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Capacities of Stacks in Sanitary Drainage Systems For Buildings

U.S. DEPARTMENT OF COMMERCE

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Capacities of Stacks in Sanitary Drainage Systems for Buildings

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Contents

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Some of the important results obtained in investigations of capacities of plumbing stacks in test systems at the National Bureau of Standards and elsewhere are discussed. Data are shown from experiments on the flow of water and air in such systems, and analyses of certain flow phenomena are given. Methods are shown for applying the results of research in hydraulics and pneumatics to the preparation of loading tables (for drainage and vent stacks) suitable for use in plumbing codes. The need for additional research in further improvement of plumbing codes is discussed.

1. Introduction

1.1. Purpose and Scope of Paper

The lack of an adequate knowledge of the hydraulics and pneumatics of building-drainage systems is one of the most serious handicaps under which the writers of plumbing codes and design handbooks must work. A building-drainage system cannot be designd with maximum economy unless the minimum sizes of pipes that can be used satisfactorily in its various parts can be computed. This is particularly true of a multistory system or of a system serving a low building which covers a large area, since many such systems are large enough and complex enough to afford opportunities for appreciable savings through the application of design methods based on research.

Attempts have been made to determine by experiment the capacities of various components of building-drainage systems. The complexity of the flow phenomena in such systems makes it necessary to simplify test conditions. Unfortunately, this limits the usefulness of the results. Hence, it is not surprising that loading tables in some plumbing codes have been based more on experience and opinion than on rational analysis and experiment. It is certain that the factors of safety used in preparing some loading tables have been excessively large. This leads directly to oversizing of pipes.

The purposes of this paper are:

1. To summarize certain aspects of experimental studies of the hydraulics and pneumatics of plumbing systems conducted at the National Bureau of Standards and other laboratories since 1921, with particular emphasis on some of the results obtained at the National Bureau of Standards during an investigation of the capacities of stacks and horizontal branches;
2. to correlate laboratory data on the flow of water and air obtained in this and other investigations;
3. to illustrate the application of research results to the computation of loads for drainage and vent stacks; and
4. to compare some of the loadings obtained from tables in currently used plumbing codes with loadings computed by methods outlined in this paper.

The most recent laboratory investigation described in this paper comprised four parts:

1. A study of the flow conditions at the junction of a drainage stack and its horizontal branches, using a specially designed flow simulator (simulated stack) with sanitary-tee stack fittings;
2. a study similar to (1), except that long-turn T-Y stack fittings were used;
3. a study similar to (1), except that a multistory test system (prototypal stack), rather than the simulated stack, was used; and
4. a study of miscellaneous items, including air flow in drain and vent pipes; pneumatic pressures in drainage stacks; air content of the layer of water flowing on the wall of a stack, and velocities in this layer. The prototypal stack was used in this part of the investigation.

1.2. General Principles of the Design of Building-Drainage Systems

The drainage system of a building requires two distinct sets of pipes. The first is required to transport the waste water and the water-borne liquid and solid wastes from the plumbing fixtures to the street sewer, septic tank, or other means of disposal. The second set of pipes, the vent system, is required to reduce the intensity of pneumatic disturbances caused by the intermittent use of the plumbing fixtures. The vent system, if properly designed, will prevent excessive depletion of the water seals of the fixture traps. These water seals must be maintained to prevent sewer air from entering the building.

In order that the drainage and vent systems may perform their functions in a manner that meets generally accepted standards of performance and that will not create health hazards or nuisance conditions, the following broad requirements should be satisfied:

1. The dimensions and arrangement of the

various components of the piping systems should be such that normal peak loads of water and water-borne wastes discharged into the drainage system may be carried away by gravity without creating excessive hydrostatic pressures, and that pneumatic-pressure fluctuations in horizontal branches and fixture drains shall not seriously deplete the water seals in fixture traps.

2. The design should be such that noise and vibration due to the flowing water are reduced to a practical minimum.

3. The various sloping pipes in the drainage system should be of such diameters and slopes that self-cleansing velocities will be attained.

4. Adequate, but not excessive, allowance should be made for the effects of fouling and corrosion in the piping systems and for cases where additional loads may be imposed on the system at some future date.

1.3. Definitions

The following definitions of some of the terms used in this paper are given in order to avoid confusion or possible misinterpretation of statements made in the paper. Except for those that are marked with an asterisk, the definitions have been taken from the American Standard National Plumbing Code A40.8–1955 [1].[1]

A *branch interval* is a length of soil or waste stack corresponding in general to a story height, but in no case less than 8 ft within which the horizontal branches from one floor or story of a building are connected to the stack.

The *building* (*house*) *drain* is that part of the lowest piping of a drainage system which receives the discharge from soil, waste, and other drainage pipes inside the walls of the building and conveys it to the building (house) sewer beginning 3 ft outside the building wall.

The **drainage stack* is the vertical main of a drainage system and may be either a soil or a waste stack.

A *drainage system* (drainage piping) includes all the piping within public or private premises, which conveys sewage, rain water, or other liquid wastes to a legal point of disposal, but does not include the mains of a public sewer system or private or public sewage-treatment or disposal plant.

A *fixture unit* is a quantity in terms of which the load-producing effects on the plumbing system of different kinds of plumbing fixtures are expressed on some arbitrarily chosen scale.

A *horizontal branch* is a drain pipe extending laterally from a soil or waste stack or building drain, with or without vertical sections or branches, which receives the discharge from one or more fixture drains and conducts it to the soil or waste stack or to the building (house) drain.

The *main vent* (referred to as the *vent stack* in this paper) is the principal artery of the venting system, to which vent branches may be connected.

The **piezometric head* is the height to which water would rise in a vertical tube connected at its lower end to a pipe containing water and open at its upper end to the atmosphere.

Plumbing fixtures are installed receptacles, devices, or appliances which are supplied with water or which receive or discharge liquids or liquid-borne wastes, with or without discharge into the drainage system to which they may be directly or indirectly connected.

A *soil pipe* is any pipe which conveys the discharge of water closets or fixtures having similar functions, with or without the discharge from other fixtures, to the building drain or building sewer.

A *stack* is the vertical main of a system of soil, waste, or vent piping.

A *stack vent* (sometimes called a waste vent or soil vent) is the extension of a soil or waste stack above the highest horizontal drain connecting to the stack.

**Terminal length* as applied to drainage stacks means the distance through which water discharged into the stack must fall before reaching terminal velocity.

**Terminal velocity* as applied to drainage stacks means the maximum velocity of fall attained by the water in the pipe, whether or not the cross section of the pipe is filled with water.

A *trap* is a fitting or device so designed and constructed as to provide, when properly vented, a liquid seal which will prevent the back passage of air without materially affecting the flow of sewage or waste water through it.

The *trap seal* is the maximum vertical depth of liquid that a trap will retain, measured between the crown weir and the top of the dip of the trap.

A *vent stack* is a vertical vent pipe installed primarily for the purpose of providing circulation of air to and from any part of the drainage system. (In this paper it is to be understood that the developed length of vent stack may include some piping in other than a vertical position.)

A *vent system* is a pipe or pipes installed to provide a flow of air to or from a drainage system or to provide a circulation of air within such system to protect trap seals from siphonage and back pressure.

A *waste pipe* is a pipe which conveys only liquid waste, free of fecal matter.

A *wet vent* is a vent which receives the discharge from wastes other than water closets.

1.4. Nomenclature

The following list of letter symbols used in the analyses and equations appearing in this paper will be useful to the reader. Insofar as possible the symbols used are in agreement with ASA standard Y10.2–1958, Letter Symbols for Hydraulics.

General terms:

A=area of cross section
D=diameter

[1] Figures in brackets indicate the literature references on page 40.

F=force
g=acceleration of gravity
h=head
L=length
p=pressure
Q=volume rate of flow (discharge rate)
R=radius
ρ=mass density (mass per unit volume)
t=time
V=mean velocity
z=elevation above datum

Subscripts:
1=refers to drainage stack
2=refers to horizontal branch
a=refers to air
t=refers to terminal conditions
v=refers to vent
w=refers to water

Special terms:
C_b=head-loss coefficient for bend.
C_L=head-loss coefficient for flow through pipe fittings and transitions in cross section
δ=function of several variables
ΔE=energy loss per unit volume of water due to flow resistance
f=Darcy-Weisbach friction coefficient
F_d=centripetal force required to cause an elementary mass of water to move in a curved path
h_b=head loss due to bend
h_d=Hydrodynamic-pressure head caused by deflection of stream
h_f=head-loss term in Darcy-Weisbach pipe-flow equation resulting from friction
h_1=pneumatic-pressure head in drainage stack
h_2=piezometric head in horizontal branch measured with reference to elevation of stack-branch junction
h_3=height to which water will rise in a vent connecting to a horizontal branch, measured with reference to elevation of stack-branch junction
h_4=pneumatic pressure head in vent connecting to horizontal branch
k_s=Nikuradse sand-roughness magnitude
L_t=terminal length (length of fall required for water in drainage stack to reach terminal velocity)
λ=a dimensionless constant determined by frictional resistance
Δm=mass of elementary volume of water
ν=kinematic viscosity
N_R=Reynolds number, a dimensionless flow parameter
p_d=hydrodynamic pressure caused by deflection of stream (corresponding to the head h_d)
ϕ=functional symbol
r_s=ratio of area of cross section of water stream in a drainage stack to total area of cross section of the stack
R_c=radius of curvature of path followed by stream when deflected
R_h=hydraulic radius, the ratio of cross section of the stream in a drain pipe to its wetted perimeter
T=thickness of layer of water flowing on wall of drainage stack
V_t=mean terminal velocity of water flowing on wall of drainage stack
ζ=deflection coefficient applicable to head loss in pipe bend

2. Previous Research on Capacities of Drainage and Vent Stacks

Attempts have been made to obtain knowledge of the flow and pressure conditions in stacks and thus to offer a rational basis for computing stack loadings. This has been difficult, for not enough has been known about the conditions in stacks to permit the establishment of a wholly satisfactory criterion for stack capacity. Hunter at the National Bureau of Standards, Dawson and Kalinske at the State University of Iowa, and Babbitt at the University of Illinois have done research on stack capacities.

2.1. National Bureau of Standards

Some of the first clear statements regarding the nature of flow in drainage stacks and a definition of stack capacity were reported by Hunter in 1923 [2]. From tests, he found that the character of flow in a partially filled vertical pipe varied with the extent to which the pipe was filled. For low rates of flow, the water was entirely on the wall of the stack; but as the flow rate was increased, the frictional resistance of the air caused the formation of short slugs of water. Increased air pressure generated by the slugs caused the water to be thrown to the wall of the stack either immediately or after falling for some distance separated into streamlets in the center of the pipe. Hunter observed that slug formation occurred in a 3-in. stack when the water-flow rate was increased to a value such that the flowing water occupied ¼ to ⅓ of the cross section of the stack. A further increase in rate of flow resulted in closely spaced slugs that did not break up readily. Hunter believed that intermittent slug formation is partially responsible for the rapid oscillations of pressure which occur in plumbing systems.

Hydrostatic head can develop in a drainage stack only when it is filled with water at some point. In the case of a stack which receives water at one elevation only, this condition would first occur at the elevation of water entrance, where the downward velocity is least.

The vertical component of the entrance velocity depends on the rate of flow by volume, the cross-sectional area of the inlet, and the angle of the entrance. This points to the capacity of the fitting as a measure of the practical capacity of the stack. (Hunter was probably thinking here of one- and two-story stacks.)

Hunter defined *fitting capacity* as the rate of flow in gallons per minute at which the water just begins to build up in the stack above the inlet branch of the fitting when no water is flowing down the stack from a higher level.

Determinations of fitting capacity were made for different type fittings on both 2- and 3-in. stacks with the water introduced at one level. It was observed that the rate of flow that caused the water to stand above the fitting inlet was greatly in excess of the rate at which the tendency to build up first appeared.

Some tests were made with inlets at two levels approximately 11 ft apart. Various rates of flow were introduced into the stack through the inlets. Any backflow into an L-shaped tube set in a side inlet of the lower fitting was taken to indicate that the fitting capacity had been exceeded. The tendency was toward an increase in capacity with water introduced at two levels instead of one. Hunter's tests indicated that stack capacity may increase with the number of inlets until the point is reached when the stack is flowing full throughout its length. From this line of reasoning, he concluded that the fitting capacities which he had determined for stacks with inlets at one level only would be less than the capacities of stacks having inlets at more than one level, and that such *fitting capacities* could be safely, but not necessarily economically, utilized as *stack capacities* for all heights of stack.

From his tests, Hunter decided that safe values for stack capacity could be computed from the equation

$$Q=kD^2, \quad (1)$$

where Q is expressed in gallons per minute, and D in inches. He gives the values

$k=22.5$ for 45° Y inlets, and
$k=11.25$ for sanitary-tee inlets.

On the basis of this reasoning and the experimental results with 2- and 3-in. stacks, he gave a table of stack capacities in BH13 [3] (see table 1).

The tests which form the basis of table 1 were made with water introduced through double-branch fittings at one level only. Hunter reported no quantitative results for the tests in which water was introduced into the stack at more than one level.

An illustration of a case in which the fitting capacity has been exceeded is shown in figure 1. This photograph was taken in the course of the most recent investigation of stack capacities at the National Bureau of Standards. It shows a 3-in. double sanitary tee with 3-in. side inlets made of transparent plastic material with its inside dimensions closely simulating those of the corresponding metal fitting. Flows of about 100 gpm are entering the fitting from each horizontal branch, but there is no flow down the stack from above the branch level. It will be observed that the water is standing up in the stack somewhat above the level of the branches. According to Hunter's formula (eq (1), using the value 11.25 for k), the capacity of the fitting is approximately 100 gpm. Therefore, it might be expected that a flow of 200 gpm would overload the fitting.

TABLE 1. *Practical carrying capacities of stacks* [a]

(Hunter)

Diameter of stack	Practical carrying capacity	
	Sanitary-tee fittings	Y or Y-and-⅛-bend fittings
in.	*gpm*	*gpm*
2	[b] 45	[b] 90
3	[b] 100	[b] 200
4	180	360
5	280	560
6	405	810
8	720	1,440

[a] For water introduced at one elevation only, through double-branch fittings.
[b] Carrying capacities for the 2- and 3-in. stacks were determined by experiment. The values for larger diameters were computed from eq (1).

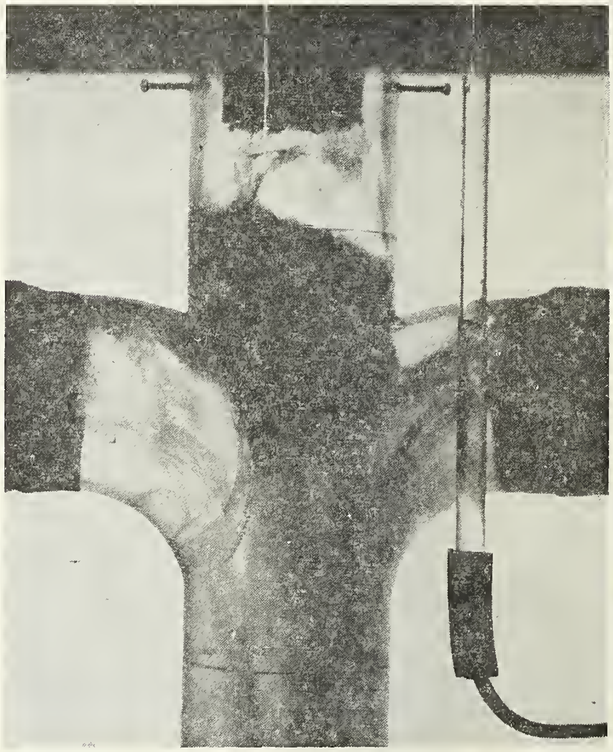

FIGURE 1. *Flow into 3-in. stack from two horizontal branches at same level, showing case in which the capacity of the fitting is exceeded (double sanitary tee fitting).*

Total flow from branches is approximately 200 gpm. No flow down stack from higher levels.

With further reference to Hunter's work [3], consideration of the design criterion that no hydrostatic head may develop in a drainage system indicates that carrying capacity for a given diameter will be less in a horizontal section of the system than in a vertical section. This suggests separate consideration of vertical and horizontal sections.

The fact that an appreciable head of water in any portion of a drainage system into which branches discharge tends to impair the efficiency of the drainage indicates a limiting condition on which to base computations of permissible capacities. Hunter felt that although an occasional head of water in certain portions of a drainage system may not be harmful, the assumption of a condition under which no head can develop in any portion of the stack or house drain is certainly a safe procedure and apparently the only one that will permit a general application of test results.

One of the most significant criteria for drainage-stack capacity suggested by Hunter is that where terminal velocity exists, a stack should not be loaded to such an extent that more than ¼ to ⅓ of the cross section of the stack is filled with water. Some such limit is required to prevent the occurrence of serious pneumatic disturbances associated with excessive rates of water flow.

It is necessary to have information on velocities in drainage stacks before computing rates of flow that will produce a water-occupied cross section bearing a given ratio to the stack cross section. Hunter [2, 4] made measurements of terminal velocities in vertical pipes, on one occasion with the pipes flowing full and on another with them flowing partially full.

He measured the rate of fall of water columns in vertical pipes up to 100 ft in height, using 1-, 2-, and 3-in. galvanized steel pipe. His experimental procedure was as follows: Gage holes were tapped in the pipe at intervals of 10 ft. A quick-opening valve was installed at the bottom of the pipe. With the valve closed, the pipe was filled with water to the level of the first gage hole. The valve was then opened quickly, and the time required for the water to flow out of the pipe was observed. This process was repeated, the pipe being filled to the height of each gage hole successively. To obtain the terminal velocity for each diameter of pipe, he plotted the lengths of the falling column as ordinates and the times of descent as abscissas. This gave a straight line in the region where the water was falling at terminal velocity, and the slope of this line gave the terminal velocity.

In order to establish limits within which the measured terminal velocities should lie, he computed terminal velocities for smooth and for very rough pipe over a range of diameters of from 1 to 8 in. These curves, together with the experimentally determined velocities, are shown in figure 2. The three experimental points lie

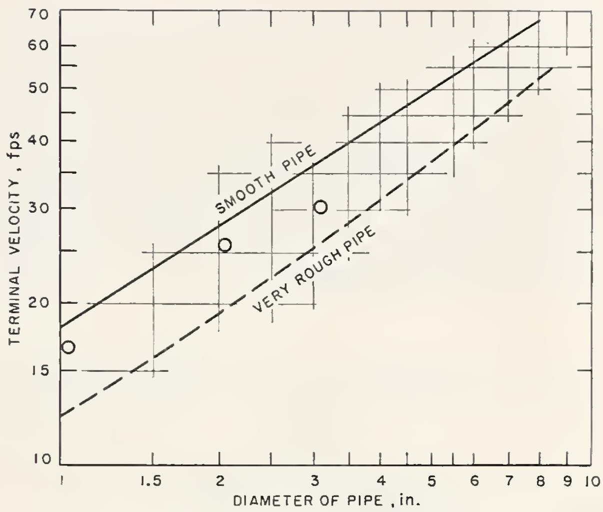

FIGURE 2. *Terminal velocities in vertical pipes flowing full under the force of gravity.*

between the two curves, as they should, and, as would be expected, they are closer to the curve for smooth pipe than to the curve for very rough pipe. Because of this satisfactory agreement of the experimental values with the values given by the smooth-pipe curve, Hunter concluded that the smooth-pipe curve given in figure 2 might be used to set the upper limit of terminal velocities for flow out of stacks completely filled with water.

Hunter [2] also measured velocities in 2- and 3-in. cast-iron stacks flowing partly full. He used a 3-in. stack 45 ft in height, open top and bottom, and introduced the water through a 45° double-Y fitting at the top of the stack. The velocities were measured with a pitot tube at the bottom of the stack. Various heights of fall of from 5 to 45 ft were used. From these tests, he found the terminal velocity of flow in the 3-in. stack to be about 16.8 fps, attained in a height of about 15 ft for a flow of 100 gpm; and 32.8 fps, attained in a height of about 45 ft for a flow of 200 gpm.

The tests on a 2-in. stack showed that in a fall of about 20 ft for a flow of 45 gpm, a terminal velocity of 18.5 fps was attained; and for a flow of 90 gpm, a terminal velocity of 24 fps was attained.

Hunter remarks that with flows of 90 gpm in the 2-in. stack and 200 gpm in the 3-in. stack, slugs of water completely filling a short length of the pipe occasionally formed, and the maximum velocity of these slugs approached the maximum velocity for a completely filled stack.

Up to this point, the discussion of Hunter's work has been confined to drainage stacks. He also studied problems of venting. It seems appropriate to mention briefly a method which he proposed for sizing vent stacks [3]. He suggested that the formula

$$(y-a)\,(x-b)=c \qquad (2)$$

be used. In this equation, y is the volume rate of water flow in gallons per minute divided by 7.5 (Hunter at that time having conceived of the "fixture unit" as a volume rate of discharge equal to 7.5 gpm); x is the length of vent stack (main vent) in feet; and a, b, and c are constants. The curve is asymptotic to the lines $y=a$ and $x=b$. By the use of certain experimental data, Hunter computed values of a, b, and c. These values are given in table 2 for vent stacks and drainage stacks of the same diameter.

TABLE 2. *Computed constants for use in venting equation*

(Hunter)

Diameter of both drainage stack and vent stack	Values of constants		
	a	b	c
in.			
3	6	33	5,780
4	8	27	11,400
5	10	20	20,280
6	12	16	31,240
8	16	12	81,040

2.2. Universities

Dawson and Kalinske at the State University of Iowa prepared two reports on an investigation of stack capacities [5, 6]. Measurements were reported of volume rates of water and air flow, pneumatic pressures, and maximum water velocities in stacks 3, 4, and 6 in. in diam and approximately 30 ft high. Each stack discharged into a short horizontal drain through a 90° bend. Various rates of flow were introduced through a horizontal branch near the top of the stack, and pressures and velocities were measured at several points down the stack.

From their tests, Dawson and Kalinske concluded that where the water attains its maximum velocity, a drainage stack should not be allowed to flow more than about one-fourth full. They felt that this criterion is a reasonable choice, since the velocity in the building drain and building sewer flowing full but not under pressure some distance from the base of the stack is roughly of the order of one-fourth of the terminal velocity in the stack. They had observed in tests that a stack flowing too full caused considerable noise and vibration, as well as pneumatic disturbances.

Dawson and Kalinske observed, as did Hunter, that too great a rate of discharge into a drainage stack at any one level caused the stack to fill up at that point due to the small vertical component of velocity of the incoming stream. Because of the pneumatic and hydraulic disturbances which are created by this condition, they concluded that the rate of flow into the stack at any one floor level must be limited. They suggested that if sanitary-tee fittings are used, the rate of flow introduced within any one branch interval should not exceed one-third of the maximum for the stack; while if 45° Y connections are used, the flow rate introduced within any one branch interval should be limited to one-half of the maximum for the stack.

Table 3 gives the maximum carrying capacities of drainage stacks suggested by Dawson and Kalinske.

TABLE 3. *Maximum carrying capacities of stacks*

(Dawson and Kalinske)

Diameter of stack	Carrying capacity
in.	*gpm*
3	90
4	180
5	350
6	560
8	1,200

The carrying capacities given in table 3 differ considerably from those in table 1 for some cases. This difference may be explained partly on the basis that table 1 really gives *fitting* capacities as indicated by a filling up of the stack with water near the fitting, while table 3 gives *stack* capacities computed for a given water-occupied cross section where terminal velocity exists in the stack some distance below the fitting. Thus, the two tables are based on different phenomena.

The measurements of terminal velocities made by Dawson and Kalinske with a pitot tube are shown in table 4. From the velocities given in

TABLE 4. *Terminal velocities in vertical pipes flowing partly full* [a]

(Dawson and Kalinske)

Diameter [b] of stack	Discharge rate (measured)	Thickness of sheet (computed)	Terminal velocity (measured)
in.	*gpm*	*in.*	*fps*
3	45	0.136	11.5
3	90	.209	15.4
3	135	.281	17.6
3	180	.346	19.5
4	90	.141	16.8
4	135	.189	19.0
4	190	.252	20.4
4	240	.311	21.2
4	300	.382	22.0
6	115	.162	12.3
6	165	.199	14.4
6	220	.221	17.4
6	345	.281	21.7
6	450	.320	25.0
6	560	.379	26.5
6	675	.446	27.5

[a] Water introduced at one elevation.
[b] Nominal diameters. Thickness of sheet computed on basis of actual diameter of standard-weight steel pipe.

TABLE 5. *Terminal velocities in vertical pipes flowing partly full* [a]

(Hunter)

Diameter [b] of stack	Discharge rate (measured)	Thickness of sheet (computed)	Terminal velocity (measured)
in.	*gpm*	*in.*	*fps*
3	100	0.219	16.8
3	200	.215	34.2
2	45	.133	18.5
2	90	.215	24.0

[a] Water introduced at one elevation.
[b] Nominal diameter. Thickness of sheet computed on basis of nominal diameter. No measurements on actual diameters were reported by Hunter for these tests.

the table, the cross-sectional areas, A_1, of the sheets of water were computed from the known values of the flow rates. The thickness, T, of the sheet in each case was then computed from the equation

$$A_1=\pi(D_1-T)T. \tag{3}$$

The values thus obtained are also given in table 4. The same computations were made from Hunter's data on terminal velocities in stacks flowing partly full and the results are given in table 5.

Dawson and Kalinske [5] derived the following expression for terminal velocity, which is expressed here in the notation of the present paper for simplicity of comparison with eq (37):

$$V_t=(Q_1 g/\pi k D_1)^{1/3} \tag{4}$$

After analysis of the factors which affect the friction coefficient k in eq (4), they concluded [6] that terminal velocities could be computed from the equation

$$V_t=3.9\left(\frac{Q_1}{D_1}\right)^{2/5} \tag{5}$$

in which V_t is expressed in feet per second, Q_1 in gallons per minute, and D_1 in inches. The data on measured velocities shown in tables 4 and 5 have been plotted in figure 3. The curve in the figure has been computed from eq (5).

The problem of computing sizes of vent stacks was studied by Dawson and Kalinske, along with the problem of sizing drainage stacks [6]. They developed a table of vent-stack sizes based on test data from the 3-, 4-, and 6-in. drainage stacks described above and on the assumption that the air flow carried by the vent stack is proportional to the product of the terminal water velocity times the cross-sectional area of the drainage stack not filled with water.

Babbitt of the University of Illinois published the results of stack tests [7]. Much of his work related to variations of pressure in the stacks with flow. He gives a discussion of "The useful capacity of 2-, 3-, and 4-in. soil stacks," in which he

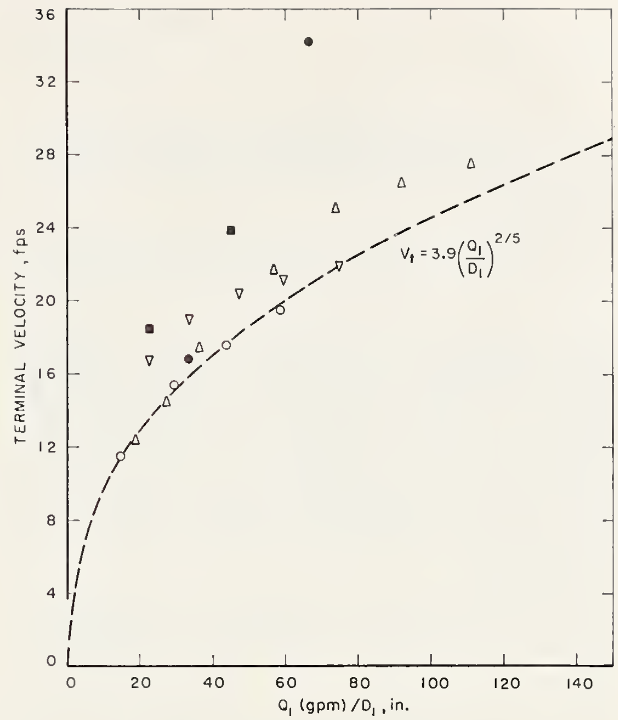

FIGURE 3. *Terminal velocities in vertical pipes flowing partially filled under the force of gravity.*

○, Dawson .... 3-in. stack
▽, ...do .... 4-in. stack
△, ...do .... 6-in. stack
■, Hunter .... 2-in. stack
●, ...do .... 3-in. stack

discusses the capacity of a soil stack to receive the discharge from plumbing fixtures. He states that a 4-in. soil stack will probably take all the water that would be delivered to it in a 5-story building, a 3-in. soil stack will probably take all the water that would be delivered to it in a 3-story residence, and a 2-in. pipe is unsuitable to be used as a soil stack. He found from tests on a 4-in. and on a 5-in. drainage stack [8] that the capacities were 200 and 500 gpm, respectively.

Babbitt also made tests [7] to determine the rate at which one horizontal waste pipe of the same diameter as the soil stack can discharge water into the soil stack through a sanitary-tee fitting without backing up water in the system at the point of junction. He gives the following values:

"2-in. soil stack, 25 gal per min for 7 seconds; 3-in. soil stack, 50 gal per min for 7 seconds; and 4-in. soil stack, 100 gal per min for 7 seconds."

Based on his test data and on empirical reasoning, Babbitt gives a series of tables for sizing vent pipes for 3- and 4-in. drainage stacks for various volume rates of water flow. However, he gives no venting tables for larger diameters of drainage stacks.

3. Test Equipment and Procedures

3.1. Tests on Interference of Flows at Junction of Drainage Stack and Horizontal Branches

a. Simulated Stack—Sanitary-Tee and Long-Turn T-Y Fittings

In the most recent National Bureau of Standards investigation of stack capacities, a simulated stack was first used which provided greater flexibility of experimental conditions and better control of pertinent variables than could be provided by the use of a prototype. Figure 4 shows this equipment in some detail. To connect the stack and the horizontal branches, sanitary-tee stack fittings were used first, followed by long-turn T-Y fittings.

In this part of the investigation as well as in those parts described under sections 3.2 and 3.3, water was delivered to the test system from a constant-level supply tank. The rates of discharge to the stack and the horizontal branches were measured by means of calibrated orifice meters.

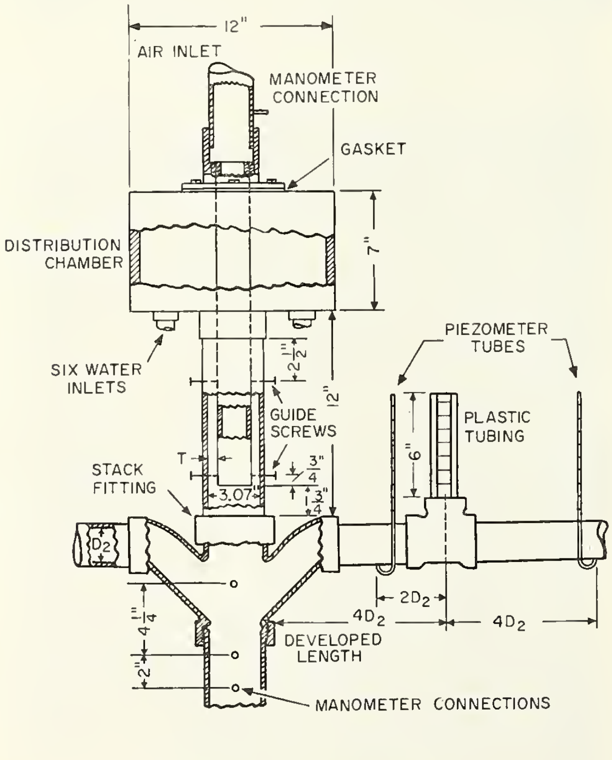

Figure 4. *Simulated stack.*

In the simulated stack, the layer of water flowing down the stack was produced at the level of the stack fitting by installing, in the stack just above the fitting through which the horizontal branches discharged, a second piece of pipe, smaller in diameter than the stack. As can be seen in figure 4, the stack terminated at its upper end in a chamber or drum supplied with water around its circumference through six 1-in. diam pipes. This construction caused water to discharge through the annular space between the stack and the inserted pipe, thus forming a moving blanket of water which simulated the layer that under service conditions is assumed to be flowing down the stack from higher floors. The diameter of the inserted pipe determined the thickness of the layer, and the volume rate at which water was introduced into the drum determined the velocity of flow.

Numerous tests were made on the simulated stack with one- and two-branch flow, for pneumatic pressures in the stack from 0.3 to 2.0 in. of water below atmospheric. Three diameters of horizontal branches were used on the 3-in. stack—1½, 2, and 3 in. Data were obtained for water-layer thicknesses of 0.16, 0.35, and 0.58 in. Thus, the tests provided nine different combinations of dimensions for which pressures and rates of flow were measured in the stack and horizontal branches.

b. Prototypal Stack—Sanitary-Tee Fittings

Because conditions existing in the simulated-stack tests did not exactly correspond to conditions in a typical multistory drainage stack in service, a part of the investigation was repeated using a prototypal stack with six branch intervals, a building drain, and a system of ventilating pipes. The important elements of this system are shown in figure 5.

In making these tests, the system was arranged so that the pneumatic pressure in the drainage stack was transmitted from the stack through a special connection to the horizontal branch at a point 4 drain diameters from the stack, as shown in figure 6. Thus, the pneumatic pressure acting on the water in the horizontal branch was the same as that in the stack, assuming equal aspirating effects at the two branch connections. Measurements with no water flowing in the branch indicated that the aspirating effects at opposite sides of the fitting did not differ by more than 0.1 in. of water for rates of flow of up to 100 gpm in the stack. Therefore, it will be assumed that the head of water indicated in the sight glass attached to the horizontal branch showed directly the difference between the total pressure in the

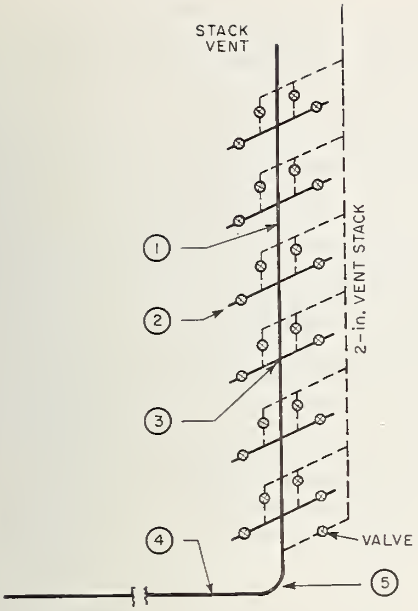

FIGURE 5. *Prototypal stack.*

1. 3-in. galvanized-steel drainage stack.
2. Horizontal branches with controlled supply of water.
3. Sanitary crosses at 8-ft intervals.
4. 4-in. cast-iron soil-pipe building drain, 50 ft long at a slope of ¼ in. per ft.
5. 4-in. long-sweep bend.

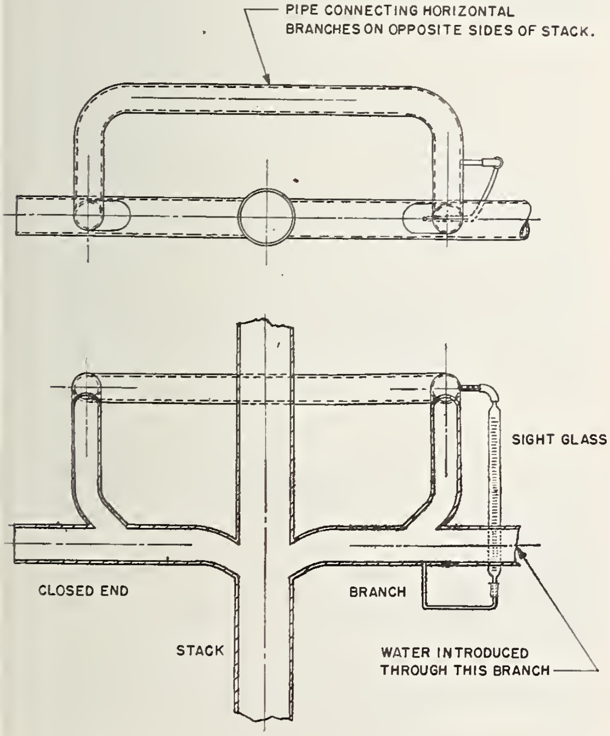

FIGURE 6. *Method for equalizing pneumatic pressures in stack and in horizontal branches.*

horizontal branch and that in the stack. This eliminated the need for actually measuring the fluctuating pneumatic pressure in the stack. It was possible to obtain relatively steady readings in most of the tests by the use of this system.

Water was introduced into the stack through a double 3- by 3-in. sanitary-tee fitting (sanitary cross) 24 ft above the horizontal branch under observation. All the water entering this fitting was introduced through one side for flows of up to about 100 gpm. For flows exceeding 100 gpm, the excess was introduced through the opposite side. For each flow introduced at this point, several different rates of flow were introduced through the single branch under observation, this branch being connected to the stack through one side of a sanitary cross, as shown in figure 6. Branch diameters of 1½ and 3 in. were selected for observation. Measurements were made of the rates of flow in the stack and in the branch, and of the head of water in the sight glass. Water velocities in the stack at the level of the horizontal branch were not measured in these tests but were computed by the method described in section 4.2. of this paper.

3.2. Tests on Air Flow in Stack Vent and in Vent to Horizontal Branch

Measurements of air flow in a 3-in. stack vent and in a 2-in. vent to a 3-in. horizontal branch were made on the test system shown in figure 5. Figure 7 shows in detail the piping arrangement at the horizontal branch to which air was delivered through the 2-in. vent. Measurements were made of air flow in the vents and of the pressure drop across the layer of water flowing on the wall of the stack.

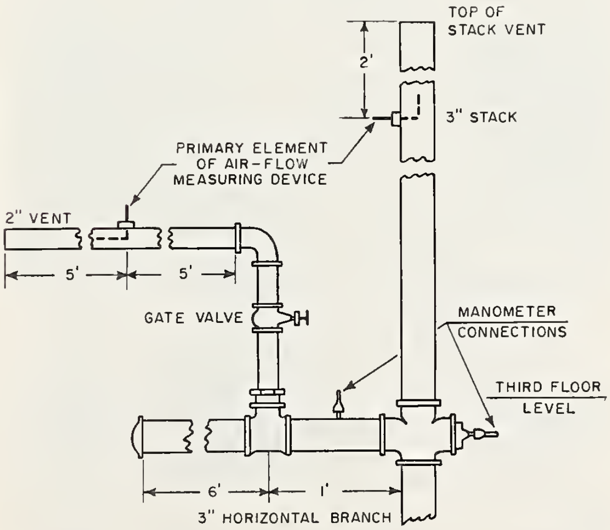

FIGURE 7. *Method for measuring air flow in venting system.*

Water was introduced 32 ft above the base of the stack (except in a few tests in which this distance was 48 ft) through one side of a 3- by 3-in. sanitary cross, and the flow of air was measured in the stack vent and in the vent to the horizontal branch shown in figure 7. This branch was at an elevation 24 ft above the base of the stack. Sanitary crosses were inserted at intervals of 8 ft in this installation, as shown in figure 5.

Before beginning these tests, all the vents were closed except the stack vent and the vent connecting to the horizontal branch at the 24-ft level. The pneumatic pressure in this horizontal branch could be controlled at will by the degree of closure of a valve placed in the vent (see figure 7). The stack vent was fully open in some of the tests and completely closed in others. Each horizontal branch, except the one through which the water was introduced, was closed. A device utilizing the principle of the hot-wire anemometer was used for measuring the air velocity at the axis of the vent to the branch and at the axis of the stack vent. Because the primary element of this device was placed at the axis of the pipes, a correction was applied to the measured values in order to obtain approximately the mean velocities instead of the velocities at the axis. In making these corrections, mean velocity was assumed to be 0.8 of the axial velocity, this value being in approximate agreement, for a value of the Darcy-Weisbach friction coefficient f of 0.03, with an equation given by Rouse [9]. The volume rates of air flow were computed in accordance with the formula, $Q=AV$.

In some of the tests, the difference between the pneumatic pressure in the horizontal branch and that in the opposite side of the 3- by 3-in. sanitary cross to which the horizontal branch was connected was measured when air was flowing in the branch. The inclined differential manometer used for these measurements indicated approximately the difference between the pneumatic pressure within the branch and that in the interior of the stack at the level of the branch. A small correction was actually applied, obtained by noting the reading on the manometer when water was introduced into the stack while preventing the entrance of air into the branch. The need for this correction probably was the result of a slight difference in the aspirating effect of the flow of water past the opposite openings of the sanitary cross. The correction varied from 0.06 in. to 0.09 in. of water, increasing with rate of water flow in the stack.

3.3. Miscellaneous Tests

a. Distribution of Air and Water in Cross Section of 3-in. Drainage Stack

In order to investigate the distribution of air and water in the cross section of a drainage stack, the test system shown in figure 5 was employed. A volume rate of water flow of 100 gpm was introduced 48 ft above the base of the stack, and sampling measurements were made just above the branch at the 16-ft level, approximately 31.5 ft below the point where water was introduced. All the vents on the test system were open; hence the flow conditions should have approximated those to be expected in service for a flow rate of 100 gpm. Figure 8 shows the principal parts of the special equipment used for sampling the flow in the stack. An impact tube of $\frac{1}{16}$-in. inside diameter, inserted into the stack with its opening facing directly upward, was used to make a traverse of the diameter. The impingement of flow onto the tip of the impact tube forced air and water through the tube and delivered it at the base of the transparent cylinder shown in the figure. At the beginning of a test, the transparent cylinder (closed at the upper end) was first filled with water and the reservoir of water around the base of the cylinder was filled to the overflow-weir level. As the impact tube delivered a mixture of air and water at the base of the cylinder, the air rose to the top and displaced the water therein until the cylinder contained only air. The water displaced from the cylinder, plus that delivered by the impact tube, was caught in a graduated measure. Thus, as the quantity of water originally contained by the inverted transparent cylinder was known, and as the quantity of water flowing over the weir, and the time required to displace a given volume of water in the cylinder could easily be measured, it was a simple matter to compute the average rates at which air and water were delivered to the cylinder.

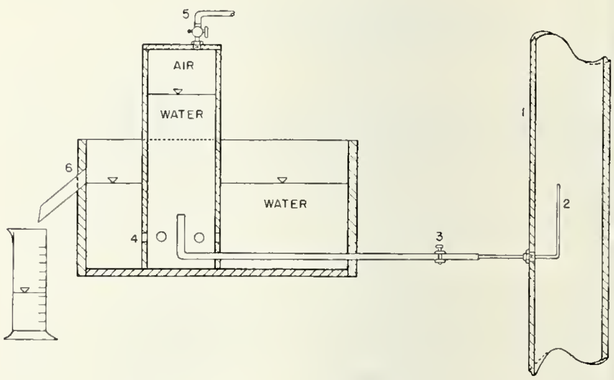

FIGURE 8. *Method for sampling air-water mixture flowing in stack.*

1. 3-in. drainage stack.
2. Sampling tube.
3. Hose clamp.
4. Circular openings.
5. Petcock and connection to vacuum source.
6. Overflow weir at same elevation as tip of sampling tube.
7. Graduated measuring vessel.

b. Velocity Distribution of Water in Cross Section of 3-in. Drainage Stack

Data on the distribution of water velocity across a diameter of the 3-in. stack shown in figure 5 were obtained for water flows of 60, 80, and 100 gpm. These data were taken at the same point at which the data described under (a) above were taken.

A static-pressure tube was inserted through the wall of the stack for the purpose of obtaining the pneumatic pressure inside the stack, which was indicated on an inclined manometer. The impact tube described under (a) above was connected to a single-leg manometer. The impact tube had been calibrated by towing it through still water at known velocities. By taking the difference between the readings obtained for the impact tube and those obtained for the static-pressure tube and referring to the calibration curve, corresponding velocities were indicated.

c. Vertical Distribution of Pneumatic Pressures within 3-in. Drainage Stack

The effect of rate and vertical distribution of water flow on pneumatic pressures within a drainage stack was studied experimentally by means of the test system shown in figure 5. In the first series of tests, water was introduced at one point 32 ft above the base of the stack. In the second series, water was introduced simultaneously at two points, 32 ft and 16 ft above the base of the stack. In each of these two series of tests, measurements of pneumatic pressures within the stack were made by means of a small static-pressure tube inserted through the side of the stack successively at a number of points distributed vertically. Data were obtained both with the venting system functioning and with all vent pipes except the stack vent closed by valves. Water-flow rates of 60 and 100 gpm were introduced at the higher point, and rates of 30 and 60 gpm were introduced at the lower point. In each case, the flow was delivered through one side of a 3- by 3-in. sanitary cross.

4. Analysis of Flow Conditions in Plumbing Stacks

4.1. Interference of Flows at Junction of Drainage Stack and Horizontal Branches

The flow from a horizontal branch into a multistory drainage stack will encounter a resistance when it meets the high-velocity blanket of water which may simultaneously flow downward on the wall of the stack. This resistance creates a backpressure (head of water) in the branch as a result of momentum changes in both the horizontal and the vertical streams. These changes are caused by the deflection of one stream by the other (see fig. 9). If the two flows become sufficiently large, the backpressure becomes excessive and interferes with the normal operation of the drainage system. The problem is to estimate the maximum rates of flow which can occur simultaneously in the stack and the horizontal branch without creating an excessive head of water in the branch. The analysis of the problem can be based on either the law of conservation of momentum or the law of conservation of energy. Because of the geometry of long-turn T-Y stack fittings, the law of conservation of energy is easier to apply in the case of such fittings than is the momentum law. Actually, the momentum law was used in an earlier paper [10] which reported the results of tests on the simulated stack using sanitary-tee fittings. The analysis of the problem made in this paper begins with an application of the law of conservation of energy.

Figure 10 shows the various terms which will be used in the analysis. The piezometer shown in this figure is for the purpose of the analysis only.

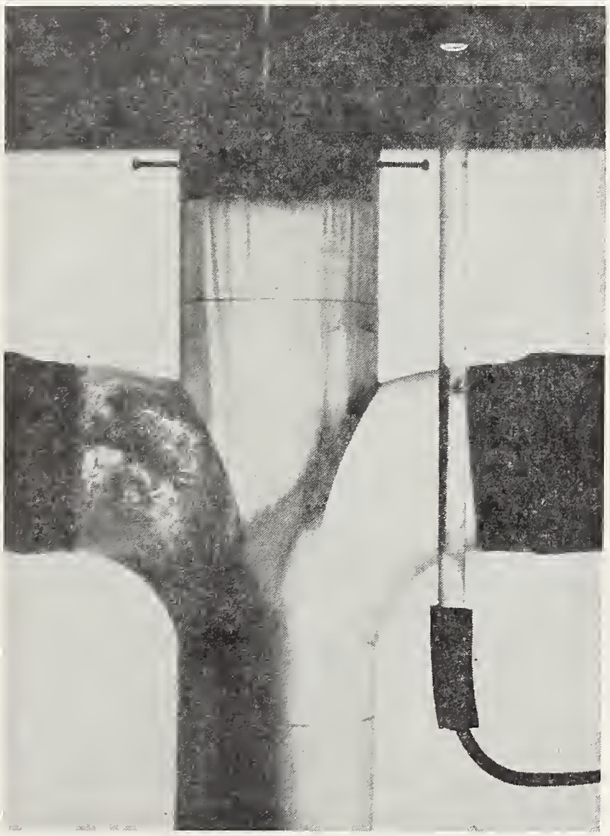

Figure 9. *Hydrodynamic backpressure in horizontal branch caused by mutual interference of flow in stack and in one horizontal branch.*

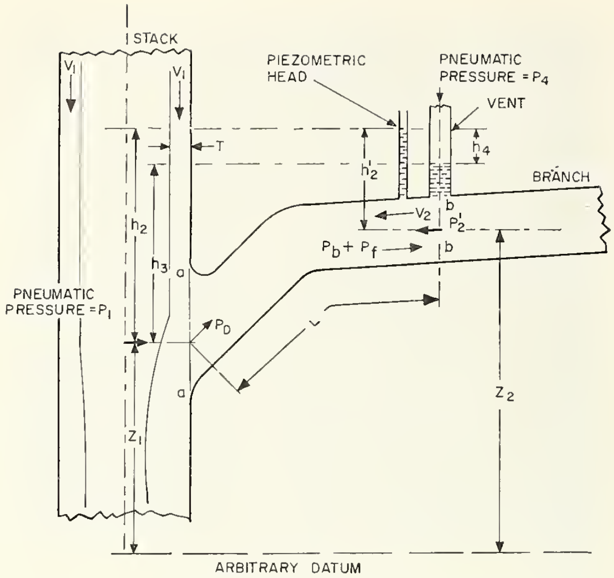

FIGURE 10. *Definition sketch showing symbols used in analysis of mutual interference of flows at stack-branch junction.*

It shows the peizometric head (the height to which the water in the branch would rise through a tube open to the atmosphere at the upper end). This head may or may not be the same as the height to which water rises in the branch or in a vent pipe connected thereto when excessive rates of flow occur simultaneously in the stack and horizontal branch. The extent to which the piezometric head and the actual water level inside the pipe differ depends on the pneumatic head in the vent h_4, which may be either positive or negative. Pressures will be expressed in height of water column through the relationship $p=\rho_w gh$. The analysis will begin by considering the change in energy of the stream of water flowing in the branch as it passes from section b-b (mean elevation z_2) to section a-a (mean elevation z_1).

The mean flux of energy through the upstream section b-b per unit volume of water flowing in the branch is

$$\rho_w g\left(\frac{V_2^2}{2g}+h_2'+z_2\right)$$

and the flux of energy through the downstream section a-a at the plane of impact with the flowing water in the stack is

$$\rho_w g\left(\frac{V_a^2}{2g}+h_a+z_1\right),$$

where V_a is the mean velocity and h_a the mean pressure head at the section of impact of the two streams.

From continuity considerations, it appears reasonable to assume that V_a is approximately equal to V_2, and it is convenient to assume that the effective mean pressure head h_a over the impact section can be represented by the sum of the pneumatic pressure head, h_1, in the stack and a dynamic pressure head, h_d, related to the curvilinear flow produced by the deflection of the stack stream by the branch stream. Thus, it is assumed that $V_a=V_2$, and $h_a=h_1+h_d$. Under these assumptions, the flux of energy through section a-a can be expressed as

$$\rho_w g\left[\frac{(V_2)^2}{2g}+h_1+h_d+z_1\right].$$

The difference between the unit flux of energy at sections b-b and a-a represents the amount of energy lost by a unit volume of water in passing from the upstream section to the downstream section. This energy loss is caused by friction in the horizontal branch and stack fitting and by the change in direction of flow produced by the fitting, and may be expressed as

$$\Delta E=\rho_w g(h_2'-h_1-h_d+z_2-z_1). \tag{6}$$

The energy loss per unit volume of water flowing through a straight pipe due to friction can be expressed as

$$\rho_w g h_f,$$

where h_f is the head loss computed from the Darcy-Weisbach formula for pipe flow.

The energy loss per unit volume due to the presence of a bend in a pipe can be expressed as

$$\rho_w g h_b,$$

where h_b is the head loss due to the bend. In a long pipe having a bend in an intermediate location, the bend loss is the sum of two components, one of which is due solely to the deflection of the stream filaments by the bend (the deflection component) and the other of which is due to the velocity disturbance caused by flow around the bend and which extends a considerable distance downstream of the bend (the tangential component). In the case under consideration the downstream section is missing, for all practical purposes. Therefore, it is reasonable to assume here that only the deflection component ζ of the bend-loss coefficient is effective. This assumption makes it possible to express the head loss between the upstream and downstream sections caused by pipe friction and by deflection of the stream filaments by the bend as

$$h_f+h_b=f\frac{L}{D_2}\frac{(V_2)^2}{2g}+\zeta\frac{(V_2)^2}{2g}. \tag{7}$$

Therefore, the energy loss per unit volume of water flowing between sections b–b and a–a due to the two causes may be expressed as

$$\Delta E=\rho_w g\frac{(V_2)^2}{2g}\left(f\frac{L}{D_2}+\zeta\right). \tag{8}$$

Substituting in eq (6), the expression $h_2' = h_2 - z_2 + z_1$ (see fig. 10), substituting the right member of eq (8) for ΔE, and dividing by $\rho_w g$, the following equation is obtained:

$$h_2 - h_1 - h_d = \left(f\frac{L}{D_2} + \zeta\right)\frac{(V_2)^2}{2g} \qquad (9)[3]$$

All the quantities in eq (9) can be measured or estimated approximately except the dynamic head, h_d. The interaction between the layer of water flowing in the stack and the flow from the branch is too complicated to analyze, except in a very general and approximate way. In making this analysis, it is assumed that the flow lines in the layer of water flowing down the stack are changed from straight lines to arcs of circles of radius R_c by the stream from the branch (see fig. 11). Obviously, this is a simplifying assumption that is not entirely correct, yet it does result in an equation which agrees fairly well with data obtained by experiment over a wide range of conditions.

Under this assumption, summing up the centripetal forces which the flow from the branch exerts on all the elementary volumes in the water layer in the stack subject to deflection (figs. 11a and 11b) results in the expression:

$$F_d = \sum \frac{\Delta m (V_1)^2}{R_c} = \sum \frac{\rho_w T \Delta s \Delta b (V_1)^2}{R_c}, \qquad (10)$$

where Δm is the mass of the elementary volume $T\Delta s\Delta b$. Then, if an average value of R_c for all elementary volumes is assumed,

$$p_d = \frac{F_d}{\Sigma \Delta s \Delta b} = \rho_w \frac{T}{R_c}(V_1)^2. \qquad (11)$$

It follows then that

$$h_d = \frac{T}{R_c g}(V_1)^2, \qquad (12)$$

and, substituting this result in eq (9), the following equation is obtained:

$$h_2 - h_1 = \frac{2T}{R_c}\frac{(V_1)^2}{2g} + \left(f\frac{L}{D_2} + \zeta\right)\frac{(V_2)^2}{2g}. \qquad (13)$$

Dividing by $h_2 - h_1$ and rearranging terms gives the equation

$$\left(f\frac{L}{D_2} + \zeta\right)\frac{(V_2)^2}{2g(h_2 - h_1)} = 1 - \frac{2T}{R_c}\frac{(V_1)^2}{2g(h_2 - h_1)}. \qquad (14)$$

All of the quantities in eq (14), except the radius of curvature of the flow lines, are subject to determination, by measurement or otherwise. The quantity R_c will now be considered in more detail.

[3] This equation is identical to eq (27) of the earlier paper [10] except for the inclusion of the bend-loss coefficient in eq (9) above. In the earlier paper, which reported results of an experiment using sanitary-tee fittings only, it was assumed that the bend loss due to the geometry of the fitting was negligible.

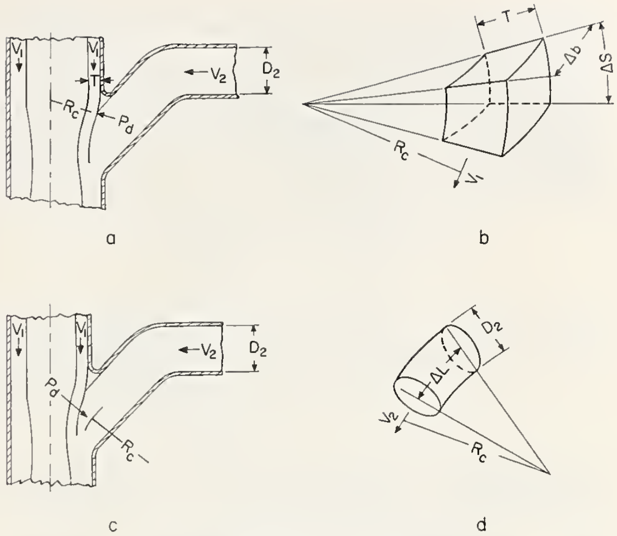

FIGURE 11. *Mutual deflection at the confluence of streams at stack-branch junction.*

a and b. Deflection of stream in stack by that in branch.
c and d. Deflection of stream in branch by that in stack.

Other things being equal, it will be assumed that R_c is directly proportional to the momentum, $\rho Q_1 V_1$, of the layer of water flowing down the stack, and that R_c is inversely proportional to the momentum, $\rho_w Q_2 V_2$, of the water in the branch. The validity of these and other assumptions made in evaluating R_c will be determined by the success obtained in fitting the final equation to the experimental data. Based on the above considerations,

$$R_c = \text{function}\left(\frac{\rho_w Q_1 V_1}{\rho_w Q_2 V_2}\right).$$

But R_c must be placed equal to a length times this function if the equation is to be dimensionally correct, and the dimension that seems to be most closely involved with R_c is the diameter, D_2, of the branch. Hence,

$$R_c = D_2 \phi\left(\frac{\rho_w Q_1 V_1}{\rho_w Q_2 V_2}\right) = D_2 \phi\left(\frac{A_1 (V_1)^2}{A_2 (V_2)^2}\right), \qquad (15)$$

where A_1 is the cross-sectional area of the water flowing down the stack at the level of the branch, and A_2 is the cross-sectional area of the stream in the branch for the branch flowing full. In order to simplify the analysis, the area A_1 will be replaced by its approximate equivalent $\pi D_1 T$. The latter expression will give values of area which are accurate within 10 percent for stacks flowing not over three-tenths full.

Hence,

$$R_c = D_2 \phi\left(4\frac{\pi D_1 T (V_1)^2}{\pi (D_2)^2 (V_2)^2}\right) = C D_2 \phi\left[\frac{D_1}{D_2} \cdot \frac{T}{D_2} \cdot \frac{(V_1)^2}{(V_2)^2}\right], \qquad (16)$$

the constant 4 being absorbed in the coefficient C. Going one step further, it will be assumed that the function ϕ is a simple power function. This was found by logarithmic plotting of experimental data to be approximately true for the ratio T/D_2, and will be assumed to be true for the two other ratios. Thus,

$$R_c=CD_2\left(\frac{D_1}{D_2}\right)^a\left(\frac{T}{D_2}\right)^a\left(\frac{(V_1)^2}{(V_2)^2}\right)^a, \text{ or}$$

$$R_c=CD_2\left(\frac{D_1}{D_2}\right)^a\left(\frac{T}{D_2}\right)^a\left[\frac{\frac{(V_1)^2}{2g(h_2-h_1)}}{\frac{(V_2)^2}{2g(h_2-h_1)}}\right]^a. \quad (17)$$

The value of R_c given by eq (17) will now be substituted in eq (14), writing for simplicity:

$$\frac{(V_1)^2}{2g(h_2-h_1)}=X \text{ and } \frac{(V_2)^2}{2g(h_2-h_1)}=Y.$$

Rearrangement and simplification give the expression:

$$\left(f\frac{L}{D_2}+\zeta\right)Y=1-C'\left(\frac{D_2}{D_1}\right)^a\left(\frac{T}{D_2}\right)^{1-a}Y^aX^{1-a}, \quad (18)$$

in which the coefficient C' is a constant.

There are two quantities, C' and a, to be determined from the experimental data. From this point on, the analysis will be carried out separately for the simulated stack and the prototypal stack.

a. Simulated Stack

In the case of the simulated stack, the construction of the test equipment was such that water flowed down the stack in a layer which had, as it approached the level of the horizontal branch under consideration, a definite known thickness T and a definite known mean velocity of flow V_1 (see fig. 4).

In the analysis applying to the case in which sanitary-tee fittings were used, the coefficient ζ appearing in eqs (9) and (18) was assumed to be zero. In other words, the resistance due to the downward deflection of the horizontal stream produced by the slightly curved passage through the fitting was neglected.

In connection with the analysis applying to long-turn T-Y fittings, a review of some of the published data on head losses in pipe bends was made. Measurements reported by Beij [11] on 90° bends between upstream and downstream pipes showed that the average deflection losses in his experiment were only about 37 percent as great as the average bend losses, the latter of which included both deflection and tangential losses. If a roughness corresponding to $k_s=0.00015$ (as given by Rouse [9] for wrought-iron or steel pipe) is assumed, a bend coefficient of 0.27 for a radius of curvature of one pipe diameter is estimated for a 90° bend on the basis of Beij's results. The radii of curvature of the bends in the long-turn T-Y fittings used in the experiment reported herein were of the order of one pipe diameter. Various investigators have suggested specific bend-loss coefficients for use with 45° and 90° bends. The values suggested for 45° bends vary from 47 to 75 percent of the values suggested for 90° bends. Based on a bend-loss coefficient of 0.27 for a 90° bend as indicated above, on a deflection loss of 37 percent of the total loss due to a bend in a long pipe line, and on a ratio of 45° bend loss to 90° bend loss of 0.47, a value of ζ of 0.047 is computed for the case under consideration herein.

The term $\frac{L}{D_2}$ in eq (18) was held constant at a value of 4.0 in the tests. Therefore, this value will be used in what follows.

If values of 0.03, 0.00, and 4.0 for f, ζ, and L/D_2 are inserted in eq (18) as it applies to the case in which a sanitary-tee fitting is used, the equation may be placed in the form

$$Y=8.33-C''\left(\frac{T}{D_2}\right)^{1-a}\left(\frac{D_2}{D_1}\right)^aY^aX^{1-a}. \quad (19)$$

In a similar fashion, if values of 0.03, 0.047, and 4.0 for f, ζ, and L/D_2 are inserted in eq (18) as it applies to the case in which a long-turn T-Y fitting is used, the equation may be placed in the form

$$Y=6.00-C''\left(\frac{T}{D_2}\right)^{1-a}\left(\frac{D_2}{D_1}\right)^aY^aX^{1-a}. \quad (20)$$

Further steps in the analysis will be simplified by combining several of the terms appearing in eqs (19) and (20) as follows:

$$C''\left(\frac{D_2}{T}\right)^a\left(\frac{D_2}{D_1}\right)^a\left(\frac{Y}{X}\right)^a=\delta. \quad (21)$$

If δ in eq (21) is substituted in eqs (19) and (20), the following equations are obtained:

$$\delta=\frac{8.33-Y}{(T/D_2)(X)} \quad (22)$$

for the sanitary-tee fittings, and

$$\delta=\frac{6.00-Y}{(T/D_2)(X)} \quad (23)$$

for the long-turn T-Y fittings.

The value of the exponent a can be determined from experimental data by logarithmic plotting of values of δ computed from eqs (22) and (23) against the variable $\frac{Y}{X}$. The slope of the lines plotted in this way gives the approximate value of a. The value of the coefficient C'' may then be determined by inserting in eq (21) the values of δ and a, together with the corresponding values of X and Y, and solving for C''. These determinations are given later in section 5.1.a, for both the sanitary-tee fittings and the long-turn T-Y fittings.

b. Prototypal Stack

The analysis of flow interference at a branch connection on a prototypal stack is made in such a way that the dimension T is not involved. It is assumed that the dynamic head h_d is caused by the deflection of the horizontal stream by the vertical stream, instead of conversely as in the case of the simulated stack. It is assumed that the horizontal stream is deflected on an arc of unknown radius of curvature, R_c. It is realized that part of the deflection of the horizontal stream is caused by gravity. However, since this effect should be small in comparison with the deflection caused by the interference of the two streams when there is appreciable flow in the stack, the effect of gravity on the curvature of the stream lines will be neglected. The centripetal force, F_d, required to cause an elementary mass Δm moving at a velocity V to follow a curved path of radius of curvature R_c will be

$$F_d=\Delta m\frac{V^2}{R_c}. \tag{24}$$

If the elementary volume is taken as a cylinder of length ΔL cut perpendicular to the axis of the horizontal branch, its mass Δm will be

$$\rho_w\frac{\pi}{4}\Delta L(D_2)^2.$$

Therefore,

$$F_d=\frac{\pi}{4}\rho_w\Delta L(D_2)^2\frac{(V_2)^2}{R_c}.$$

It is assumed that the average pressure required to cause the curvature of the stream lines is equal to the applied force divided by one-half the circumferential area of the elementary cylinder,[3] or

$$\frac{2F_d}{\pi D_2\Delta L}.$$

Thus,

$$p_d=\frac{1}{2}\rho_w D_2\frac{(V_2)^2}{R_c}\text{ or, dividing by }\rho_w g,$$

$$h_d=D_2\frac{(V_2)^2}{2gR_c}. \tag{25}$$

It appears that, in general, R_c will increase when the momentum per unit volume of water in the horizontal stream increases and will decrease when the momentum per unit volume of water in the vertical stream increases. The momentum of the water in the vertical stream which passes through a unit area in unit time is a function of

$$\frac{\rho_w A_1(V_1)^2}{A_1},\text{ or }\rho_w(V_1)^2,$$

and the momentum of the water in the horizontal stream which passes through a unit area in unit time is a function of

$$\frac{\rho_w A_2(V_2)^2}{A_2},\text{ or }\rho_w(V_2)^2.$$

Hence,

$$R_c=\phi\left(\frac{\rho_w(V_2)^2}{\rho_w(V_1)^2}\right)=\phi\left(\frac{(V_2)^2}{(V_1)^2}\right).$$

Since R_c must have the dimension of a length, and since the length which appears to be most closely associated with R_c is D_2, the expression

$$R_c=D_2\phi\left(\frac{(V_2)^2}{(V_1)^2}\right) \tag{26}$$[4]

will be set up. Substitution in eq (25) of the expression for R_c given in eq (26) yields the equation

$$h_d=\frac{(V_2)^2}{2g\phi\left(\frac{(V_2)^2}{(V_1)^2}\right)}. \tag{27}$$

If eq (27) is combined with eq (9), the following equation is obtained relating the various heads:

$$\left(f\frac{L}{D_2}+\zeta\right)\frac{(V_2)^2}{2g}=(h_2-h_1)-\frac{(V_2)^2}{2g}\phi\left(\frac{(V_1)^2}{(V_2)^2}\right). \tag{28}$$

If the function ϕ is a simple power function, if $f=0.03$, if $\zeta=0$, and if $L/D_2=4.0$ (this value of L/D_2 applying to the test equipment used), the following equation is obtained, after some rearrangement:

$$\frac{(V_2)^2}{2g(h_2-h_1)}=8.33\frac{(V_2)^2}{2g(h_2-h_1)}C\left[\frac{(V_1)^2}{(V_2)^2}\right]^a. \tag{29}$$

Now, if X and Y are introduced in the same way that they were in the development of eqs (19) and (20), eq (29) can be expressed as

$$Y=8.33-C\left(\frac{X}{Y}\right)^a Y. \tag{30}$$

---

[3] This particular assumption is not essential to the solution of the problem. The end result would be the same if it were assumed that the pressure is equal to the force divided by the area of the plane which is limited by the boundaries of the elementary cylinder and which is bisected by its longitudinal axis. This would yield the expression $F_d/D_2\Delta L$. The disappearance of the constant $\frac{2}{\pi}$ in the latter case would be taken into account in the values determined experimentally for other constants appearing later in the analysis.

[4] The end result of this analysis would be the same if it were assumed at this point that the radius of curvature R_c is a function of the relative flux of energy in the horizontal and vertical streams.

If

$$C\left(\frac{X}{Y}\right)^a=\delta \tag{31}$$

eq (30) can be written as $Y=8.33-\delta Y$, or

$$\delta=\frac{8.33-Y}{Y}. \tag{32}$$

The value of the exponent a can be determined from experimental data by logarithmic plotting of values of δ computed from eq (32) against the variable $\frac{X}{Y}$. The slope of the lines plotted in this way indicates the approximate value of a. The value of the coefficient C may then be determined by inserting in eq (31) the values of δ and a, together with the corresponding values of X and Y, and solving for C. These determinations are given later in section 5.1.b.

4.2. Terminal Velocities and Terminal Lengths

a. Derivation of Equation for Terminal Velocities

The following derivation of the equation for terminal velocities is an approximate one, in which the water is treated as if it were a rigid body sliding down the stack instead of a fluid layer with a radial velocity gradient. A more nearly correct solution would require a consideration of the turbulent boundary layer which develops in the pipe. However, because of the difficulty of obtaining an exact solution, an approximate solution is given in this paper.

The annular layer of water is treated as if it were a rigid body moving down a plane vertical wall, acted on only by the forces of gravity and wall friction. The effect of the pneumatic-pressure gradient within the air core should be considered in a rigorous solution of the problem; but, since in a properly vented stack the pneumatic-pressure gradient should be relatively small, this effect will be neglected in what follows. It is assumed that the water starts with an initial velocity V_0 downward. The velocity V_0 is less than the terminal velocity, V_t, which it will attain ultimately if the length of fall is great enough. The thickness of the layer decreases with z (the distance measured from the point of water entrance downward to the point under consideration), becoming constant when z attains the value of z_t, the terminal length.

Since, under the assumptions made above, the accelerating force is equal to the gravitational force less the frictional resistance,

$$\Delta m\frac{dV}{dt}=\Delta mg-\tau_0\pi D_1\Delta L, \tag{33}$$

where τ_0 is the wall shear per unit area, and the elementary volume of water is assumed to be πD_1 units wide. But

$$\Delta m=\rho_w Q_1\Delta t,$$

so

$$\rho_w Q_1\frac{dV}{dt}\Delta t=\rho_w Q_1 g\Delta t-\tau_0\pi D_1\Delta L. \tag{34}$$

τ_0 will now be defined by the relation,

$$\tau_0=\frac{\lambda\rho_w}{2}V^2. \tag{35}$$

ΔL will be replaced by its value, $V\Delta t$. Equation (33) then becomes

$$\rho_w Q_1\frac{dV}{dt}\Delta t=\rho_w Q_1 g\Delta t-\frac{\pi\lambda\rho_w}{2}D_1V^3\Delta t,$$

or

$$\frac{dV}{dt}=g-\frac{\pi\lambda}{2Q_1}D_1V^3. \tag{36}$$

The expression for the terminal velocity, V_t, will now be obtained by setting dV/dt equal to zero. This yields the equation

$$V_t=\left(\frac{2gQ_1}{\pi\lambda D_1}\right)^{1/3}. \tag{37}$$

It can be shown that λ is equal to $f/4$, where f is the dimensionless friction coefficient in the Darcy-Weisbach formula for pipe flow. It is a function of the Reynolds number, $N_R=TV/\nu$, approximately, and of the roughness ratio, k_s/R_h or k_s/T.

It will be necessary to modify eq (37) to eliminate the friction coefficient λ. To do this, the following equation given by Keulegan [12] for flow in open channels, based on the Manning formula, is used:

$$\frac{\overline{V}}{V_*}=8.12\left(\frac{R_h}{k_s}\right)^{1/6}, \tag{38}$$

where $\overline{V}$ is the mean velocity in the cross section and V_* is the shear velocity defined by the relation,

$$V_*=\sqrt{\tau_0/\rho_w}. \tag{39}$$

The $\overline{V}$ in eq (38) is the same as the V in the other equations. τ_0 is eliminated between eqs (38) and (39). If R_h is replaced by T, as can be done approximately, there results the equation

$$\lambda=0.0303\left(\frac{k_s}{T}\right)^{1/3}. \tag{40}$$

Substituting this value of λ in eq (37), there results

$$V_t=\sqrt[3]{21g\frac{Q_1}{D_1}\left(\frac{T_t}{k_s}\right)^{1/3}}, \tag{41}$$

T_t being written for T to indicate that the value of T is that corresponding to the terminal velocity.

One further change will be made in the expression for terminal velocity by eliminating the thickness T_t of the sheet of water by means of the relation between the thickness of the sheet, the cross-sectional area of the sheet, and the rate of flow. This relation is given by the approximate expression

$$Q_1 = \pi D_1 T_t V_t, \qquad (42)$$

or by the more accurate expression

$$Q_1 = \pi (D_1 - T_t) T_t V_t. \qquad (43)$$

Equation (42) should be sufficiently accurate for the relatively small values of T_t which are produced in drainage stacks flowing partly full. If the approximate expression is used, there results:

$$V_t = 2.22 \left(\frac{g^3}{k_s}\right)^{1/10} \left(\frac{Q_1}{D_1}\right)^{2/5}. \qquad (44)$$

The reason that the Reynolds number is not a factor in eq (44) is that the relationship (eq (38)) used to eliminate λ is based on the Manning formula which is most accurate for conditions under which λ is independent of the Reynolds number. A discussion by Rouse [9] indicates that the Manning formula is most dependable for intermediate values of relative roughness and least dependable for low values of the Reynolds number. Computations based on a cast-iron stack flowing with a water-occupied cross section of at least one-fourth of the cross section of the stack, and with a velocity in accordance with eq (44) indicate that λ is substantially independent of the Reynolds number for stacks of 4 in. in diam or larger, and that the error in the use of the Manning formula over the range of relative roughness involved ranges from approximately 7 percent for a 4-in. stack to approximately 3 percent for a 12-in. stack. The low order of magnitude of this error indicates that, in view of the proposed application of eq (44), the use of the Manning formula in its development is reasonable.

An appropriate value of k_s has been determined from data on friction losses for flow through new cast-iron soil pipe tested by Hunter [13]. This yields the approximate value, $k_s = 0.00083$ ft. (See appendix, section 9.2., for the derivation of this value.) Rouse [9] gives the value, $k_s = 0.00085$ ft, for new cast-iron pipe.

Equation (44) can be expressed in convenient form for computation by substituting the numerical values of k_s (0.00083 ft) and g (32.2 ft/sec/sec). The following equation (for cast-iron soil pipe) is obtained:

$$V_t = 12.8 \left(\frac{Q_1}{D_1}\right)^{2/5}, \qquad (45)$$

where V_t is expressed in feet per second, Q_1 is in cubic feet per second, and D_1 is in feet.

If Q_1 is expressed in gallons per minute and D_1 in inches, eq (45) becomes

$$V_t = 3.0 \left(\frac{Q_1}{D_1}\right)^{2/5}. \qquad (46)$$

Equation (46) is plotted in figure 12, together with the experimental data obtained by Hunter and by Dawson and Kalinske. An average curve having the equation

$$V_t = 4.4 \left(\frac{Q_1}{D_1}\right)^{2/5} \qquad (47)$$

is drawn through the experimental points.

As would be expected, the experimental points scatter considerably, for the terminal velocity is very difficult to measure. All the measurements lie above the curve computed from resistance measurements on cast-iron soil pipe. One possible explanation for this effect relates to the velocity distribution in the layer of water. A steep velocity gradient exists in the layer, the velocity increasing from zero at the wall to a maximum at the inner surface of the sheet. The experimenters made

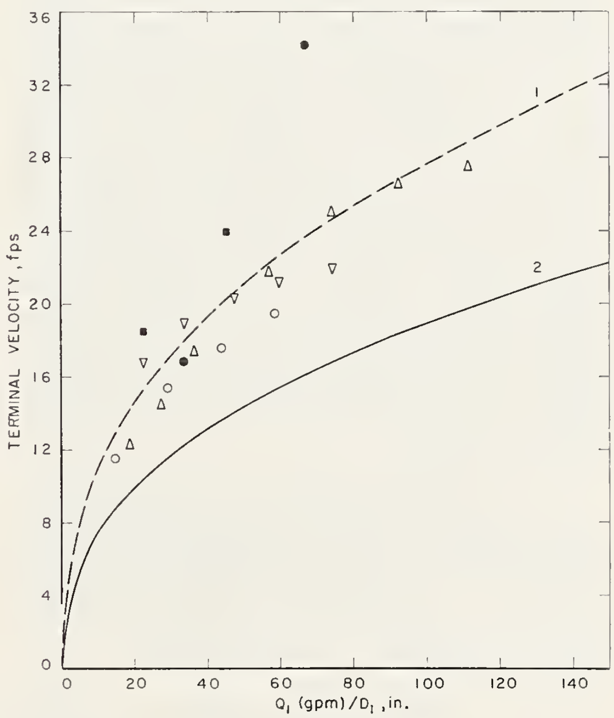

FIGURE 12. *Comparison of measured and computed terminal velocities.*

1. Average experimental curve, $V_t = 4.4\left(\frac{Q_1}{D_1}\right)^{2/5}$

2. Computed curve, $V_t = 3.0\left(\frac{Q_1}{D_1}\right)^{2/5}$, based on flow-resistance measurements in cast-iron soil pipe.

○, Dawson	3-in. stack.
▽, do	4-in. stack.
△, do	6-in. stack.
■, Hunter	2-in. stack.
●, do	3-in. stack.

their observations with pitot tubes with dynamic openings pointing vertically upward through the vertical layer. It was impossible to get the pitot tube very close to the wall where the lowest velocities existed, and hence, the velocities in this region were not taken into account in the experimental measurements reported. An indirect indication that the velocities reported by Dawson and Kalinske may be too high can be obtained by inspection of their data [5]. They computed values of Manning's n of the order of 0.006 from their experimental measurements. This compares with values of 0.012 to 0.015 for uncoated cast-iron pipe, and of 0.013 to 0.017 for galvanized wrought-iron pipe given by Horton [14]. All known measurements on gravity flow in sloping pipes of various materials have yielded values of n substantially greater than 0.006. The surprisingly low value of n indicated by the data of Dawson and Kalinske could have been the result of using velocity values that were too large in computing n. If the reported velocities are substantially greater than the true velocities, as indicated by the above discussion, the curve computed from eq (46) may be more nearly correct than are the direct measurements.

On the other hand, it is known that a negative pneumatic-pressure gradient exists for a limited distance below a point of water entrance. This tends to accelerate the water, and, if the acceleration were to be sufficiently great, velocities might exceed those indicated by eq (46). However, the data of Dawson and Kalinske [5] on water velocities as a function of distance below the point of water entrance indicate that the existence of a negative pressure gradient in the upper part of the stack was not a significant factor in connection with terminal velocities. Since eq (46) is intended for application to well-vented stacks where the pneumatic gradient is small in relation to that which existed in the experiments reported by Dawson and Kalinske, it seems reasonable to neglect the possible effect of the negative pneumatic gradient near points of water entrance on terminal velocities.

b. Derivation of Equation for Terminal Lengths

The equation for terminal lengths in layer flow down the walls of vertical stacks is derived by starting with eq (36), making the necessary transformations, and integrating the result to obtain the expression for the terminal length. It is noted first that

$$\frac{dV}{dt}=\frac{dV}{dz}\frac{dz}{dt}=V\frac{dV}{dz}. \tag{48}$$

If this substitution is made in eq (36) and the equation is solved for dz, there results

$$dz=\left(\frac{1}{g}\right)\left(\frac{VdV}{1-\frac{\pi}{2}\frac{\lambda}{g}\frac{D_1V^3}{Q_1}}\right). \tag{49}$$

If it is assumed that λ is not a function of V, and eq (37) is made use of,

$$dz=\frac{(V_t)^2}{g}\left(\frac{(V/V_t)d(V/V_t)}{1-(V/V_t)^3}\right)=\frac{(V_t)^2}{g}\left(\frac{\theta d\theta}{1-\theta^3}\right), \tag{50}$$

where $\theta=V/V_t$.

Equation (50) can be integrated directly, with the result:

$$L_t=z\Bigg|_{\theta}^{z_t}=\frac{1}{3}\frac{(V_t)^2}{g}\left[\frac{1}{2}\log_e\frac{1+\frac{V}{V_t}-\left(\frac{V}{V_t}\right)^2}{\left(\frac{V}{V_t}-1\right)^2}-\tan^{-1}\left(2\frac{V}{V_t}+1\right)\right]_0^1. \tag{51}$$

If the upper limit $(V/V_t=1)$ is substituted, there is obtained an infinite result, as the denominator of the first term in the brackets becomes zero. This difficulty is avoided by assuming that, when the velocity has reached a value equal to 0.99 times the true terminal velocity, the terminal length has been attained for all practical purposes. Making this substitution for V/V_t in eq (51), and inserting the limits, there is obtained

$$L_t=\frac{(V_t)^2}{3g}\left[\frac{1}{2}\log_e 29{,}700-\tan^{-1}2.98-\frac{1}{2}\log_e 1+\tan^{-1}1\right],$$

or

$$L_t=0.052\,(V_t)^2. \tag{52}$$

Equation (52) is useful for computing the distance through which water on the wall of a drainage stack must fall before it attains a velocity approximately equal to the terminal velocity. Figure 13 gives the terminal length as a function of terminal velocity.

If eq (52) is compared with the equation of free fall under the influence of gravity, it is found that the layer of water in the pipe must fall approximately three times as far to attain a given velocity of fall as a body falling freely under the influence of gravity. Figure 14 shows terminal length as a function of stack diameter, for two degrees of fullness. These curves were computed from eqs (46), (52), and (53). They indicate that in most practical cases the falling water will approach terminal velocity in a distance of from one to two stories.

4.3. Flow Capacities of Multistory Drainage Stacks

As indicated in section 2, previous research has shown the necessity for criteria for limiting the discharge of water into drainage stacks. The criterion developed herein is based on limitation

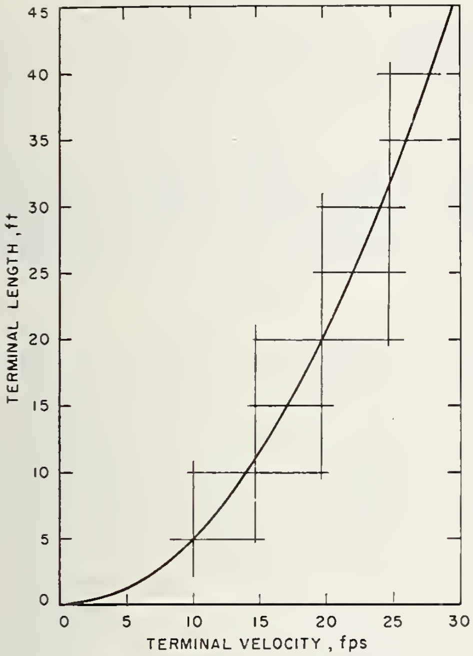

FIGURE 13. *Terminal length as a function of terminal velocity.*

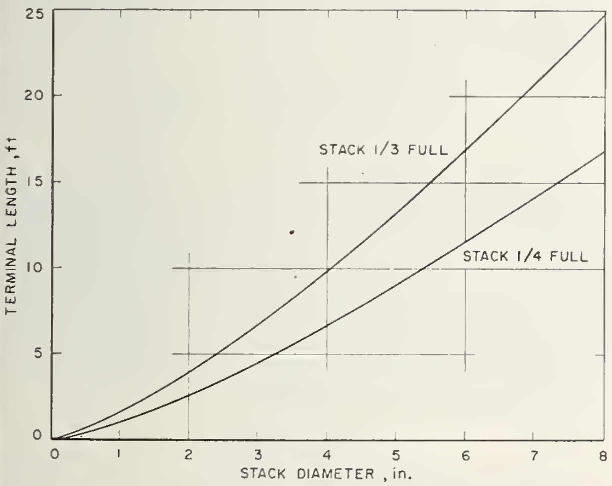

FIGURE 14. *Terminal length as a function of stack diameter.*

of the water-occupied cross section to a specified fraction, r_s, of the cross section of the stack where terminal velocity exists, as suggested by earlier investigators.

Flow capacity can be expressed in terms of the stack diameter and the water cross section. This expression,

$$Q_1=27.8(r_s)^{5/3}(D_1)^{8/3} \tag{53}$$

is derived by equating the fundamental expression for velocity, $V=Q/A$ in which

$$A=\frac{\pi r_s}{4}(D_1)^2,$$

and the expression for terminal velocity given by eq (46). In eq (53), Q_1 is the volume rate of water flow in gpm and D_1 is the diameter of the stack in inches. Since this equation is based, in part, on the approximate expression for T_t given by eq (42) and since, for a given pipe, the error from using eq (42) increases with T_t (or r_s), it is intended primarily for use where r_s is not greater than 1/3. However, analysis of eqs (41), (42), and (43) indicates that, even where the pipe is flowing full, eq (53) should give flow-rate values only about eight percent less than if eq (43) had been used in its development. This conclusion is consistent with the finding that flow-rate values computed for cast-iron soil pipe from eq (53) for $r_s=1.0$ actually are from five to ten percent less than the values computed for very rough pipes flowing full at terminal velocity as indicated by figure 2, based on Hunter's experiments.

4.4. Air Flow in Drainage Systems

The principal cause of air movement in building drainage systems is the friction developed between the high-velocity layer of water flowing down the drainage stack and the core of air which it encloses. The friction thus developed drags air along with the water. Under ideal conditions of annular flow of water at terminal velocity where there is a positive pneumatic-pressure gradient in the direction of flow, it is obvious that, *at the air-water boundary*, the air velocity may approach, but cannot exceed, the velocity of the water. However, general considerations indicate that the velocity gradient in the water section is much steeper than that in the air core. Thus, it is believed that the mean velocity of the air core can be greater than the mean velocity of the water stream. Since available data do not establish this relationship with acceptable precision, it is assumed here that the mean velocity of the air core cannot be greater than 1.5 times the mean terminal velocity of the water stream.

The analysis of air flow in a drainage stack begins by expressing the relation between air flow and water flow as

$$Q_a=\frac{A_aV_a}{A_wV_w}Q_w=\frac{1-r_s}{r_s}\frac{V_a}{V_w}Q_w. \tag{54}$$

Since Q_w is identical to Q_1 in eq (53), Q_w will be replaced by Q_1. Next, Q_1 will be replaced by the right-hand member of eq (53). This yields the equation

$$Q_a=27.8(r_s)^{2/3}(1-r_s)\frac{V_a}{V_w}\left(D_1\right)^{8/3}, \tag{55}$$

in which Q_a is in gpm and D_1 is in inches. If $\frac{V_a}{V_w}=1.5$, the equation becomes

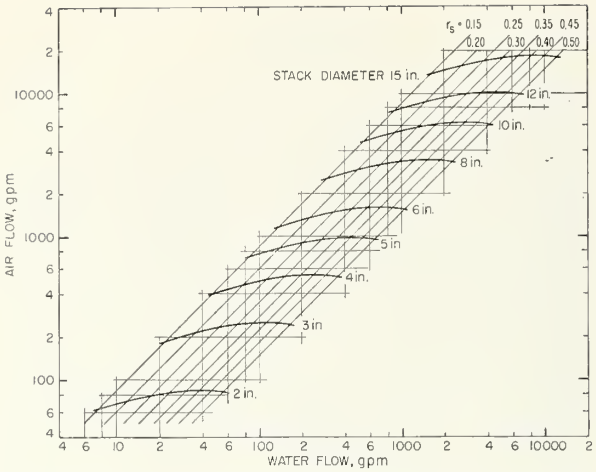

FIGURE 15. *Relationship between water- and air-flow rates for annular flow at terminal velocity in vertical pipes, computed from eqs (53) and (56).*

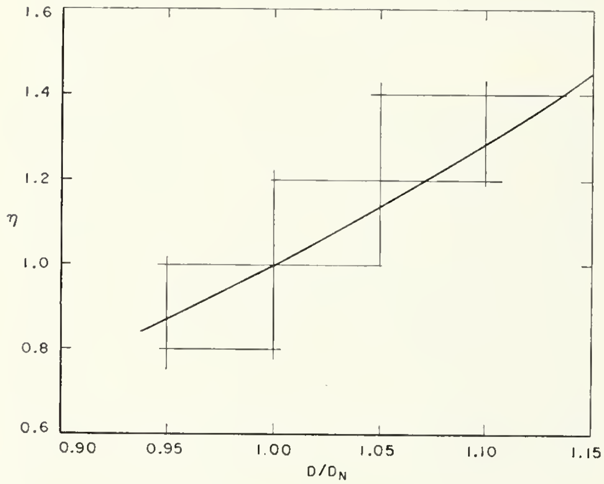

FIGURE 16. *Factor for computing effect on flow capacity of small variations in stack diameter, based on eq (57).*

$$Q_a=41.7(r_s)^{2/3}(1-r_s)(D_1)^{8/3}. \quad (56)$$

Figure 15 has been prepared from eqs (53) and (56). This figure shows the air flow computed for various flows of water in drainage stacks from 2 to 15 in. in diam. Nominal diameters of stack have been used in the computations. Figure 16 may be used in conjunction with figure 15, or with any flow-capacity equation based on the Manning formula, to estimate the effect on capacity of diameters which differ to a slight extent from the nominal values. If Q_N represents rate of discharge associated with nominal diameter D_N, and if Q represents rate of discharge associated with actual diameter D, and if $\eta=\left(\frac{D}{D_N}\right)^{8/3}$, then

$$Q=\eta Q_N. \quad (57)$$

4.5. Flow Capacities of Vent Stacks

In most plumbing codes a loading table for vents is provided. The purpose of such a table is to give the information necessary to design the vent stack for the delivery of the amount of air required for the control of pneumatic pressures at critical points in the drainage system within limits of +1 to −1 in. of water column from atmospheric. If this range of pressure can be maintained, the effects of pneumatic-pressure fluctuations on the fixture-trap seals will be negligible. The dimensions of pipes required to deliver given quantities of air at a pressure drop of 1 in. of water column can be computed from the Darcy-Weisbach formula combined with the conventional formula for expressing losses other than those associated with flow in long, straight pipes. This can be expressed as

$$L_v=\frac{1}{f}\left[2200\frac{(D_v)^5}{(Q_a)^2}-\frac{\Sigma C_L}{12}D_v\right]. \quad (58)$$

In eq (58), L_v is in feet, D_v is in inches, and Q_a is in gallons per minute; and the term ΣC_L is the algebraic sum of the loss coefficients associated with the entrance and exit conditions and with changes in section, direction, etc. A temperature of 60 °F has been assumed in developing eq (58). If only the pipe-friction loss is considered, which may usually be done without serious error in practical situations, the equation

$$L_v=\left(\frac{2200}{f}\right)\frac{(D_v)^5}{(Q_a)^2} \quad (59)$$

is obtained.

5. Test Results

5.1. Flow Capacities at Junction of Drainage Stack and Horizontal Branches

a. Simulated Stack

Tables 6 and 7 show the range of conditions investigated by use of the simulated stack shown in figure 4. The individual values in this series of measurements are shown in tables A–1 and A–2 of the appendix.

The experimental data afforded the information necessary for computing the terms X, Y, and T/D_2 appearing in eqs (19) and (20). Next, the values of δ were computed from eqs (22) and (23).

Table 6. *Range of conditions investigated in study of flow interference at junction of 3-in. simulated stack and horizontal branches, sanitary-tee drainage fittings*

1	2	3	4	5	6	7
Branch diameter	Thickness of water layer [a] on wall of stack	Number of branches flowing	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Range of flow rates in each branch	Range of head losses in branch (h_2-h_1)
in.	*in.*		*gpm*		*gpm*	*in.*
1.61	0.16	1	40	1.04	15.0 to 33.2	2.57 to 3.94
1.61	.16	1	54	1.41	13.1 to 40.3	2.94 to 4.69
1.61	.16	1	80	2.08	9.4 to 26.5	4.44 to 6.00
1.61	.16	1	98	2.55	8.8 to 17.4	5.44 to 6.38
1.61	.16	2	40	1.04	17.4 to 27.2	2.59 to 3.25
1.61	.16	2	54	1.41	7.9 to 29.2	1.94 to 4.56
1.61	.16	2	80	2.08	8.2 to 20.6	3.25 to 5.54
1.61	.16	2	98	2.55	8.2 to 13.8	4.44 to 6.19
1.61	.35	1	56	0.47	17.9 to 32.2	2.94 to 3.69
1.61	.35	1	98	.82	8.1 to 23.4	2.88 to 5.94
1.61	.35	1	137	1.14	8.4 to 14.4	4.44 to 5.96
1.61	.35	1	180	1.50	8.1 to 9.7	5.96
1.61	.35	2	56	0.47	8.6 to 24.2	1.62 to 3.29
1.61	.35	2	98	.82	8.8 to 24.8	3.06 to 5.94
1.61	.35	2	137	1.14	9.4 to 13.7	4.44 to 5.94
1.61	.35	2	180	1.50	9.2	5.94
1.61	.58	1	98	0.40	8.1 to 29.8	2.07 to 4.44
1.61	.58	1	158	.64	11.6 to 20.2	4.06 to 6.12
1.61	.58	1	203	.82	8.1 to 13.1	4.44 to 5.94
1.61	.58	1	252	1.02	8.1 to 14.5	5.94 to 7.94
1.61	.58	2	98	0.40	10.6 to 16.8	2.69 to 3.44
1.61	.58	2	158	.64	11.0 to 16.6	4.44 to 5.94
1.61	.58	2	203	.82	11.1	5.94
2.07	.16	1	40	1.04	30.0	3.12
2.07	.16	1	54	1.41	20.8 to 34.1	3.37 to 4.62
2.07	.16	1	80	2.08	23.0 to 33.6	5.56 to 7.12
2.07	.16	1	98	2.55	19.0 to 24.2	6.31 to 7.49
2.07	.16	2	40	1.04	15.1 to 38.5	1.99 to 3.06
2.07	.16	2	54	1.41	30.4	3.93
2.07	.16	2	80	2.08	15.8 to 30.8	4.34 to 6.62
2.07	.16	2	98	2.55	19.2 to 28.9	6.37 to 8.31
2.07	.35	1	56	0.47	16.3 to 40.8	2.06 to 3.25
2.07	.35	1	98	.82	20.4 to 59.6	4.06 to 7.06
2.07	.35	1	137	1.14	21.2 to 32.3	6.06 to 7.81
2.07	.35	1	180	1.50	20.1 to 21.4	7.81
2.07	.35	2	56	0.47	17.8	2.19
2.07	.35	2	98	.82	19.0 to 28.2	3.81 to 4.81
2.07	.35	2	137	1.14	17.4 to 24.5	5.31 to 6.69
2.07	.35	2	180	1.50	20.5	7.99
2.07	.58	1	98	0.40	23.8 to 49.1	3.43 to 4.43
2.07	.58	1	158	.64	24.3 to 42.3	5.81 to 7.69
2.07	.58	1	203	.82	15.4 to 25.7	5.81 to 7.81
2.07	.58	1	252	1.02	16.3 to 17.8	7.81
2.07	.58	2	98	0.40	16.9	2.31
2.07	.58	2	203	.82	18.6	6.31
2.07	.58	2	252	1.02	17.4	7.81
3.07	.16	1	80	2.08	52.1 to 128.0	4.46 to 6.46
3.07	.16	1	98	2.55	66.0 to 110.3	6.46 to 8.46
3.07	.35	1	98	0.82	80.0 to 81.0	4.46
3.07	.35	1	137	1.14	42.0 to 149.0	4.46 to 8.46
3.07	.35	1	180	1.50	49.0 to 71.1	6.46 to 8.46
3.07	.58	1	203	0.82	53.1 to 92.7	6.46 to 8.46
3.07	.58	1	252	1.02	47.8 to 53.4	7.71 to 8.46

[a] Above the stack-branch junction.

Table 7. *Range of conditions investigated in study of flow interference at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*

1	2	3	4	5	6	7
Branch diameter	Thickness of water layer [a] on wall of stack	Number of branches flowing	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Range of flow rates in each branch	Range of head losses in branch (h_2-h_1)
in.	*in.*		*gpm*		*gpm*	*in.*
1.61	0.16	1	40	1.04	26.8 to 34.4	3.64
1.61	.16	1	54	1.41	19.2 to 50.0	3.64 to 8.14
1.61	.16	1	80	2.08	10.7 to 50.0	3.64 to 9.14
1.61	.16	1	98	2.55	10.9 to 33.4	4.64 to 9.22
1.61	.16	2	40	1.04	25.0 to 38.9	3.64 to 5.22
1.61	.16	2	54	1.41	21.8 to 53.6	3.64 to 8.14
1.61	.16	2	80	2.08	11.4 to 42.0	3.64 to 8.22
1.61	.16	2	98	2.55	8.0 to 32.1	3.64 to 8.22
1.61	.35	1	56	0.47	26.6 to 26.7	3.39
1.61	.35	1	98	.82	12.9 to 44.1	3.39 to 7.72
1.61	.35	1	137	1.14	10.4 to 26.7	4.64 to 7.72
1.61	.35	1	180	1.50	8.8 to 16.4	5.59 to 7.72
1.61	.35	2	56	0.47	25.4 to 38.3	3.39 to 5.09
1.61	.35	2	98	.82	13.8 to 44.9	3.39 to 7.64
1.61	.35	2	137	1.14	13.2 to 29.7	4.64 to 7.64
1.61	.35	2	180	1.50	10.2 to 16.7	5.64 to 7.64
1.61	.58	1	98	0.40	15.0 to 53.5	3.39 to 7.64
1.61	.58	1	158	.64	11.7 to 29.3	4.64 to 7.64
1.61	.58	1	203	.82	11.9 to 19.2	5.96 to 7.72
1.61	.58	1	252	1.02	10.3 to 11.7	7.59 to 7.64
1.61	.58	2	98	0.40	14.5 to 41.3	3.39 to 6.14
1.61	.58	2	158	.64	11.8 to 29.0	4.64 to 7.64
1.61	.58	2	203	.82	7.9 to 18.4	4.64 to 7.72
1.61	.58	2	252	1.02	11.7	7.59 to 7.64
2.07	.16	1	54	1.41	39.7 to 64.4	4.29 to 5.92
2.07	.16	1	80	2.08	21.1 to 73.1	4.29 to 9.36
2.07	.16	1	98	2.55	21.0 to 50.9	5.54 to 9.36
2.07	.16	2	54	1.41	46.4 to 66.6	4.29 to 5.54
2.07	.16	2	80	2.08	20.6 to 75.6	4.29 to 9.12
2.07	.16	2	98	2.55	22.8 to 53.0	5.54 to 9.18
2.07	.35	1	98	0.82	25.1 to 72.7	4.29 to 7.62
2.07	.35	1	137	1.14	21.8 to 62.5	5.54 to 9.49
2.07	.35	1	180	1.50	22.4 to 39.6	7.49 to 9.24
2.07	.35	2	98	0.82	31.8 to 48.8	4.29 to 5.54
2.07	.35	2	137	1.14	16.8 to 59.8	4.29 to 9.18
2.07	.35	2	180	1.50	14.8 to 35.7	5.54 to 9.12
2.07	.58	1	98	0.40	48.3 to 109.2	4.29 to 9.04
2.07	.58	1	158	.64	21.0 to 72.7	4.29 to 9.24
2.07	.58	1	203	.82	18.9 to 49.5	5.54 to 9.24
2.07	.58	1	232	.94	19.3 to 39.9	6.29 to 9.24
2.07	.58	2	158	.64	27.2	4.29
2.07	.58	2	203	.82	17.3 to 26.6	4.29 to 5.80
2.07	.58	2	232	.94	19.8 to 35.7	6.29 to 9.12
3.07	.16	1	80	2.08	96.4 to 199.5	5.61 to 10.11
3.07	.16	1	98	2.55	77.5 to 165.1	5.61 to 10.68
3.07	.16	2	98	2.55	83.5	5.61
3.07	.35	1	98	0.82	115.1 to 117.2	5.61
3.07	.35	1	137	1.14	71.1 to 161.0	5.61 to 10.81
3.07	.35	1	180	1.50	50.3 to 111.9	5.61 to 10.81
3.07	.35	2	180	1.50	54.8	5.61
3.07	.58	1	158	0.64	94.0 to 142.2	5.61 to 10.36
3.07	.58	1	203	.82	64.6 to 125.8	5.61 to 10.36
3.07	.58	1	227	.92	54.5 to 107.9	5.61 to 10.36

[a] Above the stack-branch junction.

The values of δ thus obtained were plotted logarithmically against Y/X. This gave a series of straight lines with a slope of approximately 3/8. Next, from this plot, values of δ were potted logarithmically against $[(D_2/D_1)\cdot(D_2/T)]$ for several selected values of Y/X. Again, this procedure gave a series of straight lines having a slope of approximately 3/8. Therefore, a value of $a=3/8$ was adopted. Values of C'' were then computed from eq (21) inserting the value of 3/8 for a. Evidently, the same value of C'' applies approximately whether the flow is from one or from both branches. Average values of $C''=17.1$ for the sanitary-tee fittings and $C''=9.65$ for the long-turn T-Y fittings were obtained. Hence, the equations representing flow conditions at the junction of the horizontal and vertical streams of the simulated stack become, for sanitary-tee fittings,

$$Y=8.33-17.1\left(\frac{T}{D_2}\right)^{5/8}\left(\frac{D_2}{D_1}\right)^{3/8}Y^{3/8}X^{5/8}. \quad (60)$$

and for long-turn T-Y fittings

$$Y=6.00-9.65\left(\frac{T}{D_2}\right)^{5/8}\left(\frac{D_2}{D_1}\right)^{3/8}Y^{3/8}X^{5/8}. \quad (61)$$

Equations (60) and (61) can be solved for corresponding values of X and Y for any selected value of $[(T/D_2)^{5/8}\cdot(D_2/D_1)^{3/8}]$. This was done for all the conditions investigated in order to determine the agreement between the experimental data and eqs (60) and (61). Representative curves computed in this way have been drawn in figures 17 and 18. The agreement obtained indicates that the simplifying assumptions made in the analysis are justified by the results obtained.

There are certain restrictions on the application of eqs (60) and (61). First, the head-loss term appearing in the denominator of X and Y (see eqs (14) and (18)) represents the head loss between the stack and a point in the horizontal branch 4 pipe diameters from the stack. Second, the equations are based on a value of $f=0.03$ for the horizontal branches, and on a value of $\zeta=0.047$ for the bend in a long-turn T-Y drainage fitting. Third, the data on which eqs (60) and (61) are based were obtained for a 3-in. stack only. Although the analysis indicates the equations should apply to stack diameters other than 3 in. this has not yet been demonstrated experimentally.

b. Prototypal Stack

The data on single-branch flow in a prototypal stack are given in table 8. These data were obtained by use of the test system shown in figures 5 and 6.

The experimental data shown in table 8 provided the information necessary for computing the terms X and Y in eq (30). Next, values of δ were computed from eq (32). The values of δ thus obtained were plotted logarithmically against X/Y. The data from both diameters of branch plotted fairly well along a single line with a slope of approximately 0.7, hence this value was adopted for the exponent a. Then, the values of C were computed from eq (31), inserting the value 0.7 for a. An average value of $C=2.48$ was obtained in this way. Hence, the equation representing flow conditions at the junction of the horizontal and vertical streams of the prototypal stack using sanitary-tee stack fittings becomes

$$Y=8.33-2.48\,X^{0.7}Y^{0.3}. \quad (62)$$

Equation (62) can be solved for values of X corresponding to selected values of Y. This has been done and the resulting curve is shown in figure 19. The experimental data shown in table 8 have been plotted in this figure. The agreement between the curve and the plotted points is satisfactory.

There are certain restrictions on the application of eq (62). First, the equation applies only when sanitary-tee stack fittings are used and when the head-loss term appearing in the denominator of X and Y (see eqs (14) and (18)) represents the head loss between the stack and a point in the horizontal branch 4 pipe diameters from the stack. Second, the equation is based on a value of $f=0.03$. Third, the data on which eq (62) is based were obtained for a 3-in. stack only. Fourth, velocities in the stack just above the branch level are assumed to be terminal velocities.

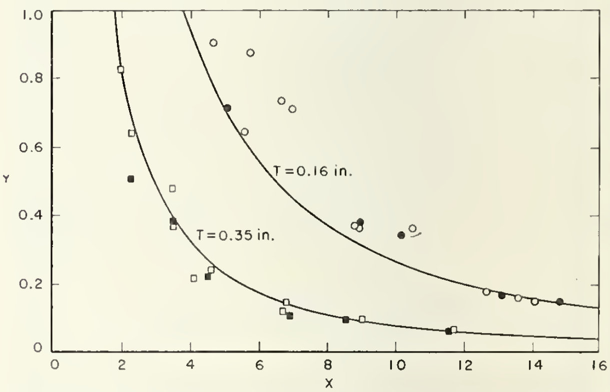

FIGURE 17. *Representative results of tests on flow interference at junction of simulated stack and horizontal branches connected with sanitary-tee fittings (1½-in. branches).*

○, □ two-branch flow
●, ■ one-branch flow

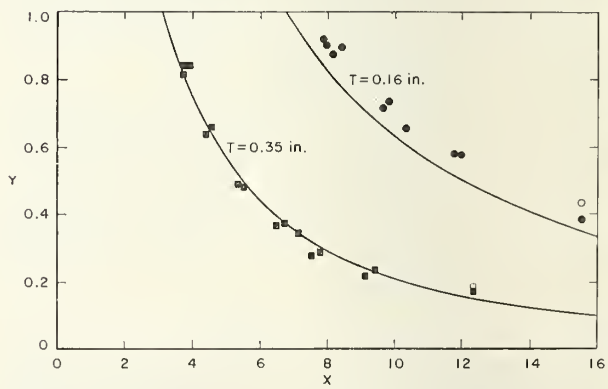

FIGURE 18. *Representative results of tests on flow interference at junction of simulated stack and horizontal branches connected with long-turn T-Y fittings (3-in. branches).*

○, □ two-branch flow
●, ■ one-branch flow

Table 8. *Data on interference of flows at junction of drainage stack and horizontal branches*

(3-in. prototypal stack, sanitary-tee drainage fittings, one-branch flow)

Branch diameter	Discharge into stack [a]	Terminal velocity in stack [b]	Discharge through branch	Velocity in branch	Head loss in branch	X	Y
in.	*gpm*	*fps*	*gpm*	*fps*	*ft*		
1.61	150	14.2	2.6	0.41	0.12	26.1	0.02
1.61	150	14.2	6.7	1.05	.20	15.7	.09
1.61	150	14.2	11.7	1.84	.29	10.8	.18
1.61	125	13.2	2.2	0.35	.10	27.1	.02
1.61	125	13.2	2.9	.46	.12	22.6	.03
1.61	125	13.2	8.1	1.27	.20	13.5	.12
1.61	125	13.2	14.7	2.31	.29	9.3	.28
1.61	100	12.1	3.2	0.50	.10	22.7	.04
1.61	100	12.1	4.5	.71	.12	18.9	.07
1.61	100	12.1	9.4	1.48	.18	12.6	.19
1.61	100	12.1	15.8	2.49	.25	9.1	.38
1.61	75	10.7	4.4	0.69	.10	17.8	.07
1.61	75	10.7	6.0	.94	.12	14.8	.11
1.61	75	10.7	10.5	1.65	.16	11.1	.26
1.61	58	9.7	5.5	0.87	.10	14.6	.12
1.61	58	9.7	9.9	1.56	.14	10.4	.27
1.61	55	9.5	5.4	0.85	.10	14.0	.11
1.61	55	9.5	11.0	1.73	.14	10.0	.33
1.61	50	9.2	5.6	0.88	.10	13.1	.12
1.61	50	9.2	8.7	1.37	.12	10.9	.24
3.07	150	14.2	24.0	1.04	.19	16.5	.09
3.07	150	14.2	39.3	1.70	.27	11.6	.17
3.07	150	14.2	64.3	2.79	.35	8.9	.34
3.07	125	13.2	29.0	1.26	.19	14.2	.13
3.07	125	13.2	46.8	2.03	.27	10.0	.24
3.07	125	13.2	75.1	3.25	.35	7.7	.47
3.07	100	12.1	33.9	1.47	.19	12.0	.18
3.07	100	12.1	57.7	2.51	.27	8.4	.36
3.07	75	10.7	39.3	1.70	.19	9.4	.24
3.07	75	10.7	62.1	2.68	.25	7.1	.45
3.07	59	9.8	45.9	1.99	.19	7.8	.32
3.07	55	9.5	48.0	2.08	.19	7.4	.35
3.07	55	9.5	64.0	2.77	.22	6.4	.54
3.07	54	9.4	48.4	2.10	.19	7.2	.36
3.07	53	9.4	63.0	2.73	.22	6.2	.52
3.07	50	9.2	49.2	2.18	.19	6.9	.37
3.07	50	9.2	70.6	3.07	.22	6.0	.66

[a] Above the stack-branch junction.
[b] Computed from eq (46) and the measured discharge rates listed in second column.

5.2. Air-Flow Measurements

Data on the flow of air delivered to the stack vent and to a single horizontal branch 8 ft below the point of water entry are shown in tables 9 and 10. The test system is shown in figures 5 and 7. Table 9 gives data obtained with the stack vent fully open, and table 10 with it completely closed. Other conditions were the same in the two cases. The data for several rates of water discharge have been taken from table 9 and plotted in figure 20.

Also, from the data of table 9, figure 21 has been prepared, showing approximately the rates of air flow delivered to the horizontal branch for various rates of water discharge in the stack for pneumatic-pressure reductions in the branch of 2.0, 1.0, and 0.5 in. of water.

Figure 22 has been prepared from the data in table 9 for a rate of water discharge of 65 gpm.

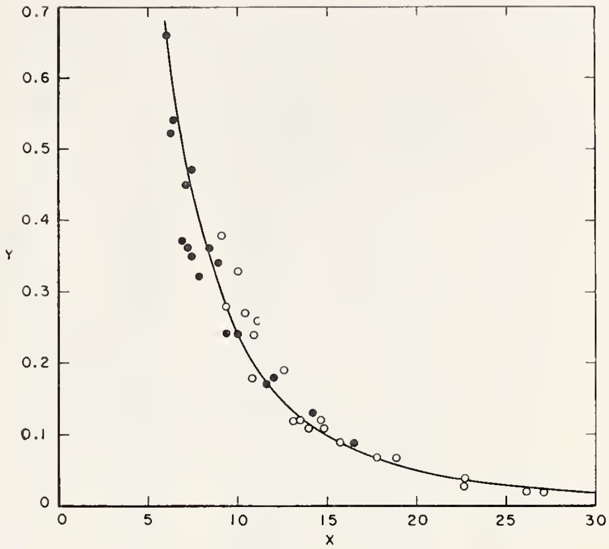

Figure 19. *Results of tests on flow interference at junction of prototypal stack and horizontal branches connected with sanitary-tee fittings, one-branch flow.*

○, 1-½-in. branch
●, 3-in. branch

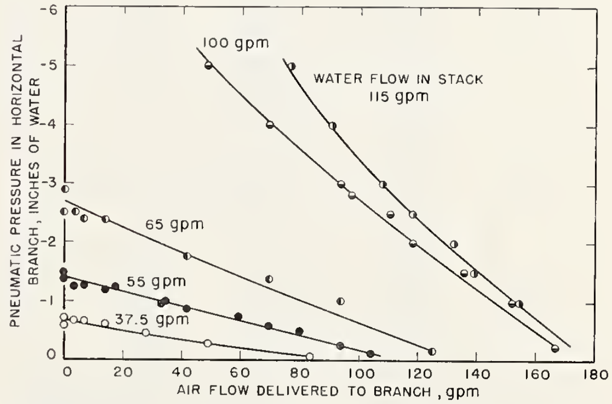

Figure 20. *Air flow delivered to horizontal branch of stack.*

3-in. stack and branch, stack vent open, water introduced 8 ft above branch.

This figure shows graphically the relations between air flow in the stack vent, air flow in the vent to the horizontal branch, and pneumatic pressure in the horizontal branch. The dashed line represents maximum rates of air flow computed from eq (56) and the uppermost solid curve represents total air-flow requirements determined experimentally on the test system shown in figures 5 and 7.

Figure 23 has been prepared for several rates of water discharge showing the total inflow of air for various pneumatic pressures maintained in the horizontal branch. These data have been taken from tables 9 and 10 and represent conditions with the stack vent open and conditions with it closed.

Table 9. *Air-flow data for 3-in. drainage stack, stack vent open*

Water flow in stack [a]	Pressure reduction in horizontal branch	Air delivered to horizontal branch	Air delivered to stack vent	Total air delivered to stack
gpm	*in. of water*	*gpm*	*gpm*	*gpm*
37.5	0.60	0	----------	----------
	.73	0	207	207
	.68	3.5	199	203
	.65	7.0	184	191
	.62	13.9	184	198
	.46	27.8	176	204
	.28	48.7	169	218
	.06	83.4	146	229
40.5	.75	0	----------	----------
	.62	11.1	----------	----------
	.50	19.5	----------	----------
	.25	59.1	----------	----------
45.0	[b] 1.00	0	----------	----------
	1.00	0	----------	----------
	0.81	0	184	184
	.75	16.7	----------	----------
	.68	3.5	176	180
	.65	7.0	176	183
	.56	13.9	161	175
	.50	38.2	----------	----------
	.44	27.8	153	181
	.26	48.7	146	195
	.25	73.0	----------	----------
	.12	83.4	130	213
55	1.50	0	----------	----------
	1.38	0	199	199
	1.25	17.4	----------	----------
	1.25	3.5	199	203
	1.25	7.0	199	206
	1.18	14.0	192	206
	1.00	34.8	184	219
	1.00	34.8	----------	----------
	0.88	41.7	184	226
	.75	59.1	----------	----------
	.59	69.5	169	239
	.50	80.0	----------	----------
	.25	93.9	----------	----------
	.12	104	130	234
60	2.00	0	----------	----------
	1.50	18.8	----------	----------
	1.00	52.1	----------	----------
	0.50	90.4	----------	----------
	.25	118	----------	----------
65	2.88	0	207	207
	[c] 2.50	0	----------	----------
	2.50	3.5	207	211
	2.38	7.0	207	214
	2.38	13.9	199	213
	1.75	41.7	184	226
	1.38	69.5	169	239
	1.00	93.9	154	248
	0.18	125	123	248
70.5	3.00	0	----------	----------
	2.50	17.4	----------	----------
	2.00	45.2	----------	----------
	1.50	73.0	----------	----------
	1.00	97.3	----------	----------
	0.50	125	----------	----------
78.3	4.00	0	----------	----------
	3.00	27.8	----------	----------
	2.50	55.6	----------	----------
	2.00	76.5	----------	----------
	1.50	93.9	----------	----------
	1.00	118	----------	----------
	0.50	146	----------	----------
86.0	5.00	0	----------	----------
	4.00	31.3	----------	----------
	3.00	62.6	----------	----------
	2.00	93.9	----------	----------
	1.00	132	----------	----------
	0.50	160	----------	----------

Finally, figure 24 has been prepared showing rates of air flow for various rates of water discharge in a 3-in. stack. The experimental points plotted in this figure represent data from table 9 for pneumatic pressures in the horizontal branch approximately 1 in. below atmospheric.

Table 9. *Air-flow data for 3-in. drainage stack, stack vent open*—Continued

Water flow in stack [a]	Pressure reduction in horizontal branch	Air delivered to horizontal branch	Air delivered to stack vent	Total air delivered to stack
gpm	*in. of water*	*gpm*	*gpm*	*gpm*
100	10.4	0	184	184
	9.6	3.5	184	188
	9.5	7.0	176	183
	9.2	13.9	176	190
	8.6	0	----------	----------
	7.4	41.7	176	218
	7.0	0	----------	----------
	5.3	69.5	146	216
	5.0	48.7	----------	----------
	4.0	69.5	----------	----------
	3.0	93.9	----------	----------
	2.8	97.1	115	212
	2.5	111	----------	----------
	2.0	118	----------	----------
	1.5	136	----------	----------
	1.0	153	----------	----------
	1.0	153	92.1	245
	0.25	167	69.0	236
115	11.3	0	----------	----------
	9.5	0	----------	----------
	5.0	76.4	----------	----------
	4.0	90.4	----------	----------
	3.0	108	----------	----------
	2.5	118	----------	----------
	2.0	132	----------	----------
	1.5	139	----------	----------
	1.0	153	----------	----------

[a] Water introduced 8 ft above level of horizontal branch to which air was delivered.
[b] A value of 0.50 in. was obtained by introducing water 24 ft above horizontal branch.
[c] A value of 1.0 in. was obtained by introducing water 24 ft above horizontal branch.

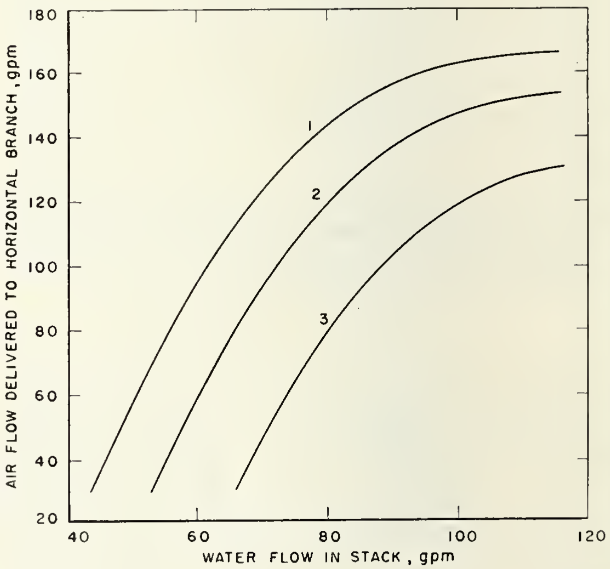

Figure 21. *Effect of pneumatic pressure and rate of water flow on air required to vent horizontal branch.*

3-in. stack and branch, stack vent open, water introduced 8 ft above branch.
1. Pneumatic pressure in branch = −0.5 in. of water.
2. Pneumatic pressure in branch = −1.0 in. of water.
3. Pneumatic pressure in branch = −2.0 in. of water.

Figure 25 gives a comparison of experimental data from several sources showing the flow of air required to maintain a pneumatic pressure within 1-in. water column of atmospheric in a horizontal branch of a 3-in. drainage stack. In the tests from which these data were obtained, with the exception of the tests made by Babbitt [7, 8], all the water flow was introduced into the stack within one branch interval above the horizontal branch under observation. In general, the data of Dawson and Kalinske [5] indicate less flow of air than do the corresponding data of Hunter [3] and of the most recent NBS investigation. Babbitt's measurements, made in regions of positive pressure, are in fair agreement with somewhat similar measurements made in the most recent NBS investigation, in regions of negative pressure.

Among the factors which may influence air flow in drainage and vent pipes are the following: type of fitting through which water is introduced; type of fitting to which horizontal branch is connected; distance from point of water entrance to horizontal branch where air flow is measured; distance from point of water entrance to base of stack; number of fittings in stack; roughness of stack and of building drain and sewer; and presence or absence of building trap or bends in building drain or sewer. Because all of these factors were not held constant in tests by different investigators, it is not surprising that the results are not in close agreement. However, in spite of their lack of close agreement, the data of figure 25 show that the maximum flow of air delivered to a region of negative pressure or carried away from a region of positive pressure, in order to maintain pneumatic pressures within 1.0 in. water column of atmospheric, was usually less than that computed from eq (56).

In figures 22 and 23, the agreement between the test results and eq (56) is close for pneumatic pressures near atmospheric in the horizontal branch. However, as the pneumatic pressure in the horizontal branch was reduced, the flow of air into the horizontal branch decreased and the flow of air into the stack vent increased, as shown in figure 22. Evidently, there existed a tendency for a certain total air inflow, part of it coming from the stack vent and part of it from the vent to the horizontal branch, to approximate the value computed from eq (56). The data of figures 23 and 24 for combined air flow in stack vent and in branch vent indicate that eq (56) may be useful to estimate upper limits for air flow under conditions similar to those in the tests on which these figures are based.

The curves shown in figure 20 show that, for pneumatic pressures in the horizontal branch only slightly below atmospheric, the pressure varies approximately in a linear fashion with the quantity of air delivered to the branch, the lowest pressure being obtained when no air is delivered to the branch.

From figure 21, it is evident that for water flows up to at least 115 gpm in the 3-in. stack, the air flow required to maintain a given pressure in the horizontal branch increased with increased water

Table 10. *Air-flow data for 3-in. drainage stack, stack vent closed*

Water flow in stack [a]	Pressure reduction in horizontal branch	Air delivered to horizontal branch
gpm	*in. of water*	*gpm*
	16.5	0
	15.2	3.5
	14.5	7.0
	14.0	13.9
37.5	10.5	41.7
	7.8	69.5
	3.1	139
	1.0	209
	0.38	236
	24.2	0
	23.2	3.5
	22.5	7.0
	21.4	13.9
45.0	16.4	41.7
	12.4	69.5
	4.4	139
	1.0	237
	0.44	257
	156	0
	105	3.5
	90.3	7.0
	36.0	13.9
	25.2	13.9
	24.0	41.7
55.0	20.5	41.7
	17.4	69.5
	15.5	69.5
	7.4	139
	6.4	139
	1.0	250
	0.50	237
	.44	264
	184	0
	122	3.5
	110	7.0
	85.0	13.9
65.0	18.0	41.7
	10.8	69.5
	2.5	139
	1.0	244
	0.38	195
	211	0
	187	3.5
	177	7.0
	147	13.9
100	61.2	41.7
	39.8	69.5
	11.8	139
	1.0	195
	0.38	195

[a] Water introduced 8 ft above level of horizontal branch to which air was delivered.

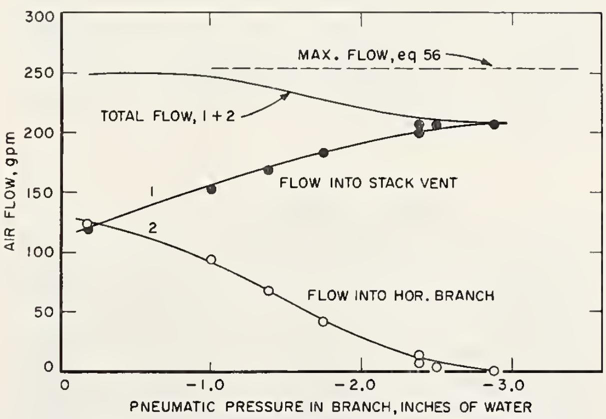

Figure 22. *Air flow in stack vent and in branch vent.*
Rate of water flow in stack, 65 gpm.

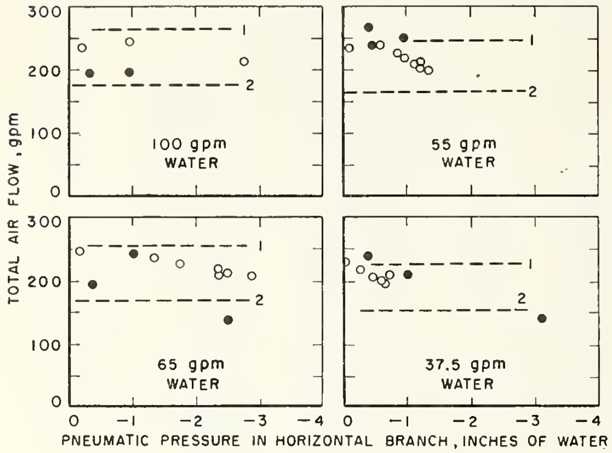

Figure 23. *Total air flow into venting system.*

Each ordinate represents the sum of the air-flow rates in the stack vent and in the branch vent.
○, stack vent open
●, stack vent closed
1, Rates computed from eq (56).
2, Equation (56) values reduced by one third.

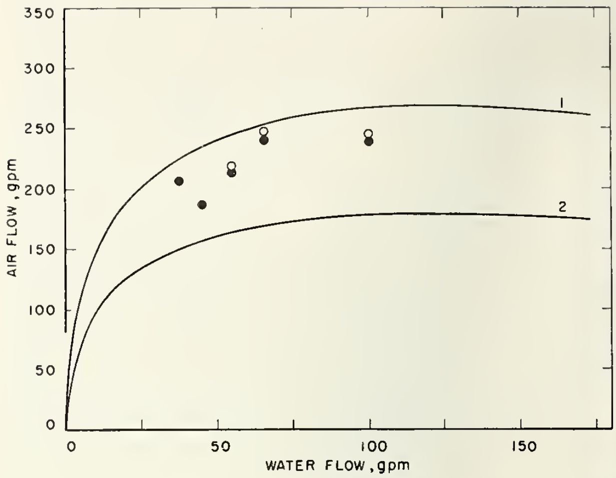

Figure 24. *Total air flow into drainage system for a pneumatic pressure of approximately 1 in. below atmospheric in horizontal branch.*

Each ordinate represents the sum of the air-flow rates in the stack vent and in the branch vent.
○, measured values from table 9 for a pneumatic pressure of −1.0 in. of water.
●, average of measured values from table 9 for pneumatic pressures in the range 0 to −2.0 in. of water.
1, Rates computed from eq (56).
2, Equation (56) values reduced by one third.

flow, but tended to level off at the higher rates. This appears reasonable, since it can be shown by use of eq (56) that for a stack of 3.07 in. diameter (the diameter used in the tests), the peak rate of air flow occurs for a water flow of the order of 120 gpm, and the air flow decreases for greater rates of water flow.

The resistance offered by the flow of water on the wall of a drainage stack to the entrance of air through a vent or horizontal branch connection has been observed by Dawson and Kalinske [5]. Certain measurements relating to this phenomenon were also made in the laboratory investigation reported herein (see section 3.2.). These measurements are not shown because of some uncertainty about their accuracy. Since the pressure heads measured were relatively low, a given error in measurement would be more significant than if the heads measured had been relatively high. However, it is believed that the measurements were sufficiently reliable to provide some general indications. Application of the same line of reasoning which produced eq (62) leads to an equation having the form

$$X^{a}Y^{1-a}\left(\frac{T}{D_2}\right)^{a}\left(\frac{D_2}{D_2}\right)^{1-a}=C. \qquad (63)$$

The exponent a evidently has the same value as in eq (62).

The mean velocity in the layer flow in the stack corresponding to any particular volume rate of water flow was computed from eq (45) (it being assumed that the water had reached terminal velocity at the branch level) and the thickness of the water layer on the wall of the stack was com-

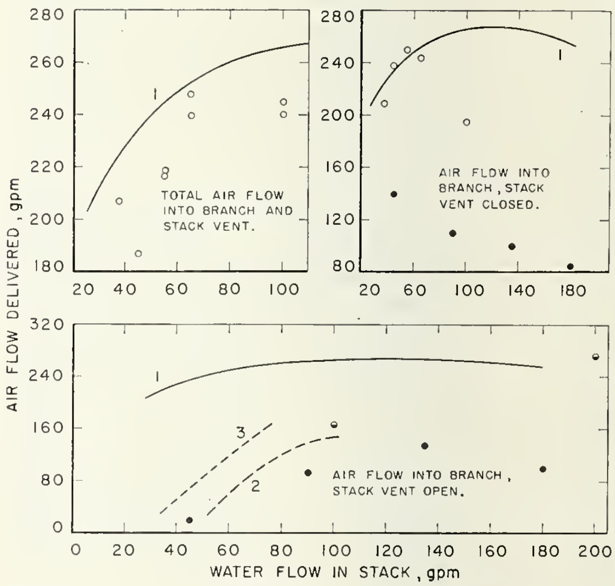

Figure 25. *Data from several sources showing air flow required to maintain a pneumatic pressure within 1-in. water column of atmospheric in horizontal branch of 3-in. drainage stack, water introduced at one elevation only.*

1, Equation (56).
2, Approximate curve based on data of table 9 and figure 21, for pneumatic pressure of −1.0 in. of water in vented branch 8 ft below point of water entrance.
3, Approximate curve based on data given by Babbitt for pneumatic pressure of +1.0 in. of water in vented branch near base of stack.
○, Values based on data of tables 9 and 10 for pneumatic pressure of −1.0 in. of water in vented branch 8 ft below point of water entrance.
●, Data from investigation by Dawson and Kalinske for pneumatic pressure of −1.0 in. of water in vented branch 8 ft below point of water entrance.
⊖, Data from investigation by Hunter for pneumatic pressure of −1.0 in. of water in vented branch only slightly below point of water entrance.

puted from eq (43). In eq (63) the terms X and Y have the following significance:

$$X=\frac{(V_1)^2}{2g(h_2-h_1)} \text{ and } Y=\frac{(V_2)^2}{2g(h_2-h_1)}.$$

The terms V_1 and V_2 represent, respectively, mean velocities in the water stream in the stack and in the air stream in the branch. The term (h_2-h_1) represents the difference in pneumatic pressure between a point inside the air core in the stack and a point inside the horizontal branch near its junction with the stack.

5.3. Miscellaneous Measurements

a. Distribution of Air and Water in Cross Section of Drainage Stack

The data taken in this portion of the investigation, in the manner described in section 3.3.a., appear in table 11. These data show that the ratio of air to water intercepted by the sampling equipment increased, with distance from the wall of the stack, to a value which appears to indicate that about as much air as water was flowing at the axis of the stack. The relative rate of measured air flow as a function of distance from the wall of the stack is shown in figure 26.

Computations indicate that not more than about 0.82 of the water actually striking the tip of the impact tube used in these tests was delivered to the sampling equipment. This value was computed as follows: First, the cross section of the drainage stack was divided into imaginary concentric areas, each area (except the one at the axis which included only one traverse point) including two points on the impact-tube traverse which were equidistant from the axis. Second, for each such area the average measured rate of flow into the impact tube was multiplied by the ratio of the concentric area served to the cross section of the tube tip. Third, the values obtained in the second step were added and the sum divided by the total known rate of water flow in the stack (in this case 100 gpm).

On the other hand, for estimating the proportion of the air which was intercepted by the impact tube, no such direct method is available. However, if it is assumed that the total air flow was that indicated by eq (56), an estimate of approximately 265 gpm for a water flow of 100 gpm is obtained. Integration of the air-flow values, shown in the third column of table 11, in a manner similar to that described above for the water intercepted indicates that, on the average, only about 0.20 of the air carried down the stack at any given point was actually intercepted by the impact tube in these tests.

It appears likely that the measured values of air and water flow in table 11 were less than the true values to a degree which depended, among other things, on the distance from the wall of the stack.

TABLE 11. *Distribution of water and air in cross section of 3-in. drainage stack for a water flow of 100 gpm introduced at one elevation*

Distance from wall of stack	Water [a] delivered to measuring apparatus	Air [a] delivered to measuring apparatus	Ratio of distance from wall of stack to radius of stack	Ratio [b] of air flow to water flow	Ratio [c] of air flow to air flow at axis of stack
in.	*cc/min*	*cc/min*			
0.096	130.1	15.6	0.063	0.120	0.108
.159	119.4	25.9	.104	.217	.180
.222	140.4	40.6	.145	.289	.282
.284	130.0	56.0	.185	.431	.389
.346	120.2	69.2	.226	.576	.481
.409	117.3	78.2	.267	.666	.543
.472	113.5	87.2	.307	.768	.605
.534	113.5	94.7	.348	.834	.657
.784	128.1	119.3	.511	.931	.828
1.034	149.0	133.8	.674	.898	.929
1.284	161.3	144.0	.837	.893	.999
1.534	156.1	144.1	1.00	.923	1.00

[a] Each value shown is the average of two measurements taken equidistant from opposite walls of the stack.
[b] Computed from values given in columns 2 and 3.
[c] Computed from values given in column 3.

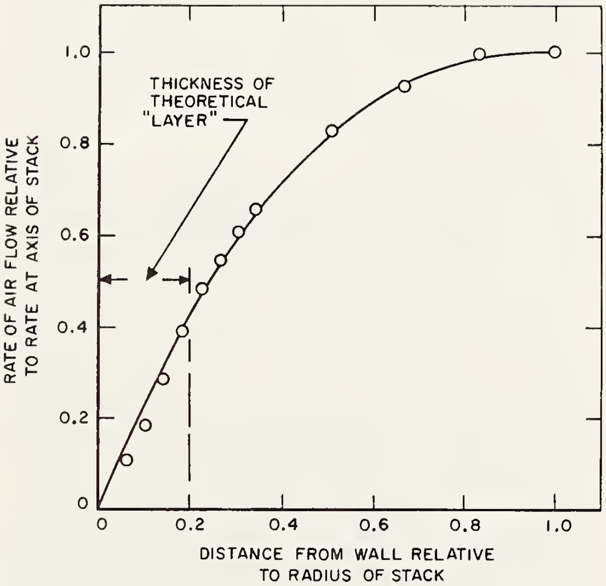

FIGURE 26. *Measured air-flow rate as a function of distance from wall of 3-in. stack*

100 gpm water introduced into stack at one elevation.

The reasons for this include the facts that (1) near the center of the stack the inertia and friction effects associated with intermittent impingement of water on the impact tube would have produced less efficient flow of water to the measuring equipment than near the wall of the stack, and (2) the conditions causing air to enter the impact tube were such as to prevent all the air intercepted by the tube tip from being delivered to the measuring equipment. Although this problem was not investigated experimentally, the assumption that the actual flow of either air or water at any point in the cross section exceeded the measured value by a fractional part which is a direct linear function of the distance from the wall of the stack yields a more reasonable picture of conditions in the stack than would a consideration of only the direct measurements reported in table 11. If this assumption is made, computations indicate that the ratio of air flow to water flow varied from approximately 1.0 to 3.7 in the region of the theoretical "air core," as shown in figure 27, reaching the value 3.7 at the center of the stack.

These computations also indicate that, within the theoretical region of water flow, the ratio of air flow at any point to the air flow at the axis of the stack ranged from zero to only about 0.12, instead of the surprisingly larger values indicated by the measurements reported in table 11 and shown in figure 26.

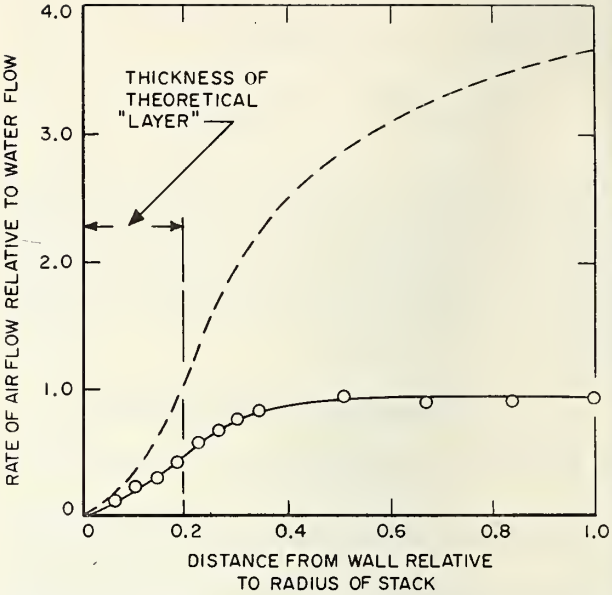

FIGURE 27. *Ratio of air-flow to water-flow rates as a function of distance from wall of 3-in. stack.*

100 gpm water introduced into stack at one elevation.
— — — estimated
——— measured

b. Velocity Distribution of Water in Cross Section of Drainage Stack

Data taken in this portion of the investigation, described in section 3.3.b., appear in figure 28. For comparison, the thickness and terminal velocity of the water layer, computed from eqs (43) and (46), respectively, are also shown in this figure for each rate of water flow.

Indirect evidence obtained during the tests indicated that some air was entrained in the falling water and that droplets and small quantities of water were thrown toward the center of the stack. The presence of fittings at 8-ft intervals may have contributed to this phenomenon. This type of flow could produce impact pressures within the theoretical "air core," such as were actually observed in the tests. Thus, the impact pressures obtained some distance from the wall of the stack may not accurately indicate water velocities, since the impact tube was calibrated for water only.

One important point which is suggested by the data shown in figure 28 is that near the wall of the stack the velocity gradient is very steep, evidently much steeper than the distribution which occurs in turbulent flow in pipes full under pressure.

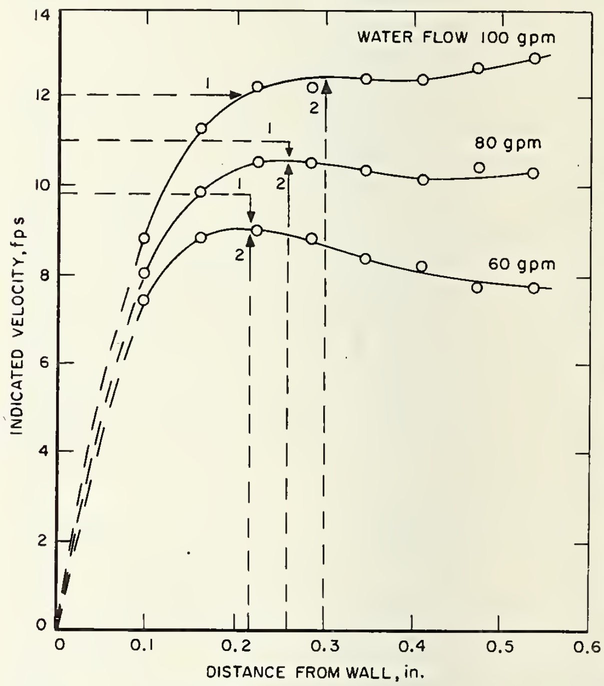

FIGURE 28. *Indicated velocities near wall* of 3-in. drainage stack.*

1. Mean terminal velocities computed from eq (46).
2. "Layer" thickness computed from eq (43).
*Indicated velocities in central part of cross section were greater than those shown in the figure.

c. Pneumatic Pressures within Drainage Stack

Data on pneumatic pressures within the test system (shown in fig. 5) for various water flows both with and without venting, were obtained in the manner described in section 3.3.c. These data are shown in figures 29 through 32. Data obtained with the venting system functioning are shown in figures 30 and 32, and those obtained with the vents closed are shown in figures 29 and 31.

The formula

$$\frac{\Delta h}{D_1}=C\left[\frac{Q_1}{(D_1)^{5/2}\sqrt{g}}\right]^{5/2}\frac{L}{D_1} \tag{64}$$

is in fair agreement, for pneumatic pressures at points more than one story below the point of water entrance, with most of the data shown in figure 29. In eq (64) Δh is the difference in pneumatic pressure between the base of the stack and any point

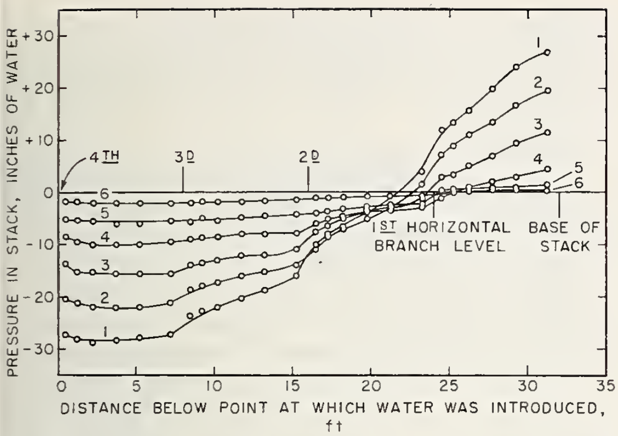

FIGURE 29. *Pneumatic pressures in 3-in. drainage stack (water introduced at fourth branch level, stack open at top but otherwise not vented) (see fig. 5 for details of test system).*

Curve number	Water flow
	gpm
1	175
2	150
3	125
4	100
5	80
6	60

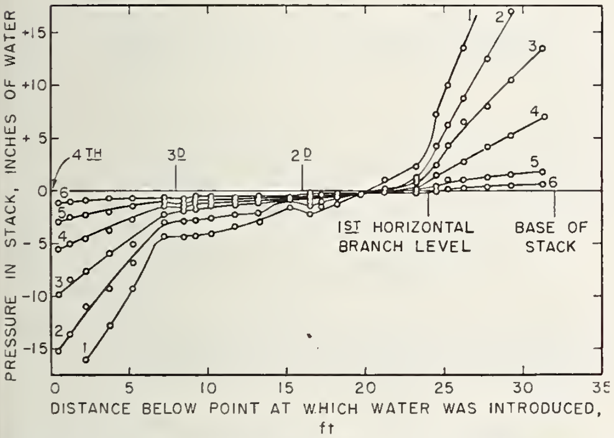

FIGURE 30. *Pneumatic pressures in 3-in. drainage stack (water introduced at fourth branch level, stack open at top, fully vented at 8-ft intervals) (see fig. 5 for details of test system).*

Curve number	Water flow
	gpm
1	175
2	150
3	125
4	100
5	80
6	60

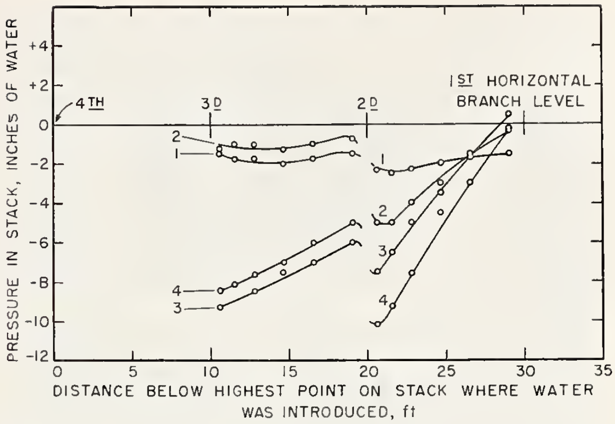

FIGURE 31. *Pneumatic pressures in 3-in. drainage stack (water introduced at second and fourth branch levels, stack open at top but otherwise not vented) (see fig. 5 for details of test system).*

Q_1 flow of water introduced 32 ft above base of stack.
Q_2 flow of water introduced 16 ft above base of stack.

Curve number	Q_1	Q_2
	gpm	*gpm*
1	60	30
2	60	60
3	100	30
4	100	60

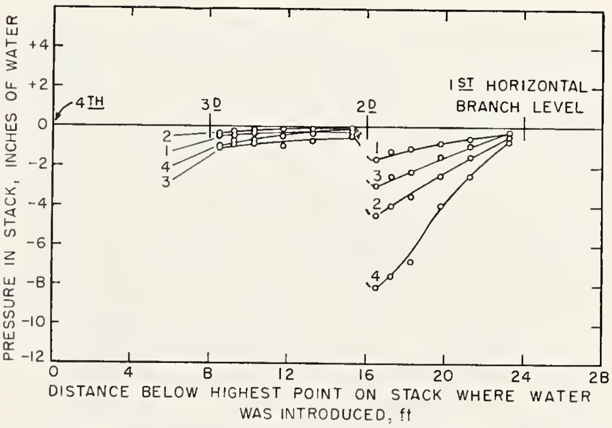

FIGURE 32. *Pneumatic pressures in 3-in. drainage stack (water introduced at second and fourth branch levels, stack open at top, fully vented at 8-ft intervals) (see fig. 5 for details of test system).*

Q_1 flow of water introduced 32 ft above base of stack
Q_2 flow of water introduced 16 ft above base of stack

Curve number	Q_1	Q_2
	gpm	*gpm*
1	60	30
2	60	60
3	100	30
4	100	60

a distance L above the base of the stack, expressed in head of water. A value of $C=0.038$ was computed from the data of figure 29, using dimensionally consistent units in eq (64).

When water was introduced into the test stack simultaneously at two points at different levels, the pneumatic pressure approached a minimum value just below the higher point. The pressure increased with distance below this point. It again decreased below and near the lower point of water entrance, after which it once more increased with distance below the latter point. The pneumatic pressure for a wide range of water flows tended to approach atmospheric at a fairly definite point in the stack when the water was introduced at one point only and when the system was vented by only the stack vent. The elevation of the point of atmospheric pressure is affectedby the resistance to flow of air and water offered by the building drain. For a given rate of water flow, the change in pneumatic pressure between two points where air could enter or leave the stack was approximately linear with respect to distance along the stack, except within the interval approximately one floor level below the point of water entrance. Within this interval, the linear relation did not apply, probably because the terminal velocity was developing here with accompanying energy and momentum adjustments in the flow of air and water.

The data of figures 29 and 30, as well as earlier data of a similar nature [5, 7, 8], indicate that the pneumatic pressure within the stack at any given point between floor levels tended to conform, over a fairly wide range, to a power function of the volume rate of water flow. The maximum value of the power appeared to be 5/2. This is similar to the finding by Babbitt that the pneumatic pressure in a vented horizontal branch is a power function of the volume rate of water flow, the exponent being less than 5/2 and greater than zero, depending on the extent of relief provided by the venting system.

Data shown in figures 29 to 32 are consistent with those obtained by earlier investigators [5, 7, 8] in showing that the maximum reduction in pneumatic pressure in a drainage stack occurs below and near a point of water entrance.

Figures 30 and 32 indicate that, even in a multistory drainage stack equipped with a venting system, pneumatic-pressure changes of appreciable magnitude may develop within the stack between the various floor levels. However, if pressures within the horizontal branches and fixture drains can be relieved by venting, this is all that is necessary to avoid siphoning or blowing the trap seals.

6. Application of Results of Investigation

6.1. Permissible Simultaneous Rates of Flow at Junction of Drainage Stack and Horizontal Branches

One application of the results of the investigation of interference of flows at the junction between a multistory drainage stack and a horizontal branch is to the prediction of the permissible rate of water flow in the stack or horizontal branch when the rate in one or the other of these components is known. This application of the results of tests on the simulated stack may be made by making certain substitutions in eqs (60) and (61) and rearranging terms. A similar application of the results reported for the prototypal stack may be made by starting with eq (62). The appropriate substitutions will now be discussed briefly.

The analysis given in section 4.1. of this paper defined the quantitites X and Y in terms of the velocities V_1 and V_2, the head difference (h_2-h_1), and g, the acceleration of gravity. In eq (42), the dimension T is expressed approximately in terms of the discharge rate Q_1, the stack diameter D_1, and the velocity V_1.

The next substitution operation is performed by setting V_1 equal to the terminal velocity given by eq (44) and expressing V_2 in terms of Q_2 and D_2. Finally, for the purpose of computing flow capacities, the numerical values of $g=32.2$ ft/sec^2 and $k_s=0.00083$ ft (see section 4.2.a. of this paper) are substituted.

It is assumed that V_1 is equal to the terminal velocity V_t, since it was shown in the earlier paper [10] and in section 4.2. of this paper that the velocity of flow in a stack under ideal conditions should nearly reach terminal velocity when the water has fallen through a distance of one branch interval below the point of entry.

This procedure of substitution leads to the equations

$$\frac{(Q_2)^2}{2g(h_2-h_1)(D_2)^4}=5.14-10.2\left(\frac{D_1}{D_2}\right)^{1/4}\frac{D_1}{(Q_1)^{3/8}}\left(\frac{g^3}{k_s}\right)^{1/16}\cdot\left[\frac{(Q_2)^2}{2g(h_2-h_1)(D_2)^4}\right]^{3/8}\left[\frac{(Q_1)^2}{2g(h_2-h_1)(D_1)^4}\right]^{5/8} \qquad (65)$$

and

$$\frac{(Q_2)^2}{(h_2-h_1)(D_2)^4}=331-30.5\left(\frac{D_1}{D_2}\right)^{1/4}\frac{D_1}{(Q_1)^{3/8}}\cdot\left[\frac{(Q_2)^2}{(h_2-h_1)(D_2)^4}\right]^{3/8}\left[\frac{(Q_1)^2}{(h_2-h_1)(D_1)^4}\right]^{5/8} \qquad (66)$$

based on the results of experiments on the simulated stack using sanitary-tee fittings.

In a similar manner, the equations

$$\frac{(Q_2)^2}{2g(h_2-h_1)(D_2)^4}=3.70-5.75\left(\frac{D_1}{D_2}\right)^{1/4}\frac{D_1}{(Q_1)^{3/8}}\left(\frac{g^3}{k_s}\right)^{1/16}\cdot\left[\frac{(Q_2)^2}{2g(h_2-h_1)(D_2)^4}\right]^{3/8}\left[\frac{(Q_1)^2}{2g(h_2-h_1)(D_1)^4}\right]^{5/8} \qquad (67)$$

and

$$\frac{(Q_2)^2}{(h_2-h_1)(D_2)^4}=238-17.1\left(\frac{D_1}{D_2}\right)^{1/4}\cdot\frac{D_1}{(Q_1)^{3/8}}\left[\frac{(Q_2)^2}{(h_2-h_1)(D_2)^4}\right]^{3/8}\cdot\left[\frac{(Q_1)^2}{(h_2-h_1)(D_1)^4}\right]^{5/8} \qquad (68)$$

have been obtained from the results of tests on the simulated stack using long-turn T-Y stack fittings.

Beginning with eq (60) and making substitutions similar to those which produced eqs (65) and (66), the equations

$$\frac{(Q_2)^2}{2g(h_2-h_1)(D_2)^4}=5.14-5.42\left(\frac{D_1}{(Q_1)^{3/8}}\right)^{2.24}\left(\frac{g^3}{k_s}\right)^{0.14}$$

$$\cdot\left[\frac{(Q_2)^2}{2g(h_2-h_1)(D_2)^4}\right]^{0.3}\left[\frac{(Q_1)^2}{2g(h_2-h_1)(D_1)^4}\right]^{0.7} \quad (69)$$

and

$$\frac{(Q_2)^2}{(h_2-h_1)(D_2)^4}=331-63.1\left(\frac{D_1}{(Q_1)^{3/8}}\right)^{2.24}$$

$$\cdot\left[\frac{(Q_2)^2}{(h_2-h_1)(D_2)^4}\right]^{0.3}\cdot\left[\frac{(Q_1)^2}{(h_2-h_1)(D_1)^4}\right]^{0.7} \quad (70)$$

are obtained, based on the results of tests on the prototypal stack using sanitary-tee stack fittings.

In order to compute numerical values of flow capacities from eqs (66), (68), and (70), it is first necessary to select a value for the term (h_2-h_1). It appears that a reasonable value would be a value that would allow the horizontal branch to flow barely full. The selection of such limiting values will be based on identical pneumatic-pressures in a drainage stack at a given elevation and in a vent connecting to a horizontal branch at the same elevation. This condition requires that there be an adequate venting system and that the stack and branches not be overloaded. Therefore, in the terminology of figure 10, $p_1=p_4$ (or $h_1=h_4$). Since $h_2=h_3+h_4$, it follows directly that $h_2-h_1=h_3$. Figure 10 indicates that h_3 is actually the water depth in the branch. Measurements made on the fittings used in this investigation to connect the stack and the horizontal branches indicated that, at a distance of 4 branch diameters from the stack, h_3 should not exceed about 0.75 times the branch diameter for sanitary-tee fittings, or about 1.8 times the branch diameter for long-turn T-Y fittings, if the branches are to flow approximately full but not under a head. Hence, it will be assumed in applying eqs (66), (68), and (70) that $(h_2-h_1)=0.75\ D_2$ for sanitary-tee stack fittings, and that $(h_2-h_1)=1.8\ D_2$ for long-turn T-Y stack fittings.

Equations (66), (68), and (70) have been solved for a 3-in. stack for the three different branch sizes used in this investigation, and the results are shown in figures 33 to 36. In these figures, any point on the curves represents a combination of flow rates which should be the maximum that can occur simultaneously without causing the head difference $(h_2-h_1)=1.8\ D_2$ for long-turn T-Y stack fittings or $0.75\ D_2$ for sanitary-tee fittings to be exceeded. Expressed in another way, the combinations of flow rates which may be taken from these curves represent the maximum rates which can be introduced simultaneously without causing a head of water to build up in a vent connecting to the horizontal branch at a distance of 4 branch diameters from the stack.

The range in values of branch discharge which may be computed from eqs (66), (68), and (70) extends beyond practical limits for the smaller flows in the stack. As a rough guide to the upper limits of discharge in the horizontal branches flowing full under no external head, it can be shown by means of the Darcy-Weisbach formula that the discharge rate should not exceed approximately 16, 29, and 78 gpm for 1½-, 2-, and 3-in. branches, respectively. These values have been computed for a slope of ¼ in. per ft and a value for f of 0.03. The limits established in this manner are indicated by horizontal lines across the curves in figures 33 to 36. Greater rates of discharge would cause the hydraulic gradient in a horizontal branch to exceed the slope of the branch.

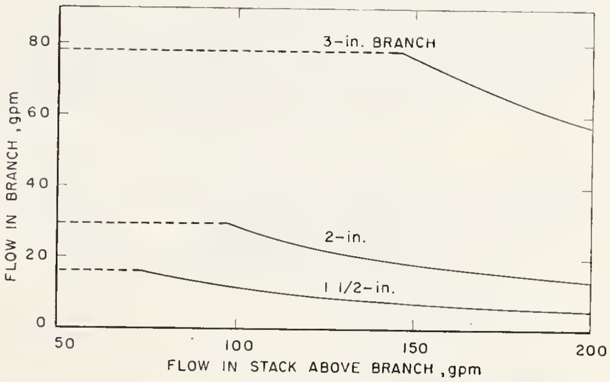

FIGURE 33. *Permissible simultaneous rates of flow computed for junction of 3-in. drainage stack and horizontal branches.*

Based on data from 3-in. simulated stack, long-turn T-Y fittings. Solid curves represent eq (68), wherein $(h_2-h_1)=1.8D_2$.

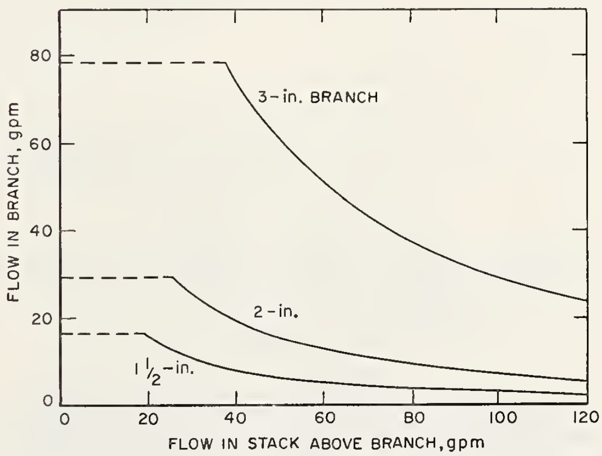

FIGURE 34. *Permissible simultaneous rates of flow computed for junction of 3-in. drainage stack and horizontal branches.*

Based on data from 3-in. prototypal stack, sanitary-tee fittings. Solid curves represent eq (70), wherein $(h_2-h_1)=0.75D_2$.

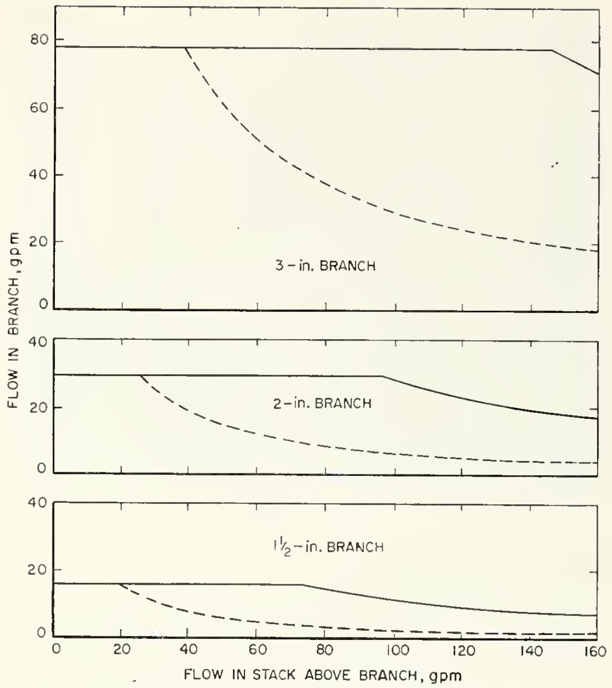

FIGURE 35. *Effect of type of stack fitting on permissible simultaneous rates of flow computed for junction of 3-in. drainage stack and horizontal branches.*

Based on data from 3-in. simulated stack.
— — — eq (66), sanitary-tee fitting, $(h_2-h_1)=0.75D_2$.
——— eq (68), long-turn T-Y fitting, $(h_2-h_1)=1.8D_2$.

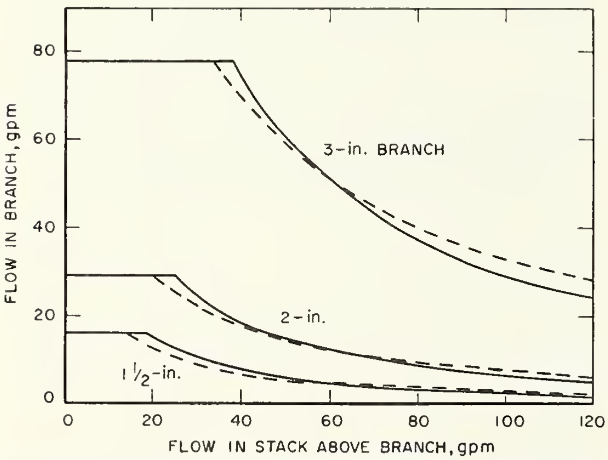

FIGURE 36. *Apparent effect of test system on permissible simultaneous rates of flow at junction of 3-in. drainage stack and horizontal branches, sanitary-tee fittings.*

$(h_2-h_1)=0.75D_2$.
——— eq (66), from tests on simulated stack.
— — — eq (70), from tests on prototypal stack.

Figure 35 gives a comparison of carrying capacities using sanitary-tee stack fittings and long-turn T-Y fittings, computed from eqs (66) and (68), respectively, based on tests on the simulated stack. It is evident that the greater capacities are obtained by the use of the long-turn T-Y fitting.

Figure 36 gives a comparison of carrying capacities based on tests on the simulated stack and on the prototypal stack using sanitary-tee stack fittings, computed from eqs (66) and (70), respectively. The two curves for each diameter of branch coincide at intermediate capacities, and do not differ greatly anywhere in the range covered in figure 36. A slight difference in the curves computed by the two methods is to be expected, since, in the prototypal stack, appreciable quantities of air were entrained in the water and not all of the water flowed in a layer on the wall of the stack. Other variables not taken into account in the investigation reported here may have contributed to the slight difference in results obtained in the two cases. However, it appears that the fundamental phenomena are quite similar in the two cases.

The fact which is most evident from figures 33 to 36 is that the occurrence of appreciable discharge in the stack simultaneously with discharge in the horizontal branches will reduce the capacities of the branches. This effect is greatest for the case in which sanitary-tee fittings are used to connect the stack and the branches.

6.2. Loads on Drainage Stacks

Figure 37 will be introduced at this point in order to provide a method for estimating peak discharge for design purposes. The concepts on which this figure is based are given elsewhere [15, 16]; hence, they will not be discussed in detail here. The design flow as represented by curve 1 of figure 37 is based on the theory of probability. It takes into account for each type of fixture the average time between uses during periods of heavy use, the length of time required for one typical operation, the average rate of discharge from the fixture, and the number of fixtures on the system under consideration. For fixture-unit loads up to 4,800, the curve has been computed from tables of the cumulative binomial probability distribution. That portion of the curve beyond 4,800 fixture units has been computed from Poisson's approximation to the binomial distribution. Curve 2 of figure 37 represents the average discharge from a system of water closets, each of which discharges 4 gal of water once in 5 min. The ordinates of curve 3 were obtained by addition of the ordinates of curves 1 and 2 for each abscissa value.

The flow capacities of drainage stacks given by Dawson and Kalinske [6] were computed by them on the assumption that the stacks flowed ¼ full. It will be observed in figure 38 that their recommended values lie very close to the computed curve for $r_s=⅓$. The reason for this is that Dawson and Kalinske assumed higher terminal velocities in developing their equation for flow capacity than have been assumed in developing eq (53) of this paper. For comparison, flow capacities derived from table 805(b)–III of BMS66 [17] and figure 37 of this paper are also shown in figure 38, these capacities having been obtained by determining from curve 1 of figure 37 of this paper the design discharges for stacks 6 in. and less in diameter, and by determining from curve 3 the design discharges for stacks 8 in. and more in diameter.

Figure 39 has been prepared from eq (53) and curve 1 of figure 37, and shows maximum fixture-unit loadings computed for various diameters of multistory drainage stacks. The dashed curves at the right of the figure are based on eq (53) and curve 3 of figure 37.
The plotted points were taken directly from certain loading tables which have been widely used [1, 17, 18].

Equation (53) should be applicable to stacks of height sufficient to produce terminal velocities and, therefore, can be looked upon as giving limiting flow capacities for tall stacks. In practice, loads on relatively short stacks may be limited by the capacities of the horizontal branches rather than by a criterion such as eq (53). The idea of allowing for stack height in establishing permissible loads is not new [17]. A simplified method of making allowance for stack height is given in section 9.3. of the appendix.

Table 12 has been prepared from eq (53) and figure 37. The values in this table are given in terms of discharge rates and also in terms of fixture units, for various diameters and relative filling of stack. Table 12 gives *maximum* values for tall stacks. It is *not* intended for use with one- and two-story stacks.

6.3. Loads on Vent Stacks

Equations (58) and (59) are useful for computing lengths and diameters of vent pipes required to carry given rates of air flow. Appropriate values of the friction coefficient should be used in applying these equations. For any particular pipe, f is an inverse function of the Reynolds number and increases with roughness of pipe material relative to diameter. Charts showing this effect [9, 19], considered together with eqs (53) and (56), indicate that values of f applying to vent stacks will vary inversely to an appreciable extent with diameter of drainage stack. However, for a given drainage stack, neither the particular diameter of vent stack likely to be used nor the particular rate of air flow within the range $r_s=0.15$ to 0.40 should have a significant effect on the value of f.

Values of f for use with eqs (58) and (59) are given in table 13. In obtaining these values, a value of 0.0010 ft absolute roughness, twice that given by Rouse [9] for galvanized steel pipe, has been assumed. This takes into account, to some extent, the expected effect of corrosion. Each value of f shown in table 13 is the average of the two values obtained from the assumption of two sizes of vent for a particular size of drainage stack, in one case the vent and the stack being of the same size and in the other case the diameter of the vent being one-half that of the stack.

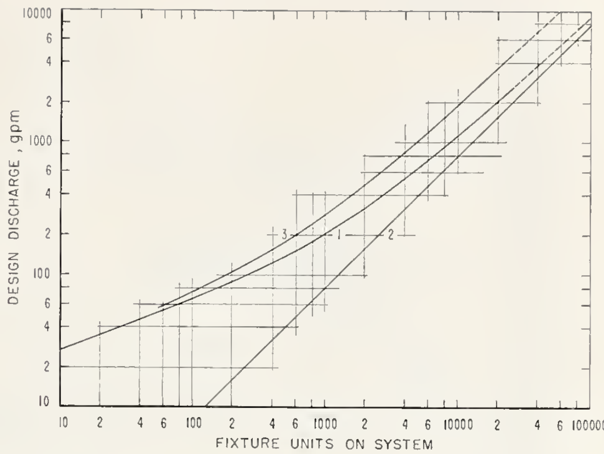

Figure 37. *Design-flow curves for plumbing-drainage systems.*

Curve 1 represents the *peak* discharge into the drainage system which, according to the theory of probability, will not be exceeded more than 1 percent of the time during periods of heaviest use.
Curve 2 represents the *average* discharge into the drainage system during periods of heaviest use computed from the discharge characteristics of water closets.
Curve 3 has been obtained by adding the ordinates of curves 1 and 2.

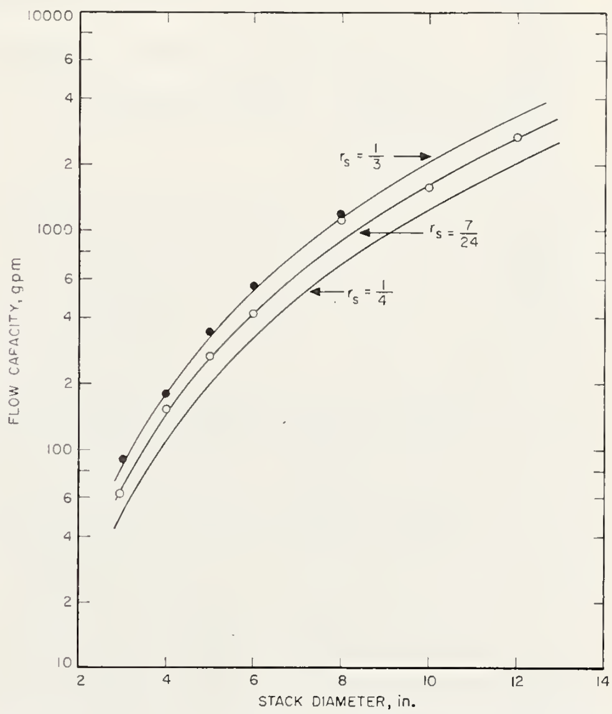

Figure 38. *Flow capacities of multistory drainage stacks for terminal water velocity.*

●, values computed by Dawson and Kalinske.
○, values based on eq (53), on maximum fixture-unit loadings from reference 17, and on design-flow rates from curves 1 and 3 of figure 37 (curve 1 for diameters of 6 in. or less; curve 3 for diameters of 8, 10, and 12 in.).

Laboratory experiments on simplified test systems have yielded results indicating that eq (56) is useful for estimating an upper limit to the total volume rate of air flow into or out of the

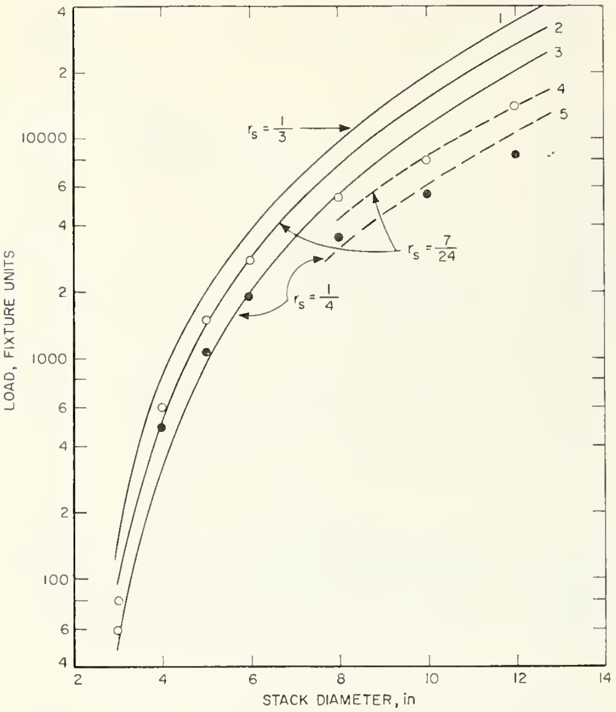

FIGURE 39. *Maximum fixture-unit loadings on multistory drainage stacks.*

Curves 1, 2, and 3 are based on eq (53) and on curve 1 of figure 37.
Curves 4 and 5 are based on eq (53) and on curve 3 of figure 37.
○, values from reference 17.
●, values from references 1 and 18.

system. However, the use of eq (56) to predict the flow of air through a typical vent stack at any particular point probably would result in an overestimate of the air demand. There are three reasons for this: (1) Some air is normally delivered to the system through the stack-vent as well as through the vent stack. (2) Recirculation of air within the main and branch vents and drains tends to reduce the quantity of air which must be moved through the vent stack at any single point. (3) Some air is ordinarily carried out of the system through the building drain and building sewer, thus reducing the quantity of air which must be relieved in areas of positive pressure near the base of the drainage stack. Data obtained by Dawson and Kalinske [5] for 3-, 4-, and 6-in. drainage stacks and those of table 9 of this paper for a 3-in. stack give maximum air demand, exclusive of air flow through the stack-vent, of the order of 50 to 75 percent of the hypothetical maximum. For these reasons, values computed from eq (56) have been reduced by ⅓ in developing table 14. This is equivalent to the use of eq (55) with the mean velocities of the air core and water stream being the same. The permissible lengths of vent pipe given in this table have been computed from eq (59). Equation (59) has been used instead of the more accurate eq (58) because it is simpler to apply and because the errors resulting from its use are not of serious importance in most instances with which this

TABLE 12. *Maximum loads on multistory drainage stacks* [a]

Stack diameter	Proportion of cross section occupied by falling water	Water discharge rate	Equivalent load
in.		*gpm*	*Fixture units*
3	0.15	22	----------
3	.20	35.6	21
3	.25	51.6	53
3	.29	66.8	100
3	.30	70	110
3	.33	83.4	160
4	.15	47.5	43
4	.20	76.7	140
4	.25	111	320
4	.29	144	530
4	.30	151	580
4	.33	180	850
5	.15	86.1	190
5	.20	139	490
5	.25	202	940
5	.29	261	1400
5	.30	273	1500
5	.33	326	2000
6	.15	140	500
6	.20	226	1100
6	.25	328	2000
6	.29	424	2900
6	.30	444	3100
6	.33	529	3800
8	.15	301	1800
8	.20	487	3400
8	.25	706	5600
8	.29	913	7600
8	.30	957	7900
8	.33	1140	9800
10	.15	546	4000
10	.20	883	7200
10	.25	1280	11000
10	.29	1660	15000
10	.30	1730	16000
10	.33	2070	19000
12	.15	889	7300
12	.20	1440	13000
12	.25	2080	20000
12	.29	2690	26000
12	.30	2820	27000
12	.33	3360	34000
15	.15	1610	15000
15	.20	2600	25000
15	.25	3770	38000
15	.29	4880	50000
15	.30	5110	53000
15	.33	6100	64000

[a] Loads given are upper limits computed for terminal-velocity conditions in tall stacks, and for conditions under which stack is not overloaded within any single-branch interval as determined by the criterion given in section 9.3. of the appendix.

TABLE 13. *Values of the friction coefficient f for use in computing maximum permissible lengths of vent stacks*

Diameter of drainage stack	f [a]
in.	
3	0.0367
4	.0330
5	.0307
6	.0286
8	.0260
10	.0242
12	.0230
15	.0214

[a] Computed by averaging values obtained (for stacks flowing ¼ full in accordance with eqs (53) and (55) wherein V_a/V_w=1.0 in eq (55)) with D_v=0.5D_l, and D_v=1.0D_l. A value of k_s=0.001 ft has been assumed, this being twice the value given by Rouse [9] for new galvanized-iron pipe.

TABLE 14. *Size and length of vent stacks*

Diameter of drainage stack	Proportion of cross section occupied by falling water	Water discharge rate	Air discharge rate	Load on drainage stack	Maximum developed length of vent [a]												
					1½-in. vent	2-in. vent	2½-in. vent	3-in. vent	3½-in. vent	4-in. vent	5-in. vent	6-in. vent	8-in. vent	10-in. vent	12-in. vent	14-in. vent	16-in. vent
in.		*gpm*	*gpm*	*Fixture units*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*
3	0.15	22.0	125	----------	42	145	355	1040									
	.20	35.6	142	21	32	110	270	805									
	.25	51.6	155	53	27	94	230	680									
	.29	66.8	162	100	25	86	210	620									
	.30	70.0	163	110	24	85	205	610									
	.33	83.4	167	160	23	81	200	585									
	.15	47.5	269	43		35	85	250	520	975							
	.20	76.7	307	140		27	65	195	400	750							
	.25	111	334	320		23	55	165	335	635							
	.29	144	349	530		21	50	150	310	580							
	.30	151	352	580		20	49	147	305	570							
	.33	180	359	850		19	47	140	290	545							
	.15	86.1	488	190			28	82	170	320	985						
	.20	139	556	490			21	63	130	245	760						
	.25	202	605	940			18	53	110	207	640						
	.29	261	633	1,400			16	49	101	189	585						
	.30	273	637	1,500			16	48	99	186	575						
	.33	326	651	2,000			15	46	95	179	555						
6	.15	140	793	500				33	69	130	400	1,000					
	.20	226	904	1,100				26	53	100	310	775					
	.25	328	984	2,000				22	45	84	260	655					
	.29	424	1,030	2,900				20	41	77	240	595					
	.30	444	1,040	3,100				19	40	76	235	590					
	.33	529	1,060	3,800				19	39	73	225	565					
8	.15	301	1,710	1,800						31	95	240	940				
	.20	487	1,950	3,400						24	73	185	720				
	.25	706	2,120	5,600						20	62	155	610				
	.29	913	2,220	7,600						18	56	140	555				
	.30	957	2,230	7,900						18	56	140	550				
	.33	1140	2,280	9,800						17	53	135	525				
10	.15	546	3,100	4,000							31	78	305	960			
	.20	883	3,530	7,200							24	60	235	735			
	.25	1280	3,840	11,000							20	51	200	625			
	.29	1660	4,020	15,000							18	46	180	570			
	.30	1730	4,050	16,000							18	46	180	560			
	.33	2070	4,140	19,000							17	44	170	535			
12	.15	889	5,040	7,300								31	120	380	940		
	.20	1440	5,740	13,000								24	94	295	720		
	.25	2080	6,250	20,000								20	79	250	610		
	.29	2690	6,540	26,000								18	72	225	555		
	.30	2820	6,580	27,000								18	71	225	550		
	.33	3360	6,720	34,000								17	68	215	525		
15	.15	1610	9,130	15,000									40	125	305	480	940
	.20	2600	10,500	25,000									31	96	235	370	720
	.25	3770	11,300	38,000									26	81	200	310	610
	.29	4880	11,900	50,000									24	74	180	290	555
	.30	5110	11,900	53,000									23	73	180	280	550
	.33	6100	12,200	64,000									22	70	170	270	525

[a] Drainage-stack diameters used in computations are nominal. Vent-pipe diameters used in computations are the actual diameters given in current standards for standard steel pipe 12 in. or less in diameter, and for Schedule 40 steel pipe of 14- and 16-in. diam. It is to be understood, in the use of this table, that the developed length of vent may include some piping in an other-than-vertical position.

Table 15. *Equivalent lengths of vent pipe due to entrance conditions*

Drainage-stack diameter	Equivalent lengths [a]													
	Any diameter of vent	1½-in. vent	2-in. vent	2½-in. vent	3-in. vent	3½-in. vent	4-in. vent	5-in. vent	6-in. vent	8-in. vent	10-in. vent	12-in. vent	14-in. vent	16-in. vent
in.	*pipe diam*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*
3	40.9	5	7	8	10									
4	45.4		8	9	12	13	15							
5	48.9			10	13	14	16	21						
6	52.5				13	15	18	22	26					
8	57.7						19	24	29	38				
10	62.1							26	31	41	52			
12	65.3								33	43	54	65		
15	70.1									47	58	70	77	88

[a] These values have been computed from the second term of the right-hand member of eq (58). A value of $C_L=1.5$ and table 13 values of f have been used. A sharp-corner exit into an infinite reservoir has been assumed. The value $C_L=1.5$ includes the head loss due to a sharp-corner entrance from an infinite reservoir and the head loss due to acceleration of the air from rest.

Table 16. *Factors for computing equivalent lengths of vent stacks due to various fittings and changes in cross section*

Drainage-stack diameter	Factor, β [a]												
	1½-in. vent	2-in. vent	2½-in. vent	3-in. vent	3½-in. vent	4-in. vent	5-in. vent	6-in. vent	8-in. vent	10-in. vent	12-in. vent	14-in. vent	16-in. vent
in.	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	*ft*
3	3.66	4.69	5.61	6.96									
4		5.22	6.23	7.75	8.96	10.2							
5			6.70	8.33	9.63	10.9	13.7						
6				8.94	10.3	11.7	14.7	17.8					
8						12.9	16.2	19.4	25.6				
10							17.4	20.9	27.5	34.5			
12								22.0	28.9	36.3	43.5		
15									31.1	39.0	46.7	51.1	58.4

[a] Equivalent length (in feet) is computed from the equation $L_e=\beta C_L$.
Values of C_L applicable to various fittings and changes in cross section are given in figure 40. The values of β given in this table are based on table 13 values of *f*.

paper is concerned. Dawson and Kalinske [6] give an equation of the same form as eq (59) for use in sizing vent stacks. Strictly speaking, formulas such as eqs (58) and (59) should be applied only to the flow of incompressible fluids. However, with very little error, they may be applied to the case of air flow at a pressure drop of 1 in. of water column. The fixture-unit loads in table 14 have been derived from eq (53) and figure 37.

The values given in table 14 vary in a reasonable manner with air and water flow. The permissible lengths of vent computed by one authority [6] are somewhat less than those given in table 14, but those given by certain other authorities [1, 17, 18] agree well with table 14.

Although eq (59) is sufficiently accurate for use where pipe-friction losses are large in relation to other types of losses, special situations may arise in which it will be desirable to make allowance for losses such as those due to entrance conditions, changes in cross section and direction of flow, and presence of fittings. Such an allowance might be desirable in the case of a relatively short pipe carrying a large rate of flow. Table 15 computed from eq (58), gives equivalent lengths of pipe which should be subtracted from the vent lengths given in table 14 in order to take into account entrance conditions associated with a sharp-corner entrance from an infinite reservoir.

Approximate allowance for the losses due to various fittings can be made by considering the resistance offered by a fitting as equivalent to that produced by a certain length of pipe of the same diameter as the fitting. The equivalent length depends on the loss coefficient for the fitting, the pipe diameter, and roughness of pipe material. Figure 40 gives values of C_L applicable to several types of fittings. Equivalent lengths may be computed from the values of C_L given in figure 40 and the values of β listed in table 16 where

$$L_e=\beta C_L. \qquad (65)$$

Some handbooks list equivalent lengths of various fittings directly in feet.

6.4. Comparison of Loads Given by Plumbing Codes with Computed Values for Drainage and Vent Stacks

Permissible loadings for multistory drainage stacks and vent stacks given by three well-known sources [1, 17, 18] are in fair agreement with values computed by methods described in some detail in this paper.

The basic concepts of fluid flow in drainage and vent stacks discussed by Dawson and Kalinske [5, 6] are reasonably consistent with those on which

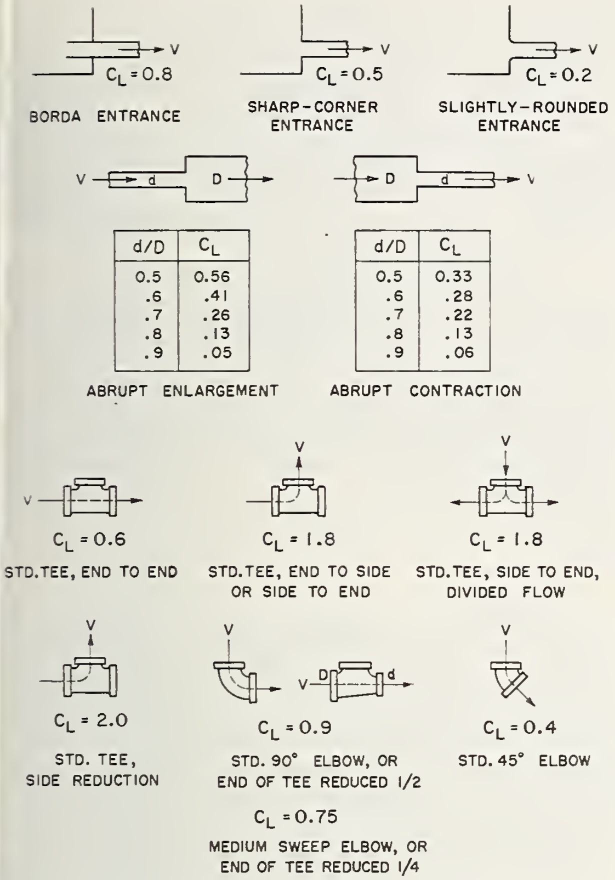

FIGURE 40. *Some commonly used head-loss coefficients for flow through pipe fittings and transitions in cross section.*

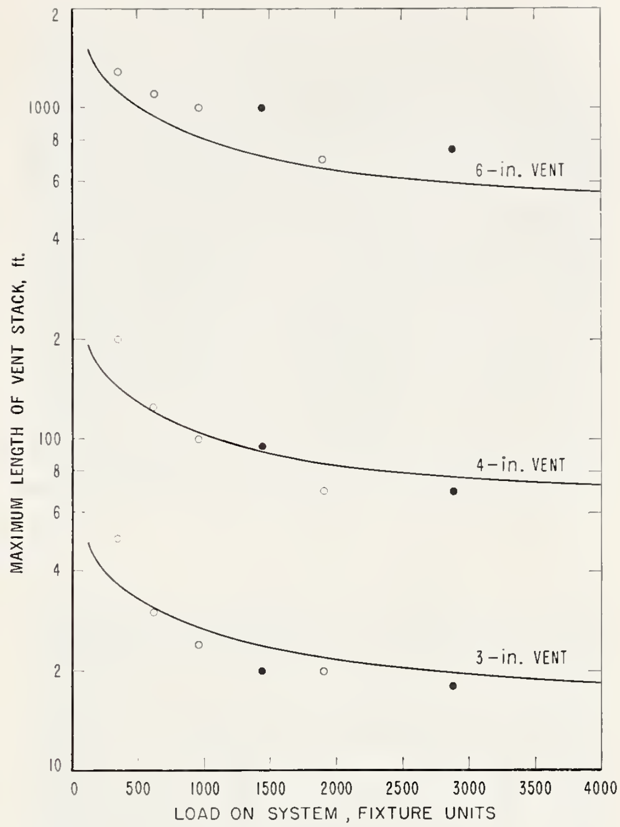

FIGURE 41. *Comparison of maximum lengths of vent stacks for 6-in. drainage stack.*

Curves represent computed values taken from table 14.
○, values from references 1 and 18.
●, values from reference 17.

this paper is based, but the manner in which the probability of simultaneous discharge of plumbing fixtures was taken into account by Dawson and Kalinske resulted in permissible fixture-unit loadings which are much less for large diameters than those obtained from the three other sources mentioned above. In what follows, references 1, 17, and 18 will be referred to as the *model codes*.

The comparison, for maximum loadings on multistory drainage stacks, between values taken directly from the loading tables of the model codes and values computed by methods given in this paper was shown in figure 39. Figure 41 shows a similar comparison of maximum lengths of vent stacks for a 6-in. drainage stack.

Based on figures 39 and 41, on other figures (not shown) similar to figure 41 (these being for drainage-stack diameters other than 6 in.), and on a detailed study of the loading tables in six municipal plumbing codes selected at random (three adopted before 1951 and three later), the following observations have been made:

a. Loading Tables for Drainage Stacks

1. Some municipal codes permit as much as nine times the fixture-unit loadings for drainage stacks permitted by other municipal codes.

2. The two municipal codes agreeing most closely with the model codes on the matter of maximum loads permitted on drainage stacks were adopted after 1953. The more liberal of these gives values agreeing quite well with the solid computed curve for $r_s = 1/4$ in figure 39; and, for stack diameters of 8, 10, and 12 in., it gives values greater than do any of the other codes analyzed in this investigation. Some municipal codes give fixture-unit values ranging down to as little as 1/7 of those computed for $r_s = 1/4$.

3. In general, the municipal codes adopted since the Report of the Coordinating Committee for a National Plumbing Code was issued (1951) permit greater loads on multistory drainage stacks than do the older municipal codes.

4. The model codes give values, for maximum loadings on multistory stacks of 6-in. diameter and less, which fall between the values computed for $r_s = 1/4$ and $r_s = 1/3$ (solid curves, fig. 39). For larger diameters, the values given by the model codes are less than those represented by the solid curve for $r_s = 1/4$.

b. Loading Tables for Vent Stacks

1. Of the six municipal codes analyzed in detail, two of those adopted before 1951 and one of those adopted later give maximum lengths of vent stacks unaffected by diameter of drainage stack or by different loadings on a given diameter of drainage stack. Hence, these codes cannot be expected to give values agreeing with those computed by the method given in this paper in which both stack diameter and drainage load are taken into account. In some cases, the values given by these codes are greater, and in some cases less, than the computed values or values taken from the model codes.

2. Of the three remaining municipal codes analyzed, one gives values for maximum lengths of vent stacks agreeing fairly well with the computed values, one gives values for the larger diameters of drainage stacks and vents which are generally less than the computed values, and one gives values which are less than the computed values for most diameters of drainage stacks and vents.

3. All three of the model codes give values for maximum lengths of vent stacks which agree fairly well with the values computed in this paper. Such deviations as do exist do not appear to follow any consistent trend. Of the three model codes, BMS66 [17] gives values agreeing most closely with the computed values.

4. It is evident from a study of the venting tables of a number of plumbing codes that there is great diversity in the loading ranges covered. It is difficult to compare fairly the requirements of the different codes, since in making such a comparison it becomes necessary, in the case of certain codes, to estimate the maximum lengths of vents for loadings outside the ranges given in the tables.

7. Conclusions

7.1. Interference of Flows at Junction of Drainage Stack and Horizontal Branches

Section 6.1 of this paper gives a method for estimating the maximum permissible rate of flow in a horizontal branch for any given rate of flow in a drainage stack (or vice-versa) when the two flows occur simultaneously. The experimental work on which the equations are based has been carried out on 3-in. drainage stacks only. The application of the method is through the use of eqs (66), (68), and (70).

The hydrodynamic head created at the junction of a drainage stack and a horizontal branch when flow occurs simultaneously in both components of the system should be limited to a value which will not cause water to back up into drainage or vent pipes connecting to the horizontal branch. This criterion should be taken into account in computing loads for multistory drainage stacks. Its importance in relation to other criteria can be determined only through further study and research.

7.2. Flow Capacities of Drainage Stacks

Flow capacities of multistory drainage stacks may be computed from eq (53) for various degrees of filling. Research has indicated that stacks should not be loaded so heavily that they flow more than $\frac{1}{4}$ to $\frac{1}{3}$ full at terminal velocity. Equation (53) is intended as an upper limit to flow capacity where stack height is sufficient to insure that stack capacity will not be governed by the capacities of the horizontal branches or by the capacities of the fittings at the junctions between the stack and the horizontal branches.

7.3. Air Flow in Drainage Systems

The maximum flow of air which could reasonably be expected to be carried down a *drainage stack* may be computed from eq (56) for various degrees of filling of the stack. However, for several reasons (see section 6.3), the use of eq (56) will give flow rates larger than are likely to occur anywhere in a *vent stack*. Therefore, it has been assumed in this paper that the maximum rate of air flow to be carried by a vent stack will be $\frac{2}{3}$ of that computed from eq (56).

The vent stack should be so sized that pneumatic pressures anywhere within it, or within fixture drains or horizontal branches which it vents, will not differ from atmospheric by an amount great enough to destroy the water seals in fixture traps. Equations (58) and (59) may be used to compute vent-stack diameters or lengths for a pressure drop of 1-in. water column and for any given flow of air.

A phenomenon which has not been studied in much detail is that which governs the mutual interference of streams of air and water at the juntion of a drainage stack and a vent pipe. Although measurements have been made which show a pressure drop across the layer of water on the wall of the drainage stack, it is not immediately apparent whether this fact is significant from the practical standpoint. The protection of trap seals against pneumatic-pressure fluctuations depends generally on the existence of pneumatic pressures near atmospheric within horizontal branches and fixture drains, rather than within the drainage stack itself. Nevertheless, the phenomenon should be recognized in order to attain a better understanding of the flow of air and water in building-drainage and venting systems.

7.4. Loading Tables

Table 12 gives upper limits for loads on tall multistory soil and waste stacks. The values in table 12 were computed from eq (53) and curve 1 of figure 37. A method for computing permissible loads for stacks of low or moderate height is given in section 9.3 of the appendix.

Table 14 gives maximum permissible length of vent stacks for soil and waste systems. The length values in table 14 were computed from eq (59), wherein Q_a is taken as ⅔ of the value computed from eq (56).

7.5. Miscellaneous Phenomena

a. Distribution of Air and Water in Cross Section of Drainage Stack

The assumption of an annular layer of water flowing down the wall of a drainage stack, and of a central core of air carried along by the water, represents an ideal condition which is probably not fully attained in many practical situations. However, in spite of this, the concept is useful in estimating maximum values for air and water flow in drainage stacks.

b. Velocity Distribution of Water in Cross Section of Drainage Stack

Available data on water velocities in drainage stacks indicate that the velocity gradient is very steep close to the wall of the stack, becoming less steep with distance away from the wall. In a stack having branch connections at each floor level, droplets and small masses of water may fall at relatively high velocities in the central area of the cross section of the stack.

c. Pneumatic Pressures within Drainage Stack

The flow of water in a drainage stack may cause pneumatic pressure changes of sufficient magnitude to destroy the water seals of fixture traps not protected by a venting system. Adequate venting will prevent the occurrence of excessive pressure fluctuations within horizontal branches and fixture drains. Fluctuations of appreciable magnitude may still develop within the drainage stack between floor levels but these do not affect trap seals adversely. Least pressures occur immediately below a point of water entrance, and greatest pressures occur near the base of the stack. The pressure at any point is a function of rate of discharge, elevation of point of water entrance, degree of venting, and geometry of the system.

7.6. Need for Further Research

a. Design-Flow Problems

Earlier in this paper it was pointed out that loading tables for plumbing codes must be based not only on the flow capacities of the component parts of the plumbing system but also on the design flow. The design flow is that rate of flow which is estimated to occur sufficiently often to cause unsatisfactory performance if not adequately provided for in the design of the system. For systems serving more than a very limited number of fixtures, this requires a systematic method of computing the maximum rate of simultaneous discharge from a given group of fixtures which, over a long period of time, will not be exceeded except for a specified small fraction of the time during periods of heavy use. The design flow is often estimated by a method based on the theory of probability. Such a method is represented by curve 1 of figure 37, part of which was developed earlier by Hunter [15]. A discussion of Hunter's procedure was presented by Eaton and French [16].

For some time it has been known that, for relatively large systems, this method of computing design flow yields rates appreciably smaller than those obtained by certain other methods which have been used. Other factors being equal, computed pipe sizes would be smaller, and this is in the interest of economy. Field evidence has pointed to the possibility that design flows obtained by Hunter's method may, nevertheless, be greater than flows actually occurring in systems of moderate size, such as those in apartment buildings. The opinion is sometimes expressed by plumbing officials and design engineers that flow estimates obtained by Hunter's method may be unrealistic for systems, or branches of systems, comprising a small number of fixtures. In fairness to Hunter, it should be remembered that he pointed out that his method is most applicable to large systems. For these reasons, and because the data on which some of the computations made by Hunter were based are now thought to be obsolete or incomplete, there appears to be a need for further study of this problem, from both a theoretical and a practical standpoint, including an analysis of continuous records of flow in existing plumbing systems.

A method for estimating the simultaneous flows likely to be discharged from two separate groups of plumbing fixtures is needed. This problem must be solved before the results of hydraulic studies of flow interference at stack-branch junctions can be fully utilized by the writers of plumbing codes.

b. Flow-Capacity Problems

Although much of the difference in loading-table values in various plumbing codes may be the result of the different ways in which the design-flow problem is treated, at least a part of the difference in table values is caused by the different flow capacities assumed. Applications of research in this field have relied to a considerable extent on extrapolation of data from limited tests. The use of design criteria based on steady, uniform flow appears to be inconsistent with the occurrence of surging flow in some parts of the plumbing system. Knowledge of flow capacities should be augmented through careful research on several problems, as follows:

(1) Flow of Air in Venting Systems

Further investigation of air flow in venting systems is required in order to obtain information on the flow and recirculation of air in complex venting systems. So far, most investigations have been made on relatively simple systems, and the application of the results of such investigations may be unrealistic with respect to more complex systems. It appears likely that certain economies in pipe sizing could be effected if the proper allowances for recirculation of air and for height of fall of water in complex venting systems could be made.

(2) Interference of Flows at Stack-Branch Junctions

The investigation of flow interference at stack-branch junctions reported in this paper shows a method that can be used to study the problem. Numerical results have been obtained for certain conditions. Data are needed for stacks of several diameters and for forms of construction not used in the investigation reported.

(3) Velocity Distribution of Water, and Air-Water Distribution in Cross Section of Drainage Stack

Velocity distribution and air-water distribution affect the flow of air carried down the drainage stack, the head of water created in horizontal branches as a result of mutual interference of simultaneous flows, and the flow capacity of the drainage stack. A more complete and accurate knowledge of velocity distribution and air-water distribution than that obtained so far is required before desirable refinements can be introduced into the analysis of certain flow problems.

(4) Detergent Foam in Plumbing Systems

Another factor which may affect flow capacities of drainage and vent pipes under certain circumstances is the use of synthetic detergents, which are now being used in large quantities. Plumbing inspectors report that foam is sometimes forced back past trap seals of lower-floor sinks and other fixtures. They attribute this to the use of synthetic detergents in kitchen and laundry equipment and report that the occurrence is becoming increasingly commonplace in apartment buildings. The problem has been recognized in Great Britain, as well as in this country. Wise and Croft [20] report tests in which they observed that detergent foam increased pressures at the base of a drainage stack. This phenomenon should be taken into account in the design of drainage and venting systems in which detergents are likely to be used in a way that may cause frequent trouble. It is unlikely that the detergent-foam problem and its effects on system design can be fully understood until further research is conducted under controlled conditions.

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9. Appendix

9.1. Individual Measurements Relating to Interference of Flows at Junction of Simulated Stack and Horizontal Branches

Tables 6 and 7 show the *range* covered by certain measurements of flow conditions in the simulated stack. The *individual measurements* are listed in tables A–1 and A–2. The values of (h_2-h_1) shown in column 6 of table A–1 and in column 7 of table A–2 were computed by adding to the observed depths of water above the branch invert (at a distance of 4 branch diameters from the stack) the corrections for elevation listed in table A–3, and by subtracting the pneumatic-pressure head in the stack. This fixed the reference level for elevation at the intersection of the inner circumference of the stack and the center line of the passageway through the fitting.

9.2. Computation of the Absolute Roughness, k_s, for Cast-Iron Soil Pipe

This section gives the method by which data on friction losses in cast-iron soil pipe have been used to compute an equivalent value of the absolute roughness for such pipe. The discussion begins with the presentation of data on friction losses obtained by Hunter [13].

From a 1948 unpublished paper "Friction losses in short pipes and culverts," by Garbis H. Keulegan,

$$\sqrt{8/f}=4.75-2.5\,(k_s/R)+5.75\,(1+k_s/R)^2\log_{10}(1+R/k_s). \quad \text{(A–1)}$$

As k_s/R is very small,

$$\sqrt{8/f}=4.75+5.75\log_{10}(R/k_s), \quad \text{(A–2)}$$

approximately.

Next, the data in the last two columns of table A–4 were plotted, and a curve faired through the points. The curve was then extended to the point $\log_{10} R=0$, corresponding to $R=1$ in. This procedure yielded a value of approximately 16.24 for $\sqrt{8/f}$ corresponding to $\log_{10} R=0$. The values $R=1.0$ and $\sqrt{8/f}=16.24$ were substituted in eq (A–2), from which

$$\log_{10}\left(\frac{1}{k_s}\right)=2.00,$$

and

$$k_s=0.010 \text{ in., or } 0.00083 \text{ ft.}$$

9.3. Effect of Drainage-Stack Height on Permissible Loads

Many plumbing codes include a table which gives permissible maximum loads on drainage stacks, the same limits applying irrespective of stack height. In practice, code-imposed limitations on the loads for the various horizontal branches and branch intervals of the stack tend to govern the loads actually placed on short stacks. If stack height is not taken into account in computing permissible maximum loads, a set of values may be obtained which is uneconomical for tall stacks. Such load limits are particularly applicable to stacks having only one or two branch intervals.

There are two extreme conditions which should govern permissible loads on stacks. The first condition is represented by a stack, of one or two branch intervals, for which the permissible load may be governed by the limits for single horizontal branches. The second condition is represented by a tall stack having a number of horizontal branches. A greater total load on a stack of a given diameter is justified under the second condition than under the first. A method which takes stack height into account in assigning permissible stack loads is especially applicable to stacks having three or more branch intervals and to systems with relatively small horizontal branches.

The method of assigning load limits on drainage stacks according to stack height, which is briefly outlined below, is similar to the method given in BMS 66 [17]. The following terminology will be employed:

n=the number of branch intervals

$\gamma=\left(\frac{1}{n}+\frac{1}{2}\right)$

B=permissible fixture-unit load on a single horizontal branch of diameter equal to the stack

TABLE A–1. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, sanitary-tee drainage fittings, pneumatic pressure (h_1) in stack −0.3 in.*[a]

1	2	3	4	5	6	7	8	9	10	11
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*			*in.*	*gpm*				
1.61	0.16	40	1.04	1	2.57	24.4	5.6	1.077	12.95	3
1.61	.16	40	1.04	1	2.94	32.3	4.9	1.650	11.05	4
1.61	.16	40	1.04	1	3.12	15.0	4.6	0.335	24.96	6
1.61	.16	40	1.04	1	3.94	33.2	3.7	1.301	15.27	8
1.61	.16	40	1.04	2	2.59	17.4	5.6	0.543	18.05	10
1.61	.16	40	1.04	2	3.06	24.3	4.7	.897	15.85	11
1.61	.16	40	1.04	2	3.25	27.2	4.5	1.058	15.13	12
1.61	.16	54	1.41	1	2.94	13.1	9.0	0.271	18.03	13
1.61	.16	54	1.41	1	2.94	17.2	9.0	.468	14.34	14
1.61	.16	54	1.41	1	4.69	29.8	5.6	.880	14.36	15
1.61	.16	54	1.41	1	4.69	40.3	5.6	1.610	10.33	16
1.61	.16	54	1.41	2	2.94	15.1	9.0	0.361	16.03	17
1.61	.16	54	1.41	2	3.94	24.9	6.7	.732	14.08	18
1.61	.16	54	1.41	2	1.94	7.9	13.6	.150	17.65	21
1.61	.16	54	1.41	2	3.00	15.2	8.8	.358	16.28	22
1.61	.16	54	1.41	2	3.75	24.0	7.0	.714	13.80	23
1.61	.16	54	1.41	2	4.56	29.2	5.8	.869	14.19	24
1.61	.16	80	2.08	1	4.44	9.4	13.1	.093	21.85	29
1.61	.16	80	2.08	1	4.44	14.6	13.1	.223	15.45	30
1.61	.16	80	2.08	1	5.44	12.4	10.7	.131	21.64	31
1.61	.16	80	2.08	1	6.00	26.5	9.7	.544	12.82	32
1.61	.16	80	2.08	2	3.25	8.2	17.8	.096	17.71	40
1.61	.16	80	2.08	2	4.56	13.0	12.7	.172	17.42	41
1.61	.16	80	2.08	2	5.54	20.6	10.5	.356	14.65	42
1.61	.16	98	2.55	1	5.44	8.8	16.0	.066	21.89	48
1.61	.16	98	2.55	1	6.38	17.4	13.6	.221	15.11	49
1.61	.16	98	2.55	2	4.44	8.2	19.6	.070	18.83	53
1.61	.16	98	2.55	2	6.19	13.8	14.1	.143	17.61	54
1.61	.35	56	0.47	1	2.94	17.9	2.3	.507	19.99	65
1.61	.35	56	.47	1	3.00	17.9	2.2	.497	20.43	66
1.61	.35	56	.47	1	3.56	32.2	1.9	1.354	13.90	68
1.61	.35	56	.47	1	3.69	32.2	1.8	1.306	14.50	69
1.61	.35	56	.47	2	1.62	8.6	4.1	0.212	19.81	71
1.61	.35	56	.47	2	1.94	12.3	3.5	.363	17.80	72
1.61	.35	56	.47	2	2.94	20.1	2.3	.639	18.02	73
1.61	.35	56	.47	2	3.29	24.2	2.0	.828	17.11	74
1.61	.35	98	.82	1	2.88	8.1	7.1	.106	18.54	90
1.61	.35	98	.82	1	3.06	8.1	6.7	.100	19.71	91
1.61	.35	98	.82	1	4.44	13.8	4.6	.199	18.95	92
1.61	.35	98	.82	1	4.56	15.2	4.5	.236	18.02	93
1.61	.35	98	.82	1	5.94	20.6	3.5	.332	18.46	94
1.61	.35	98	.82	1	5.94	23.4	3.5	.429	16.58	95
1.61	.35	98	.82	2	3.06	8.8	6.7	.118	18.48	101
1.61	.35	98	.82	2	4.44	15.0	4.6	.236	17.72	102
1.61	.35	98	.82	2	5.94	24.8	3.5	.481	15.76	103
1.61	.35	137	1.14	1	4.44	8.4	9.0	.074	18.37	116
1.61	.35	137	1.14	1	4.96	11.4	8.1	.122	16.22	117
1.61	.35	137	1.14	1	5.96	13.0	6.7	.132	17.64	118
1.61	.35	137	1.14	1	5.96	14.4	6.7	.162	16.28	119
1.61	.35	137	1.14	2	4.44	9.4	9.0	.093	16.84	126
1.61	.35	137	1.14	2	5.94	13.7	6.8	.147	16.87	127
1.61	.35	180	1.50	1	5.96	8.1	11.6	.051	18.06	142
1.61	.35	180	1.50	1	5.96	9.7	11.6	.073	15.73	143
1.61	.35	180	1.50	2	5.94	9.2	11.7	.066	16.33	151
1.61	.58	98	0.40	1	2.07	8.8	4.3	.174	15.17	152
1.61	.58	98	.40	1	2.07	8.1	4.3	.147	16.20	153
1.61	.58	98	.40	1	3.13	15.0	2.9	.334	15.08	154
1.61	.58	98	.40	1	3.13	15.0	2.9	.334	15.08	155
1.61	.58	98	.40	1	4.44	27.6	2.0	.798	12.75	156
1.61	.58	98	.40	1	4.44	29.8	2.0	.930	11.83	157
1.61	.58	98	.40	2	2.69	10.6	3.3	.194	17.11	166
1.61	.58	98	.40	2	3.44	16.8	2.6	.381	15.13	167
1.61	.58	158	.64	1	4.06	11.6	5.7	.154	13.35	174
1.61	.58	158	.64	1	4.69	13.4	5.0	.178	13.80	175
1.61	.58	158	.64	1	5.94	19.4	3.9	.295	13.05	176
1.61	.58	158	.64	1	6.12	20.2	3.8	.310	13.02	177
1.61	.58	158	.64	2	4.44	11.0	5.2	.127	15.24	184
1.61	.58	158	.64	2	5.94	16.6	3.9	.216	14.81	185
1.61	.58	203	.82	1	4.44	8.1	8.6	.069	14.12	190
1.61	.58	203	.82	1	4.50	8.8	8.5	.080	13.43	191

See notes at end of table.

TABLE A–1. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, sanitary-tee drainage fittings, pneumatic pressure (h_1) in stack −0.3 in.*[a]—Continued

1	2	3	4	5	6	7	8	9	10	11
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*			*in.*	*gpm*				
1.61	0.58	203	0.82	1	5.94	12.2	6.5	0.116	13.81	192
1.61	.58	203	.82	1	5.94	13.1	6.5	.134	13.07	193
1.61	.58	203	.82	2	5.94	11.1	6.5	.096	14.86	201
1.61	.58	252	1.02	1	5.94	8.1	10.0	.051	14.44	206
1.61	.58	252	1.02	1	5.94	9.5	10.0	.071	12.79	207
1.61	.58	252	1.02	1	7.94	12.4	7.5	.090	13.96	208
1.61	.58	252	1.02	1	7.94	14.5	7.5	.123	12.37	209
2.07	.16	40	1.04	1	3.12	30.0	4.6	.487	22.68	220
2.07	.16	40	1.04	1	3.12	30.0	4.6	.487	22.68	221
2.07	.16	40	1.04	2	1.99	15.1	7.3	.193	25.11	226
2.07	.16	40	1.04	2	3.06	38.5	4.7	.818	17.67	228
2.07	.16	54	1.41	1	3.37	20.8	7.8	.217	22.91	232
2.07	.16	54	1.41	1	3.37	20.8	7.8	.217	22.91	233
2.07	.16	54	1.41	1	4.25	34.1	6.2	.462	19.34	234
2.07	.16	54	1.41	1	4.62	34.1	5.7	.425	21.13	235
2.07	.16	54	1.41	2	3.93	30.4	6.7	.397	19.66	239
2.07	.16	80	2.08	1	5.56	23.0	10.4	.161	21.60	246
2.07	.16	80	2.08	1	5.56	23.0	10.4	.161	21.60	247
2.07	.16	80	2.08	1	6.81	33.6	8.5	.280	19.62	248
2.07	.16	80	2.08	1	7.12	33.6	8.1	.268	20.54	249
2.07	.16	80	2.08	2	4.34	15.8	13.4	.097	22.52	251
2.07	.16	80	2.08	2	5.87	25.1	9.9	.181	21.30	252
2.07	.16	80	2.08	2	6.62	30.8	8.8	.242	20.45	253
2.07	.16	98	2.55	1	6.31	19.0	13.8	.097	22.12	258
2.07	.16	98	2.55	1	6.37	19.0	13.7	.096	22.34	259
2.07	.16	98	2.55	1	7.49	24.2	11.6	.132	21.81	260
2.07	.16	98	2.55	1	7.49	24.2	11.6	.132	21.81	261
2.07	.16	98	2.55	2	6.37	19.2	13.7	.098	22.16	264
2.07	.16	98	2.55	2	8.31	28.9	10.5	.170	21.08	265
2.07	.35	56	0.47	1	2.06	15.0	3.3	.184	25.88	266
2.07	.35	56	.47	1	2.06	16.3	3.3	.218	24.21	267
2.07	.35	56	.47	1	2.69	28.7	2.5	.517	19.92	268
2.07	.35	56	.47	1	2.81	28.7	2.4	.495	20.87	269
2.07	.35	56	.47	1	3.19	40.8	2.1	.881	17.30	270
2.07	.35	56	.47	1	3.25	40.8	2.1	.865	17.67	273
2.07	.35	56	.47	2	2.19	17.8	3.1	.244	24.02	274
2.07	.35	98	.82	1	4.06	20.4	5.1	.173	20.15	279
2.07	.35	98	.82	1	4.06	22.2	5.1	.205	18.84	280
2.07	.35	98	.82	1	5.81	36.6	3.5	.389	18.11	281
2.07	.35	98	.82	1	5.81	36.6	3.5	.389	18.11	282
2.07	.35	98	.82	1	6.56	56.0	3.1	.807	14.08	283
2.07	.35	98	.82	1	7.06	59.6	2.9	.849	14.38	284
2.07	.35	98	.82	2	3.81	19.0	5.4	.160	19.98	286
2.07	.35	98	.82	2	4.81	28.2	4.3	.279	18.48	287
2.07	.35	137	1.14	1	6.06	21.2	6.6	.125	19.33	293
2.07	.35	137	1.14	1	6.31	24.4	6.4	.159	18.04	294
2.07	.35	137	1.14	1	7.69	32.3	5.2	.229	17.66	295
2.07	.35	137	1.14	1	7.81	30.8	5.1	.205	18.65	296
2.07	.35	137	1.14	2	5.31	17.4	7.6	.096	19.72	299
2.07	.35	137	1.14	2	6.69	24.5	6.0	.151	19.09	300
2.07	.35	180	1.50	1	7.81	20.1	8.9	.087	18.52	307
2.07	.35	180	1.50	1	7.81	21.4	8.9	.099	17.65	308
2.07	.35	180	1.50	2	7.99	20.5	8.7	.089	18.67	313
2.07	.58	98	0.40	1	3.43	24.3	2.6	.291	18.02	316
2.07	.58	98	.40	1	3.56	23.8	2.5	.269	19.05	317
2.07	.58	98	.40	1	4.31	49.1	2.1	.944	12.28	319
2.07	.58	98	.40	1	4.43	48.8	2.0	.907	12.74	321
2.07	.58	98	.40	2	2.31	16.9	3.9	.209	16.10	326
2.07	.58	158	.64	1	5.81	24.3	4.0	.172	17.05	334
2.07	.58	158	.64	1	5.81	25.7	4.0	.192	16.31	335
2.07	.58	158	.64	1	7.69	40.6	3.0	.362	15.00	336
2.07	.58	158	.64	1	7.69	42.3	3.0	.393	14.49	337
2.07	.58	203	.82	1	5.81	15.4	6.6	.069	17.77	350
2.07	.58	203	.82	1	5.81	16.7	6.6	.081	16.70	351
2.07	.58	203	.82	1	7.81	24.3	4.9	.128	16.85	352

See notes at end of table.

TABLE A–1. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, sanitary-tee drainage fittings, pneumatic pressure (h_1) in stack —0.3 in.*[a]—Continued

1	2	3	4	5	6	7	8	9	10	11
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*			*in.*	*gpm*				
2.07	0.58	203	0.82	1	7.81	25.7	4.9	0.143	16.13	353
2.07	.58	203	.82	2	6.31	18.6	6.1	.093	16.71	356
2.07	.58	252	1.02	1	7.81	16.3	7.6	.057	17.50	368
2.07	.58	252	1.02	1	7.81	17.8	7.6	.068	16.36	369
2.07	.58	252	1.02	2	7.81	17.4	7.6	.065	16.65	374
3.07	.16	80	2.08	1	4.46	52.1	13.0	.213	18.53	381
3.07	.16	80	2.08	1	4.46	54.5	13.0	.233	17.87	382
3.07	.16	80	2.08	1	6.46	105.3	9.0	.600	15.08	384
3.07	.16	80	2.08	1	6.46	128.0	9.0	.887	12.54	385
3.07	.16	98	2.55	1	6.46	66.0	13.5	.236	17.39	400
3 07	.16	98	2.55	1	6.46	68.3	13.5	.253	16.91	401
3.07	.16	98	2.55	1	8.46	107.8	10.3	.481	15.29	402
3.07	.16	98	2.55	1	8.46	110.3	10.3	.503	14.98	403
3.07	.35	98	0.82	1	4.46	80.0	4.6	.502	15.17	410
3.07	.35	98	.82	1	4.46	81.0	4.6	.515	15.01	411
3.07	.35	137	1.14	1	4.46	42.0	9.0	.138	16.94	422
3.07	.35	137	1.14	1	4.46	42.8	9.0	.144	16.69	423
3 07	.35	137	1.14	1	6.46	75.4	6.2	.308	15.49	424
3.07	.35	137	1.14	1	6.46	76.6	6.2	.318	15.29	425
3.07	.35	137	1.14	1	8.46	148.5	4.7	.912	11.28	426
3.07	.35	137	1.14	1	8.46	149.0	4.7	.918	11.25	427
3.07	.35	180	1.50	1	6.46	49.0	10.7	.130	15.55	436
3.07	.35	180	1.50	1	6.46	49.0	10.7	.130	15.55	437
3.07	.35	180	1.50	1	8.46	70.2	8.2	.204	15.41	438
3.07	.35	180	1.50	1	8.46	71.1	8.2	.209	15.26	439
3.07	.58	203	0.82	1	6.46	53.1	5.9	.153	15.39	465
3.07	.58	203	.82	1	6.46	60.1	5.9	.196	13.95	466
3.07	.58	203	.82	1	8.46	84.5	4.5	.295	13.98	467
3.07	.58	203	.82	1	8.46	92.7	4.5	.355	12.94	468
3.07	.58	252	1.02	1	7.71	53.4	7.7	.129	14.00	479
3.07	.58	252	1.02	1	8.46	47.8	7.0	.094	16.76	480

[a] Above the stack-branch junction.

Note: Missing numbers in the series in column 11 represent data obtained for conditions outside the range over which it is reasonable to expect the analysis in section 4.1. to apply. All data included in the following categories were omitted:
1. Data in which branch velocity was less than half of that required to produce computed steady flow capacity for a full pipe not under external head.
2. Data in which branch discharge for two-branch flow exceeded the criterion for fitting capacity given in section 2.1, wherein the effective stack diameter was assumed to be the computed air-core diameter.
3. Data in which the horizontal momentum in ono branch exceeded half the momentum in the stack just above the branch.

TABLE A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
1.61	0.16	40	1.04	−0.3	1	3.64	26.8	4.0	0.917	11.98	492
1.61	.16	40	1.04	−.3	1	3.64	34.4	4.0	1.511	8.77	493
1.61	.16	40	1.04	−.3	2	3.64	25.0	4.0	0.798	12.92	529
1.61	.16	40	1.04	−.3	2	4.64	38.9	3.1	1.516	10.19	530
1.61	.16	40	1.04	−2.0	2	5.22	38.9	2.8	1.348	11.89	541
1.61	.16	54	1.41	−0.3	1	3.64	19.2	7.3	0.471	11.50	556
1.61	.16	54	1.41	−.3	1	3.64	20.8	7.3	.553	10.67	557
1.61	.16	54	1.41	−.3	1	4.64	25.4	5.7	.646	11.51	558
1.61	.16	54	1.41	−.3	1	4.64	28.8	5.7	.831	10.11	559
1.61	.16	54	1.41	−.3	1	6.14	37.4	4.3	1.059	10.51	560

See notes at end of table.

Table A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*—Continued

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
1.61	0.16	54	1.41	−0.3	1	6.14	38.4	4.3	1.116	10.19	561
1.61	.16	54	1.41	−.3	1	8.14	49.0	3.2	1.371	10.66	562
1.61	.16	54	1.41	−.3	1	8.14	50.0	3.2	1.428	10.37	563
1.61	.16	54	1.41	−2.0	1	5.96	38.4	4.4	1.150	9.82	571
1.61	.16	54	1.41	−2.0	1	6.21	37.4	4.3	1.047	10.66	572
1.61	.16	54	1.41	−2.0	1	7.96	50.0	3.3	1.460	10.07	573
1.61	.16	54	1.41	−2.0	1	8.09	49.0	3.3	1.380	10.58	574
1.61	.16	54	1.41	−0.3	2	3.64	21.8	7.3	0.607	10.20	579
1.61	.16	54	1.41	−.3	2	4.64	30.9	5.7	.957	9.36	580
1.61	.16	54	1.41	−.3	2	6.14	42.4	4.3	1.361	8.98	581
1.61	.16	54	1.41	−.3	2	8–14	53.6	3.2	1.641	9.39	582
1.61	.16	54	1.14	−2.0	2	4.84	30.9	5.5	0.917	9.84	587
1.61	.16	54	1.14	−2.0	2	6.59	42.4	4.0	1.268	9.84	588
1.61	.16	80	2.08	−0.3	1	3.64	10.7	15.9	0.146	11.55	598
1.61	.16	80	2.08	−.3	1	3.64	10.7	15.9	.146	11.55	599
1.61	.16	80	2.08	−.3	1	4.64	15.2	12.5	.231	11.15	600
1.61	.16	80	2.08	−.3	1	4.64	15.4	12.5	.238	11.03	601
1.61	.16	80	2.08	−.3	1	6.14	23.6	9.4	.422	10.26	602
1.61	.16	80	2.08	−.3	1	6.14	25.0	9.4	.473	9.73	603
1.61	.16	80	2.08	−.3	1	8.14	35.4	7.1	.716	9.50	604
1.61	.16	80	2.08	−.3	1	8.14	37.6	7.1	.807	8.93	605
1.61	.16	80	2.08	−.3	1	9.14	43.3	6.3	.954	8.76	606
1.61	.16	80	2.08	−.3	1	9.14	50.0	6.3	1.272	7.37	607
1.61	.16	80	2.08	−2.0	1	6.22	21.2	9.3	0.336	11.43	612
1.61	.16	80	2.08	−2.0	1	6.22	21.8	9.3	.355	11.16	613
1.61	.16	80	2.08	−2.0	1	7.59	29.5	7.6	.533	10.51	614
1.61	.16	80	2.08	−2.0	1	7.84	30.6	7.4	.555	10.52	615
1.61	.16	80	2.08	−0.3	2	3.64	11.4	15.9	.166	10.98	626
1.61	.16	80	2.08	−.3	2	4.64	18.2	12.5	.332	9.57	627
1.61	.16	80	2.08	−.3	2	6.14	27.8	9.4	.585	8.81	628
1.61	.16	80	2.08	−.3	2	8.14	42.0	7.1	1.007	7.90	629
1.61	.16	80	2.08	−2.0	2	4.96	18.2	11.7	0.310	10.27	634
1.61	.16	80	2.08	−2.0	2	6.09	27.8	9.5	.590	8.73	635
1.61	.16	80	2.08	−2.0	2	8.22	42.0	7.1	.998	7.99	636
1.61	.16	98	2.55	−0.3	1	4.64	10.9	18.8	1119	11.32	646
1.61	.16	98	2.55	−.3	1	4.64	11.4	18.8	.130	10.92	647
1.61	.16	98	2.55	−.3	1	6.14	17.2	14.2	.224	10.45	648
1.61	.16	98	2.55	−.3	1	6.14	18.8	14.2	.268	9.70	649
1.61	.16	98	2.55	−.3	1	8.14	26.0	10.7	.386	9.87	650
1.61	.16	98	2.55	−.3	1	8.14	28.0	10.7	.448	9.24	651
1.61	.16	98	2.55	−.3	1	9.14	30.8	9.5	.483	9.60	652
1.61	.16	98	2.55	−.3	1	9.14	33.4	9.5	.567	8.89	653
1.61	.16	98	2.55	−2.0	1	6.09	17.2	14.3	.226	10.36	662
1.61	.16	98	2.55	−2.0	1	6.34	18.8	13.7	.259	10.03	663
1.61	.16	98	2.55	−2.0	1	7.96	26.0	10.9	.395	9.64	664
1.61	.16	98	2.55	−2.0	1	8.22	28.0	10.6	.443	9.34	665
1.61	.16	98	2.55	−2.0	1	9.09	33.4	9.6	.571	8.84	666
1.61	.16	98	2.55	−2.0	1	9.22	30.8	9.4	.478	9.69	667
1.61	.16	98	2.55	−0.3	2	3.64	8.0	23.9	.082	11.27	672
1.61	.16	98	2.55	−.3	2	4.64	13.5	18.8	.183	9.54	673
1.61	.16	98	2.55	−.3	2	6.14	21.0	14.2	.334	8.82	674
1.61	.16	98	2.55	−.3	2	8.14	32.1	10.7	.589	8.13	675
1.61	.16	98	2.55	−2.0	2	4.84	13.5	18.0	.175	9.96	680
1.61	.16	98	2.55	−2.0	2	6.22	21.0	14.0	.330	8.95	681
1.61	.16	98	2.55	−2.0	2	8.22	32.1	10.6	.583	8.22	682
1.61	.35	56	0.47	−0.3	1	3.39	26.6	2.0	.970	11.01	683
1.61	.35	56	.47	−.3	1	3.39	26.7	2.0	.978	10.96	684
1.61	.35	56	.47	−.3	2	3.39	25.4	2.0	.885	11.59	697
1.61	.35	56	.47	−.3	2	4.64	38.3	1.4	1.470	10.33	698
1.61	.35	56	.47	−2.0	2	4.96	25.4	1.4	0.605	17.89	701
1.61	.35	56	.47	−2.0	2	5.09	38.3	1.3	1,340	11.65	702
1.61	.35	98	.82	−0.3	1	3.39	12.9	6.1	0.228	10.80	705
1.61	.35	98	.82	−.3	1	3.39	12.9	6.1	.228	10.80	706
1.61	.35	98	.82	−.3	1	4.64	21.0	4.4	.442	9.88	707
1.61	.35	98	.82	−.3	1	4.64	21.2	4.4	.450	9.79	708

See notes at end of table.

TABLE A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*—Continued

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
1.61	0.35	98	0.82	−0.3	1	6.14	30.7	3.3	0.714	9.35	709
1.61	.35	98	.82	−.3	1	6.14	32.3	3.3	.790	8.87	710
1.61	.35	98	.82	−.3	1	7.64	40.2	2.7	.983	9.02	711
1.61	.35	98	.82	−.3	1	7.64	44.1	2.7	1.183	8.08	712
1.61	.35	98	.82	−2.0	1	4.96	21.0	4.1	0.413	10.61	715
1.61	.35	98	.82	−2.0	1	4.96	21.2	4.1	.421	10.52	716
1.61	.35	98	.82	−2.0	1	6.22	32.3	3.3	.780	9.01	717
1.61	.35	98	.82	−2.0	1	6.34	30.7	3.2	.691	9.70	718
1.61	.35	98	.82	−2.0	1	7.72	40.2	2.7	.973	9.13	719
1.61	.35	98	.82	−2.0	1	7.72	44.1	2.7	1.171	8.19	720
1.61	.35	98	.82	−0.3	2	3.39	13.8	6.1	0.261	10.21	721
1.61	.35	98	.82	−.3	2	4.64	23.5	4.4	.553	8.90	722
1.61	.35	98	.82	−.3	2	6.14	34.4	3.3	.896	8.29	723
1.61	.35	98	.82	−.3	2	7.64	44.9	2.7	1.227	7.90	724
1.61	.35	98	.82	−2.0	2	5.22	23.5	3.9	0.492	10.12	726
1.61	.35	98	.82	−2.0	2	6.34	34.4	3.2	.868	8.61	727
1.61	.35	98	.82	−2.0	2	7.59	44.9	2.7	1.235	7.84	728
1.61	.35	137	1.14	−0.3	1	4.64	10.4	8.6	0.108	11.67	731
1.61	.35	137	1.14	−.3	1	4.64	12.2	8.6	.149	10.28	732
1.61	.35	137	1.14	−.3	1	6.14	16.3	6.5	.201	10.85	733
1.61	.35	137	1.14	−.3	1	6.14	19.2	6.5	.279	9.47	734
1.61	.35	137	1.14	−.3	1	7.64	24.0	5.2	.351	9.84	735
1.61	.35	137	1.14	−.3	1	7.64	26.7	5.2	.434	8.95	736
1.61	.35	137	1.14	−2.0	1	6.22	16.3	6.4	.199	11.00	741
1.61	.35	137	1.14	−2.0	1	6.22	19.2	6.4	.276	9.60	742
1.61	.35	137	1.14	−2.0	1	7.72	24.0	5.2	.347	9.95	743
1.61	.35	137	1.14	−2.0	1	7.72	26.7	5.2	.429	9.05	744
1.61	.35	137	1.14	−0.3	2	4.64	13.2	8.6	.175	9.65	746
1.61	.35	137	1.14	−.3	2	6.14	21.0	6.5	.334	8.77	747
1.61	.35	137	1.14	−.3	2	7.64	29.7	5.2	.537	8.11	748
1.61	.35	137	1.14	−2.0	2	6.34	21.0	6.3	.323	9.07	751
1.61	.35	137	1.14	−2.0	2	7.59	29.7	5.3	.540	8.05	752
1.61	.35	180	1.50	−0.3	1	5.64	8.8	12.3	.064	11.52	755
1.61	.35	180	1.50	−.3	1	5.64	10.6	12.3	.093	9.97	756
1.61	.35	180	1.50	−.3	1	6.64	12.4	10.4	.108	10.41	757
1.61	.35	180	1.50	−.3	1	6.64	13.3	10.4	.124	9.85	758
1.61	.35	180	1.50	−.3	1	7.64	15.4	9.1	.144	10.11	759
1.61	.35	180	1.50	−.3	1	7.64	16.4	9.1	.164	9.62	760
1.61	.35	180	1.50	−2.0	1	5.59	10.6	12.4	.093	9.88	763
1.61	.35	180	1.50	−2.0	1	5.72	8.8	12.1	.063	11.68	764
1.61	.35	180	1.50	−2.0	1	6.59	13.3	10.5	.125	9.77	765
1.61	.35	180	1.50	−2.0	1	6.84	12.4	10.1	.105	10.72	766
1.61	.35	180	1.50	−2.0	1	7.59	16.4	9.1	.165	9.55	767
1.61	.35	180	1.50	−2.0	1	7.72	15.4	9.0	.143	10.22	768
1.61	.35	180	1.50	−0.3	2	5.64	10.2	12.3	.086	10.27	770
1.61	.35	180	1.50	−.3	2	6.64	13.4	10.4	.126	9.79	771
1.61	.35	180	1.50	−.3	2	7.64	16.7	9.1	.170	9.48	772
1.61	.35	180	1.50	−2.0	2	5.72	10.2	12.1	.085	10.42	774
1.61	.35	180	1.50	−2.0	2	6.72	13.4	10.3	.124	9.91	775
1.61	.35	180	1.50	−2.0	2	7.59	16.7	9.1	.171	9.41	776
1.61	.58	98	0.40	−0.3	1	3.39	15.0	2.6	.309	11.62	777
1.61	.58	98	.40	−.3	1	3.39	15.6	2.6	.334	11.24	778
1.61	.58	98	.40	−.3	1	4.64	24.5	1.9	.601	10.45	779
1.61	.58	98	.40	−.3	1	4.64	25.8	1.9	.667	9.93	780
1.61	.58	98	.40	.3	1	6.14	38.4	1.5	1.116	8.93	781
1.61	.58	98	.40	−.3	1	6.14	38.9	1.5	1.146	8.79	782
1.61	.58	98	.40	−.3	1	7.64	49.0	1.2	1.461	8.60	783
1.61	.58	98	.40	−.3	1	7.64	53.5	1.2	1.742	7.55	784
1.61	.58	98	.40	−2.0	1	4.96	24.5	1.8	0.563	11.25	787
1.61	.58	98	.40	−2.0	1	5.09	25.8	1.8	.608	11.01	788
1.61	.58	98	.40	−2.0	1	5.84	38.4	1.5	1.174	8.39	789
1.61	.58	98	.40	−2.0	1	6.09	38.9	1.5	1.155	8.70	790
1.61	.58	98	.40	−2.0	1	7.44	53.5	1.2	1.789	7.27	791
1.61	.58	98	.40	−2.0	1	7.59	49.0	1.2	1.471	8.52	792
1.61	.58	98	.40	−0.3	2	3.39	14.5	2.6	0.288	11.97	793
1.61	.58	98	.40	−.3	2	4.64	28.0	1.9	.786	9.13	794
1.61	.58	98	.40	−.3	2	6.14	41.3	1.5	1.292	8.15	795
1.61	.58	98	.40	−2.0	2	5.34	28.0	1.7	0.683	10.71	798
1.61	.58	98	.40	−2.0	2	6.09	41.3	1.5	1.302	8.06	799
1.61	.58	158	.64	−0.3	1	4.64	11.7	5.0	0.137	10.87	803

See notes at end of table.

TABLE A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*—Continued

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
1.61	0.58	158	0.64	−0.3	1	4.64	13.3	5.0	0.177	9.81	804
1.61	.58	158	.64	−.3	1	6.14	20.4	3.8	.315	9.19	805
1.61	.58	158	.64	−.3	1	6.14	20.5	3.8	.318	9.15	806
1.61	.58	158	.64	−.3	1	7.64	25.9	3.0	.408	9.41	807
1.61	.58	158	.64	−.3	1	7.64	29.3	3.0	.522	8.40	808
1.61	.58	158	.64	−2.0	1	4.96	13.3	4.7	.166	10.50	811
1.61	.58	158	.64	−2.0	1	5.09	11.7	4.6	.125	11.95	812
1.61	.58	158	.64	−2.0	1	6.34	20.4	3.7	.305	9.51	813
1.61	.58	158	.64	−2.0	1	6.34	20.5	3.7	.308	9.47	814
1.61	.58	158	.64	−2.0	1	7.46	25.9	3.1	.418	9.17	815
1.61	.58	158	.64	−2.0	1	7.46	29.3	3.1	.535	8.18	816
1.61	.58	158	.64	−0.3	2	4.64	11.8	5.0	.140	10.80	818
1.61	.58	158	.64	−.3	2	6.14	19.6	3.8	.291	9.51	819
1.61	.58	158	.64	−.3	2	7.64	29.0	3.0	.512	8.48	820
1.61	.58	158	.64	−2.0	2	6.16	19.6	3.8	.290	9.54	823
1.61	.58	158	.64	−2.0	2	7.59	29.0	3.1	.515	8.42	824
1.61	.58	203	.82	−0.3	1	6.14	11.9	6.3	.107	10.44	829
1.61	.58	203	.82	−.3	1	6.14	12.4	6.3	.116	10.10	830
1.61	.58	203	.82	−.3	1	7.64	17.4	5.0	.184	9.64	831
1.61	.58	203	.82	−.3	1	7.64	19.2	5.0	.224	8.89	832
1.61	.58	203	.82	−2.0		5.96	12.4	6.4	.120	9.80	837
1.61	.58	203	.82	−2.0	1	6.46	11.9	5.9	.102	10.99	838
1.61	.58	203	.82	−2.0	1	7.59	19.2	5.1	.226	8.83	839
1.61	.58	203	.82	−2.0	1	7.72	17.4	5.0	.182	9.74	840
1.61	.58	203	.82	−0.3	2	4.64	7.9	8.3	.063	10.80	842
1.61	.58	203	.82	−.3	2	6.14	12.5	6.3	.118	10.04	843
1.61	.58	203	.82	−.3	2	7.64	18.4	5.0	.206	9.21	844
1.61	.58	203	.82	−2.0	2	5.09	7.9	7.5	.057	11.86	846
1.61	.58	203	.82	−2.0	2	6.22	12.5	6.2	.117	10.17	847
1.61	.58	203	.82	−2.0	2	7.72	18.4	5.0	.204	9.31	848
1.61	.58	252	1.02	−0.3	1	7.64	10.3	7.7	.065	11.12	855
1.61	.58	252	1.02	−.3	1	7.64	11.7	7.7	.083	10.08	856
1.61	.58	252	1.02	−2.0	1	7.59	10.3	7.8	.065	11.05	863
1.61	.58	252	1.02	−2.0	1	7.59	11.7	7.8	.084	10.01	864
1.61	.58	252	1.02	−2.0	2	7.64	11.7	7.7	.083	10.08	867
1.61	.58	252	1.02	−2.0	2	7.59	11.7	7.8	.084	10.01	870
2.07	.16	54	1.41	−0.3	1	4.29	39.7	6.2	.620	11.91	891
2.07	.16	54	1.41	−.3	1	4.29	41.3	6.2	.671	11.45	892
2.07	.16	54	1.41	−.3	1	5.54	62.5	4.8	1.190	9.78	893
2.07	.16	54	1.41	−.3	1	5.54	64.4	4.8	1.264	9.42	894
2.07	.16	54	1.41	−2.0	1	5.92	62.5	4.5	1.114	10.62	900
2.07	.16	54	1.41	−2.0	1	5.92	64.4	4.5	1.183	10.24	901
2.07	.16	54	1.41	−0.3	2	4.29	46.4	6.2	0.847	10.15	906
2.07	.16	54	1.41	−.3	2	5.54	66.6	4.8	1.351	9.02	907
2.07	.16	80	2.08	−.3	1	4.29	21.1	13.5	0.175	12.68	914
2.07	.16	80	2.08	−.3	1	4.29	23.8	13.5	.223	11.49	915
2.07	.16	80	2.08	−.3	1	5.54	29.7	10.5	.269	12.46	916
2.07	.16	80	2.08	−.3	1	5.54	33.7	10.5	.346	11.18	917
2.07	.16	80	2.08	−.3	1	7.54	53.3	7.7	.636	10.24	918
2.07	.16	80	2.08	−.3	1	7.54	55.0	7.7	.677	9.92	919
2.07	.16	80	2.08	−.3	1	9.04	72.8	6.4	.990	9.08	920
2.07	.16	80	2.08	−.3	1	9.04	73.1	6.4	.998	9.03	921
2.07	.16	80	2.08	−2.0	1	7.62	55.0	7.6	.670	10.04	926
2.07	.16	80	2.08	−2.0	1	7.74	53.3	7.5	.620	10.54	927
2.07	.16	80	2.08	−2.0	1	9.24	72.8	6.3	.968	9.32	928
2.07	.16	80	2.08	−2.0	1	9.36	73.1	6.2	.964	9.42	929
2.07	.16	80	2.08	−0.3	2	4.29	20.6	13.5	.167	12.92	930
2.07	.16	80	2.08	−.3	2	5.54	34.2	10.5	.356	11.04	931
2.07	.16	80	2.08	−.3	2	7.54	57.0	7.70	.727	9.57	932
2.07	.16	80	2.08	−.3	2	9.04	75.6	6.4	1.067	8.69	933
2.07	.16	80	2.08	−2.0	2	7.62	57.0	7.6	0.720	9.69	936
2.07	.16	80	2.08	−2.0	2	9.12	75.6	6.4	1.058	8.78	937
2.07	.16	98	2.55	−0.3	1	5.54	21.0	15.7	0.134	12.84	940
2.07	.16	98	2.55	−.3	1	5.54	23.8	15.7	.173	11.61	941
2.07	.16	98	2.55	−.3	1	7.54	35.5	11.5	.282	11.49	942

See notes at end of table.

Table A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*—Continued

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
2.07	0.16	98	2.55	−0.3	1	7.54	38.9	11.5	0.339	10.62	943
2.07	.16	98	2.55	−.3	1	9.04	48.3	9.6	.436	10.64	944
2.07	.16	98	2.55	−.3	1	9.04	50.9	9.6	.484	10.14	945
2.07	.16	98	2.55	−2.0	1	7.74	35.5	11.2	.275	11.81	950
2.07	.16	98	2.55	−2.0	1	7.74	38.9	11.2	.330	10.92	951
2.07	.16	98	2.55	−2.0	1	9.30	48.3	9.4	.423	10.97	952
2.07	.16	98	2.55	−2.0	1	9.36	50.9	9.3	.467	10.53	953
2.07	.16	98	2.55	−0.3	2	5.54	22.8	15.7	.158	12.02	955
2.07	.16	98	2.55	−.3	2	7.54	38.9	11.5	.339	10.62	956
2.07	.16	98	2.55	−.3	2	9.04	53.0	9.6	.525	9.77	957
2.07	.16	98	2.55	−2.0	2	5.74	22.8	15.2	.153	12.47	958
2.07	.16	98	2.55	−2.0	2	7.62	38.9	11.4	.335	10.74	959
2.07	.16	98	2.55	−2.0	2	9.18	53.0	9.5	.517	9.93	960
2.07	.35	98	0.82	−0.3	1	4.29	25.1	4.8	.248	12.85	985
2.07	.35	98	.82	−.3	1	4.29	30.8	4.8	.373	10.78	986
2.07	.35	98	.82	−.3	1	5.54	38.0	3.7	.440	11.75	987
2.07	.35	98	.82	−.3	1	5.54	50.2	3.7	.768	8.98	988
2.07	.35	98	.82	−.3	1	7.54	66.4	2.7	.987	9.49	989
2.07	.35	98	.82	−.3	1	7.54	72.7	2.7	1.183	8.52	990
2.07	.35	98	.82	−2.0	1	5.92	50.2	3.5	0.719	9.68	995
2.07	.35	98	.82	−2.0	1	5.99	38.0	3.4	.407	12.78	996
2.07	.35	98	.82	−2.0	1	7.62	66.4	2.7	.977	9.61	997
2.07	.35	98	.82	−2.0	1	7.62	72.7	2.7	1.171	8.63	998
2.07	.35	98	.82	−0.3	2	4.29	31.8	4.8	0.398	10.48	1001
2.07	.35	98	.82	−.3	2	5.54	48.8	3.7	.726	9.24	1002
2.07	.35	137	1.14	−.3	1	5.54	21.8	7.2	.145	12.35	1011
2.07	.35	137	1.14	−.3	1	5.54	30.8	7.2	.289	9.30	1012
2.07	.35	137	1.14	−.3	1	7.54	36.4	5.3	.297	11.15	1013
2.07	.35	137	1.14	−.3	1	7.54	46.3	5.3	.480	9.01	1014
2.07	.35	137	1.14	−.3	1	9.04	50.2	4.4	.471	10.18	1015
2.07	.35	137	1.14	−.3	1	9.04	62.5	4.4	.729	8.23	1016
2.07	.35	137	1.14	−2.0	1	7.74	36.4	5.2	.289	11.46	1021
2.07	.35	137	1.14	−2.0	1	7.74	46.3	5.2	.468	9.27	1022
2.07	.35	137	1.14	−2.0	1	9.24	62.5	4.3	.714	8.44	1023
2.07	.35	137	1.14	−2.0	1	9.49	50.2	4.2	.448	10.73	1024
2.07	.35	137	1.14	−0.3	2	4.29	16.8	9.3	.111	11.70	1025
2.07	.35	137	1.14	−.3	2	5.54	26.0	7.2	.206	10.71	1026
2.07	.35	137	1.14	−.3	2	7.54	44.0	5.3	.433	9.44	1027
2.07	.35	137	1.14	−.3	2	9.04	59.8	4.4	.668	8.61	1028
2.07	.35	137	1.14	−2.0	2	7.55	44.0	5.3	.433	9.45	1031
2.07	.35	137	1.14	−2.0	2	9.18	59.8	4.4	.658	8.76	1032
2.07	.35	180	1.50	−0.3	1	7.54	22.4	9.2	.112	11.78	1037
2.07	.35	180	1.50	−.3	1	7.54	29.6	9.2	.196	9.42	1038
2.07	.35	180	1.50	−.3	1	9.04	30.4	7.7	.173	11.11	1039
2.07	.35	180	1.50	−.3	1	9.04	39.6	7.7	.293	8.93	1040
2.07	.35	180	1.50	−2.0	1	7.49	29.6	9.2	.197	9.35	1045
2.07	.35	180	1.50	−2.0	1	7.74	22.4	8.9	.109	12.09	1046
2.07	.35	180	1.50	−2.0	1	9.18	39.6	7.5	.288	9.07	1047
2.07	.35	180	1.50	−2.0	1	9.24	30.4	7.5	.169	11.37	1048
2.07	.35	180	1.50	−0.3	2	5.54	14.8	12.5	.067	11.90	1049
2.07	.35	180	1.50	−.3	2	7.54	26.0	9.2	.151	10.46	1050
2.07	.35	180	1.50	−.3	2	9.04	35.7	7.7	.238	9.74	1051
2.07	.35	180	1.50	−2.0	2	7.55	26.0	9.2	.151	10.47	1053
2.07	.35	180	1.50	−2.0	2	9.12	35.7	7.6	.236	9.83	1054
2.07	.58	98	0.40	−0.3	1	4.29	48.3	2.1	.918	8.51	1055
2.07	.58	98	.40	−.3	1	4.29	48.3	2.1	.918	8.51	1056
2.07	.58	98	.40	−.3	1	5.54	64.0	1.6	1.248	8.32	1057
2.07	.58	98	.40	−.3	1	5.54	66.4	1.6	1.343	7.93	1058
2.07	.58	98	.40	−.3	1	7.54	86.2	1.2	1.663	8.27	1059
2.07	.58	98	.40	−.3	1	7.54	91.9	1.2	1.891	7.47	1060
2.07	.58	98	.40	−.3	1	9.04	101.6	1.0	1.927	8.23	1061
2.07	.58	98	.40	−.3	1	9.04	109.2	1.0	2.227	7.22	1062
2.07	.58	98	.40	−2.0	1	6.05	64.0	1.5	1.143	9.29	1065
2.07	.58	98	.40	−2.0	1	6.05	66.4	1.5	1.230	8.88	1066
2.07	.58	158	.64	−0.3	1	4.29	21.0	5.4	0.174	10.03	1079

See notes at end of table.

TABLE A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*—Continued

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
2.07	0.58	158	0.64	−0.3	1	4.29	23.8	5.4	0.223	9.06	1080
2.07	.58	158	.64	−.3	1	5.54	31.8	4.2	.308	9.27	1081
2.07	.58	158	.64	−.3	1	5.54	35.5	4.2	.384	8.42	1082
2.07	.58	158	.64	−.3	1	7.54	53.9	3.1	.650	7.98	1083
2.07	.58	158	.64	−.3	1	7.54	55.5	3.1	.690	7.75	1084
2.07	.58	158	.64	−.3	1	9.04	71.0	2.6	.941	7.36	1085
2.07	.58	158	.64	−.3	1	9.04	72.7	2.6	.987	7.17	1086
2.07	.58	158	.64	−2.0	1	5.80	31.8	4.0	.294	9.73	1089
2.07	.58	158	.64	−2.0	1	5.86	35.5	4.0	.363	8.94	1090
2.07	.58	158	.64	−2.0	1	7.62	53.9	3.1	.644	8.08	1091
2.07	.58	158	.64	−2.0	1	7.62	55.5	3.1	.682	7.85	1092
2.07	.58	158	.64	−2.0	1	9.24	71.0	2.5	.921	7.56	1093
2.07	.58	158	.64	−2.0	1	9.24	72.7	2.5	.966	7.36	1094
2.07	.58	158	.64	−0.3	2	4.29	27.2	5.4	.291	8.10	1095
2.07	.58	203	.82	−.3	1	5.54	18.9	6.9	.109	10.37	1105
2.07	.58	203	.82	−.3	1	5.54	23.0	6.9	.161	8.87	1106
2.07	.58	203	.82	−.3	1	7.54	32.6	5.1	.238	9.17	1107
2.07	.58	203	.82	−.3	1	7.54	38.0	5.1	.323	8.05	1108
2.07	.58	203	.82	−.3	1	9.04	44.5	4.2	.370	8.50	1109
2.07	.58	203	.82	−.3	1	9.04	49.5	4.2	.458	7.73	1110
2.07	.58	203	.82	−2.0	1	7.62	32.6	5.0	.235	9.27	1115
2.07	.58	203	.82	−2.0	1	7.62	38.0	5.0	.320	8.14	1116
2.07	.58	203	.82	−2.0	1	9.18	44.5	4.2	.364	8.64	1117
2.07	.58	203	.82	−2.0	1	9.24	49.5	4.2	.448	7.91	1118
2.07	.58	203	.82	−0.3	2	4.29	17.3	8.9	.118	8.56	1119
2.07	.58	203	.82	−.3	2	5.54	26.6	6.9	.216	7.88	1120
2.07	.58	203	.82	−2.0	2	5.80	26.6	6.6	.206	8.26	1124
2.07	.58	232	.94	−0.3	1	6.29	19.3	8.0	.100	9.82	1129
2.07	.85	232	.94	−.3	1	6.29	22.0	8.0	.130	8.86	1130
2.07	.58	232	.94	−.3	1	7.54	25.3	6.6	.143	9.54	1131
2.07	.58	232	.94	−.3	1	7.54	29.6	6.6	.196	8.40	1132
2.07	.58	232	.94	−.3	1	9.04	34.4	5.5	.221	8.96	1133
2.07	.58	232	.94	−.3	1	9.04	39.9	5.5	.297	7.91	1134
2.07	.58	232	.94	−2.0	1	6.24	22.0	8.0	.131	8.78	1137
2.07	.58	232	.94	−2.0	1	6.61	19.3	7.6	.095	10.33	1138
2.07	.58	232	.94	−2.0	1	7.36	29.6	6.8	.201	8.19	1139
2.07	.58	232	.94	−2.0	1	7.62	25.3	6.6	.142	9.64	1140
2.07	.58	232	.94	−2.0	1	9.12	39.9	5.5	.295	7.98	1141
2.07	.58	232	.94	−2.0	1	9.24	34.4	5.4	.216	9.17	1142
2.07	.58	232	.94	−0.3	2	6.29	19.8	8.0	.105	9.62	1144
2.07	.58	232	.94	−.3	2	7.54	26.6	6.6	.158	9.16	1145
2.07	.58	232	.94	−.3	2	9.04	35.7	5.5	.238	8.69	1146
2.07	.58	232	.94	−2.0	2	6.42	19.8	7.8	.103	9.83	1148
2.07	.58	232	.94	−2.0	2	7.42	26.6	6.8	.161	9.01	1149
2.07	.58	232	.94	−2.0	2	9.12	35.7	5.5	.236	8.77	1150
3.07	.16	80	2.08	−0.3	1	5.61	96.4	10.3	.580	9.81	1163
3.07	.16	80	2.08	−.3	1	5.61	108.3	10.3	.731	8.74	1164
3.07	.16	80	2.08	−.3	1	7.36	134.9	7.9	.865	9.48	1165
3.07	.16	80	2.08	−.3	1	7.36	140.8	7.9	.942	9.04	1166
3.07	.16	80	2.08	−.3	1	8.86	170.4	6.5	1.147	9.05	1167
3.07	.16	80	2.08	−.3	1	8.86	176.5	6.5	1.230	8.66	1168
3.07	.16	80	2.08	−.3	1	10.11	198.8	5.7	1.368	8.78	1169
3.07	.16	80	2.08	−.3	1	10.11	199.5	5.7	1.377	8.74	1170
3.07	.16	80	2.08	−2.0	1	7.16	140.8	8.1	0.969	8.75	1173
3.07	.16	80	2.08	−2.0	1	7.44	134.9	7.8	.856	9.60	1174
3.07	.16	98	2.55	−0.3	1	5.61	77.5	15.5	0.375	9.30	1181
3.07	.16	98	2.55	−.3	1	5.61	79.9	15.5	.398	9.06	1182
3.07	.16	98	2.55	−.3	1	7.36	108.7	11.8	.562	9.16	1183
3.07	.16	98	2.55	−.3	1	7.36	111.2	11.8	.588	8.96	1184
3.07	.16	98	2.55	−.3	1	8.86	134.1	9.8	.710	9.16	1185
3.07	.16	98	2.55	−.3	1	8.86	138.2	9.8	.754	8.88	1186
3.07	.16	98	2.55	−.3	1	10.36	161.2	8.4	.877	9.03	1187
3.07	.16	98	2.55	−.3	1	10.36	165.1	8.4	.920	8.80	1188
3.07	.16	98	2.55	−2.0	1	7.31	111.2	11.9	.592	8.89	1191
3.07	.16	98	2.55	−2.0	1	7.44	108.7	11.7	.556	9.27	1192
3.07	.16	98	2.55	−2.0	1	9.06	134.1	9.6	.694	9.39	1193
3.07	.16	98	2.55	−2.0	1	9.06	138.2	9.6	.738	9.11	1194
3.07	.16	98	2.55	−2.0	1	10.56	165.1	8.2	.903	9.00	1195
3.07	.16	98	2.55	−2.0	1	10.68	161.2	8.1	.851	9.36	1196
3.07	.16	98	2.55	−0.3	2	5.61	83.5	15.5	.435	8.70	1197

See notes at end of table.

Table A–2. *Data on interference of flows at junction of 3-in. simulated stack and horizontal branches, long-turn T-Y drainage fittings*—Continued

1	2	3	4	5	6	7	8	9	10	11	12
Branch diameter	Thickness of water layer [a] on wall of stack	Rate of flow [a] in stack	Ratio of stack velocity [a] to computed terminal velocity	Pneumatic pressure [a] in stack	Number of branches flowing	Head loss in branch	Rate of flow in each branch	Stack parameter	Branch parameter	Coefficient	Test number
D_2	T	Q_1	$\frac{V_1}{V_t}$	h_1		h_2-h_1	Q_2	X	Y	C	
in.	*in.*	*gpm*		*in.*		*in.*	*gpm*				
3.07	0.35	98	0.82	−0.3	1	5.61	115.1	3.7	0.826	9.60	1203
3.07	.35	98	.82	−.3	1	5.61	117.2	3.7	.857	9.42	1204
3.07	.35	137	1.14	−.3	1	5.61	71.1	7.1	.315	9.96	1219
3.07	.35	137	1.14	−.3	1	5.61	77.4	7.1	.374	9.25	1220
3.07	.35	137	1.14	−.3	1	7.36	97.9	5.4	.456	10.03	1221
3.07	.35	137	1.14	−.3	1	7.36	104.1	5.4	.515	9.47	1222
3.07	.35	137	1.14	−.3	1	8.86	124.3	4.5	.610	9.81	1223
3.07	.35	137	1.14	−.3	1	8.86	134.0	4.5	.709	9.10	1224
3.07	.35	137	1.14	−.3	1	10.36	155.3	3.9	.814	9.34	1225
3.07	.35	137	1.14	−.3	1	10.36	161.0	3.9	.875	8.98	1226
3.07	.35	137	1.14	−2.0	1	7.31	104.1	5.5	.519	9.40	1229
3.07	.35	137	1.14	−2.0	1	7.56	97.9	5.3	.444	10.32	1230
3.07	.35	137	1.14	−2.0	1	9.06	134.0	4.4	.693	9.34	1231
3.07	.35	137	1.14	−2.0	1	9.31	124.3	4.3	.581	10.37	1232
3.07	.35	137	1.14	−2.0	1	10.81	155.3	3.7	.781	9.81	1233
3.07	.35	137	1.14	−2.0	1	10.81	161.0	3.7	.839	9.44	1234
3.07	.35	180	1.50	−0.3	1	5.61	50.3	12.3	.158	9.44	1248
3.07	.35	180	1.50	−.3	1	5.61	56.1	12.3	.196	8.64	1249
3.07	.35	180	1.50	−.3	1	7.36	66.4	9.4	.210	9.96	1250
3.07	.35	180	1.50	−.3	1	7.36	74.5	9.4	.264	9.05	1251
3.07	.35	180	1.50	−.3	1	8.86	81.4	7.8	.262	10.20	1252
3.07	.35	180	1.50	−.3	1	8.86	89.5	7.8	.316	9.41	1253
3.07	.35	180	1.50	−.3	1	10.36	99.2	6.7	.332	10.16	1254
3.07	.35	180	1.50	−.3	1	10.36	111.9	6.7	.423	9.13	1255
3.07	.35	180	1.50	−2.0	1	7.56	74.5	9.2	.257	9.31	1258
3.07	.35	180	1.50	−2.0	1	7.68	66.4	9.0	.201	10.41	1259
3.07	.35	180	1.50	−2.0	1	9.06	89.5	7.6	.309	9.63	1260
3.07	.35	180	1.50	−2.0	1	9.31	81.4	7.4	.249	10.74	1261
3.07	.35	180	1.50	−2.0	1	10.56	99.2	6.6	.326	10.36	1262
3.07	.35	180	1.50	−2.0	1	10.81	111.9	6.4	.405	9.56	1263
3.07	.35	180	1.50	−0.3	2	5.61	54.8	12.3	.187	8.80	1264
3.07	.58	158	0.64	−.3	1	5.61	94.0	4.1	.551	7.94	1282
3.07	.58	158	.64	−.3	1	5.61	104.7	4.1	.684	7.14	1283
3.07	.58	158	.64	−.3	1	7.36	119.7	3.2	.681	8.48	1284
3.07	.58	158	.64	−.3	1	7.36	128.1	3.2	.780	7.91	1285
3.07	.58	158	.64	−.3	1	8.86	137.8	2.6	.750	9.07	1286
3.07	.58	158	.64	−.3	1	8.86	138.1	2.6	.753	9.05	1287
3.07	.58	158	.64	−.3	1	10.36	141.8	2.2	.679	10.52	1288
3.07	.58	158	.64	−.3	1	10.36	142.2	2.2	.683	10.49	1289
3.07	.58	203	.82	−.3	1	5.61	64.6	6.8	.260	8.10	1294
3.07	.58	203	0.82	−.3	1	5.61	64.6	6.8	.260	8.10	1295
3.07	.58	203	.82	−.3	1	7.36	85.6	5.2	.348	8.47	1296
3.07	.58	203	.82	−.3	1	7.36	85.6	5.2	.348	8.47	1297
3.07	.58	203	.82	−.3	1	8.86	108.4	4.3	.464	8.37	1298
3.07	.58	203	.82	−.3	1	8.86	108.4	4.3	.464	8.37	1299
3.07	.58	203	.82	−.3	1	10.36	125.8	3.7	.534	8.64	1300
3.07	.58	203	.82	−.3	1	10.36	125.8	3.7	.534	8.64	1301
3.07	.58	227	.92	−.3	1	5.61	54.5	8.6	.185	8.10	1306
3.07	.58	227	.92	−.3	1	5.61	54.5	8.6	.185	8.10	1307
3.07	.58	227	.92	−.3	1	7.36	72.8	6.5	.252	8.46	1308
3.07	.58	227	.92	−.3	1	7.36	72.8	6.5	.252	8.46	1309
3.07	.58	227	.92	−.3	1	8.86	90.6	5.4	.324	8.53	1310
3.07	.58	227	.92	−.3	1	8.86	90.6	5.4	.324	8.53	1311
3.07	.58	227	.92	−.3	1	10.36	107.9	4.6	.393	8.65	1312
3.07	.58	227	.92	−.3	1	10.36	107.9	4.6	.393	8.65	1313
3.07	.58	227	.92	−1.6	1	6.43	54.5	7.5	.162	9.33	1314
3.07	.58	227	.92	−1.6	1	7.18	72.8	6.7	.258	8.24	1315
3.07	.58	227	.92	−1.6	1	8.93	90.6	5.4	.322	8.61	1316
3.07	.58	227	.92	−1.8	1	6.01	54.5	8.0	.173	8.70	1317
3.07	.58	227	.92	−1.8	1	7.36	72.8	6.5	.252	8.46	1318
3.07	.58	227	.92	−1.8	1	9.11	90.6	5.3	.315	8.79	1319

[a] Above the stack-branch junction.

Note: Missing numbers in the series in column 12 represent data obtained for conditions outside the range over which it is reasonable to expect the analysis in section 4.1. to apply. All data included in the following categories were omitted:

1. Data in which branch velocity was less than half of that required to produce computed steady flow capacity for a full pipe not under external head.
2. Data in which branch discharge for two-branch flow exceeded the criterion for fitting capacity given in section 2.1., wherein the effective stack diameter was assumed to he the computed air-core diameter.
3. Data in which the horizontal momentum in one hranch exceeded half the momentum in the stack just ahove the hranch.

I=permissible fixture-unit load within any single branch interval

S=permissible maximum load on stack, in fixture units

For stacks having only one branch interval,

$$I_{(n=1)}=S_{(n=1)}=1.5B. \qquad \text{(A-3)}$$

For stacks having two or more branch intervals,

$$I_{(n\geqq 2)}=\frac{\gamma I_{(n=1)}}{2}=\frac{\gamma S_{(n=1)}}{2}=\frac{3\gamma B}{4}, \qquad \text{(A-4)}$$

and

$$S_{(n\geqq 2)}=\frac{\gamma n I_{(n=1)}}{2}=\frac{\gamma n S_{(n=1)}}{2}=\frac{3\gamma n B}{4}. \qquad \text{(A-5)}$$

Table A–5 shows the steps involved in computing by use of eq (A–5) permissible stack loads relative to permissible single-branch loads for pipe of the same diameter as the stack, or relative to permissible loads for stacks having one branch interval.

The concepts described above will now be applied to the development of loading tables for soil and waste stacks of various heights. Table A–6 gives permissible loads for horizontal branches (B) and for single-interval loads on one-story stacks of the same diameter ($I_{n=1}$). The values of B given in the table are based on Hunter's research on capacities of horizontal drains. These values were used later by plumbing code writers [1].

For diameters greater than 3 in., the single-interval loads in table A–6 are about one-third as large as those obtained by applying the fitting capacities for double sanitary-tee fittings (given in table 1) to curve 1 of figure 37.

Table A–7, giving permissible loads for soil and waste stacks having one or two branch intervals, has been computed from eqs (A–3) and (A–5) and from the values given in table A–6. Table A–8 gives permissible loads for stacks of various heights, computed from eq (A–5) and from the values given in table A–6. Load limits for tall stacks have been taken from table 12 for stacks with 7/24 (0.29) of their cross sections occupied by water falling at terminal velocity.

TABLE A–3. *Elevation corrections to observed values of head loss through branches, simulated-stack tests*

Branch diameter	Elevation correction [a]	
	Sanitary-tee fitting	Long-turn T-Y fitting
in.	*in.*	*in.*
1.61	−0.36	+1.34
2.07	−.49	+1.74
3.07	−.84	+2.06

[a] Correction takes into account the following factors:
1. Shifting of reference level from invert to center of pipe section;
2. Change in elevation of center line of pipe due to ¼-inch-per-foot slope toward stack over a developed length of 4 branch diameters;
3. Change in elevation of passageway through fitting due to geometry of fitting at junction between branch and stack.

TABLE A–4. *Hunter's data [a] on friction losses for new cast-iron soil pipe flowing full*

Nominal diameter	Actual diameter	f	8/f	$\sqrt{8/f}$	$\log_{10}R$
in.	*in.*				
2	2.06	0.0301	266	16.30	0.0128
3	2.90	.0258	310	17.60	.161
4	3.93	.0243	329	18.15	.293
5	4.85	.0250	320	17.90	.385

[a] Reference 13.

TABLE A–5. *Computation of permissible stack loads relative to permissible single-branch loads for pipe of same diameter as stack, or relative to permissible loads for stacks having one branch interval*

Number of branch intervals, n	$\frac{1}{n}+\frac{1}{2}$, γ	γn	Relative loads		
			I/B	S_n/B	S_n/S_1
1	1.5	1.5	1.5	1.5	1.0
2	1.0	2.0	0.75	1.5	1.0
3	0.833	2.5	.625	1.875	1.25
4	.75	3.0	.562	2.25	1.5
5	.70	3.5	.525	2.625	1.75
6	.667	4.0	.50	3.0	2.0
7	.643	4.5	.482	3.375	2.25
8	.625	5.0	.469	3.75	2.5
9	.611	5.5	.458	4.125	2.75
10	.600	6.0	.45	4.5	3.0
12	.583	7.0	.437	5.25	3.5
15	.567	8.5	.425	6.375	4.25

TABLE A–6. *Load limits for horizontal branches and single-interval stacks*

Pipe diameter	Load limits	
	Horizontal branch	Single-interval stack
in.	*f.u.*	*f.u.*
2	6	8
2½	12	20
3 (soil)	[a] 20	[a] 30
3 (waste)	32	48
4	160	240
5	360	540
6	620	930
8	1,400	2,100
10	2,500	3,750
12	3,900	5,850
15	7,000	10,500

[a] Not more than two water closets.

TABLE A–7. *Maximum loads for soil and waste stacks having one or two branch intervals*

Diameter of stack	Maximum load on stack
in.	*f.u.*
1¼	2
1½	4
2	8
2½	20
3 (soil)	[a] 30
3 (waste)	48
4	240
5	540
6	930
8	2,100
10	3,750
12	5,850
15	10,500

[a] Not more than two water closets within each branch interval.

TABLE A–8. *Maximum loads for multistory soil and waste stacks*

Diameter of stack	Number of branch intervals																Load limit [a] for tall stack
	3		4		5		6		8		10		12		15		
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
in.	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*	*f.u.*
2	3	9															10
2½	8	24	7	28													28
3 (soil)	[b] 12	[c] 36	[b] 11	[c] 44	[b] 10	[c] 50	[b] 10	[c] 60									[c] 102
3 (waste)	20	60	18	72	17	85	16	96									102
4	100	300	90	360	84	420	80	480									530
5	225	675	205	820	190	950	180	1, 080	170	1, 360							1, 400
6	385	1, 155	350	1, 400	325	1, 625	310	1, 860	290	2, 320	280	2, 800					2, 900
8	875	2, 625	785	3, 140	735	3, 675	700	4, 200	655	5, 240	630	6, 300	612	7, 350			7, 600
10	1, 560	4, 680	1, 405	5, 620	1, 310	6, 550	1, 250	7, 500	1, 170	9, 360	1, 125	11, 250	1, 095	13, 100			15, 000
12	2, 435	7, 305	2, 195	8, 780	2, 045	10, 225	1, 950	11, 700	1, 825	14, 600	1, 755	17, 550	1, 705	20, 500	1, 655	24, 800	26, 000
15	4, 375	13, 125	3, 935	15, 740	3, 675	18, 375	3, 500	21, 000	3, 280	26, 240	3, 150	31, 500	3, 060	36, 700	2, 975	44, 600	50, 000

Note.—Columns headed A = Maximum load within any one branch interval; columns headed B = Maximum load on stack.

[a] These limits are applicable only when the maximum load within any one branch interval is not greater than $N\left(\frac{1}{2n}+\frac{1}{4}\right)$, where N=permissible load on a stack of one or two branch intervals; and n=number of branch intervals on the stack under consideration.

[b] Not more than two water closets.

[c] Not more than six water closets.

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