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DEVELOPMENT AND DESIGN OF WATERCOURSE JUNCTION JET PUMPS

Thomas Trout
W. Doral Kemper
Rick Aust

Water Management Research Project
Colorado State University
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Many farmers in Pakistan experience difficultures due to insufficient head or elevation of the water in their irrigation system. This problem is especially acute on public tubewell supplemented watercourses. A low head jet pump device which utilizes the excess energy of tubewell water to raise the elevation of surface canal water was developed to help solve this problem. Both laboratory and field studies are described which show that these watercourse junction jet pumps can solve the problem, even though their efficiencies range from only 14 and 18%, and can be built inexpensively. Their primary use will be to: (a) allow canal turnouts, which are often submerged when the tubewell is turned on, to flow freely; or (b) irrigate, or more efficiently irrigate, the higher elevation croplands. Both graphical and analytical procedures are described for the design of jet junctions.

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ABSTRACT

Many farmers in Pakistan experience difficulties due to insufficient head or elevation of the water in their irrigation system. This problem is especially acute on public tubewell supplemented watercourses. A low head jet pump device which utilizes the excess energy of tubewell water to raise the elevation of surface canal water was developed to help solve this problem. Both laboratory and field studies are described which show that these watercourse junction jet pumps can solve the problem, even though their efficiencies range from only 14 and 18%, and can be built inexpensively. Their primary use will be to: (a) allow canal turnouts, which are often submerged when the tubewell is turned on, to flow freely; or (b) irrigate, or more efficiently irrigate, the higher elevation croplands. Both graphical and analytical procedures are described for the design of jet junctions.

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NOMENCLATURE

A	cross-sectional area (cm^2)
A_p	pipe cross-sectional area (cm^2)
C_L	loss coefficient
C_{LT}	summation of all friction and form loss coefficients
D	mixing chamber diameter (cm)
D_n	normal flow depth (cm)
D_p	pipe diameter (cm)
d	nozzle diameter (cm)
E	efficiency (%)
E_m	maximum efficiency at a given flow ratio (%)
f	relative roughness coefficient for pipes
H	head on a mogha (cm)
H_j	jet head (cm)
H_s	suction fluid head (cm)
H_t	head of combined fluids (cm)
Δh	head loss (cm)
Δh_j	head loss through the junction jet pump (cm)
Δh_m	minimum modular head for a mogha (cm)
ΔH_p	head loss in conveyance pipe (cm)
L	mixing chamber length (cm)
L_p	length of conveyance pipe (m)
M	flow ratio (Q_s/Q_j)
M_o	optimum flow ratio for a given area ratio
N	head ratio $(H_j-H_s)/(H_j-H_t)$
n	Manning's roughness coefficient

Q	flow rate (liters per second (ℓps))
Q_o	free flow mogha flow rate (ℓps)
Q_j	jet flow rate (ℓps)
Q_s	suction fluid or surface water flow rate (ℓps)
Q_t	flow rate of combined fluids (ℓps)
R	area ratio (d^2/D^2)
S	slope of the water surface during steady uniform flow
s	nozzle setback distance
V	flow velocity (m/sec)
V_p	pipe flow velocity (m/sec)
W	mogha width (cm)
Y	mogha opening height (cm)

SECTION I

INTRODUCTION

The Indus Basin is relatively flat with an average slope from the foothills of the Himalayas to the Arabian Sea of only 20 centimeters per kilometer (.0002 m/m). The large irrigation system which has been built on this plain consequently had to be carefully designed to insure the provision of adequate water elevation or "head" to move the water through the conveyance system and onto each commanded field. This huge effort was largely successful as the diversion and conveyance system has been working adequately for many years.

However, some farmers are now experiencing problems irrigating their fields. This is due partially to some cases of original design weaknesses or overextension of the system to serve higher lands, but is primarily due to changes in the system since the original construction.

One important change which has affected the head in the system is the natural evolution of the channels and land surface due to sediment transport and deposition. The three main rivers from which irrigation water is diverted in Pakistan carry an annual sediment load of about 350 million cubic meters from the mountains and foothills (Tamburi, 1974). Of the total sediment load, roughly 80% is suspended sediment. Assuming that half of the suspended sediment is diverted into the irrigation system, the irrigation channels and 10 million hectares of land irrigated from the system has aggraded at the average rate of

one centimeter every seven years (before the construction of major storage facilities). This implies that, in the nearly one century which part of the basin has been irrigated, the land surface has risen, on the average, 14 cm. Obviously, the sediment deposition has not been evenly distributed and many areas will have aggraded at least double this amount. This rise in the land surface has decreased the head from the fixed diversion points. Little can be done to reverse the effects of this process other than periodic redesign and reconstruction of the total irrigation system.

The sediment has also been deposited in the irrigation canals, raising the water levels and reducing their capacity. This combined effect has often resulted in both reduced flow rates and water surface levels in the tails of many of the canals (distributaries and minors), and again has reduced the head available to some of the farmers. Improved maintenance of the canal system could alleviate this problem.

Another factor which has reduced the working head for some irrigators has been the installation of government tubewells (wells) at the head of their watercourses (tertiary conveyance systems). Nearly 9000 tubewells have been installed to date under the Salinity Control and Reclamation Program (SCARP) and more are planned in the near future (WAPDA, 1979). Most of this SCARP tubewell water is mixed with the water flowing from the canal in the watercourse. The increased flows raise the water surface level in the watercourse channels, which are not redesigned for the

combined flows, by as much as 10-20 cm. This reduces the head available to push water from the irrigation canals into the watercourse, and compounds the problems caused by sediment aggradation.

A final factor which has led to a decreasing working head available to irrigators is the deteriorated condition of the watercourses. Poorly maintained watercourse channels become clogged with vegetation which slows the flow velocity, increases the flow depth, accelerates sediment deposition, and causes more head to be used in conveying the water to the fields.

The Colorado State University Water Management Research Project and Mona Reclamation Experimental Project found that reconstruction of watercourse channels to proper grade and subsequent regular cleaning and maintenance of the channels could result, in addition to reducing conveyance losses, to increasing the head available to farmers so that they would receive their full allocation from the canals and could still easily irrigate their fields on most watercourses. The implementation of an On-Farm Water Management Project, which is extending these watercourse improvements to many areas, is presently expanding rapidly in Pakistan.

However, on some watercourses, especially those with SCARP tubewell supplemented flows, a problem with insufficient head still exists even after watercourse improvement. The increased flows still cause submergence of the mogha (canal outlet) and a reduction in surface water supply. Recognizing

that some unutilized excess energy is usually available from the SCARP tubewell water, which is often discharged 100 to 150 cm above the level of the watercourse (or with 100 to 150 cm of excess head), the researchers began to investigate means of utilizing this excess energy to provide the head required to operate the irrigation system more effectively. The result of this research effort is the development of a device called a watercourse junction jet pump (also referred to as a jet junction), which utilizes a hydraulic jet pump to transfer part of the excess tubewell water energy to the surface water, thus increasing its head. The advantages of jet junctions are their relatively low costs and very low maintenance requirements. (They have no moving parts.) Although jet junctions are relatively inefficient by the strict definition of the term, when they utilize otherwise wasted energy, efficiency need not be a major concern.

The jet pump concept has been used in many applications around the world, but has generally been adapted to high energy driving fluid sources. Research was thus conducted to test and adapt the technology to a low energy driving fluid (the tubewell water) and then to test the practicability in the field for the specific intended purpose.

This manual will review some of the more important studies carried out by other authors in the past, describe the experimental work carried out by this project in the laboratory and in the field, and give recommendations and procedures for the design and installation of jet junctions

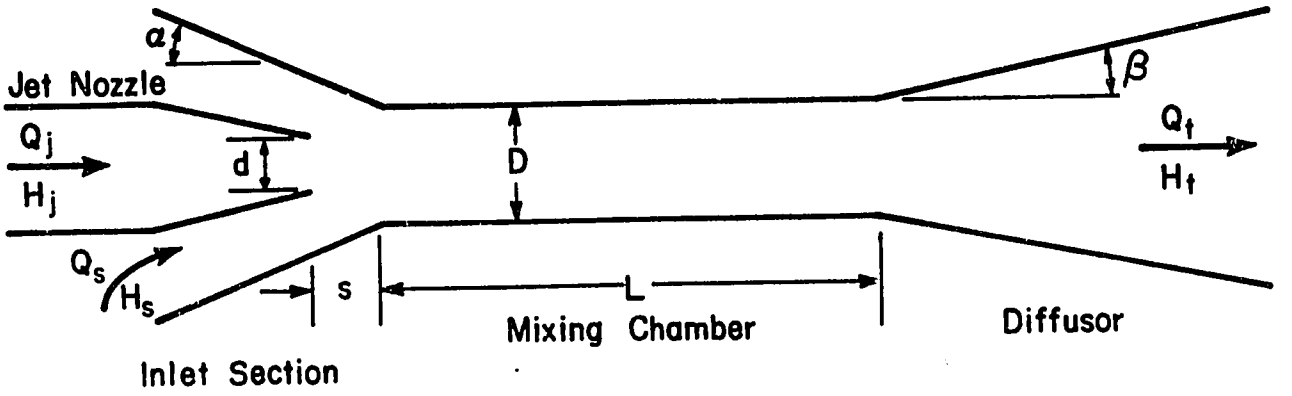
in Pakistan. Although the developmental work was carried out for a specific need in Pakistan, the concepts are general and the device could be adapted for use in other countries where water from one source needs to be raised; and water from another source that has some excess energy can be mixed with it.

SECTION II

REVIEW OF PAST WORK

A jet pump, or ejector, is a device with no moving parts which hydraulically transfers part of the energy of a fluid under higher pressure or head to a lower pressure fluid, resulting in a combined flow with an intermediate pressure. The energy transfer is accomplished by converting the pressure heads of the fluids to velocity heads and then allowing the fluids to turbulently mix in a closed conduit (no free surface) mixing chamber. Figure 1 shows a schematic of the basic components of a jet pump.

A jet pump has four basic components. The nozzle converts the energy of the higher pressure fluid to kinetic energy. It should be designed to achieve a maximum velocity with the least total energy loss. The inlet section of the mixing chamber funnels the suction fluid into the mixing chamber while minimizing the energy loss of the suction fluid. The mixing chamber allows a turbulent mixing and transfer of momentum between the two fluids. It should be long enough and of a sufficiently small diameter to insure nearly complete mixing, but short enough and of a sufficiently large diameter to minimize friction losses. The diffusor section is designed to reduce the flow velocity of the combined fluids through a gradual area expansion in order to convert the kinetic energy back to pressure head. The expansion should be gradual enough that the moving fluid does not separate from the walls, which would result in considerable energy dissipating turbulence.



d = Diameter of Jet Nozzle

D = Diameter of Mixing Chamber

s = Setback of Jet Nozzle

L = Length of Mixing Chamber

α = Inlet Angle

β = Diffusor Angle

Q_j = Jet Flow Rate

H_j = Jet Fluid Total Energy (Converted to Head)

Q_s = Suction Flow Rate

H_s = Suction Fluid Total Energy (Converted to Head)

Q_t = Combined Flow Rate

H_p = Combined Fluid Total Energy (Converted to Head)

Figure 1. Schematic of jet pump showing design parameters.

The performance of a jet pump is expressed in terms of efficiency, E, defined by the product of the dimensionless flow ratio, M:

$$M = Q_s/Q_j \quad , \tag{1}$$

and the dimensionless head ratio, N;

$$N = \frac{H_t - H_s}{H_p - H_t} \quad , \tag{2}$$

or;

$$E = MN = \frac{Q_s(H_t - H_s)}{Q_p(H_p - H_t)} \quad , \tag{3}$$

(Cairns and Na, 1969; Mueller, 1964; Reddy and Kar, 1968). Although jet pumps could ideally achieve efficiencies of 1.0, due to friction and form losses in the pump and incomplete momentum transfer between the fluids, maximum efficiencies of only 30 to 42% for pumps working under relatively high driving fluid pressures (4 to 60 meters of head) have been achieved (Cairns and Na, 1969; Mueller, 1964). Several authors (Reddy and Kar, 1968 and Mueller, 1964) have derived similar maximum efficiencies from analytical models of ejectors.

The primary factors affecting jet pump performance for a given flow ratio or desired head ratio are:

1. the ratio of nozzle to mixing chamber area, R;

$$R = \frac{(\pi/4)d^2}{(\pi/4)D^2} = \frac{d^2}{D^2} \quad , \tag{4}$$

2. the setback of the nozzle exit from the mixing chamber entrance, s, usually expressed as a ratio of the nozzle diameter, d;

3. the length of the mixing chamber, L, often expressed as a ratio of the mixing chamber diameter, D; and
4. the angles of the inlet and diffusor sections, α and β.

Although some authors also studied various profiles of nozzles and entrance and exit sections (Mueller, 1964; Reddy and Kar, 1968), the added sophistication generally did not add significantly to pump performance.

A common finding of past studies is that to achieve maximum efficiencies, the area ratio, R, must decrease for larger flow ratios. Figure 2 presents the results of two experimental studies which show this interdependence. A similar relationship can be predicted by a theoretical analysis of jet pumps (Mueller, 1964; Reddy and Kar, 1968). All three previously referenced studies indicate that for M values between 0.3 and 0.8, if the area ratio is sized properly for the flow ratio, relatively high efficiencies can be achieved. The authors disagree on the flow ratio for which an ejector giving the highest possible efficiency can be designed.

The optimum nozzle setback seems to be dependent on nozzle and inlet section profiles as well as flow and area ratios. All three studies agree that an optimum is not sharply defined, but little variation in performance is observed with setback ratios, s/d, between 1.0 and 1.4. Cairns and Na (1969) indicate that an optimum setback increases with increasing area ratios.

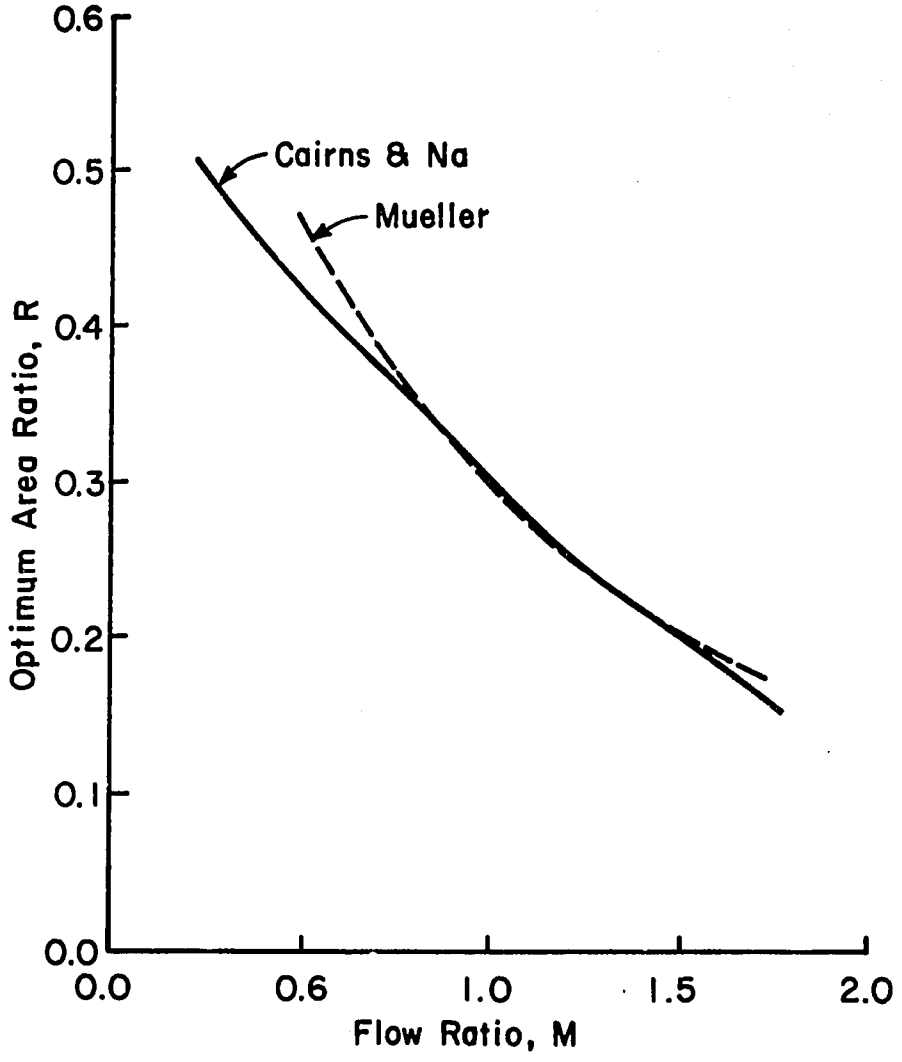


Figure 2. Experimental results showing the area ratio, R, which gives the highest efficiency for different flow ratios, M (Mueller, 1964, Cairns and Na, 1969).

Mixing chamber lengths which were reported to give the highest pump efficiencies varied from L/D ratios of 4.1 (Cairns and Na, 1969) to 18 (Reddy and Kar, 1968). Several studies indicate optimum lengths between 5 and 8 times the mixing chamber diameter (Mueller, 1964). Some of this variation could be a result of different materials used since optimum chamber length will depend upon the chamber inner roughness and on the flow velocities, with both parameters affecting the mixing rate.

Many studies have been carried out to determine allowable rates of flow contraction and expansion without causing flow separation and turbulence and thus high energy losses. Recommended entrance section angles for jet pumps, α, are in the range of 15 to 25°. Cairns and Na (1969) found diffusor angles, β, of 2.7 to 4.0^{o} to give highest efficiencies while Mueller (1964) determined 2.5^{o} to be optimum.

Table 1 summarizes the recommendations of the three referenced studies plus other studies which are summarized in Mueller (1964).

A factor which was not discussed in any of the referenced studies is the affect of size of the mixing chamber, D, on the pump efficiency for different values of jet and suction flow rates, or the optimum fluid velocity in the mixing chamber. Consequently, it is difficult to extrapolate the work to heads and flow rates beyond those experimentally tested. Most data was collected from small models (D<5cm) operating under moderate to large heads (H_j>10m).

Table 1. Recommended design parameters for jet pumps.

Author	R	s/d	L/D	α	β
Mueller (1964)	.44-.50[2]	0.7-1.2	7		2.5°
Reddy and Kar (1968)	.33-.54[2]	1-2	18	20-24°	
Cairns and Na (1969)	[2]	0.8-2.0[2]	3.5-4.5	20°	2.8-4°
Goshn and O'Brien[1]	.18-.54	1.0	6		2.8°
Shultz and Fasol[1]	.5	0.38-1.8	7.8		2.9°

1/From Table 2, p. 101 in Mueller (1964).
2/Varies with flow ratio.

SECTION III

DEVELOPMENT OF JET JUNCTIONS

Recognizing the need for raising the elevation of the water delivered by Indus Basin canals to more easily serve the fields, a study was begun to explore the possibilities of exploiting the excess energy of the water delivered from public tubewells for this purpose. An initial attempt involved building a sloping open channel from the tubewell outflow to the surface supply channel such that at the junction, the two flows were moving nearly parallel. This initial device is illustrated in Figure 3. The intention was to increase the momentum of the tubewell water in the direction of the surface flow with the hope that part of this momentum would be transferred, via shear and turbulent mixing, to the surface water, resulting in a combined flow with a higher head, rather than a total dissipation of the excess tubewell water energy. However, most of the excess energy was simply dissipated at the junction in the form of surface turbulence. The elevation of the combined flows was raised only slightly relative to the upstream surface supply elevation.

The experiment made it obvious that to gain the energy transfer achievable in jet pumps, the mixing process must take place in a closed system with no free water surface so that the kinetic energy can be reconverted to pressure or elevation head. Consequently, an attempt was made to adapt the traditional jet pump to the required conditions, i.e. inflow from and discharge to an open conveyance system, and a relatively low pressure driving fluid.

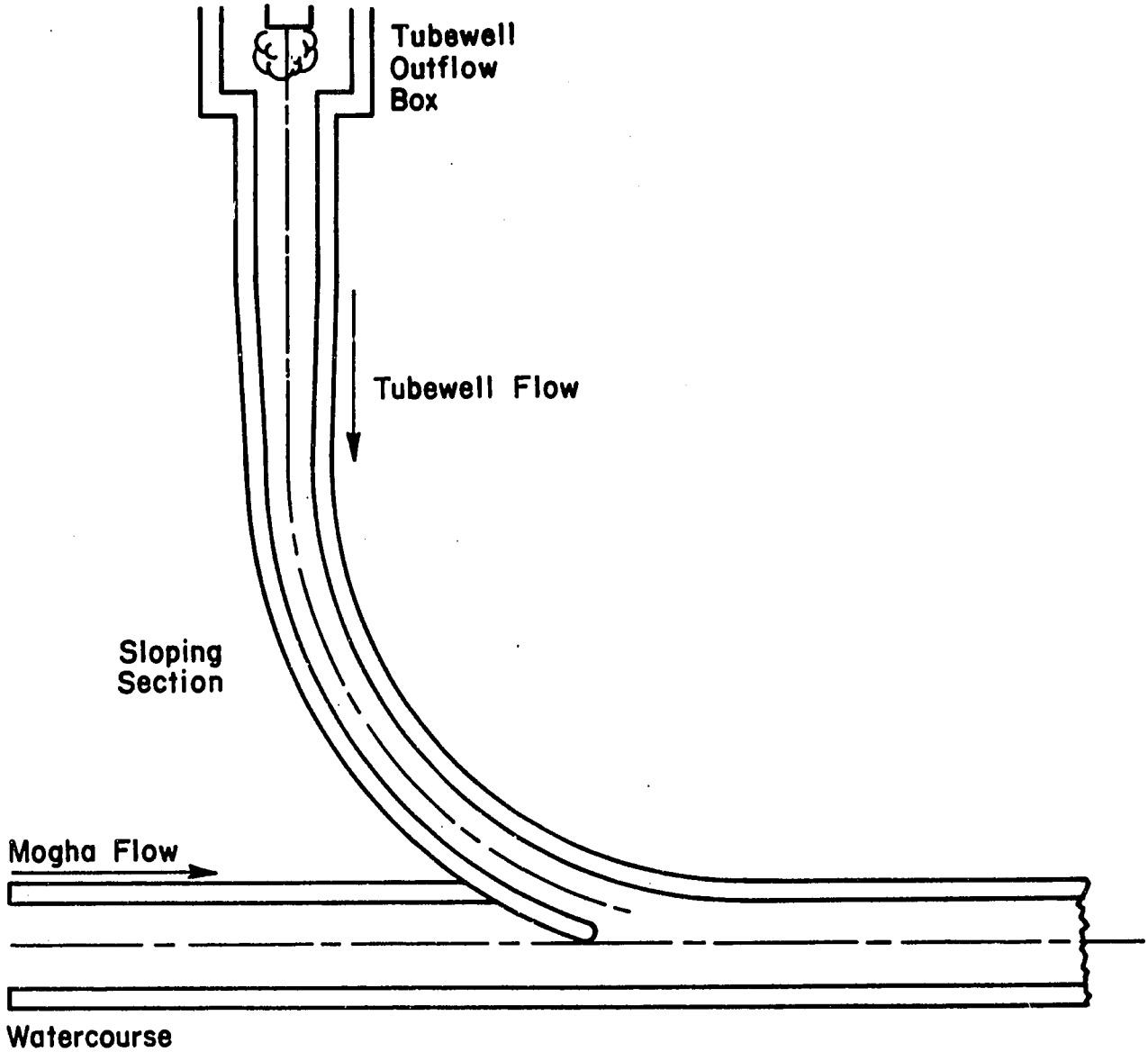


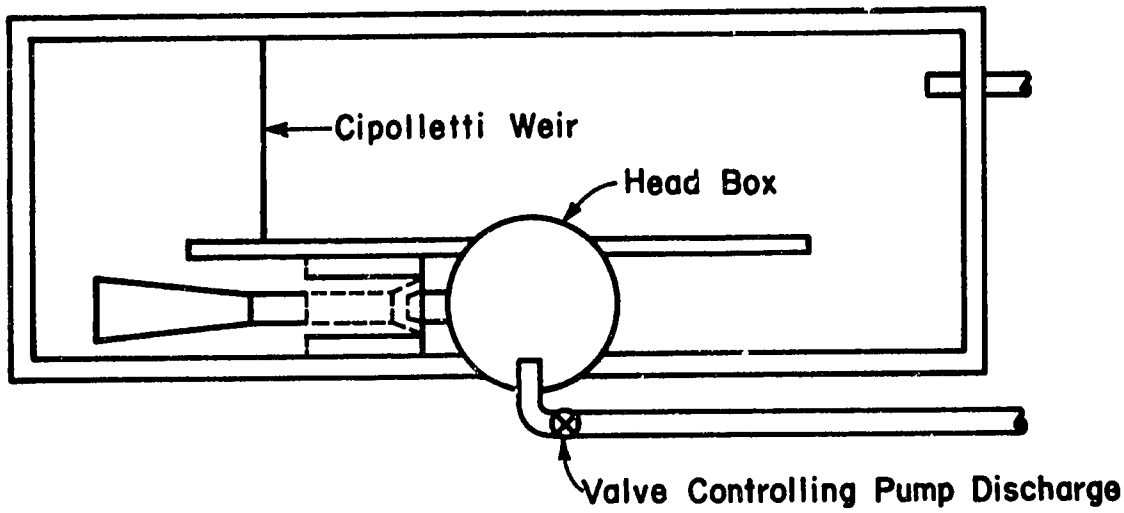
Figure 3. Layout of first jet junction at SCARP Tubewell #MN-51 in the Mona Reclamation Experimental Project (Mona).

Initial Jet Junction Model

An initial full scale jet junction model was built at the Colorado State University Engineering Research Center in 1977 (Figure 4). The primary purpose of the model was to determine whether the use of a jet pump for the conditions encountered on Pakistan watercourses was feasible. The initial model was constructed according to the design parameters suggested in the literature. A mixing chamber diameter, D, of 25.4 cm was chosen arbitrarily. Adjustable parameters included the mixing chamber length, L, and the nozzle setback distance, s. The experimental program also evaluated to benefits of the diffusor. Table 2 gives the model dimensions, based on terms defined in Figure 1.

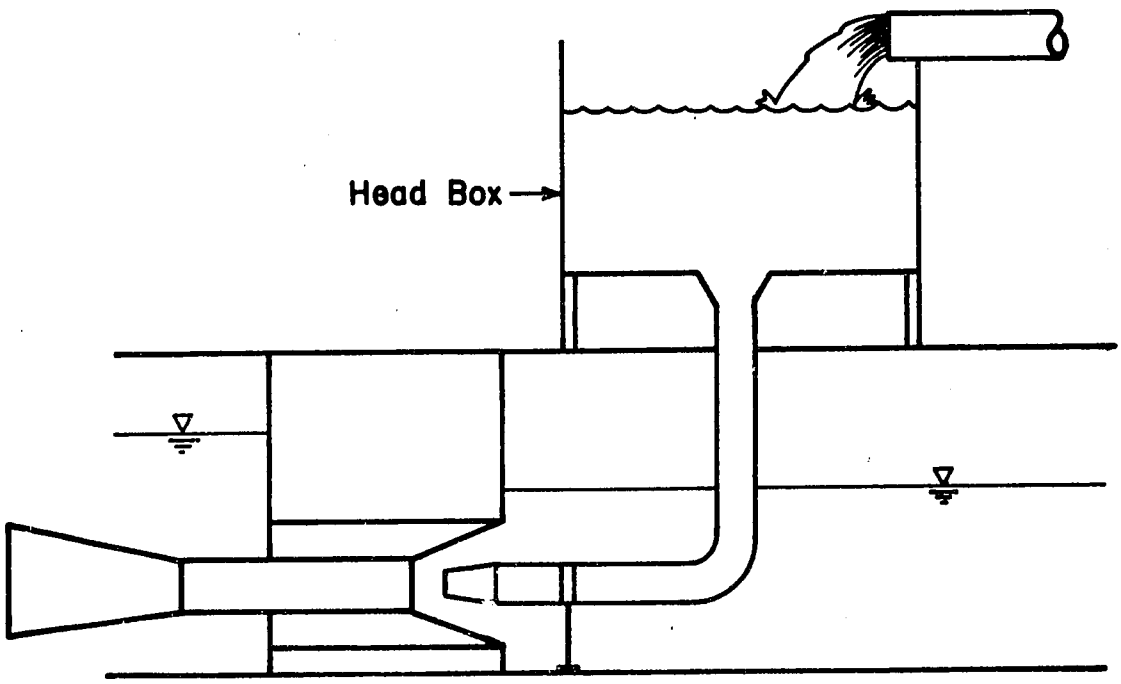
Table 2. Dimensional and experimental parameters of the initial jet junction model.

d	= 12.7 cm
D	= 24.5 cm
R	= .25
s	= 12.7, 15.2, and 19.1 cm
s/d	= 1.0, 1.2 and 1.5
L	= 142.2, 213.4 and 248.5 cm
L/D	= 5.8, 8.7 and 11.6
α	= 20°
β	= 4.5^{o}
Q_j	= 28 - 64 ℓps
H_j	= 15 - 110 cm
Q_s	= 0 - 90 ℓps



Scale 1:60

Top View



Scale 1:30

Side View

Figure 4. Illustration of the initial jet junction prototype tested at CSU.

Although some problems existed in the initial experimental design which limited the dependability of the results, the prototype did indicate that low head jet junctions were feasible. The initial model operated at efficiencies above 25%, indicating that 40 ℓps of canal water could be raised 30 cm utilizing 40 ℓps of tubewell water with a head of 150 cm, or with 60 ℓps of tubewell water with a head of 110 cm (relative to the upstream water surface).

Initial Field Installations

Based on the results of the initial model tests, junction jet pumps were installed on two watercourse systems in Pakistan in 1978/79 to test both the technical and economic feasibility under field conditions. Both watercourses are located within the boundaries of the Mona Reclamation Experimental Project (MREP).

The two watercourses chosen are typical of many found in Pakistan. The commanded area is relatively flat and only slightly below the level of the irrigation canal (distributary). Thus, even though the watercourse conveyance channels were built on a low grade and thoroughly cleaned, the moghas (canal outlets) of both watercourses were submerged at least part of the time and thus did not transmit the full design water supply from the canal.

Public (SCARP) tubewells had been installed near the head of both watercourses to supplement the canal water supply and lower the groundwater table. When the tubewells were running, the water depth in the watercourses increased due to the

increased flow, and further submerged the mogha. During the irrigation of some high fields, the water level in the watercourse was actually higher than that in the canal and the farmers would block the mogha to prevent losing their pumped water to the canal. This was especially distressing to the farmers since the tubewell water which contained more salts than the canal water (800 mg/ℓ vs. 170 mg/ℓ) was intended to be mixed with the surface supply to improve the quality. Both tubewells discharged 1.2 to 1.5 meters above the elevation of the water surface in the watercourse.

The jet junction as installed at the watercourse on which SCARP Tubewell #60 is located is shown in Figure 5. This initial installation utilized a 20 cm steel pipe to carry the pumped water from the tubewell approximately 10 meters to the jet pump located in the watercourse. The pump, shown in Figure 6, was made from concrete pipe set on a brick masonry foundation. The nozzle was fabricated from steel plate.

Because of the large amount of steel pipe required and the high cost of steel in Pakistan, the cost of this initial installation was Rupees 12,000 (U.S. $1200). Consequently, for the second installation on Tubewell #62 watercourse, instead of piping the tubewell water to the watercourse, the watercourse was diverted to the tubewell outflow box and a nozzle was installed on a short length of pipe leading directly from the box (Figure 7). The walls of the tubewell outflow box were built up with brick masonry to allow water to pond inside to the elevation required to create the head

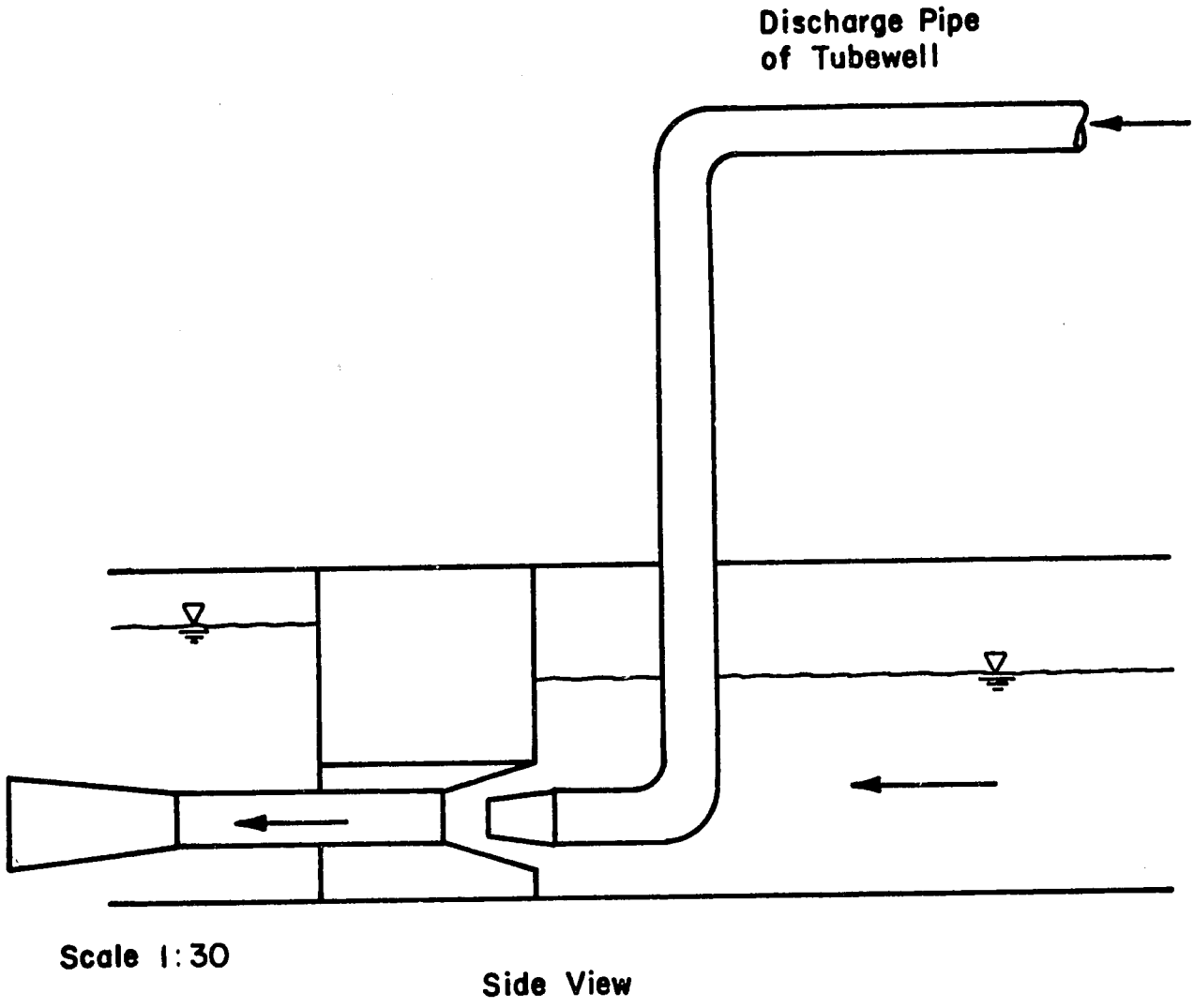


Figure 5. Jet junction installation at Tubewell #MN-60, Mona.

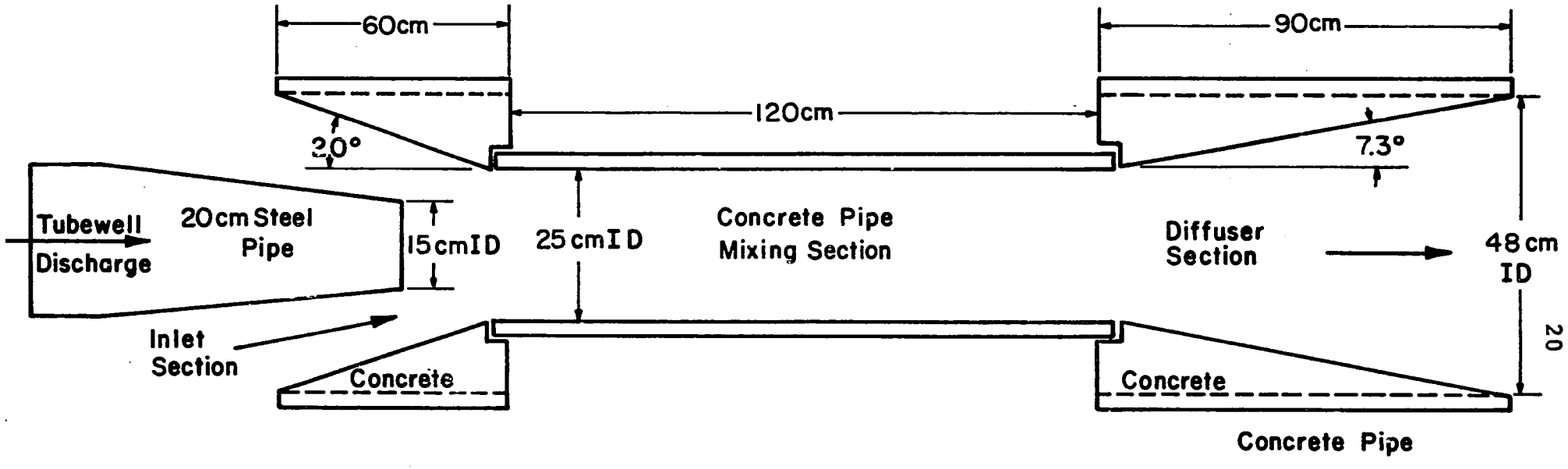


Figure 6. Enlarged view of the jet pump device installed and tested at Tubewell #MN-60, Mona. (Similar to Tubewell #MN-62 installation.)

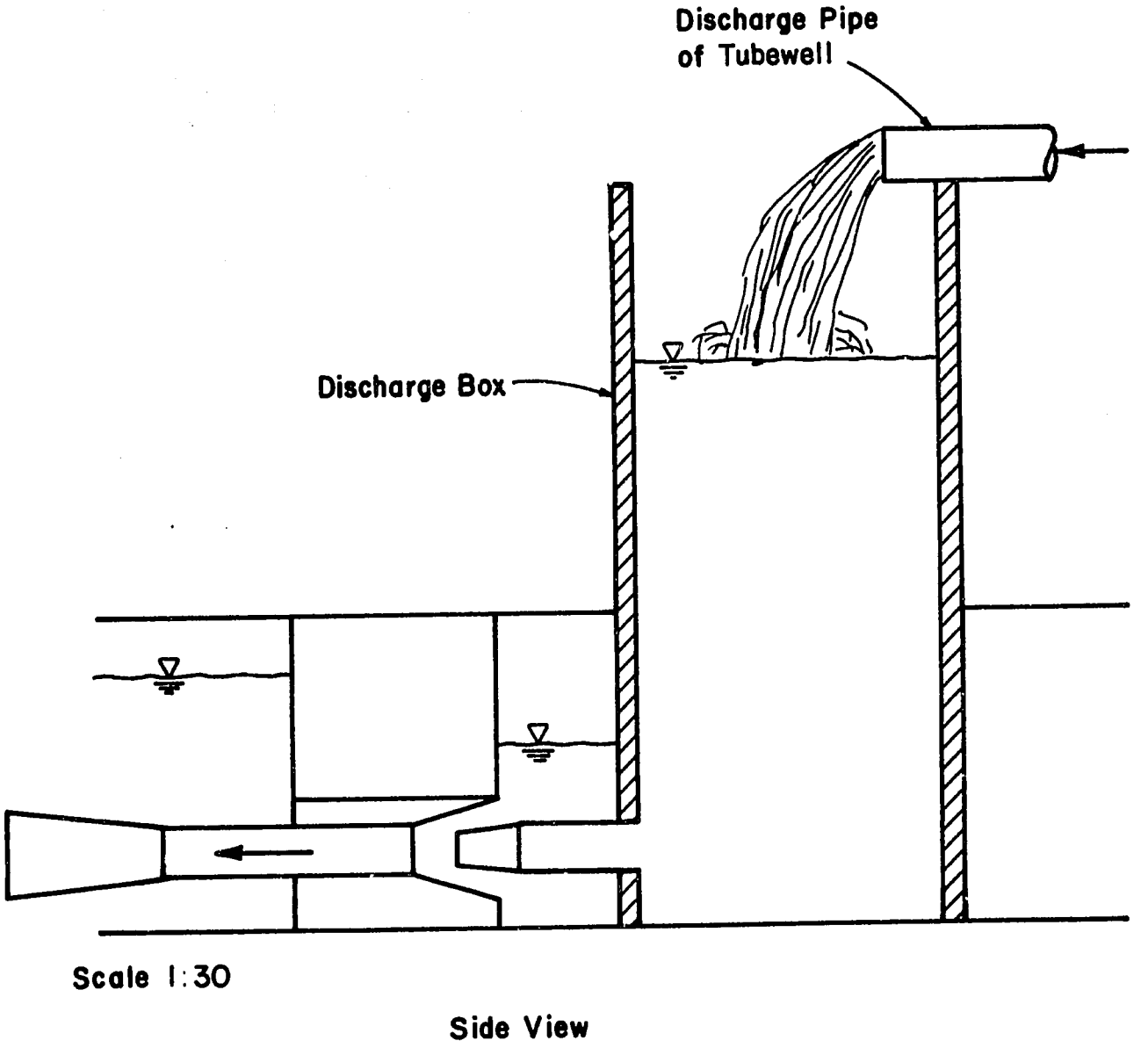


Figure 7. Tubewell junction jet pump installation at MN-62, Mona.

necessary for the jet. The jet pump was essentially the same as that used on Tubewell #60 except no diffusor was used. Initially a concrete nozzle was used, but its thick walls restricted the canal water flow and caused trash accumulation, and it was later replaced by a steel nozzle. The cost of materials for this second installation was only Rs 1000 (U.S. $100), primarily for the concrete pipe and brick masonry.

The performance of the two field installations is summarized in Table 3. In both cases the water level below the canal turnout was lowered sufficiently that the mogha flowed freely and the maximum discharge entered into the watercourse. In neither case was the pumping head or energy usage of the tubewell increased.

Efficiencies of both installations are lower than that measured on the initial model. One probable cause of the lower efficiency is the use of concrete for the inlet section, mixing chamber, and diffusor of the pump. The concrete has a higher surface roughness, and thus would cause higher friction losses than the metal used in the model. The efficiencies of the Tubewell #62 junction is quite low because no diffusor was used and exit losses were thus very high. Also, for the Tubewell #62 jet junction test with the 14 cm nozzle, the canal water supply was temporarily low due to a reduced canal flow, and the nozzle size, or area ratio, was too high when compared with the flow ratio to achieve high efficiencies. Regardless of the lower efficiencies, the jet junction installations fulfilled the requirements and the second installation

Table 3. Results of jet junction field tests in Pakistan.

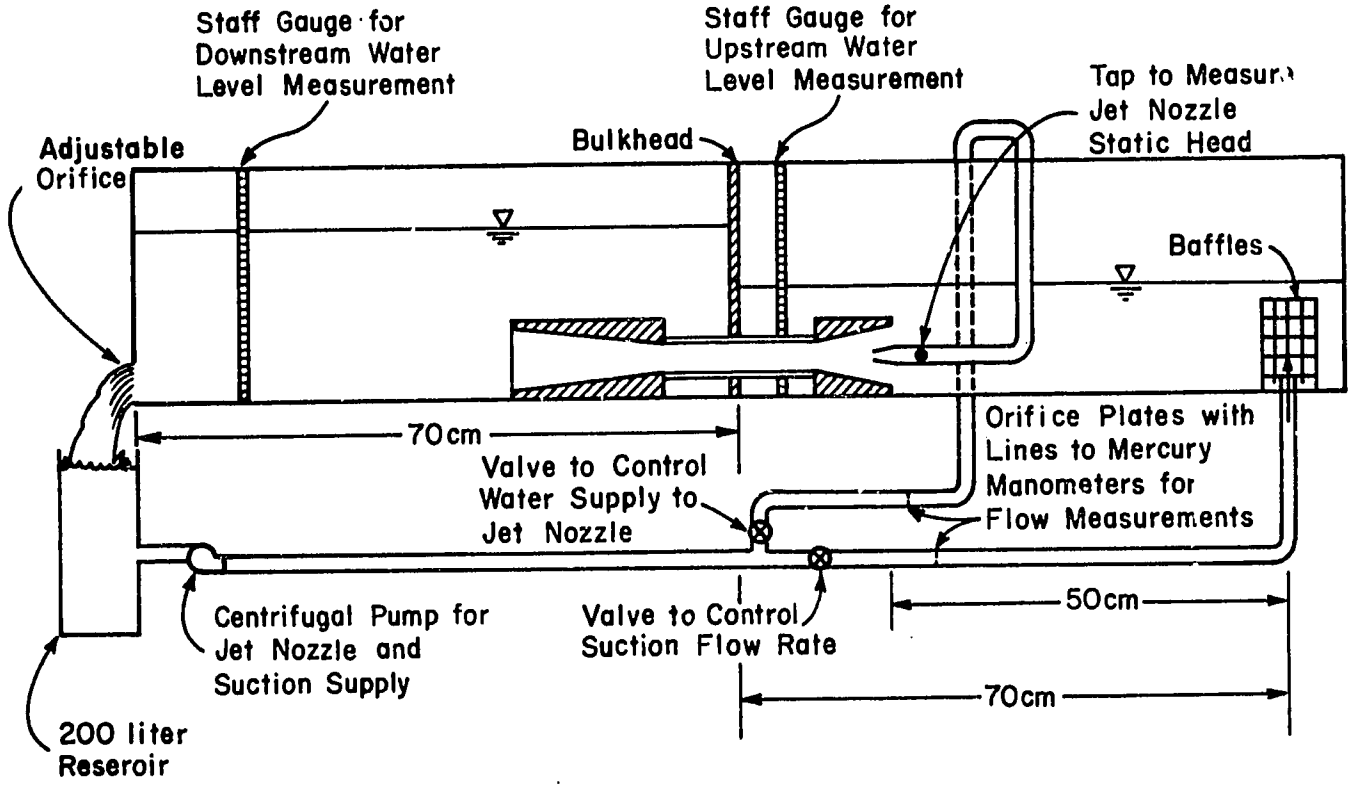
	TW MN-60	TW MN-62	
	14.7 cm nozzle	13.3 cm nozzle	14.0 cm nozzle
Watercourse flow, Q_s (ℓps)	60.6	34.0	18.7
Tubewell flow, Q_j (ℓps)	101.9	77.8	77.8
Total flow, Q_T (ℓps)	102.4	111.8	96.5
Net head at tubewell, H_j (cm)	152	134	124
Net lift produced by jet pump, H_t-H_s (cm)	35	27	25
Flow ratio, M	0.59	0.44	0.24
Head ratio, N	0.30	0.25	0.25
Efficiency, E(%)	17.8%	10.8%	6.1%
Area ratio, R	0.34	0.28	0.30

indicated that they could be built inexpensively in the field.

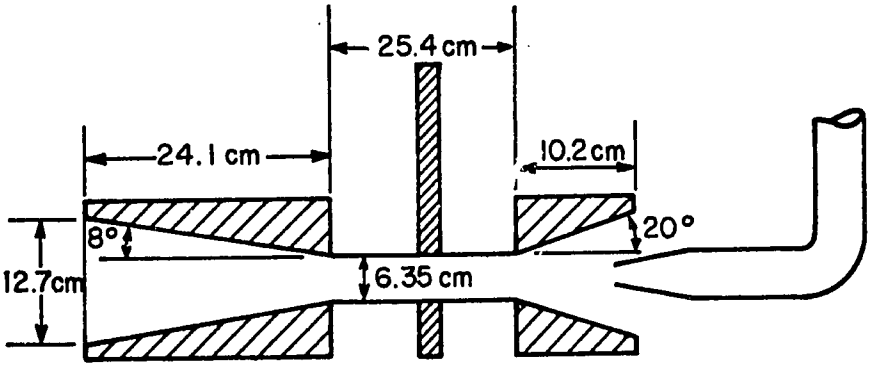
Laboratory Testing of a Geometric Scale Model

A transparent 1:4 scale model jet junction was constructed from plexiglass (Figure 8). The primary purpose of the model was for demonstration, but some testing was also carried out. The geometric model did appear to be the correct choice since the model did perform comparable to the full scale model when similar velocities were maintained. The range of flow rates in the scale model were about 1/16 the range of flow rates in the full scale model. Efficiencies remained fairly constant over this range. Maximum efficiencies in the model were only 18%. A more apparent modeling method, a Reynold's model, would have required velocities in the mixing chamber in the range of 5 to 9 meters per second. These high velocities could not be tested in the model.

The plexiglass model was tested with two nozzle diameters placed at several nozzle setbacks. Figures 9 and 10 show head ratio vs flow ratio plots for sets of data comparing area ratios, R, of 0.275 and 0.36 and setback ratios, s/d, of 0.6, 0.7, 0.8 and 0.9. The relationship between area ratio and flow ratio which gives maximum efficiencies is similar to that reported by Mueller (1964) and Cairns and Na (1969) as shown in Figure 2. The nozzle setback had no effect on pump performance over the range tested, again concurring with the results of previous studies which indicated pump performance is not sensitive to this factor. Both of these plots



a. Jet Junction Model Setup



b. Detail of Jet Pump (Side View)

Figure 8. Schematic diagram of the jet junction 1:4 model.

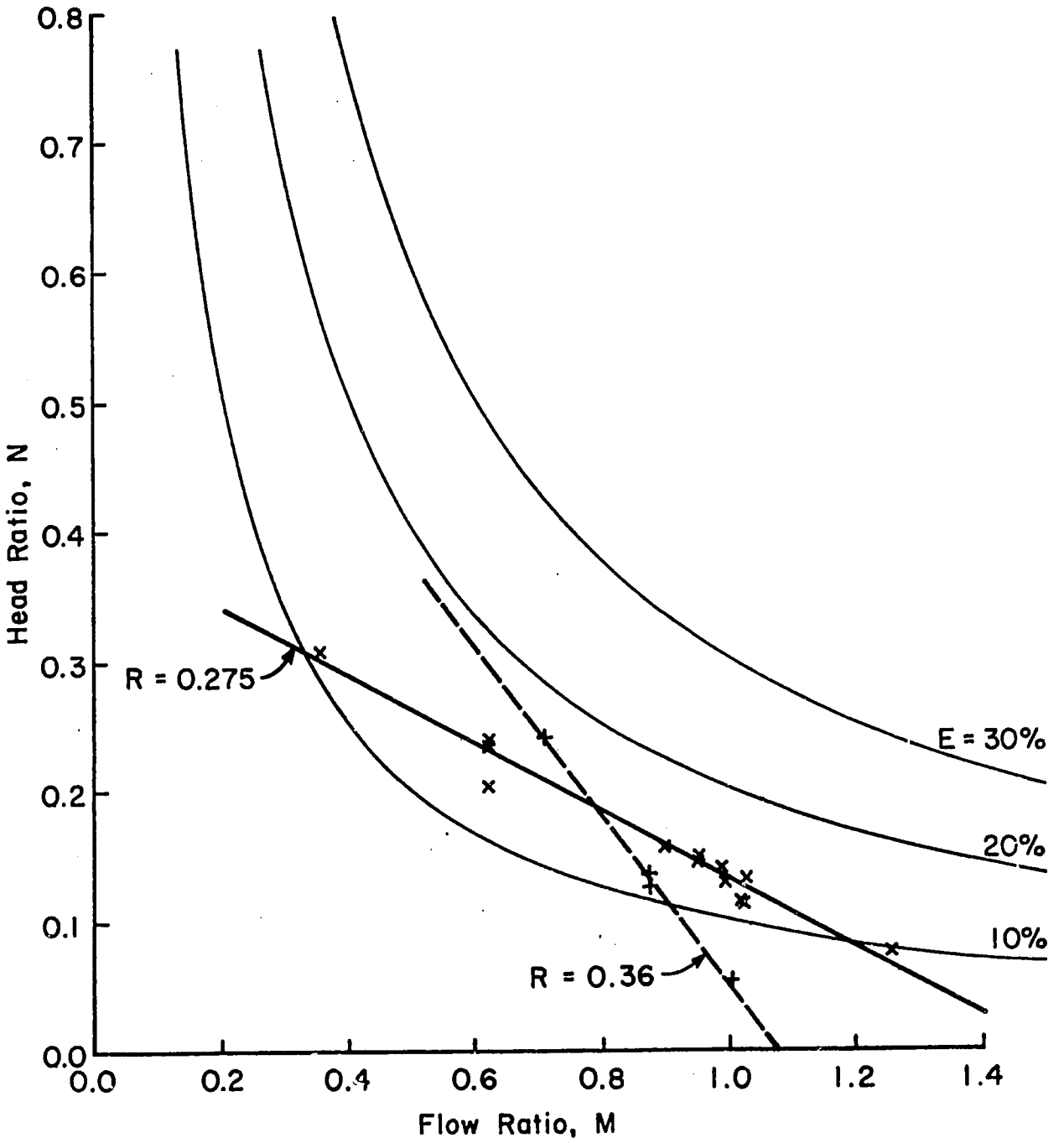


Figure 9. Head ratio, N, vs. flow ratio, M, for area ratios, R, of 0.36 and 0.275 for the geometric scale model jet junction.

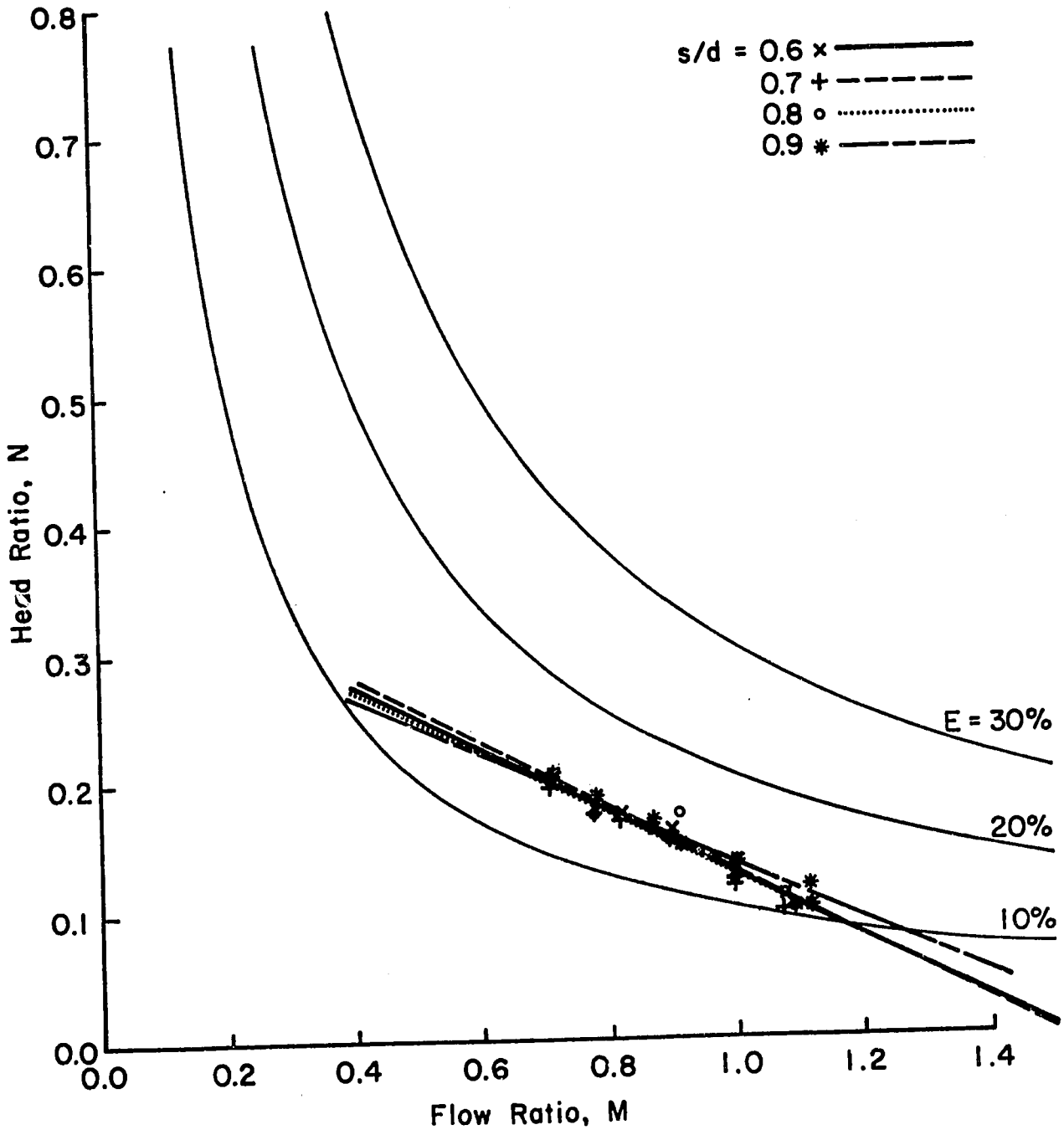


Figure 10. Head ratio vs. flow ratio data for geometric scale model jet junction for R=.275, and nozzle setback ratios, s/d, of 0.6, 0.7, 0.8 and 0.9.

(Figures 9 and 10) exhibit a linear relationship between head ratio and flow ratio.

Laboratory Testing of a Full Scale Jet Junction Prototype

Having proven the feasibility of jet junctions in the field, a full scale prototype was constructed in the Hydraulics Laboratory of the CSU Engineering Research Center in order to more fully determine the effects of various geometric parameters on jet junction performance. Parameters tested included nozzle diameter, d, mixing chamber length, L, and the effect of eliminating the diffusor. The studies were designed to assist in the formulation of design recommendations for low head jet junctions under conditions encountered in Pakistan.

Experimental Design

The prototype jet junction was installed in the 1.2 m (height) x 2.4 m (width) x 61 m (length) recirculating flume in the CSU Engineering Research Center Hydraulics Laboratory. Figure 11 shows the experimental arrangement. Nozzle flow was pumped from a sump using a centrifugal pump. Flow rates in the 15 cm delivery line were measured with a circular orifice plate. The orifice plate and delivery pipe were rated in a calibration stand using a standard orifice plate. Static head at the nozzle was measured from a static manometer tap 30 cm upstream of the nozzle. The velocity head of the flow at the tap was calculated from the flow rate and pipe cross-sectional area, and the two energy terms were summed to obtain total head for the nozzle fluid.

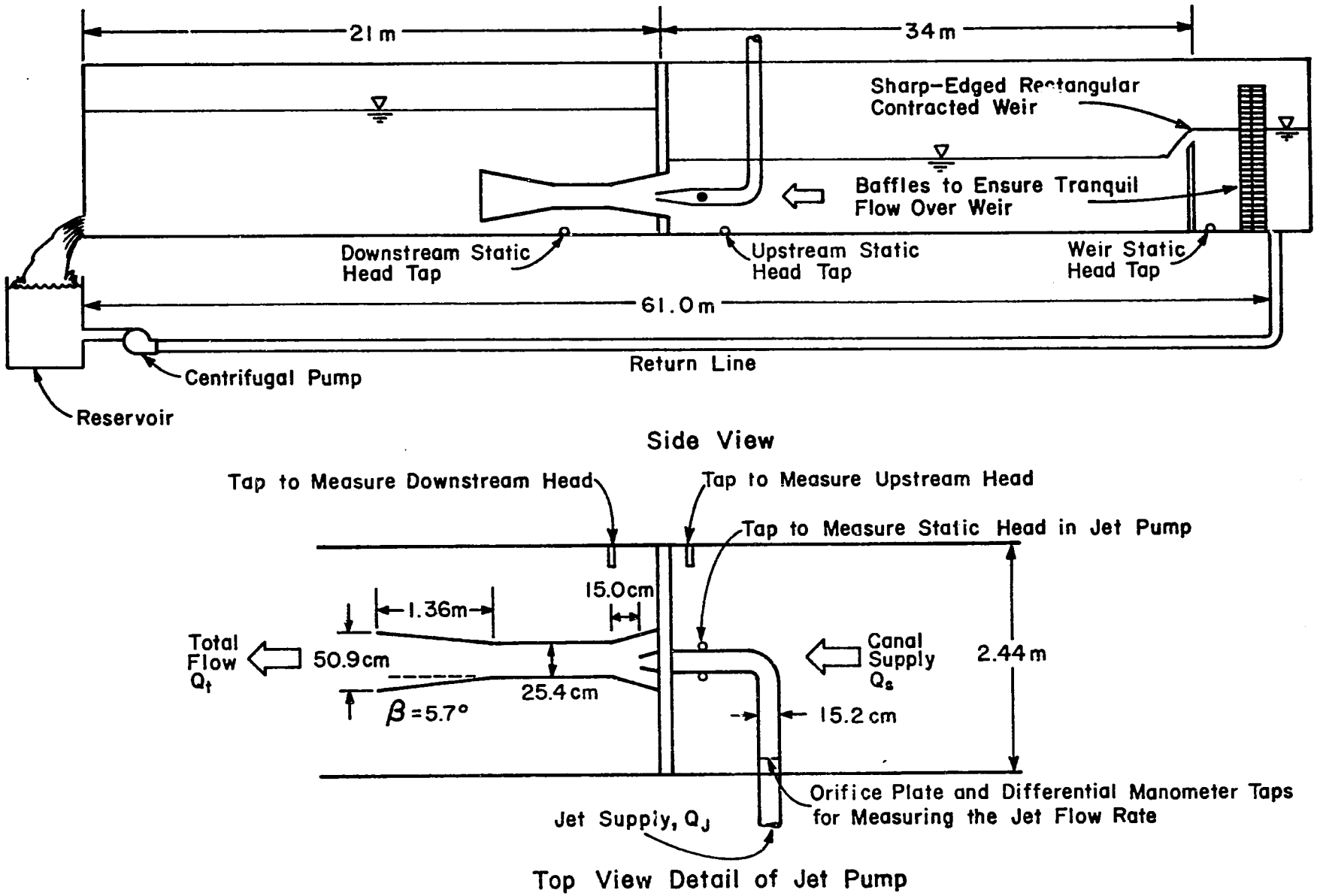


Figure 11. Laboratory arrangement for the jet junction prototype.

Suction flow rate was measured with a rectangular contracted weir having a crest length of 152 cm. The weir was calibrated volumetrically in the flume. The Kindsvater-Carter equation with a coefficient of 28.95 was found to apply to the weir.

Upstream and downstream water surface elevations were measured with static manometer taps located in the side of the flume. The kinetic energy of the suction flow, as well as the combined flow, was insignificantly small.

The jet pump was constructed from steel. Jet nozzles could be interchanged, one or two 56 cm extensions could be added to the 112 cm long mixing chamber, and the diffusor could be removed. Table 4 lists the fixed and variable dimensions and parameters of the prototype jet junction.

Table 4. Jet junction laboratory prototype dimensions and parameters

d	= 10.2, 12.7, 14.0 and 15.2 cm
D	= 24.5 cm
R	= 0.16, 0.25, 0.30 and 0.36
s	= 15.2 cm
s/d	= 0.67, 0.83, 0.92 and 1.0
L	= 112, 168 and 224 cm
L/D	= 4.4, 6.6 and 8.8
α	= 21.4°
β	= 5.4°
Q_j	= 0 - 82 ℓps
H_j	= 0 - 400 cm
Q_s	= 6 - 94 ℓps

Results

The results of the laboratory testing of the full scale jet junction prototype are summarized in the form of graphs relating two dimensionless quantities, the head ratio and the flow ratio. (A complete listing of the results is given in Appendix B.) The product of these two quantities is defined as the efficiency, and equi-efficiency lines were also drawn on the graphs. The head ratio vs. flow ratio data consistently plot as straight lines with negative slopes for each geometric configuration of the prototype. Thus, each set of data can be summarized, using least squares curve fitting techniques, by an equation of the form:

$$N = a - bM. \tag{5}$$

Figure 12 shows such a data plot and the regression line and its equation for the prototype with a 12.7 cm nozzle and a 112 cm long mixing chamber with the diffusor. Figures 13 through 16 show N vs. M plots of all prototype data collected with the diffusor attached. Tables 5 and 6 list the number of data points, regression equation and coefficient of determination, r^2, for each set of data representing one configuration.

When the regression lines representing all data collected with each nozzle size and with the diffusor are drawn on one graph (Figure 17), the effect of nozzle diameter, or the area ratio, $R = d^2/D^2$, is apparent. As the flow ratio increases, smaller area ratios give the maximum efficiencies. Although the scatter in the data makes it difficult to establish an

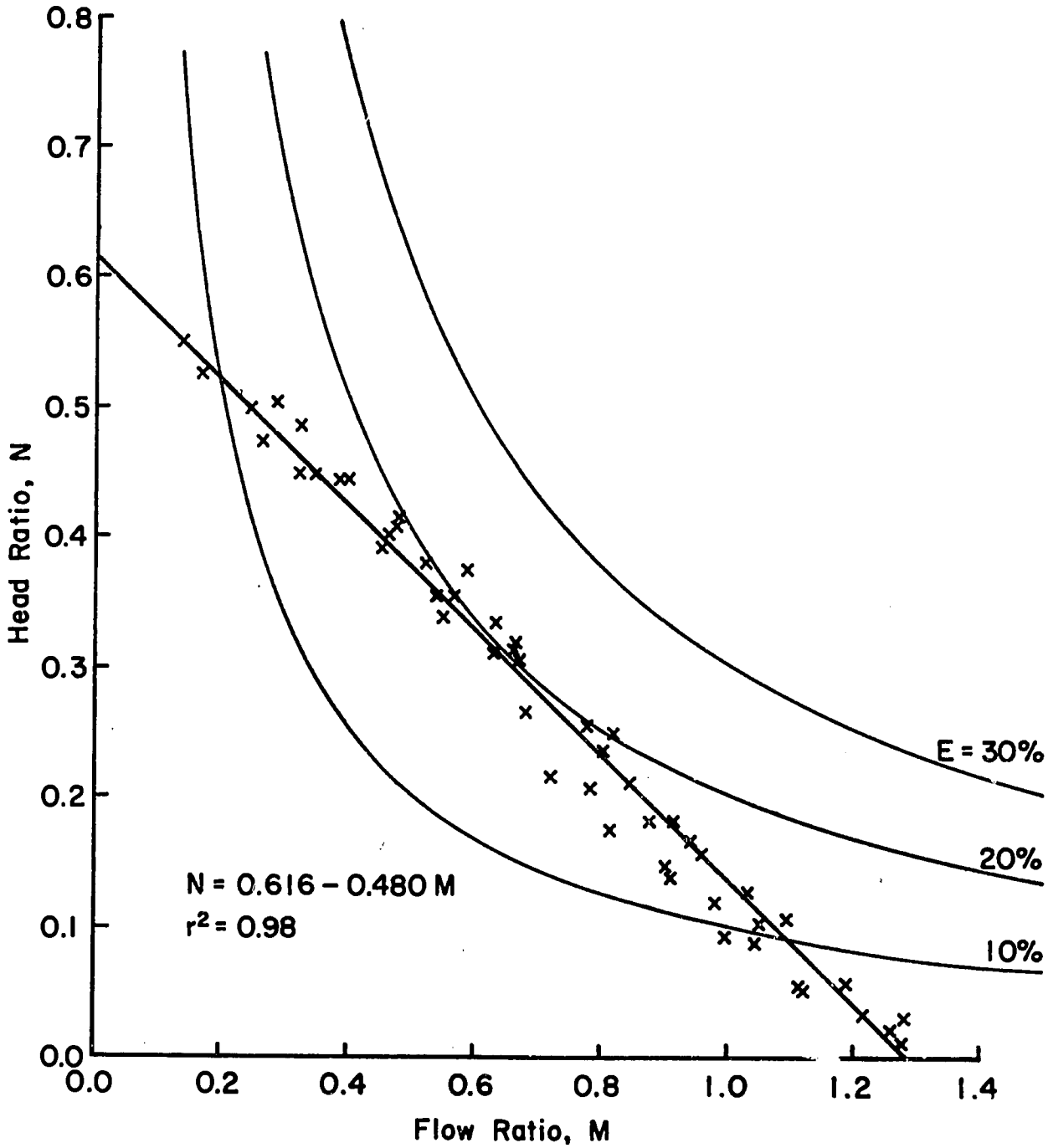


Figure 12. Plot of head ratio, N, vs. flow ratio, M, data and the regression line which best fits the data for the prototype with R=0.25, L/D=4.4, and with the diffusor.

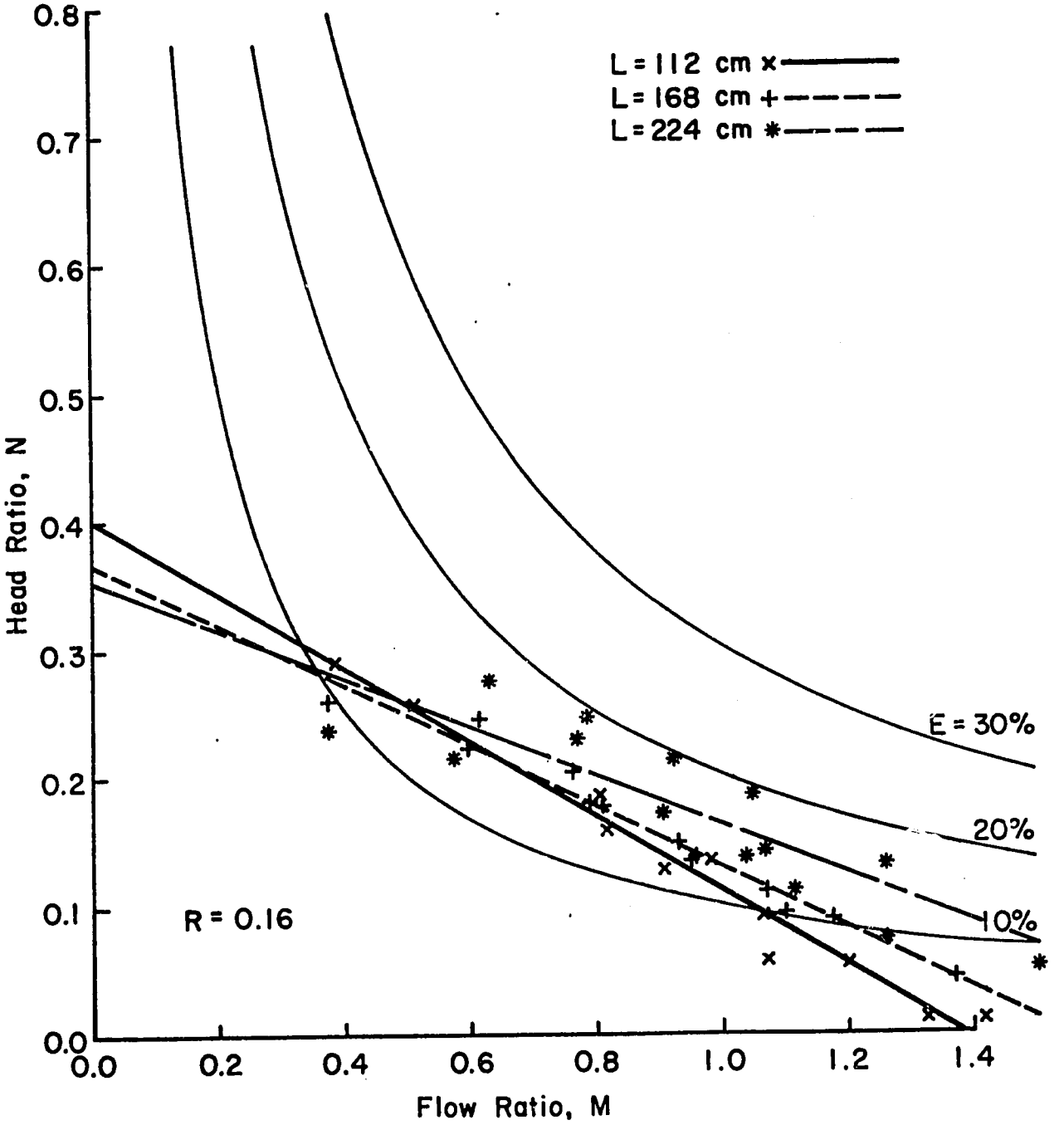


Figure 13. Head ratio, N, vs. flow ratio, M, for the jet junction prototype with a 10.2 cm nozzle.

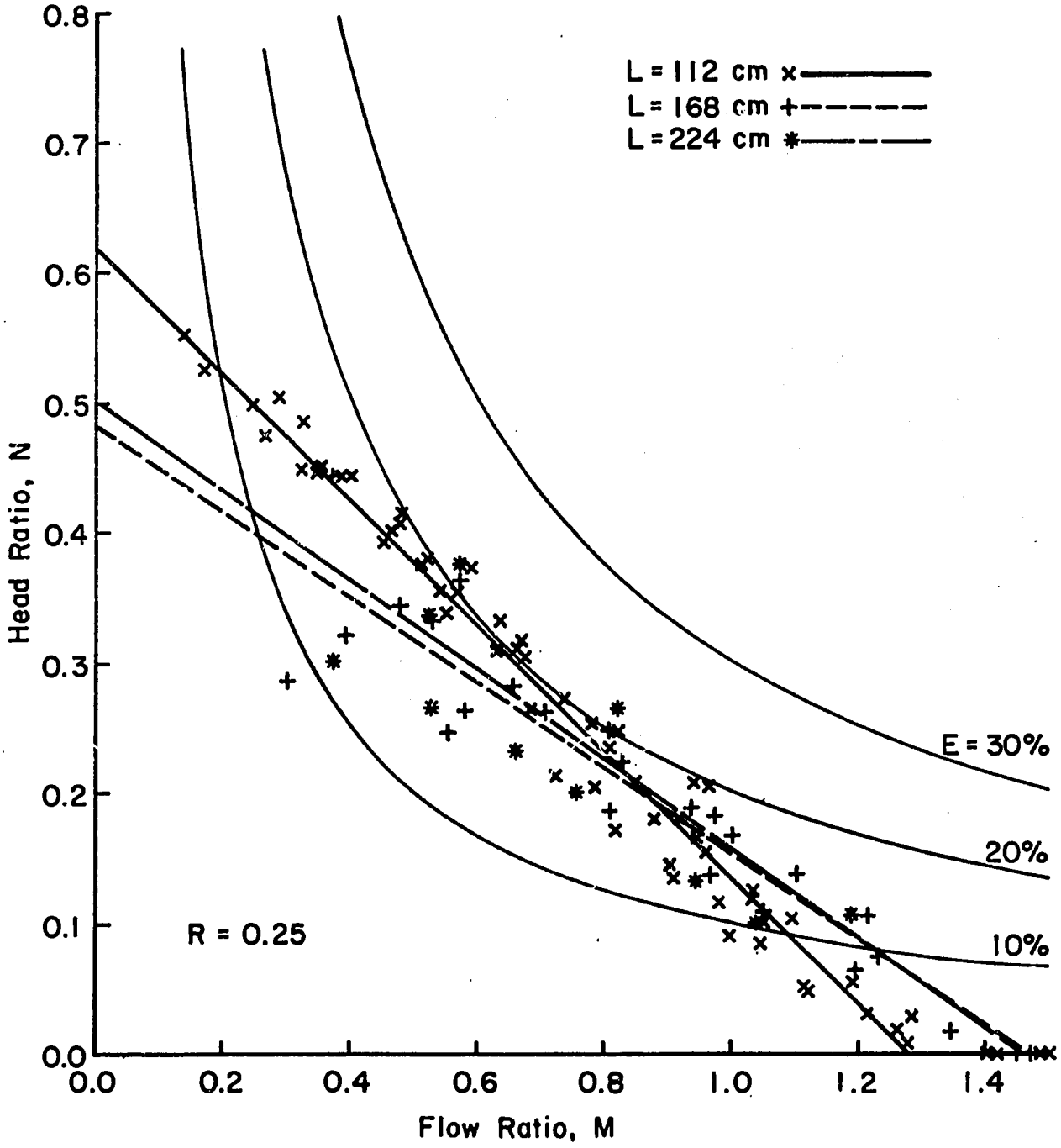


Figure 14. Head ratio, N, vs. flow ratio, M, for the jet junction prototype with a 12.7 cm nozzle.

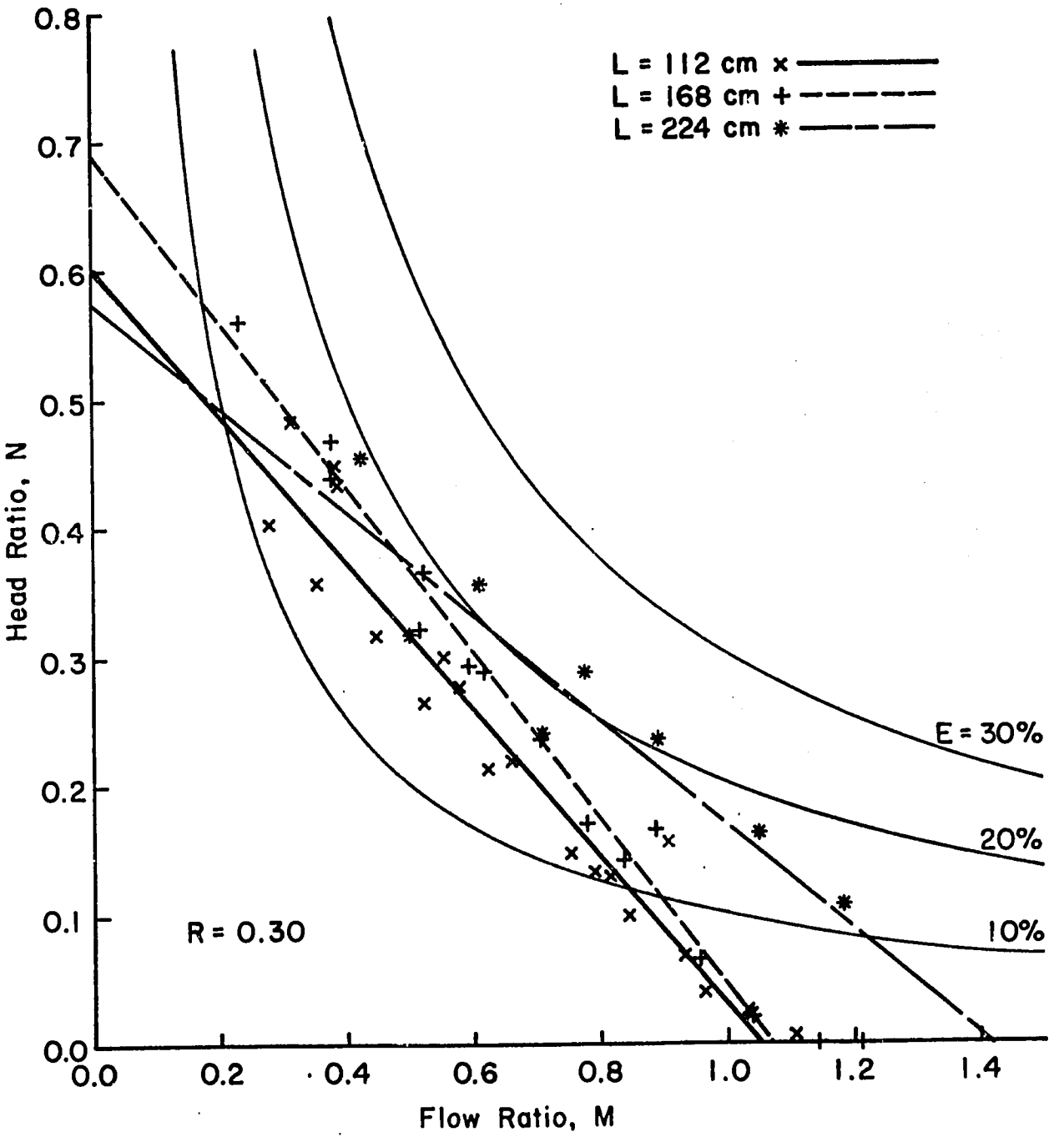


Figure 15. Head ratio, N, vs. flow ratio, M, for the jet junction prototype with a 14.0 cm nozzle.

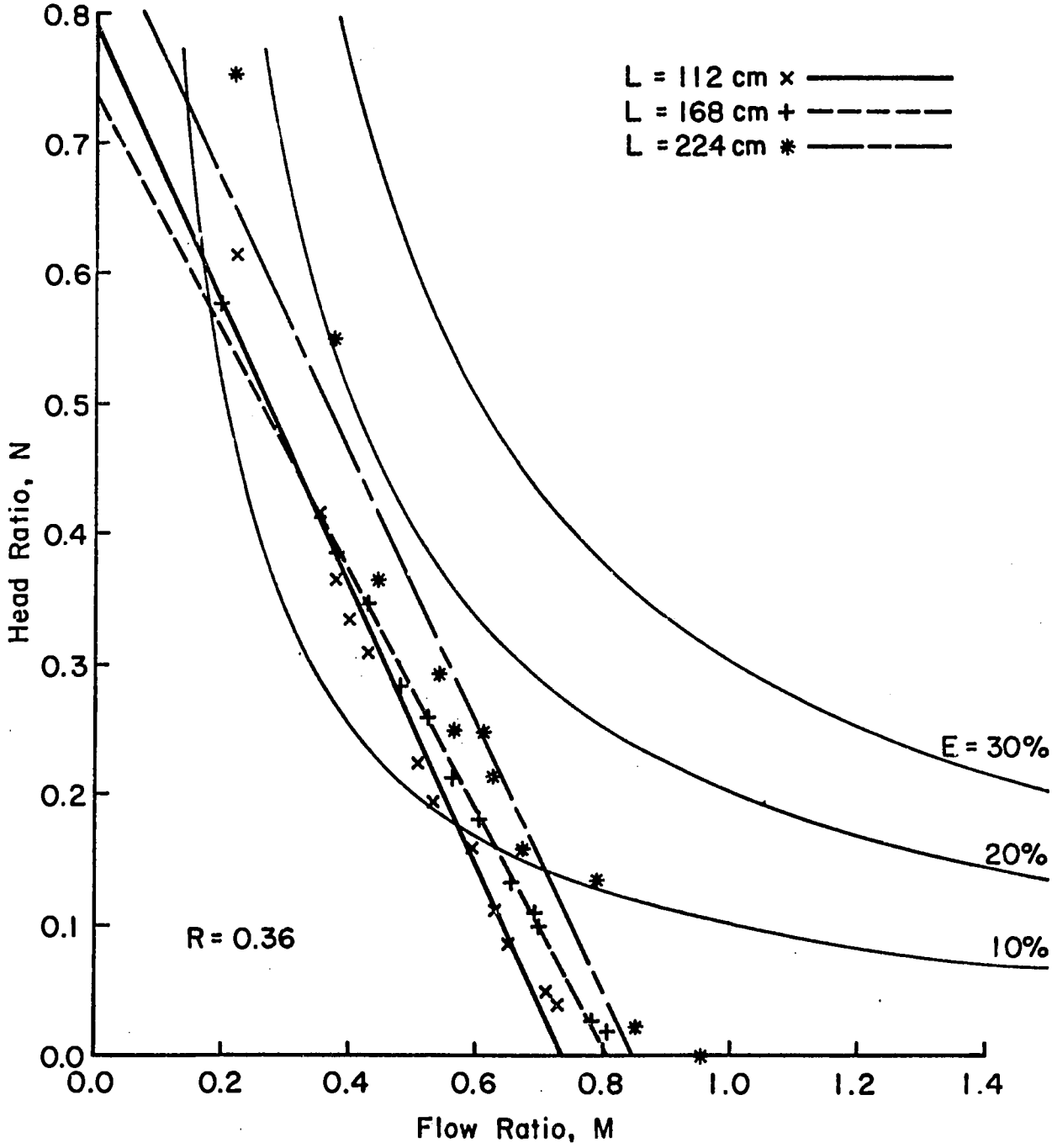


Figure 16. Head ratio, N, vs. flow ratio, M, for the jet junction prototype with a 15.2 cm nozzle.

Table 5. Head vs. flow ratio regression equations, optimum flow ratios, and maximum projected efficiencies for each geometric configuration tested with the diffusor.

L/D	4.4	6.8	8.8	Combined
R	n=11	n=14	n=14	n=39
.16	N=0.400-.289M	N=.367-.237M	N=.353-.190M	N=.371-.234M
	r^2=.97	r^2=.98	r^2=.79	r^2=.83
	M_o=.69	M_o=.77	M_o=.93	M_o=.79
	E_M=13.8%	E_M=14.2%	E_M=16.5%	E_M=14.7%
.25	n=55	n=23	n=14	n=92
	N=.616-.480M	N=.481-.325M	N=.502-.341M	N=.575-.431M
	r^2=.98	r^2=.87	r^2=.76	r^2=.92
	M_o=.64	M_o=.74	M_o=.74	M_o=.67
	E_M=19.8%	E_M=17.8%	E_M=18.4%	E_M=19.1%
.30	n=20	n=14	n=9	n=43
	N=.603-.573M	N=.691-.644M	N=.575-.405M	N=.613-.538M
	r^2=.95	r^2=.99	r^2=.87	r^2=.87
	M_o=.53	M_o=.54	M_o=.71	M_o=.57
	E_M=15.9%	E_M=.18.5%	E_M=20.5%	E_M=17.5%
.36	n=11	n=12	n=12	n=35
	N=.788-1.070M	N=.737-.909M	N=.878=1.031M	N=.788-.976M
	r^2=.97	r^2=.996	r^2=.92	r^2=.89
	M_o=.37	M_o=.41	M_o=.43	M_o=.40
	E_M=14.5%	E_M=14.9%	E_M=18.7%	E_M=15.9%
Average E_M	$\overline{E}_M$=16.0%	$\overline{E}_M$=16.4%	$\overline{E}_M$=18.5%	$\overline{E}_M$=16.8%

Table 6. Head vs. flow ratio regression equations, optimum flow ratios, and maximum projected efficiencies for each geometric configuration tested without the diffusor.

L/D	4.4	6.8	8.8	Combined
R				
.25	n=16	n=18	n=15	n=48
	N=.356-.397	N=.380-398	N=.368-.383	N=.338-.266
	r^2=.96	r^2=.97	r^2=.95	r^2=.37
	M_o=.45	M_o=.48	M_o=.48	M_o=.64
	E_M=8.0%	E_M=9.1%	E_M=8.8%	E_M=10.8%
.30	n=6	n=7	n=5	n=18
	N=.422-.543	N=.565-.668	N=.437-.517	N=.489-.595
	r^2=.99	r^2=.51	r^2=.99	r^2=.64
	M_o=.39	M_o=.42	M_o=.42	M_o=.41
	E_M=8.2%	E_M=12.0%	E_M=9.2%	E_M=10.0%
Average E_M	$\overline{E}_M$=8.1%	$\overline{E}_M$=10.6%	$\overline{E}_M$=9.4%	$\overline{E}_M$=10.4%

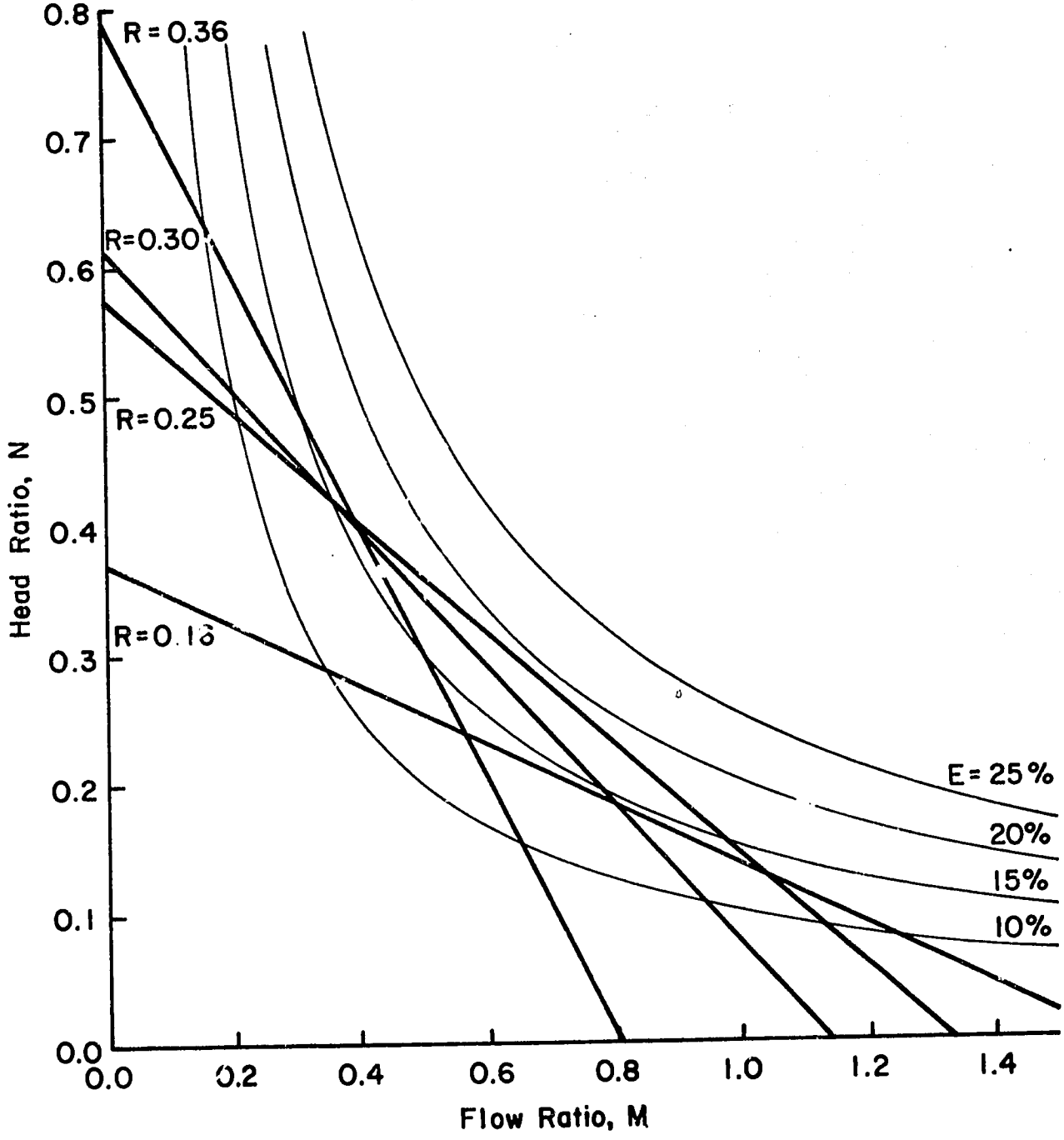


Figure 17. Regression lines representing the combined N vs. M data for each area ratio, R.

exact relationship between the area ratio that results in the maximum efficiency and the flow ratio, the optimum R values for the prototype lie within the shaded area in Figure 18.

The velocity ratio at the entrance to the mixing chamber, V_s/V_j, is also dependent upon R and M:

$$\frac{V_s}{V_j} = \frac{Q_s/A_s}{Q_j/A_j} = \frac{Q_s A_j}{Q_j A_s} = \frac{Q_s}{Q_j}\left(\frac{A_j}{A_c - A_j}\right) = \frac{Q_s}{Q_j}\left(\frac{1}{\frac{A_c}{A_j} - 1}\right) = \frac{M}{\frac{1}{R} - 1} , \qquad (6)$$

where A_c is the cross-sectional area of the mixing chamber. Thus equi-velocity ratio lines can also be drawn on Figure 18. The optimum velocity ratio for the jet junction prototype is seen to remain fairly constant at 0.2. This is significantly lower than the optimum velocity ratios of 0.4 found by Cairns and Na (1969) and Mueller (1964) whose data is also plotted on Figure 18. This would imply that a higher percentage of the energy loss in the higher head pumps occur in the nozzle, and that relatively smaller nozzles (lower area ratios and velocity ratios) should be used in low head jet pumps.

The second geometric parameter studied with the laboratory prototype was the affect of mixing chamber length on jet junction performance. The data presented in Figures 13 through 16 inconsistently indicate that the longest mixing chamber length (L = 224 cm, L/D = 8.8) is slightly more efficient than the shorter lengths. A maximum efficiency for the regression line representing each data set is given in Table 5. This optimum point is where the regression line touches the

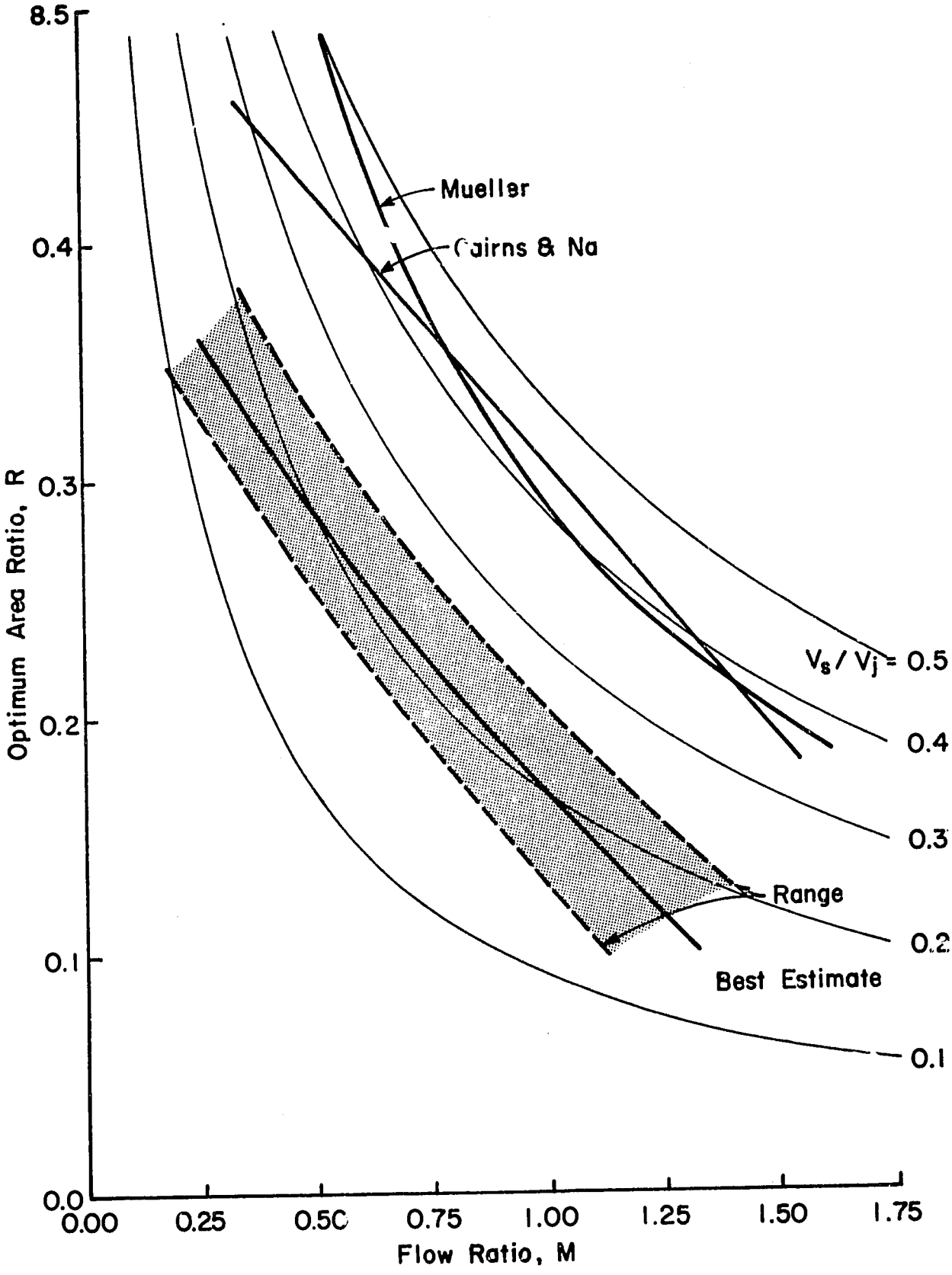


Figure 18. Area ratios, R, which resulted in maximum jet pump efficiencies for the jet junction prototype and according to Mueller (1964) and Cairns and Na (1969). Figure also shows equi-velocity ratio, V_s/V_j, lines.

highest equi-efficiency line on Figures 13 through 16. The optimum flow ratio at which the maximum efficiency is achieved, M_o, was determined by setting the derivative of the efficiency equation (Eq. 1) equal to zero:

$$E = MN = M(a - bM) = aM - bM^2$$

$$\frac{dE}{dM} = 0 = a - 2bM$$

$$M_o = \frac{a}{2b} \quad , \tag{7}$$

where a and b are the regression coefficients (Eq. 5). The maximum efficiency, E_M, at this optimum flow ratio would be:

$$E_M = aM_o - bM_o^2 = \frac{a^2}{ab} - \frac{a^2}{4b} = \frac{a^2}{4b} \ . \tag{8}$$

From Table 5, it can be seen that the average maximum efficiencies, $\overline{E}_M$ for each of the three mixing chamber lengths is:

$$\frac{L}{D} = 4.4 \quad ; \quad \overline{E}_M = 16.0\%$$

$$\frac{L}{D} = 6.6 \quad ; \quad \overline{E}_M = 16.4\%$$

$$\frac{L}{D} = 8.8 \quad ; \quad \overline{E}_M = 18.5\%$$

Previous studies of higher velocity jet pumps have indicated optimum lengths in the range of 5 to 8 mixing chamber diameters. Because of the lower velocities and thus lower friction losses, a longer optimum length would be expected for low head jet pumps. However, as the data suggests, the gain in efficiency from doubling the chamber length is only about 2 percentage points and the costs involved in the larger structure often

will not merit the increased efficiency. In concrete pipe mixing chambers, as would be used in the field, the efficiency gain would be even less due to higher surface roughness.

Figures 13 to 16 indicate that, although the chamber length which gives the higher efficiencies at low flow ratios is inconsistent between the various configurations, the efficiencies increase with L at higher flow ratios for all geometries. Apparently, the mixing process is more rapid when the velocity ratio is small, or when the jet velocity is large relative to the velocity of the suction fluid. Consequently, for jet junctions designed with larger than optimum area ratios, longer mixing chamber lengths will be more important for achieving high efficiencies.

The jet junction prototype was also tested without the diffusor section to evaluate the resulting loss of efficiency and the consequent cost effectiveness of the diffusor. Figure 19 and Table 6 indicate that jet junction efficiencies are reduced 40 to 50% and that the optimum flow ratio is lowered significantly when the jet junction diffusor is removed. These dimensionless ratios, M and N, disguise the true affect of removing the diffusor--that of increasing the head losses in the junction. Head loss measurements taken in the jet junction without the jet operating ($Q_j = 0$) indicated that the head loss coefficient for the entrance section, mixing chamber and diffusor, was 0.88 while without the diffusor, the C_L value was 1.63. This would indicate a head loss due to removal of the diffusor, ΔH, of:

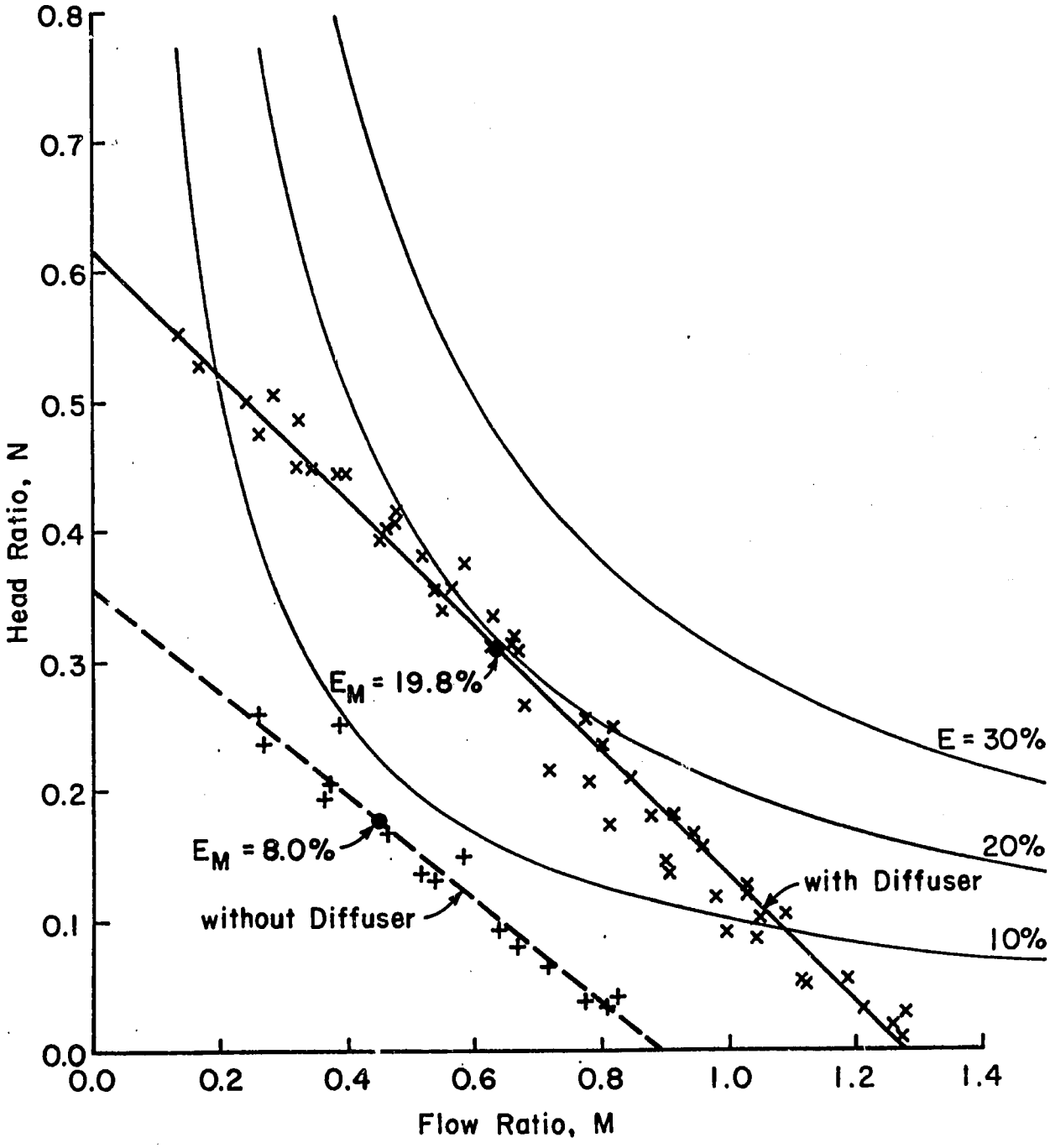


Figure 19. Comparison of jet junction prototype performance with and without the diffusor, for R=0.25 and L/D=4.4.

$$H = (163 - 0.88)\frac{V^2}{2g} = 0.75\ \frac{V^2}{2g} \quad .$$

Thus, the loss of efficiency due to the removal of the diffusor should roughly be proportional to the square of the velocity, and thus the square of the combined flow rates, Q_t. This relationship is not indicated by the data which shows little influence of total flow rate upon the efficiency decrease. Due to the fact that the diffusor does nearly double the jet junction efficiencies, it will nearly always be cost effective.

A design parameter which was not evaluated in the study and was not discussed in the literature is the size of jet junction required for different flow rates. It would be expected that for a given size of jet pump, efficiencies would decrease at very low flow rates due to inefficient energy transfer between the fluids, and at high flow rates due to high friction losses. Consequently, for a given design flow rate, a given pump size (or mixing chamber diameter) or range of sizes should give the optimum performance. All that could be determined from the prototype was that, within the range of flows tested, no variation in efficiency with flow rate could be determined. The velocity of the combined fluids in the mixing chamber varied from 0.9 to 3.2 m/sec. Figure 20 shows the maximum efficiencies obtained for each geometric configuration (with the diffusor) and for each value of Q_j tested, vs. combined flow rate. No relationship is indicated. The performance of the one-fourth scale model similarly did not change with combined flow rate. Combined

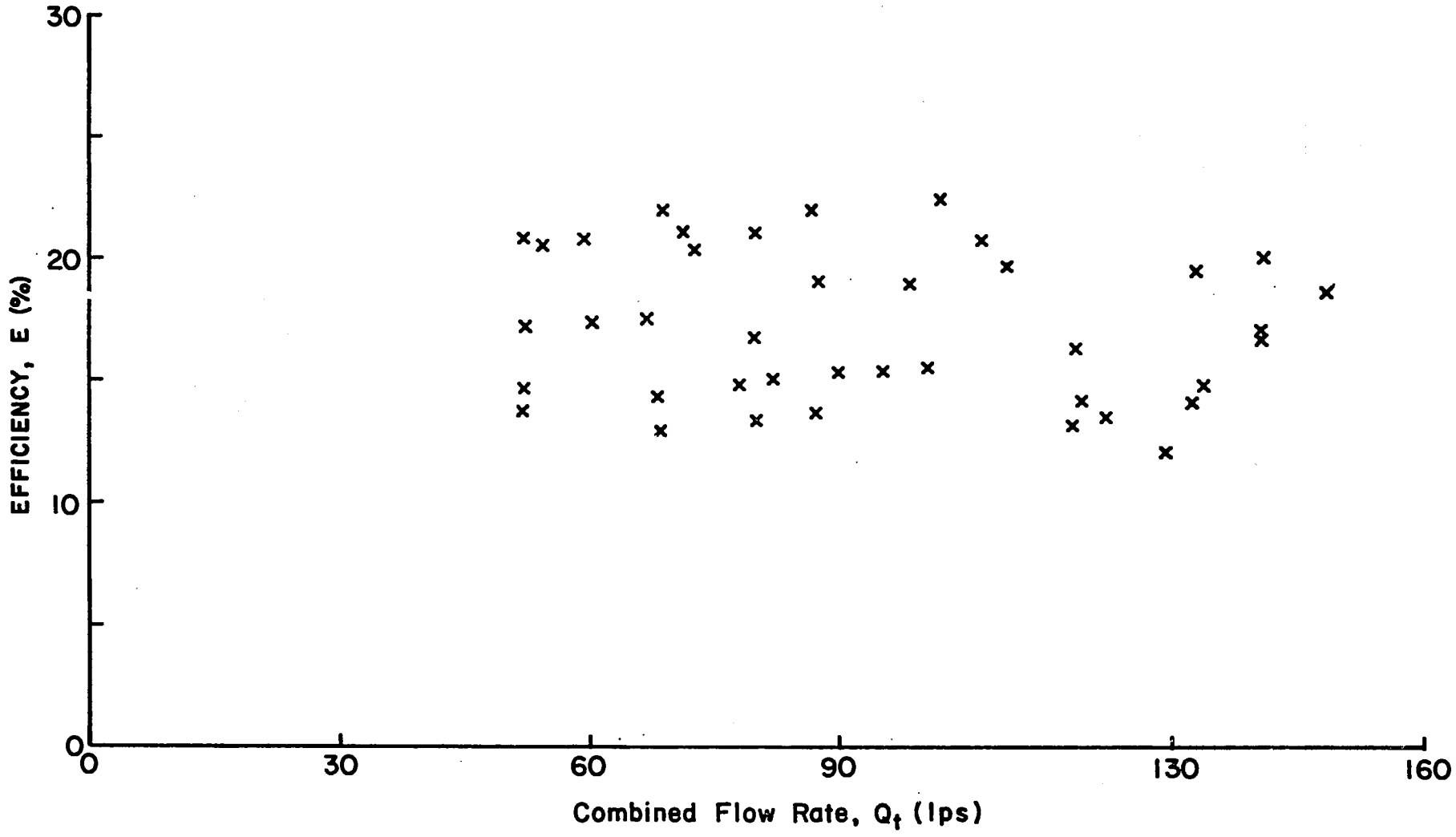


Figure 20. Maximum efficiencies achieved with each geometric configuration (with diffusor) and jet flow rate, vs. the combined flow rate, Q_t.

velocities between 0.5 and 1.8 m/sec were tested in the scale model. Tests did indicate that the head loss in the prototype is proportional to the square of the velocity. Consequently, the energy transfer process must become more efficient at higher velocities at about the same rate as the head loss increases, resulting in fairly constant overall efficiencies.

SECTION IV

JET JUNCTION DESIGN

Four input values are needed to determine the geometric parameters required for jet junction design. They are:

1. the suction or mogha flow rate, Q_s,
2. the jet or tubewell flow rate, Q_j,
3. The available jet head, or elevation of tubewell discharge above the desired upstream channel water surface, H_j, and
4. the desired head or water surface elevation gain downstream compared to upstream of the junction, H_t.

Figure 21 illustrates these four quantities. Surveying equipment and flow measurement devices will be required to establish these values. Descriptions of this equipment and its use are given in the Watercourse Improvement Manual (Trout and Kemper, 1980), or the Training Manual for Agricultural Water Management Specialists (Westfall, 1980).

Determination of Mogha and Tubewell Flow Rates

Design flow rates of moghas and tubewells are available from the Irrigation Department Executive Engineer's Office. However, because flow rates often vary widely from design values, both values should be checked in the field with flow measurement devices such as flumes, orifice plates, or flow meters.

Care should be taken so that the measurement device used does not change the flow rate. For example, an orifice plate on a tubewell discharge pipe will increase the pumping head

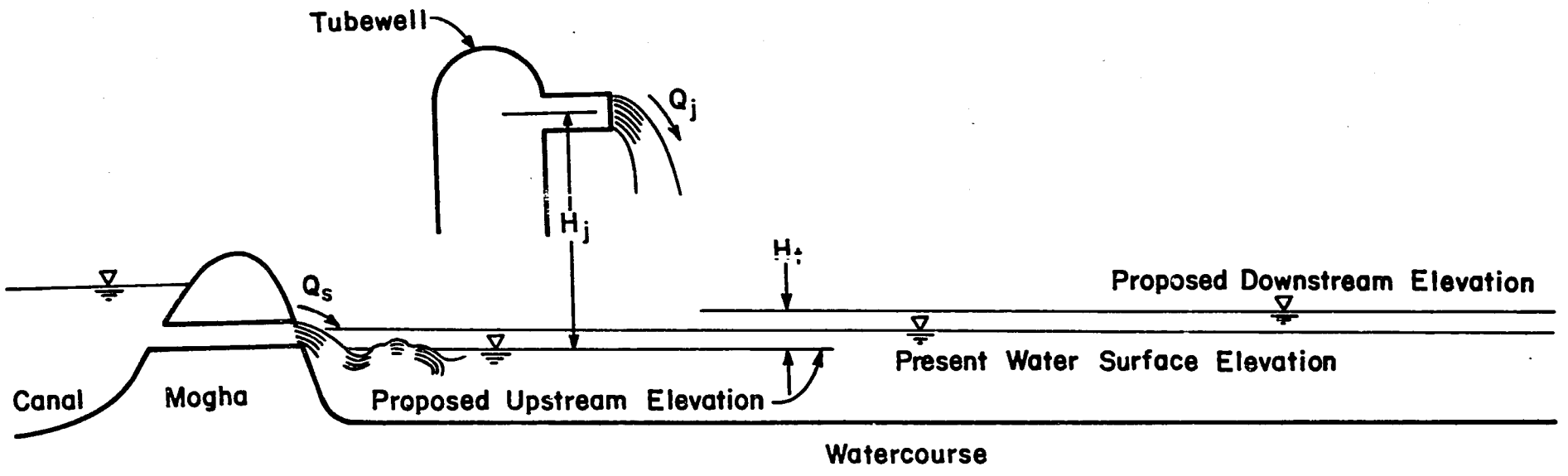
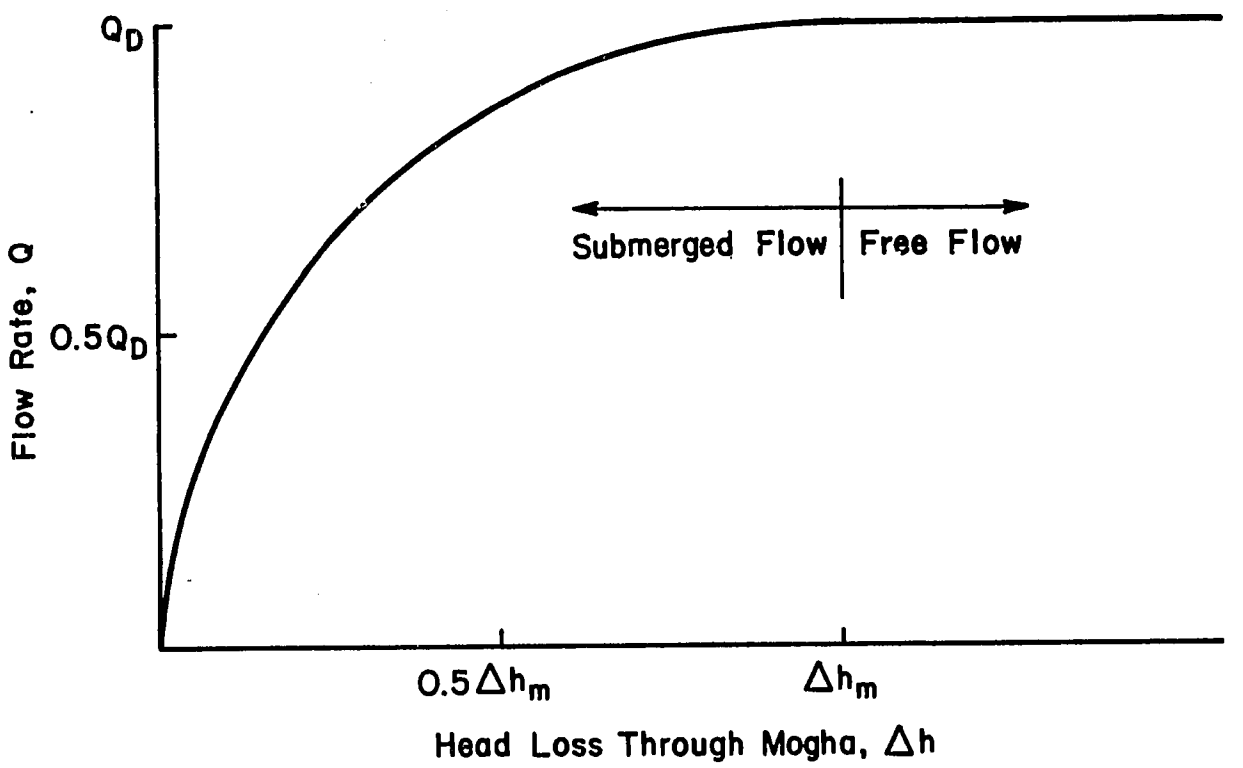


Figure 21. Schematic showing the four parameters required for jet junction geometric design.

and decrease the flow. Measuring flow from a submerged or nearly submerged mogha must be done very carefully, because any accurate measurement device increases the water surface elevation upstream of the device and will further submerge the mogha and reduce the flow. Figure 22 illustrates how increasing the water surface level downstream of a mogha and decreasing the head loss through the mogha, Δh, below that required for free flow, Δh_m, can affect the flow rate. When mogha submergence may be a problem, flow measurement should be made with minimum head loss in the device and: (a) while the water is flowing to a lower field; (b) when the tubewell is turned off; and/or (c) after the channels have been recently cleaned so the flow depth upstream of the device is minimal. In addition, the flow measurement should be made a few hundred meters downstream of the mogha so much of the raised water level upstream of the measurement device has a chance to dissipate before reaching the mogha. If mogha flow cannot be measured during free flow conditions, either design flow rates, or rates calculated from the mogha dimensions and the proper equation from Figure 22 must be used to establish the free flow rate. The equations in Figure 22 can also be used to help estimate whether or not the mogha is submerged. A hydraulic jump downstream of the mogha is a sure indication of free flow.

Mogha flows will also vary with the water level (or flow rate) in the canal (distributary or minor), so irrigation department officials or farmers should be asked whether the



Free flow flow rate, Q_D, and minimum free flow head loss, Δh_m, for commonly used moghas (canal outlets)(adopted from Ali, 1975).

For open flume moghas (Crump open flume):

$$Q_D = 0.017\ WH^{3/2}$$

$$\Delta h_m = 0.2\ H$$

For orifice moghas (adj. orifice semi-module):

$$Q_D = 0.04\ WY\ \sqrt{H-Y}$$

$$\Delta h_m = 0.83\ (H-Y) - .5\ (W)$$

where: Q_D = free flow flow rate (ℓps)

Δh_m = minimum free flow head loss (minimum modular head)(cm)

W = mogha opening width (cm)

Y = mogha opening height (cm)

H = upstream head above mogha floor (cm)

Figure 22. Sample graph and equations for estimating mogha flow characteristics.

level during the measurement is above or below the normal level. If levels and thus mogha flows vary widely, this variation should be noted and considered during design.

Determination of Design Heads

Before the design heads can be established, the desired water surface elevations upstream and downstream of the proposed jet junction must be determined. This will require a knowledge of the problems experienced such as mogha submergence or difficulty in irrigating high fields. If the primary problem is mogha submergence, then the upstream level needs to be lowered. If the problem is inability to irrigate high fields, then the water level below the junction needs to be increased. In reality, these two perceived problems are interconnected and usually result from an insufficient grade between the mogha and at least a portion of the fields. With the tubewell off, irrigating higher areas is especially difficult, while with the tubewell running, the increased flow depth submerges the mogha.

While designing the desired water surface elevations, a decision must be made as to whether the same conveyance system is to be used both with the tubewell and jet pump running, and while the tubewell is turned off and only canal water is flowing. Designing a system for both flow situations will constrain the flexibility that the jet junction can provide. But the alternative will require either dual conveyance systems or a complex water scheduling program in which the canal water is distributed to farmers with lower fields near the

head of the watercourse whenever the tubewell is off. The choice, which should be made by the water users, will depend upon the scheduling and dependability of the tubewell, the topography and degree of the elevation problem, the ratios of the two flows, the layout of the conveyance system, and the cooperativeness of the water users. The two conditions will be discussed separately.

Whichever condition is chosen, Figure 23 can be used to indicate the initial feasibility of any proposed design. Any H_j and H_t combination which falls below the proper flow ratio line should be feasible. The derivation of this figure will be explained later.

Condition 1: One conveyance system designed for both combined and only canal supply (conjunctive channel usage)

Under this condition, the downstream channels can be raised only to the extent that canal water will still flow through them when the tubewell is turned off without submerging the mogha. Water raised above the normal flow depth level of the combined flow in the downstream channel will flow more quickly (due to a steeper energy grade) until, in a few hundred meters, it is flowing uniformly at the normal depth, thus dissipating its extra energy. This implies that the only benefit of the jet junction is to enable the present watercourses to carry the combined flows without submerging the mogha.

This benefit is more significant than it may initially seem. Figure 24 shows the effect of changes in flow rate on

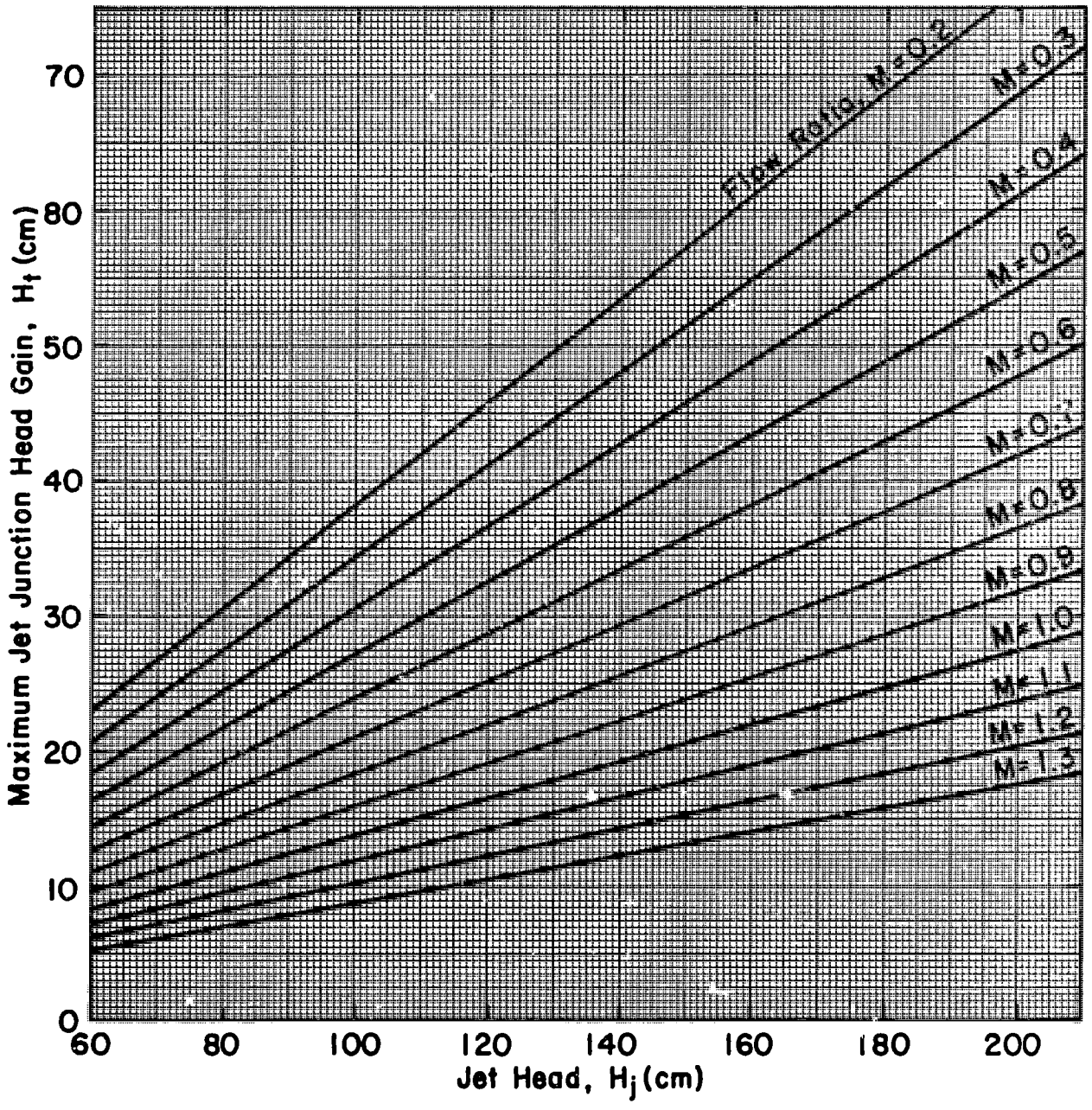


Figure 23. Potential jet junction head gain, H_t, vs. jet head, H_j, for various flow ratios, M, and the optimal area ratio.

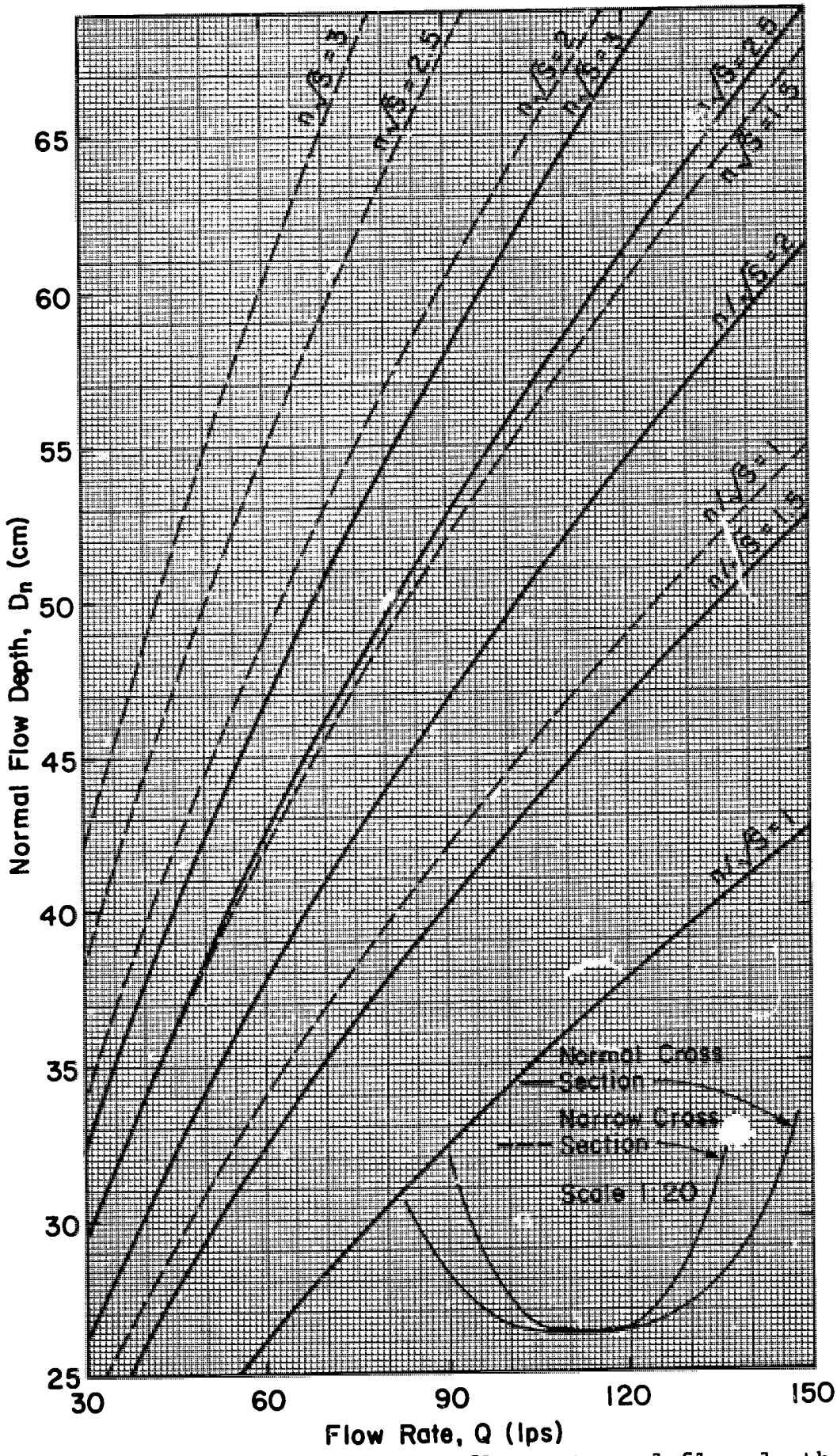


Figure 24. Relationship between flow rate and flow depth for two channel cross sections and several roughness coefficient, n, and slope, S, values.

flow depth in a typically shaped irrigation channel (also shown in the figure). Adding 30 ℓps of tubewell water to a channel with moderate vegetation ($n \approx 0.04$) and a relatively flat slope ($s \approx 0.0004$) carrying 30 ℓps of canal water would increase the flow depth nearly 12 cm. (This figure can be used to indicate flow depth changes for most earthen channels, but not absolute flow depth since it is based on a given cross section.) In a flat gradient watercourse system, an additional 12 cm of elevation will often submerge the mogha. So the jet junction can allow a mogha which normally flows free with the tubewell turned off to also flow free with it turned on.

The design elevation gain, H_t, for a jet junction under this conjunctively used channel condition, would thus be the difference in the downstream channel elevation with and without the tubewell running. This difference will normally vary between 10 and 20 cm. It can be measured in the existing channels by monitoring depths with a fixed staff gauge both with and without the tubewell running, or predicted with sufficient accuracy from Figure 24. If the channels are to be rebuilt, Figure 24 shows that by building them deeper and narrower, more advantage can be gained by the jet junction since the flow depth increase when the tubewell water is added will be greater.

Two other factors should be considered when designing the water surface elevation upstream and downstream of a jet junction in a conjunctively used watercourse.

The first consideration involves the following conditions: (a) raising the channels to more easily irrigate the fields is an important factor; (b) the mogha presently flows freely when the tubewell is off; and (c) the tubewell runs most of the time. A decision could then be made to raise the channels slightly, somewhat submerging the mogha and thus reducing the flows (or at least reducing the safety factor) when the tubewell is off, in order to gain the extra few centimeters of head at the field. Figure 22 shows that a small amount of mogha submergence reduces the discharge very little. Measurements of Δh vs. Q for the particular mogha will indicate the amount of flow decrease which could be expected. This option of course requires rebuilding the watercourse system below the junction at a higher elevation. It must be remembered that water cannot be raised in the existing channels beyond their normal flow depth.

The second consideration is, due to friction losses, the canal water will lose head as it passes through the jet junction without the tubewell running, thus raising the water level upstream of the device. Tests on the laboratory prototype indicated that the loss coefficient for the jet junction ($Q_j = 0$) was 0.82. Increasing this by about 20% for concrete field installations (this should be checked in initial field installations and adjusted as needed), a conservative loss coefficient of 1.0 should be used. Head losses through the junction, Δh_j, would thus be:

$$\Delta h_j = 1.0 \frac{V^2}{2g} \tag{9}$$

for velocity, V, in meters per second, Δh_j, in meters, and with the acceleration of gravity, g, equal to 9.81 m/sec^2. For flow rates, Q_s, in ℓps, mixing chamber diameter, D, in cm, and head loss, Δh_j, in cm, the equation would reduce to:

$$\Delta h_j(\text{cm}) = 826 \frac{Q^2(\ell\text{ps})}{D^4(\text{cm})}, \tag{9a}$$

or, for a 25.4 cm diameter mixing chamber:

$$\Delta h_j(\text{cm}) = .002Q^2 \tag{10}$$

A graph of Δh_j vs. Q for various D values is shown in Figure 25. Head losses in jet junctions of 2 to 8 cm will be common.

This head loss can be avoided by constructing a bypass around the junction, although the gate in the bypass will also create some head loss. If no bypass is constructed, the junction head loss will increase the upstream water surface elevation by an amount equal to the head loss. This may not allow the channels to be raised as previously suggested. In fact, if the increased elevation causes mogha submergence, the channels may have to be lowered. Construction of a junction bypass will often be a less costly alternative to lowering the channels.

This head loss only needs to be considered when the tubewell is off and will not affect other calculations. It is built into the jet pump design graphs and is in fact the primary reason why the efficiencies are less than 100%.

The elevation gain desired from the jet junction, H_t, in conjunctively use channel systems will be:

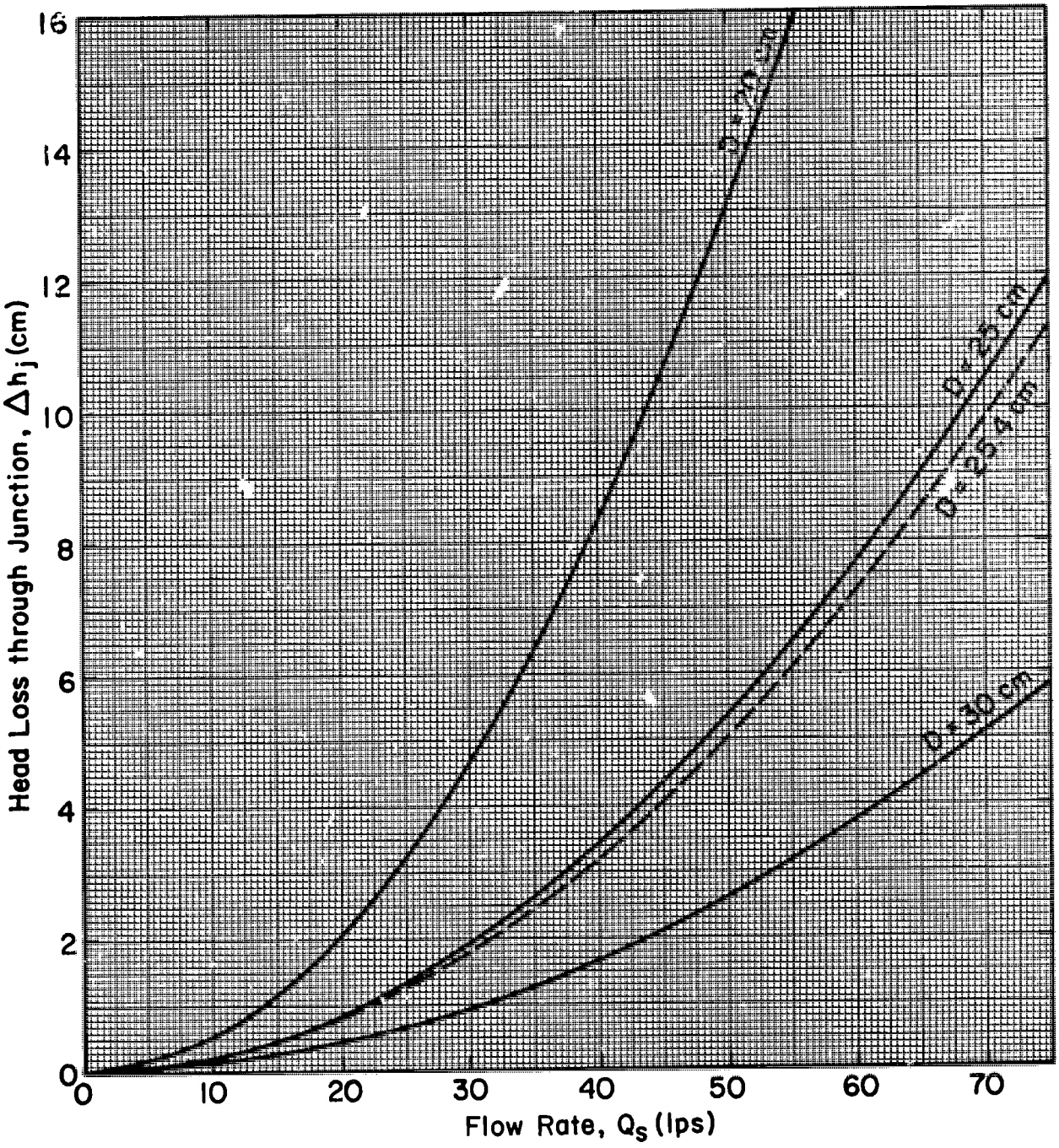


Figure 25. Head loss through a non-operating jet junction of various mixing chamber diameters, D.

1. the increased normal flow depth in the downstream channel due to the addition of tubewell water,
2. minus, the head loss of the canal water passing through the junction (unless a bypass is built),
3. plus, any amount the channels are to be raised,
4. plus, a safety factor to insure against mogha submergence when the jet junction is operating.

This safety factor is to insure that the mogha flows freely even if the channels become choked with vegetation and flow depths increase due to increased roughness. Figure 24 shows that increasing the roughness coefficient from .03 to .06 can easily increase flow depths by 10 cm or more. (This factor should also be considered when deciding whether to raise the channels.) Trout and Kemper (1980) further explain the affects of vegetation on flow depths and illustrate water-courses with various roughness coefficients. A safety factor as large as 10 cm would be desirable, but as indicated by Figure 23, this often cannot be achieved. Therefore, the safety factor should remain flexible during the design process.

Condition 2: Conveyance system designed only for use with the jet junction operating.

Determination of the design heads for only jet junction operation is simpler, because either the upstream or downstream water surface elevation can be established independent of the present channel system. If the criteria is to raise the water from the present channel to serve certain fields, then the design upstream elevation is the present elevation

while the required downstream elevation is established by a topographic survey of the fields to be irrigated and a design of the conveyance system to serve those fields from the junction (see Trout and Kemper, 1980, for methods to design channel systems). This situation would occur if a totally new watercourse is being constructed, or if a farmer wished to build his own jet junction on his own branch driven by a private tubewell.

If the objective is to free a submerged mogha without reconstructing the watercourse below the junction, then the downstream water surface elevation would be the existing one with the tubewell running, and the upstream elevation would be that required to allow the mogha to flow freely, plus some safety factor as discussed previously. In either case, the head gain in the junction, H_t, is the difference between the desired downstream and upstream elevations, as depicted in Figure 21.

For either condition, the total excess head available from the tubewell water would be the elevation difference between the center of the discharge pipe and the desired water surface level upstream of the junction. However, some of this head will be dissipated in the pipes which convey the water to the nozzle and thus will not be available to drive the nozzle. The amount of head loss in conveyance will depend both on the form losses in the pipeline at the bends and entrance, and the friction losses in the pipe.

As previously stated, head losses are generally proportional to the square of the velocity. The proportionality constant is termed the loss coefficient, C_L. Loss coefficients for various types of pipe fittings and transitions are listed in most practical hydraulics books. Generally, 90° bends and abrupt entrances from still water into a pipeline, the transitions which will be most common in a jet junction delivery line, each have loss coefficients of about 0.5. Thus, a short delivery line such as the one shown in Figure 7 where friction losses are small, would have a total C_L value of 0.5 due to the entrance from the outfall box to the pipeline. If the delivery line is attached directly to the tubewell discharge pipe and has two 90° bends before the nozzle, the total C_L value for form losses would be 1.0.

Friction losses in pipes are due to the rubbing of the water against rough walls. It is proportional, in addition to the square of the flow velocity, to the length of the pipe, and is inversely proportional to the pipe diameter. Friction loss coefficients can also be expressed in terms of the loss coefficient, C_L, with the equation:

$$C_L = f\frac{L_p}{D_p} \tag{11}$$

where: L_p = the pipe length (m)

D_p = the pipe inner diameter (cm), and

f = 1.6 for plastic pipe

2.0 for steel pipe, and

3.5 for concrete pipe.

These f factors are dependent upon the pipe material and manufacturing process, the pipe diameter, and the Reynold's number for the flow and are consequently variable (Albertson, Barton and Simons, 1960). The values given are average values for the pipe sizes and flow velocities expected. Equation 11 implies that 20.3 cm steel pipe would have a loss coefficient of 2.0/20.3 = 0.10 cm per meter of length, while a 20.3 cm concrete pipe would have an equivalent loss coefficient of 3.5/20.3 = 0.17 cm/m. Friction losses can generally be ignored for very short pipe lengths.

The pipe flow velocity, V_p, will depend upon the flow rate and pipe cross-sectional area, A_p. The velocity is calculated by the continuity equation:

$$V = Q/A \quad . \tag{12}$$

Thus, the delivery pipe head loss ΔH_p can be calculated by the equation,

$$\Delta H_p = C_{LT} \frac{V^2}{2g} = C_{LT} \frac{Q_j^2}{2gA^2} = C_{LT} \frac{Q_j^2}{2g(\pi^2/16)D_p^4} \ , \tag{13}$$

where C_{LT} equals the sum of all the form and friction loss coefficients. For Q_j in ℓps, ΔH_p in cm, and the pipe inner diameter, D_p, in cm, Equation 13 becomes:

$$\Delta H_p = \frac{C_{LT}\ 826.3\ Q_j^2}{D_p^4} \tag{13a}$$

Figure 26 illustrates solutions for this equation for two common pipe diameters (25.4 cm (8") and 15.2 cm (6")) and for C_{LT} values of 0.5 and 1.0. A convenient way to use the figure is to determine the velocity head for the flow rate

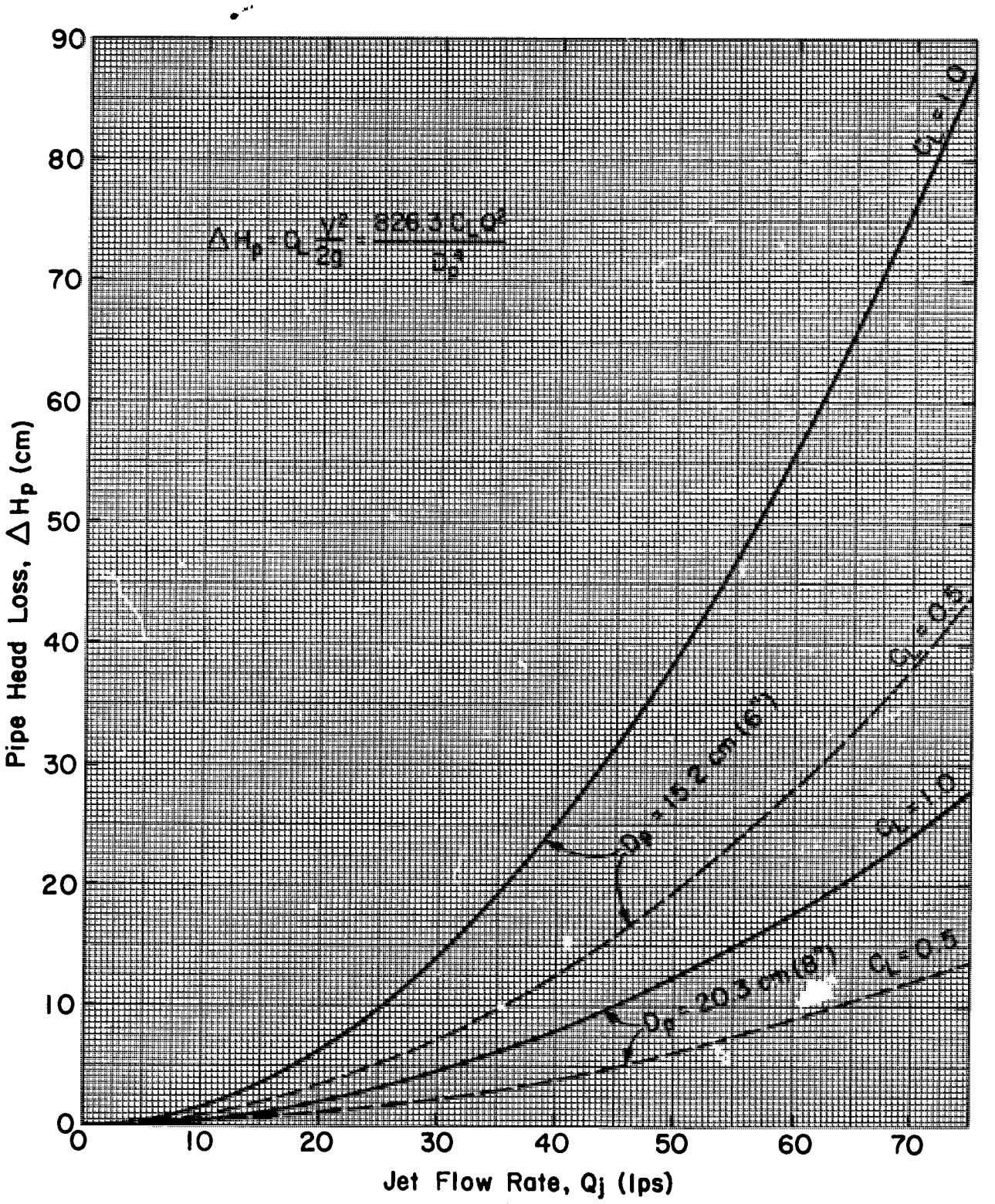


Figure 26. Head loss, ΔH_p in the nozzle delivery pipe for 15.2 cm (6") and 20.3 cm (8") delivery pipe and head loss coefficients, C_L, of 0.5 and 1.0.

from the $C_L = 1.0$ curve for the proper pipe diameter, and multiply this value times C_{LT}.

The delivery pipe head loss must be subtracted from the total available head from the tubewell water to get the head available at the nozzle, H_j.

Designing the Jet Pump

After the input parameters, Q_s, Q_j, H_j, and H_t, are determined, the dimensioning of the jet junction can be completed with the use of three graphs, Figures 27, 28 and 29, or with equations which describe the graphs. The actual design solution is over constrained, since one of the four parameters will be determined by a design derived from the other three, so the design process may involve prioritizing the inputs and/or trial and error solution techniques. The graphical design procedure will be explained first.

Graphical Design Procedure

The first graph, Figure 27, of head ratio, N, vs. flow ratio, M, represents a summary of the results of the prototype study presented in the preceeding section. The heavy line in Figure 27 represents a reasonable upper performance limit which could be achieved with a well designed jet junction. Figures 13 to 16 show the variability of this upper limit and indicate the importance of monitoring field installations and adjusting this design line as needed. If the point representing the desired flow ratio:

$$M = Q_s/Q_j \quad , \tag{1}$$

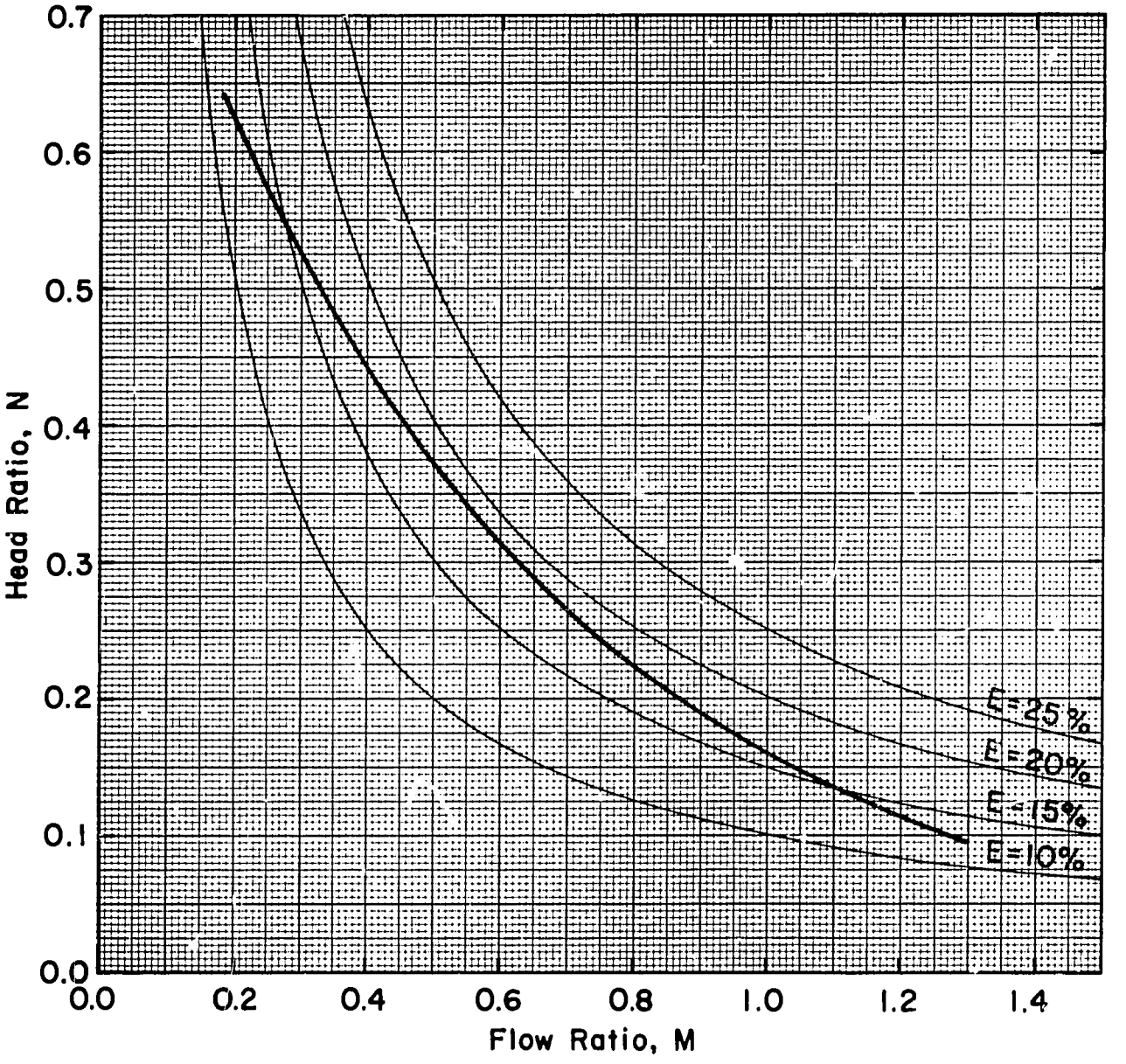


Figure 27. Optimum head ratio vs. flow ratio relationship for low head jet junctions.

and head ratio:

$$N = \frac{H_t}{H_j - H_t}, \quad (H_s = 0), \tag{2}$$

for a particular set of input parameters is below this line, then the desired head gain, H_t, is achievable. Figure 23 which is based on this optimum relationship, can also be used to determine the feasibility of a solution as well as additional gain which can be achieved if the design is adjusted toward an optimum design. If the desired head ratio is above the heavy line on Figure 27, or above the proper flow ratio line on Figure 23, then one of the parameters must be adjusted until the design point falls on or below the optimum design line. Adjustment can be made most easily by reducing, through adjustment in the channel levels, the desired head gain, H_t, or by coupling the jet nozzle directly to the tubewell discharge pipe and designing the nozzle to create a higher head, H_j. Figure 23 can be used to estimate the required parameter changes. Direct coupling to the tubewell will decrease Q_j roughly proportional to the increase in the tubewell pumping head (total dynamic head) if the tubewell pump is operating efficiently, and may change the head loss in the delivery line (Figure 26).

Once a feasible set of input parameters is decided upon, the nozzle and mixing chamber diameters must be chosen to achieve the desired head gain. The nozzle diameter must be chosen to utilize the available head, and the mixing chamber diameter to give the proper area ratio. Figure 28 shows the head, H_j, required to drive a nozzle of a given diameter, d,

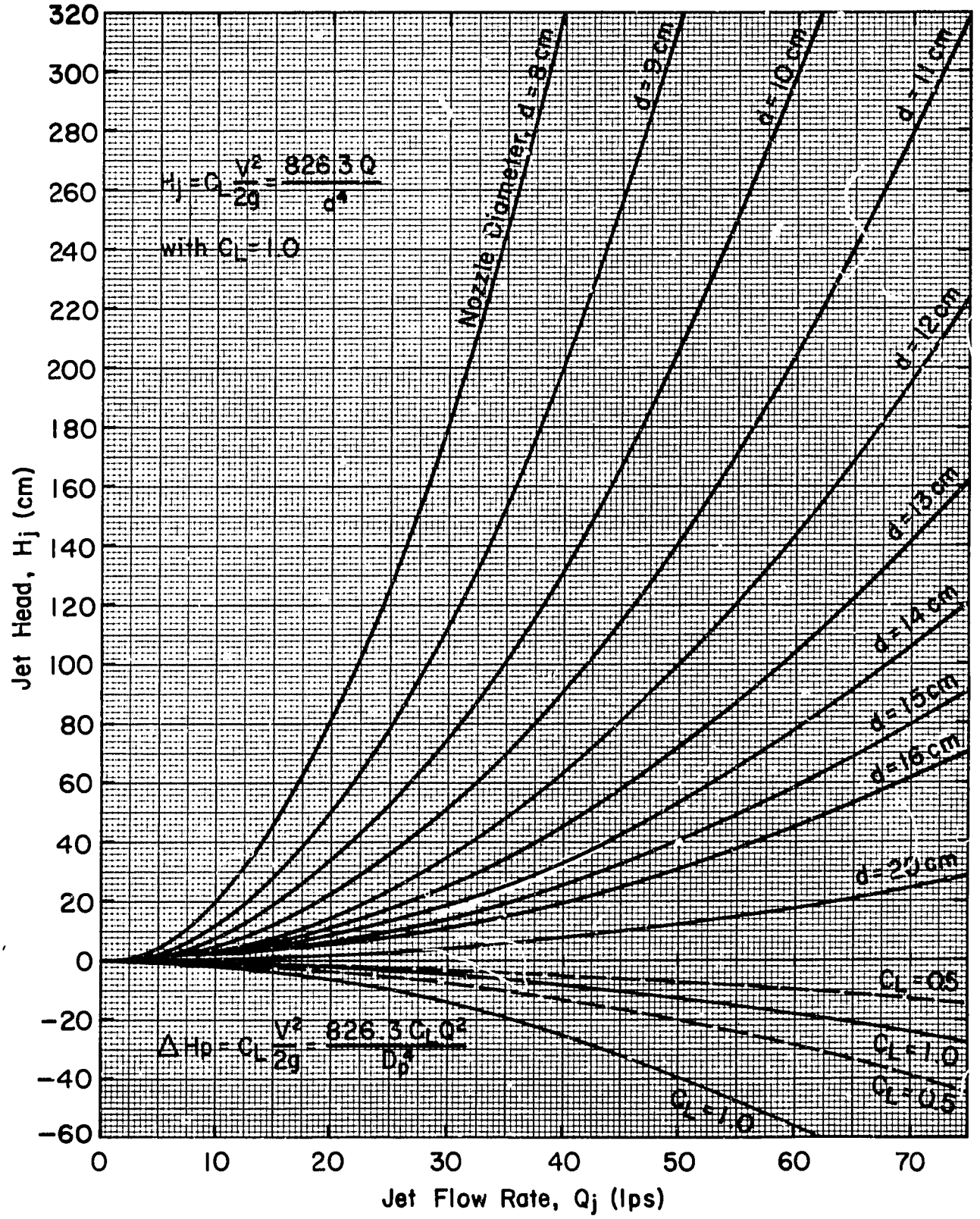


Figure 28. Head required to drive various diameter nozzles at different flow rates, and delivery pipe losses vs. flow rate.

at the desired flow rate, Q_j. This figure is based on Eq. 13 with the nozzle coefficient, C_L, equal to 1.0 and the nozzle diameter, d, used in place of the pipe diameter. The proper diameter is determined by finding the point on the graph representing the design H_j and Q_j values and estimating the nozzle diameter represented by that point by interpolating between the diameter curves. If the head loss in the conveyance pipe has not yet been subtracted from the total available tubewell water head, this can also be done graphically with the bottom portion of Figure 28.

At the design flow ratio, the optimum area ratio, R, can be determined from Figure 29. The required mixing chamber diameter can then be calculated from the formula:

$$D = d/\sqrt{R} \quad , \tag{14}$$

or can be estimated by interpolating between the mixing chamber diameter lines given in Figure 29 at the chosen nozzle diameter.

By following this technique, the head gain, H_t, predicted by Figure 23 should be achieved. If this achievable value is larger than the required gain, the excess can be considered a safety factor, or it can be reduced by utilizing a larger nozzle, thus reducing H_j and the height of outflow box required at the tubewell, and/or by choosing a non-optimal mixing chamber diameter, allowing the use of standardized mixing chamber pipe sizes.

In order to utilize a standard mixing chamber pipe size, a non-optimum area ratio will usually result. A non-optimum

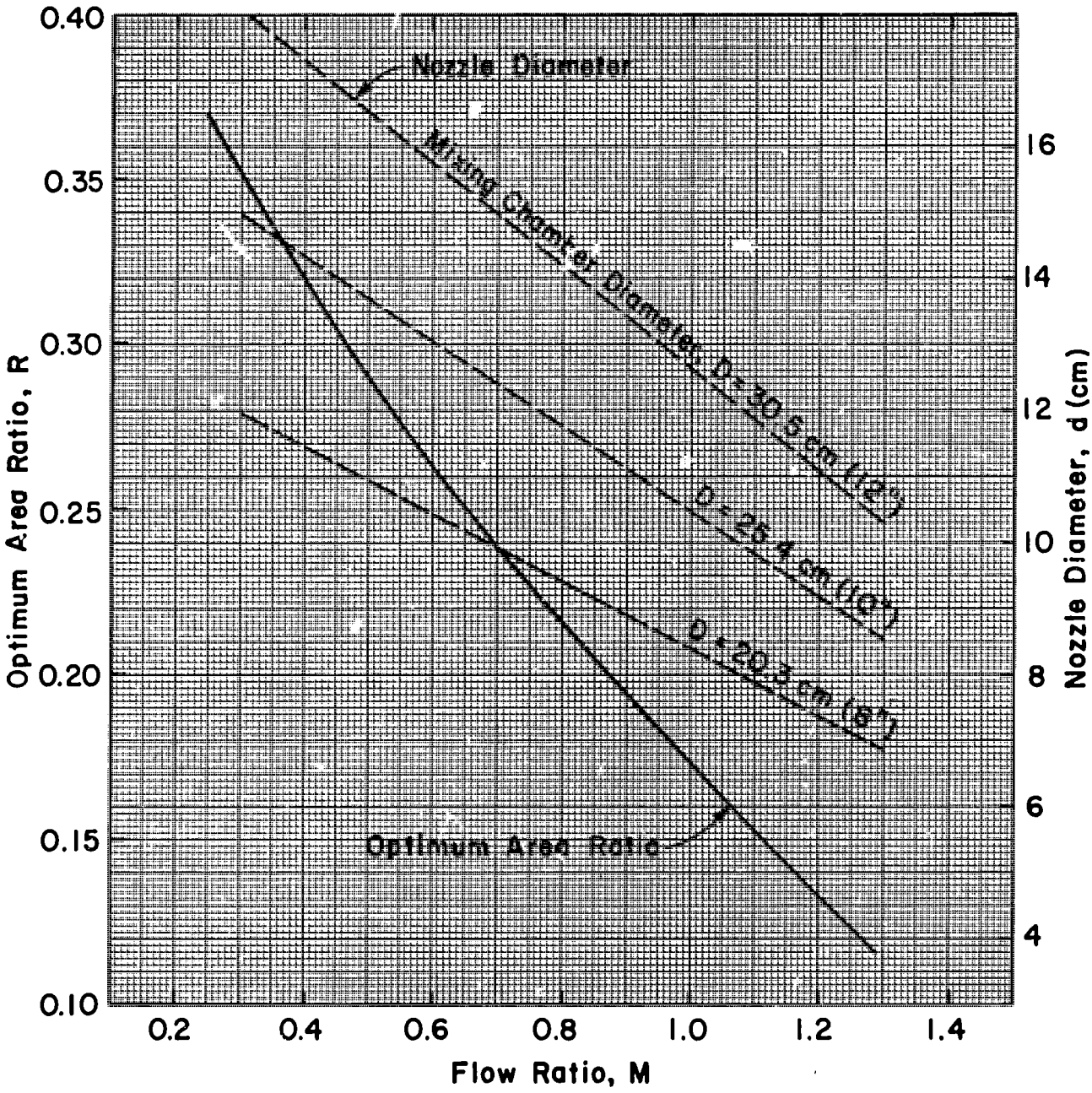


Figure 29. Optimum area ratio, $R = d^2/D^2$, and nozzle diameter vs. flow ratio, M.

situation will also occur if there are fluctuations in any of the design parameters, such as the mogha flow rate (a common occurrence). The head gain at these non-optimal operating conditions can also be checked with the design graphs. Figures 12 to 16 indicate that a jet junction with a given geometric configuration exhibits a linear N vs. M relationship. This straight line touches the optimal design curve (Figure 27) at the flow ratio which is optimal for the actual area ratio, R (Figure 29). Consequently, by following a straight line tangent to the design curve (Figure 27) at this optimal flow ratio, to the actual flow ratio, the actual head ratio, N, can be predicted, and from this value, the actual head gain, H_t, can be determined by solving Eq. 2 for H_t.

$$H_t = \frac{NH_j}{1 + N} \tag{15}$$

This process will be demonstrated in examples which follow.

Analytical Design Procedure

The empirical graphs shown in Figures 27 and 29 can be represented by mathematical equations, allowing jet junction design to also be determined analytically. The equations which represent the curves shown in Figures 27 and 29, respectively, are:

$$N = .869e^{-1.7M} \tag{16}$$

and

$$R = .4423 - .3342M + .0631M^2 = (.665 - .251M)^2 \tag{17}$$

These two equations, along with the nozzle head loss relationship shown in Figure 28 (Eq. 13) can be manipulated to give the

analytical design equations used in the following design procedures (see Appendix 1 for the derivations).

1. For a given flow ratio, $M = Q_s/Q_j$, and jet head, H_j, the maximum head gain which can be achieved is:

$$H_t = \frac{NH_j}{1 + N} \quad , \tag{15}$$

where: $N = .869e^{1.7M}$ (16)

2. If this head gain is sufficient and desirable the required nozzle size can be calculated by:

$$d = \left(\frac{826.3Q_j^2}{H_j}\right)^{\frac{1}{4}} \quad . \tag{18}$$

3. The required mixing chamber diameter is then given by:

$$D = \frac{d}{.665 - .251M} \quad . \tag{19}$$

If less head gain is sufficient, either:

1. H_j can be reduced, appropriate d and D values can be calculated from Eqs. 18 and 19, and the resulting H_t from Eqs. 15 and 16. The minimum H_j which will still give the desired head gain, H_t, is:

$$H_j = \frac{H_t(1 + N)}{N} \quad , \tag{20}$$

where N is again calculated by Eq. 16; or

2. a non-optimal design can be chosen, allowing standardization of components. Estimating H_t under this non-optimal condition is given below.

If H_t, given by Eq. 15, is insufficient, some means must be found to increase H_j, such as direct coupling of the nozzle conveyance pipe to the tubewell. The required H_j is given

by Eq. 20, and the nozzle and mixing chamber diameters by Eqs. 18 and 19.

At any final design, the efficiency, E, of the jet junction can be estimated as:

$$E = MN \tag{3}$$

When a non-optimal area ratio is used, due to standardization of components or changes in input parameters, the operating point must be determined by an analytical duplication of the graphical technique previously described:

1. the optimum flow ratio at the actual nozzle and mixing chamber diameter is:

$$M_o = 2.65 - 3.98\ d/D \quad . \tag{21}$$

2. the head ratio, N, at the actual but non-optimum flow ratio, M, is:

$$N = (1 - 1.7\ (M - M_o)).869e^{-1.7M_o} \tag{22}$$

(This is equivalent to following a tangent from the optimum N vs. M curve (Figure 27) at the optimum flow ratio to the actual flow ratio.)

3. the head gain, H_t, for this configuration would be given by Eq. 15 utilizing N from Eq. 22.

4. the efficiency, E, would again be:

$$E = NM \quad , \text{ and} \tag{3}$$

5. the efficiency decrease, ΔE, due to the non-optimality of the solution would be:

$$\Delta E = E_o - E = (.869e^{-1.7M} - N)M \quad , \tag{23}$$

where N is calculated from Eq. 22.

Other Design Considerations

Since chamber length does not have a large or consistent affect on jet junction performance, shorter lengths can be used unless achieving maximum efficiencies is a primary goal, or if non-optimum area ratios larger than that prescribed by the flow ratio are chosen and high efficiencies are required. Chamber length should generally be no shorter than 5 times the diameter, nor longer than 10 times the diameter. Thus, for a 25.4 cm diameter pipe, the length should be at least 127 cm, but could be as much as 250 cm if high efficiencies are important. Standard, or easily manufactured pipe lengths should be chosen, such as 122 cm (4 ft.), 183 cm (6 ft.), or 244 cm (8 ft.).

Entrance and diffusor cones should have angles, α and β (defined in Figure 1), no greater than 20° and 7°, respectively. Although the referenced previous studies indicated optimum efficiencies at smaller diffusor angles, higher angles can be used efficiently with the higher surface roughness and lower Reynold's numbers of the flows in the junctions. Also, any small efficiency increase usually would not merit the extra cost of longer diffusors. The diameter at the wide end of both components should be approximately double the mixing chamber diameter so that the area is 4 times larger and the velocity head is thus 16 times smaller. This would require entrance section lengths about 1.5 times and diffusor lengths about 4 times the mixing chamber diameter. Again, standard sizes of entrance sections and diffusors should be selected to facilitate fabrication.

The nozzle should extend into the entrance section up to about one nozzle diameter away from the mixing chamber ($s/d = 1$). This spacing can vary between 20% less to 50% more ($0.8 < s/d < 1.5$) without significantly affecting junction performance.

The jet junction should be set low enough that the entrance and exit are submerged when the junction is in operation.

Two examples will illustrate the design process.

Example 1

A tubewell is to be installed near the head of a watercourse. However, the head drop, Δh, through the open flume mogha is presently only 7 cm while the upstream head on the mogha, H, is 25 cm. Since the minimum modular head, Δh_m, would be about 20% of H (Figure 22) or 5 cm, the mogha will be submerged if tubewell water is added to the watercourse. The mogha flow is measured to be 40 ℓps under free flow conditions which is close to the design flow according to Irrigation Department records of 36 ℓps. The average slope of the water surface, S, in the initial 300 m of watercourse is measured to be 0.00035 or 0.35 m/km. The roughness coefficient is estimated to be 0.035 due to the short grasses which are normally present, giving an $n/\sqrt{S}$ value of 1.87. The design flow of the tubewell is 50 ℓps which will lead to an increase in the normal flow depth in the watercourse from about 29 cm to about 45 cm, or an increase of about 16 cm. This determination, utilizing Figure 24, is shown on Figure 30.

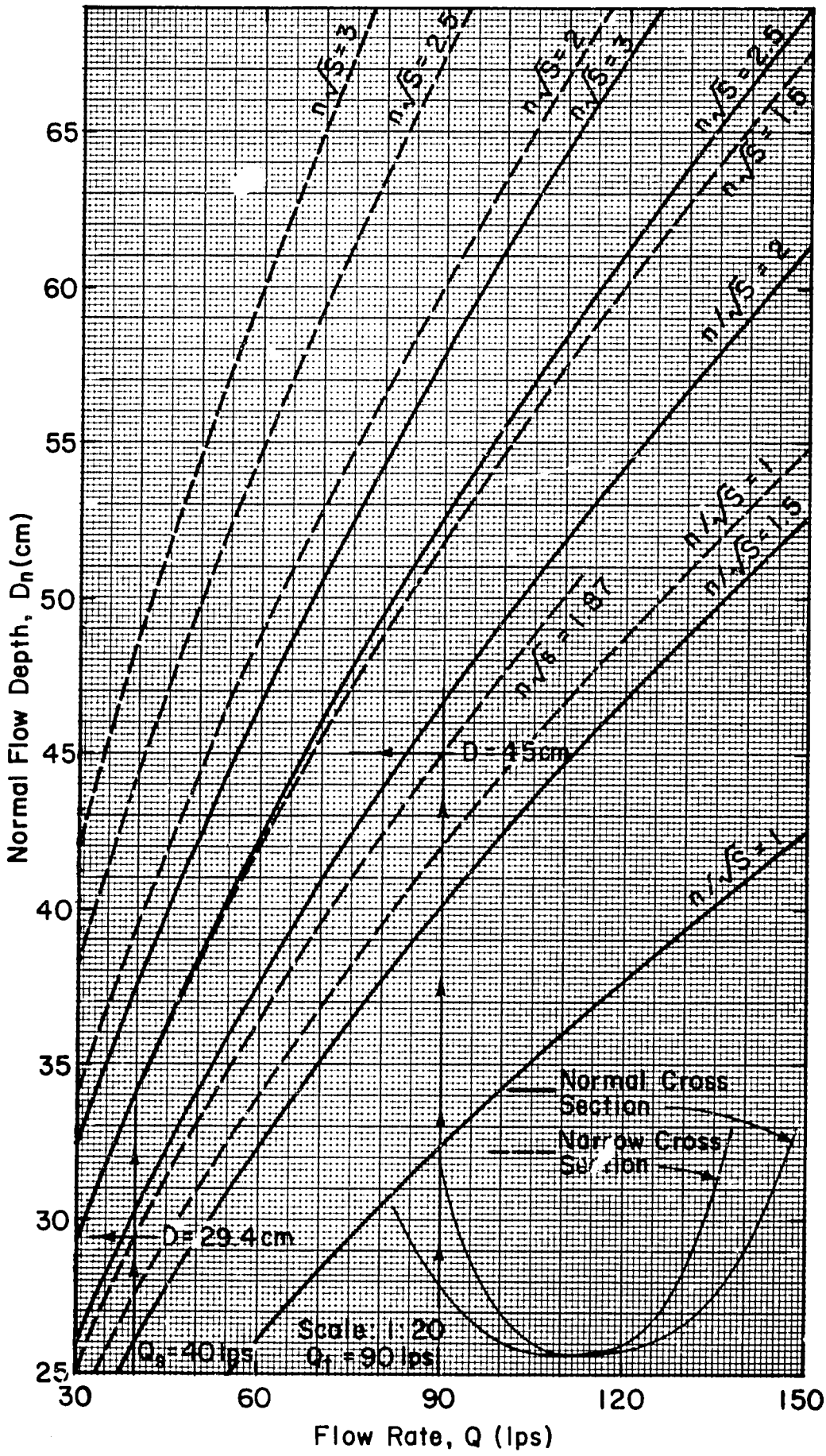


Figure 30. Determination of the normal flow depth change for Example 1 (from Fig. 24).

Assuming that a 25.4 cm diameter mixing chamber will be used, the head loss through the proposed junction when the tubewell is not operating will be about 3 cm (Figure 25) which will cause initial submergence of the mogha. Since the gate which would be required in a bypass would also cause some head loss, it is decided not to construct a bypass but to lower the existing watercourse by about 3 cm in the initial 100 meters. The elevation gain required from the jet junction, H_t, will thus be 16 cm + 3 cm or 19 cm to maintain the water level below the mogha at its present elevation, with the tubewell operating.

The tubewell is to be constructed with a fall of about 60 cm from the center of the discharge pipe into the outflow box and another fall of about 70 cm from the box into the watercourse, so a total available head, H_j, of 130 cm will be assumed. The short, 20.3 cm diameter delivery pipe is proposed to lead from the side of the outflow box to the nozzle with one 90° elbow (C_{LT} = 0.5 + 0.5 = 1.0). Figure 26 (or 28) indicates that about 12 cm of the available head will be lost in the delivery pipe, leaving 118 cm to drive the nozzle. Figure 31 illustrates this determination. Thus, the head ratio, N, is (Eq. 2):

$$N = \frac{H_t}{H_j - H_t} = \frac{19 \text{ cm}}{118 \text{ cm} - 19 \text{ cm}} = 0.192 ,$$

and the flow ratio, M, will be (Eq. 1):

$$M = \frac{Q_s}{Q_j} = \frac{40}{50} = 0.8.$$

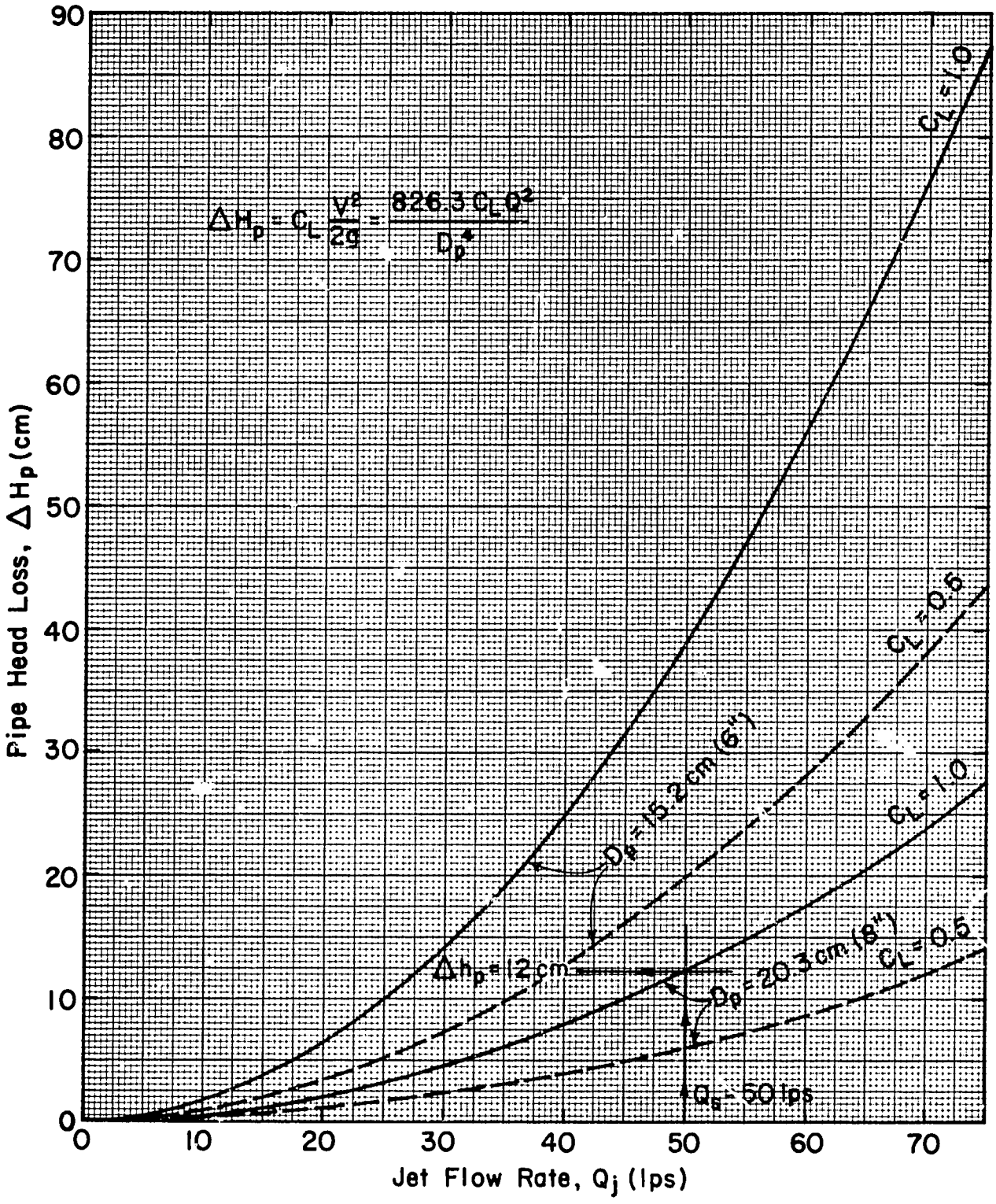


Figure 31. Conveyance pipe head loss for Example 1 (from Fig. 26).

These values cross on Figure 27 below the maximum design line (illustrated on Figure 32), showing that the desired head gain, H_t, can be achieved.

Figure 23 shows that a maximum head gain, H_t, of 22 cm could be achieved with the available jet head (illustrated on Figure 33). Achieving this maximum head, which will lower the upstream water level an additional 3 cm, would allow for a small safety factor to insure against mogha submergence. This maximum H_t could be achieved by choosing a nozzle diameter, d, to utilize all 118 cm of jet head, and a mixing chamber diameter, D, according to the required area ratio, R. These values would be:

d = 11.5 cm (from Fig. 28, illustrated in Fig. 34)

R = .217 (from Fig. 29, illustrated in Fig. 35),

and thus

$$D = \frac{d}{\sqrt{R}} = 24.7 \text{ cm.} \quad \text{(Eq. 14)}$$

If this additional 3 cm of gain were not desired, the required 19 cm gain could be achieved with an H_j of 104 cm (illustrated on Figure 33) or by using a standard mixing chamber diameter of 25.4 cm with a d value of 11.8 (Figure 35) and an H_j of 108 cm (Figure 34).

Water users on the watercourse indicated that during some periods, the mogha will flow as much as 40% above its normal flow rate. The jet junction performance should also be checked under this condition. The new flow ratio would be (Eq. 1):

$$M = \frac{40 \text{ ℓps} \times 1.40}{50} = 1.12$$

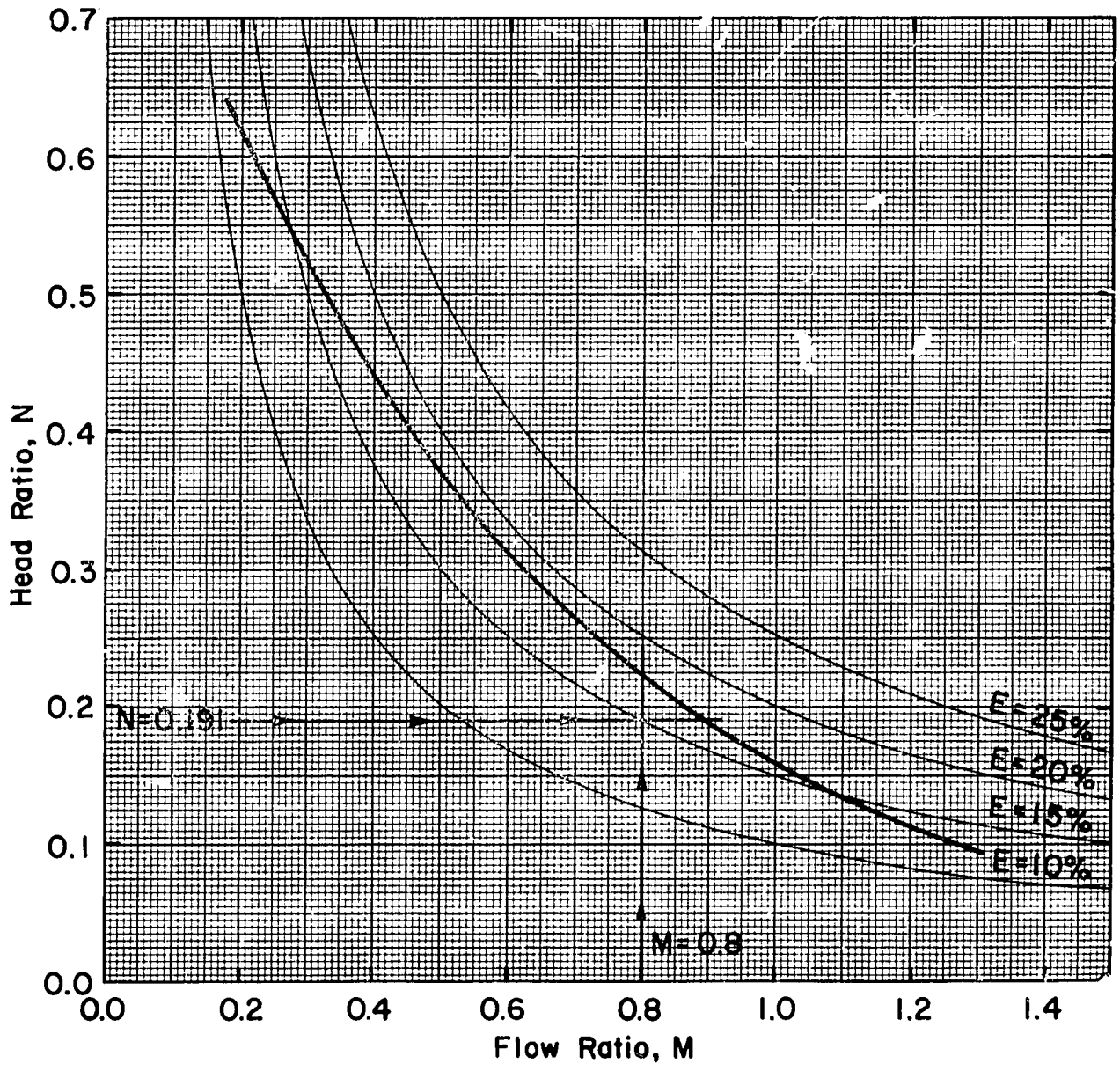


Figure 32. Illustration of the design point for the parameters in Example 1 (from Fig. 27).

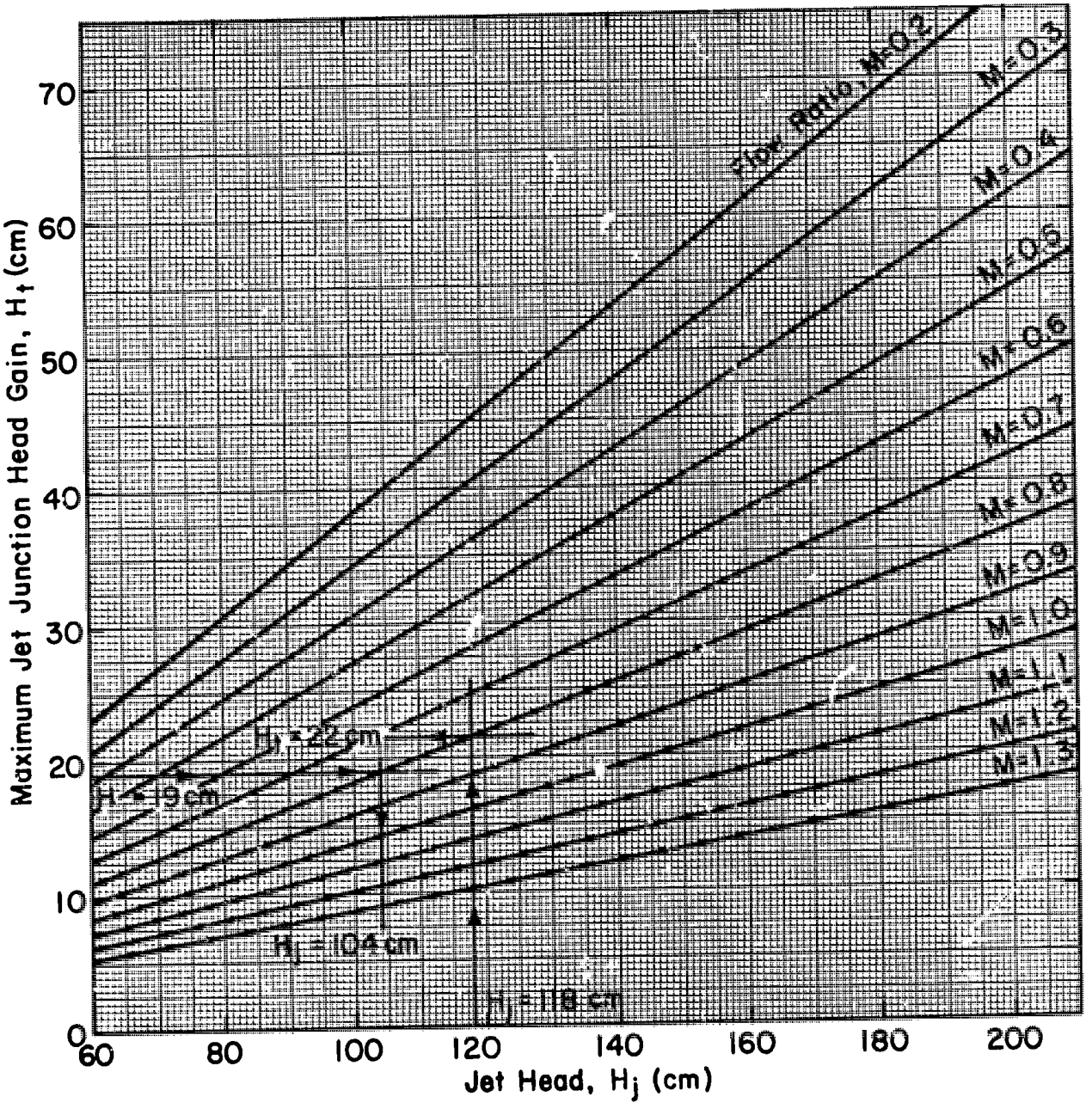


Figure 33. Illustration of the maximum possible head gain and minimum possible jet head for Example 1 (from Fig. 23)

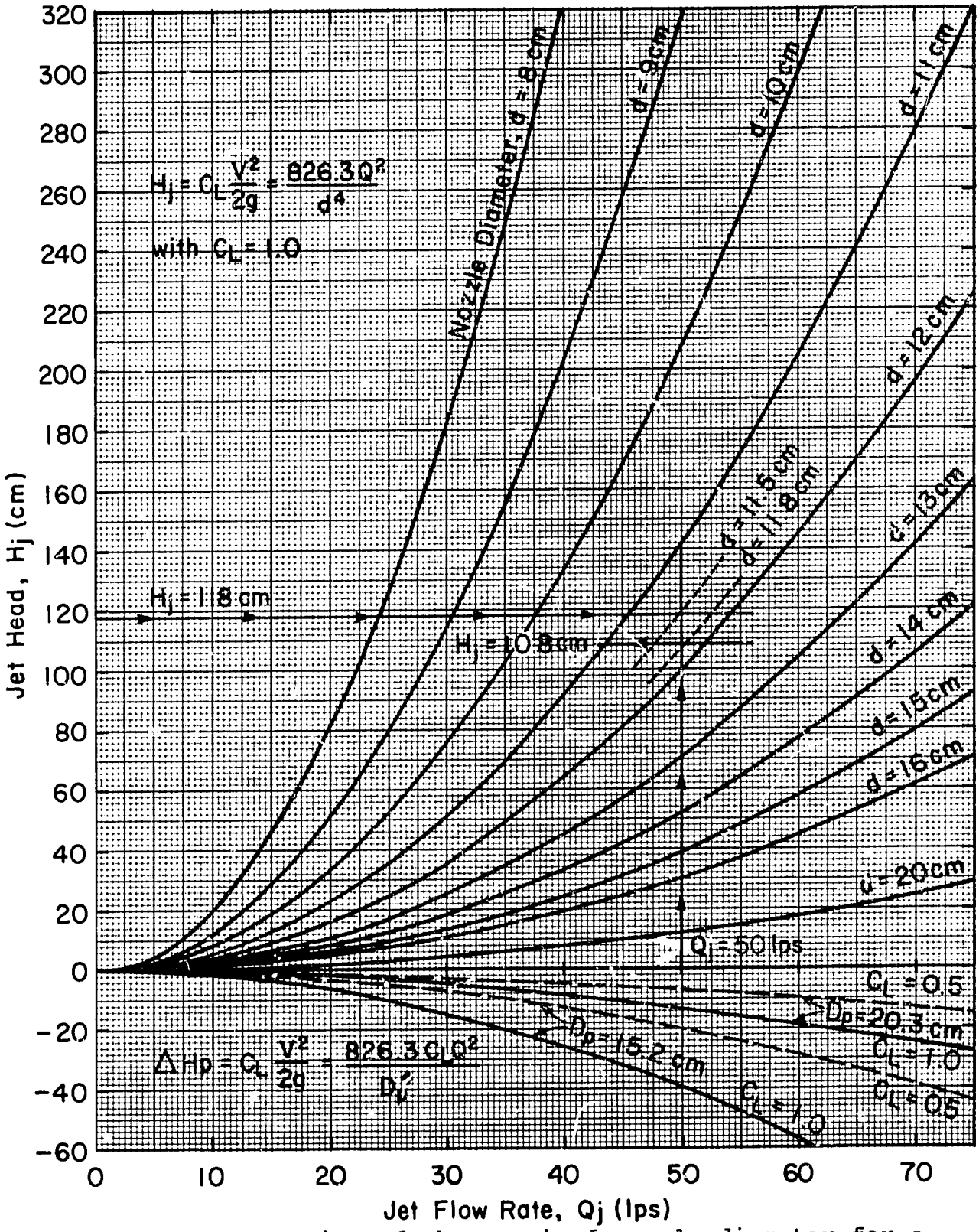


Figure 34. Illustration of the required nozzle diameter for a maximum head gain and jet head required to drive a 11.8 cm nozzle matched to a standard sized mixing chamber for Example 1 (from Fig. 28).

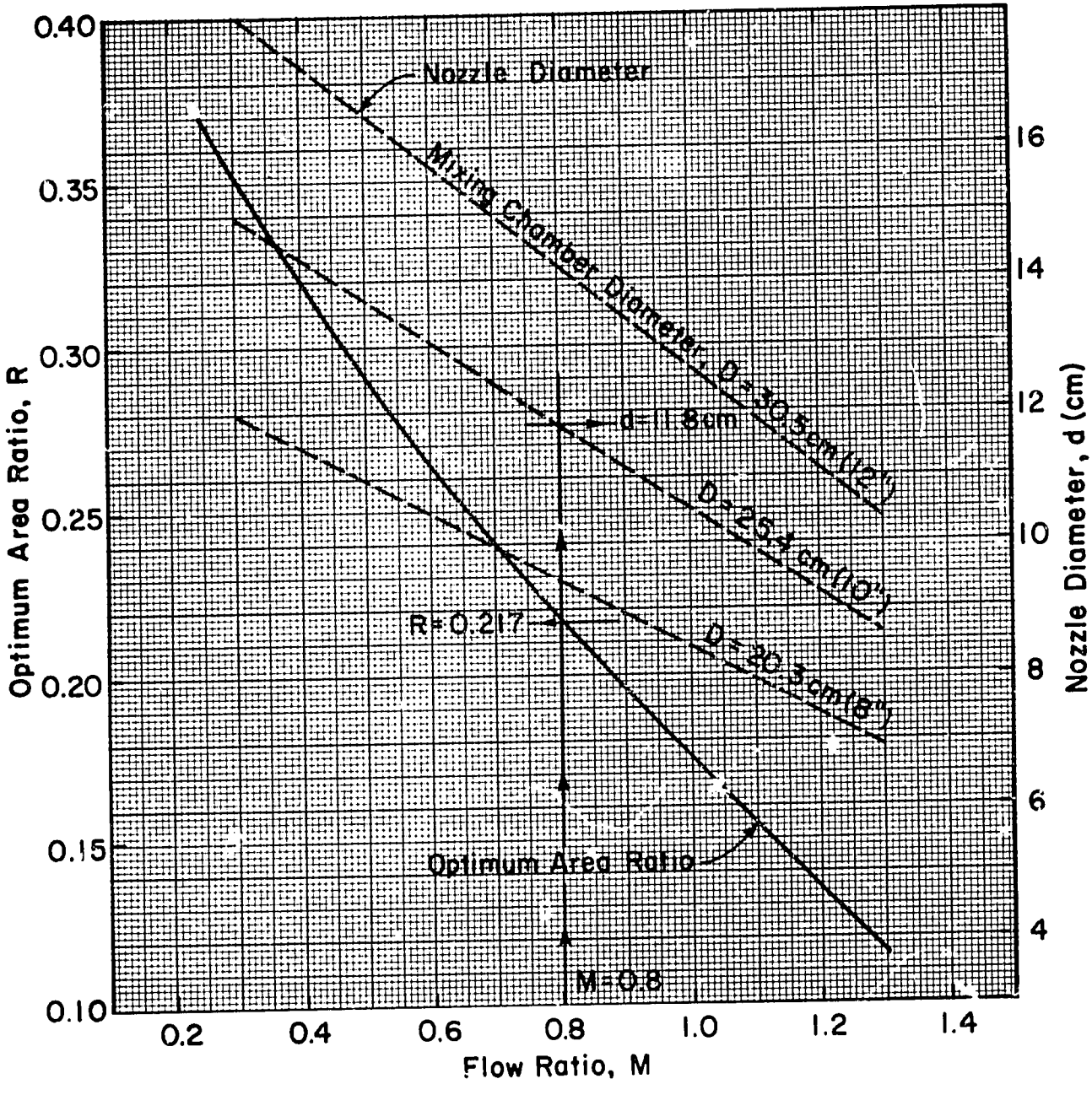


Figure 35. Illustration of the optimum area ratio and nozzle diameter for a standard 25.4 cm mixing chamber for Example 1 (from Fig. 29).

By drawing a straight line tangent to the optimal design curve (Figure 27) at the design flow ratio (0.8) to the new flow ratio (1.12), the head ratio which will be achieved under that condition can be determined. This graphical process is shown in Figure 36. The N value at M = 1.12 is about 0.10. This gives a head gain, H_t, of only:

$$H_t = \frac{NH_j}{1 + N} = \frac{0.10(108)}{1 + 0.10} = 9.8 \text{ cm} \qquad \text{(Eq. 15)}$$

The large decrease is a result both of the higher proportion of the total flow which must be lifted and the decreased jet junction efficiency (from E = 18% to E = 11%) since the design is no longer optimal. If this decrease is unacceptable, a jet junction could be designed for an intermediate mogha flow rate, Q_s. In fact, a pump could be designed for the optimum area ratio at the flow ratio of 1.12 (R = 0.135), and achieve a head ratio of 0.2 and thus a head gain at Q_s = 40 ℓps of 20 cm and a head gain at 56 ℓps (140% of 40 ℓps) of 14 cm with the available 118 cm of jet head. This second performance line is also shown on Figure 36.

Also, the 16 ℓps increase in mogha flow would result from a 6 cm increase in the head, H, on the mogha (derived from the open flume discharge equation given in Figure 22) which would allow a 5 cm increase in the water level downstream of the mogha without causing submergence. The water level below the junction would increase only 2 cm because of the combined flow increase from 90 to 106 ℓps (Figure 24). Thus, 3 cm less head gain, or H_t = 16 cm, is required from the junction at the increased flow rate.

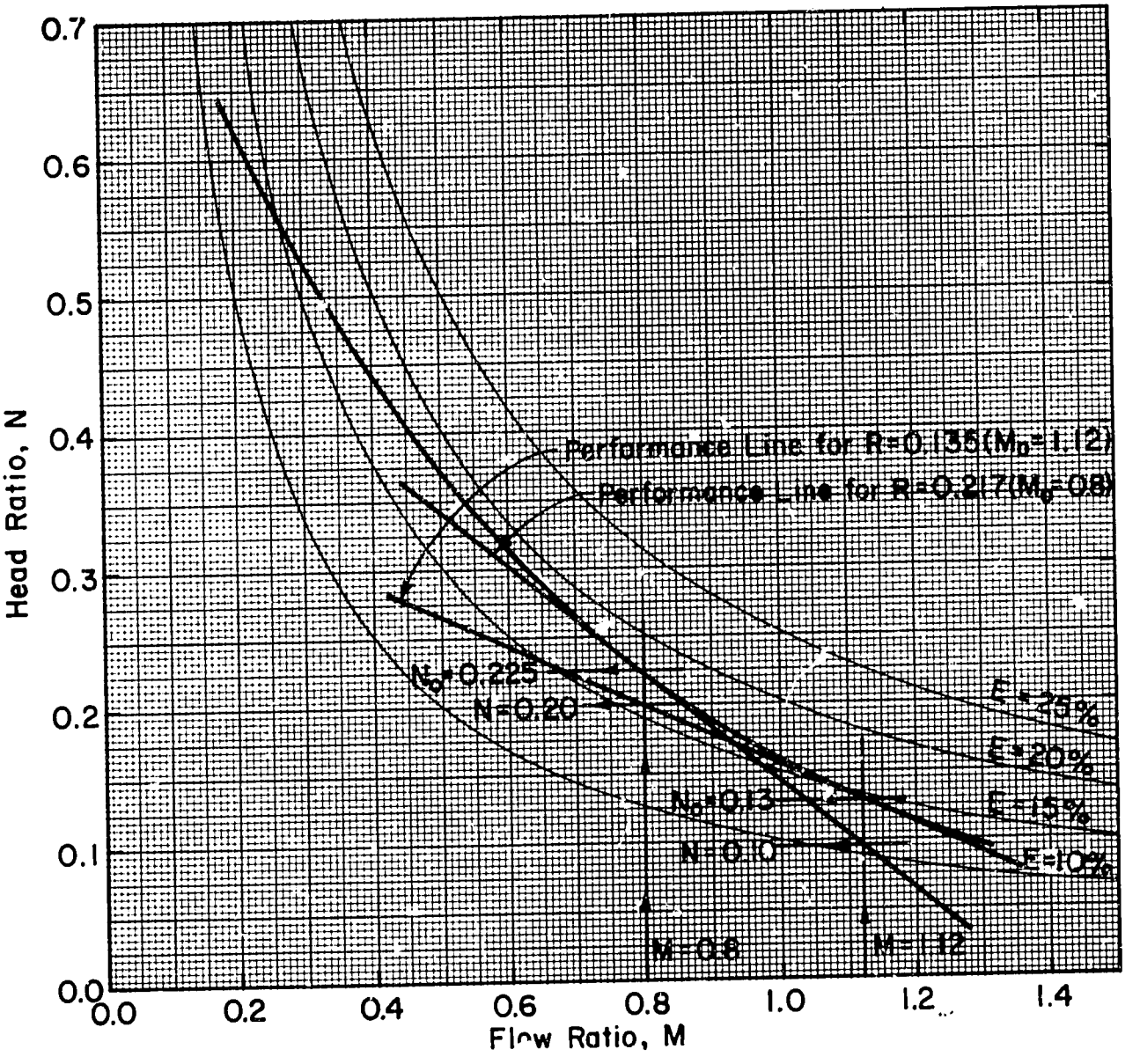


Figure 36. Two non-optimal design solutions for Example 1 (utilizing Fig. 27).

The entrance section for the jet junction should be 1.5 D or about 38 cm long (D = 25.4 cm), while the diffusor should be about 4 D or 102 cm long. Both sections should be 2 D = 51 cm in diameter at the widest part. The mixing chamber should be about 5 D or 130 cm long. The nearest standard size, 122 cm, should be used.

Example 2

A farmer, who owns a private tubewell but also uses canal water has difficulty irrigating his relatively high land with the canal water. He would thus like to install a jet junction to utilize his tubewell water to lift the canal water, rather than install a separate low lift pump. He realizes he must consequently run his tubewell whenever he receives canal water.

A survey of his fields indicates that the canal water would have to be lifted 30 cm from the main watercourse to his branch to easily irrigate all his fields. The watercourse carries about 30 ℓps to his branch, and his tubewell pumps 30 ℓps. His present discharge pipe is 160 cm above the watercourse water surface level. The head loss in the 4 meter steel delivery pipe (15 cm pipe with 1 elbow ($C_{LT} = \frac{2.0 \times 4}{15} + 0.5 = 1.03$)) would be 14 cm (Eq. 11 and Fig. 26) leaving a jet head of 146 cm.

The analytical method will be used to design his jet pump. The flow ratio is (Eq. 1):

$$M = 30 \text{ ℓps}/30 \text{ ℓps} = 1.0$$

At this flow ratio, the maximum head ratio which could be expected would be (Eq. 16):

$$N = .869e^{-1.7M} = .869e^{-1.7(1)} = 0.159 \quad .$$

Thus the maximum head which could be gained, H_t, would be (Eq. 15):

$$H_t = \frac{NH_j}{1 + N} = \frac{.159(146)}{1 + .159} = 20 \text{ cm} \ .$$

Since this is less than required, the farmer decides to attach the delivery pipe directly to the tubewell discharge pipe to allow his tubewell pump to generate the required head. The required jet head would be (Eq. 20):

$$H_j = \frac{H_t(1 + N)}{N} = \frac{30(1 + .159)}{.159} = 219 \text{ cm}$$

A valve, manometer tube, and flow measuring device were attached to his tubewell discharge to determine that, at the 73 cm (219-146 cm) of increased head required, the tubewell flow decreased to 28 ℓps. This could also have been estimated by equating the percent increase in total pumping head (assuming 10 m total lift):

$$\frac{0.73 \text{ m}}{10 \text{ m total lift}} = 0.073 = 7.3\% \ ,$$

with the projected percent decrease in flow rate:

30 ℓps x 0.073 = 2.2 ℓps.

The pump was operating near the peak of its efficiency curve, and the energy usage changed very little. This farmer decides the loss of 2 ℓps of tubewell water is worth the extra 10 cm of lift of the canal water. He also decides:

1. to install a bypass for his tubewell water so that he does not lose the 2 ℓps when he does not use the jet junction, and

2. learning a lesson from the affect of head on pump flow rate, to discharge his bypass directly into his branch watercourse at the water surface and thus reduce his pumping head by about 140 cm or 14% and increase his tubewell flow rate by a comparable amount.

Under these new flow conditions, the flow ratio would be:

$$M = 30/28 = 1.07 \ ,$$

the maximum head ratio would be:

$$N = .869e^{-1.7(1.07)} = 0.141 \ ,$$

and the required jet head would be:

$$H_j = \frac{H_t(N + 1)}{N} = \frac{30(.141 + 1)}{0.141} = 243 \text{ cm.}$$

This further increased head requirement, due to the decreased flow rate, will cause Q_j to decrease by one more liter per second, to 27 ℓps, so:

$$M = 30/27 = 1.11$$

$$N = .869e^{-1.7(1.11)} = 0.132$$

$$H_j = \frac{30(1 + .132)}{.132} = 260 \text{ cm}$$

The further decrease in Q_j is small enough to be ignored.

The nozzle which would be driven at 27 ℓps under 260 cm of head would be (Eq. 18):

$$d = \left(\frac{826.3\ Q_j^2}{H_j}\right)^{\frac{1}{4}} = \left(\frac{826.3(27)^2}{260}\right)^{\frac{1}{4}} = 6.9 \text{ cm}$$

The mixing chamber diameter, D, which will give the proper area ratio for the flow ratio is (Eq. 19):

$$D = \frac{d}{.665 - .251M} = \frac{6.9}{.665 - .251(1.11)} = 17.9 \text{ cm} .$$

Since this size is not readily available, a 20.3 cm diameter is chosen. This combination would result in an area ratio which would be optimal at a flow ratio, M_o, of (Eq. 21):

$$M_o = 2.65 - 3.98 \frac{d}{D} = 2.65 - 3.98 \left(\frac{6.9}{20.3}\right) = 1.30 .$$

The resulting head ratio at the actual flow ratio of 1.11 is (Eq. 22):

$$N = (1-1.7(M-M_o)).869e^{-1.7M_o} = (1-1.7(1.11-1.30)).869e^{-1.7(1.3)}$$
$$= .126 .$$

The actual head gain at this head ratio would be (Eq. 15):

$$H_t = \frac{NH_j}{1 + N} = \frac{.126(260)}{1 + .126} = 29 \text{ cm} ,$$

which is judged acceptable.

The other design parameters will now be:

1. mixing chamber length: $L = 8D = 8(20.3) = 162$ cm. A 182 cm (6') pipe will be used. The longer length is because of the high efficiencies desired.
2. entrance section length = $1.5\ D = 1.5(20.3) = 30$ cm
3. diffusor length = $4D = 4(20.3) = 81$ cm
4. entrance and exit diameter = $2D = 2(20.3) = 40.3$ cm

SECTION V

JET JUNCTION FABRICATION AND INSTALLATION

A jet junction consists of three primary components:

1. a conveyance line from the tubewell to the junction, including the nozzle;
2. the junction jet pump entrance section, mixing chamber, and diffusor; and
3. a structure to support the jet pump and prevent erosion.

Examples of these parts are shown in Figures 5, 6 and 7.

The conveyance line can be constructed of concrete, plastic (PVC) or steel pipe. Because of the wall thickness of concrete pipe, it may restrict the canal water flow if allowed to extend too far into the jet pump entrance section. Because of the high cost of both PVC and steel pipe, the delivery line should be made as short as possible. A practical method of minimizing this pipe length is to move the watercourse and junction adjacent to the tubewell discharge pipe or box, as was done in the installation shown in Figure 7. The use of steel or PVC pipe can also be minimized by conveying the water to the edge of the watercourse in buried concrete pipe and using the more expensive pipe for only the last section. By redirecting the watercourse to flow away from the discharge pipe or box, an elbow can be saved, reducing both the cost and head loss. By directing a short straight pipe directly out of the outflow box at the proper elevation (Fig. 7), all elbows can be eliminated.

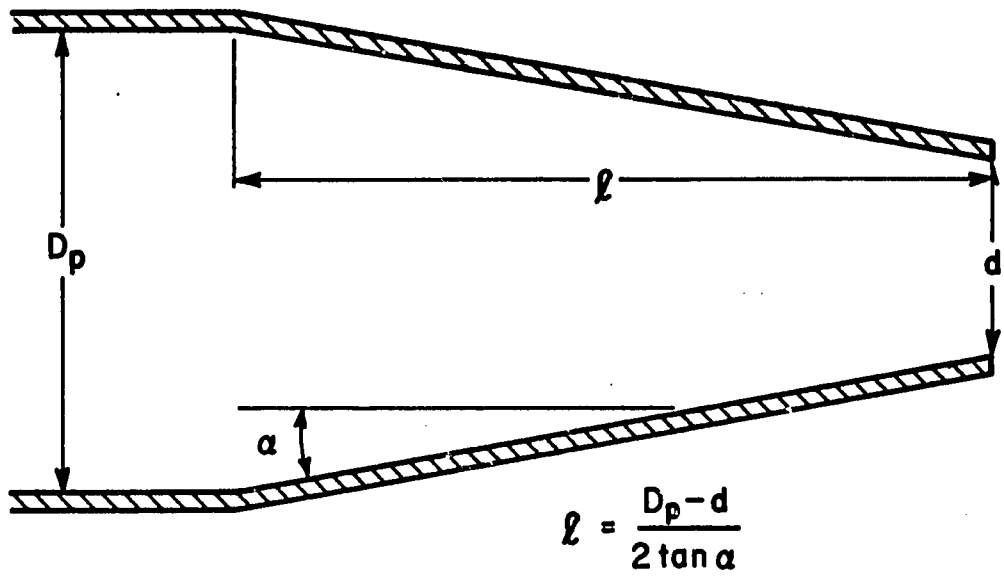
Pipe diameters chosen will depend upon the flow rate and allowable head loss (Fig. 26).

If the existing outflow box is used, the sides should be raised above the required jet head elevation and the outflow closed or gated. The jet delivery pipe should be flush with the inside wall of the box to reduce losses. Rounding the edge of the entrance will further reduce the loss coefficient and consequent head loss.

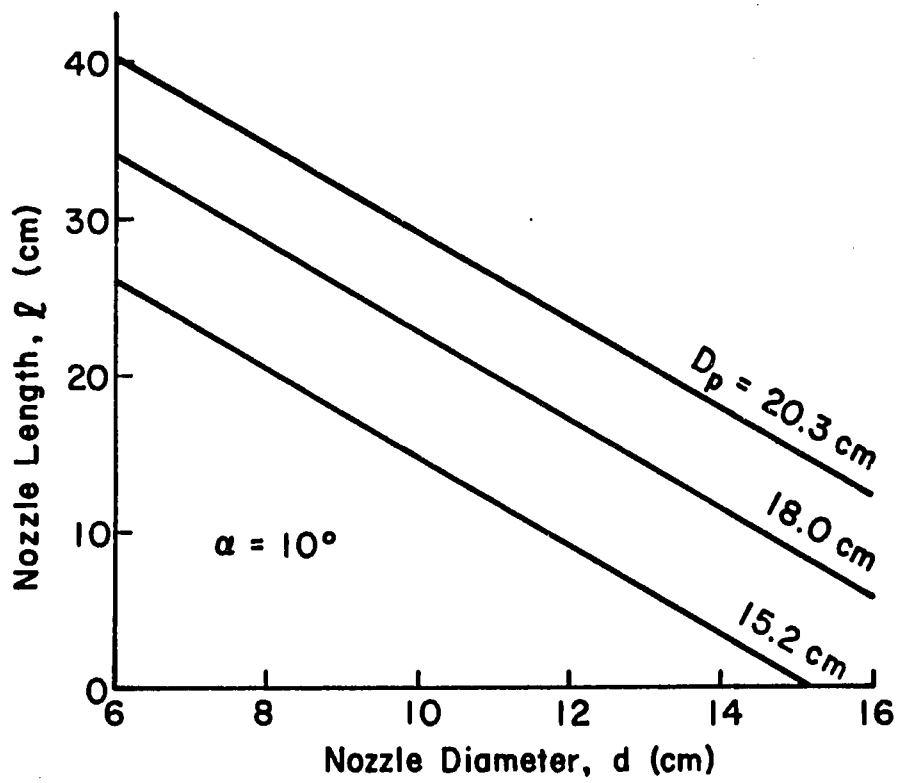
A jet pump bypass for the tubewell water will be desirable if the required head, H_j, is larger than the excess available head. This can be easily accomplished with an outflow box by installing an opening and gate in the box. In a directly connected system, since large valves are expensive, more practical alternatives might be to make it easy to remove the nozzle, the discharge line, or a cap from a tee in the line.

Nozzles can be most easily manufactured from sheet or plate metal wrapped in a conical shape and welded. The nozzle could be welded or bolted to the delivery line. The cone angle of the nozzle has little effect on the nozzle loss coefficient and is thus not too important. Half angles of 10° are suggested. Nozzle fabrication could be standardized by making all nozzles with a fairly small outlet diameter (such as 7 cm) and cutting them off at the length which gives the diameter, d, required for each individual installation. Figure 37 shows a suggested nozzle design and the relationship between the design parameters.

The entrance section and diffusor can be fabricated most inexpensively from concrete. Initial fabrications were made



a. Schematic of Nozzle



b. Design Curves for α = 10°

Figure 37. Jet nozzle design.

in concrete pipe spin molds by simply increasing the pipe wall thickness toward the narrow end (Figure 6). Although this technique simplifies the production process, the material costs increase and the handling becomes very difficult due to the large volume of concrete involved. Utilizing a conically shaped mold is recommended. This could be a static mold, or, especially for the longer diffusor, a spin mold. The molds could be made with removable inserts of various sizes for the narrow end which would allow the same mold to be used for several mixing chamber diameters.

Since a well supported and protected junction jet pump requires little internal strength, reinforcement requirements, wall thicknesses, and concrete mixes will be determined by transportation and handling methods and installation techniques. A lip or some other allowance should be made for easy attachment of the sections to the mixing chamber. This attachment point must be smooth on the inner surface. Rounding this joint would lead to slightly higher efficiencies. The inner surface should be as smooth as possible to reduce friction losses. Attachment points can be constructed into the entrance section to anchor braces which hold the nozzle in place.

The mixing chamber can be easily manufactured from concrete pipe. Pipes of various lengths can be made from one mold with the use of movable inserts in the mold. As with the entrance section and diffusor, material and reinforcement requirements will be determined from experience. The inside

surface should be as smooth as possible. Also, the fabrication should provide easy attachment to the inlet and diffusor sections.

Because of the total length of the jet junction, some type of stabilizing support will be required. This foundation or cradle could be made from concrete or masonry, depending on relative material costs. Cutoff walls at the entrance and exit will protect these exposed sections and prevent piping or erosion. The junction can then be covered with soil for protection and used as a culvert to pass over the watercourse. As stated previously, the junction must be set so that the top of the entrance section is below the upstream water surface.

The layout of the jet junctions will depend upon each existing situation. As a general guideline, it is generally less costly to move a watercourse than to convey tubewell water under pressure, so the watercourse should usually be relocated near the tubewell outlet. Also, less head loss is involved in changing the direction, even quite abruptly, of water moving at a slow velocity in a watercourse, than of higher velocity water in a pipeline. Consequently, the watercourse should generally be redirected in line with the nozzle conveyance pipe rather than installing numerous elbows in the conveyance line. Figure 38 shows one possible layout which utilizes these principles. Figure 7 shows a cross section for such a layout.

If a bypass around a junction is constructed for the canal water, the bypass will need a check gate or nucca in

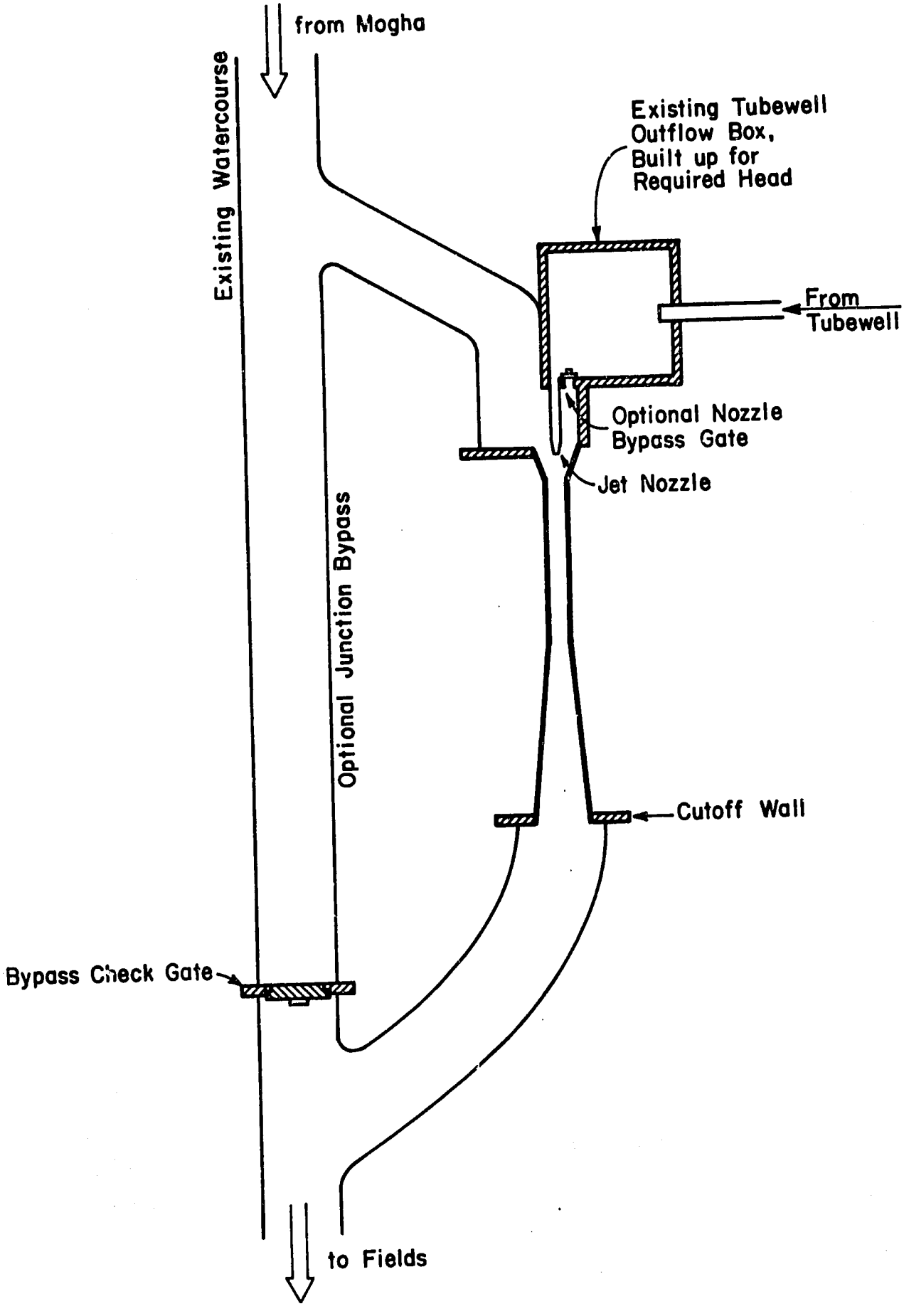


Figure 38. One suggested jet junction layout.

the bypass facing downstream so that the raised water level downstream does not recirculate through the bypass (Figure 38). When the tubewell is off and the check is open, the canal water will seek the path of lowest resistance and will thus flow both through the junction and the bypass, lowering the overall head loss at the junction. If tubewell water is sometimes used without the canal flowing and the junction is some distance from the mogha, a check gate may also be desirable upstream from the junction that would face downstream to prevent tubewell water from filling the upstream watercourse channel.

Sometimes SCARP tubewells are built to serve two watercourses. The flow is divided proportionally with some type of critical flow division box. Adapting jet junctions to divided tubewell flow will be more difficult, because:

1. the equitable division of the water requires several centimeters of fall or head loss, wasting part of the available jet head, and
2. the watercourses are generally some distance apart requiring that the tubewell water be carried, under pressure, to at least one of the watercourses.

The flows could be proportionally divided with the use of two free flowing weirs which flow from the main outflow box into two attached boxes--one for each watercourse. The sides of the boxes must of course be raised sufficiently to create the required jet head. The weirs must be set high enough that both flow freely. They must be located such that

turbulence from the tubewell discharge is minimal or at least affects both similarly.

The width and bottom elevation of each weir must be set to give the proper proportional flow at the measured tubewell flow rate. The easiest method is to set both weir bottoms at the same elevation and vary the weir widths proportional to the desired flow division. For example, if 60% of the flow is to go to one watercourse, then the width of its weir should be 50% (60%/40% = 150%) wider than the width of the other weir. This method will give exact results for Cipolletti and suppressed rectangular weirs and will be within ±2% for contracted rectangular weirs if the overflow depth is less than 1/5 the width. The weirs can be either sharp or broad crested as long as the shape of the crest is the same for both. Wider weirs are recommended because they require less head loss.

The water can be conveyed to a distant watercourse jet junction through buried concrete or plastic pipe. The head losses in this pipe must be added to the form losses shown in Figure 25 to derive the total conveyance head loss. The loss coefficient, C_L, for friction losses can be calculated with Eq. 11. Often, the weir loss plus the pipe friction losses will dissipate most of the available excess energy from the tubewell, making a jet junction located more than 50 meters from the tubewell impractical. Of course, if the water is divided properly, a jet junction could be installed on only the nearby watercourse.

SECTION VI

ECONOMICS OF JET JUNCTIONS

The Benefits

Watercourse junction jet pumps lift canal water to a higher level to facilitate irrigation of higher fields and/or allow otherwise submerged moghas to flow freely and at the design flow rate. In an irrigated basin such as the Indus Basin where water is in shorter supply than culturable land, lifting water to irrigate difficult to serve land which could otherwise be redistributed to lower lands, has little economic value. Jet junctions create no new water--they only redistribute it.

However, assuming that bringing an irrigation system closer to its original designed distribution will improve its efficiency, some improved usage (higher water use efficiency) of the water might occur, from which an economic benefit equal to the value of the resulting increased crop production, would be derived. In the Indus Basin, this benefit will probably be small, and would be very difficult to evaluate.

Raising the water to a higher elevation will allow easier and more efficient utilization of the water on higher lands. It can be conveyed more quickly in smaller channels with less loss and managed more easily at the field. But, the same efficiency increase could also be derived from redistributing the water to lower, easier to irrigate, land.

However, for an established farmer in an established irrigated area, great benefit can be derived from the lift

given by a jet junction. He gets his full flow and/or more easily and efficiently irrigates his land. If maintaining, or improving the lot of established farmers is important, a benefit is derived. By serving his needs, the government or its agent also gains favor in the farmers' eyes.

An additional benefit which can be derived on many SCARP tubewell supplemented watercourses, is improving the quality of the irrigation water. Much groundwater is of sufficiently low quality (due to dissolved salts) that it is difficult for the farmers to use. Consequently, the SCARP tubewell water was designed to be mixed with the good quality surface water supplies to improve the overall quality of the water being applied onto croplands. On watercourses with submerged moghas the full canal supply is not available and the designed mixing does not occur, forcing farmers to use lower quality water. Jet junctions in these cases can result in improved irrigation water quality.

As this discussion indicates, the benefits derived by an economy from jet junctions are difficult to evaluate because they are primarily indirect and often involve value judgments. The final decision by a government agency whether or not to install jet junctures should consequently be made for "site specific" situations wherein the benefits can easily be discerned.

The Costs

A jet junction utilizes water at a higher elevation to lift canal water from a lower elevation to an intermediate

level. In the case of a tubewell source, the pumped water is discharged at an elevation above the water level in the watercourse. This excess pumping required energy, and the additional power requirement costs excess money. Therefore, there is an energy cost associated with jet junctions. What has been called excess available energy is excess only because the tubewell water was discharged at an elevation higher than was necessary. The energy cost could be saved by discharging the tubewell at the elevation of the watercourse water surface. This can be accomplished by attaching pipe to the existing pump discharge pipe that would have its discharge end located below the water level in the watercourse. Consequently, if all design alternatives are considered, the excess energy cost must be charged to the jet junction.

Well designed low head jet junctions are only about 20% efficient. Only 20% of the power derived from the excess head of the tubewell water is utilized. When this jet pump efficiency is multiplied times the tubewell pumping plant efficiency of probably around 60%, the overall energy usage efficiency of the excess power is only about 12%.

The alternative means of lifting the canal water would be to use a low lift propeller pump. These pumps can be inexpensively manufactured locally. Since the pump could be located near the tubewell, it could be driven by a small (1 horsepower) electric motor. Total capital cost would be comparable to that of the jet junctions. The low tolerance and simple pumps and the electric motors would also have low

maintenance costs. An efficiency for these pumping plants above 30% certainly should be obtainable. This implies that the actual energy cost, per unit water pumped, would be less than half that of the junction jet pump. Also, the mechanical pump offers the added flexibility of various locations (constrained by energy availability), lifts, and operating times, rather than needing to operate conjunctively at the tubewell location.

However, from the viewpoint of the farmer, the tubewell is there, and the excess energy from the tubewell water does exist, and will probably continue to exist, so there really is no extra cost to the irrigators in utilizing it. No alternative can compete with a jet junction having free power available. Determining the energy costs, like the benefits, depends on the viewpoint--the selected farmers benefiting from the structure, all farmers, or the government.

The capital cost of a jet junction will depend upon the conditions and layout. The two initial field installations cost Rs 12,000 and Rs 1000 (US $1200 and $100) for materials (1978/79 prices). This latter figure should be attainable for well designed systems with standardized parts. Design and construction supervision and labor costs would raise the total cost to about $150 per installation. Considering that there are practically no repair or maintenance costs associated with jet pumps because there are no moving parts, the capital and maintenance costs of jet junctions is low, compared to any other means of lifting the water.

The use of jet junctions on purely economic grounds is difficult to justify when all aternatives are considered. However, if a decision is made to lift the canal water on a watercourse, and a tubewell does exist which has excess available head, a jet junction is the most efficient way to accomplish the task.

SECTION VII

CONCLUSIONS

1. Jet junctions are a viable means of utilizing excess energy from tubewell water to raise canal water.
2. The most critical factor in jet pump performance is the area ratio, R = nozzle area/mixing chamber area. The optimum area ratio is related to the flow ratio, $M = Q_s/Q_j$.
3. Jet junction performance is not too sensitive to flow ratio if the proper area ratio is used.
4. A diffusor approximately doubles the efficiency of jet junctions.
5. Jet junction performance increases slightly with mixing chamber lengths in the range of 4 to 9 times the diameter, especially for area ratios less than the optimum.
6. The primary difference between high and low head jet pumps appears to be that optimum velocity ratios, V_s/V_j, are reduced by about 50% for low head jet pumps.
7. The economics of jet junctions depend upon the viewpoint from which benefits are calculated and the assumption of a free energy source to the beneficiaries.

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APPENDIX A

Development of Jet Junction Analytical Design Equations

By the definition of head ratio:

$$N = \frac{H_t}{H_j - H_t} \quad , \quad (H_s = 0) \tag{3}$$

Solving Eq. 3 for H_t:

$$H_t = \frac{H_j N}{1 + N} \tag{15}$$

Solving for H_j:

$$H_j = \frac{H_t (1 + N)}{H_j} \tag{20}$$

An analytical relationship between M and N can be derived by linear regression techniques on the transformed empirical relationship shown in Figure 27. The resulting best fit equation is:

$$N = .869e^{-1.7M} \tag{16}$$

$$r^2 = .992$$

where r^2 is the coefficient of determination. The theoretical relationship between H_j and Q_j, shown graphically in Figure 29 is:

$$H_j = \frac{826.3Q_j^2}{d^4} \quad , \quad (C_L = 1) \tag{14}$$

Solving for d:

$$d = \left(\frac{826.3Q_j^2}{H_j}\right)^{1/4} \tag{18}$$

The optimum nozzle diameter, d, which will give the N:M relationship in Eq. 16 can be determined from the empirical

R vs. M relationships shown in Figure 29. The d vs. M relationships plot as straight lines (indicating the R vs. M curve is a 2nd degree polynomial):

$$d = (.665 - .251M)D \tag{A-1}$$

When these equations are combined, the optimum H_t can be determined directly from the flow rates, Q_s and Q_j. The required jet head and nozzle diameter is also given.

Often, the required jet head, H_j, is not available, or the optimum nozzle diameter, d, is not preferable. The flow ratio, M, however is usually fixed. In these cases, a non-optimal solution must be chosen which will result in decreased jet junction efficiencies. If a non-optimal jet head is chosen, the nozzle diameter required to pass the flow at that H_j is calculated by Eq. 18. The optimum flow ratio M_o for this nozzle diameter, or any arbitrarily chosen diameter, is determined by solving Eq. A-1 for M:

$$M_o = 2.65 - 3.98 \frac{d}{D} \tag{21}$$

Since this solution is non-optimal, a head value less than that predicted by Eq. 16 will result.

The experimental results indicated that jet pump data collected for a given area ratio exhibited a linear relationship between N and M which is tangent to the optimum N:M design curve at the optimum area ratio. Therefore, by following a tangent from the optimum flow ratio, M_o, at the chosen nozzle diameter (or area ratio) to the actual flow ratio, the actual N value can be determined. This process is shown analytically in Figure A-1, and can be duplicated

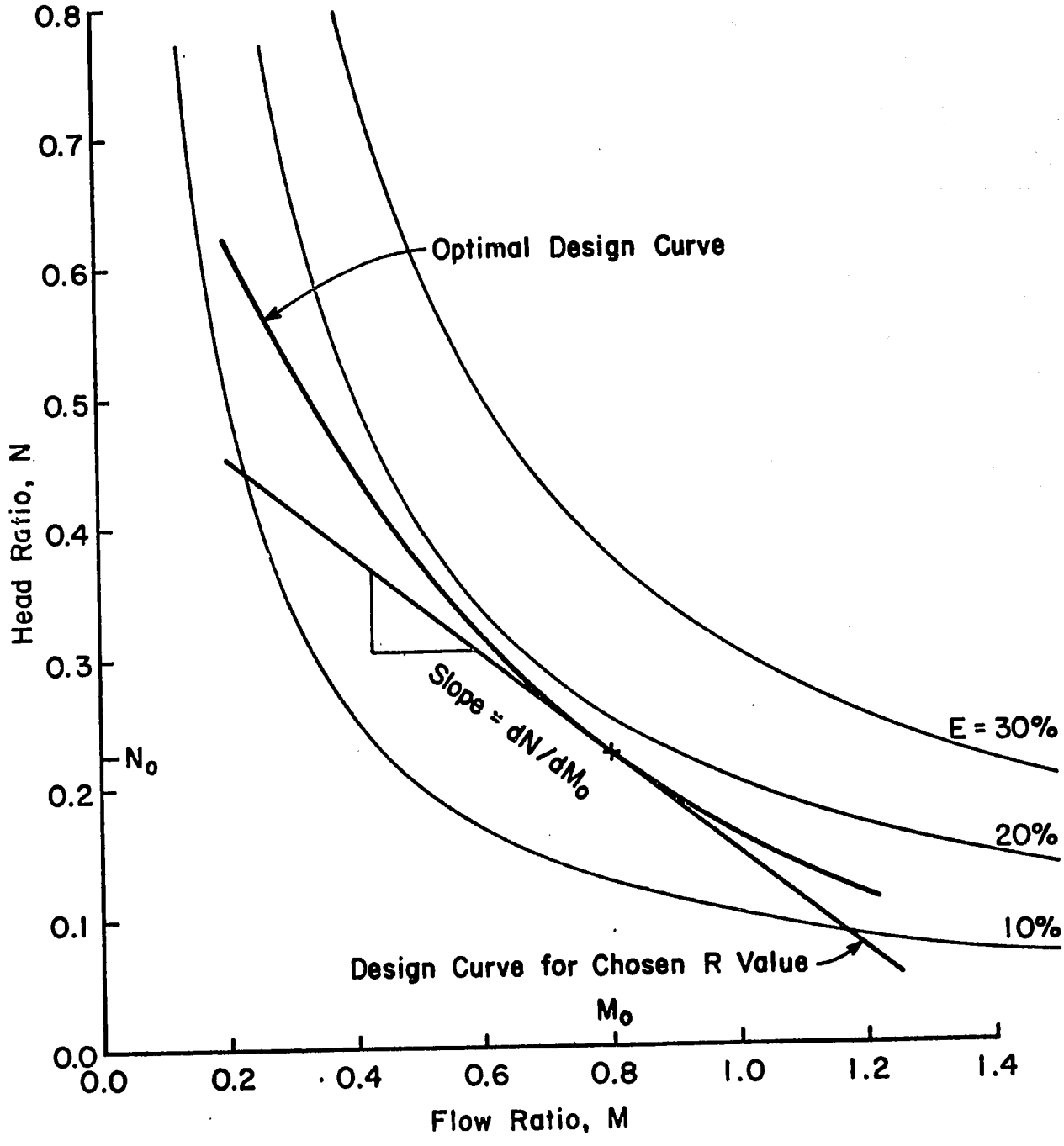

Figure A-1. Graphical depiction of the non-optimal solution technique.

mathematically utilizing the optimum head ratio value, N_o at M_o, given by Eq. 16, and the slope of Eq. 16 at M_o given by its first derivative at that point, as shown below.

$$N_o = .869e^{-1.7M_o} \tag{16}$$

$$\text{Slope} = \frac{dN}{dM} = (-1.7).869e^{-1.7M_o}$$

So:

$$N = N_o + (M - M_o)\frac{dN}{dM} =$$

$$.869e^{-1.7M_o} + (M - M_o)(-1.7)(.869e^{-1.7M_o})$$

or:

$$N = (1 - 1.7(M - M_o)).869e^{-1.7M_o} \tag{22}$$

Once the N value is determined, the actual head gain, H_t, can be calculated by Eq. 15.

APPENDIX B

Table A-1. Laboratory jet junction prototype data.

	Qs (lps)	Ht (cm)	Qj (lps)	Hj (cm)	M	N	E (%)	Dad[1] (cm)	L (cm)	Diff[2] (Y/N)
1	17.0	50.3	64.5	156.8	0.264	0.473	12.5	5.0	112	1
2	20.8	48.2	64.5	155.8	0.322	0.448	14.4	5.0	112	1
3	25.2	44.4	64.5	157.5	0.452	0.392	17.7	5.0	112	1
4	33.6	42.6	64.5	154.6	0.521	0.380	19.6	5.0	112	1
5	42.8	36.3	64.5	152.2	0.661	0.313	20.7	5.0	112	1
6	54.5	26.1	64.5	151.0	0.845	0.209	17.7	5.0	112	1
7	56.6	22.8	64.5	149.0	0.979	0.181	15.9	5.0	112	1
8	67.7	14.1	64.5	149.5	1.050	0.104	10.9	5.0	112	1
9	72.2	7.3	64.5	148.0	1.120	0.052	5.8	5.0	112	1
10	82.2	1.9	64.5	147.3	1.276	0.013	1.7	5.0	112	1
11	9.3	38.8	54.5	112.8	0.169	0.524	8.8	5.0	112	1
12	15.6	37.1	54.5	110.9	0.287	0.502	14.4	5.0	112	1
13	21.8	34.5	54.5	112.4	0.399	0.443	17.7	5.0	112	1
14	32.1	30.6	54.5	112.6	0.589	0.373	22.0	5.0	112	1
15	36.7	26.8	54.5	111.1	0.666	0.318	21.2	5.0	112	1
16	43.9	20.9	54.5	109.8	0.806	0.235	18.9	5.0	112	1
17	52.4	14.7	54.5	108.5	0.962	0.157	15.1	5.0	112	1
18	59.5	10.4	54.5	107.9	1.092	0.107	11.7	5.0	112	1
19	69.6	3.2	54.5	106.5	1.278	0.031	4.0	5.0	112	1
20	76.2	0.2	54.5	107.8	1.399	0.002	0.2	5.0	112	1
21	81.9	0.0	54.5	0.0	1.502	-0.001	-0.2	5.0	112	1
22	15.6	32.0	48.7	90.0	0.139	0.550	[illegible]	5.0	112	1
23	25.9	29.5	48.7	90.5	0.326	0.484	15.[illegible]	5.0	112	1
24	23.4	26.3	48.7	89.7	0.479	0.414	17.8	5.0	112	1
25	30.9	22.3	48.7	89.1	0.633	0.333	21.1	5.0	112	1
26	37.6	18.0	48.7	88.5	0.776	0.255	19.8	5.0	112	1
27	44.6	13.5	48.7	87.9	0.915	0.182	16.7	5.0	112	1
28	50.3	9.5	48.7	87.9	1.032	0.122	12.6	5.0	112	1
29	61.3	1.9	48.7	86.4	1.259	0.022	2.8	5.0	112	1
30	68.7	0.0	48.7	0.0	1.405	-0.001	-0.1	5.0	112	1
31	15.5	18.6	39.8	60.7	0.387	0.442	17.1	5.0	112	1
32	22.6	15.8	39.8	60.4	0.567	0.355	20.1	5.0	112	1
33	32.6	11.3	39.8	56.4	0.820	0.249	20.4	5.0	112	1
34	41.0	6.8	39.8	59.9	1.031	0.128	13.2	5.0	112	1
35	51.0	1.6	39.8	58.8	1.282	0.031	4.0	5.0	112	1
36	59.1	0.0	39.8	0.0	1.486	-0.001	-0.1	5.0	112	1
37	[illegible]	13.2	32.4	39.8	0.244	0.497	12.1	5.0	112	1
38	15.[illegible]	11.3	32.4	39.3	0.476	0.405	19.3	5.0	112	1
39	21.6	9.1	32.4	39.0	0.672	0.305	20.5	5.0	112	1
40	30.6	5.4	32.4	37.9	0.945	0.167	15.8	5.0	112	1
41	38.4	2.0	32.4	37.3	1.188	0.058	6.9	5.0	112	1
42	45.9	0.0	32.4	0.0	1.418	-0.001	-0.1	5.0	112	1
43	45.6	3.8	37.6	116.8	1.213	0.034	4.1	5.0	112	1
44	22.8	50.0	66.0	162.2	0.346	0.446	15.4	5.0	112	1
45	30.6	46.5	66.0	162.4	0.464	0.401	18.6	5.0	112	1
46	36.3	40.3	66.0	159.7	0.550	0.338	18.6	5.0	112	1
47	44.[illegible]	33.4	66.0	159.2	0.681	0.265	18.0	5.0	112	1
48	51.7	27.0	66.0	158.1	0.783	0.206	16.[illegible]	5.0	112	1
49	59.5	20.0	66.0	157.2	0.902	0.146	13.2	5.0	112	1
50	64.7	16.6	66.0	155.7	0.980	0.119	11.7	5.0	112	1
51	68.8	12.6	66.0	156.1	1.043	0.088	9.2	5.0	112	1
52	73.5	6.9	66.0	132.2	1.114	0.055	6.1	5.0	112	1
53	36.9	70.9	81.6	251.8	0.452	0.392	17.7	5.0	112	1
54	43.9	64.4	81.6	246.3	0.538	0.354	19.0	5.0	112	1
55	51.3	56.2	81.6	237.3	0.629	0.310	19.5	5.0	112	1
56	58.8	47.1	81.6	266.4	0.720	0.215	15.5	5.0	112	1
57	66.6	39.3	81.6	265.2	0.815	0.174	14.2	5.0	112	1
58	74.3	31.9	81.6	264.7	0.910	0.137	12.5	5.0	112	1
59	81.4	22.4	81.6	263.0	0.997	0.093	9.3	5.0	112	1
60	31.8	50.7	81.6	270.2	0.389	0.231	9.0	5.0	224	0

1/Nozzle diameter, d.
2/1 = diffusor; 0 = no diffusor.

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Table A-1. Laboratory jet junction prototype data. (Cont'd.)

I	Qe (lps)	Ht (cm)	Qj (lps)	Hj (cm)	M	N	E (%)	Dia (cm)	L (cm)	Diff? (Y/N)
61	38.1	44.4	81.6	268.8	0.467	0.198	9.3	5.0	224	0
62	46.2	36.8	81.6	266.8	0.566	0.160	9.1	5.0	224	0
63	51.7	30.8	81.6	265.9	0.633	0.131	8.3	5.0	224	0
64	59.9	23.7	81.6	265.1	0.733	0.098	7.2	5.0	224	0
65	67.3	17.4	81.6	266.1	0.825	0.070	5.8	5.0	224	0
66	73.9	4.0	81.6	268.2	0.905	0.015	1.4	5.0	224	0
67	19.7	25.1	57.3	147.9	0.345	0.204	7.0	5.0	224	0
68	32.6	15.3	57.3	146.4	0.570	0.117	6.7	5.0	224	0
69	40.4	11.0	57.3	146.5	0.705	0.081	5.7	5.0	224	0
70	43.3	8.8	57.3	146.0	0.756	0.064	4.8	5.0	224	0
71	53.8	0.8	57.3	159.3	0.940	0.005	0.5	5.0	224	0
72	58.1	0.0	57.3	0.0	1.014	-0.001	-0.1	5.0	224	0
73	14.9	10.2	37.6	52.2	0.397	0.244	9.7	5.0	224	0
74	23.1	6.3	37.6	52.1	0.614	0.137	8.4	5.0	224	0
75	31.2	2.9	37.6	51.4	0.830	0.059	4.9	5.0	224	0
76	21.5	34.4	57.3	148.4	0.376	0.302	11.4	5.0	224	1
77	30.3	31.0	57.3	147.7	0.529	0.266	14.1	5.0	224	1
78	37.8	27.6	57.3	147.3	0.661	0.233	15.4	5.0	224	1
79	43.3	24.6	57.3	146.4	0.756	0.202	15.3	5.0	224	1
80	54.2	17.3	57.3	145.6	0.946	0.135	12.8	5.0	224	1
81	59.5	13.6	57.3	144.7	1.039	0.104	10.8	5.0	224	1
82	21.5	14.8	37.6	54.0	0.573	0.377	21.6	5.0	224	1
83	13.4	17.0	37.6	54.5	0.355	0.451	16.0	5.0	224	1
84	30.9	10.6	37.6	50.5	0.821	0.267	21.9	5.0	224	1
85	36.3	8.6	37.6	50.1	0.965	0.207	20.0	5.0	224	1
86	44.6	4.9	37.6	49.2	1.187	0.110	13.1	5.0	224	1
87	15.6	28.6	57.3	149.9	0.272	0.236	6.4	5.0	112	0
88	21.0	24.2	57.3	149.4	0.367	0.193	7.1	5.0	112	0
89	29.7	18.0	57.3	149.3	0.519	0.137	7.1	5.0	112	0
90	38.4	11.1	57.3	147.7	0.672	0.081	5.4	5.0	112	0
91	44.6	5.5	57.3	147.8	0.779	0.039	3.0	5.0	112	0
92	55.2	0.0	57.3	0.0	0.964	-0.001	-0.1	5.0	112	0
93	14.7	10.8	37.6	53.8	0.391	0.250	9.8	5.0	112	0
94	22.0	7.0	37.6	54.0	0.586	0.150	8.8	5.0	112	0
95	31.2	2.2	37.6	53.2	0.830	0.043	3.6	5.0	112	0
96	36.3	0.0	37.6	0.0	0.965	-0.001	-0.1	5.0	112	0
97	21.8	56.1	81.6	273.5	0.267	0.258	6.9	5.0	112	0
98	30.6	46.0	81.6	271.3	0.375	0.204	7.6	5.0	112	0
99	38.1	39.0	81.6	272.3	0.467	0.167	7.8	5.0	112	0
100	44.3	31.5	81.6	272.2	0.542	0.131	7.1	5.0	112	0
101	52.4	23.2	81.6	269.7	0.642	0.094	6.0	5.0	112	0
102	58.8	16.8	81.6	270.8	0.720	0.066	4.8	5.0	112	0
103	66.2	8.9	81.6	269.8	0.811	0.034	2.8	5.0	112	0
104	73.9	0.3	81.6	274.7	0.905	0.001	0.1	5.0	112	0
105	14.2	12.0	37.6	39.3	0.379	0.437	16.6	5.5	168	1
106	22.3	8.8	37.6	38.6	0.594	0.293	17.4	5.5	168	1
107	30.8	4.6	36.8	37.0	0.838	0.142	11.9	5.5	168	1
108	39.1	0.7	37.6	37.3	1.040	0.020	2.1	5.5	168	1
109	42.9	0.0	37.6	0.0	1.143	-0.001	-0.1	5.5	168	1
110	13.4	32.7	57.3	91.2	0.233	0.558	13.0	5.5	168	1
111	21.8	28.8	57.3	90.7	0.380	0.466	17.7	5.5	168	1
112	30.0	24.1	57.3	90.1	0.524	0.364	19.1	5.5	168	1
113	35.4	20.0	57.3	89.5	0.618	0.287	17.7	5.5	168	1
114	44.6	13.0	57.3	88.7	0.779	0.171	13.3	5.5	168	1
115	54.9	5.5	57.3	88.1	0.958	0.066	6.3	5.5	168	1
116	59.5	2.0	57.3	88.1	1.039	0.023	2.4	5.5	168	1
117	69.2	0.0	57.3	0.0	1.209	-0.001	-0.1	5.5	168	1
118	14.5	12.5	37.6	40.5	0.385	0.447	17.2	5.5	112	1
119	21.8	8.6	37.6	39.8	0.579	0.277	16.0	5.5	112	1
120	30.6	4.5	37.6	39.2	0.814	0.130	10.6	5.5	112	1
121	38.8	0.9	37.6	38.0	1.032	0.023	2.4	5.5	112	1
122	18.0	29.9	57.3	92.0	0.314	0.482	15.2	5.5	112	1

Table A-1. Laboratory jet junction prototype data. (Cont'd.)

I	Qs (lps)	Ht (cm)	Qj (lps)	Hj (cm)	M	N	E (%)	Dia (cm)	L (cm)	Diff? (Y/N)
123	22.3	27.5	57.3	90.9	0.390	0.433	16.9	5.5	112	1
124	31.8	20.8	57.3	90.3	0.555	0.299	16.6	5.5	112	1
125	37.8	16.2	57.3	89.9	0.661	0.219	14.5	5.5	112	1
126	45.2	10.5	57.3	89.3	0.790	0.134	10.6	5.5	112	1
127	55.2	3.5	57.3	88.2	0.964	0.041	4.0	5.5	112	1
128	23.1	60.4	82.0	210.4	0.281	0.403	11.3	5.5	112	1
129	29.2	55.3	82.0	209.8	0.356	0.358	12.7	5.5	112	1
130	36.9	50.6	82.0	210.8	0.450	0.316	14.2	5.5	112	1
131	42.9	44.0	82.0	209.9	0.524	0.265	13.9	5.5	112	1
132	51.0	36.6	82.0	208.5	0.622	0.213	13.2	5.5	112	1
133	61.7	26.8	82.0	207.6	0.752	0.148	11.1	5.5	112	1
134	69.2	18.9	82.0	207.9	0.844	0.100	8.4	5.5	112	1
135	76.2	13.4	82.0	206.9	0.929	0.069	6.4	5.5	112	1
136	84.7	5.9	82.0	207.7	1.033	0.029	3.0	5.5	112	1
137	90.5	1.6	82.0	207.4	1.104	0.008	0.9	5.5	112	1
138	14.0	16.3	37.6	53.2	0.373	0.443	16.5	5.0	168	1
139	21.5	13.9	37.6	52.3	0.573	0.363	20.8	5.0	168	1
140	30.3	10.3	37.6	51.4	0.806	0.250	20.1	5.0	168	1
141	36.6	7.9	37.6	51.0	0.973	0.184	17.9	5.0	168	1
142	46.2	3.6	37.6	49.7	1.230	0.078	9.6	5.0	168	1
143	54.5	0.0	37.6	0.0	1.450	-0.001	-0.1	5.0	168	1
144	16.6	35.7	54.7	160.1	0.303	0.287	8.7	5.0	168	1
145	22.3	35.2	56.7	144.7	0.393	0.322	12.7	5.0	168	1
146	32.9	30.2	56.7	144.2	0.581	0.265	15.4	5.0	168	1
147	31.4	28.8	56.7	144.7	0.553	0.248	13.7	5.0	168	1
148	45.9	22.6	56.7	143.0	0.809	0.188	15.2	5.0	168	1
149	54.9	17.4	56.7	142.6	0.967	0.139	13.4	5.0	168	1
150	59.5	14.2	56.7	142.2	1.049	0.111	11.6	5.0	168	1
151	67.7	8.8	56.7	139.8	1.193	0.067	8.0	5.0	168	1
152	76.2	2.8	56.7	141.5	1.343	0.020	2.7	5.0	168	1
153	83.5	0.0	56.7	0.0	1.471	-0.001	-0.1	5.0	168	1
154	14.5	8.9	37.6	49.9	0.385	0.216	8.3	5.0	168	0
155	20.8	8.2	37.6	51.9	0.552	0.187	10.3	5.0	168	0
156	28.6	4.3	37.6	51.0	0.760	0.092	7.0	5.0	168	0
157	40.0	0.0	37.6	0.0	1.065	-0.001	-0.1	5.0	168	0
158	17.5	28.6	57.3	149.4	0.306	0.237	7.2	5.0	168	0
159	23.6	24.5	57.3	149.2	0.413	0.196	8.1	5.0	168	0
160	29.7	19.8	57.3	146.4	0.519	0.156	8.1	5.0	168	0
161	36.6	15.7	57.3	148.5	0.639	0.118	7.5	5.0	168	0
162	43.3	9.7	57.3	146.7	0.756	0.071	5.4	5.0	168	0
163	54.2	1.1	57.3	157.9	0.946	0.007	0.7	5.0	168	0
164	18.5	62.2	81.3	253.6	0.227	0.325	7.4	5.0	168	0
165	22.8	59.1	81.3	272.2	0.281	0.277	7.8	5.0	168	0
166	28.9	54.0	81.6	272.4	0.353	0.247	8.7	5.0	168	0
167	34.8	46.2	81.6	271.5	0.426	0.205	8.7	5.0	168	0
168	45.2	36.5	81.6	270.4	0.554	0.156	8.6	5.0	168	0
169	55.2	24.9	81.6	269.4	0.676	0.102	6.9	5.0	168	0
170	60.6	20.7	81.6	269.7	0.742	0.083	6.2	5.0	168	0
171	70.0	11.6	81.6	269.0	0.857	0.045	3.9	5.0	168	0
172	74.7	5.6	81.6	262.0	0.915	0.022	2.0	5.0	168	0
173	84.3	0.0	81.6	0.0	1.032	-0.001	-0.1	5.0	168	0
174	39.1	70.3	81.6	274.8	0.479	0.344	16.5	5.0	168	1
175	43.3	67.4	81.6	270.4	0.530	0.332	17.6	5.0	168	1
176	57.3	55.8	81.3	268.7	0.705	0.262	18.5	5.0	168	1
177	67.3	48.7	81.3	265.1	0.828	0.225	18.6	5.0	168	1
178	76.2	42.3	81.3	265.0	0.938	0.190	17.8	5.0	168	1
179	81.4	38.3	81.3	263.8	1.001	0.170	17.0	5.0	168	1
180	89.6	32.3	81.3	261.0	1.103	0.141	15.5	5.0	168	1
181	61.7	9.7	81.6	206.9	0.756	0.049	3.7	5.5	224	0
182	45.2	19.7	82.4	194.0	0.549	0.113	6.2	5.5	112	0
183	36.9	3.8	50.1	278.2	0.736	0.014	1.0	5.5	112	0

Table A-1. Laboratory jet junction prototype data. (Cont'd.)

I	Qs (lps)	Ht (CM)	Qj (lps)	Hj (CM)	M	N	E (%)	Dia (CM)	L (CM)	Diff? (Y/N)
184	28.0	12.4	57.3	90.7	0.490	0.158	7.7	5.5	112	0
185	42.6	1.6	57.3	88.3	0.744	0.019	1.4	5.5	112	0
186	15.4	6.7	37.6	39.4	0.410	0.205	8.4	5.5	112	0
187	29.7	0.0	[illegible]	0.0	0.791	0.001	0.1	5.5	112	0
188	14.0	7.7	[illegible]	39.3	0.373	0.242	9.0	5.5	168	0
189	28.6	1.6	37.6	38.6	0.760	0.042	[illegible]	5.5	168	0
190	28.9	14.5	57.3	90.9	0.504	0.189	9.5	5.5	168	0
191	43.6	4.5	57.3	[illegible]	0.761	0.053	4.0	5.5	168	0
192	42.6	27.7	82.4	212.7	0.517	[illegible]	7.8	5.5	168	0
193	59.1	13.1	82.4	211.7	0.718	0.066	4.7	5.5	168	0
194	19.0	6.9	37.6	22.2	0.505	0.449	22.7	5.5	168	0
195	73.1	27.3	82.4	209.4	0.887	0.166	14.7	5.5	168	1
196	58.1	40.6	82.4	211.8	0.705	0.237	16.7	5.5	168	1
197	42.6	51.8	82.4	213.3	0.517	0.321	16.6	5.5	168	1
198	98.6	25.5	81.3	259.3	1.212	0.169	13.2	5.0	168	1
199	42.6	68.4	81.3	272.0	0.524	0.336	17.6	5.0	224	1
200	59.9	57.6	81.3	268.5	0.736	0.273	20.1	5.0	224	1
201	76.6	45.9	81.3	265.4	0.942	0.209	19.7	5.0	224	1
202	16.1	12.6	37.6	40.3	0.428	0.453	19.4	5.5	224	1
203	33.6	7.4	37.6	38.9	0.893	0.235	21.0	5.5	224	1
204	44.4	3.7	37.6	37.8	1.182	0.108	12.8	5.5	224	1
205	35.1	23.7	57.3	90.3	0.612	0.356	21.8	5.5	224	1
206	44.6	20.0	57.3	89.7	0.779	0.287	22.4	5.5	224	1
207	60.2	12.4	57.3	88.1	1.052	0.164	17.3	5.5	224	1
208	41.2	50.4	82.0	209.2	0.503	0.317	15.9	5.5	224	1
209	58.4	40.1	82.0	207.3	0.713	0.240	17.1	5.5	224	1
210	74.7	28.0	82.0	206.7	0.910	0.157	14.3	5.5	224	1
211	12.5	8.4	37.6	39.3	0.333	0.271	9.0	5.5	224	0
212	34.1	0.0	37.6	0.0	0.908	-0.001	-0.1	5.5	224	0
213	34.8	10.6	57.3	90.7	0.607	0.132	8.0	5.5	224	0
214	45.9	2.2	57.3	90.0	0.802	0.025	2.0	5.5	224	0
215	46.6	22.9	81.6	209.3	0.571	0.123	7.0	5.5	224	0
216	14.2	7.0	37.6	25.2	0.379	0.386	14.6	6.0	168	1
217	29.4	0.6	37.6	24.4	0.783	0.027	2.1	6.0	168	1
218	30.0	11.9	57.3	57.8	0.524	0.260	13.6	6.0	168	1
219	46.2	1.0	57.3	55.6	0.808	0.019	1.5	6.0	168	1
220	46.6	20.9	82.4	118.8	0.566	0.213	12.0	6.0	168	1
221	57.3	11.0	82.4	117.9	0.696	0.103	7.2	6.0	168	1
222	50.0	18.2	82.4	118.8	0.607	0.181	11.0	6.0	168	1
223	39.7	26.3	82.4	119.6	0.482	0.282	13.6	6.0	168	1
224	39.7	5.7	57.3	56.8	0.694	0.111	7.7	6.0	168	1
225	24.7	15.1	57.3	58.3	0.431	0.348	15.0	6.0	168	1
226	24.7	2.8	37.6	24.3	0.657	0.132	8.7	6.0	168	1
227	7.5	9.3	37.6	25.4	0.199	0.573	11.4	6.0	168	1
228	8.3	9.2	37.6	21.5	0.220	0.749	16.4	6.0	224	1
229	14.2	7.6	37.6	21.4	0.379	0.548	20.8	6.0	224	1
230	23.1	4.3	37.6	21.5	0.614	0.248	15.2	6.0	224	1
231	29.7	3.0	37.6	24.9	0.791	0.135	10.7	6.0	224	1
232	36.0	0.0	37.6	0.0	0.957	-0.001	-0.1	6.0	224	1
233	20.5	17.0	57.3	57.9	0.358	0.415	14.8	6.0	224	1
234	32.6	11.4	57.3	57.2	0.570	0.249	14.2	6.0	224	1
235	38.8	7.2	57.3	56.8	0.677	0.158	10.7	6.0	224	1
236	36.6	31.3	81.6	117.1	0.448	0.364	16.3	6.0	224	1
237	44.6	26.3	81.6	116.6	0.546	0.291	15.9	6.0	224	1
238	51.3	20.5	81.6	116.4	0.629	0.214	13.5	6.0	224	1
239	57.0	14.8	81.6	115.2	0.698	0.148	10.3	6.0	224	1
240	69.6	2.6	81.6	111.9	0.853	0.024	2.0	6.0	224	1
241	8.3	9.5	37.6	25.0	0.220	0.611	13.4	6.0	112	1
242	14.2	6.6	37.6	24.8	0.379	0.364	13.8	6.0	112	1
243	22.3	3.4	37.6	24.4	0.594	0.159	9.4	6.0	112	1
244	22.8	14.4	57.3	57.6	0.399	0.333	13.3	6.0	112	1

Table A-1. Laboratory jet junction prototype data. (Cont'd.)

I	Qs (lps)	Ht (CM)	Qj (lps)	Hj (CM)	N	N	ε (%)	Dia (CM)	(CM)	Diff? (Y/N)
245	30.6	9.2	57.3	56.7	0.534	0.193	10.3	6.0	112	1
246	37.2	4.4	57.3	55.7	0.650	0.085	5.5	6.0	112	1
247	41.7	2.1	57.3	56.9	0.728	0.039	2.8	6.0	112	1
248	35.4	28.0	82.4	118.9	0.429	0.308	13.2	6.0	112	1
249	42.0	21.5	82.4	118.0	0.510	0.223	11.4	6.0	112	1
250	52.1	11.6	82.4	116.3	0.632	0.111	7.0	6.0	112	1
251	58.4	5.5	82.4	115.9	0.710	0.050	3.5	6.0	112	1
252	14.0	25.8	37.6	134.8	0.373	0.237	8.6	4.0	224	1
253	21.5	23.9	37.6	134.9	0.573	0.215	12.3	4.0	224	1
254	28.9	21.5	37.6	115.5	0.768	0.229	17.6	4.0	224	1
255	40.0	16.7	37.6	133.8	1.065	0.143	15.2	4.0	224	1
256	36.0	52.4	57.3	243.0	0.628	0.275	17.3	4.0	224	1
257	44.9	47.8	57.3	242.3	0.785	0.246	19.3	4.0	224	1
258	52.3	42.4	57.3	241.3	0.921	0.213	19.6	4.0	224	1
259	59.9	38.1	57.3	242.8	1.046	0.186	19.5	4.0	224	1
260	71.9	28.3	57.3	241.0	1.256	0.133	16.7	4.0	224	1
261	89.6	12.2	57.3	242.9	1.566	0.053	8.3	4.0	224	1
262	76.6	49.3	74.0	406.3	1.035	0.138	14.3	4.0	224	1
263	66.9	60.4	74.0	411.7	0.904	0.172	15.6	4.0	224	1
264	82.2	41.0	74.0	407.1	1.111	0.117	12.4	4.0	224	1
265	93.0	28.2	74.0	409.3	1.256	0.074	9.3	4.0	224	1
266	20.8	17.2	37.6	125.1	0.552	0.159	8.8	4.0	224	0
267	27.4	13.6	37.6	121.5	0.730	0.126	9.2	4.0	224	0
268	34.4	8.9	37.6	124.1	0.917	0.077	7.1	4.0	224	0
269	44.3	3.2	37.6	122.9	1.178	0.027	3.2	4.0	224	0
270	26.3	43.0	57.3	249.7	0.460	0.208	9.6	4.0	224	0
271	36.0	35.1	57.3	248.8	0.628	0.164	10.3	4.0	224	0
272	42.6	29.8	57.3	249.3	0.744	0.136	10.1	4.0	224	0
273	54.9	18.1	57.3	157.4	0.958	0.130	12.5	4.0	224	0
274	73.1	1.1	57.3	220.6	1.276	0.005	0.6	4.0	224	0
275	62.4	36.1	74.0	259.1	0.843	0.162	13.7	4.0	224	0
276	43.3	59.3	74.0	402.3	0.585	0.173	10.1	4.0	224	0
277	74.3	22.6	74.0	392.4	1.003	0.061	6.1	4.0	224	0
278	81.4	14.0	74.0	393.1	1.100	0.037	4.1	4.0	224	0
279	87.6	6.8	74.0	404.9	1.183	0.017	2.0	4.0	224	0
280	30.3	18.4	37.6	122.2	0.806	0.177	14.3	4.0	168	1
281	14.0	25.7	37.6	124.9	0.373	0.259	9.7	4.0	168	1
282	22.3	22.4	37.6	123.5	0.594	0.222	13.2	4.0	168	1
283	35.7	14.7	37.6	123.5	0.949	0.135	12.8	4.0	168	1
284	35.1	48.6	57.3	246.1	0.612	0.246	15.1	4.0	168	1
285	43.5	41.8	57.3	246.9	0.760	0.204	15.5	4.0	168	1
286	53.1	32.0	57.3	245.4	0.927	0.150	13.9	4.0	168	1
287	62.8	21.2	57.3	243.9	1.097	0.095	10.4	4.0	168	1
288	78.2	10.4	57.3	240.7	1.366	0.045	6.1	4.0	168	1
289	58.1	61.6	74.0	404.1	0.784	0.180	14.1	4.0	168	1
290	70.8	47.5	74.0	392.0	0.956	0.138	13.2	4.0	168	1
291	79.0	40.0	74.0	397.1	1.067	0.112	12.0	4.0	168	1
292	86.7	33.1	74.0	401.4	1.172	0.090	10.5	4.0	168	1
293	101.2	16.2	74.0	392.7	1.367	0.043	5.9	4.0	168	1
294	14.5	25.2	37.6	112.2	0.385	0.289	11.1	4.0	112	1
295	30.6	15.3	37.6	111.8	0.814	0.159	12.9	4.0	112	1
296	44.9	5.7	37.6	106.9	1.195	0.056	6.7	4.0	112	1
297	53.1	1.3	37.6	110.6	1.413	0.012	1.7	4.0	112	1
298	51.7	27.8	57.3	245.0	0.903	0.128	11.6	4.0	112	1
299	29.2	50.2	57.3	245.7	0.509	0.257	13.1	4.0	112	1
300	60.6	20.6	57.3	244.3	1.059	0.092	9.7	4.0	112	1
301	75.4	2.6	57.3	235.4	1.318	0.011	1.4	4.0	112	1
302	59.5	64.7	74.0	414.4	0.804	0.185	14.9	4.0	112	1
303	72.3	48.7	74.0	409.6	0.977	0.135	13.2	4.0	112	1
304	79.0	22.6	74.0	412.1	1.067	0.058	6.2	4.0	112	1
305	53.5	59.7	81.6	271.2	0.655	0.282	18.5	5.0	168	1