U. S. DEPARTMENT OF COMMERCE

BUILDING MATERIALS AND STRUCTURES

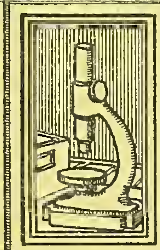
REPORT BMS28

Backflow Prevention in Over-Rim Water Supplies

by

GENE E. GOLDEN
and ROY B. HUNTER

NATIONAL
BUREAU OF STANDARDS



The program of research on building materials and structures, carried on by the National Bureau of Standards, was undertaken with the assistance of the Central Housing Committee, an informal organization of governmental agencies concerned with housing construction and finance, which is cooperating in the investigations through a subcommittee of principal technical assistants.

The Forest Products Laboratory of the United States Department of Agriculture is cooperating with both committees on investigations of wood constructions.

[For list of BMS publications and how to purchase, see cover page III.]

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The National Bureau of Standards is a fact-finding organization; it does not "approve" any particular material or method of construction. The technical findings in this series of reports are to be construed accordingly.

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Foreword

During the greater part of the past 18 years an experimental study of problems relating to the functions and performance of the water-distributing pipes, the plumbing fixtures and fittings, the drain pipes, and the vent pipes of the plumbing systems of buildings has been in progress at the National Bureau of Standards. These investigations are being made to determine the proper sizes, arrangement, and connections of water supply, drain, and vent pipes for the satisfactory and safe or sanitary operation of the plumbing fixtures and for effective drainage from the building. Where the conclusions from these studies have been accepted and applied in plumbing regulations and practices, better sanitary and drainage conditions and lower cost of construction through simplification of piping layouts have resulted. This program has been continued during the past two years with particular reference to low-cost housing.

The determination of practical and effective means of preventing the contamination of the potable water supply of a building by backflow from plumbing fixtures or drains is one of the important problems studied in the investigations reported in Bureau Research Paper RP1086. This report relates to a particular problem of prevention of backflow; namely, the prevention of backflow from over-rim supply fixtures, such as lavatories. The study, which is a continuation of the Bureau's work on backflow in plumbing systems, was instituted by the Bureau and carried to completion by the Plumbing Fixture Manufacturers' Research Associateship, whose sponsors are the Vitreous China Plumbing Fixtures Association, Sanitary Cast Iron Enameled Ware Association, Sanitary Brass Institute, and National Brass Association.

The principles demonstrated and the data furnished make possible the specification of safe air gaps in plumbing codes throughout the country in a simple and rational manner which, in its turn, should make for uniformity of regulation and simplicity of design and construction. A suggested form of specification is included, which is in agreement with the report of the American Standards Association's Subcommittee on Air Gaps, in the formulation of which the authors had the privilege of assisting.

Lyman J. Briggs, *Director.*

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CONTENTS

ABSTRACT

This report describes the methods used and the results obtained in the investigation of the prevention of backflow from plumbing fixtures with over-rim supply by means of air gaps between the supply opening and the highest possible liquid level in the fixture. The previous work is discussed and the data necessary for a complete understanding of the subject are presented. The treatment has been developed from the point of view of the construction of the supply fitting as well as its location with respect to the fixture. Finally, recommendations are offered in a form suitable for use in field inspection.

List of Symbols

Δh = Critical air gap, when there is no wall effect.

$\Delta h'$ = Critical air gap, when there is a wall effect.

H = Safe air gap.

d = Actual internal diameter.

d_e = Equivalent internal diameter.

D_1 = Actual external diameter.

h_a = Atmospheric pressure in feet of air column.

h_{a_0} = Atmospheric pressure in feet of air column at 65° F and 50-percent humidity.

ρ_a = Density of atmospheric air.

P_a = Absolute atmospheric pressure.

P_r = Absolute pressure in evacuated tank or system.

P_c = Absolute pressure in evacuated tank corresponding to the critical-pressure ratio, r_c.

r = pressure ratio, P_r/P_a.

V_r = Volume of the evacuated tank.

g = Acceleration of gravity.

t_0 = Time in seconds for pressure in tank to rise from zero to P_r.

t = Time in seconds for pressure in tank to rise from some initial pressure to P_r.

Δt = Time in seconds for pressure in tank to rise from zero to initial pressure.

k = Ratio of the specific heat at constant volume to that at constant pressure.

T = Effective wall thickness $=(D_1-d_e)/2$.

I. INTRODUCTION

Under our present standards of living, plumbing is considered an essential and integral part of practically every building where a supply of water is available. Hence the program of research on building materials and structures includes a project on plumbing.[1]

One of the problems included in the project is that of the structural requirements for plumbing necessary to prevent the pollution of the drinking-water supply by the flow of impure water into it through backflow connections [2] between the piping system that carries the potable water supply and any piping system or plumbing equipment that may carry or contain impure or nonpotable water, for example, plumbing drains and plumbing fixtures. This report deals with one particular phase of the problem; namely, the structural requirements necessary to insure against backflow through faucets and other valves similarly installed. The general problem of backflow connections has been treated more fully in a previous paper [1].[3]

It is common knowledge that the pressure in many building water-distributing pipes is frequently reduced below atmospheric pressure, as indicated by the failure of water to flow from a faucet or other supply valve when it is opened. These reductions in pressure may be produced in many ways, such as an excessive use of water in the building or its vicinity, the drawdown produced by fire-fighting apparatus, shut-off of the city or building water supply, breaks in street water mains, or in the building supply system. Reduction in pressure from these causes may be sufficient to allow a vacuum to form in the building water pipes in any upfeed water-supply system.

If a faucet spout or similar water-supply opening dips below the surface of the water in a plumbing fixture or other open vessel, water will be siphoned back through the valve whenever it is open or leaking, and the water pressure in the supply system at the level of the water surface in the fixture system is below atmospheric pressure. It is also well known that water may be lifted vertically across an air gap into a faucet by the atmospheric pressure in conjunction with a vacuum in the water-supply line, as illustrated in figure 1, in which an evacuated tank represents an evacuated water-supply line, the glass tube a faucet spout and the glass jar a plumbing fixture. Similarly, water may be lifted through partially enclosed supply passages; for example, through the jet passage of a water closet and the flush pipe from a flushing valve.

II. PREVIOUS WORK ON THE SUBJECT

In addition to the paper [1] previously referred to, the experimental work of Zinkil [2] of the Crane Co., Chicago, Ill., and that of Dawson and Kalinske at the University of Wisconsin [3] and the University of Iowa [4] are of particular interest in connection with the lifting of water across an air gap, as shown in figure 1.

Zinkil's data for round tubes, ranging from 0.128 to 0.807 inch in internal diameter cover the following conditions: (1) the tube set vertically over a water surface, (2) the tube set vertically with an adjacent vertical wall extending past the tube and touching the tube wall, and (3) the end of the tube set at an angle with the water surface. He also investigated the effects of elongated, or oval, tube openings. The data are remarkably consistent, and from them Zinkil drew the following conclusions: (1) increasing the intensity of the vacuum above 15 inches of mercury caused no appreciable increase in the critical air gap (the maximum vertical distance across which water can be lifted), (2) the critical gap will be practically the same for an elongated opening as for a circular opening of the same cross-sectional area, (3) when the spout opening is set at an angle not in excess of 30° from the horizontal, the critical air gap for this arrangement will be equal to the critical air gap for the same opening set horizontally, provided the gap for the included opening is taken as the average distance of the opening from the water surface.

The published work of Dawson and Kalinske [3, 4] contain no experimental data and hence provide no material for independent analysis.

[1] BMS1, Research on Building Materials and Structures for Use in Low-Cost Housing. Price 10 cents. See cover page III.

[2] It recently was recommended at a meeting of the American Standards Association Subcommittee on Air Gaps, January 20, 1939, to discontinue the use of the word "cross-connection" in reference to plumbing systems and to substitute for it "backflow connections." This is to avoid any possibility of conflict with the water-works usage of the term "cross-connection," signifying a continuous enclosed connection between two water supplies, one of which is nonpotable.

[3] Figures in brackets indicate the literature references at the end of this paper.

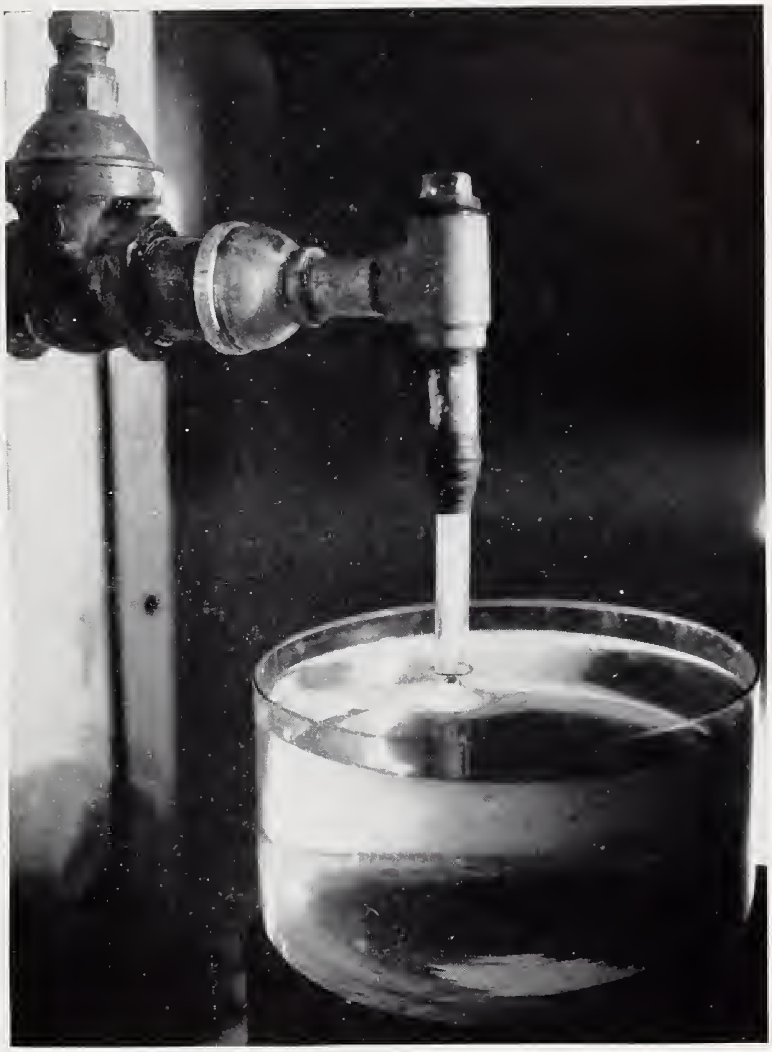


FIGURE 1.—*Backflow across air gap.*

It is noteworthy, however, that their conclusions agree substantially with those of Zinkil.

Neither Zinkil nor Dawson and Kalinske published any experimental data that definitely apply to passages, such as those formed by the interior of commercial faucets or definitely connect the conclusions in regard to tubes with any designated or readily measurable dimension of a faucet. Nor did they give complete information regarding the effects of the external diameter of tubes and faucets on the critical air gap.

III. PURPOSE AND SCOPE OF THE INVESTIGATION

The experiments reported in this paper were made to complete the data required to connect the existing data for tubes with the backflow characteristics and dimensions of faucets and other supply openings and to verify the conclusions previously drawn in regard to the critical air gap for faucets. The ultimate purpose is to enable a safe air gap to be specified in terms of some readily measurable dimension of the faucet itself.

IV. OUTLINE OF THE PROBLEM

1. Definition of Safe and Critical Air Gaps

Water can be lifted across a vertical air gap into the water-supply lines by atmospheric pressure, as illustrated in figure 1, when a partial vacuum exists in the supply system.

The *critical air gap*, Δh, will be defined as the minimum vertical distance across which backflow *cannot* be started by the effects of atmospheric pressure in combination with the vacuum in the tank. A safe air gap is any gap greater than the critical air gap, and the question of the proper margin of safety to be added to the critical air gap will be taken up in the discussion which follows the development of the formulas governing the air gap.

2. Statement of the General Problem

The ultimate purpose of this investigation is to determine the critical air gap, Δh, for supply openings in terms of the various factors which have an appreciable effect on it, and to reduce the resulting relation to a form such that the safe air gap can be determined readily in any particular case.

3. Factors Affecting the Critical Air Gap

The factors which conceivably may influence the critical air gap are

(a) Magnitude of the vacuum pressure in the supply system,
(b) Air backflow capacity of faucets,
(c) Dimensions and shape of the faucet spout,
(d) Position of the faucet spout with respect to nearby fixture walls,
(e) Temperature of the water in the fixture,
(f) Atmospheric conditions, and
(g) Physical characteristics of the liquid in the fixture.

4. Discussion of the Factors

As has been indicated, this paper is supplementary to the paper, Cross-connections in Plumbing Systems [1], in which more detailed demonstrations of some of the points in the ensuing discussion are presented. Hence, the results and conclusions given in that paper will be utilized in the present problem insofar as they are applicable and will be elaborated only to the extent necessary to make their application clear.

(*a*) *Magnitude of the Vacuum Pressure*

It has been demonstrated [1] that if air flows from the atmosphere through an opening into an evacuated system, the velocity of the air increases with decrease in the system pressure until some critical-pressure ratio is reached, after which any further decrease in the system pressure causes no sensible increase in the velocity of the air. The air velocity existing in the opening at this critical vacuum may be called the critical velocity and is equal to the velocity of sound in air under the conditions existing in the opening. As pressure waves for this type of flow can travel no faster than sound in air, it is obvious that the effect of any decrease in the system pressure below the critical cannot be felt upstream of the opening. This maximum backflow of air is attained at vacuum pressures of approximately half an atmosphere, and hence protection against a vacuum of 15 inches of mercury will protect any system from backflow when exposed to any possible vacuum.

(*b*) *Air Backflow Capacity of Faucets*

The capacity of a tube or faucet for the backflow of air obviously affects the critical air gap through the velocity of the air flowing into the end of the tube or faucet above the water surface. There are two resulting effects that exert an influence on the height through which water can be lifted to the tube or faucet opening: (1) If air is to flow into the opening, there must be a reduction in pressure below atmospheric pressure there, and this reduction causes the level of the water below the opening to rise somewhat; (2) the flow of air over the surface of the water toward the opening exerts a frictional drag on the water, so that a surface current is set up, moving radially inward to a point directly below the opening, tending to pile up the water at this point still further. Now, if the velocity of the air is great enough, and if the water surface is sufficiently close to the faucet opening, some of this water will be carried vertically upward into the opening and back into the system (see figs. 1 and 5). Obviously, the greater the velocity of backflow of air, the greater is the height through which the water can be lifted; that is, the greater is the critical air gap.

If we are dealing with the backflow of air through cylindrical tubes, the problem of expressing the backflow of air is relatively simple, since the quantity (or velocity) of flow can be expressed in terms of the internal diameter of the tube and other factors that have a smaller effect. However, with faucets the problem is not so simple. The passageway in a faucet is not a simple cylindrical passage of uniform diameter, but is a curved irregular passage with abrupt changes in section. Furthermore, the most restricted cross section, which may be expected to control the backflow, is not easily accessible to measurement and may vary greatly in different types of faucets.

Under these circumstances, the logical method of procedure appears to be to measure the air backflow capacity of the wide-open faucet when a pressure reduction of at least 15 inches of mercury exists between the free atmosphere and the system to which the faucet is attached. This air backflow capacity can then be expressed by assigning to the faucet an "equivalent diameter" equal to the diameter of some simple standard form of opening through which the same quantity of air will flow under the same pressure drop.

This was the procedure adopted in [1] for the measurement of air backflow capacity, and the reference standard adopted was a series of sharp-edged thin-plate orifices. The same reference standard will be used for faucets. The details of determining the equivalent diameters of faucets will be given in section V–3 of the paper.

(*c*) *Dimensions and Shape of the Faucet Spout*

The critical air gap will depend on the dimensions and shape of the faucet spout. As already noted in section II, Zinkil demonstrated that (1) the critical air gap for an elongated spout is the same as that for a circular spout of the same cross-sectional area, and that (2) for spout openings set at an angle up to 30° to the water surface, the mean air gap equals that for an opening of the same area parallel to the water surface.

It is obvious, that as elongation and inclination of the spout are carried beyond the limits of Zinkil's work, the effect will be to decrease the critical air gap, and hence no further consideration need be given these factors. However, the thickness of the wall at the end of the spout may be expected to increase the critical air gap as the wall thickness increases, and therefore it seemed desirable to supplement Zinkil's work by determining the effect of wall thickness on the air gap.

(*d*) *Position of the Faucet Spout with Respect to Nearby Fixture Walls*

The effect of position of the faucet spout with respect to nearby fixture walls was also studied by Zinkil. Using tubes, he determined (1) the effect on the critical air gap of a wall tangent to the outside of the tube and, (2) the distance from the inside edge of the tube at which the effect of the wall on the critical air gap becomes negligible. However, he published no data on the effect of two nearby walls or on the effect of walls at intermediate distances from the tube. Hence it was decided to determine the effect of these conditions on the critical air gap.

(*e*) *Temperature of the Water in the Fixture*

It has been commonly assumed previously that the temperature of the water in the fixture has a negligible effect on the critical air gap. It seemed desirable to verify this assumption.

(*f*) *Atmospheric Conditions*

It has also been assumed heretofore that variations in atmospheric conditions have no appreciable effect on the critical air gap. This is not strictly true, as the analysis in section IV–3–a of reference [1] leads to an equation containing a term representing the height of a hypothetical air column, h_a, and attention is called there to the fact that h_a varies with temperature and humidity. The effect of these factors on the air gap may be expected to be comparatively small. However, the quantitative effect of variation in h_a will be investigated later on in this paper.

(*g*) *Characteristics of the Liquid in the Fixture*

It seemed desirable to determine the effect on the critical air gap of various liquids in the fixture in order to insure that due consideration be given to the liquid characteristics density, viscosity, and surface tension.

5. Statement of the Specific Problem and Method of Approach

The specific problem now is to determine the critical air gap for faucets, when the pressure reduction across them is at least 15 inches of mercury (critical vacuum), in terms of their air backflow capacity (determined by their equivalent diameters), their spout dimensions (outside diameters), their position with respect to nearby fixture walls, and atmospheric conditions.

The method of approach to the problem was to find first a convenient empirical form of a modification of the general equation for tubes as given in the earlier paper [1]:

$$\Delta h/d = \text{function } (d/D_1,\ d/h_a), \tag{1}$$

where

Δh = the critical air gap,

d = the internal diameter of the tube,

D_1 = the external diameter of the tube,

h_a = the height of a hypothetical air column of uniform density exerting at its base a pressure equal to that of the atmosphere.[4]

which takes into account the effects of the external diameter of the tubes and of atmospheric conditions. A systematic series of experiments to determine the effects of the various factors was made on tubes rather than on faucets, because it was simpler to make up a series of tubes of various internal and external diameters to cover the desired range of conditions than to obtain a suitable series of faucets.

Actually, since the internal spout diameter of a faucet is meaningless in this connection, as explained earlier, eq 1 was written in the form

$$\Delta h/d_e = \text{function } (d_e/D_1,\ d_e/h_a), \tag{2}$$

where d_e is the equivalent diameter of a sharp-edged thin-plate orifice, having the same air backflow capacity as the faucet.

[4] $h_a = P_a/\rho_a$, where P_a is the barometric pressure in pounds per square foot, and ρ_a is the density of the air at pressure P_a in pounds mass per cubic foot. Now, since ρ_a varies directly with P_a, the ratio P_a/ρ_a will remain constant unless the value of ρ_a is changed independently of P_a by changes in temperature and humidity from the assumed values. Figure 3 shows the variation of h_a with temperature for dry and moist air. The data on which figure 3 is based may be obtained from the Smithsonian Physical Tables or from the Handbook of Chemistry and Physics, Chemical Rubber Publishing Co., Cleveland, Ohio.

Following this, the critical air gaps and equivalent diameters were measured experimentally for the faucets, and the resulting values were substituted in the empirical equation obtained for the tubes to ascertain whether the same equation applied with reasonable accuracy to the faucets. This was found to be the case.

Finally, data were obtained on the effect of adjacent walls on the critical air gaps for a representative tube and it was assumed that the effect on faucets would be quantitatively the same.

V. EXPERIMENTAL PROCEDURE

1. Experimental Apparatus

The apparatus used in all of the tests consisted of two interconnected 318-gallon tanks which could be used singly or together, a vacuum pump for evacuating the tanks, and a mercury manometer for measuring the pressure in the tanks. For determining the air-flow characterictics of the thin-plate orifices used as reference standards, and of the tubes and faucets, each device in turn was connected to the evacuated tank, and the rate of rise of pressure in the tank was measured.

For measuring the critical air gaps for the tubes and faucets, a 12-inch glass jar 6 inches deep was used to represent the flooded fixture. See figure 5.

2. Devices Tested

(a) *Orifices*

For use as a reference standard; that is, as a basis for assigning equivalent diameters to tubes and faucets, a series of thin-plate orifices was constructed and tested to determine their air-flow characteristics. The orifice diameters used were 1/16, 1/8, 1/4, 3/8, 1/2, and 3/4 inch, and in no instance did the thickness of orifice plate exceed one-half the diameter of the orifice.

(b) *Tubes*

The dimensions of the tubes tested are given in table 1. The tubes used consisted of two

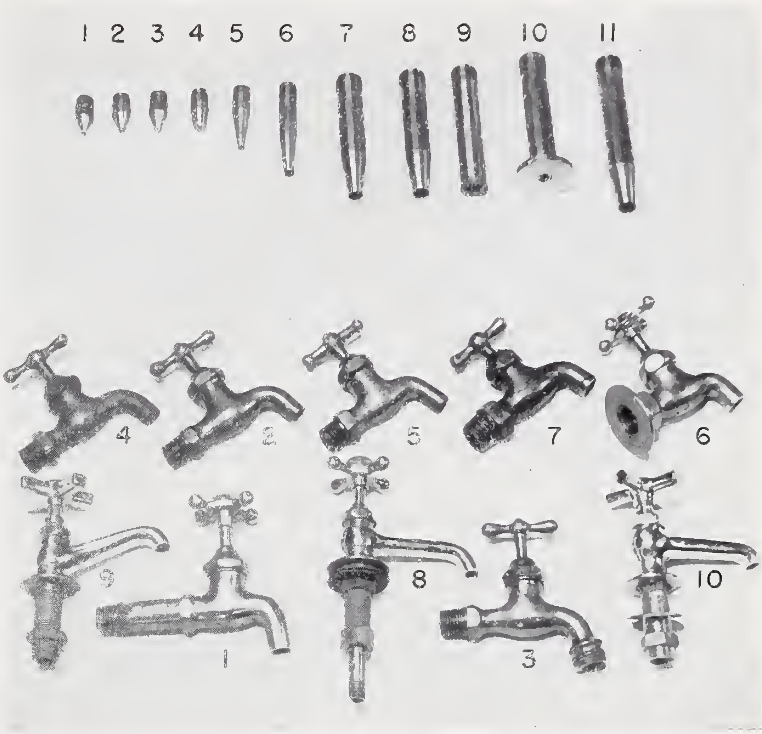
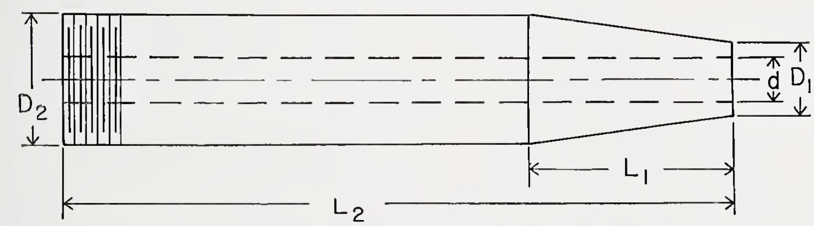


FIGURE 2.—*Tubes and faucets used.*

groups of four, each group having a given nominal internal diameter, 0.25 and 0.50 inch, respectively, but having the external diameter varied within each group to give a series of values of the ratio of internal to external diameter. There are also three additional sharp-edged tubes, making eleven in all. See figure 2.

TABLE 1.—*Tubes for air-gap determination*



Tube Number	d	D_1	d/D_1	D_2	L_1	L_2	Pipe thread
	in.	*in.*	*in.*	*in.*	*in.*	*in.*	
1	0.125	0.125	1.00	.625	0.50	1.50	3/8
2	.125	.160	0.78	.625	.50	1.50	3/8
3	.125	.250	.50	.625	.50	1.50	3/8
4	.125	.500	.25	.625	.50	1.50	3/8
5	.250	.250	1.00	.625	1.56	2.56	3/8
6	.375	.375	1.00	.625	1.50	3.81	3/8
7	.500	.500	1.00	1.000	1.50	5.00	3/4
8	.500	.666	0.75	1.000	0.00	5.00	3/4
9	.500	1.000	.50	1.000	.00	5.00	3/4
10	.500	2.000	.25	1.000	(a)	5.00	3/4
11	0.625	0.625	1.00	1.000	1.50	6.31	3/4

a 2-inch plate soldered on end of tube.

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Viewed from another angle, it is apparent that the five sharp-edged tubes form a geometrically similar series, and the three remaining pairs, having equal diameter ratios, form similar series from which results for tubes of intermediate diameters can be obtained by virtue of the principle of dynamical similarity. See figure 6. Such an arrangement allows investigation of the effects of variation in internal and external diameter with a minimum number of tubes.

(c) *Faucets*

A group of 10 faucets, as illustrated in figure 2 and described in table 6, was used in the investigation.

3. Determination of Equivalent Diameters of Tubes and Faucets

The following equation was developed in the earlier publication [1] for expressing the air backflow characteristics of orifices and other devices in terms of the rate of change of pressure in the evacuated tank to which the devices were attached.

$$\frac{P_r}{P_a}=r=C\frac{\pi}{4}\sqrt{\frac{2k}{k-1}\left(\frac{P_c}{P_a}\right)^{2/k}\left[1-\left(\frac{P_c}{P_a}\right)^{\frac{k-1}{k}}\right]}\cdot\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0, \tag{3}$$

where

- C=the coefficient of discharge of the device;
- k=the ratio of the specific heat of the air at constant volume to that at constant pressure: in this case k may be taken equal to 1.4;
- P_a=atmospheric pressure;
- P_c=pressure in the evacuated tank corresponding to the critical-pressure ratio, r_c;
- d=diameter of the device being tested;
- g=acceleration of gravity;
- h_a=height of a hypothetical atmosphere of uniform density, ρ_a, exerting the pressure, P_a, at its base;
- V_r=volume of the evacuated tank;
- $r=P_r/P_a$, where P_r is the absolute pressure in the tank;
- t_0=time in seconds for the pressure in the tank to rise from zero to P_r.

When one of the orifices is mounted on an evacuated tank of volume, V_r, and measurements of time, tank pressure, and atmospheric temperature and humidity are taken, as air is allowed to flow through the orifice into the tank, the necessary data are obtained to plot $\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0$ against r. The proper value of h_a can be obtained from figure 3.

Table 2 contains the data for three representative sharp-edged plate orifices. The values of r from table 2, when plotted against $\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0$, give the curve of figure 4. This curve, using a self-consistent system of units, may be expressed for values of r less than 0.6 as

$$r=0.5\,\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0. \tag{4}$$

Table 2.—*Representative data for thin-plate orifices*

[V_r=42.5 cubic feet]

t	Δt	$t_0=t+\Delta t$	$\frac{d^2\sqrt{gh_a}}{V_r}.t_0$	r
Orifice 8. d=0.0416 foot (0.50 inch); thickness=0.250 inch.				
sec	*sec*	*sec*		
0.0	5.1	5.1	0.199	0.10
5.0	5.1	10.1	.394	.20
10.0	5.1	15.1	.588	.30
15.2	5.1	20.3	.791	.40
20.4	5.1	25.5	.994	.50
25.4	5.1	30.5	1.189	.60
31.2	5.1	36.3	1.415	.70
38.0	5.1	43.1	1.680	.80
46.0	5.1	51.1	1.991	.90
100.0	5.1	105.1	4.096	1.00
Orifice 9. d=0.0416 foot (0.500 inch); thickness=0.125 inch.				
0.0	5.0	5.0	0.195	0.10
5.0	5.0	10.0	.390	.20
10.0	5.0	15.0	.585	.30
15.2	5.0	20.2	.787	.40
20.2	5.0	25.2	.982	.50
26.0	5.0	31.0	1.216	.60
32.2	5.0	37.2	1.450	.70
39.8	5.0	44.8	1.746	.80
49.0	5.0	54.0	2.104	.90
95.0	5.0	100.0	3.897	1.00
Orifice 12. d=0.0208 foot (0.25 inch); thickness=0.125 inch.				
0.0	20.5	20.5	0.200	0.10
20.0	20.5	40.9	.399	.20
41.0	20.5	61.5	.599	.30
61.8	20.5	82.3	.802	.40
82.2	20.5	102.7	1.000	.50
103.2	20.5	123.7	1.205	.60
126.0	20.5	146.5	1.427	.70
152.4	20.5	172.9	1.685	.80
186.0	20.5	206.5	2.012	.90
300.0	20.5	320.5	3.121	1.00

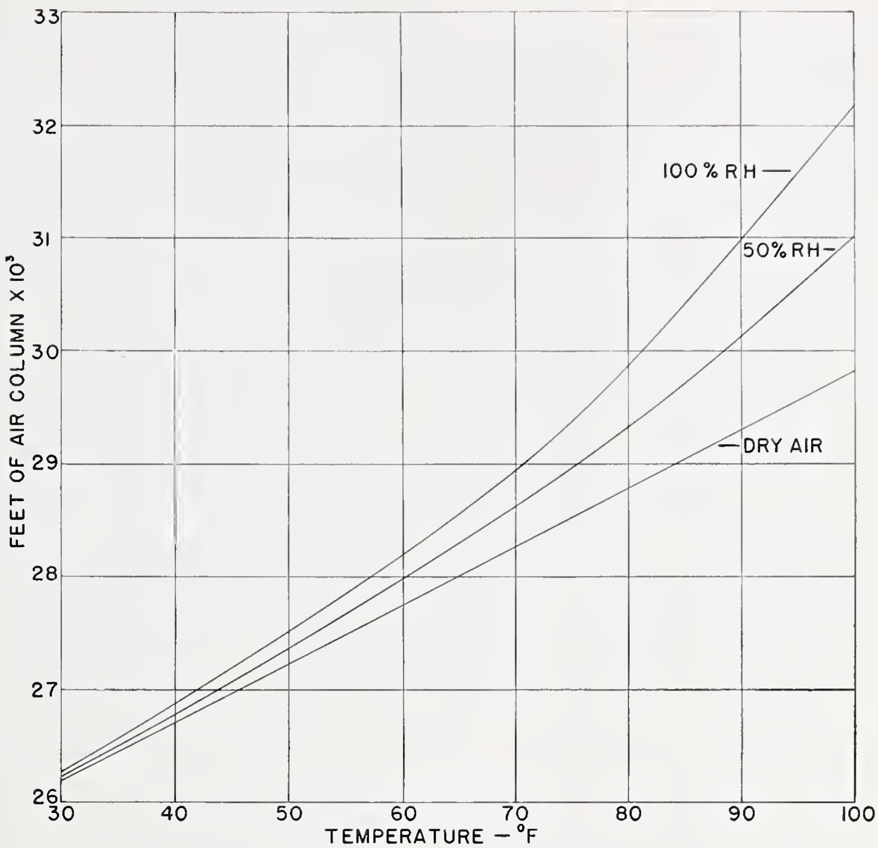


FIGURE 3.—*Values of h_a for various temperatures and for two relative humidities.*

h_a, atmospheric pressure in feet of air.

Equation 4 is based on an atmospheric temperature of 65° F and a relative humidity of 50 percent, which represent the laboratory conditions during the tests. This gives a reasonable working curve for domestic applications and may be used with fair accuracy for any determination of d_e in which the atmospheric conditions are not known. However, if the atmospheric conditions vary appreciably from those stated above, the appropriate value of h_a can be obtained from figure 3, interpolating, if necessary, for the existing humidity.

In this investigation the capacity for backflow of air through any device, such as a tube or faucet, in terms of the diameter of an orifice geometrically similar to the reference orifices, was determined in the following manner. The device was mounted on the evacuated tank and measurements taken in the same way as for the orifices. If the curve of figure 4 is now entered for any value of $r<0.6$, for which t_0 is known, a value of d can be determined. This value of d may be called the "equivalent diameter", d_e, of the tube or faucet and represents the diameter of an orifice geometrically similar to the reference orifices which has an air backflow capacity equal to that of the device.

TABLE 3.—*Representative data for tubes*

	t	Δt	$t_0=t+\Delta t$	$\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0$	d_e	r
Tube 1.—V_r=42.5 cubic feet						
	sec.	*sec.*	*sec.*		*in.*	
	0.0	93.1	93.1	0.200	0.1175	0.10
	91.8	93.1	184.9	.400	.1178	.20
	191.6	93.1	284.7	.600	.1165	.30
	280.6	93.1	373.7	.800	.1173	.40
	374.4	93.1	467.5	1.000	.1173	.50
Average					0.117	
Tube 5.—V_r=42.5 cubic feet						
	0.0	22.6	22.6	0.200	0.2382	0.10
	22.4	22.6	45.0	.400	.2388	.20
	45.0	22.6	67.6	.600	.2386	.30
	67.1	22.6	89.7	.800	.2392	.40
	90.0	22.6	112.6	1.000	.2386	.50
Average					0.239	
Tube 10.—V_r=88.8 cubic feet						
	0.0	11.6	11.6	0.200	0.4724	0.10
	12.0	11.6	23.6	.400	.4724	.20
	24.0	11.6	35.6	.600	.4724	.30
	36.0	11.6	47.6	.800	.4724	.40
	47.2	11.6	48.8	1.000	.4724	.50
Average					0.472	

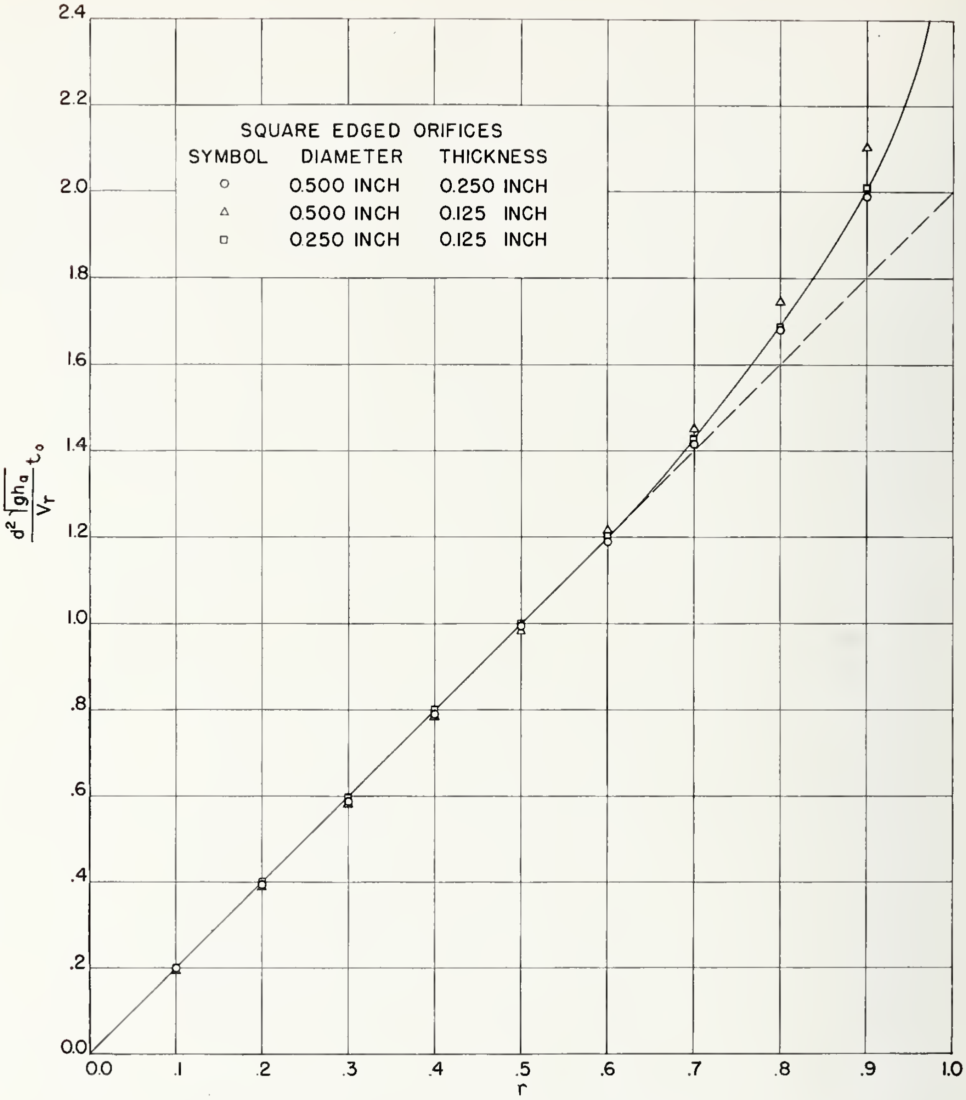


FIGURE 4.—*Pressure ratio, P_r/P_a, plotted against* $\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0$ *for orifice plate.*

d, orifice diameter; *g*, acceleration of gravity; h_a, atmospheric pressure in feet of air; V_r, volume of the evacuated system; and t_0, time of flow for pressure in evacuated system to rise from 0 to pressure at time t_0.

Representative data for three tubes and three faucets are given in tables 3 and 4, respectively.

This procedure was followed for all of the tubes, and the average values of d_e, each determined from several readings, are tabulated in table 5. The same procedure, when applied to the faucets shown in figure 2, gave the values of d_e tabulated in table 6.

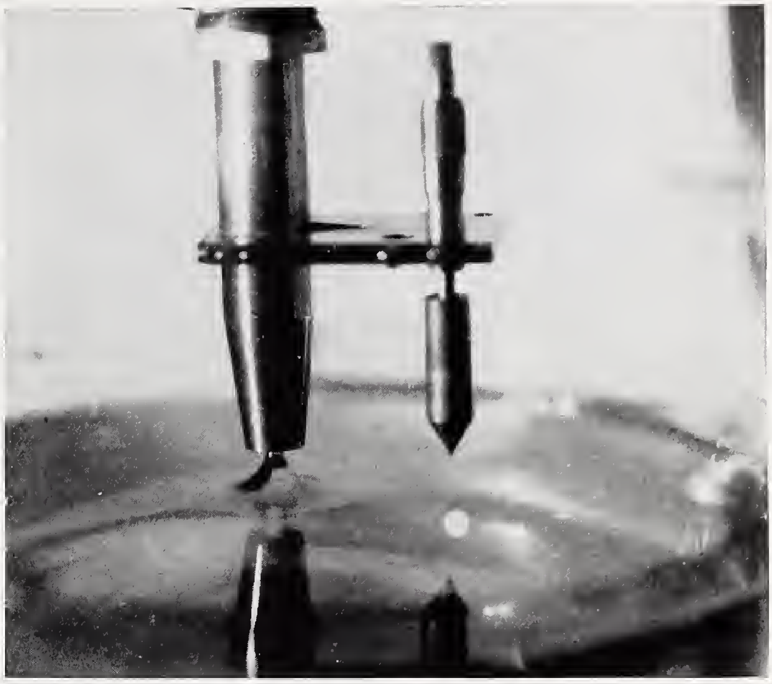


FIGURE 5.—*Backflow across air gap into tube.*

TABLE 4.—*Representative data for faucets*

[V_r=42.5 cubic feet]

Faucet number	t	Δt	$t_0=t+\Delta t$	$\frac{d^2\sqrt{gh_a}}{V_r}\cdot t_0$	d_e	r
	sec	*sec*	*sec*		*in.*	
1	0.0	9.6	9.6	0.200	0.3654	0.10
	9.7	9.6	19.3	.400	.3647	.20
	19.1	9.6	28.7	.600	.3661	.30
	28.8	9.6	38.4	.800	.3654	.40
	38.3	9.6	47.9	1.000	.3660	.50
Average					.366	
3	0.0	9.5	9.5	0.200	0.3675	0.10
	9.3	9.5	18.8	.400	.3695	.20
	18.7	9.5	28 2	.600	.3695	.30
	28.1	9.5	37.6	.800	.3695	.40
	37.5	9.5	42.0	1.000	.3695	.50
Average					0.369	
9	0.0	13.9	13.9	0.200	0.302	0.10
	14.0	13.9	27.9	.400	.302	.20
	28.5	13.9	42.4	.600	.302	.30
	42.0	13.9	55.9	.800	.302	.40
	56.1	13.9	70.0	1.000	.302	.50
Average					.302	

TABLE 5.—*Equivalent diameters and critical air gaps for tubes*

Tube number	d	D_1	d_e	Δh	d_e/D_1
	in.	*in.*	*in.*	*in.*	*in.*
1	0.125	0.125	0.117	0.239	0.939
2	.125	.160	.116	.244	.724
3	.125	.250	.116	.257	.463
4	.125	.500	.116	.277	.232
5	.250	.250	.239	.412	.955
6	.375	.375	.358	.589	.955
7	.500	.500	.481	.789	.962
8	.500	.666	.478	.811	.719
9	.500	1.000	.477	.843	.477
10	.500	2.000	.472	.910	.236
11	.625	.625	.583	.935	.932

TABLE 6.—*Equivalent diameters and critical air gaps for faucets*

Faucet number	d	D_1	d_e	Δh [a] measured
	in.	*in.*	*in.*	*in.*
1	0.512	0.695	0.366	0.625
2	.500	.628	.321	.543
3	.587	.950	.369	.657
4	.460	.640	.368	.620
5	.485	.640	.360	.619
6	.600	.775	.395	.656
7	.600	.775	.390	.656
8	.400	.613	.314	.539
9	.542	.986	.302	.578
10	.375	.586	.286	.531

[a] For faucets 5, 6, 8, 9, 10—read with plain rule, precision about 1/64 inch=0.015 inch, approximately.

4. MEASUREMENT OF CRITICAL AIR GAPS

In order to measure the critical air gaps of the tubes and faucets each was mounted in turn on the vacuum tank directly above the glass jar, as illustrated in figure 5, in which tube 8 is shown during the process of backflow. The micrometer point gage used for measuring the gap is shown mounted on the tube.

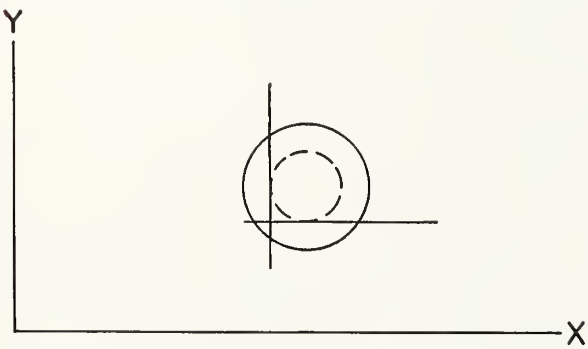
The average of several determinations of the critical air gap for 11 of the tubes is tabulated as Δh in table 5. The critical gaps were determined in the following manner: Starting with the water surface within the distance Δh of the end of the tube, a vacuum in excess of 15 inches of mercury was applied and maintained. As the air gap approached its maximum value the flow became intermittent, and small waves appeared on the water surface. When this occurred, the valve was closed and the surface allowed to become quiet, then the quick-acting valve was opened slowly and backflow allowed to resume. This was done several times for each determination; and the first gap reached, across which no visible amount of water could be drawn after slowly closing and reopening the valve, was called the critical air gap.

The measurement of the critical air gap for the faucets proceeded along the same lines, the faucet being wide open when the air gap was created. It was not feasible to mount the micrometer gage on faucets 5, 6, 8, 9, and 10, and hence the critical air gap was measured for these faucets by means of a scale reading in sixty-fourths of an inch. The average of several readings on each faucet is tabulated under Δh in table 6.

5. Effect of Water Temperature on Critical Air Gaps

In order to determine the effect on the critical air gap of variations in the temperature of the water in the fixture, a series of air-gap measurements was made for tube 8 with water temperatures between 40° and 196° F. No measurable effect of water temperature on the critical air gap was found.

Table 7.—*Effect of nearby walls on critical air gaps*



Case 1 Touching one wall				Case 2 Moving away from one wall				Case 3 Moving away from two walls			
x	y	$\Delta h'$	$\Delta\%$	x	y	$\Delta h'$	$\Delta\%$	x	y	$\Delta h'$	$\Delta\%$
in.	*in.*	*in.*		*in.*	*in.*	*in.*		*in.*	*in.*	*in.*	
∞	∞	0.817	0.0	∞	∞	0.817	0.0	∞	∞	0.817	0.0
0.25	0.25	1.259	54.0	∞	0.25	.968	18.5	0.25	0.25	1.259	54.0
.50	.25	1.132	38.5	∞	.50	.980	20.0	.75	.75	1.094	34.0
.75	.25	1.062	30.0	∞	.75	1.079	32.0	1.25	1.25	1.155	44.0
1.75	.25	0.970	18.7	∞	1.25	0.897	9.8	1.75	1.75	1.066	35.0
4.75	.25	.968	18.5	∞	1.75	.844	3.3	2.25	2.25	0.827	1.2

6. Effect of Adjacent Walls

The effect of one or two nearby walls was determined for one tube, No. 9, by placing it at various positions with respect to two walls at right angles to each other and measuring the critical air gap. These data are presented in table 7, in which $\Delta h'$ is the critical air gap when influenced by nearby walls and $\Delta\%$ is the percentage increase over the critical air gap Δh.

7. Effect of Different Liquids on the Critical Air Gap

The effect on the critical air gap was determined for dust-covered water, soapy water, sugar solution, lubricating oil, and gasoline. The results are tabulated in table 8.

Table 8.—*Effect of different liquids on critical air gaps as determined for pure water, with tube 6*

Liquid	Difference in Δh from that for pure water	Change in Δh compared with that for pure water
	in.	*Percent*
Water	0.000	0.0
Water covered with sawdust	+.002	+.4
Water covered with aluminum powder	+.004	+.8
Water covered with cork dust	+.001	+.2
Soap solution	+.019	+3.3
Soapy water	+.018	+3.2
Sugar solution	−.025	−4.7
Lubricating oil (SAE 30)	+.010	+1.8
Gasoline	+.049	+8.7

VI. ANALYSIS OF EXPERIMENTAL DATA

1. Empirical Equation for the Critical Air Gap for Tubes

In order to get a consistent expression for the critical air gap, the data given in table 5 for the series of tubes will be considered. Plotting Δh versus d_e/D_1 from table 5 on logarithmic paper, as shown in figure 6, results in two parallel straight lines through the points for the tubes having internal diameters of 0.125 inch and 0.500 inch. Because the sharp-edged tubes may be considered geometrically similar, it is permissible to draw lines through the points obtained for the tubes 0.250, 0.375, and 0.625 inch in diameter parallel to those through the points for the tubes having internal diameters of 0.125 inch and 0.500 inch. These lines represent the curves which would be

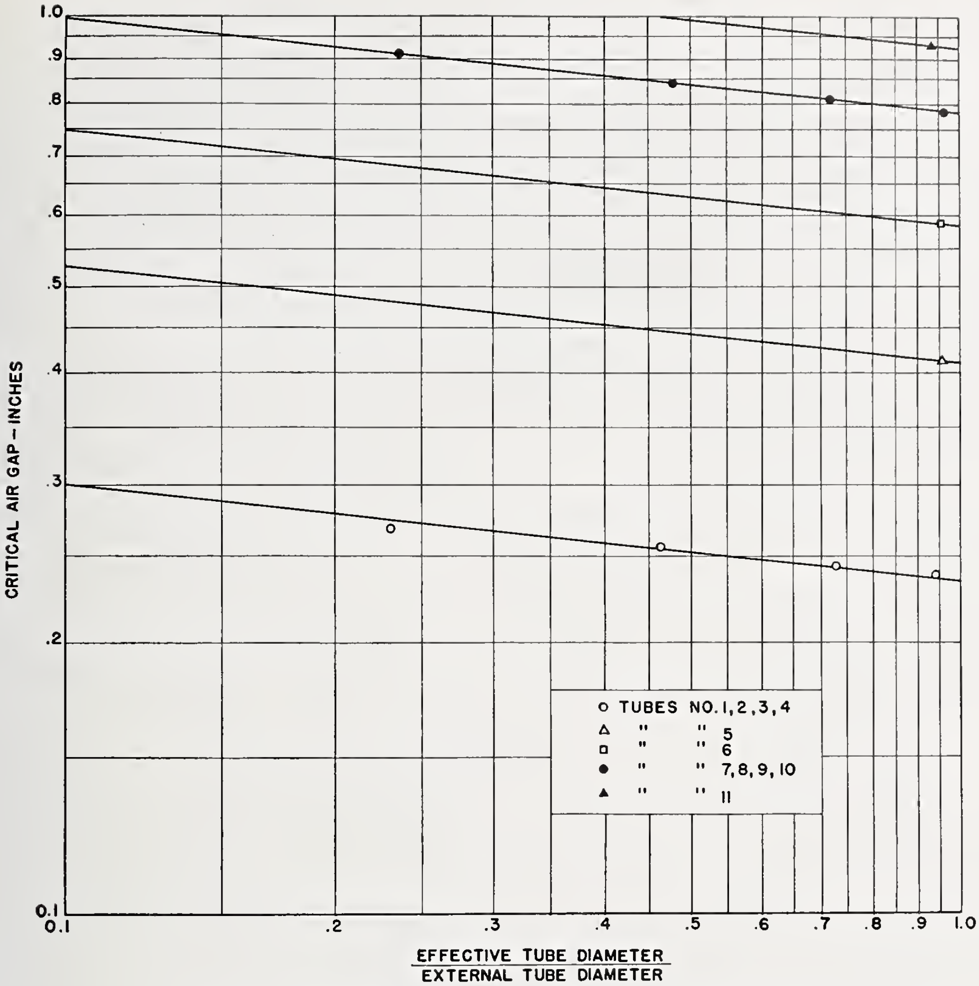


FIGURE 6.—*Diameter ratio, d_e/D_1, plotted against Δh for tubes.*

d_e, "equivalent diameter" of tubes; D_1, external diameter of tube spout; and Δh, critical air gap.

found from a series of tubes of the same internal diameter as the sharp-edged tubes.

This family of curves gives a series of similar expressions which may be expressed approximately by

$$\Delta h = C\left(\frac{d_e}{D_1}\right)^{-0.1}, \tag{5}$$

in which the coefficient C varies with d_e. Equation 5 includes the effect of the external diameter, D_1, on the critical air gap, whereas the effect of atmospheric conditions is hidden in the coefficient C and must be brought out in explicit form by a further consideration of the general eq 3.

In table 9 are listed the values of C found from figure 5 for each of the five measured values of the average effective diameter of the tubes

TABLE 9.—*Air-gap coefficients for tubes*

Internal diameter, d	Average effective diameter, d_e	Coefficient, C
in.	*in.*	*in.*
0.125	0.116	0.236
.250	.240	.411
.375	.358	.585
.500	.477	.786
.625	.583	.929

Over at least a limited range of values of the variables d_e/D_1 and d_e/h_a, eq 3 can be expressed as

$$\frac{\Delta h}{d_e} = c(d_e/D_1)^x (d_e/h_a)^y, \tag{6}$$

where c, x, and y are constants, and x has already been found approximately equal to -0.1.

Comparing eq 6 with eq 5, it is obvious that

$$C = cd_e(d_e/h_a)^y, \tag{7a}$$

or

$$C = [c/(h_a)^y]d_e^{1+y}, \tag{7b}$$

where $c/(h_a)^y$ is a numerical constant for given atmospheric conditions.

Upon plotting logarithmically the values of C from table 9 against the corresponding average values of d_e for each size of tube as given in table 5, it is found that the results can be represented closely, for the tubes larger than 0.125 inch, by the empirical equation

$$C = 1.50d_e^{0.9}, \tag{8}$$

where C and d_e are in inches, so that $y = -0.1$.

Equation 7b shows that the numerical factor is proportional to $1/h_a^y$; i. e., to $h_a^{+0.1}$. Hence by designating by h_{a_0} the value of h_a for which the value 1.50 was obtained, the effect of varying h_a may be made explicit by writing

$$C = 1.50\left(\frac{h_a}{h_{a_0}}\right)^{+0.1} d_e^{0.9}, \tag{9}$$

or since under the conditions of test, $h_{a_0} = 28{,}300$ feet,

$$C = 0.538h_a^{+0.1}d_e^{0.9},$$

in which C and d_e are in inches and h_a is in feet.

Equation 6 by substitution becomes

$$\frac{\Delta h}{d_e} = 0.538h_a^{+0.1}\left(\frac{d_e^2}{D_1}\right)^{-0.1}, \tag{10}$$

which is the general formula for the critical air gap for tubes, in which it is understood that all quantities are in inches except h_a, which is in feet.

The variation in value of $(h_a)^{0.1}$ for a considerable range in atmospheric temperature is given in table 10, and it is obvious that its effect on eq 10 will be small; hence, if the average value is used, eq 10 may be simplified, for practical purposes, to read

$$\frac{\Delta h}{d_e} = 1.50\left(\frac{D_1}{d_e^2}\right)^{0.1}, \tag{11}$$

or

$$\Delta h = 1.50d_e^{0.8}D_1^{0.1}, \tag{12}$$

for dimensions in inches.

The data for the tubes are plotted in figure 7 with $\Delta h/d_e$ versus D_1/d_e^2. It should be noted that for the tubes smaller than 0.250-inch diameter there is an increase in the measured air gap of 7.5 percent over eq 12. It is probable that the increase is due to the larger proportional effect on the air gap for small tubes of the ripples on the water surface caused by the intermittent backflow of water which occurs as the critical value is approached.

TABLE 10.—*Effect of temperature on h_a*

Temperature	Relative humidity	h_a	$(h_a)^{0.1}$	Deviation in $(h_a)^{0.1}$ from value at 65° F
°F	*Percent*	*Feet*	*(Feet)* $^{0.1}$	*Percent*
32	50	26,300	2.767	−0.6
65	50	28,300	2.787	.0
100	50	30,600	2.808	+.7

2. Application of Air-Gap Equation to Faucets

It is now possible to compare the performance of the faucets with that of the tubes by plotting the experimental results for the faucets from table 6 in figure 7. It can be seen that the faucet data are in fair agreement with the equation found for the tubes, deviations being small and on the safe side. From this it may be concluded that eq 11 or 12 can be used for determining the critical air gap for faucets with fair accuracy and complete safety.

3. Effect of Adjacent Walls

Consideration of table 7 shows that the critical air gap does not vary in a uniform manner as the tube is moved away from the wall or walls. This is due to the fact that when the tube is at a small distance from the walls; e. g., 0.75 inch in cases 2 and 3, the small waves caused by the intermittent backflow, as the limiting value of the critical air gap is approached, are reflected from the nearby walls and tend to increase the height of the waves under the tube spout. This is made apparent by a considerable increase in the agitation of the water surface with accompanying increase in noise as small particles of water are drawn up from the higher wave crests. As a conse-

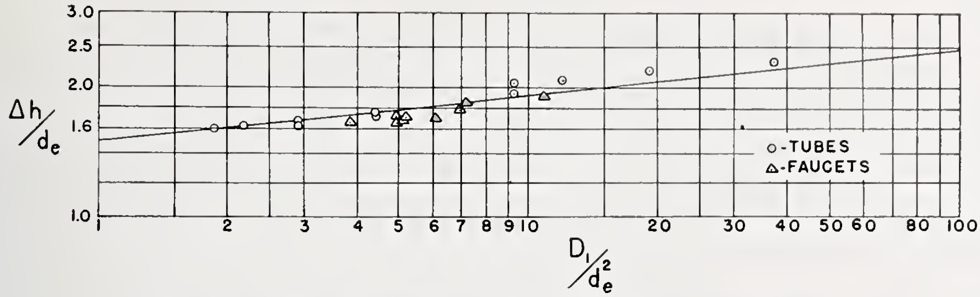


FIGURE 7.—$\Delta h/d_e$ *plotted against* $d_e{}^2/D_1$ *for tubes and faucets.*

d_e, equivalent diameter; D_1, external spout diameter; and Δh, critical air gap.

quence, it seems that the most practical way of taking account of the presence of nearby walls is arbitrarily to increase the critical air gap, Δh, for no walls as follows:

Position of spout with respect to nearby walls		*Upper limit of critical air gap*
1 wall	$x<3d_e$	$1.3\Delta h$.
	$x>3d_e$	$1.0\Delta h$.
2 walls	x and $y<4d_e$	$1.5\Delta h$.
	x or $y<4d_e$	$1.3\Delta h$.
	x and $y>4d_e$	$1.0\Delta h$.

Values of x and y, as indicated in table 7.

VII. PRACTICAL APPLICATION OF RESULTS

It is now possible to express the critical air gap for a faucet in terms of its tip dimensions and equivalent diameter. The quantitative effect of nearby walls has also been demonstrated.

It is obvious that eq 12 is not in a form suitable for use in field inspection. However, for practical purposes it may be simplified by writing it in the following form:

$$\Delta h = 1.50 d_e^{0.8}(d_e+2T)^{0.1} \qquad (13)$$

or

$$\Delta h = 1.50 d_e^{0.9}(1+a)^{0.1} \qquad (14)$$

where

$$T=\frac{D_1-d_e}{2}=\text{effective wall thickness and}$$

$$a=\frac{2T}{d_e}$$

Table 11 has been prepared to show the percentage increase in Δh for various values of a as the ratio of effective wall thickness to equivalent diameter increases.

TABLE 11.—*Effect of the ratio of effective wall thickness to equivalent diameter on critical air gap*

$a=\frac{2T}{d_e}$	$(1+a)^{0.1}$	Increase in Δh
		Percent
0	1.0	0.0
0.1	1.010	1.0
.2	1.018	1.8
.3	1.027	2.7
.4	1.034	3.4
.5	1.041	4.1
.6	1.048	4.8
.7	1.054	5.4
.8	1.061	6.1
.9	1.066	6.6
1.0	1.072	7.2
1.25	1.084	8.4
1.50	1.096	9.6
2.00	1.116	11.6
3.00	1.149	14.9

It is evident on inspection of the table that the percentage increase in Δh is slight as the wall thickness increases, and if reference is made to a faucet of representative dimensions, No. 10, table 6, a simple computation will show that the wall thickness could be increased by more than half an inch before the critical air gap would increase 10 percent. This being true, it is possible to conclude that, if a suitable amount is added to the critical air gap to form the safe air gap, consideration of the effect of wall thickness can be safely omitted in the vast majority of cases. However, if it is desired to calculate the effect of wall thickness on the critical air gap, this may be accomplished by means of table 11. If the factor in parentheses is assumed equal to 1, eq 14 becomes

$$\Delta h = 1.50 d_e^{0.9} \qquad (15)$$

It is obvious that when d_e is less than 1 inch, which is usually the case for plumbing fixtures, Δh will be greater than $1.50d_e$. For small values of d_e, such as 0.125 inch, the value of $\Delta h = 2d_e$ is closely approached for thin-walled spouts. Hence, for use in field inspection, it seems that a safe limit will be $H=2d_e$, where H represents the required air gap and is the vertical distance between the horizontal plane of the rim of the fixture and a horizontal plane through the center of the faucet spout.

It is evident in table 8 that the changes caused in Δh by variation in the physical characteristics of the liquid in the fixture are negligible, when compared to the margin of safety listed in conclusion 10. Hence, it is reasonable to conclude that for practical installation purposes no additional allowance need be made for liquids other than water.

The necessity for laboratory determinations of d_e may be avoided by using, instead of d_e, the diameter of the smallest clear passage in the faucet. This dimension, which is called the "effective diameter" in the report of the American Standards Association Sub Committee on Air Gaps, January 20, 1939, will be slightly larger than d_e and hence will introduce a small additional factor of safety.

Practical considerations of construction and inspection make it desirable to set a minimum limit to the value of the safe air gap in practice. This is a purely arbitrary value that must be based on practical experience and supported by the consensus of opinion. It has been recommended to the American Standards Association by its committee on air gaps that this lower limit be set at 1 inch. To date there has been no criticism of this value, and for the purpose of this paper it will be accepted. If this be done, it immediately becomes apparent that if the required air gap, H, be specified as equal to $2d_e$, with H never less than 1 inch, a factor of safety is introduced which is of reasonable magnitude. Furthermore, this factor of safety is sufficient to take care of nearly all variations in the wall thickness of the faucet spout or of any increase in Δh above $2d_e$ in the small-diameter openings.

VIII. CONCLUSIONS

1. A working value of the equivalent diameter, d_e, of a faucet (i. e., the diameter of the reference orifice which has an air backflow capacity equal to that of the faucet) may be obtained by using the diameter of the smallest clear passage between the faucet spout and its tailpiece.

2. Within commercial limits of variation the elongation of faucet spouts and their angle of inclination to the water surface has no effect on the mean value of the critical air gap.

3. The critical air gap may be determined for any faucet when there is no wall effect by means of the relation

$$\frac{\Delta h}{d_e}=0.538h_a^{0.1}(d_e^2/D_1)^{-0.1}, \tag{10}$$

in which

Δh = the critical air gap in inches
h_a = atmospheric pressure in feet of air
d_e = the equivalent diameter in inches
D_1 = the external diameter in inches

4. Normal variations in atmospheric conditions may be expected to introduce an effect in eq 10 of less than 1 percent.

5. Commercial variations in the effective wall thickness for faucets, $(D_1-d_e)/^2$, may be expected to introduce an effect in eq 10 that is less than 10 percent.

6. Equation 10, rewritten in the approximate form $\Delta h = 1.50\ d_e^{0.9}$, is sufficiently accurate for most purposes.

7. Practical considerations of construction and inspection require that a minimum value be set for the required air gap; it is suggested that the minimum value be 1 inch.

8. The foregoing conclusions allow the statement that safety may be attained economically, when there are no walls closer than $4d_e$, by specifying the air gap as not less than $2d_e$.

9. Safety may be obtained when there is a wall effect by specifying that: If one or two walls extending *above the rim of the fixture* or vessel are within the horizontal distance four times d_e measured from the nearest internal

wall of the spout, the air gap shall be not less than $3d_e$.

10. For purposes of regulation and inspection, safe air gaps for lavatory faucets and other faucets which have no nearby walls closer than $4d_e$ may be specified as follows:

	Minimum additional margin of safety, from eq 15 (Inches)	*Required air gap H (Inches)*
Diameter of smallest clear passage between spout and tailpiece—		
up to and including ½ inch	0.20	1
from ½ inch to and including ¾ inch	.34	1½
from ¾ inch to and including 1 inch	.50	2
greater than 1 inch	(1)	(2)

[1] Increasingly greater than 0.50 inch.
[2] Two times effective diameter inches.

11. Variations in the characteristics of the liquid in the fixture may be expected to cause an increase in Δh which is considerably less than the margin of safety listed in conclusion 10.

Acknowledgment is made to G. H. Keulegan of the National Hydraulic Laboratory staff for helpful suggestions in outlining the experimental procedure followed in the investigation; and to H. N. Eaton, Chief of the Hydraulic Section of the National Bureau of Standards for a critical reading of the paper and valuable suggestions as to the form of presentation of results.

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