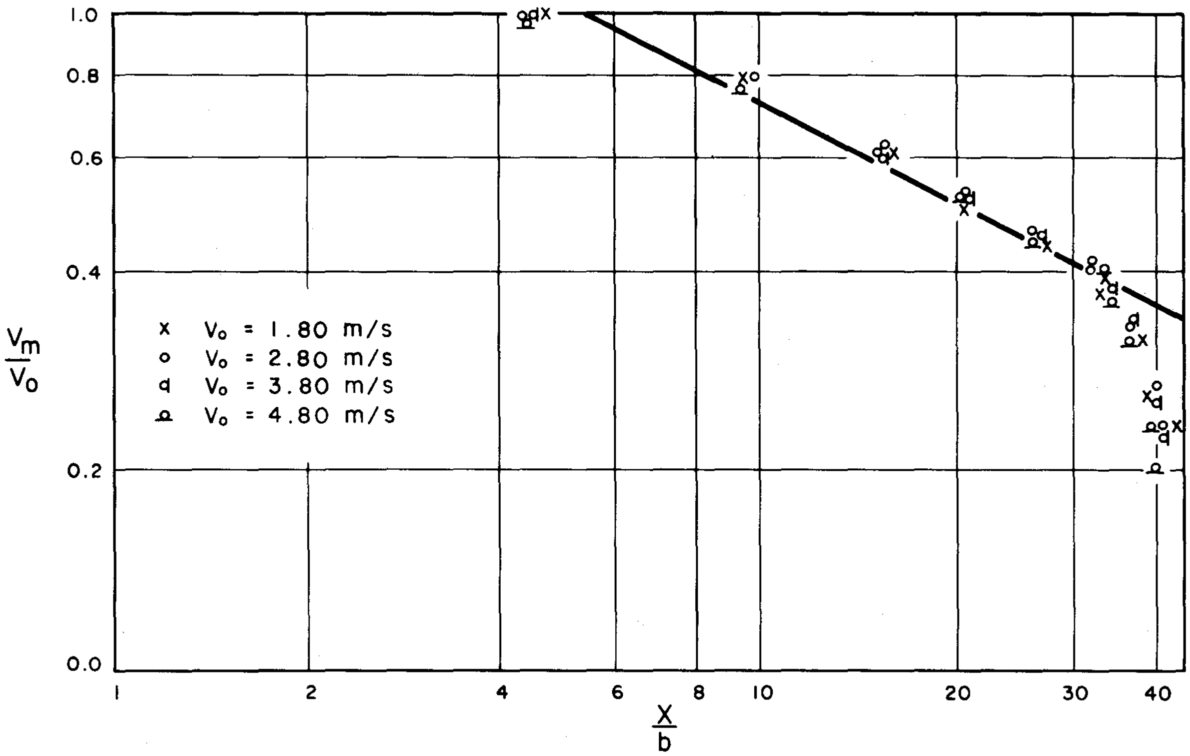

Figure 7.—Distribution of center-line velocity.

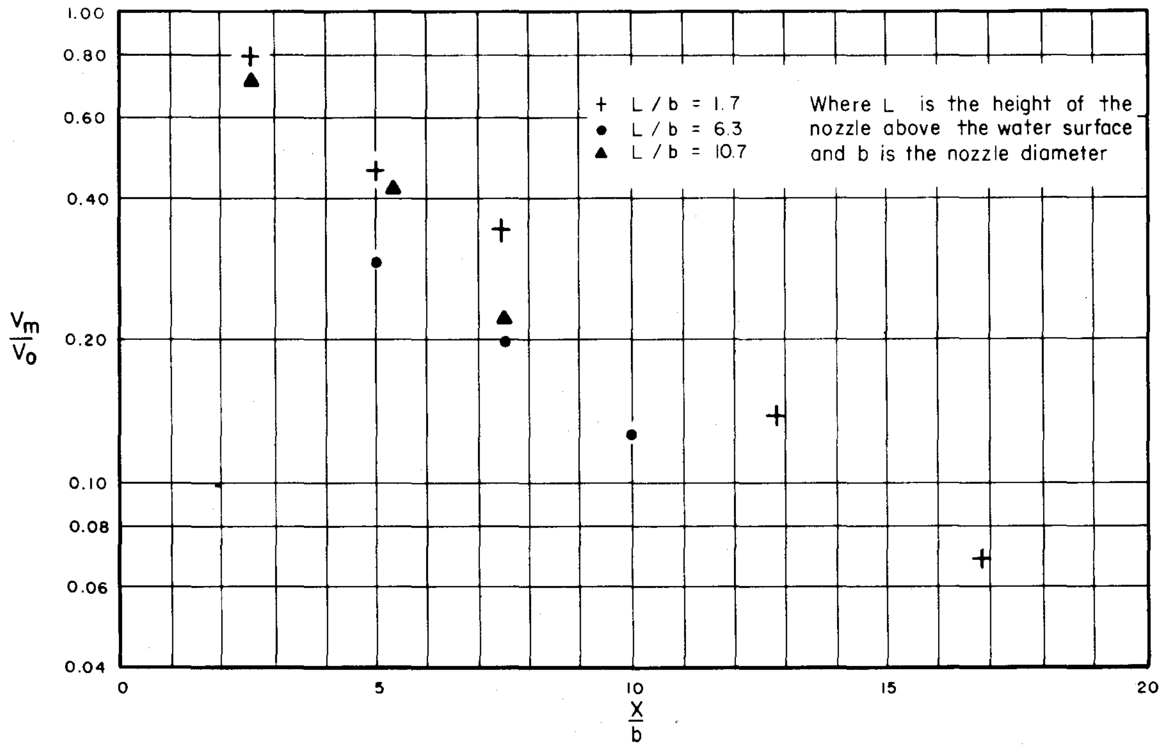

Figure 8.—Velocity decay of jet along the centerline in both air and water.

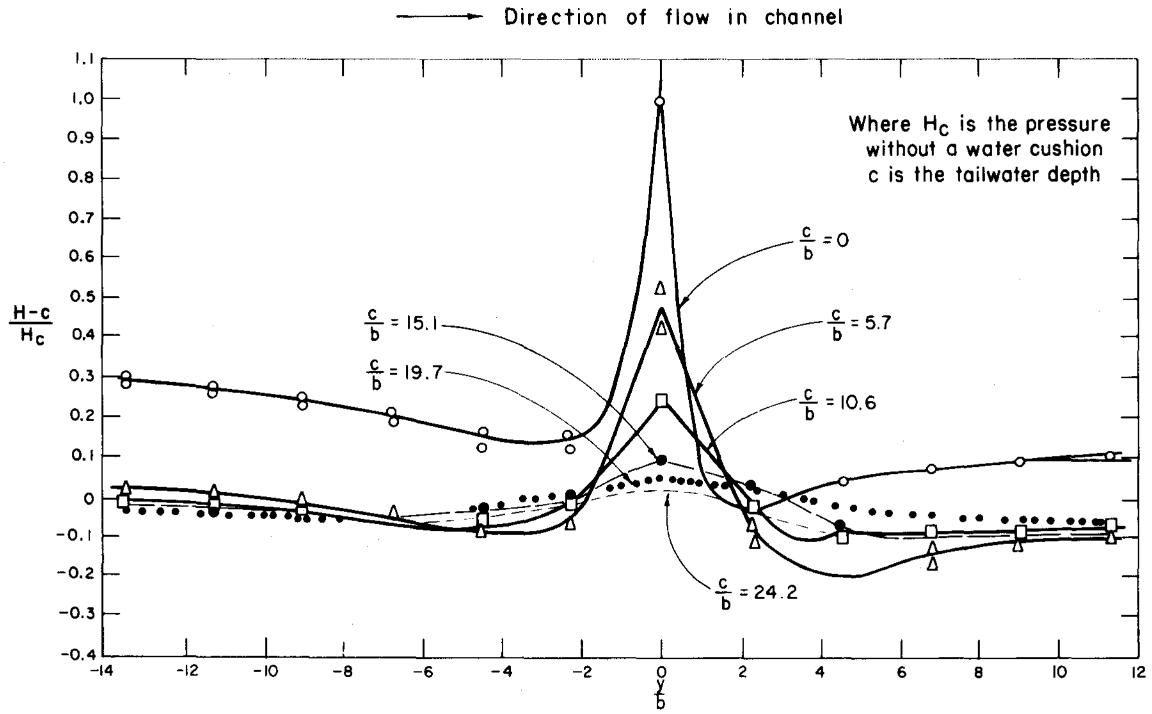

Figure 9.—Distribution of pressures on bottom of plunge basin.

impact, which was caused by the water striking the floor and then deflecting upward as it traveled away from the point of impact.

h. For shallow cushions, $c/b < 8$, the maximum pressure at the bottom is the same as without a water cushion.

i. The water cushion acts as a low pass filter and eliminates pressure fluctuations above 10 hertz.

During the early 1960's, a study was done by Häusler [8] on a circular jet plunging into a water cushion. Figure 10 is a sketch of the apparatus used. Discharge was measured with a V-notch weir and the pressures at the table were measured with a manometer system. The pressures were corrected for the height of the tailwater to obtain the pressure above the hydrostatic depth. The height of the fall H varied from 2.4 to 3.60 m; nozzle diameters used were 40,60, and 90 mm. The depth of the tailwater c above the table varied from 0 to 1.60 m. A typical plot is shown (fig. 11) of the excess central pressure measured from the tests. Note that the pressure distribution was constant at the stagnation pressure for depths less than y_c. The limit of the zone of flow establishment is y_c. Below y_c the pressure increases with depth faster than the hydrostatic pressure increases. Häusler developed a series of empirical equations to define the central pressure for the various regions and these are summarized here. However, he did not present data about the decay of the pressure going radially away from the point of impact.

The depth that the jet penetrates the pool and will cause pressure equal to the full reservoir head is:

$$y_c = 2.32\,D + 0.02\,H \tag{7}$$

where:

$$D = \sqrt{\frac{4Q}{\pi V}} \text{ or jet width and } V = \sqrt{2gH}$$

The above equations were developed from a "best fit line" through the experimental data. Due to the variability of the data some differences between observed and predicted values should be expected.

The following relationship was developed for central pressure beyond y_c:

$$P/\gamma = H\,10^{\left(\frac{y-y_c}{m}\right)} \tag{8}$$

where:

$m = -0.225\,Q^{0.35}$

The limiting depth y_s for the central pressure is given by:

$$y_s = m \log\left[\frac{-m}{2.3026\,H}\right] + y_c \tag{9}$$

Beyond the tailwater given by y_s, the pressures decrease but may not follow the values of pressure computed by equation 9. However, the depth at which the pressure, computed by equation 9, is about zero will be the maximum depth required to completely dissipate the jet.

COMPARISON OF EMPIRICAL CRITERIA

Several criteria have been reviewed and summarized in this report (table 1) for easy comparison. The third column of table 1 lists the the limits of the zone of flow establishment. The second column lists the end of the zone of established flow. Any basin that is deeper than the criteria in the third column should not have high excess pressure on the bottom of the basin.

If the tailwater depth of the basin is less than the limit of flow establishment, the full head from the reservoir will exist on the basin floor. Plunge basins with depths greater than that in column 3 (table 1) will not have pressures significantly higher than hydrostatic. Häusler [8] developed empirical relationships for excess pressures between these two regions.

Data from Service (Water and Power Resources Service) model tests of Crystal and Morrow Point spillways (table 2) are compared with Häusler's relationships. The Crystal maximum pressure data are higher than the computed values because the spillway concentrates the flow toward the center of the basin. Normally a falling jet will expand as it falls in air. This is probably the main reason for the differences between the pressures.

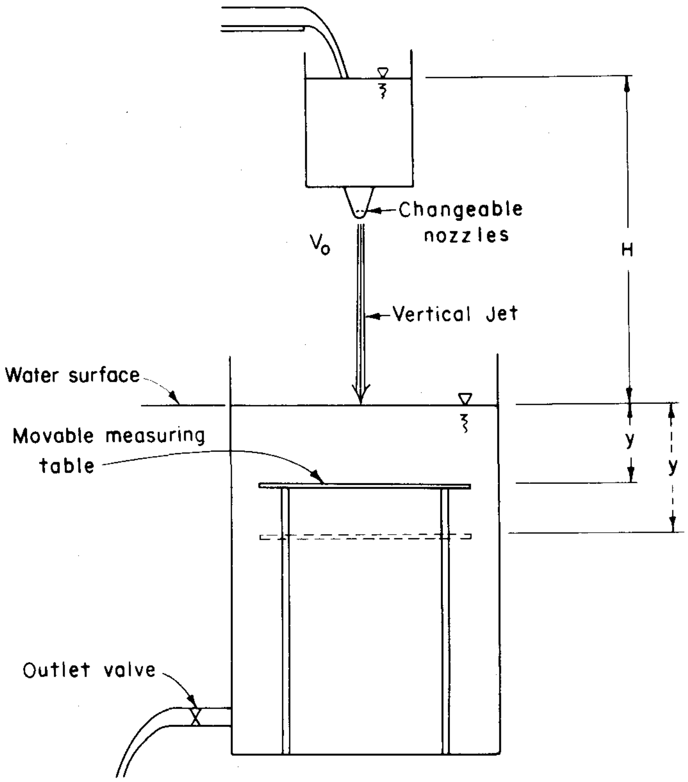

Figure 10.—Sketch of Häusler apparatus.

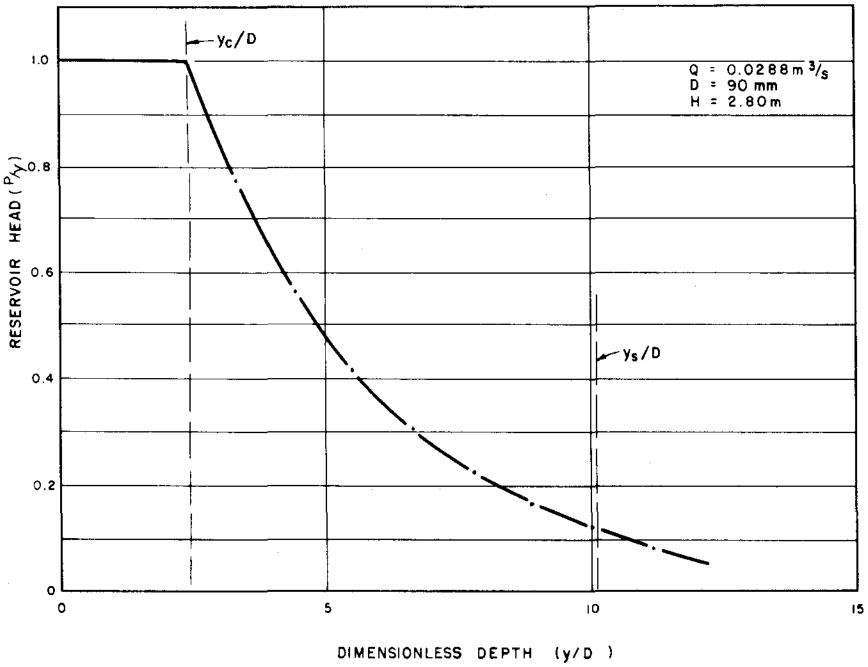

Figure 11.—Excess pressure decay in the tailwater.

Data from the Morrow Point spillway test show the maximum instantaneous pressures for the recommended design, and the revised alternate design. The differences between these two designs show the change in pressure that can result by causing the jet to be distributed over a larger area. Computed values are shown and they are about the same as pressures for the revised alternate design.

Both the Crystal and Morrow Point data were for a nearly horizontal spillway jet which drops nearly vertically into a plunge basin. The empirical relationship developed by Häusler was for a vertical jet pointed directly at the water surface. Despite these differences, pressures estimated by Hausler's equations predict pressures quite well and can be used to estimate pressures in a plunge basin.

Table 1.—*Criteria for various flow regions*

Name	*Flow establishment*	*Established flow*
1. Circular Jets		
Albertson [7]	$X/d < 6.2$	$X/d > 37;\ V_m = 0.2\ V_o$
Häusler [8]	$y_c = 2.32\ D + 0.02\ H$	$y_s = m \log \left[\frac{-m}{2.3026\ H}\right] + y_c$ where: $m = -0.225\ (Q^{0.35})$
2. Two-dimensional slots or jets		
Albertson [7]	$X/b < 5.2$	at $X/b = 100;\ V_{max} \approx 0.2\ V_o$
Cola [1]	$X/b <$ 5 to 7	$X \approx 40b$

Table 2.—*Comparison of model tests to Häusler's equations*

Discharge m³/s	H (m)	P/γ measured (m)		P/γ computed (m)
Crystal				Häusler
1174.9	64.65	20.4		10.0
565.7	66.35	13.1		7.1
338.6	66.78	7.8		5.5
265.8	67.30	2.0		0
Morrow Point				
		Recommended	Alternate	
1132.7	121.62	53.9	86.9	106.4
962.8	121.62	30.8	52.6	64.6
730.6	120.09	34.3	46.8	58.8
487.0	120.09	19.5	24.2	50.1
243.5	120.09	12.9	31.1	66.4

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