TR-1039

FLUID AMPLIFICATION

1. Basic Principles

R. W. Warren

S. J. Peperone

15 August 1962

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DIAMOND ORDNANCE FUZE LABORATORIES
ORDNANCE CORPS ● DEPARTMENT OF THE ARMY
WASHINGTON 25, D. C.

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FOR THE COMMANDER:
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FOREWORD

Fluid amplification without the use of moving parts has been proved feasible. The basic operation of a fluid amplifier depends on the change of direction of a high-energy fluid stream by a lower-energy flow of fluid. DOFL is now investigating flow-control techniques for use in developing fluid systems capable of amplification, feedback, memory, logic functions, analog computations, and digital computations.

The most attractive features of such systems are simplicity, reliability, and resistance to extreme environments of shock, vibration, temperature, and nuclear radiation. The components may be simply blocks of metal, ceramic, or plastic containing suitable passages.

This report is the first of a series to be issued on the theoretical aspects and the design of fluid systems, all to be entitled "Fluid Amplification," with each carrying an appropriate subtitle. Many will be tutorial. References to material outside of this series will be kept to a minimum.

Nomenclature

	Unit
a = Control to power nozzle area ratio equal to control to power nozzle width ratio	nondimensional
d = Distance downstream from power nozzle	ft
p = Total pressure above ambient	lbf/ft^2
v = Velocity	fps
A = Area	ft^2
G = Gain	nondimensional
Q = Volume flow rate = vA	ft^3/sec
w = Nozzle width	ft
η = Efficiency	nondimensional
θ_s = Power jet deflection angle	radians
θ_c = Angle to center of collector	radians
ρ = Density	lbm/ft^3
g_c = Gravitational constant = 3.2. $lbm\ ft/lbf\ sec^2$	

Subscripts

i = Input (control)

j = Power jet

o = Output

P = Power

ABSTRACT

Studies made on pure fluid amplification have resulted in an overall program for design and development of fluid amplifiers, both bistable and proportional, with no moving parts.

Both flow and pressure at the receiving apertures of the proportional-type device depend on the power jet strength and flow direction. Since the flow direction is controlled by a low-energy jet, the output from the apertures is an amplified version of the control jet input. The energy controlled in the amplifier is an order of magnitude larger than the controlling energy

If the walls are relatively close to the interaction region, the stream has a marked tendency to attach to one of the walls. This wall-attachment phenomenon causes the fluid stream to shift completely from one output to the other in response to a control jet pulse, thereby permitting bistable operation. For a proportional unit, the walls are positioned much farther out to minimize the wall effect.

Specifically covered in this report are the effects of the wall and splitter positions in bistable operation, and an analysis of the gain for proportional operation.

GENERAL

Pneumatic and hydraulic systems have been widely applied in the transfer and control of energy. The concept of a fluid-operated control system with no moving parts broadens the area of usefulness. High reliability and relatively rapid response can be obtained under severe environmental conditions that preclude the use of electronic or mechanical equipment.

Figure 1 shows a simple amplifier design in which a low-energy flow of fluid directs a higher-energy fluid stream. This control action is the basic operating principle of the two types of amplifiers described in this report. A main or power jet chamber (p_j) supplies, from a reservoir, a high-velocity stream of fluid, either gas or liquid. The chambers and jet nozzles (p_i) on the right and left of the power jet produce jets of fluid

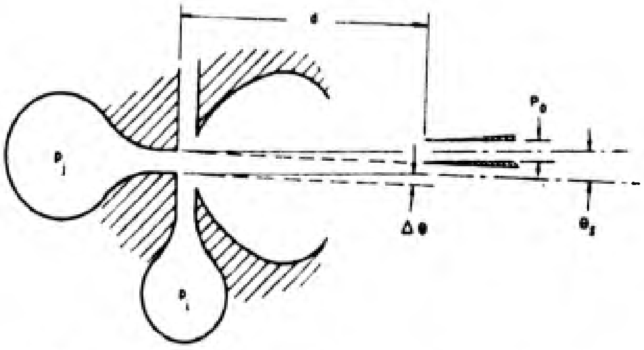


Figure 1. Basic fluid amplifier.

that impinge on and deflect the power jet. In this proportional amplifier, flow and pressure at the receiving apertures depend on the power jet strength and direction of flow. Because the direction of flow is controlled by the low-energy jet, the output at the apertures is an amplified version of the control jet input. The energy controlled can be an order of magnitude larger than the controlling energy.

The walls of this unit (fig. 1) are positioned relatively far from the region where the streams meet and interact. If the walls are positioned adjacent to the interaction region, as shown in figure 2, the power stream will have a marked tendency to attach to one of the walls. This tendency is utilized to obtain bistable operation, in which control jet pulses shift the power stream between two output apertures. In the proportional unit, however, the wall effect must be minimized.

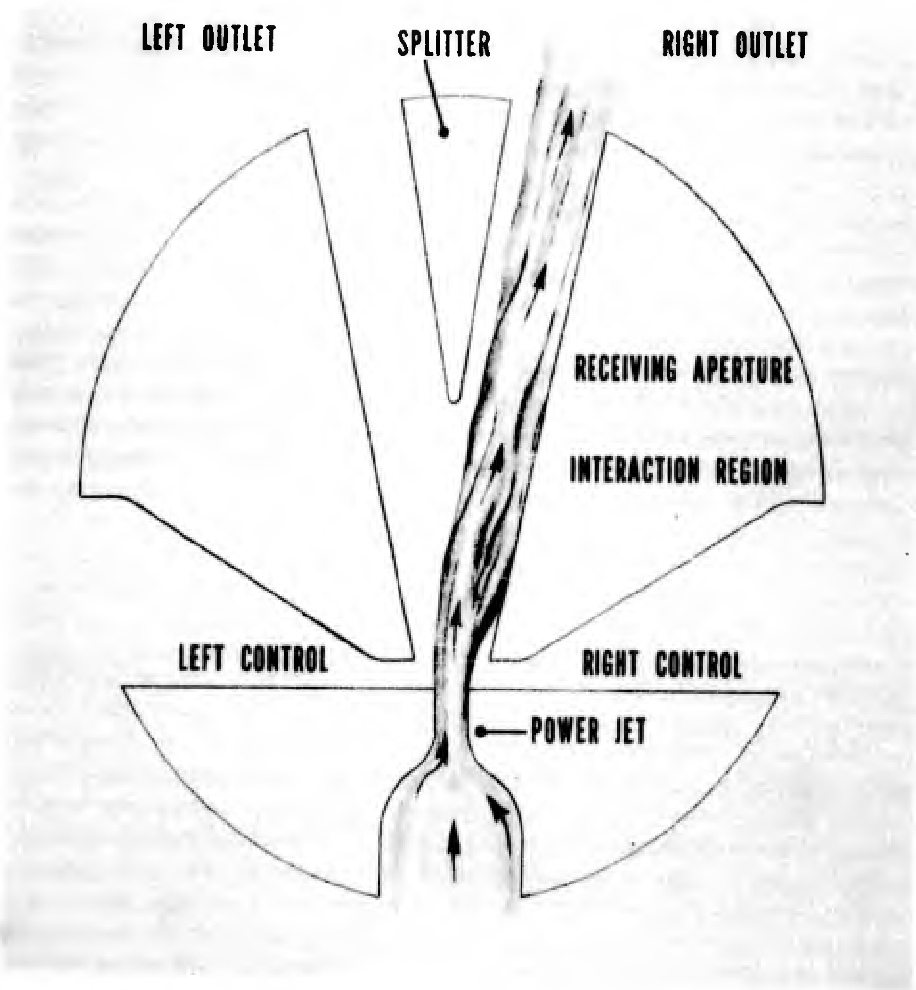


Figure 2. Diagram of fluid bistable element.

The proportional and bistable units are essentially two-dimensional or cylindrical; that is, the shape can be generated by moving a line element parallel to itself. The height (or depth) of a unit is the extent of the unit in the third dimension, i.e., the length of the line element (fig. 3).

For scaling purposes, all dimensions are normalized in terms of the width of the power nozzle opening. The aspect ratio is the height divided by the power nozzle diameter.

Units may be machined or stamped and top and bottom plates added (with suitable inlet and outlet apertures) to make the unit equal in height to the thickness of the metal used. Units may be etched or molded. Two units may be placed face-to-face to obtain a height equal to twice the etched or molded depth, or a top plate may be added to make the height equal to the etched depth.

The two sets of mechanical units most commonly used in connection with fluid flow will be used. These are the English system, corresponding to the modified Newton's law, and the CGS system, as follows:

(1) Modified Newton's Law Engineering (English) System

$$f = \frac{m}{g_c} a$$

where

f = force (lbf)
m = mass (lbm)
a = acceleration (ft/sec^2)
g_c = conversion factor ($32.2\ lbm\text{-}ft/lbf\text{-}sec^2$)

(2) CGS (Gauss) System Using Newton's Law

$$f = ma$$

where

f = force (dynes or $gr\text{-}cm/sec^2$)
m = mass (gr)
a = acceleration (cm/sec^2)

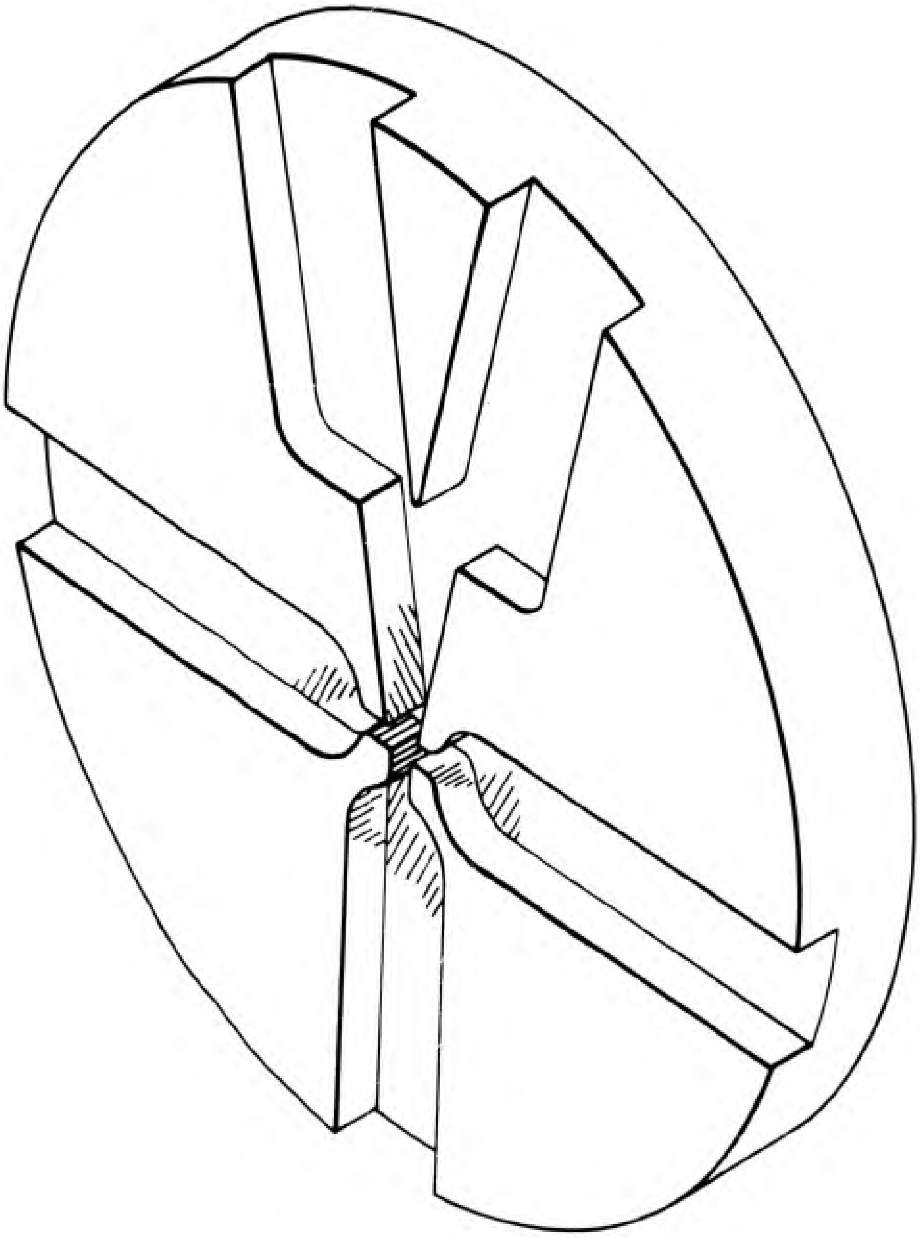


Figure 3. Internal pattern of a typical element.

PART I: BOUNDARY WALL EFFECT IN FLUID AMPLIFIERS

R. W. Warren

1. FLOW-CONTROL METHODS

The effects in the zone of a fluid stream flowing between boundary walls and emerging in a similar medium (a gas stream in gas or a liquid stream in liquid) are shown in figure 4. As the fluid jet issues from the nozzle, its particles collide with those of the surrounding fluid. By these collisions the jet entrains a portion of the surrounding fluid, forming a broader stream which issues from the downstream opening of the inclosure. The removal of fluid from the interaction region lowers the pressure in the zone between the stream and the boundary walls. The low-pressure zone induces a flow from the higher pressure region beyond the opening to maintain equilibrium. When the stream is closer to one wall than the other, the area available for counterflow on the near side is decreased while that on the far side is increased. A decrease in area impedes the counterflow and results in an even lower local pressure between the stream and the wall. The increased area on the opposite side facilitates the counterflow and establishes a pressure approaching ambient. Because of the low local pressure existing near the one wall and the higher pressure on the opposite side, the stream is forced toward the wall, resulting in an even greater pressure differential. Thus, a self-reinforcing action occurs that quickly shifts the stream completely against one wall as shown in figure 5.

Once the stream is forced against a wall, the pressure differential holds it there as long as the stream flows. The stream constantly entrains fluid from the low-pressure region, the losses being replenished by a recirculation from the jet stream as shown in the lower right section of figure 5. The low-pressure region is called a low-pressure bubble or pocket. As one proceeds along the wall downstream of the low-pressure bubble indicated in figure 5, the pressure suddenly increases greatly at the point of attachment. This high pressure region tends to seal off the low-pressure bubble from pressures existing in the region downstream of the point of attachment. Equilibrium is established when the volume of the replenishing flow equals the volume of the fluid entrained from the low-pressure region. This equilibrium pressure is a direct function of stream velocity; increasing or decreasing the velocity of the stream changes the volume of fluid entrained, thereby resulting in greater or lesser pressure differentials across the stream. As the stream is introduced into the chamber through the nozzle, it can be caused to attach to a selected wall by a relatively slight asymmetry of the walls. This feature is designated "reset."

1.1 Fluid Injection

To shift the stream from one wall to another, control-stream orifices can be introduced on the sides of the power stream as shown in figure 2. If fluid is allowed to enter the low-pressure region on the right

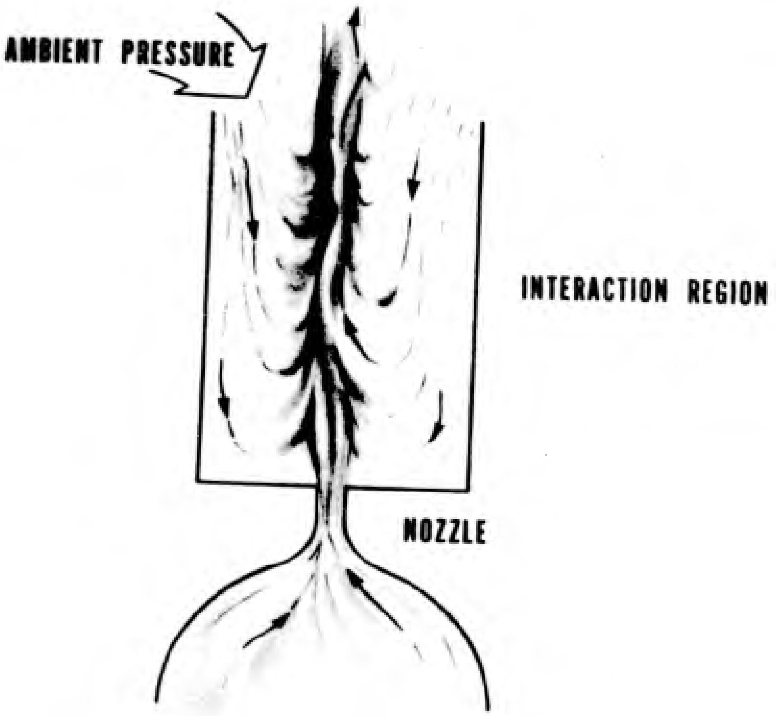


Figure 4. Initial fluid flow between parallel walls.

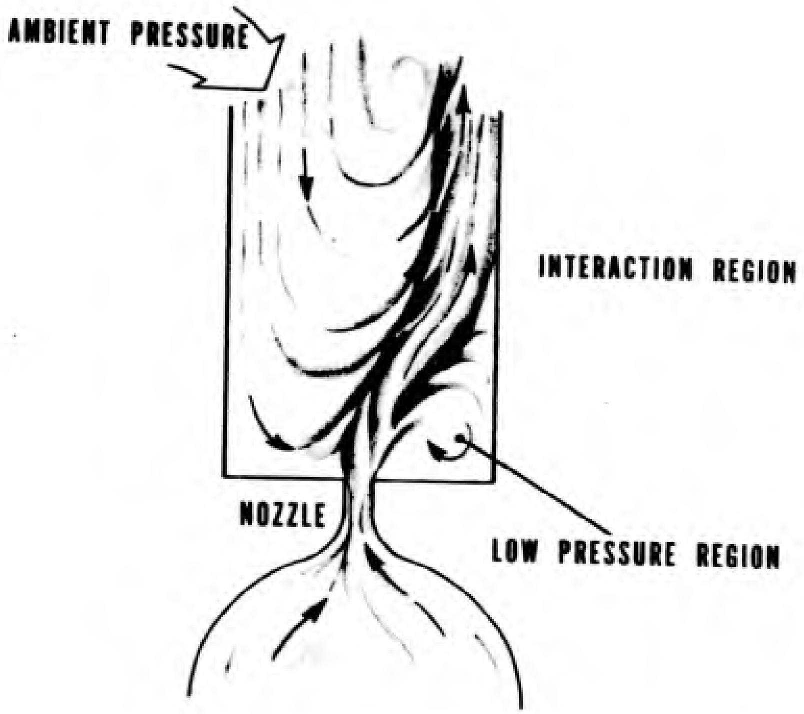


Figure 5. Final fluid flow between parallel walls.

at a greater rate than the stream can entrain and remove it, the pressure will increase. As the pressure on the right increases to near that on the left, the differential pressure approaches zero and the stream moves toward the center. If more fluid enters the right pocket by injection and counterflow than the left receives by counterflow alone, the stream will incline to the left. As soon as the powerstream crosses the centerline, the self-reinforcing action (described in section 1) occurs and the stream attaches to the left wall. Fluid need be injected only until the powerstream has crossed the centerline to effect complete switching. Thus, merely by inhibiting entrainment or providing the desired entrainment, the direction of the submerged stream can be controlled.

1.2 Fluid Removal

The stream may also be switched from right-to-left by withdrawal of fluid from the left side of the stream instead of the injection method performed on the right side (section 1). If fluid is removed at a greater rate than the counterflow can replace it, the pressure on the left falls below that on the right, and the stream inclines toward the center. By continuing the removal of fluid until the stream is past the center, the stream can be shifted to the left wall.

1.3 Sidewall Arrangement—Entrainment

Locating the sidewalls farther from the stream reduces their ability to attract the stream; decreasing the sidewall length downstream of the point at which the stream attaches also reduces their effect. By either of these variables, a switching unit can be designed to yield a deflection that is a desired function of controlled-fluid injection.

The operations described are for a power jet that partially fills the interaction region. Moving the boundary walls toward the centerline, or increasing the pressure to the power jet until the compressed fluid expands and attaches to both boundary walls, results in the flow shown in A of figure 6. Here, the entrainment effect of the power jet lowers the pressure equally in each of the control chambers. Without a control signal flow, the power-jet stream is undeflected and flows along the centerline. When fluid is allowed to enter through one control nozzle, the pressure on that side increases, the stream detaches from the near wall, and inclines toward the opposite wall B of figure 6. When control flow ceases, the stream again fills the exit and flows along the centerline. Deflection that is a function of control jet momentum can be obtained in this mode of operation.

1.4 Splitter Effects on Fluid Bistable Elements

Entrainment and momentum exchange, which occur whenever a fluid jet passes through a region of similar fluid, together with frictional losses, etc., cause degradation (loss of energy and pressure) of the stream, which increases with the distance from the nozzle. Therefore, to obtain maximum output pressure and power, it is necessary to locate the receiving apertures as close as possible to the power nozzle.

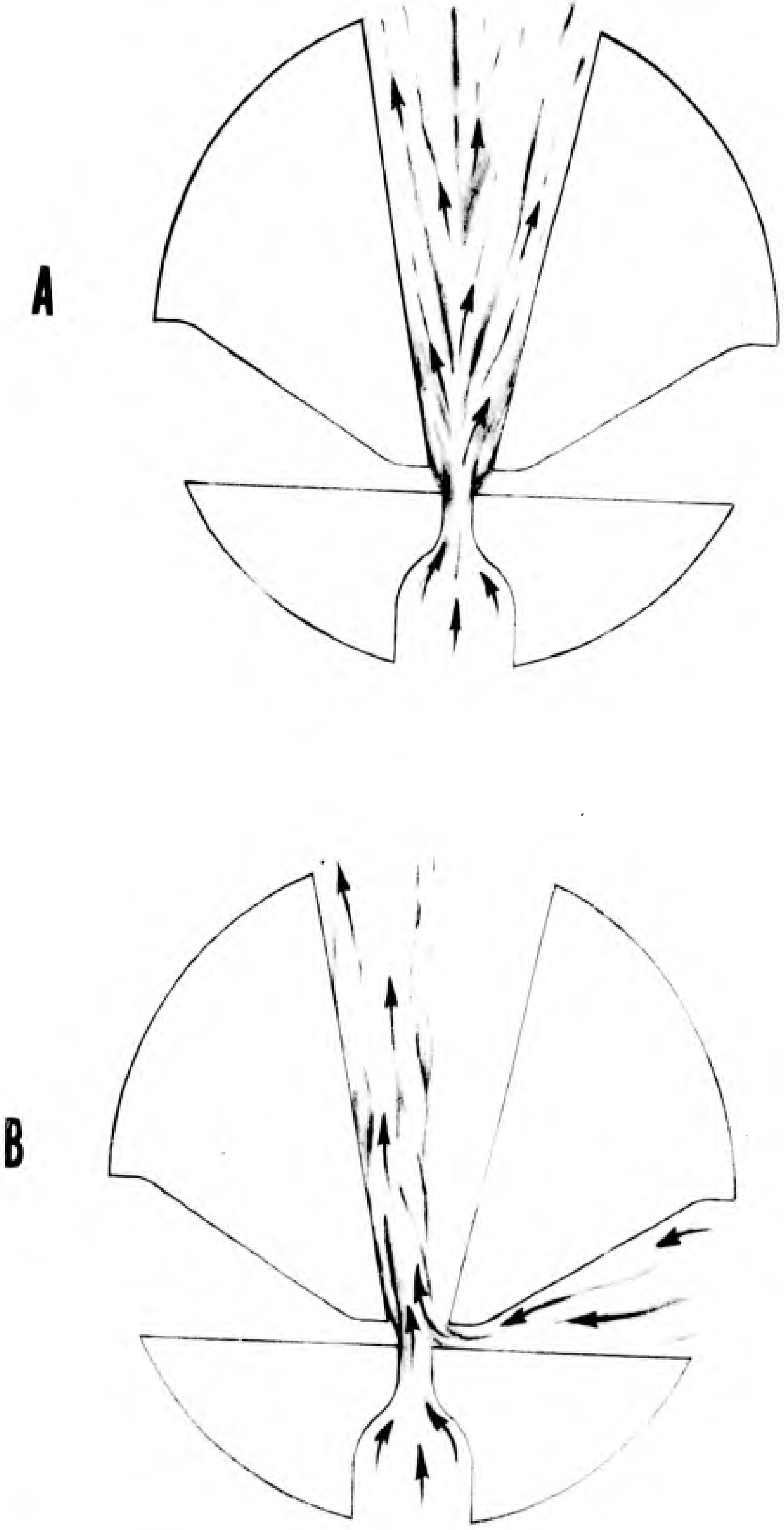


Figure 6. Control of completely filled bistable element.

A splitter (as shown in fig. 2) may be used to provide discrete outputs for the interaction region. Since a small pulse of control fluid can direct the delivery of a large power stream, considerable amplification is obtained. The relative position of the splitter with respect to the power jet nozzle, as well as the length and location of the boundary walls, affects the operating characteristics of the unit.

To explain the effect of splitter location on operation of fluid devices, a unit is considered in which the sidewalls and splitter walls are planes diverging 12 degrees from the nozzle centerline. The distance between the boundary walls near the base of the interaction region is approximately 3 nozzle widths. The influence of splitter position on the operational characteristics of the unit is affected by the ratio of pressures at the input and output ends of the power-jet nozzle, the pressure drop across the power-jet nozzle, and the overall interaction-region configuration. In addition, operation varies with the fluid characteristics, fluid thermodynamic state, and minimum local pressure in the unit.

However, in general, the following relationships between the splitter position and operational characteristics of the unit have been found to hold for air supplied at pressures up to 55 psia.

If the splitter is 0 to 2 nozzle widths downstream from the exit of the power nozzle (row 0-2, fig. 7), the flow divides about equally, but can be forced to deliver a greater portion to one side or the other by applying a corresponding control signal. The sidewall influence alone is insufficient to deflect the power jet, since the differential pressure (developed by entrainment over an effective sidewall distance of only 2 nozzle widths) is small, and the stream is split before the small differential force can be effective. The pressure differential developed over this short length, however, results in a larger deflection by a given control signal than that provided by an open system without boundary walls.

A different operational mode is obtained when the splitter is located between 3 and 5 nozzle widths downstream from the exit of the power nozzle (row 3-5, fig. 7). For this configuration, the flow is affected appreciably by the boundary layer. Before a control signal is added, a greater portion of the power-jet flow is delivered to one side of the splitter. The sidewall influence alone is insufficient to deflect all the power jet to one side, because, since the splitter is relatively close to the power nozzle, the stream would have to be turned through a large angle to be diverted wholly to one side. However, after the stream is deflected to the boundary wall, the greater part remains there even after the control signal is removed.

Another operational mode is obtained when the splitter is positioned 6 to 12 nozzle widths downstream. For this configuration, the power-jet flow is so affected by the extended boundary layer that, even without a control signal, the power-jet flow will be delivered entirely to one of the channels. The stream area over which an effective pressure differential

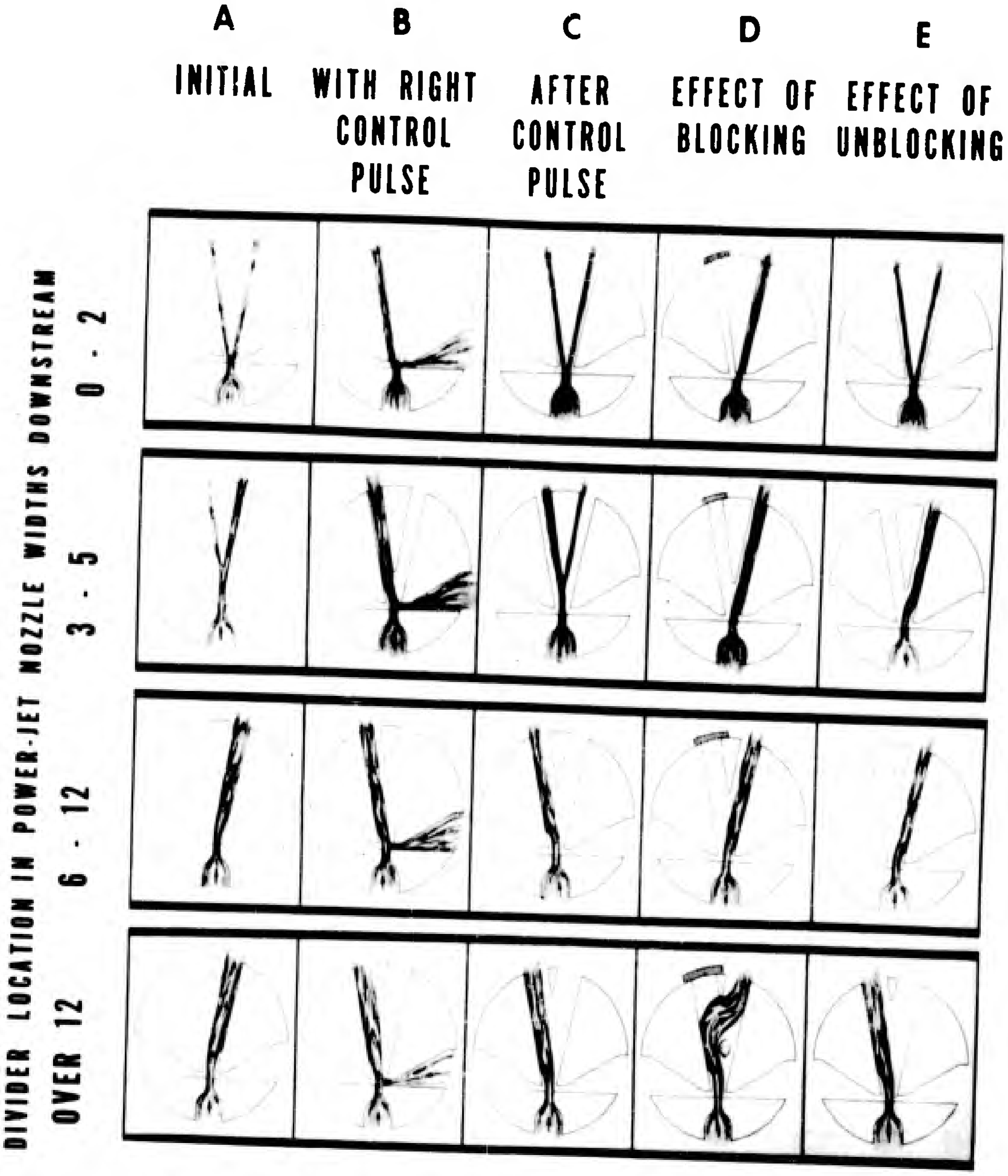


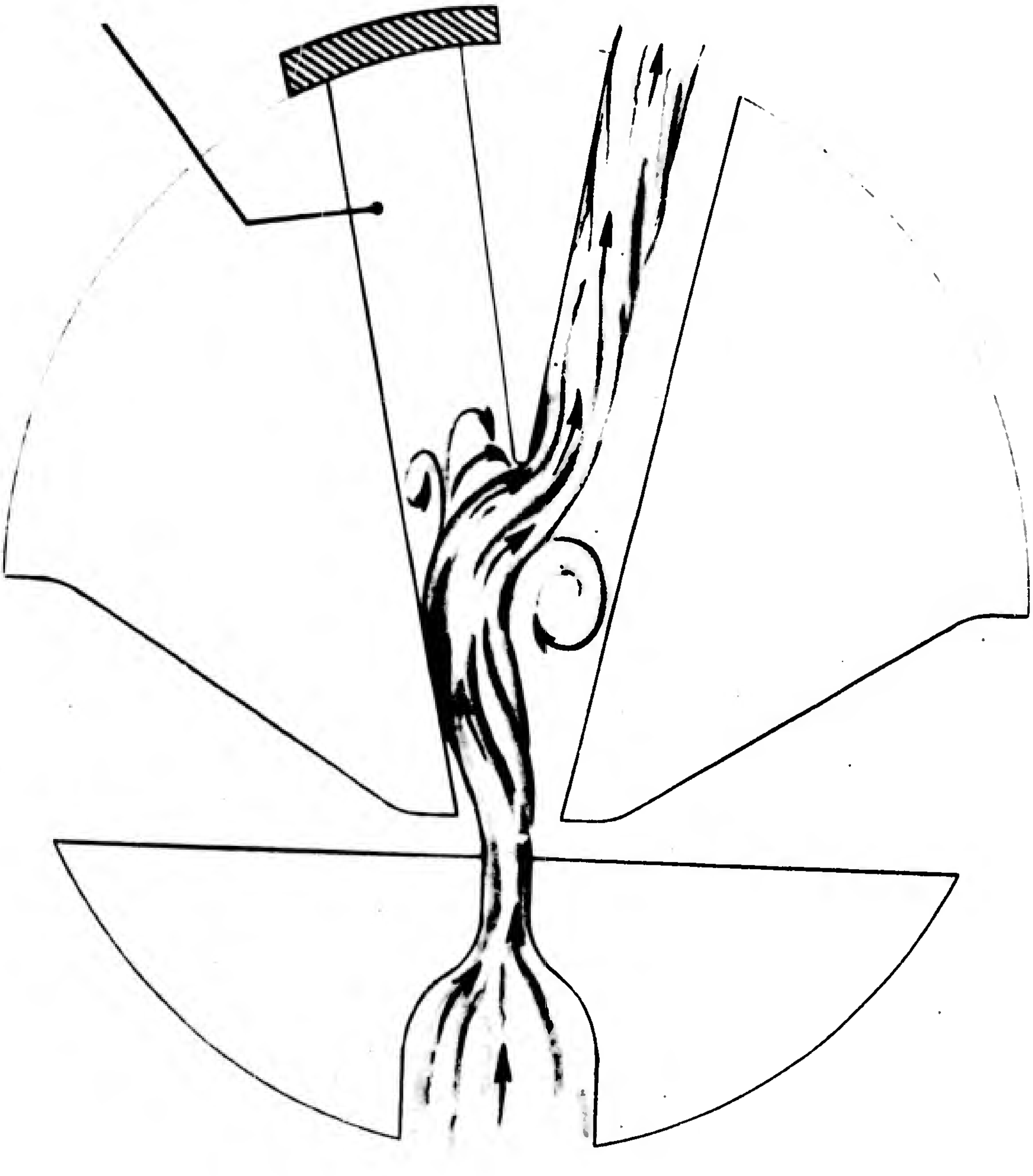
Figure 7. Effect of splitter position on characteristics of fluid bistable element.

can be developed is now relatively large. The power stream is deflected into contact with the sidewall slightly downstream from (or at) the splitter leading edge, sealing off a boundary layer region, which is being evacuated by the entrainment action of the power stream on one side and is restricted on the other side by the adjacent sidewall. This results in a high effective pressure differential across the power stream, deflecting it into one output channel.

Should the output be blocked, pressure backs up throughout the channel downstream from the divider leading edge and into the low-pressure region where the power jet attaches to the sidewall. Additional fluid forced into the channel must reverse its flow to exit around the splitter through the opposite output channel. Consequently, the two counterflowing regions produce a substantial amount of turbulence that affects the laminar flow pattern in the region where the stream attaches to the wall. The turbulence degrades the seal between the power jet and sidewall so that the local high pressure at this point forces additional fluid into the sealed low-pressure boundary region. As a result, the differential pressure across the stream is reversed, and the jet is deflected to the unblocked output channel. This reversal effect may be utilized for switching instead of (or in addition to) the control effected by the fluid-injection technique. That is, switching of the units may be accomplished by intentionally blocking or loading the output passage to which the flow is directed. Blocking the outlet toward which fluid is <u>not</u> directed also affects the flow.

Assume, for example that the stream is flowing out the right outlet—when the left outlet becomes blocked, its counterflow ceases. With no counterflow fluid entrained by the stream, the pressure tends to equalize on the two sides of the stream, the stream leaves the right boundary wall and flows toward the centerline. Since the left channel is blocked and all flow must issue through the right channel, the stream is forced to attach to the right side of the splitter. When the left channel is unblocked, counterflow resumes in the left channel and the stream reattaches to the right boundary wall.

When the splitter is positioned more than 12 nozzle widths downstream from the power-nozzle exit, the stream attaches to the boundary wall upstream from the leading edge of the splitter. When the outlet accepting the flow becomes blocked, the resulting increase of turbulence and back pressure is primarily downstream from the attachment point and has less effect on the attachment region than when the splitter is positioned closer to the power-nozzle exit. However, back pressure may initiate reverse flow down the boundary layer to the area of attachment. The power-stream high local static pressure distribution at the attachment region, together with the viscous effects associated with the velocity distribution, resists reverse flow into the



DYNAMIC PRESSURE MAINTAINED IN LEFT PASSAGE

Figure 8. Memory characteristic of fluid binary element.

sealed region. Therefore, the sense (or direction) of the effective differential pressure across the stream is not reversed; the stream remains locked to the original sidewall, even though no control is being applied. As long as the outlet passage (to which the stream is directed by the boundary-layer effect) remains blocked, the stream is forced around the splitter and goes out the opposite outlet. Dynamic pressure, however, is maintained on the blocked outlet as shown in figure 8. When the outlet is unblocked, flow returns to its original outlet even without a control pulse. The ability of a stream to maintain dynamic pressure on a particular outlet even though the outlet is totally blocked is termed memory. It is a volatile memory in that it persists only as long as there is flow. If flow ceases and is then restarted, the stream attaches to the boundary wall in the reset position. The memory characteristic of this type unit may be enhanced by an abrupt change of slope (or hook) in the sidewall.

2. SUMMARY

The primary objective of this study was to establish a broad guide in the design concepts of pure fluid bistable operations. It should be remembered that the ranges of splitter locations given for specific modes of operation in fluid bistable elements are not precise. An ambiguous region exists in which the unit is sensitive to fluid characteristics, power-stream pressure, angles of the sidewalls, setback, and other parameters. Therefore, the limits given are merely typical; they will vary according to the exact dimensions, pressures, geometrical configurations, and other variables.

PART II: PROPORTIONAL FLUID AMPLIFICATION

S. J. Peperone

The objective of the proportional fluid amplifier is to achieve without moving parts control of fluid power by a lesser amount of power. One of the most important quantities, therefore, is the power gain.

Although the discussion that follows is highly idealized, it is intended to serve as an introduction to the concepts involved in proportional fluid amplification.

The power gain of a control element is the magnitude of the ratio of signal power output to signal power input. For the fluid amplifier using an incompressible fluid, the power gain G_{pq} is given by

$$G_{pq} = \left|\frac{\Delta p_o \Delta Q_o}{\Delta p_i \Delta Q_i}\right| \tag{1}$$

where p is total pressure, Q is volume flow rate, and the subscripts i and o refer to control input and amplifier output, respectively. It should be noted that the definition is in terms of small increments, i.e., low-level signals. The increment should be small enough so that the element can be considered to be linear.

Other quantities of interest are pressure gain G_p and flow gain G_Q, which are defined as

$$G_p = \frac{\Delta p_o}{\Delta p_i} \tag{2}$$

$$G_Q = \frac{\Delta Q_o}{\Delta Q_i} \tag{3}$$

A fourth quantity of general interest is the efficiency of the element, which is defined as the ratio of signal power output to total power input and is given by

$$\eta = \frac{\Delta p_o \Delta Q_o}{p_i Q_i + p_j Q_j} \tag{4}$$

where the subscript j refers to the power jet, so that $p_j Q_j$ is the power input from the power jet. Efficiency can never be greater than unity since the output power can never be greater than the total input power. The power gain of the element, however, can be greater than unity since this is just the ratio of output power to input signal power and not total input power.

To understand how a fluid control element achieves gain, consider a jet of fluid issuing from a power nozzle. The kinetic energy of a segment of this stream 1-sec long—the power—is $\rho A v^3/2g_c$ where ρ is the density of the fluid, v is its velocity, g_c is the gravitional conversion factor, and A is the cross-sectional area of the power nozzle. The fluid power resides in the velocity of the stream. Now, if fluid is directed normal to the power jet as shown in figure 1 (Part I), the resulting angle of deflection θ_s of the power jet is

$$\theta_s = \frac{w_i \rho_i v_i^2}{w_j \rho_j v_j^2} \qquad (5)$$

This results from momentum conservation and assumes ambient static pressure in the interaction region; w_i is the control nozzle width; w_j is the power nozzle width.

Then using $p = \frac{1}{2g_c} \rho v^2$ for both the control and power jets, it follows that

$$\theta_s = a \frac{p_i}{p_j} \qquad (6)$$

where the pressure is that above ambient, and a is the control nozzle to power nozzle area ratio as well as the nozzle width ratio, since the height is constant; that is

$$a = \frac{w_i}{w_j}$$

Assume now that the power jet retains its original velocity and volume flow characteristics out to a distance d from the power nozzle, and that a collector is placed at this point. Let the center of the collector be at an angle $\theta_c = w_j/d$ when there is no control pressure. As the control pressure is increased, the power jet deflects and the pressure in the collector increases. If a control pressure p_i just sufficient to cause a deflection of $\theta_s = \theta_c$ is used, the output pressure will increase to p_j (assuming no losses), resulting in a pressure gain of p_j/p_i. Since $\theta_c = w_j/d$, the pressure gain is (using eq 6)

$$G_p = \frac{p_j}{p_i} = \frac{a}{\theta_s} = a \frac{d}{w_j} \qquad (7)$$

Hence, for a control to power nozzle area ratio of unity and $d/w_j = 10$, an idealized pressure gain of 10 is calculated.

Again making the assumption that when $\theta_s = \theta_c$, $Q_o = Q_j$; it follows for flow gain, using $Q = A\,(pg_c/2\rho)^{1/2}$ where A is the aperture area, that

$$G_Q = \frac{w_j}{w_i}\left(\frac{p_j}{p_i}\right) = \frac{1}{a}\left(\frac{p_j}{p_i}\right)^{1/2} \qquad (8)$$

and from eq (7)

$$G_Q = \left(\frac{d}{aw_j}\right)^{1/2} \qquad (9)$$

or

$$G_Q = \frac{1}{a}\,(G_p)^{1/2} \qquad (10)$$

For the former conditions ($a = 1$; $d/w_j = 10$), a flow gain of 3.2 is calculated. The power gain then is 32, provided all the power can be delivered to the load. It should be noted that the input signal amplitude is too large to be completely consistent with the gain definitions.

The case of small signal variations about a bias, which is a more complex problem, will be discussed in a subsequent report.

To achieve a more realistic model, one of the most important aspects to consider is the power stream profile as a function of downstream distance. Considerable work has been done in this area for the case of the unbounded jet.* Typical profile data for a bounded jet are given in figure 9. It will be noted that the stream maintains its uniform profile out to only 3 or 4 nozzle widths and thereafter approaches a normal or Gaussian distribution.

It is apparent that the analysis presented is highly idealized and serves only to introduce the basic principles involved in fluid amplification. Nevertheless, an upper limit on efficiency can be determined. According to Albertson,* the ratio of stream power at a distance d to the power at the output of the nozzle (fig.10) is

$$\eta = 1 - 0.035\,\frac{d}{w_j}\ ; \quad d < 5\,w_j \qquad (11)$$

$$\eta = 1.86\sqrt{\frac{w_j}{d}}\ ; \quad d > 5\,w_j \qquad (12)$$

Hence, at $d/w_j = 10$, the upper limit on efficiency would be 60 percent; and at $d/w_j = 5$, the limit would be 83 percent. To increase

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*M. L. Albertson et al, "Diffusion of Submerged Jets" ASCE, Dec 1948.

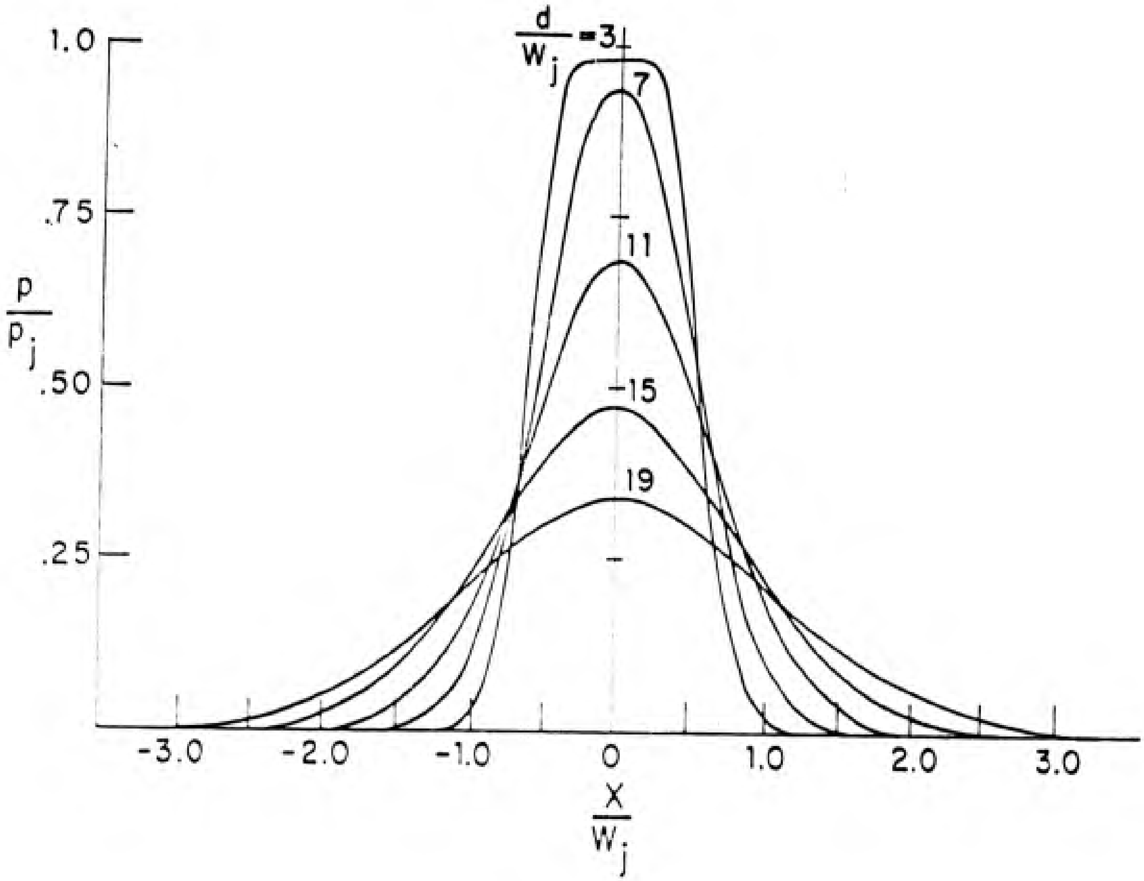

Figure 9. Stream total pressure versus cross-stream displacement with downstream distance as a parameter.

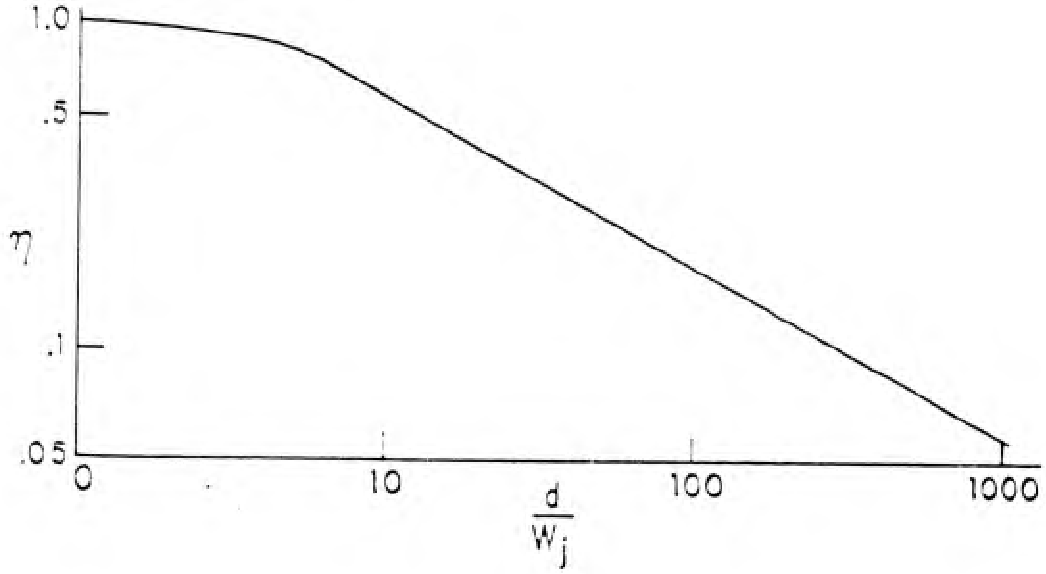

Figure 10. Ratio of stream power at d/w_j to stream power at nozzle output for the unbounded jet.

the accuracy of the calculations, the input signal power must be included and losses in the collectors must be considered. A large power gain, of course, minimizes the effect of input signal power on efficiency.

It should be noted that walls in the region between the power jet and apertures can cause the unit to become bistable as reported in Part I. Simply removing the walls, however, may give rise to other problems, since acoustic wave reflections can cause stream instability. The best guide is to design the unit so that only the pressure difference induced by the control jets can exist across the power stream. A short connection between the two sides of the stream is sometimes used for this purpose.

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