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WATERHAMMER/CAVITATION

Assessment & Prevention

- WHAT IS WATERHAMMER
- WATERHAMMER CATEGORIES
- WATERHAMMER PHENOMENON
- WATERHAMMER ASSESSMENT
- WATERHAMMER PREVENTION
- INDUSTRY EXPERIENCES
- WHAT IS CAVITATION
- WHERE IT OCCURS
- HOW TO IDENTIFY
- EFFECTS OF CAVITATION
- CAVITATION DAMAGE
- DESIGN CONSIDERATIONS

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CAVITATION

1.0 What is Cavitation

In a flowing liquid if the static pressure is dropped below the vapor pressure corresponding to the liquid temperature (or the temperature is increased above the saturation temperature corresponding to the liquid pressure), vapor bubbles (cavities) will be generated. If these bubbles are carried downstreams by the liquid to a region of higher static pressure (or lower temperature) then the bubbles will collapse. the region of the flow where bubbles exist is the cavitating region, whereas the observed damage is at the location of the bubble collapse.

Cavitation is distinguished from flashing or boiling flow in that no pressure recovery occurs downstream in the latter type of flow, and therefore no bubble collapse occurs.

2.0 Where Cavitation is likely to occur in Systems

- Orifices (Pressure profile across an Orifice, Figure-1)
- Valves
- Venturies
- Pump Suction
- Pipe Fittings (Elbows, TEEs, etc.), (Figures 2 and 3)
- Bumps

3.0 Identification of Cavitation

This process of bubble formation, growth, and collapse produces oscillation in the flow regime that can be identified by distinct sound. The sound may range from occasional popping (at the onset of cavitaion) to a sound like frying bacon as cavitation level increases. Extensive cavitation sounds like gravel flowing through the system. Because the flow oscillation associated with cavitation is broad band, pipe vibtation will also be associated with cavitation.

4.0 Effects of Cavitation/Damage

Cavitation produces undesirable effects on piping system and components. It generates undesirable noise, may cause erosion, restrict flow capacity of the system, and may cause pipe failure due to pipe failure.

The erosion observed in cavitating fluid is due to bubble collapse near the pipe wall. Studies have shown that as a result of bubble collapse the liquid jets with velocities of 300 to 2000 feet per second will impact the pipe wall. At this high impact velocity, the local pressure at the wall could be as high as 10,000 atm. The continuous bomardment of the metal surface will result in the pitted configuration observed in most damaged components.

5.0 Design Considerations

For system susceptible to cavitation, the designer should ensure that under operating conditions, the system is either free from cavitation or has acceptable level of cavitation. Levels of cavitation are defined below.

Incipient Cavitation -	The onset of cavitation. No objectionable noise and no damage.
Critical Cavitation -	Continuous light cavitation usually adopted as the design criterion. Noise and vibtation are acceptable and only minor damage after long periods.
Incipient Damage -	Onset of surface pitting after short period of operation.
Choking Cavitation -	Flow is not increased if downstream pressure is decreased. Maximum vibration and noise.

Cavitation at pump suction is well taken care by satisfying Vendor's NPSH requirements. Valves and Orifices are genarally the common source of cavitation problems encountered in power plants. The following sections provide basic guidance on how to avoid cavitation of orifices and valves.

ORIFICES

(See Figure-1 for a pressure profile across an Orifice)

Cavitaiton Index

$$\sigma = (P_d - P_v)/(P_u - P_d)$$

$$= (P_d - Pv)/\Delta P \qquad \text{(Reference 1)}$$

Where: σ = Orifice Cavitation Index

P_u = Upstream Pressure, psia

P_d = Downstream Pressure, psia

P_v = Vapor Pressure, psia

The above calculated "cavitation Index" is compared to accepatable "Cavitation Level" (see Figure 5) which is experimently determined . If the cavitaion index is equal to, or higher than the cavitaion level, the orifice size is acceptable. If a single orifice fails to satisfy cavitation criterion, multiple orifices are required. The spacings between orifices must allow complete pressure recovery, which is achieved by placing the orifices 6-8 pipe diameters apart. The "β" ratio (orifice diameter/pipe inside diameter) of orifices shall be in increasing order along the flow. Sample Problem-1 illustrates selection of orifice(s) to have cavitation free operation.

When enough space is not available, multi hole type orifice plate (perforated plate), or a cone type orifice is recommended.

Other definitions of Cavitation Parameter

$$\sigma = \frac{(h_u - h_v)}{U^2/2g} \qquad \text{and}$$

$$\sigma = \frac{(h_u - h_v)}{(h_u - h_d)} \qquad \text{(Reference 2)}$$

Where: σ = Cavitation parameter
h_u = Upstream head
h_v = Vapor head
h_v = Downstream head
U = Upstream velocity
g = Gravitational constant

Reference-2 utilizes reference velocities for a component size and upstream head at which a type of cavitation commences. These velocities are then corrected to other component sizes and upstream head conditions using empirical relationships with experimentally derived coefficients.

VALVES

Colorado State University tested some valves for Hydraulic and Cavitation characteristics. The test data indicate that the critical cavitation index does not only depend on the valve opening (area ratio) but is also dependent on VALVE SIZE, UPSTREAM PRESSURE, and VALVE TYPE. Figure-9 through-12 show results of such tests. Figure-12 also includes a curve for the critical cavitation index for a thin orifice plate for comparison to that of a valve.

For a valve to operate completely cavitation free, operating conditions should never approach those corresponding to the critical cavitation index. Operation beyond critical cavitation is never recommended.

Analytically, it may not always be possible to accurately predict when a valve will start to cavitate. Therefore, monitoring for noise and vibration levels at the required operating point is recommended.

Reference 2 provides guidelines for determining cavitation parameter for valves. Sample Problem-2 is used as an illustration for a butterfly valve.

6.0 References

1. Technical Paper, "Eliminating cavitation from pressure-reducing orifices", CHEMICAL ENGINEERING DECEMBER 12,1983

2. INTERNAL FLOW SYSTEMS, by Donald S. Miller, Volume 5 in the BHRA (British Hydromechanics Research Association)Fluid Engineering Series

$\Delta P = 120$ psig =
$4500 = 236 (d_1)^2 (.62) \sqrt{\frac{120}{61}} \Rightarrow d_1^2 = 21.927 \text{ in}^2$
$d_1 = 4.68 \text{ in}$

SAMPLE PROBLEM-1

$\sigma = \frac{15-5}{120} = 0.08$ use $\beta \geq 0.7$

Pump discharges water to atmosphere (See Figure-4). $\frac{d}{D} = \frac{4.68}{14} = .33$

Pipe size:	14-inch, Schedule 40
Flow:	4500 gpm
Pressure drop across orifice(s):	120 psid
Fluid temperature:	160° F

Determine the size of orifice(s) for cavitation free operation. Neglect piping friction loss. Use Figure 5 for comparing calculated cavitation index (σ).

SAMPLE PROBLEM-2

Water flows from a reservoir at higher elevation to the reservoir at lower elevation, and flow is to be controlled by a butterfy valve (See Figure-6). Determine the cavitation free range of control for the A-type butterfly valve from fully closed to fully open position. Loss coefficients for butterfly valve types are shown in Figure-7. Accepatance criteria is critical cavitation velocity.

Pipe Size:	30-inch, Schedule-40
Valve Size:	30-inch diameter
Water Temperature:	90° F
K-for Piping between "A" to "B" :	17
K-for Piping between "C" to "D" :	7
K-for butterfly valves types:	Shown in Figure-7

Based on Reference-2, Cavitation velocities for a butterfly valve are determined as follows:

$$U_i \text{ or } U_c = C_1 . (U_{ir} \text{ or } U_{cr}) . [(h_u - h_v)/50]^{0.39}$$

and

$$U_{ch} = U_{rch} \, [(h_u - h_v)/50]^{0.5}$$

Where:

U_i, U_c, and U_{ch} are incipient, critical or choking cavitation velocity (to be determined) for a given butterfly valve.

C_1 is correction factor for the valve size used, Figure-8

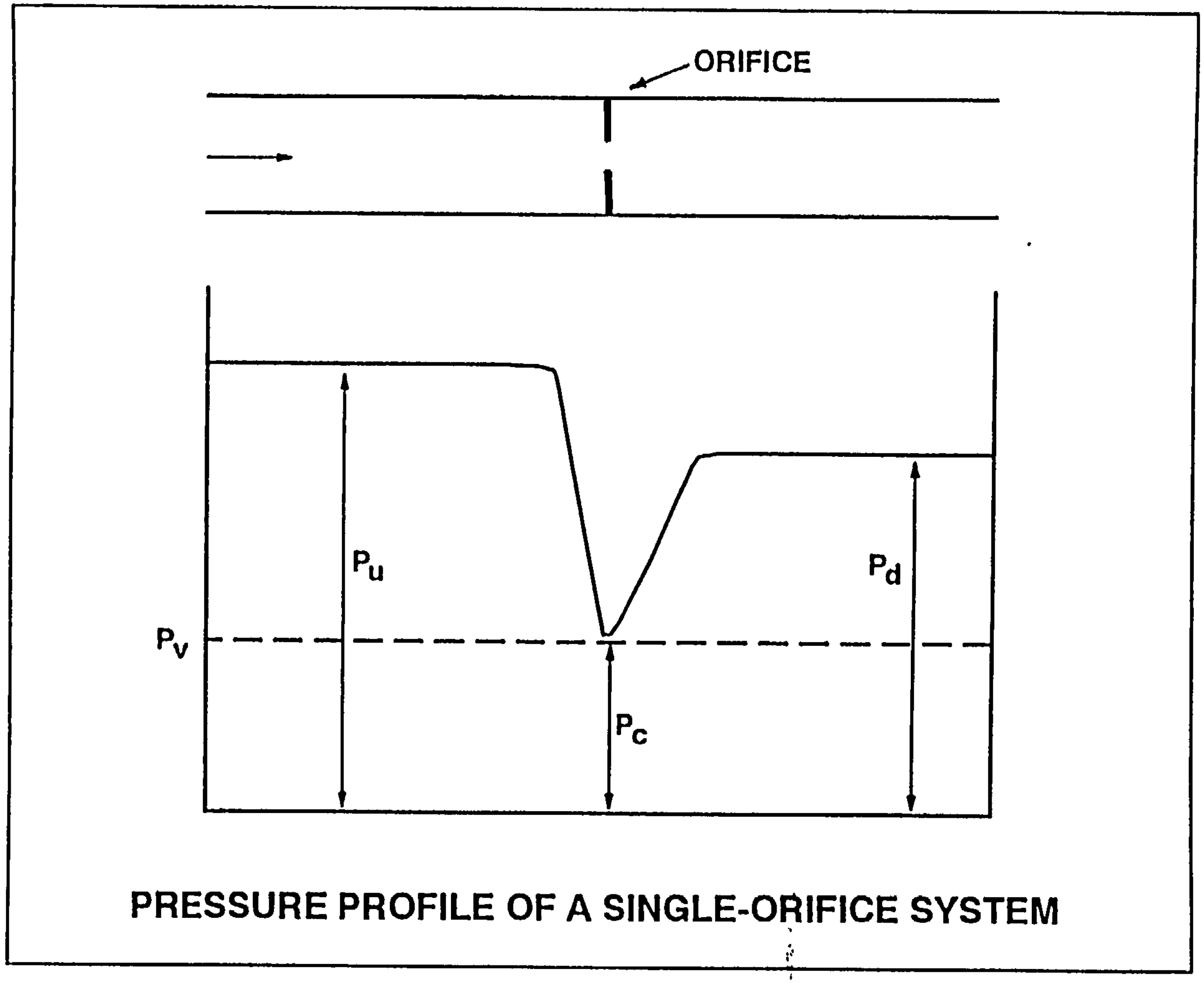
U_{ir}, U_{cr}, and U_{chr} are the reference cavitation velocities (incipient, critical, or choking as applicable) for the base valve, shown in Figure-8.

h_u = upstream head of the valve (meters)

h_v = vapor head (meters)

"50" = "$h_u - h_v$" value (in meters) for the base valve (size 0.3m diameter)

CAUTION: USE DIMENSIONAL UNITS APPROPRIATELY



P_u = Pressure upstream of the orifice

P_c = Pressure at the vena-contracta

P_d = Pressure downstream of the orifice

P_v = Vaper pressure of the flowing fluid

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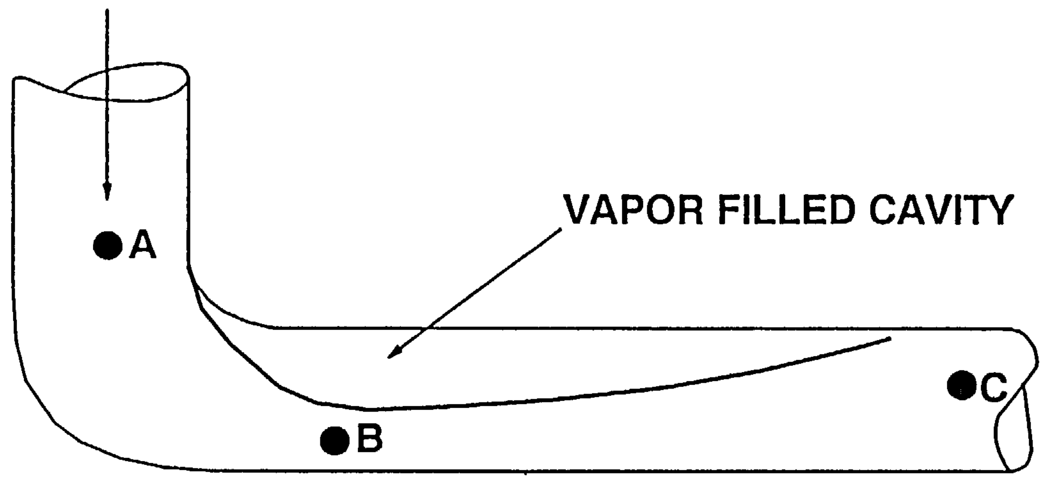
FIGURE - 1



ELBOW

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FIGURE - 2

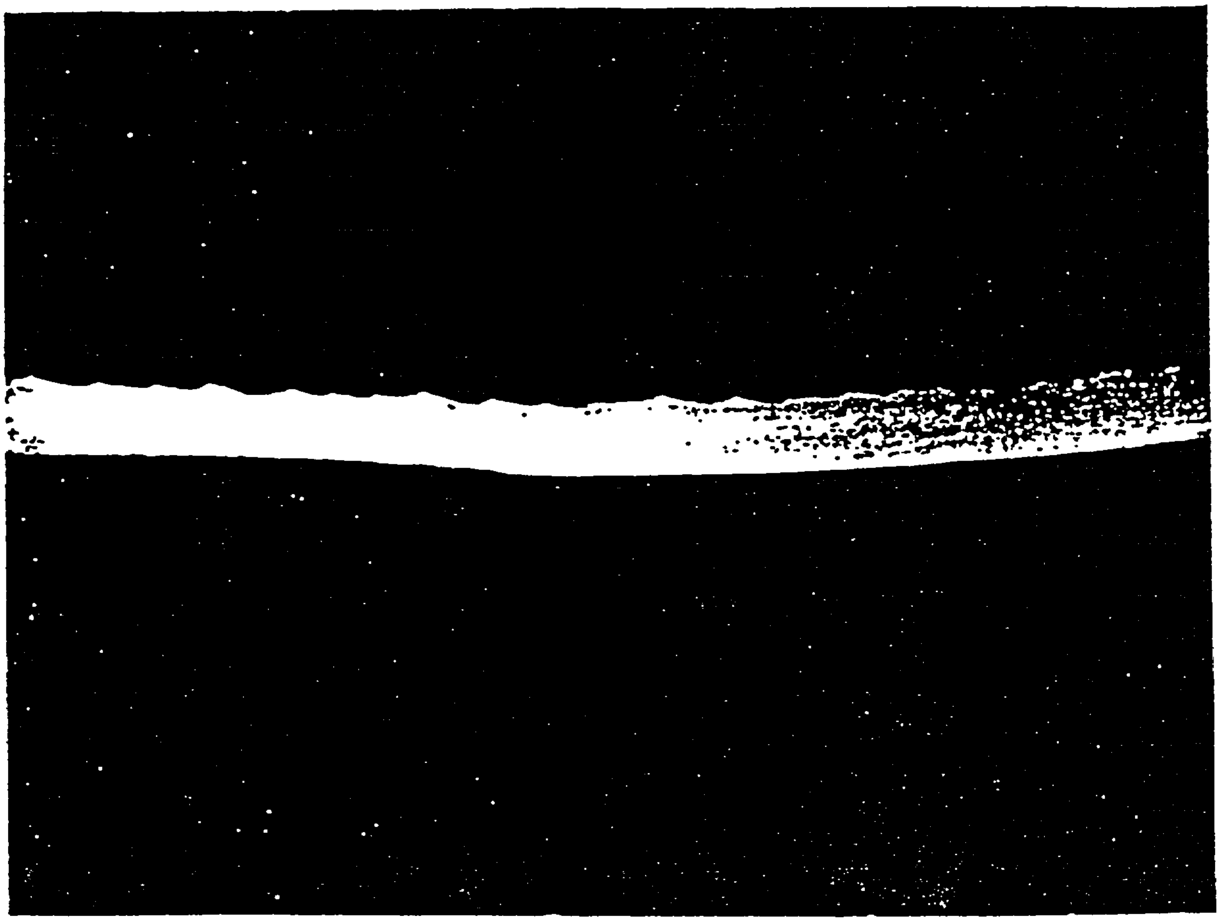
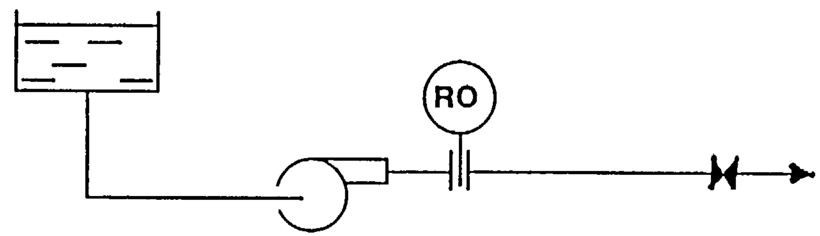


FIGURE - 3

INCORRECT SOLUTION:

(1 stage orifice)



CORRECT SOLUTION:

(2 oriface stages)

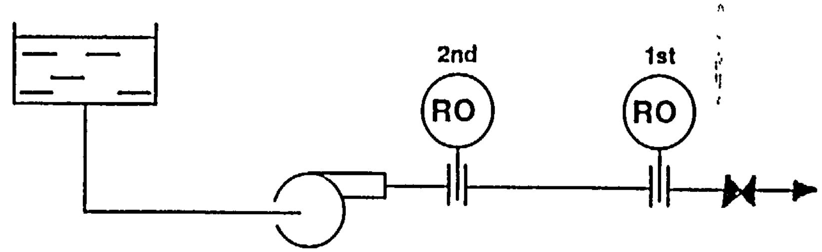


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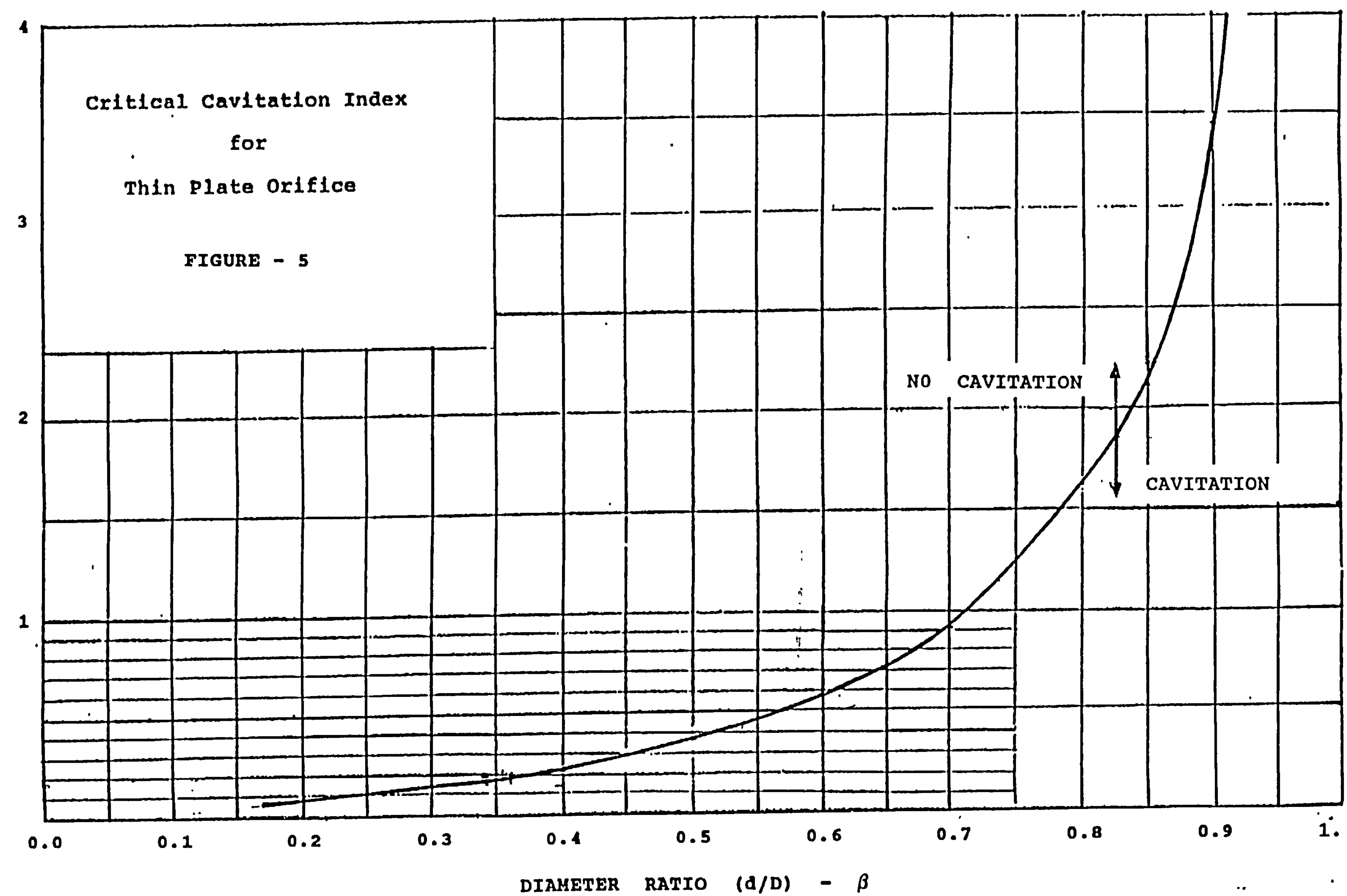
FIGURE - 4


Critical Cavitation Index
for
Thin Plate Orifice
FIGURE - 5
NO CAVITATION
CAVITATION
4
3
2
1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.
DIAMETER RATIO (d/D) - β

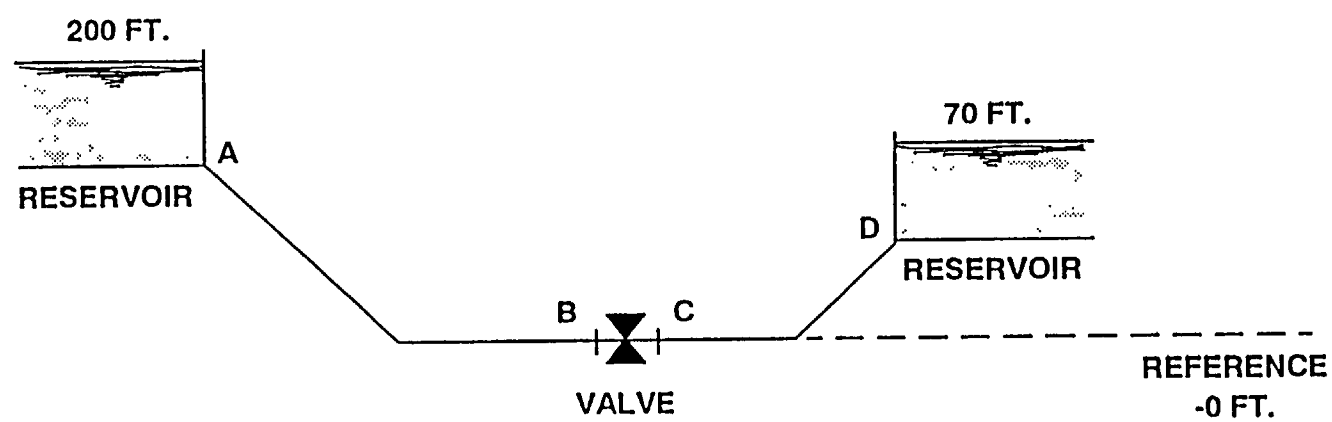


FIGURE - 6

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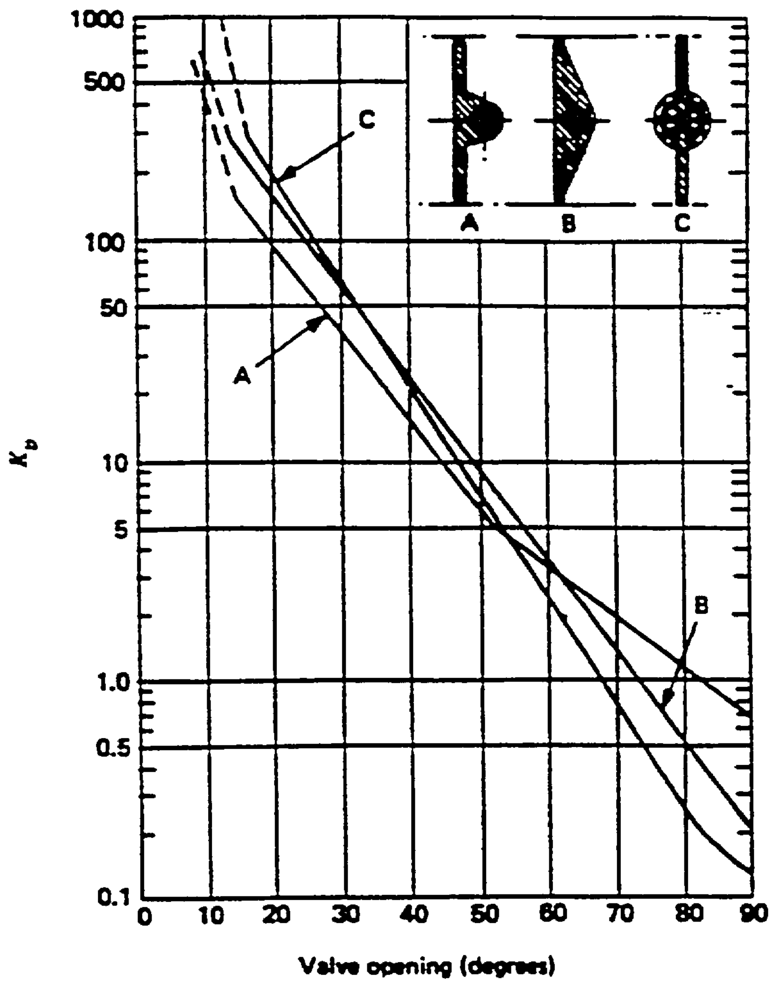
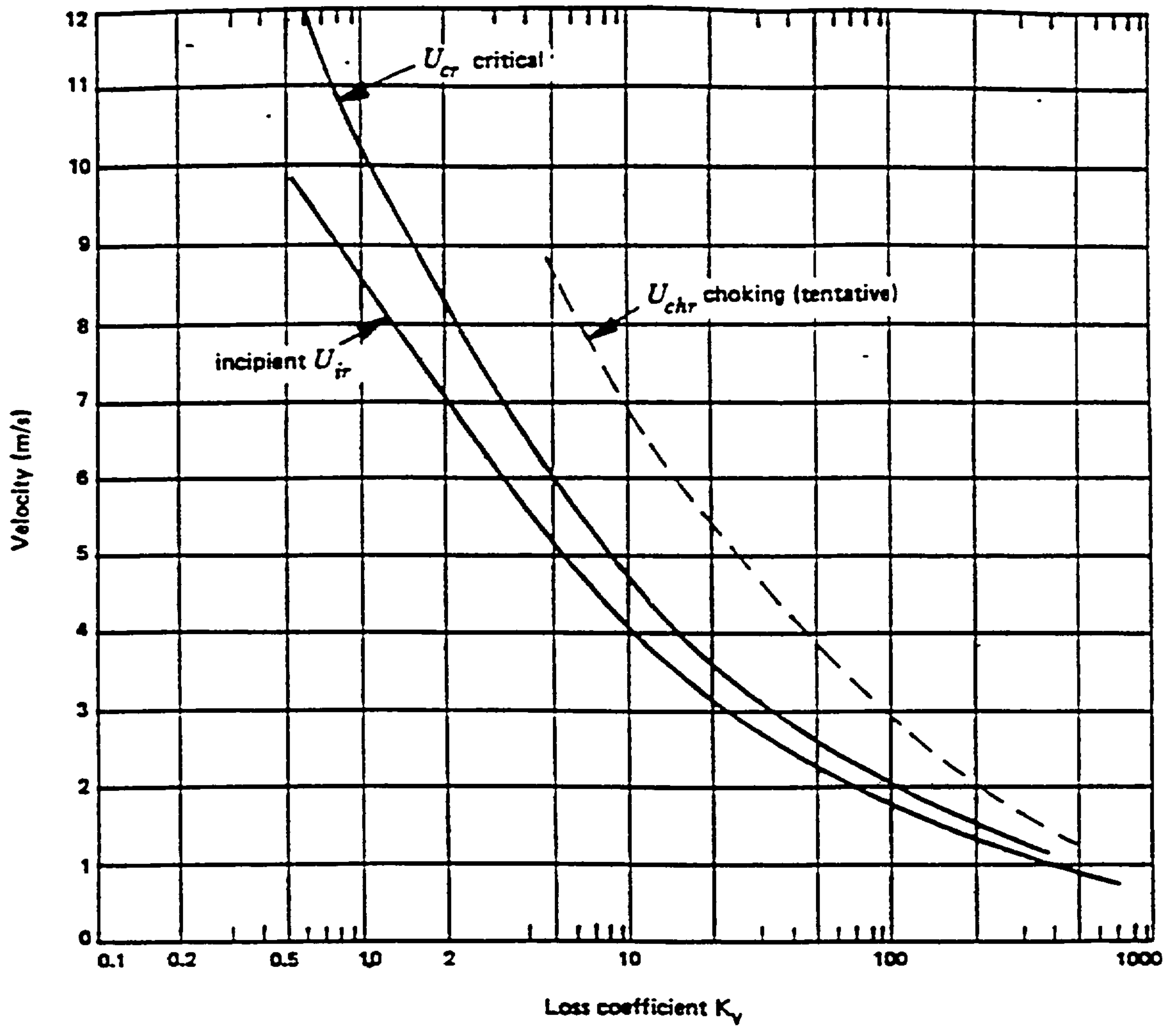
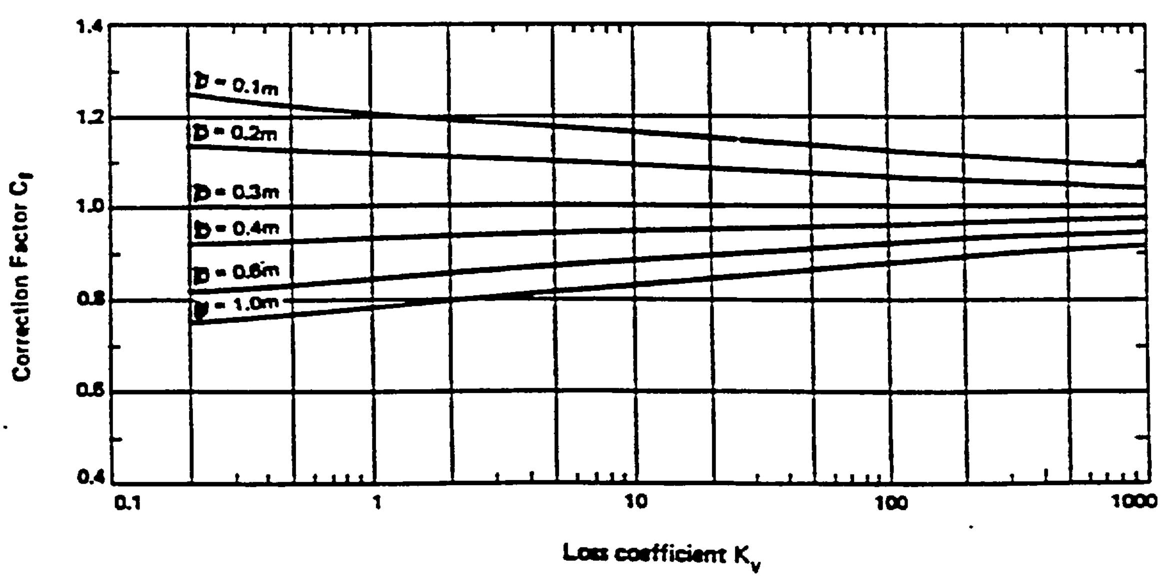


Loss Coefficients for Butterfly Valves
(from Reference 2, Figure 14.19)

FIGURE - 7



Cavitation Velocities for Butterfly Valves
(from Reference 2, Figure 6.22)



Correction Factors for Valve Size
(from Reference 2, Figure 6.23)

FIGURE - 8

FIGURE - 9

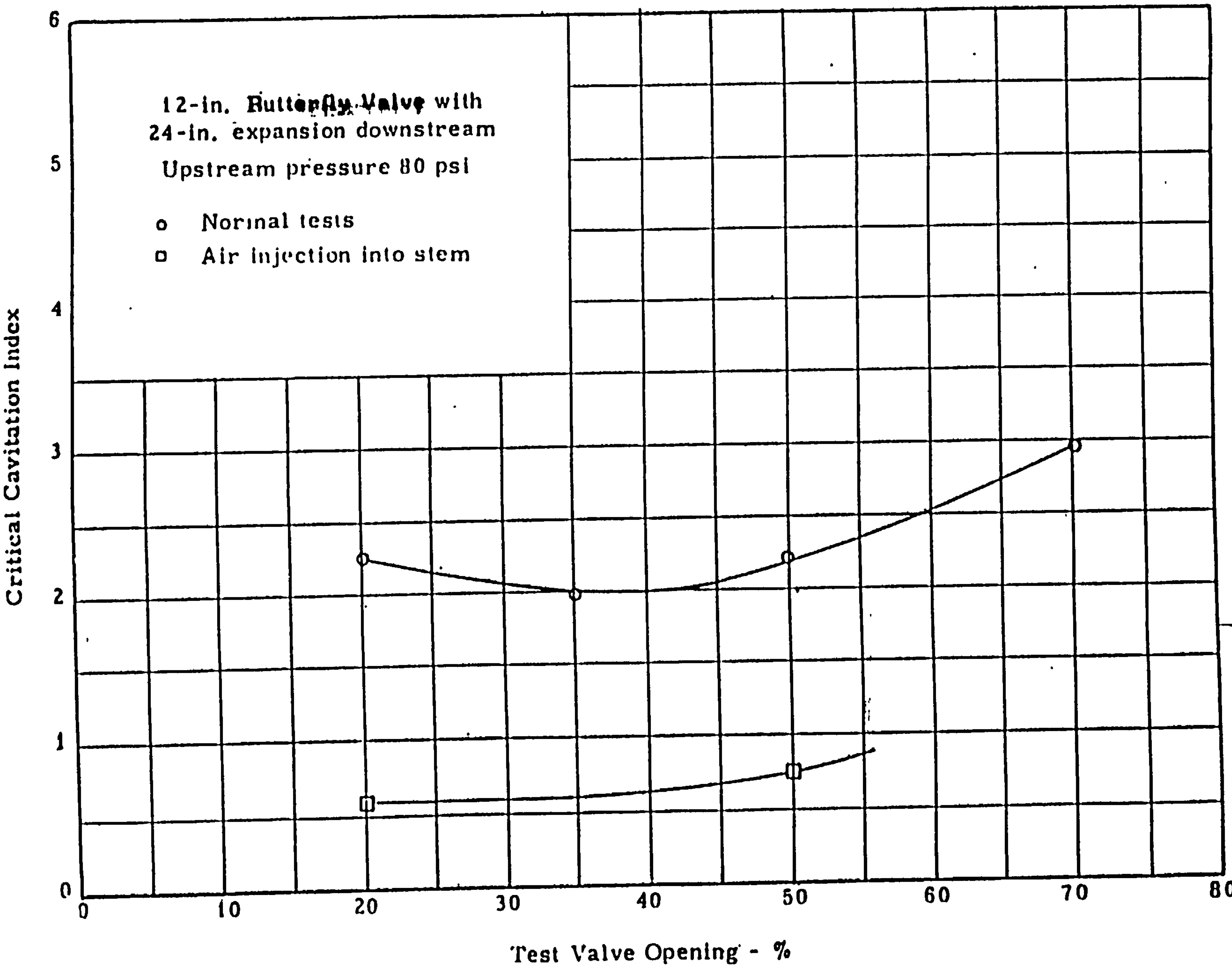
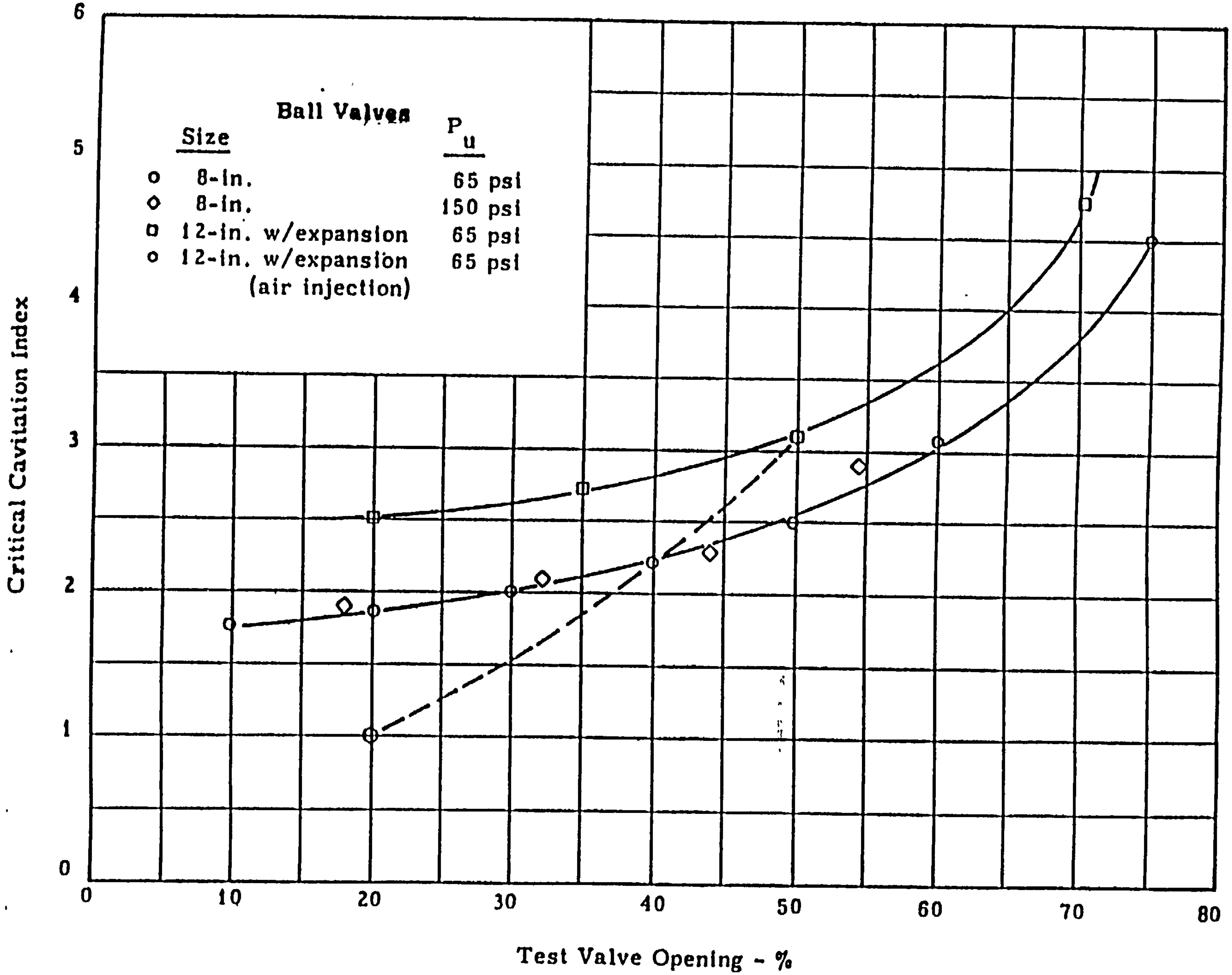
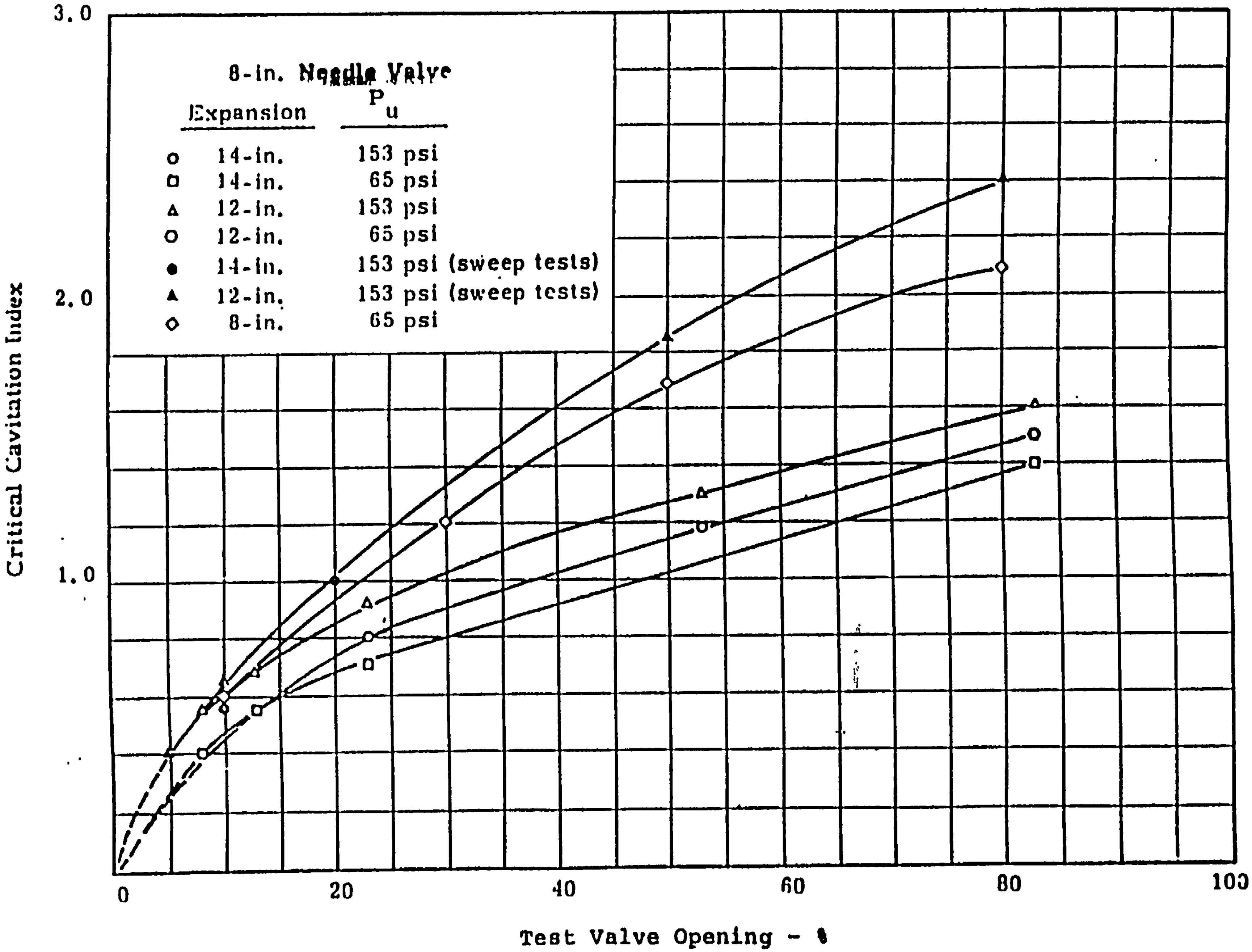

12-in. Butterfly Valve with
24-in. expansion downstream
Upstream pressure 80 psi
o Normal tests
□ Air injection into stem
Critical Cavitation Index
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
Test Valve Opening - %

FIGURE - 10



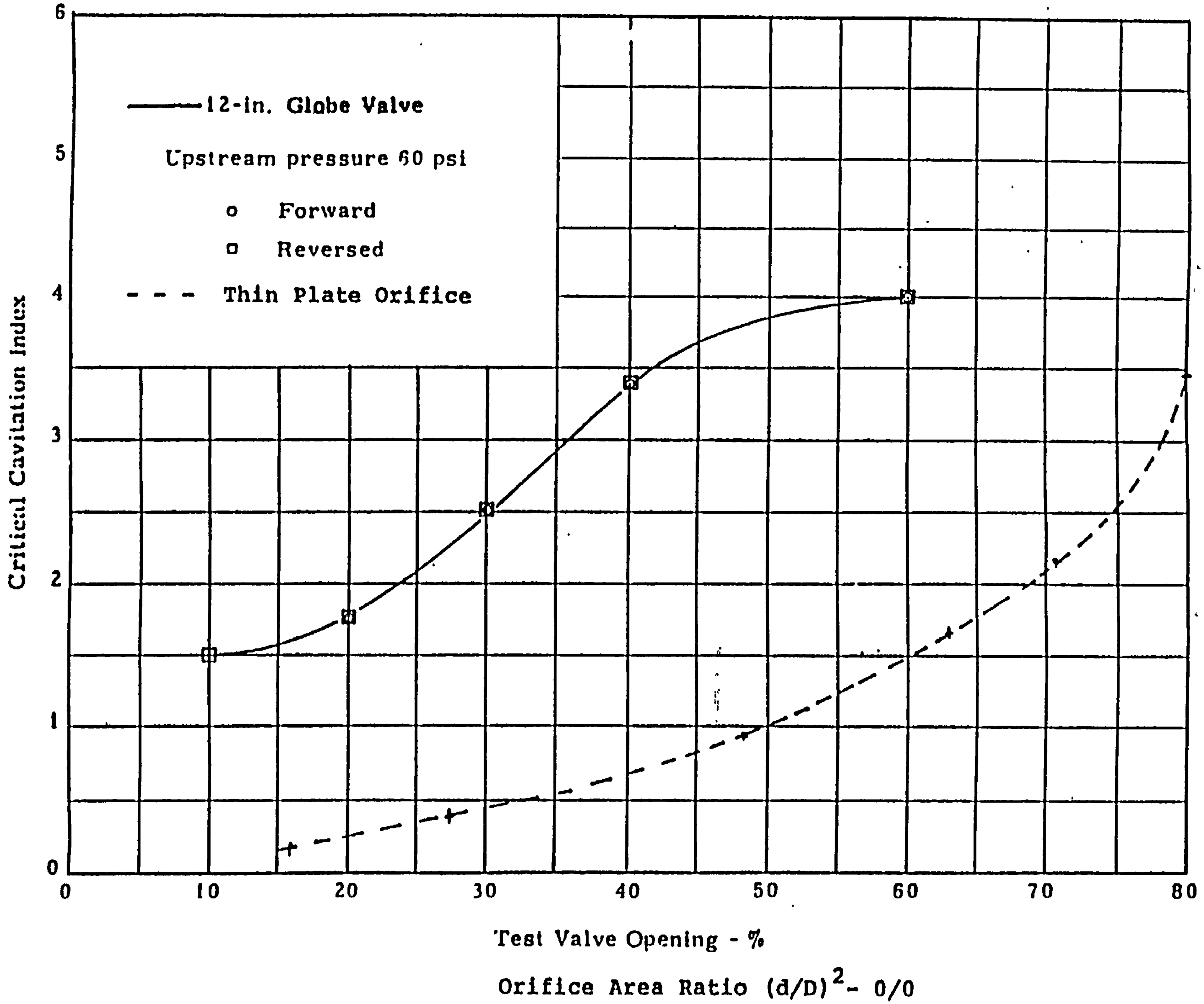
Ball Valves
Size
P u
o 8-in. 65 psi
◇ 8-in. 150 psi
□ 12-in. w/expansion 65 psi
o 12-in. w/expansion 65 psi
(air injection)
Critical Cavitation Index
Test Valve Opening - %
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80

FIGURE - 11



8-in. Needle Valve
Expansion
P_u
14-in. 153 psi
14-in. 65 psi
12-in. 153 psi
12-in. 65 psi
14-in. 153 psi (sweep tests)
12-in. 153 psi (sweep tests)
8-in. 65 psi
3.0
2.0
1.0
0
20
40
60
80
100
Critical Cavitation Index
Test Valve Opening - %

FIGURE - 12


12-in. Globe Valve
Upstream pressure 60 psi
Forward
Reversed
Thin Plate Orifice
Critical Cavitation Index
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
Test Valve Opening - %
Orifice Area Ratio (d/D)2- 0/0

Eliminating cavitation from pressure-reducing orifices

Multiple orifices can avert the cavitation, and resulting noise and vibration, caused by single orifices in hydraulic systems

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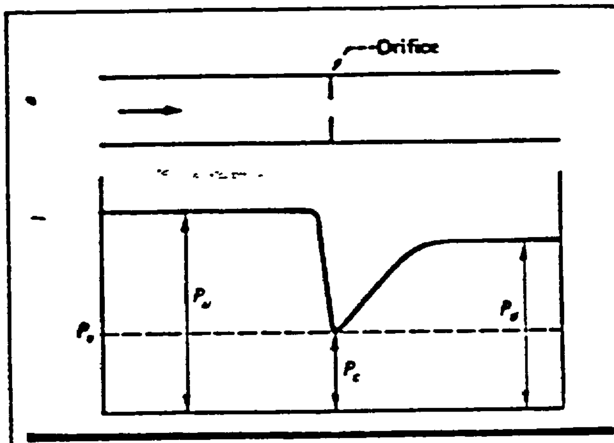
☐ Fig 1 illustrates flow through a single orifice in a pipe: P_u is the pressure upstream of the orifice; P_c, the vena-contracta pressure; and P_d, the pressure downstream of the orifice. The last pressure, P_d, must be higher than the vapor pressure, P_v, of the flowing fluid.

If P_c falls below P_v, bubbles form, the first stage of cavitation. As the fluid moves downstream, the bubbles collapse under the higher pressure, P_d, in the final stage of cavitation. The implosions generate noise and vibration, and accelerate the erosion of the piping [1].

If P_d is kept below P_v, two-phase flow continues downstream as a flashing mixture without cavitation.



Pressure profile of a single-orifice system — Fig. 1

Cavitation criterion

To avoid orifice cavitation, the orifice size selected for the pressure-drop requirement must be checked against an orifice cavitation index, which is then compared to a cavitation level. If the index is equal to, or higher than, the cavitation level, the orifice size is acceptable.

The index was defined by Tullis and Govindarajan [2]:

$$\sigma = (P_d - P_v)/(P_u - P_d) = (P_d - P_v)/\Delta P \qquad (1)$$

They also experimentally determined acceptable cavitation levels. These, σ_r, vs. orifice-to-pipe-dia. ratios, β, for various pipe sizes are shown in Fig. 2. At these cavitation levels, noise is low and steady, and no damage will result.

When a single orifice fails to satisfy the cavitation criterion, two or more orifices in series are required. In multiple-orifice systems, the spacings between orifices must allow complete pressure recovery, which is achieved when the circumference of the orifice jet expanding toward the pipe wall equals that of the inside pipe. Fig. 3 relates these distances to β [3].

Design of single-orifice systems

To design a single-orifice system free from cavitation:

1. Size the orifice for the required flowrate and pressure drop by means of Eq. (2):

$$\Delta P = K(V^2/2)\rho \qquad (2)$$

Determine the resistance factor, K, for the orifice by inserting the flowrate and orifice pressure drop into Eq. (2). Having the K value, find the orifice size from Fig. 5.

2. Check that the orifice size obtained from Step 1 satisfies the cavitation criterion. Calculate the cavitation index, σ, for the orifice via Eq (1), and get the corresponding acceptable cavitation level, σ_r, from Fig. 2. Compare σ to σ_r: If $\sigma \geq \sigma_r$, the size of the single orifice is acceptable; if $\sigma < \sigma_r$, multiple orifices are required.

Design of multiple-orifice systems

Each orifice in a multiple system (illustrated in Fig. 4) is sized to meet the cavitation criterion:

1. Assume a β value for the first orifice, OR_1 (the one furthest downstream). With this β value, determine the corresponding resistance factor, K, from Fig 5.

2. Substitute the value for K obtained in Step 1 into Eq. (2) to find the ΔP across OR_1.

3. Substitute this calculated ΔP into Eq. (1) to determine the cavitation index, σ.

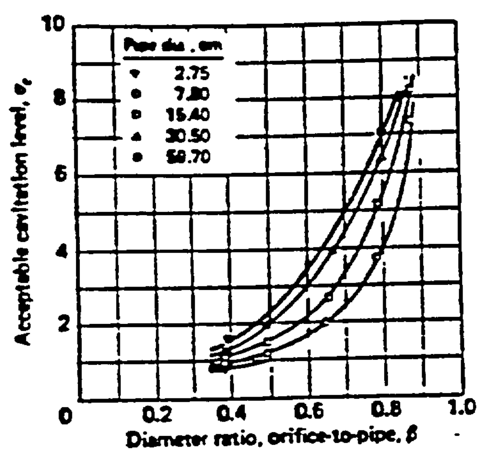
4. With the β value assumed in Step 1, find the acceptable cavitation level, σ_r, in Fig. 2.

5. Compare σ to σ_r. If $\sigma \geq \sigma_r$, the assumed β is satisfactory. (To have the minimum number of orifices for a specific flowrate and pressure-drop requirement, the value of σ should be kept as close as possible to σ_r.) If $\sigma < \sigma_r$, choose a larger β value and repeat Steps 1 through 5 until $\sigma \geq \sigma_r$.

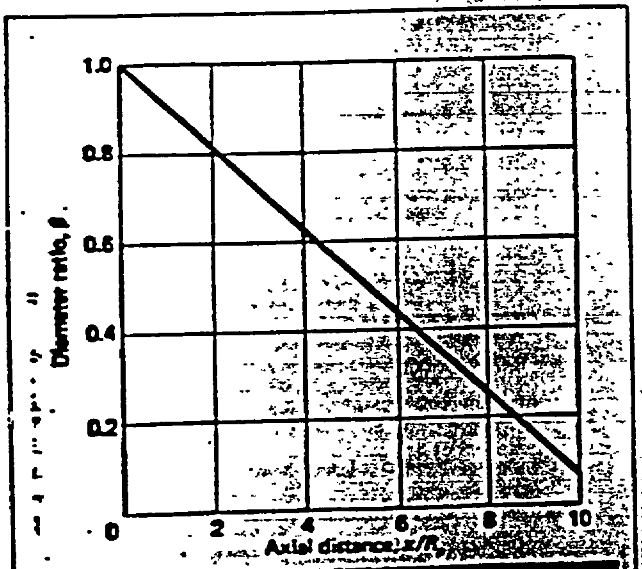
6. The downstream pressure, P_{2d}, of the second ori-

Nomenclature

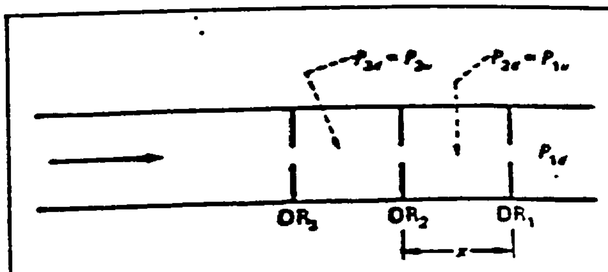
- A Pipe flow area, m²
- K Resistance factor
- m Mass flowrate, kg/s
- P_d Backpressure, kPa
- P_u Orifice upstream pressure, kPa
- P_v Vapor pressure, kPa
- R_p Pipe internal radius, m
- V Flow velocity, m/s
- x Distance for orifice jet circumference to fill pipe circumference, m
- β Diameter ratio of orifice to pipe
- ρ Density, kg/m³
- σ Cavitation index
- σ_r Acceptable cavitation level



Acceptable cavitation level related to orifice-to-pipe-dia. ratio [2] Fig. 2



Distance downstream of orifice for complete pressure recovery [3] Fig. 3



Pressure relationships in the design of a multiple-orifice system Fig 4

fice, OR_2, is set equal to the upstream pressure, P_{1u}, of the first orifice, OR_1, etc. (as indicated in Fig. 4)

7. The last orifice (the one furthest upstream) is sized as was described for a single-orifice system

8. After all the orifices have been sized, determine the necessary distances between the orifices for cavitation-free operation by means of Fig. 3. For example, find the proper distance between OR_1 and OR_2 (Fig 4), enter the value of β for OR_2 into Fig. 3 and obtain the corresponding value of x/R_p. Having the pipe radius, R_p, determine the proper distance, x, between OR_1 and OR_2

Example illustrates the procedure

Design an orifice system for a 186.0-kg/s flowrate of water through a NPS12 Sch. 80 pipe. The upstream pressure and temperature are 10,340 kPa and 138°C, respectively, and the orifice backpressure is 690 kPa. The vapor pressure and density of water at 138°C are 340 kPa and 928.0 kg/m³, respectively. The pipe's inside radius is 0.145 m, and its flow area is 0.066 m².

First determine the flow velocity through the pipe.

$$V = m/\rho A = 186.0/(928.00)(0.066) = 3.0 \text{ m/s}$$

1. Try a single orifice, sizing it via Eq. (2).

$$(10{,}340 - 690)\ 1{,}000 = K[(3.0)^2/2]\ 928.0$$

With $K = 2{,}300$, $\beta = 0.186$, from Fig. 5.

2. Check whether the orifice size $\beta = 0.186$ satisfies the cavitation criterion. Via Eq. (1):

$$\sigma = (690 - 340)/(10{,}340 - 690) = 0.036$$

With $\beta = 0.186$, Fig 2 gives: $\sigma_r = 1.1$.

As $(\sigma = 0.036) < (\sigma_r = 1.1)$, one orifice system does not meet the criterion, and a multiple system must be designed:

1. Assume that $\beta_1 = 0.4$ for the first orifice, OR_1 (the one furthest downstream). With this β_1, $K = 90$.

2. Determine the pressure drop via Eq (2).

$$\Delta P = 90\ [(3.0)^2/2]\ 928.0 = 375.8 \text{ kPa}$$

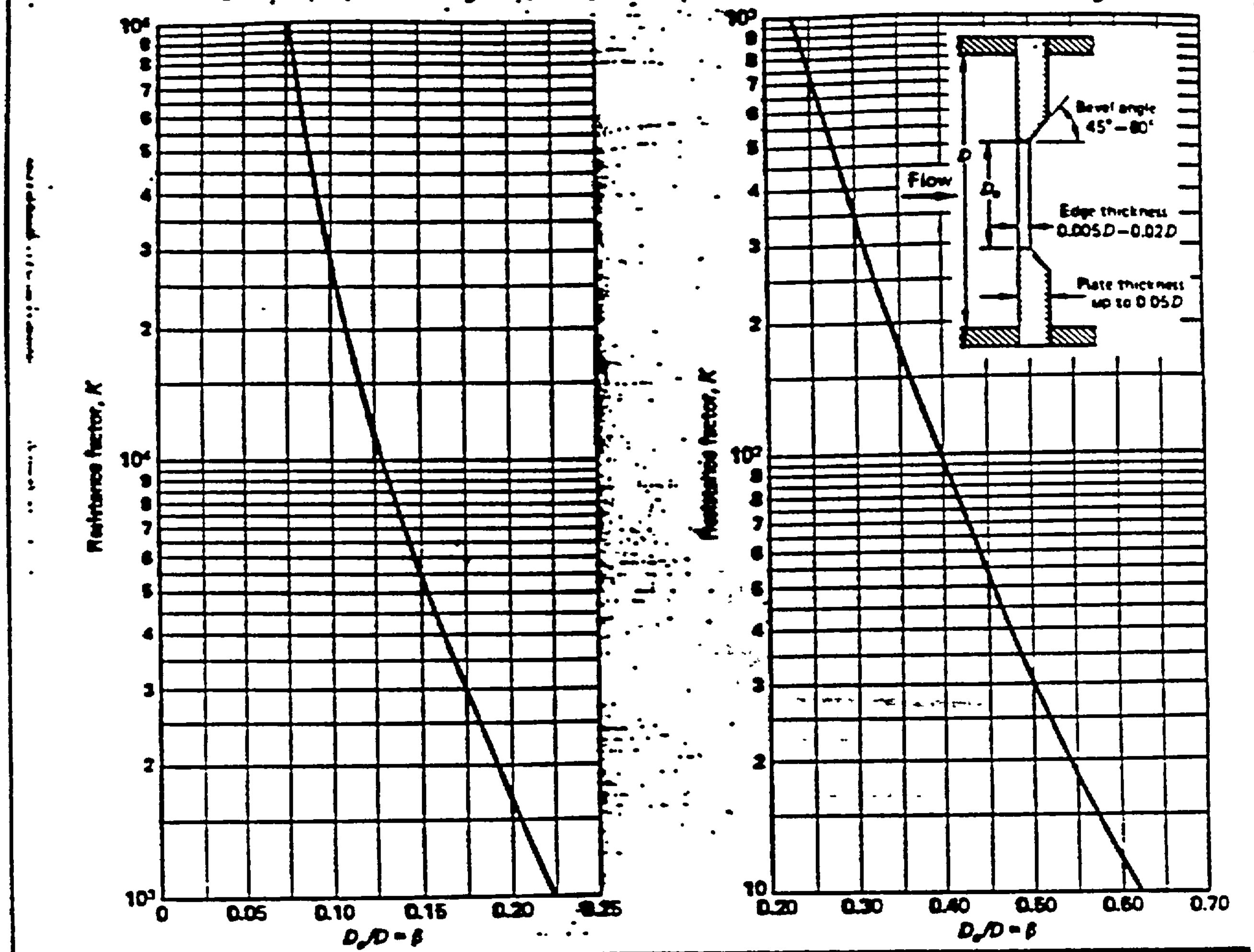
3. Substitute this ΔP value into Eq. (1):

$$\sigma_1 = (690 - 340)/375.8 = 0.93$$

4. With $\beta_1 = 0.4$, $\sigma_r = 1.3$, from Fig. 5.

5. Because $(\sigma_1 = 0.9) < (\sigma_r = 1.3)$, the cavitation criterion has not been met. Try a larger orifice size—e.g., $\beta_1 = 0.45$. Repeating the foregoing procedure yields $\sigma_1 = 1.62$ and $\sigma_r = 1.6$, which satisfy the criterion.

6. The sizes of the remaining orifices are determined as previously described—i.e., the downstream pressure.



Relationship of resistance factor to orifice-to-pipe-dia. ratio for sharp-edged orifices [4] Fig. 5

P_{2d}, of the second orifice, OR_2, is set equal to the upstream pressure, P_{1u}, of the first orifice, OR_1, etc.

7. Size the final orifice, as has been described.
8. Lastly, find the distances between the orifices.

J. Matley, Editor

References

1. Sales, G. F., Cavitation in Control Valves, *Instrument and Control Systems*, Vol. 34, November 1961
2. Tullis, J. P., and Govindarajan, R., Cavitation and Size-Scale Effects for Orifices," *J. of Hydraulic Div.*, American Soc. of Civil Engineers, March 1973
3. Teyssandier, R. G., and Wilson, M. P., "The Paradox of the Vena Contracta," American Soc. of Mechanical Engineers, Paper No. 73-WA/FM-9
4. Miloanovic, M., and Tung, P. C., Sizing of Throttling Orifices, *Heating/Piping/Air Conditioning*, December 1978
5. Kinderman, W. J., and Wales, E. W., Fluid Flow Through Two Orifices in Series, *Trans. American Soc. of Mechanical Engineers*, January 1957
6. Benjamin, M. W., and Miller, J. G., The Flow of Saturated Water Through Throttling Orifices, *Trans. American Soc. of Mechanical Engineers*, July 1941
7. Numachi, J. P., et al., Cavitation Effect on the Discharge Coefficient of the Sharp-Edged Orifice Plate, *J. of Basic Engineering*, March 1960.
8. Tullis, J. P., et al., Perforated Plates as Hydraulic Energy Dissipators, in "Computer and Physical Modelling in Hydraulic Engineering," by Ashton, G., American Soc. of Civil Engineers, 1980
9. Watson, W. W., Evolution of Multijet Sleeve Valve, *J. of Hydraulic Div.*, American Soc. of Civil Engineers, June 1977.
10. Tullis, J. P., Choking and Supercavitating Valves, *J. of the Hydraulic Div.*, American Soc. of Civil Engineers, December 1971.
11. Driskell, L., Control Valve Sizing with ISA Formulas, *Instr. Tech.*, July 1974.

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Milen Mikasinovic is a senior design specialist with Ontario Hydro. His responsibilities include design and construction of mechanical equipment for the power and chemical process industries. Holder of a B.S. in mechanical engineering from the University of Belgrade, Yugoslavia, he is a registered engineer in Ontario, a member of the Canadian Soc. for Professional Engineers, and the author of a handbook of fluid flow (published in Yugoslavia) and of several articles published in U.S. technical journals.