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RECOMMENDED PRACTICE FOR FLOW MEASUREMENT IN WASTEWATER TREATMENT PLANTS WITH VENTURI TUBES AND VENTURI NOZZLES

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RECOMMENDED PRACTICE FOR FLOW MEASUREMENT IN WASTEWATER TREATMENT PLANTS WITH VENTURI TUBES AND VENTURI NOZZLES

by

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16. ABSTRACT

Venturi tubes and venturi nozzles are suitable for in-plant flow measurement of raw influent, treated effluent, return activated sludge, certain digested sludges, and for air and gas flows. However, they are not generally recommended for measurement of raw primary sludge.

For classical venturi tubes which operate under optimum prescribed conditions, the primary-element discharge coefficient is predictable to within a basic uncertainty of about 1 percent. For standard venturi nozzles this basic uncertainty ranges from about 1 percent to 2 percent. Errors in the secondary system must be considered in addition to estimate the uncertainty of the output measurement. The primary-element uncertainty increases to over 3 percent in venturi tubes for a variety of less-than optimum conditions such as insufficient upstream approach length, roughening and aging, and low Reynolds number. For cases in which the "standard" uncertainty is acceptable to the user, the initial performance check consists of the calibration of the secondary system as described in section 11.2. However, non-standard tubes and/or installations may require an initial field calibration of the primary-element coefficient as well as the secondary system. The primary calibrations are described in section 11.3 and usually involve either volumetric or dilution methods, or comparison with a reference meter.

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FOREWORD

The U. S. Environmental Protection Agency was created because of increasing public and Government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This document, the first of a series, represents an effort to provide improved guidelines for the selection, installation, calibration and maintenance of instruments used for monitoring and process control in wastewater treatment plants.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Venturi tubes and venturi nozzles are suitable for in-plant flow measurement of raw influent, treated effluent, return activated sludge, certain digested sludges, and for air and gas flows. However, they are not generally recommended for measurement of raw primary sludge.

The classical venturi tube and the standard venturi nozzle have very specific requirements for construction and installation, which are described in sections 4, 5, 6 and 7 of this document. There are also specific requirements on the secondary system which are described in section 8.

For classical venturi tubes which operate under optimum prescribed conditions, the primary-element discharge coefficient is predictable to within a basic uncertainty of about 1 percent. For standard venturi nozzles this basic uncertainty ranges from about 1 percent to 2 percent. Errors in the secondary system must be considered in addition in order to estimate the uncertainty of the output measurement. The primary-element uncertainty increases to over 3 percent in venturi tubes for a variety of less-than-optimum conditions such as insufficient upstream approach length, roughening and aging, and low Reynolds number. Similar effects can be expected for venturi nozzles although they are not as well-documented.

For cases in which the "standard" uncertainty is acceptable to the user, the initial performance check consists of the calibration of the secondary system as described in section 11.2. However, nonstandard tubes and/or installations may require an initial field calibration of the primary-element coefficient as well as the secondary system. The primary calibrations are described in section 11.3 and usually involve either volumetric or dilution methods, or comparison with a reference meter.

Methods of estimating the uncertainty of the calibration (reference) measurements are given (section 11.4) so that the performance of the on-line system can be equitably evaluated.

This report was submitted as part of Interagency Agreement No. 78-D-X0024-1 between the Environmental Protection Agency and the National Bureau of Standards.

CONTENTS

1. SCOPE OF RECOMMENDED PRACTICE

1.1 This practice covers classical venturi tubes, truncated classical venturi tubes, and venturi nozzles in circular pipes flowing full.

1.2 This practice covers venturi tubes and nozzles for use in wastewater treatment plants, i.e., for flowrate measurement of influent wastewater, treated effluent, air to aeration tanks, raw sludge, digested sludge, and activated sludge.

1.3 This practice covers:
- Meter (primary element) construction and configuration;
- Meter (primary element) installation requirements;
- Secondary element installation requirements; and
- Performance checks and error estimates.

1.4 The purpose of this practice is to provide users with a technical base that enables them to:
- Specify the proper instrument (type and size) for the various applications;
- Check the measuring system after installation; and
- Monitor subsequent performance as necessary.

2. NOMENCLATURE AND DEFINITIONS

2.1 Nomenclature. Terms are defined here and where they first appear in the text.

c = tracer concentration, in flow measurement by dilution
d = throat diameter
g = acceleration due to gravity
Δh = differential head on meter in terms of height of the flowing fluid
Δp = differential pressure on meter
q = flowrate of added tracer, in flow measurement by dilution
A = throat area, $\pi d^2/4$
B = $1/(1 - \beta^4)^{1/2}$
C = flow coefficient
D = inlet diameter
M = geometric constant in equation [6]
N = geometric constant in equation [6]
Q = volumetric flowrate
Q_m = mass flowrate of air
R = Reynolds number, VD/ν
U = average velocity
β = diameter ratio, d/D
δ = uncertainty, in equation [6]
ε = expansibility factor, in gas flow
ρ = density of flowing fluid
ν = kinematic viscosity of flowing fluid (length^2/time)

2.2 Definitions.

2.2.1 Density -- Mass per unit volume of fluid, or weight per unit volume divided by the value of acceleration due to gravity.

2.2.2 Hydraulic grade line -- A profile of the piezometric or static pressure level of the fluid at all points along a line; in a liquid flow, the height to which the liquid would rise in a piezometer tube.

2.2.3 Non-Newtonian fluid -- A fluid which does not exhibit the simple linear Newtonian relation between shear stress, laminar velocity gradient and viscosity. For example, a threshold yield stress may have to be exceeded before flow can start (plastic fluid) or the behavior may depend upon prior history of motion (thixotropic fluid).

2.2.4 Primary element -- In this context the primary element is the venturi device itself, which generates the pressure difference, the measurable parameter that characterizes the flowrate.

2.2.5 Purge -- A continuous flow of external, clean water inward to the venturi tube through the pressure taps to clean and flush the taps.

2.2.6 Reynolds number -- A dimensionless number characterizing the ratio between inertial and viscous effects in a flow. Low Reynolds numbers (below about 2000) describe laminar flows, which are dominated by viscous effects. See section 4.5.2.

2.2.7 Secondary element -- The device which measures the differential pressure generated by the primary element.

2.2.8 Specific gravity -- Ratio of the density of a fluid to that of pure water at 4 degrees Celsius.

2.2.9 Uncertainty -- Twice the standard deviation of a number of points scattered about an average value. The true value of a measurement has a 95 percent probability of falling within this band.

2.2.10 Venturi tube -- A device which, by a relatively long converging section, gradually contracts an originally parallel flow to a higher velocity (smaller area) parallel flow and then diverges it gradually back to a lower velocity. (See Figure 1, 4.2.1).

2.2.11 Venturi nozzle -- A nozzle-type curvilinear and relatively abrupt contraction followed by a gradual divergence similar to that of the venturi tube. (See Figure 2, 6.2.1.)

3. PRINCIPLES

3.1 The volumetric flowrate, Q, is given by

$$Q = CAB(2g\Delta h)^{1/2} \qquad [1]$$

where, in compatible units:

$A = \pi d^2/4$
d = throat diameter
$B = 1/(1 - \beta^4)^{1/2}$
β = ratio of throat to inlet diameter, d/D
Δh = pressure difference between inlet and throat pressure taps in terms of height of flowing fluid
g = acceleration due to gravity
C = flow coefficient, a function of geometry, roughness and Reynolds number.

3.2 Alternatively, Δh can be expressed as $\Delta p/\rho g$, where Δp is the pressure difference in terms of force per area and ρ is the density of the flowing fluid. Equation [1] then becomes

$$Q = CAB(2\Delta p/\rho)^{1/2} \qquad [2]$$

3.2.1 For practical purposes the density of influent or effluent sewage can be considered to be the same as that of water.

3.2.2 For sludge flows the density of the sludge may differ enough from that of water to be taken into account in the equations. See section 10.3.

3.3 For air (or other gases) the flowrate is determined from

$$Q = C\varepsilon AB(2\Delta p/\rho_1)^{1/2} \qquad [3]$$

where

ρ_1 = air density at inlet
ε = expansibility factor given in the Appendix

3.4 The recommended values for C will be given in sections 4.5.2 and 6.5.2 for tubes and nozzles which meet the requirements of sections 4 through 7 for standard conditions.

3.4.1 For tubes and nozzles which do not meet standard requirements but for which equations 1 and 2 are still valid, see sections 4.5.3 and 6.5.4.

3.4.2 If a standard value of C can be applied, it is only necessary to use equation [1] and [2] with an independent pressure difference measurement to check the performance of the secondary system. See section 11.2.

4. SPECIFICATIONS FOR CLASSICAL VENTURI TUBES

4.1 General. Adherence to the following specifications is required only for those meters which are to be used with the standard coefficients of section 4.5.2 (footnote 1).

4.2 Overall Geometry.

4.2.1 The venturi tube consists (progressing downstream) of a cylindrical inlet section of the same diameter of the upstream pipe, a conical convergent section leading into a cylindrical throat section (throat-to-inlet diameter ratio is β), and a conical divergent section. See Figure 1.

Comment: A meter geometry of course can be specified for procurement purposes simply by referring to the appropriate published standard. However, important details of the geometry are furnished in the following so that the user can check critical dimensions before installation.

Comment: The geometry requirements cited in the following have been adapted from ISO specifications (1).* Of the three options included by ISO, only the rough-cast convergent is

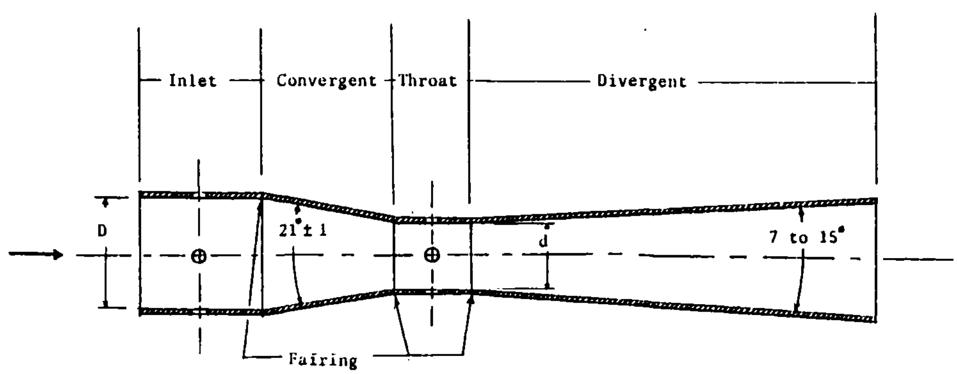

Figure 1. Classical venturi tube.

*Numbers in parentheses are references listed in section 12.

considered here, partly because it is the most common type in the United States (2, p. 230) and also because exposure to sewage is likely to roughen any smoother configuration anyway.

4.2.2 Mark the direction of flow clearly with an arrow on the outside of tube to prevent installation error.

4.2.3 Inlet Section.

4.2.3.1 The diameter, D, of the inlet section shall be within 0.01D of the diameter of the upstream pipe.

4.2.3.2 The roundness of the inlet section shall be such that no diameter differs from the mean diameter by more than 0.004D.

4.2.3.3 The length of the inlet section is preferably 1D. However, for D larger than about 35 cm (14 in) the length may be reduced to 0.25D + 25 cm (10 in).

4.2.3.4 The inlet section should be faired into the convergent section with a radius of 1.375D (± 20 percent).

4.2.3.5 The inlet section should be no rougher than the convergent section.

4.2.4 Convergent Section.

4.2.4.1 The convergence angle shall be 21 degrees ± 1 degree.

4.2.4.2 The convergence angle shall be conical to within 0.004D when checked with a template.

4.2.4.3 The conical convergent section shall be faired into the throat with a radius of between 3.625d and 3.75d, where d is the throat diameter.

4.2.4.4 The surface of the convergent section should have a sand cast finish, but it should be free of cracks, protuberances, depressions or other obvious irregularities which could still satisfy paragraph 4.2.4.2.

4.2.5 Throat.

4.2.5.1 The length of the throat shall be 1d. This is measured from the intersections of the extended conical convergent and divergent sections with the extended throat cylinder.

4.2.5.2 The throat roundness shall be such that no diameter in the plane of the pressure taps differs from the mean of at least four equally spaced measurements by more than

0.001d.

4.2.5.3 The average throat diameter, d, shall be such that the ratio $\beta = d/D$ is between 0.30 and 0.75.

4.2.5.4 The downstream end of the cylindrical throat should be faired into the conical divergent section with a radius of approximately 10d. See also paragraph 4.2.6.1.

4.2.5.5 The throat section shall be machined or of equivalent smoothness.

4.2.6 Divergent Section.

4.2.6.1 The conical divergent section can diverge with an included angle as large as 15 degrees, but 7 or 8 degrees is preferable. If a 15 degree angle is used, the radius cited in paragraph 4.2.5.4 should be decreased to about 5d.

4.2.6.2 The divergent section can be truncated if necessary by up to 35 percent of its length without changing the flow coefficient or substantially changing the head loss.

4.3 Pressure Taps.

4.3.1 The upstream pressure taps shall be located upstream of the intersection (projected straight lines) of the cylindrical entrance and conical convergent sections by a distance of 0.5D $\pm$ 0.25D for D up to 15 cm (6 in.) and 0.5D - 0.25D, +0 for larger sizes.

4.3.2 The throat pressure taps shall be located downstream of the intersection (projected straight lines) of the conical convergent and cylindrical throat sections by a distance of 0.5d $\pm$ 0.02d.

4.3.3 In general (for clean fluids) there should be at least four pressure taps in a plane perpendicular to the tube axis at each of the above locations, with the taps evenly distributed around the periphery. See sections 4.3.5 for dirty fluids.

4.3.4 When multiple taps are used as in paragraph 4.3.3 they should be connected by an annular chamber of which the cross-sectional area is more than half the total area of the tapping holes. Double this area if asymmetric flows are suspected. The connection from the annular ring to the secondary tubing should not be directly opposite any of the taps.

4.3.5 For metering dirty fluids and sludge, use only one pressure tap at each measuring station (3). An exception can be made if it can be shown to the satisfaction of involved parties that clogging of annular rings can be avoided. See section 5.4.4 for possible effect on accuracy. See also section 4.3.7 for sewage and sludge lines.

4.3.6 Pressure taps shall be smooth and burr-free on the inside tube surface. The maximum tap-hole diameters shall be 0.1D and 0.13d for inlet and throat taps, respectively, but not larger than 1 cm (0.4 in) nor smaller than 0.4 cm (0.16 in). The diameter of the tap holes shall remain constant for a distance of at least 2-1/2 diameters.

4.3.7 Special considerations for sewage/sludge lines.

4.3.7.1 The following precautions pertain to sewage in all stages of processing including treated effluent as well as to sludges.

4.3.7.2 Pressure taps for use with sewage and sludge should have built-in capability for manual rodding of holes. See section 8 for details.

4.3.7.3 For sewage and sludge the tap hole diameters should be at least the maximum size recommended in paragraph 4.3.6.
Comment: For larger venturi tubes, maximum diameters of 1.9 cm (3/4 in) have been found advantageous in reducing clogging without materially reducing accuracy.

4.3.7.4 See also paragraphs 4.3.5 and 5.5.5.

4.3.8 Proprietary systems employing flush diaphragms at the taps rather than open taps are also acceptable provided the following conditions are met.

4.3.8.1 The diaphragms must always be flush with the surface.

4.3.8.2 The system must meet accuracy requirements for secondary systems as cited in paragraph 8.1.

4.3.8.3 Provision must be made for the user to check the system accuracy, preferably by providing an alternate set of conventional open taps.

4.4 Materials and Construction.

4.4.1 In principle the venturi tubes can be made of any material which can be formed or machined to geometric specifications, is stable, and can meet the surface requirements of paragraphs 4.2.3.5, 4.2.4.4, and 4.2.5.5.

4.4.2 In practice, venturi tubes for clean fluids are generally made of cast iron with bronze-lined throat. These materials may also be adequate for influent sewage and treated effluent (footnote 2). However, bronze or stainless-steel lining of both the convergent and throat sections is recommended for this application.

4.4.3 Grease-resistant linings are recommended (but are not compulsory) for lines carrying sludge (4, p. 69) (footnote 3).

4.4.4 The fabrication method must provide for smooth transitions throughout the venturi tube; that is, if the tube is not fabricated in one piece, provision must be made to avoid offsets at the assembly joints.

4.5 Discharge Coefficients.

4.5.1 This section provides information for:
- Determining the coefficient C for use in equation [1], [2] or [3] for tubes which meet the fabrication specifications of sections 4.1 through 4.4, and which further meet the installation specifications of section 5; and
- Ascertaining the validity of manufacturers' values of C for tubes which differ from standard tubes.

4.5.2 Standard venturi tubes <u>fabricated and installed in conformance with sections 4 and 5</u> can be assigned a basic coefficient C of 0.984 for use in equation [1] and [2] when the following restrictions are observed:
(a) Pipe diameter, D, between 10 and 80 cm (about 4 to 32 in);
(b) β between 0.3 and 0.75; and
(c) Reynolds number, R, above 200,000. Here the Reynolds number is defined as

$$R = UD/\nu$$

where U is the average velocity in the inlet pipe of diameter D and ν is the kinematic viscosity of the flowing liquid. See also paragraph 4.5.2.3.

4.5.2.1 The value of C with the restrictions above has an uncertainty of about 0.7 percent (1).

4.5.2.2 For flows which do not meet the Reynolds number requirement of 200,000 the following estimates can be made:

R	C	Uncertainty, %
150,000	0.982	1.0
100,000	0.976	1.5
60,000	0.966	2.0
40,000	0.957	2.5

4.5.2.3 The Reynolds number condition of paragraph 4.5.2(c) above is considered to be firmly supported by data up to a Reynolds number of 2×10^6. Also, the preponderance of evidence suggests that C remains the same for even higher values of R, so for the purposes of this practice no restriction is placed on maximum R.

4.5.2.4 Before applying the coefficients cited in this section, the user should examine sections 5 and 9 for estimate of effects of on-site conditions and section 10.3 for sludge flows.

4.5.3 Nonstandard venturi tubes, i.e., those which do not conform to the specifications of sections 4.1 through 4.4, can still be acceptable provided the following conditions are met.

4.5.3.1 The manufacturer shall furnish detailed information on C, which shall have been determined from laboratory experiments or referenced to earlier standards. This information should include Reynolds number dependence, estimated roughness dependence and uncertainty of C, along with the tube dimensions necessary to achieve the given value of C. The manufacturer must be able to document upon request the number and type of experiments performed along with enough related information to establish for the involved parties the validity and stability (against abrupt shifts due to hydrodynamic causes, for example) of the discharge coefficient, C. Similarly, if the values of C are based on adaptations of existing values rather than on experiments, the rationale for these values will be made available to the user on request.

4.5.3.2 A manufacturer may find it necessary or desirable to use a form of equation different from those given in section 3, or graphs and tables rather than equations. In any event he shall furnish information equivalent to that of paragraph 4.5.3.1.

4.5.3.3 The manufacturer shall inform the user of any changes in the standard installation requirements of section 5 and shall be able to document the reasons for such changes on request. The absence of notification of such changes implies the applicability of section 5.

4.5.3.4 Failure of a nonstandard venturi tube to qualify under section 4.5.3 requires an in-place calibration of the meter system. See section 11.4.

5. INSTALLATION REQUIREMENTS FOR VENTURI TUBES

5.1 General.

5.1.1 Section 5 describes installation conditions which insure that flows entering the venturi tube are of sufficient quality for the discharge coefficients of section 4.5 to be valid. See paragraph 4.5.3.3 for non-standard venturi tubes.

5.1.2 If any of the following installation requirements cannot be met, or if fittings are used which are not covered in this section, the system may still be acceptable without a full calibration if it can be shown independently to the satisfaction of the involved parties that acceptable entry flows exist.

5.2 Valves.

5.2.1 If a flow control valve is necessary in the line, place it downstream of the venturi tube. See paragraph 5.4.5 for downstream distance.

5.2.2 If an isolation valve is necessary upstream of the venturi, use a gate valve and make certain that it is fully open during flowmeter measurements. See Table 1 for minimum upstream distances.

5.3 Pumps.

5.3.1 In the case of centrifugal pumps, locate the venturi tube on the inlet (suction) side (2) whenever this can be done without introducing subatmospheric pressure in the throat. If location on the discharge side is unavoidable, allow a minimum length of 10D between pump and venturi (5).

5.3.2 If a reciprocating pump is used, e.g., in a sludge line, the venturi tube cannot be recommended for accurate measurement. To minimize the error (which usually will be such as to indicate an apparently higher flow) locate the venturi tube as far as possible downstream of the pump (2).

5.4 Bends and Other Fittings.

5.4.1 Table 1 gives recommended minimum straight lengths between the closest upstream fitting and the upstream pressure taps of the venturi tube. These lengths are the minimum for which the uncertainties in C given in paragraphs 4.5.2.1 and 4.5.2.2 are valid (1).

5.4.2 Table 2 gives shorter allowable straight lengths between the closest upstream fitting and the venturi tube for which an additional 0.5 percent uncertainty in C must be considered. Add this 0.5 percent arithmetically to the uncertainties given in paragraph 4.5.2.1 and 4.5.2.2 (1).

5.4.3 If several fittings (other than 90-degree bends) are in series upstream of the venturi tube, the minimum straight length between the second and first (closest) upstream fitting should be equal to one-half the Table 1 value for the second fitting with $\beta = 0.7$, regardless of the actual β value. This length causes no additional uncertainty in C. If one-half the corresponding Table 2 value is used, add another 0.5 percent to the uncertainty in C.

5.4.4 Single-tap venturi tubes.

5.4.4.1 If a single-tap venturi tube is downstream of a single bend, orient the tap perpendicular to the plane of the bend whenever possible.

5.4.4.2 The distances in Tables 1 and 2 pertain to tubes with multiple taps and annular chambers. Use Table 1 distances for single taps. There is very limited evidence available (footnote 4) which suggests an additional 1 percent uncertainty in C for single-tap tubes close to asymmetric disturbances such as upstream bends.

TABLE 1.

MINIMUM NUMBER OF PIPE DIAMETERS BETWEEN SELECTED FITTINGS AND VENTURI TUBE

β	Single 90° Bend, Radius < D	Two or More 90° Bends in Same Plane	Reducer, 3D to D Over Length of 3.5D*	Expander, 0.75D to D, Over Length of D	Gate Valve Fully Open
0.30	0.5	1.5	0.5	1.5	1.5
0.35	0.5	1.5	1.5	1.5	2.5
0.40	0.5	1.5	2.5	1.5	2.5
0.45	1.0	1.5	4.5	2.5	3.5
0.50	1.5	2.5	5.5	2.5	3.5
0.55	2.5	2.5	6.5	3.5	4.5
0.60	3.0	3.5	8.5	3.5	4.5
0.65	4.0	4.5	9.5	4.5	4.5
0.70	4.0	4.5	10.5	5.5	5.5
0.75	4.5	4.5	11.5	6.5	5.5

*Abrupt symmetrical reductions with diameter ratio larger than 1/2, use 30D; for entrance from large reservoir, total distance to primary should exceed 30D even if there is an intervening fitting that allows a smaller value.

TABLE 2.

MINIMUM NUMBER OF PIPE DIAMETERS BETWEEN SELECTED UPSTREAM FITTINGS VENTURI TUBE FOR 0.5 PERCENT ADDED UNCERTAINTY

β	Single 90° Bend Radius ≥ D	Two or More 90° Bends in Same Plane	Two or More 90° Bends, Different Planes*	Reducer, 3D to D Over Length of 3.5D†	Expander, 0.75D to D, Over Length of D	Gate Valve Fully Open
0.30	+	0.5	0.5	+	0.5	0.5
0.35	+	0.5	0.5	0.5	0.5	0.5
0.40	+	0.5	0.5	0.5	0.5	1.5
0.45	0.5	0.5	0.5	0.5	1.0	1.5
0.50	0.5	1.5	8.5	0.5	1.5	1.5
0.55	0.5	1.5	12.5	0.5	1.5	2.5
0.60	1.0	2.5	17.5	0.5	1.5	2.5
0.65	1.5	2.5	23.5	1.5	2.5	2.5
0.70	2.0	2.5	27.5	2.5	3.5	3.5
0.75	3.0	3.5	29.5	3.5	4.5	3.5

*These fittings have an effect even 40D downstream; hence no entry in Table 1.
+Since fittings cannot be closer than 0.5D to venturi tube, only the Table 1 values are valid here.
†Abrupt symmetrical reductions with diameter ratio larger than 1/2, use 15D; for entrance from large reservoir, total distance to primary should exceed 15D even if there is an intervening fitting that allows a smaller value.

5.4.4.3 Do not use lengths smaller than 1.0D with single-tap tubes.

5.4.5 Downstream fittings. Conditions downstream of a venturi tube have comparatively little effect on its performance, but fittings should not be placed closer than 4d downstream of the throat taps.

5.4.6 Straighteners. In clean fluids only, flow straighteners can be installed upstream of the venturi tube in cases where there are fittings not covered by Tables 1 and 2. Standardized straightener designs are available (1, 2) but require long straight pipe lengths (20D and 22D upstream and downstream, respectively). Therefore, it is likely that an independent demonstration of suitability with shorter lengths will frequently be resorted to in accordance with paragraph 5.1.2.

5.5 Pipeline.

5.5.1 Size upstream. At the junction between the pipe and the venturi tube inlet section, the mean pipe diameter must be within ± 1 percent of the inlet diameter D. Further, no measured pipe diameter for a distance of 2D upstream should differ from this measured mean by more than $\pm$ 2 percent.

5.5.2 Size downstream. The downstream pipe diameter should not be less than 90 percent of the diameter of the end of the divergent section of the venturi tube.

5.5.3 Roughness. For a distance of 10 diameters upstream or for at least the distances given in Tables 1 and 2 the pipe surface should be the equivalent of smooth new commerial pipe. Further, for the two diameters immediately upstream of the venturi tube the pipe surface should be as smooth as the cast convergent. There should be no pitting, incrustations or deposits. See section 9.2.2 for effects on C of rougher pipes.

5.5.4 Gaskets. Do not allow gaskets to protrude into the interior, particularly at joints close to the entrance to the venturi tube.

5.5.5 Orientation. In sewage and sludge flows, or for any flows in which there are solids or condensate, it is recommended that the venturi device be placed in a horizontal line.

5.6 Alignment.

5.6.1 The angular alignment of the pipe axis and venturi tube axis should be within 1 degree.

5.6.2 The offset between the pipe and venturi tube centerlines at the junction plane should not exceed 0.005D.

5.7 Other Considerations.

5.7.1 Drain holes. Install drain holes and vent holes in the pipe close to the meter as appropriate, but be certain that the holes are closed while flow measurements are being made.

5.7.2 Tube selection considerations.

5.7.2.1 When a completely clean fluid is flowing, select the venturi tube size so that, for the minimum flowrate that is to be accurately metered, the head differential is at least 2.5 cm (1 in) of water. Substantially larger deflections will usually prevail for sewage and sludge flows because of the upstream velocity requirements. See section 10 for sludge flow velocities.

5.7.2.2 Avoid sub-atmospheric pressures in the throat.

5.7.3 Accessibility.

5.7.3.1 Design the installation so that the primary and secondary devices are accessible with reasonable effort.

5.7.3.2 It is desirable that, whenever possible, by-passes be built into the flow circuits so that the primary devices can be removed for examination. Hand holes that are located and designed so that no other specifications are violated can also be useful for the examination of venturi-tube interiors.

6. SPECIFICATIONS FOR VENTURI NOZZLES

6.1 General. Adherence to the following specifications is required only for those meters which are to be used with the standard coefficients of section 6.5.2.

6.2 Overall Geometry.

6.2.1 The venturi nozzle consists (progressing downstream) of a convergent section with rounded profile leading into a cylindrical throat section (throat-to-inlet pipe diameter ratio is β), and a conical divergent section. The shape of the convergent section depends upon whether β is greater or less than 2/3. See Figure 2.

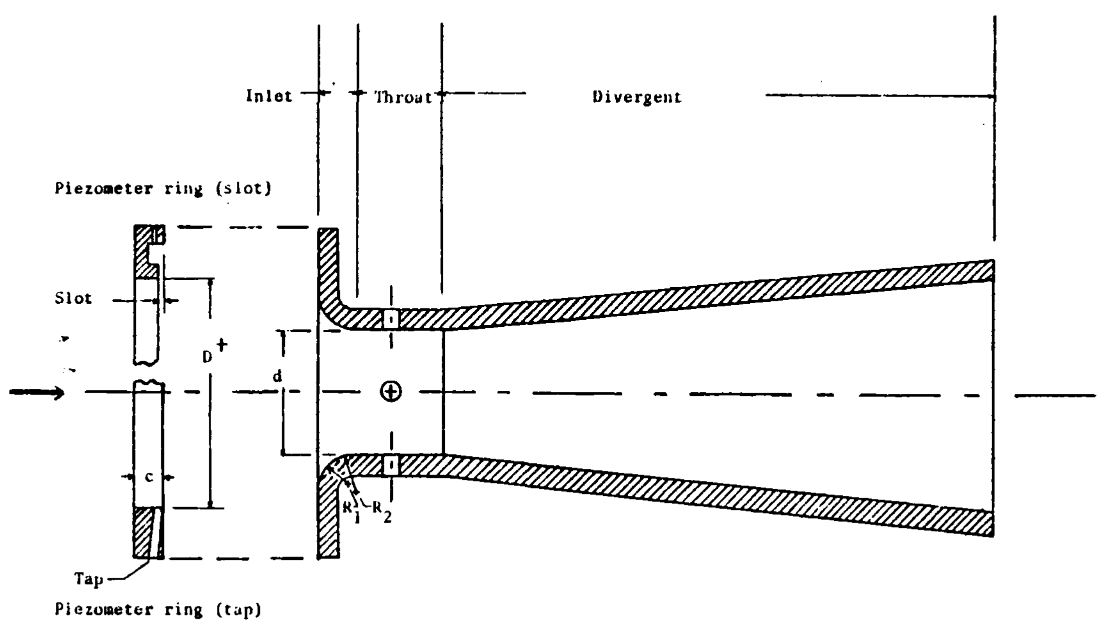

Figure 2. Standard venturi nozzle (shown for d/D < 2/3).

6.2.2 Inlet section, β < 2/3.

6.2.2.1 The upstream portion of the convergent section consists of a flat face perpendicular to the tube axis. The outer diameter of this flat surface is equal to the inside diameter of the upstream pipe and the inner diameter is equal to 1.5d, where d is the throat diameter. The radial width of this flat face approaches zero as β approaches 2/3.

6.2.2.2 The flat face of 6.2.2.1 is tangent to a circular arc section of radius R_1 equal to 0.2d $\pm$ 10% (for $\beta < 0.5$) or $\pm$ 3% (for $\beta > 0.5$. The center of this arc is 0.2d from the inlet (flat face) and 0.75d from the nozzle axis.

6.2.2.3 The circular arc of 6.2.2.2 is tangent to a second circular arc radius R_2 equal to d/3 $\pm$ 10% (for $\beta < 0.5$) or $\pm$ 3% (for $\beta > 0.5$). The center of this arc is 0.304d from the flat face and 5/6 d from the nozzle axis.

6.2.3 Inlet section, β > 2/3.

6.2.3.1 When d is larger than 2D/3, there can be no flat face and the curved section extends to the wall. The inlet is fabricated as though β < 2/3 and the face is machined down until the inner diameter of the flat portion is equal to D. See Figure 2.

6.2.4 Throat section.

6.2.4.1 The total length of the throat section is 0.70d to 0.75d. See 6.3.3.2 for location of pressure taps.

6.2.4.2 The diameter d is determined as the mean of four diameter measurements made in different axial planes at approximately even intervals. The diameter at any throat cross section shall not differ from this mean by more than 0.1 percent. (See paragraph 7.5.1 for determination of diameter D.)

6.2.5 Divergent section.

6.2.5.1 The total included angle of the divergent section shall not exceed 30 degrees. Within this limit the divergence angle affects the pressure loss but not the flow coefficient.

6.2.5.2 The divergent section may be truncated similarly to the classical venturi tube of paragraph 4.2.6.2.

6.2.5.3 There is no fairing at the junction of the cylindrical throat and the divergent section. However, any burrs should be removed.

6.3 Pressure Taps.

6.3.1 Upstream pressure taps.

6.3.1.1 Piezometer ring. The diameter of the piezometer ring must be no less than 1.00D and no greater than 1.04D, with the thickness not to exceed that shown in Figure 3.

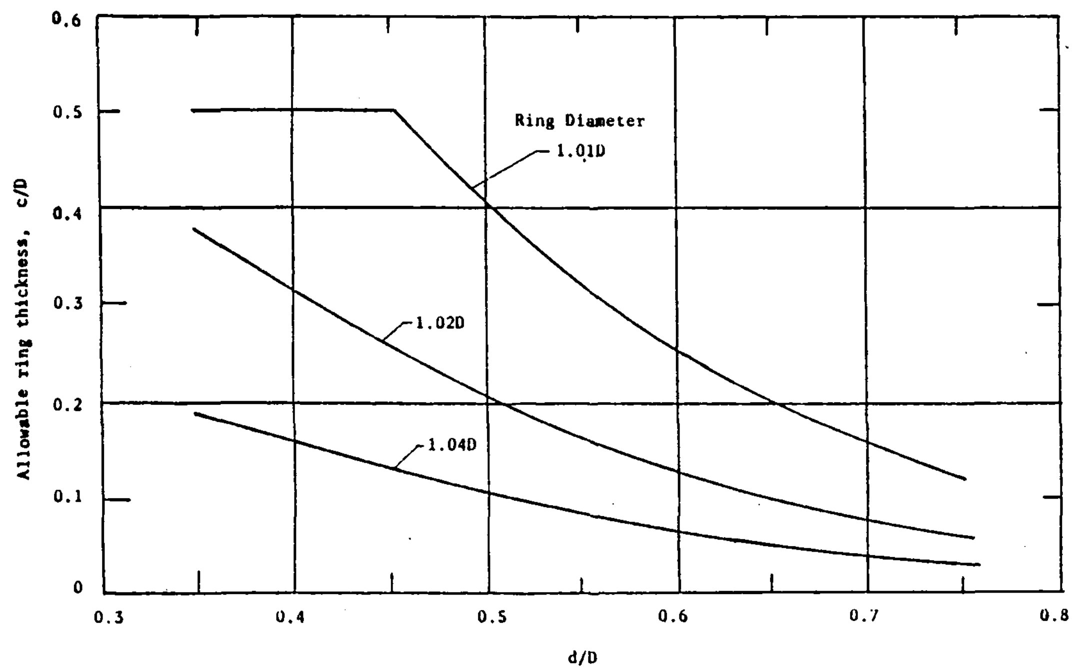

Figure 3. Allowable piezometer (carrier) ring thickness for venturi nozzles.

6.3.1.2 Upstream taps are always corner taps and may be in the form of individual taps or an annular slot as in Figure 2. See also paragraph 6.3.4.1 for dirty fluid cases.

6.3.1.3 The diameter of the individual taps or the width of the annular slot must be between 0.005D and 0.03D for $\beta < 0.65$; and between 0.01D and 0.02D for $\beta > 0.65$, except that the limiting values shall be between 1 mm and 10 mm for clean fluids.

6.3.1.4 Individual corner tappings should be, as closely as possible, perpendicular to the nozzle axis.

6.3.2 Throat pressure taps.

6.3.2.1 The throat pressure taps are always individual taps leading into an annular chamber or ring. There should be at least four of these taps, evenly spaced around the throat circumference. See paragraph 6.3.4.1 for exception.

6.3.2.2 The throat pressure taps are located 0.3d downstream from the beginning of the cylindrical throat section.

6.3.2.3 The diameter of the throat taps must be less than or equal to 0.04d and between 0.2 and 1.0 cm.

6.3.3 General pressure tap conditions.

6.3.3.1 The face of the taps must be circular, smooth and burr-free.

6.3.3.2 Length of slot should be at least twice its width; length of individual taps at least 2.5 times diameter. See also paragraph 4.3.4.

6.3.4 Special considerations for dirty fluids and sewage or sludge lines.

6.3.4.1 In order to avoid geometries that may encourage fouling, it is recommended that single rather than multiple taps be used in dirty fluids unless it can be shown that annular rings can be prevented from clogging. See section 7.4 for effect on accuracy.

6.3.4.2 Taps for use with dirty fluids, and particularly with sewage and sludge, must have built-in capability for manual "rodding" of the holes.

6.3.4.3 For sewage and sludge, always use the maximum hole diameter permitted under paragraphs 6.3.1.3 and 6.3.2.3.

6.3.4.4 Observe the precautions of this section for all stages of in-process sewage up through and including treated effluent. See also paragraph 7.5.4.

6.3.6 Proprietary systems employing flush diaphragms at the taps rather than open taps are also acceptable provided the following conditions are met.

6.3.6.1 The diaphragms must always be flush with the surface.

6.3.6.2 The system must meet accuracy requirements for secondary systems as cited in paragraph 8.3.

6.3.6.3 Provision must be made for the user to check the system accuracy, preferably by providing an alternate set of conventional open taps.

6.4 Materials and Construction.

6.4.1 Venturi nozzles may be made of any material which can be formed or machined to geometric specifications, is stable, and which also can conform to paragraphs 6.4.2 and 6.4.3.

6.4.2 The roughness of the convergent and throat surfaces should not exceed the equivalent of smoothly finished cast bronze.

6.4.3 The material shall have corrosion resistance appropriate to the intended use of the nozzle.

6.4.4 See also paragraphs 4.4.3 and 4.4.4.

6.5 Discharge Coefficients.

6.5.1 This section provides information for:

- Determining the coefficient C for use in equation [1], [2] or [3] for venturi nozzles which meet the fabrication specifications of sections 6.1 through 6.4, and which further meet the installation specifications of section 7; and
- Ascertaining the validity of manufacturers' values of C for nozzles which differ from standard ones.

6.5.2 Standard venturi nozzles fabricated and installed in accordance with sections 6 and 7 have a basic discharge coefficient given by (see also Figure 4)

$$C = 0.986 - 0.196\beta^{4.5}$$

when the following restrictions are also observed:

(a) Pipe diameter, D, between 6.5 and 50 cm (about 2-1/2 to 20 inches);
(b) Throat diameter larger than 5.0 cm (about 2 inches);
(c) β between 0.316 and 0.775;
(d) Reynolds number, R, between 150,000 and 2,000,000.
(e) The relative roughness of the pipe, k/D, for a distance of at least 10D upstream of the nozzle, is within the following limits.

for β =	0.35,	$k/D < 25 \times 10^{-4}$
	0.40,	$< 10.6 \times 10^{-4}$
	0.45,	$< 7.1 \times 10^{-4}$
	0.50,	$< 5.6 \times 10^{-4}$
	0.60,	$< 4.5 \times 10^{-4}$
	> 0.75,	$< 3.9 \times 10^{-4}$

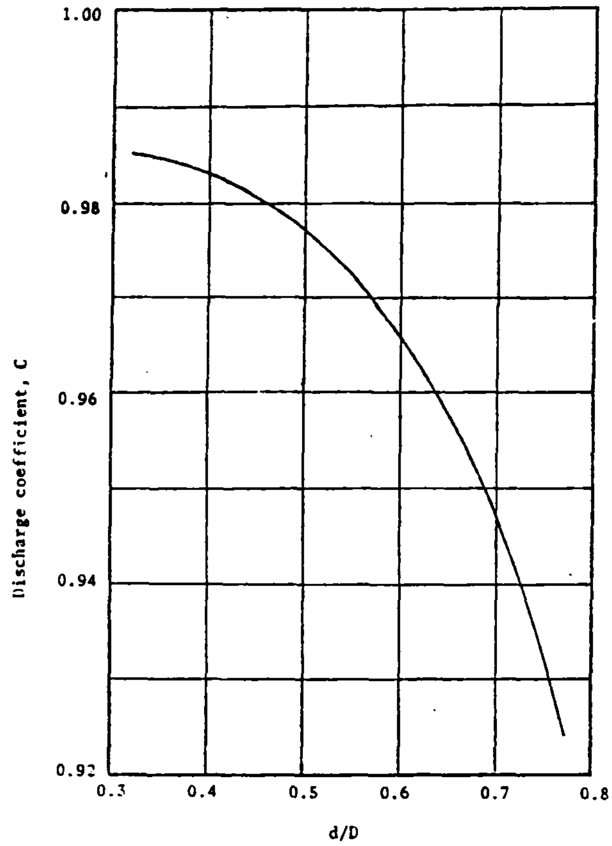

Figure 4. Venturi nozzle discharge coefficient.

Here k is a roughness height for which guidelines are given in Table 3. Before applying the foregoing coefficients, the user should examine sections 7 and 9 for possible effects of on-site conditions.

6.5.3 Within the foregoing limits the uncertainty of the coefficient ranges from a little over 1 percent for the smallest β to almost 2 percent for the largest β. (This uncertainty is actually based on $C/\sqrt{1 - \beta^4}$, but is given here for convenience on C.) Also, although published standards do not cite values of venturi-nozzle C for Reynolds numbers lower than above, comparison with nozzle data suggests an additional uncertainty of at least 1 percent for R as low as 50,000.

6.5.4 Nonstandard venturi nozzles, i.e., those which do not conform to the specifications of sections 6.1 through 6.4, can still be acceptable provided the following conditions are met.

TABLE 3.

EXAMPLES OF PIPE ROUGHNESS

	Material	Condition	k,* mm
I.	Aluminum	Smooth	0.03
	Brass	Smooth	0.03
	Copper	Smooth	0.03
	Glass	Smooth	0.03
	Plastic	Smooth	0.03
II.	Steel	New, seamless, cold drawn	0.03
		New, seamless, hot drawn	0.05-0.10
		New, seamless, rolled	0.05-0.10
		New, longitudinal welds	0.05-0.10
		New, bituminizing	0.03-0.05
		New, spiral welds	0.10
		Slight rust	0.10-0.20
		Rusty	0.20-0.30
		Encrusted	0.50-2.0
		Heavily Encrusted	2.0
		Galvanized	0.13
		Bituminized, normal	0.10-0.20
III.	Cast Iron	New	0.25
		Rusty	1.0-1.5
		Encrusted	1.5
IV.	Asbestos Cement	New	0.03
		Normal, not insulated	0.05

*Roughness height.

6.5.4.1 The manufacturer shall furnish detailed information on C, which shall have been determined from laboratory experiments or referenced to earlier standards. This information shall include Reynolds number dependence, roughness dependence and uncertainty of C, along with the meter dimensions necessary to achieve the given values of C. The manufacturer shall be able to document upon request the number and type of experiments performed along with enough related information to establish for the involved parties the validity and stability (against abrupt shifts due to hydrodynamic causes, for example) of the discharge coefficient, C. Similarly, if the values of C are based on adaptations of existing values rather than on experiments, the rationale for these values shall be made available to the user on request.

6.5.4.2 A manufacturer may find it necessary or desirable to use a form of equation different from those given in section 3, or graphs and tables rather than equations. In any event, he shall furnish information equivalent to that of paragraph 6.5.4.1.

6.5.4.3 Install nonstandard venturi nozzles in conformance with section 7, unless the information provided by the manufacturer includes documentation which either requires or justifies exceptions.

6.5.4.4 Failure of a nonstandard venturi nozzle to qualify under section 6.5.4 requires an in-place calibration of the meter system. See section 11.4.

7. INSTALLATION REQUIREMENTS FOR VENTURI NOZZLES

7.1 General.

7.1.1 Section 7 describes installation conditions which insure that flows entering the venturi nozzle are of sufficient quality for discharge coefficients of section 6.5 to be valid. See paragraph 6.5.4.3 for nonstandard nozzles.

7.1.2 If any of the following installation requirements cannot be met, or if fittings are used which are not covered in this section, the system may still be acceptable without a full calibration if it can be shown independently to the satisfaction of the involved parties that acceptable flows exist.

7.2 Valves.

7.2.1 If a flow control valve is necessary in the line, place it downstream of the venturi nozzle. See Tables 4 and 5 for minimum downstream distance for gate and globe valves.

7.2.2 If an isolation valve is necessary upstream of the nozzle, use a gate valve and make certain that it is fully open during flow measurements. See Tables 4 and 5 for minimum upstream distances.

7.3 Pumps.

7.3.1 In the case of centrifugal pumps, locate the venturi nozzle on the inlet (suction) side whenever this can be done without introducing subatmospheric pressure in the throat. There are no published guidelines for cases where nozzle placement on the discharge side of the pump is unavoidable. However, it is reasonable to assign longer minimum distances than for the venturi tube (paragraph 5.3.1) and a minimum length of 20D is recommended.

7.3.2 See paragraph 5.3.2 for reciprocating pumps.

7.4 Bends and Other Fittings.

7.4.1 Table 4 gives recommended minimum straight pipe lengths between the closest upstream and downstream fittings and the venturi nozzle. These lengths are the minimum for the uncertainties of paragraph 6.5.3 to apply.

7.4.2 Table 5 gives shorter allowable straight lengths between the closest upstream fitting and the venturi tube for which an

TABLE 4.

MINIMUM NUMBER OF PIPE DIAMETERS BETWEEN SELECTED FITTINGS AND VENTURI NOZZLE

β	Single 90° Bend*	Two or More 90° Bends, in Same Plane	Two or More 90° Bends, in Different Planes	Reducer, 2D to D, Length 1.5D to 3D†	Expander, 0.5D to D, Length 1D to 2D	Globe Valve Fully Open	Gate Valve Fully Open	All listed Fittings, When Downstream
0.30	10	16	34	5	16	18	12	5
0.35	12	16	36	5	16	18	12	5
0.40	14	18	36	5	16	20	12	6
0.45	14	18	38	5	17	20	12	6
0.50	14	20	40	6	18	22	12	6
0.55	16	22	44	8	20	24	14	6
0.60	18	26	48	9	22	26	14	7
0.65	22	32	54	11	25	28	16	7
0.70	28	36	62	14	30	32	20	7
0.75	36	42	70	22	38	36	24	8
0.80	46	50	80	30	54	44	30	8

*Includes tee with flow from one branch only.

†Abrupt symmetrical reductions with diameter ratio larger than 1/2, use 30D; for entrance from large reservoir, total distance to primary should exceed 30D even if there is an intervening fitting that allows a smaller value.

TABLE 5.

MINIMUM NUMBER OF PIPE DIAMETERS BETWEEN SELECTED FITTINGS AND VENTURI NOZZLE FOR 0.5 PERCENT ADDED UNCERTAINTY

β	Single 90° Bend*	Two or More 90° Bends, in Same Plane	Two or More 90° Bends, in Different Planes	Reducer, 2D to D, Length 1.5D to 3D†	Expander, 0.5D to D, Length 1D to 2D	Globe Valve Fully Open	Gate Valve Fully Open	All listed Fittings, When Downstream
0.30	6	8	17		8	9	6	2-1/2
0.35	6	8	18		8	9	6	2-1/2
0.40	7	9	18		8	10	6	3
0.45	7	9	19		9	10	6	3
0.50	7	10	20	5	9	11	6	3
0.55	8	11	22	5	10	12	7	3
0.60	9	13	24	5	11	13	7	3-1/2
0.65	11	16	27	6	13	14	8	3-1/2
0.70	14	18	31	7	15	16	10	3-1/2
0.75	18	21	35	11	19	18	12	4
0.80	23	25	40	15	27	22	15	4

*Includes tee with flow from one branch only.
†Abrupt symmetrical reductions with diameter ratio larger than 1/2, use 15D; for entrance from large reservoir, total distance to primary should exceed 15D even if there is an intervening fitting that allows a smaller value.

additional 0.5 percent uncertainty in C must be considered. Add this 0.5 percent arithmetically to the uncertainties given in paragraph 6.5.3.

7.4.3 If several fittings (other than 90-degree bends) are in series upstream of the venturi tube, the minimum straight length between the second and first (closest) upstream fitting should be equal to one-half the Table 4 value for the second fitting with $\beta = 0.7$, regardless of the actual β value. This length causes no additional uncertainty in C. If one-half the corresponding Table 5 value is used, add another 0.5 percent to the uncertainty in C.

7.4.4 Single-tap venturi nozzles.

7.4.4.1 If a single-tap venturi nozzle is downstream of a single elbow, orient the tap at a right angle to the plane of the bend whenever possible.

7.4.4.2 The distances in Tables 4 and 5 pertain to tubes with multiple taps and annular chambers. Use Table 4 distances for single-tap nozzles. Allow 0.5 percent added uncertainty.

7.4.5 Straighteners. In clean fluids only, flow straighteners can be installed upstream of the venturi nozzle for cases where the lengths required by Tables 4 and 5 are not available or where fittings other than those listed are used. Straight pipe lengths are required for 20D and 22D upstream and downstream of the straightener, respectively. Standardized straightener designs are available (1,2). If these lengths are not available, see paragraph 5.1.2.

7.5 Pipeline.

7.5.1 Size. For at least 2D upstream of the nozzle, the pipe should be cylindrical to the extent that no diameter differs from an average diameter by more than 0.3 percent. This average diameter is the mean of at least four diameter measurements made in at least three planes in the first 0.5D upstream, including the inlet (0.0D) plane. The average diameter so obtained is the value of D used to determine β. The downstream diameter should be within 3 percent of the divergent-section downstream diameter for a distance of at least 2D measured from upstream face.

7.5.2 Joints. The foregoing 2D pipe length should be a single pipe; i.e., there should be no joints in it. Pipe joints farther upstream, up to the first fitting, are permitted, but they should have steps or offsets not exceeding those indicated in Figure 5.

7.5.3 Roughness. The pipe must be clean, free of pits and deposits, and for at least 10D upstream of the nozzle should have maximum roughnesses as cited in paragraph 6.5.2. See paragraph 9.2.2.2

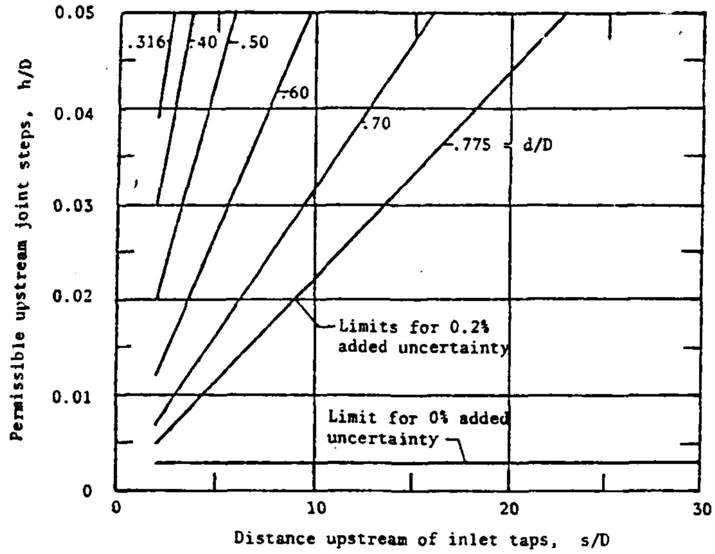

Figure 5. Upstream joint steps for venturi nozzle.

for effects of rougher pipes.

7.5.4 Orientation. See paragraph 5.5.5.

7.5.5 Gaskets. Gaskets installed near the nozzle should not protrude beyond the inner pipe surface (or into the annular ring) and should be thinner than 0.03D.

7.6 Alignment.

7.6.1 The nozzle axis should be aligned with the pipe axis to within ± 1 degree.

7.6.2 The piezometer ring must not protrude inside the pipe diameter at any point. The permissible lack of concentricity between the nozzle and pipe centerlines at the junction plane is given in Figure 6.

7.7 Other Considerations.

7.7.1 Drain holes. Install drain and vent holes upstream of the nozzle. If they are close to the nozzle their diameters should not exceed 0.08D, but in no case should they be closer than 0.5D to the nearest pressure tap or longitudinally aligned with a pressure tap. Be certain that drains and vents are closed off while measurements are being made.

7.7.2 Nozzle selection considerations. See section 5.7.2.

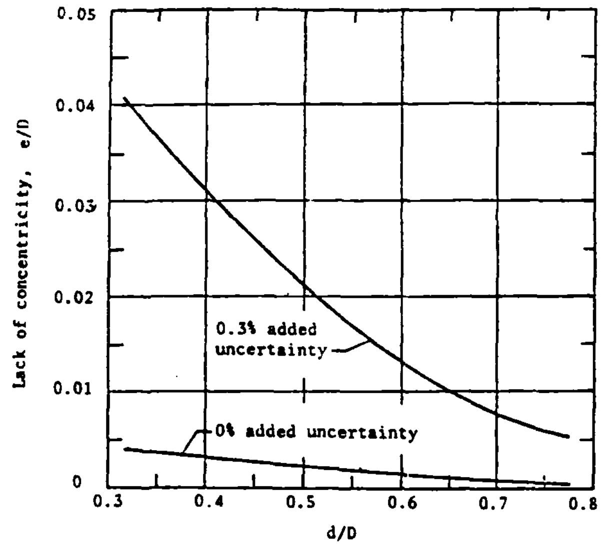

Figure 6. Allowable lack of concentricity for venturi nozzles.

7.7.3 Accessibility. See section 5.7.3.

8. SPECIFICATIONS FOR SECONDARY SYSTEMS

8.1 General.

8.1.1 The accuracy of each device within the secondary system (e.g., transducer/transmitter, receiver, recorder) shall be within 1/2 percent of full scale (footnote 1). Alternatively, this specification can be replaced with an accuracy requirement on the entire system.

8.1.2 The manufacturer must furnish with each secondary device instructions for maintenance and for servicing that can be done in the field.

8.2 Location Requirements.

8.2.1 Locate an indicator gage in the immediate vicinity of the primary element for convenience in performance checking.

8.2.2 Place the differential pressure transmitter below the hydraulic grade line, to facilitate positive bleeding of lines.

8.3 Transmission.

8.3.1 Do not use pneumatic transmission unless the distances involved are less than 300 m (1000 ft) and temperatures are always above freezing.

8.3.2 The pressure differential shall be transmittable in computer-compatible form or be capable of future conversion to such a form.

8.4 Connections Between Primary and Secondary.

8.4.1 General. A major object of this section is to avoid accumulations of gas or sediment in the connecting lines. To this end, arrangements other than those cited here are acceptable where it can be shown that the objective is accomplished. This section does not apply to enclosed proprietary systems of sections 4.3.8 or 6.3.6.

8.4.2 Air flow. If air (or other gas) is being measured, connect the secondary tubing near the top of the vertical meridian plane. If there is an annular ring, include provision for occasional (manual) draining of condensate from the bottom.

8.4.3 Liquid flow.

8.4.3.1 If a clean liquid is flowing, the secondary tubing should connect to the primary in the lower half of the periphery (6) in order to prevent the trapping of gas. Preferably make the connection in a zone about 45 degrees below the horizontal meridian (6). Treated effluent is not a clean liquid for this purpose.

8.4.3.2 For dirty (i.e., containing solids or gas bubbles) liquids, where there is only one pressure tap at each station as recommended in section 4.3.5, the secondary tubing connects directly to that tap. Orient the tube so that the tap is in the upper half of the meridian plane, preferably at about 45 degrees from the horizontal. If there are multiple taps and an annular ring, use a settling chamber and/or gas collector (or equivalent devices) at the bottom and top of the ring, respectively, in addition to the devices recommended in section 8.4.4.

8.4.4 Connecting tubing.

8.4.4.1 Connecting tubing should be installed so that it has a slope of at least 1 on 12 relative to the horizontal. It is preferable that this slope be continuously upward or continuously downward; however, this is often not possible where it causes, for example, placement of the secondary device in an inconvenient position or above the hydraulic grade line. In any case the highest and lowest points in the connecting tubing should be equipped with gas collectors (or bleed valves) and sediment chambers or condensate collectors as appropriate. Examples are shown in Figure 7.

8.4.4.2 The connecting tubing should be valved or otherwise fitted so that all portions of the lines can be flushed as necessary.

8.4.4.3 The tubing material should be resistant to corrosion. The tubing bore should be at least 1 cm or 3/8 inch (6).

8.4.5 Other considerations.

8.4.5.1 Place shut-off valves in each line next to the primary and preferably also next to the secondary, if such valves are not already an integral part of the secondary.

8.4.5.2 Include a valved by-pass across the secondary instrument, located between the secondary instrument and its shut-off valves, for use in zero checks, unless such a by-pass is furnished as an integral part of the secondary

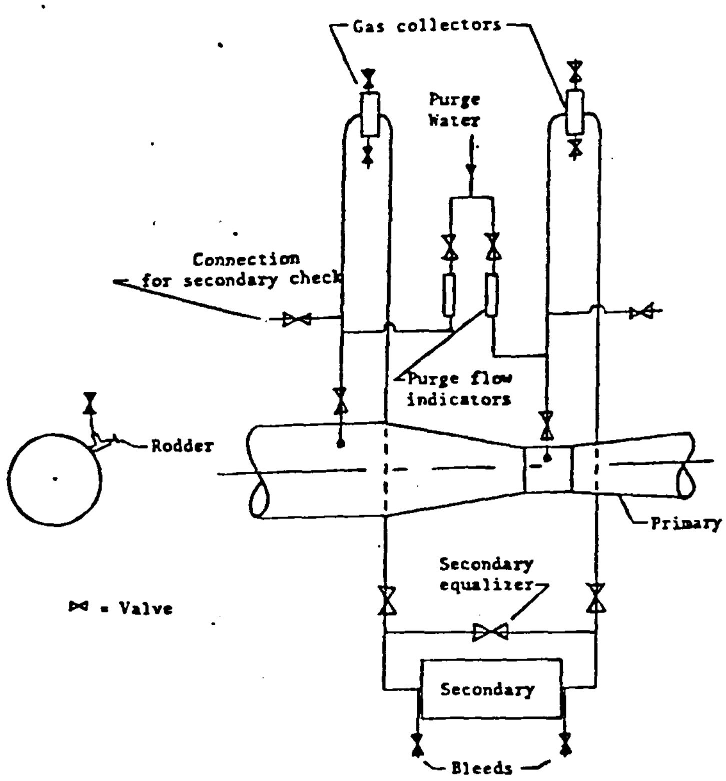

Figure 7. Typical secondary connections.

instrument.

8.4.5.3 Incorporate valved tees in each of the pressure lines, preferably near the primary, so that an independent pressure-differential measuring device can be installed for the performance checks of section 11. The geometry between this connection and the pressure tap should be the same in both pressure lines.

8.5 Purging.

8.5.1 Continuous purging of pressure taps is required in sewage and sludgeflows. This purging is preferably done with tap water.

8.5.2 The head loss in the tubing between the purge water connection and the tap should be the same in both of the lines so that the pressure differential is essentially unaffected. This can be accomplished by making the two paths geometrically similar and by keeping the purge flowrate the same in both legs. Install a variable area flowmeter or equivalent and a flow control valve in each of the purge water lines for flow adjustment.

8.5.3 The purge supply pressure should be at least 10 psi higher than the highest pressure anticipated at the tap. When flow throughout the venturi is steady, the purge flow should be valved down to the lowest flow consistent with good control. If the flow through the venturi is unsteady, the purge flow should be at least fast enough to keep dirty fluid from flowing into the tubing as the capacity of the secondary device changes. In any case purge flow should be made high enough during bleeding of the secondary lines to keep clean fluid in the lines.

9. ERROR SOURCES

9.1 Primary Elements.

9.1.1 Geometry. The effect of fabrication errors resulting in geometry differing from that of sections 4.2, 4.3, 6.2 and 6.3 cannot be quantitatively estimated. Treat such cases as nonstandard meters in accordance with sections 4.5.3 and 6.5.4 for venturi tubes and nozzles, respectively.

9.1.2 Roughness.

9.1.2.1 Tube. Roughening the meter itself is known to reduce C. There is insufficient data to quantify this effect, but it appears not to exceed 2 percent (1). Because meters with rough-cast convergents are less susceptible to roughness effects than those with machined convergents, an estimated reduction of 1 percent in C is suggested for venturi tubes that have been in routine treatment plant use, with an added tolerance of 0.5 percent. See also paragraph 10.3.4.4.

9.1.2.2 Nozzle. No experimental information is available on the effect of nozzle roughness on the discharge coefficient. In the absence of any guidelines, treat it the same as the venturi tube of paragraph 9.1.2.1.

9.1.3 Taps. Substantial errors can be introduced by imperfections in tap geometry. The throat taps are more critical in this regard than the inlet taps because of the high throat velocities, i.e., similar but nonstandard inlet and throat taps will not necessarily cancel their errors in a differential pressure measurement. Burrs, corrosion and incrustations can have serious effects on the pressure measurement, particularly in single-tap venturis. Monitoring the tap hole condition of meters which have been on-line in adverse environments is therefore particularly important.

9.2 Installation.

9.2.1 Upstream lengths which do not meet the minimum conditions of Tables 2 and 4 cause errors which cannot be estimated. An in-place calibration generally is required, with the following exceptions.

9.2.1.1 In-place calibration requirements can be waived if inflow of adequate quality is demonstrated under paragraph

5.1.2 or 7.1.2.

9.2.1.2 For venturi tubes which have multiple taps and annular chambers, the installation error is unlikely to exceed 3 percent (3). The in-place calibration requirement can be waived if this is an acceptable figure. This paragraph does not pertain to venturi nozzles.

9.2.2 Roughness of upstream pipe.

9.2.2.1 Venturi tubes. The values of C in section 4.5.2 are premised on the use of commercially smooth pipe upstream. It is generally accepted that upstream pipe roughness, by virtue of its effect on velocity distribution, increases C by an amount which increases for larger values of the diameter ratio, β. There is insufficient data available to quantify this error. However, an increase of 1 percent for large-β tubes in treatment plants is a reasonable estimate, along with an additional 0.5 percent uncertainty. It is likely that the smallest-β tubes will be relatively insensitive to this effect. See also paragraph 10.3.4.4.

9.2.2.2 Venturi nozzles. There is insufficient experimental information to quantify errors due to pipe roughness. The roughness requirements of paragraph 6.5.2 show that sensitivity to this effect increases with b ratio. For β larger than 0.6, relatively smooth pipes are specified and the effect of actual in-plant roughness can be expected to be larger than the corresponding effect for venturi tubes.

9.3 Pulsations. Pulsating flow, such as that caused by reciprocating pumps, will cause the meter reading to be too high, in part because the true discharge is proportional to the average of the square roots of the instantaneous pressure differentials while the indicated flow usually is proportional to the square root of the average of the instantaneous pressure differentials. See paragraph 5.3.2.

10. OPERATION AND MAINTENANCE REQUIREMENTS

10.1 Secondary System.

10.1.1 Regularly bleed the secondary lines and/or vent the gas collectors at the high points of the lines as provided for in paragraph 8.4.4.1. The frequency of this operation can be determined only from experience with each situation. When flows are expected to contain substantial amounts of gas or entrained air, the secondary lines should have been equipped with gas collectors rather than bleed valves. If these collectors do not have automatic venting capability, they should be manually vented once per shift to start with, until the appropriate frequency is determined from experience.

10.1.2 Regularly check the sediment chambers or remove sediment through valves at the low points of the secondary lines. If the secondary tubing is connected at the recommended position along the primary (section 8.4.3) and purge flows are always in use, this check probably can be made much less frequently than that of the preceding paragraph. Again, the frequency will be determined from experience gained from initial monitoring.

10.1.3 It is recommended that all secondary lines occasionally be thoroughly flushed with purge flows higher than those normally used. The frequency of such flushing will depend upon the frequency with which solids enter the secondary lines and on the cleaniness of the purge flow.

10.1.4 Check the zero reading of the secondary device by closing the connections to the primary and opening the equalizing valve between the two sides of the secondary instrument (paragraph 8.4.5.2), or as otherwise provided for by the manufacturer. This check should be made daily at first until more experience is gained on the drift behavior of the system.

10.1.5 Follow manufacturers' instructions for routine instrument maintenance.

10.1.6 Make periodic checks of the secondary system using independent manometry as described in section 11.2. This should be done when the system is first installed and periodically (order of weekly) thereafter until a final interval is determined from experience.

10.1.7 Check purge flows at least once each shift and more frequently if there are flowrate changes through the primary. Equalize as necessary.

10.1.8 Before resumption of flow following a period of shut-down, be certain that purge fluid is flowing. Bleed the secondary lines before resuming measurements.

10.2 Primary.

10.2.1 Use the rodding device on the pressure taps daily.

10.2.2 If the primary has annular rings, check them periodically for gas, sediment or condensate accumulation as in paragraph 10.1.1.

10.2.3 Using the vent valve upstream of the primary, check periodically for gas accumulation.

10.2.4 Long term maintenance on venturi tubes and venturi nozzles consists primarily of examination of the interior of the primary and the immediate upstream pipe in cases where this is possible through diversion of flow elsewhere. Upon examination a decision can be made as to whether use of the venturi can continue with the same or adjusted (estimated) coefficient or a complete calibration (section 11.3) is necessary. The interval between such examinations depends largely upon the hostile nature of the flowing fluid, with sewage and sludge flows requiring the most careful monitoring.

10.3 Sludge Flows.

10.3.1 General.

10.3.1.1 The hydraulic characteristics of sludge are not well-defined, not only because most sludges exhibit non-Newtonian behavior to some degree but also because their make-up differs from plant to plant. The recommendations in this section have been assembled from experiences reported in the literature and should be regarded as estimates only. Further research on the behavior of sludges in measuring devices is required before standard practices can be outlined for this area.

10.3.1.2 See section 8.5 for purge flow requirements, which are especially important in sludge applications.

10.3.2 Raw primary sludge.

10.3.2.1 Venturi tubes and venturi nozzles are not recommended for accurate measurement of raw primary sludge because of the difficulty of attaining in this sludge a fully turbulent flow with the effective Reynolds numbers cited in sections 4.5 and 6.5.

10.3.2.2 If use of a venturi device is unavoidable:

- Keep minimum velocities high, preferably about 8 ft/sec (245 cm/sec).
- Use large values of β, particularly in the smaller pipe sizes, so that the throat will pass large primary particles.
- Use a density in equation [2] based on a specific gravity of 1.02, if a density correction is not built in to the secondary recorder.
- Treat the recorded flowrate as an approximate value since there is no basis for estimating the error limits without a field calibration. The volumetric calibration method of section 11.4.2 is generally the most appropriate here.
- Pay particular attention to the internal inspection recommendation of paragraph 10.2.4, since the grease content of raw primary sludge is very high.

10.3.3 Activated sludge.

10.3.3.1 In general, fresh activated sludge has a solids content that is low enough for its hydraulic behavior in turbulent flow to be similar to (but slightly more viscous than) that of water and it can be metered accordingly, as described in the following.

10.3.3.2 For the purposes of applying equation [1] or [2], consider the density of fresh activated sludge to be no more than 1 percent greater than that of water.

10.3.3.3 The effective viscosity of fresh activated sludge is difficult to predict, but it may be in the neighborhood of 1-1/2 to 2 times that of water. To estimate a value of C, it is suggested a pipe Reynolds number be first calculated from the meter reading as though the fluid were water, and then divided by 1.5 or 2 to obtain an estimate sludge Reynolds number. For venturi tubes use section 4.5 to estimate the adjusted C. No adjustment is warranted if the estimated sludge Reynolds number is greater than 150,000. (Note that the standard venturi nozzle does not have recommended values of coefficients for Reynolds numbers less than 150,000. It is suggested that, down to Reynolds numbers of 40,000, the standard coefficients be used but with <u>additional</u> uncertainty of 1 percent, an estimate obtained by assuming that the Reynolds-number dependence of the venturi nozzle is similar to that of the nozzle.)

10.3.3.4 Maintain velocities greater than 60 to 90 cm/sec (2 to 3 ft/sec).

10.3.3.5 The foregoing parts of section 10.3.3 do not pertain to thickened activated sludge, for which the effective viscosity is substantially higher and less predictable.

10.3.4 Digested sludge.

10.3.4.1 Flow of well-digested sludge in concentrations (solids content) up to approximately 4 percent can be measured with venturi devices. The digestion process apparently breaks up the raw sludge solids into particles that are small enough so that at high velocities there is essentially a turbulent Newtonian flow.

10.3.4.2 Maintain average velocities (in the pipe) of at least 50 cm/sec (5 ft/sec).

10.3.4.3 The effective viscosity of the digested sludge cannot be accurately predicted. If, for estimating purposes, a value of about 10 times that of water is used for 4 percent sludge; the effective Reynolds numbers are likely to be in the lowest range cited in paragraph 4.5.2.2 for venturi tubes, suggesting a C of 0.96 with an uncertainty of $\pm$ 3 percent. (Corresponding estimates for 3 percent sludge would be C = 0.97 $\pm$ 2-1/2 percent.) A field calibration would be necessary to obtain more precise values. See paragraph 10.3.3.3 for venturi nozzles.

10.3.4.4 For Reynolds numbers as low as 40,000 upstream of a venturi tube (only), the pipe-roughness correction of paragraph 9.2.2.1 should be omitted. If the Reynolds number based on the throat diameter of the venturi tube is less than 100,000, omit the tube-roughness correction of paragraph 9.1.2.1.

10.3.4.5 For 4 percent sludge, use a density in equation [2] that is based on a specific gravity of about 1.02. Adjust this value for lower concentrations where warranted.

10.3.4.6 Because digested sludge is notably high in gas content, precautions against gas accumulation in the lines should be emphasized. See sections 10.1 and 8.5.

11. PERFORMANCE CHECKS AND CALIBRATIONS

11.1 General.

11.1.1 Standard venturi tubes and venturi nozzles.

11.1.1.1 Section 11.1.1 pertains to venturi tubes and nozzles which conform to all fabrication and installation requirements of sections 4 and 5 or 6 and 7.

11.1.1.2 A newly installed venturi system which meets the requirements of paragraph 11.1.1.1 requires only a check on the secondary system, provided that the uncertainties in C cited in sections 4.5.2 and 6.5.3 (or as increased for specified conditions cited in subsequent sections) are acceptable. See paragraph 11.1.1.4 for follow-on monitoring.

11.1.1.3 To check the performance of the secondary system, make an independent measurement of the pressure using equation [1] for liquid flows and equation [3] for compressible flows, and compare it with the output reading of the installed system. See section 11.2 for details.

11.1.1.4 The performance of the venturi system of paragraph 11.1.1.2 must be checked periodically after it has been in use. Again, a check of the secondary system alone can be acceptable provided that:

- The combination of fluid properties, velocity and venturi material is such that severe corrosion and grease coatings can be ruled out; and
- A value of C is selected consistent with normal roughening of the tube in routine use. See section 9.1.2.

Comment: There is an element of risk in this procedure in that any errors caused by small irregularities which may have developed near the edge of the pressure taps will go undetected. This is of particular concern in single-tap venturis. Make periodic internal inspections of the tube where feasible.

11.1.2 Nonstandard venturi tubes and venturi nozzles.

11.1.2.1 Venturi tubes or venturi nozzles which are nonstandard only in their dimensions but which meet the information requirements on C described in section 4.5.3 or 6.5.4 can be checked in the same manner as the standard tubes of section 11.1.1.

11.1.2.2 Venturi tubes or venturi nozzles which are nonstandard because they fail to meet the installation specifications of section 5 or 7 require a complete calibration after installation (see section 11.4), unless it can be shown to the satisfaction of all parties concerned that adequate inflow conditions exist or unless the conditions of paragraph 9.2.1.2 prevail. Once C has been established with a full calibration over the anticipated range of flow, future checks can be made in accordance with paragraph 11.1.1.4.

11.2 Calibrating the Secondary System with Manometers.

11.2.1 Install a manometer (or its equivalent according to paragraph 11.2.1.3) at the connections provided under paragraph 8.4.5.3.

11.2.1.1 Do not use mercury manometers for differentials less than 5 cm (2 in) of mercury; below this level use air-water manometers.

11.2.1.2 The manometry used for this purpose must conform to accepted good practice.

- As was the case for the secondary systems in section 8, the manometer tubing must provide for gas bleeding and for zero checks as needed.
- The scale should permit reading the meniscus position at least to the nearest 0.5 mm (0.02 in).
- Use glass tubing of large enough bore to minimize the effect on the meniscus of dirt deposited on the wall.

11.2.1.3 If a differential pressure transducer is used instead of a manometer, it must be of demonstrable accuracy to the satisfaction of the involved parties. Information on its measurement uncertainty must be available for later use in paragraph 11.6.2.1.

11.2.2 Use the purging system (section 8.5) to keep clean water in the manometer tubes.

11.2.2.1 Check to see that the purge flows are small and equal in both legs.

11.2.2.2 Where necessary, adjust the manometer reading for the difference in density between the purge water and the flowing liquid.

11.2.2.3 Any uncertainty in the density of the latter should be taken into account in the uncertainty estimate in section 11.4.

11.2.2.4 After the manometer readings of paragraph 11.2.3 below have been made, it is advisable to stop the purge flow just long enough to make another set of manometer readings in order to ascertain whether the pressure differential calls for adjustment in purge flow rate to one of the legs. Flow through the primary must remain constant during this process.

11.2.3 Use the manometer to check the secondary system in the following manner.

11.2.3.1 Before each series of measurements check or bleed the manometer lines, check the manometer zero and purge flows.

11.2.3.2 When the line flow appears to be steady, make several manometer readings in fairly rapid succession. Increase the number of readings if the manometer columns are oscillating. Use the average of these readings, adjusted per paragraph 11.2.2.2, for the head difference. In general it is not advisable to dampen oscillations by closing down on valves in the manometer line as error can be introduced in that way.

11.2.3.3 For liquid flows, compute the flowrate from equation [1] using the head differential from paragraph 11.2.3.2 and either the standard or the manufacturer's value of C.

11.2.3.4 Repeat this process several times for the same flowrate. Compare the results with the flowrates indicated and/or recorded simultaneously by the secondary system. To determine whether the differences are within agreed-upon limits, refer to section 11.6.2.

11.2.3.5 Recheck the manometer zero after each series of measurements at a given flowrate has been completed.

11.2.3.6 For compressible flows it is also necessary to measure the absolute pressure and temperature near the inlet section so that the inflow gas density and expansibility factor can be determined for use in equation [3].

11.2.3.7 If the venturi device is to measure a range of flows, perform the foregoing procedure for at least three flowrates--low, medium and high.

11.2.3.8 The foregoing paragraphs have assumed that the secondary system output is in terms of flowrate. If the readout is directly in terms of differential head or pressure, the evaluation can be made after paragraph 11.2.3.2.

11.2.3.9 After examining the results of paragraph 11.2.3.7, adjust or repair the secondary device as necessary.

11.3 Calibrating the Secondary System with Standpipes.

11.3.1 Instead of installing a manometer across the primary device and in parallel with the secondary device, differential pressures can be applied directly to the secondary device using water standpipes.

11.3.2 The usual practices of good manometry should be observed in order to obtain accurate measurements of the applied heads.

11.3.3 This method is most convenient for relatively small differential pressures.

11.4 Calibration of the Complete System.

11.4.1 General.

Section 11.4 pertains to complete, in-place calibrations of those venturi measuring systems which do not qualify for a secondary-only calibration under sections 11.1.1 and 11.1.2.

11.4.1.1 The purpose of section 11.4 is to provide a general overview of methods for determining in-place values of the coefficient C so that, coupled with a separate calibration of the secondary system, a complete calibration of the measuring system is accomplished.

11.4.1.2 Therefore, as part of the complete calibration, check the secondary system separately (and simultaneously, for convenience) in accordance with section 11.2. In this way, those differences between the reference and recorded flowrates which are chargeable to the primary device can be assigned to it, and future monitoring of meters which qualify under paragraph 11.1.1.4 can be restricted to the secondary system.

11.4.1.3 During the tests to determine C, use a manometer or equivalent to measure the pressure difference. See sections 11.2.1 and 11.2.2 and paragraphs 11.2.3.1

and 11.2.3.2.

11.4.1.4 If the venturi is going to measure a range of flows, perform the calibrations for at least three flowrates --low, medium, and high.

11.4.1.5 Repeat the calibration process several times if possible at each flowrate and use the average measured flowrate to determine C from equation [1] using the manometer measurement and the measured Q.

11.4.1.6 There is no single calibration method applicable to all situations. The choice may depend not only on technical factors described in the following sections but also on such factors as availability of skilled manpower, funds, in-plant laboratory capability, etc. The purpose of the following sections is to point out some advantages and disadvantages of several common calibration methods and conditions for their use. The major calibration methods are:
- Volumetric
- Comparison with reference meter
- Dilution
- Salt velocity
- Velocity-area traverse

11.4.2 Volumetric calibration.

11.4.2.1 Volumetric calibration can be used for all liquid and sludge flows. Its feasibility depends upon the availability of suitable tank space and connecting piping. The potential accuracy is high, provided that:
- The tank is regular in configuration so that its lateral dimensions can be measured within acceptable limits of accuracy.
- The tank is large enough to permit a test run of sufficient length for the effect of timing errors at the start and finish to be kept within acceptable limits.
- The change in liquid level during the run is large enough so that the starting and finishing depths (probably obtained by the "on-the-run" method) can be measured within acceptable relative error limits.
- The flowrate remains relatively constant during the run.

11.4.2.2 The volumetric method can be used to calibrate venturi-type meters in intermittently operating pumping stations by using the fall of sewage level in the wet wall during a pumping cycle. It is necessary to correct for the inflow occurring during the pumping-out process. However, the standard open-tap venturi tube is not suitable for intermittent flows because of the likelihood of trapping air in the secondary lines.

11.4.2.3 The volumetric method is often the only basic calibration method practical for raw primary sludge. See section 10.3.2.

11.4.2.4 Estimate the uncertainty of this method as a combination of the estimated uncertainties of the measurements of the lateral area, the depth change and the time.

11.4.3 Comparison with a reference meter.

11.4.3.1 In this context a reference meter is a flowrate measurement device whose performance can be referenced to published standards or recommended practices that are acceptable to the parties involved. Examples include:
- Standard venturi tubes and venturi nozzles as described in this document
- Orifice plates (1)
- Thin plate weirs (7) (footnote 5)
- Venturi flumes (7) (footnote 5)
- Parshall flumes (8) (footnote 5)

11.4.3.2 Such meters must meet all requirements of accepted standards in fabrication, installation and use.

11.4.3.3 The performance information available or obtainable for the reference instrument must include estimates of uncertainty so that error estimates can be made for the purposes given in section 11.6.3.

11.4.3.4 When a differential-pressure type of meter is used as a reference device, measure the pressure differential with a U-tube manometer. If necessary, a transducer can be used under the terms of paragraph 11.2.1.3.

11.4.3.5 When a critical-flow type of open-channel meter is used as a reference device, measure its head with a point gage or similar direct depth measuring instrument after a careful determination of the zero-depth condition. If it is necessary to use a float gage or other commercial instrument for this purpose, information must be available on its measurement errors so that uncertainties can be estimated.

11.4.3.6 If it is impossible to meet the requirements of paragraph 11.4.3.1, it may be acceptable to use as a reference meter a device for which there are no published standards provided that:

- The device has had a recent calibration and/or its current accuracy can be otherwise demonstrated satisfactorily;
- The device is used under the same conditions for which it was calibrated or for which its accuracy was otherwise demonstrated;
- Sufficient information is available to permit the involved parties to agree on its uncertainty.

Examples of such devices are:
- Propeller meters (footnote 6)
- Segmental orifices
- Electromagnetic flowmeters

11.4.4 Dilution method.

11.4.4.1 In the dilution method the flowrate is deduced from the dilution of measurable properties, e.g., color, conductivity or fluorescence of tracer chemicals added to the flow in known amounts. The calibration can be done by either the constant-rate injection method, or the slug injection method. The constant-rate method is recommended here because it appears more practical for in-plant use and because documentation on it is available in the form of published standards, e.g. (1, 10).

11.4.4.2 In the constant-rate injection method, a tracer solution of accurately known concentration is injected upstream at a rate which is constant and accurately measurable. At a downstream distance long enough for complete mixing, the flow is sampled and the concentration determined after a steady state or concentration "plateau" is attained. The flowrate, Q, is then determined from

$$Q = q(c_1 - c_2)/(c_2 - c_o) \qquad [4]$$

where: q is the rate at which the sample of concentration c_1 is injected; c_2 is the measured "plateau" concentration downstream; and c_o (which may be close to zero) is the background concentration of the tracer chemical existing in the flow.

11.4.4.3 This method requires accurate measurement of q and of all concentrations. Skilled personnel and specialized equipment are needed. The potential accuracy is high under optimum conditions; see references (9, 10) for methods of estimating errors.

11.4.4.4 The tracer chemical must be conservative, since losses by absorption to the solids component will be reflected as an apparent reduction in c_2. The fluorescent dye Rhodamine WT has been successfully used in sewage without losses. There are no reports of its application to sludge flows and this use is not recommended.

11.4.4.5 This method requires fully turbulent flow.

11.4.5 Salt-velocity method.

11.4.5.1 In the salt-velocity method, brine is injected suddenly at an upstream station in such a way that it becomes well distributed across the section very rapidly. The time of passage of the salt pulse between two downstream stations is measured by means of electrodes which detect the increased conductivity associated with the passage of the brine. The flowrate then can be determined provided the volume of the pipe between the electrodes is accurately known. This method has a potential for 1 percent accuracy under optimum conditions. The accuracy actually obtained depends upon the tranverse mixing and coherence of the injected brine slug, upon the accuracy of determination of the centers of gravity of the tracer conductivity and the time separating them, as well as upon the accuracy of the aforementioned volume determination.

11.4.5.2 This method requires a length of (preferably straight) pipe upstream of the first electrode sufficient to insure complete lateral mixing of the salt. This length can be as short as 4D when the injection is accomplished internally in the standard manner (2). However, for injections from the pipe periphery a substantially greater length is required. The distance between electrodes must be a minimum of 4D.

11.4.5.3 Brine injection must be sudden, with the injection interval of the order of 1 second with no leakage thereafter.

11.4.5.4 The electrodes must provide equal increments of conductivity for equal segments of cross-sectional area. Because the electrodes are intrusive the method is not suitable for flows in which there are fouling solids.

11.4.5.5 This method requires fully turbulent flow.

11.4.5.6 This method requires the liquid being measured to have a significantly smaller electrical conductivity than the brine.

11.4.5.7 See reference (2) for further details of this method.

11.4.6 Velocity-area method.

11.4.6.1 The velocity-area method involves the measurement of a number of velocities, each representative of the velocity within an incremental area, and summing the resulting velocity-area products over the flow cross-section.

11.4.6.2 Because most velocity-measuring instruments are intrusive and because a substantial amount of immersion time is needed, the velocity-area method cannot be used in flows containing fouling solids, nor can it be used in conduits where the blockage effect is excessive.

11.4.6.3 In view of paragraph 11.4.6.2 there are likely to be few in-plant situations where this method can be used. However, for those cases where the method is suitable:

- Use only velocity-measuring instruments which have been calibrated recently and whose performance in regard to uncertainties can be documented.
- Consult reference (11) or (12) for distribution of velocity-sampling points in the cross-section, descriptions of apparatus, and for other conditions on the measurements.

11.5 Approximate Methods.

11.5.1 It may be useful on occasion to have a relatively quick and inexpensive way of knowing whether or not a flowmeter is even approximately correct. Measurements in the $\pm$ 10 percent uncertainty range are adequate for this purpose. Some examples are given in this section; all involve measurement of a head difference with a manometer or its equivalent.

11.5.2 Elbow meters.

11.5.2.1 The accelerations associated with flow around a curve of radius r cause a pressure difference in the radial direction which can be used to deduce a flowrate in a full conduit. This method, which has been investigated mainly for 90-degree pipe elbows, requires measurement of the head difference between two diametrically opposite pressure taps drilled in the plane of the bend and half way between the end flanges of the elbow, i.e., at the 45-degree position.

11.5.2.2 The flowrate can be estimated from the following analytically determined expression.

$$Q = (r/2D)^{1/2}(\Pi D^2/4)(2g\Delta h)^{1/2} \quad [5]$$

Here, r is the radius of curvature of the elbow centerline, D is the elbow (and pipe) diameter and Δh is the measured head difference as previously defined.

11.5.2.3 The elbow performance is more sensitive to the radius of curvature of the inside bend than to that of the outside bend. Therefore it is desirable, when practicable, to determine r by measuring the inner bend curvature and adding half the diameter rather than to use a nominal value of r.

11.5.2.4 The elbow should be preceded by about 10 diameters of straight upstream pipe. There is insufficient information with which to evaluate such effects as pipe roughness and Reynolds number, except to note that with decreasing Reynolds number the flow is less than that predicted by equation [5]. Therefore added caution must be exercised in its application to sludge flows.

11.5.2.5 Examination of published experimental results suggests that equation [5] cannot be depended upon for accuracies better than roughly $\pm$ 10 percent (see footnote 7 for possible exception).

11.5.2.6 However, it should be noted that an elbow meter that is carefully fabricated and installed and properly calibrated can be as effective a flowmeter as other types of pressure differential devices. The foregoing paragraphs of section 11.5.2 pertain to uncalibrated elbows only.

11.5.3 Valves. Butterfly valves are sometimes furnished with flowrate vs. angle-of-opening data which can be used for approximate checks on flowmeters. Such measurements would of course be affected to an unknown extent by upstream conditions such as presence of fittings and roughness and by Reynolds number.

11.5.4 Measurements for monitoring.

11.5.4.1 Differential-head measurements can be used, without regard to their absolute accuracy, to monitor changes in the system and to observe whether the flowmeter is responding in a consistent manner.

11.5.4.2 In addition to the measurements heretofore cited in section 11.5, the head difference between the suction and discharge sides of a centrifugal pump can be used for monitoring, provided that (for a given speed of rotation) its head decreases continuously with increasing discharge over the range of interest. In principle this method can be used directly for approximate flow measurements provided that the head difference (which includes the difference in $V^2/2g$) is determined in the same way it was done to establish the head-discharge curves. Generally head-discharge curves are presented for cold water and would not necessarily be valid for sludges of substantially higher viscosity.

11.5.4.3 Monitoring the head loss in an upstream (or similar) section of pipe from the time of its installation can provide a basis for making pipe-roughness adjustments to C.

11.6 Estimating Errors.

11.6.1 Error estimates provide an assessment of the uncertainty of a measurement. One method of estimating the uncertainty of a flowrate determination based on equation [1] is to combine individual uncertainties as follows for a venturi tube.

$$\delta Q/Q = [(\delta C/C)^2 + M^2(\delta D/D)^2 + N^2(\delta d/d)^2 + (1/4)(\delta\Delta h/\Delta h)^2]^{1/2} \quad [6]$$

with $M = 2\beta^4/(1 - \beta^4)$

$N = 2/(1 - \beta^4)$

δ = uncertainty

The second and third terms inside the brackets are usually small, since the diameter uncertainties are limited, e.g., by paragraphs 4.2.3.2 and 4.2.5.2.

11.6.2 Application to secondary-system.

11.6.2.1 In order to compare the indicated flowrate with the flowrate computed from manometer measurements (paragraph 11.2.3.4) it is first necessary to estimate the uncertainty of the latter, or "reference," flowrate.

11.6.2.2 For this purpose often only the first and last bracketed terms in equation [6] need be considered. The first term is either the standard uncertainty (paragraph 4.5.2.1 or 6.5.3) or the uncertainty furnished by the manufacturer. The last bracketed term allows for an estimate of the manometer reading error, typically 1 percent and preferably not more than 2 percent at low flowrates. Any uncertainty in the density of the flowing liquid compared with the manometer liquid should be included here.

11.6.2.3 The tolerance estimated from equation [6] represents a band (its width may increase at low flows) of uncertainty about the flowrate determined in paragraph 11.2.3.3.

11.6.2.4 Compare the flowrate recorded by the on-line measuring system at the time of the manometer readings with that determined in paragraph 11.2.3.3. The recorded flowrate should not fall outside of the tolerance band by more than the errors allowed in transmitting, receiving and recording the differential pressure signal in paragraph 8.1.1. For example, if the uncertainty in C and in Δh are both 1 percent at a particular flowrate, the resulting uncertainty in Q is 1.1 percent. If the specifications (section 8.1) require a 2 percent accuracy for that flowrate, the allowable difference between recorded and reference flowrate could be slightly over 3 percent.

11.6.2.4 The above method of comparison is an illustration only. Other methods agreed on by the involved parties are acceptable. The important point is that the uncertainty of the reference measurement should be taken into account when evaluating another measurement.

11.6.3 Other error estimates.

11.6.3.1 To estimate the uncertainty of a flow measurement, it is necessary to combine the error estimated from the secondary-system calibration with an estimate of the uncertainty in C. Such uncertainties have been cited earlier in this document for a limited number of specific conditions for which some information is available.

11.6.3.2 When it is necessary to use one of the calibration methods of section 11.4 to determine C, an uncertainty estimate satisfactory to all parties must be derived based on the quality of the tests. Guidelines for estimating uncertainty are available in the cited references.

12. REFERENCES

(1) International Standards Organization, "Measurement of Fluid Flow by Means of Orifice Plates, Nozzles and Venturi Tubes Inserted in Circular Cross-Section Conduits Running Full," ISO/DIS 5167, 1976, draft revision of R781.

(2) American Society of Mechanical Engineers, "Fluid Meters - Their Theory and Application," 6th ed., 1971, 345 E. 47 St. New York, NY 10017.

(3) American Society for Testing and Materials, "Standard Method of Flow Measurement of Water by the Venturi Meter Tube," ASTM D2458-69.

(4) Water Pollution Control Federation, "Wastewater Treatment Plant Design," WPCF Manual of Practice No. 8, 1977.

(5) Hydraulic Institute, "Standards for Centrifugal, Rotary and Reciprocating Pumps," 12th edition.

(6) International Standards Organization, "Fluid Flow in Closed Conduits--Connections for Pressure Signal Transmissions Between Primary and Secondary Elements," ISO 2186 - 1973.

(7) British Standards Institution, Standard No. 2680-4A, "Methods of Measurement of Liquid Flow in Open Channels: Part 4A, Thin Plate Weirs and Venturi Flumes," 1965.

(8) American Society for Testing and Materials, "Standard Method for Open Channel Flow Measurement of Industrial Water and Industrial Waste Water by the Parshall Flume," ASTM D1941-67.

(9) International Standards Organization, "Measurement of Water Flow in Closed Conduits--Tracer Methods, Part I; General," ISO No. 2975/1, 1974.

(10) International Standards Organization, "Measurement of Water Flow in Closed Conduits--Tracer Methods, Part II; Constant Rate Injection Method Using Non-Radioactive Tracers," ISO DIS 2975/II.

(11) British Standards Institution, Standard No. BS1042-2A, "Methods for The Measurement of Fluid Flow in Pipes, Part 2, Pitot Tubes; Part 2A, Class A Accuracy," 1973.

(12) International Electrotechnical Commission, "International Code for the Field Acceptance Tests of Hydraulic Turbines," Publication 41, 1963.

APPENDIX A. FOOTNOTES

(1) The specifications of sections 4 and 6 may appear unrealistically rigid for sewage plant application. However, the quality of the final measurement depends upon the performance of the complete measurement system, i.e., primary plus secondary elements. Because substantial errors can be introduced in the sensing, transmission and recording of the pressure differential, it is to the user's advantage not only to give the secondary unit extensive attention, but also to minimize errors in the primary, thereby keeping the total error within reasonable limits.

(2) Conflicting experiences are reported here. Keefer ("The Effect of Sewage on Cast Iron Venturi Meters," Eng. News-Record, 112, Jan. 11, 1934, p. 46) reported that domestic sewage did not adversely affect cast iron venturis after 12 years of use. These 42 x 21 meters had been coated originally with a coal tar varnish and the throats were bronze lined. Also, the meters always had been kept filled so there was no alternate wetting and drying. On the other hand, Richardson ("Venturi Meters for Sewage," Eng. News-Record, 112, Apr. 12, 1934, p. 482) reported gradual but serious accumulation of deposits, although the type of deposit was not specified. Crossley ("Has Your Treatment Works Too Many Instruments?," Progress in Water Technol., 6, 1974, Pergamon Press) cites a 36 x 27 inch mixed liquor venturi tube which was examined after 30 years of service and, apart from a few barnacles on the inlet cone, the throat was smooth although slightly pitted.

(3) Again conflicting experiences are reported. Scott ("Magnetic Flowmeter --A New Sludge Meter," Prog. in Water Technol., 6, 1974, Pergamon Press) lists several plastics used in magnetic flowmeters to prevent grease build-up. However, a discussor of this paper claimed that only glass had been proven effective.

(4) Experiments reported by Halmi ("Practical Guide to the Evaluation of the Metering Performance of Differential Producers," ASME, Jour. Fluids Eng., March 1973) showed an effect of tap orientation up to about 8D downstream of a short radius elbow for a $\beta = 0.75$ meter. Although this meter was a proprietary one with convergence shape different from that of the classical tube, it appears that a conservative approach should allow for additional uncertainty.

(5) Open channel measuring devices are included in this list because it may be possible, for example, to calibrate an influent venturi tube against a good effluent weir system (provided that change of storage within the plant can be avoided) or against a flume elsewhere in the plant.

(6) There is an American Water Works Association standard, AWWA C704-70 for propeller-type cold-water meters for main line applications.

(7) Replogle, et al., ("Evaluation of Pipe Elbows as Flow Meters," Proc. Amer. Soc. Civ. Eng. 92, IR3, 1966) indicated that uncalibrated elbow meters could be accurate to within ± 3 percent if empirical coefficients were used to modify equation [5] as shown below. The empirical coefficients listed here were obtained from and should be used only for commercial cast flanged elbows.

- Multiply the right hand side of equation [5] by the following coefficients for specific elbow sizes.

12-inch	coeff. = 1.048
10-inch	coeff. = 1.021
6-inch	coeff. = 0.983
3-inch (long)	coeff. = 1.014
3-inch (short)	coeff. = 0.994

- Also, instead of applying the exponent 1/2 to the measured head, use (for the above range of diameters)

$$\text{Exponent} = 0.489 + 0.038D$$

- Extrapolation of these results to larger sizes is not recommended.
- Access to the inside of the elbow is necessary to achieve this accuracy. Dimensions must be carefully measured for use in equation [5]. Use the inner bend surface radius (obtained from a plaster cast if necessary) as a base for determining "r" and check to see that the measured radius is constant.
- Maintain at least 20 straight pipe diameters upstream for this accuracy.

APPENDIX B. EXPANSIBILITY FACTORS, ε

Adiabatic Factor, k	$(\frac{d}{D})^4$	Ratio of absolute pressure, throat to inlet 0.98	0.96	0.94	0.92	0.90	0.85	0.80	0.75
1.2	0	0.987	0.975	0.962	0.949	0.936	0.903	0.869	0.834
	0.1	0.986	0.971	0.957	0.942	0.928	0.891	0.854	0.817
	0.2	0.983	0.967	0.950	0.934	0.918	0.877	0.837	0.797
	0.3	0.980	0.961	0.942	0.924	0.905	0.860	0.816	0.773
	0.4	0.977	0.954	0.932	0.911	0.890	0.839	0.791	0.745
	0.41	0.976	0.953	0.931	0.909	0.888	0.837	0.788	0.742
1.3	0	0.988	0.977	0.965	0.953	0.941	0.910	0.878	0.846
	0.1	0.987	0.973	0.960	0.947	0.933	0.899	0.865	0.829
	0.2	0.985	0.969	0.954	0.939	0.924	0.886	0.948	0.810
	0.3	0.982	0.964	0.947	0.929	0.912	0.870	0.828	0.788
	0.4	0.979	0.958	0.937	0.917	0.897	0.850	0.804	0.760
	0.41	0.978	0.957	0.936	0.915	0.895	0.847	0.801	0.757
1.4	0	0.989	0.978	0.967	0.956	0.945	0.916	0.886	0.856
	0.1	0.988	0.975	0.963	0.950	0.938	0.906	0.873	0.840
(air)	0.2	0.986	0.972	0.957	0.943	0.929	0.893	0.858	0.822
	0.3	0.983	0.967	0.950	0.934	0.918	0.878	0.839	0.800
	0.4	0.980	0.960	0.941	0.922	0.904	0.859	0.815	0.773
	0.41	0.980	0.960	0.940	0.921	0.902	0.857	0.813	0.770
1.66	0	0.991	0.982	0.972	0.963	0.953	0.929	0.903	0.877
	0.1	0.990	0.979	0.969	0.958	0.947	0.920	0.892	0.863
	0.2	0.988	0.976	0.964	0.952	0.939	0.909	0.878	0.846
	0.3	0.986	0.972	0.958	0.944	0.930	0.895	0.861	0.827
	0.4	0.983	0.966	0.950	0.934	0.918	0.878	0.840	0.802
	0.41	0.983	0.966	0.949	0.932	0.916	0.876	0.837	0.799