Frost Closure of Roof Vents in Plumbing Systems

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Frost Closure of Roof Vents in Plumbing Systems

Herbert N. Eaton and Robert S. Wyly

Building Materials and Structures Report 142

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Foreword

For several years the National Bureau of Standards conducted for the Housing and Home Finance Agency of the Federal Government a series of investigations of the physical aspects of the flow phenomena in the sanitary drainage systems of buildings. Problems of venting were involved in these investigations, and this led naturally later to a consideration of how the partial or complete closure of roof vents by frost in cold weather might affect the venting of a building drainage system. Very little information as to the conditions under which frost closure might occur is available, and, as a result, the requirements in plumbing codes have generally been based on local practices without any regard to the consideration of the factors that affect its occurrence.

Because of the importance of the problem, the Housing and Home Finance Agency requested the National Bureau of Standards to undertake an experimental investigation of this phenomenon as part of a broad investigation of building drainage systems, the physics of the closure of vents by frost being emphasized, rather than the effects of such closure on the drainage system. Experimental studies were conducted in which the roof vent of a simulated building drainage system was enclosed in a low-temperature chamber, and vents as large as 3 inches in diameter were completely closed by frost.

Later, when the report was being written, a theoretical analysis was made of the heat-transfer processes that are involved in the freezing of a roof vent, and this analysis made it possible to predict to what extent an exposed roof vent of any given diameter will freeze up under any given conditions.

The experimental part of the investigation was undertaken for the Housing and Home Finance Agency as part of the research program of that Agency under its statutory authority. The analysis of the problem and the writing of this report were sponsored by the National Bureau of Standards.

A. V. Astin, *Director.*

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Results are reported of a laboratory investigation of the freezing up of roof vents in extremely cold weather and an analysis is given of the heat-transfer process that leads to the partial or complete closure of these vents by frost under sufficiently severe conditions. Information as to the occurrence of frost closure in Canada and methods used there to avoid or minimize the freezing up of roof vents is also included.

1. Introduction

It has been recognized for years that in severely cold weather the roof-vent pipes of building drainage systems may be rendered ineffective as a result of the accumulation of frost inside the vent pipe. When waste water flows down a stack, it carries air with it because of the friction exerted by the falling water on the core of air in the middle of the pipe cross section, and this air is carried away through the building drain or through vents connecting to the lower portion of the stack or to the building drain. The air thus removed must be replaced, and this occurs normally by means of inflow through the roof vent. Hence if this inflow is prevented or restricted because the roof vent is wholly or partly blocked by frost, the pneumatic pressure in the system may fall, when fixtures are discharging into the stack, until air is sucked into the system through the trap seals of the fixtures attached to the system. This may lead to sufficient losses of water in the trap seals of fixtures to allow slight excesses of pneumatic pressure that occur when fixtures are discharging to force sewer air through the reduced trap seals into the rooms of the building.

Occurrences of partial or complete closure during very cold weather have been reported from northern states in this country and from Canada [1].[1] Various expedients, such as requiring the use of minimum sizes of roof vents larger than those that would be required for adequate venting in normal weather; the requirement that the vents be enlarged at or a little below the roof line; and the reduction of the exposed length of vent to the minimum that is feasible have been proposed and are being used successfully in Canada.

The formation of ice or frost in a roof vent results from the condensation and freezing of the moisture carried by the relatively warm air that rises in the stack during periods of cold weather at times when there is little or no flow of waste water down the stack. When this warm moist air comes in contact with the cold inner surface of the vent pipe above the roof of the building, some of its moisture condenses on the wall of the vent pipe, where it may freeze if the outdoor air temperature is low enough. The formation of frost or ice inside of the vent pipe becomes possible whenever the temperature of the inner wall drops at least to the freezing point and remains there for some time, provided there is a stream of warm moist air rising through the vent constantly or intermittently. In very cold weather it may happen that the vent pipe will be at a temperature below 32° F for some distance from its upper end; for example, when it extends down through an unheated attic or similar space beneath the roof.

Moisture is carried to the cold portion of the vent pipe by several means, any or all of which may be going on simultaneously:

1. The principal cause is the existence of an upward current of air in the stack or vent due to temperature differences between the outside atmosphere and the air in the stack and sewer. In systems connected directly to a street sewer or a septic tank without the insertion of a house trap, the weight of the heavier cold air outdoors acts through the manholes or other openings, causing an upward motion of moisture-laden, warmer—and hence lighter—air inside the house drainage system. This convection can take place also in systems having a house trap with a fresh-air vent on the building side of the trap, but to a lesser extent, since the air entering through this vent is at the temperature of the outdoor air and cannot rise in the stack until it is warmed somewhat.

2. Diffusion of water vapor in the stack may be a minor factor. Whenever fixtures are discharged, water vapor is introduced into the stack in high concentration, especially if very hot water is discharged. This water vapor tends to diffuse through the stack and venting system and may in this way come in contact with the cold surface of the vent pipe.

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

3. Air currents are set up by the intermittent discharge of the fixtures owing to the displacement of the air in the drainage system and to friction between the air and the water. This may temporarily reverse the direction of the normal convective current and tend to chill the stack and roof vent by drawing cold outdoor air into the system through the roof vent.

4. Pressure changes in the vent pipe induced by wind blowing past the vent or by gusts striking down on the opening in the vent owing to the presence of nearby buildings may increase or decrease the rate of flow of air in the vent. It has also been suggested that the frosting of the vent will be affected by the tendency of cold outdoor air to force its way into the vent near the wall of the pipe, where the velocity of the rising air is least.

As will be shown later in this paper, frost closure of a roof vent may assume either of two general forms, or a combination of the two. The first form, the one that is analyzed in this paper, is that of a layer of ice or frost which builds up annularly on the interior wall of the vent, until, if conditions are severe enough and last long enough, the vent pipe may be completely blocked by frost. The other way in which the vent may be blocked by frost is through the building up from the rim of the vent pipe of a frost cap which may assume various forms. As this cap builds up, a hole remains in the center of the cap, permitting air from the stack to flow up through it. However, under sufficiently severe conditions, this hole gets smaller and smaller, until the frost cap may completely close the vent. A photograph of such a frost cap is shown in figure 1.

Figure 1. *Frost cap.*

2. Purpose and Scope of the Investigation

This investigation was undertaken at the suggestion of the Housing and Home Finance Agency as a result of questions that arose in meetings of the Uniform Plumbing Code Committee when that Committee was preparing its report. Doubt was expressed that complete frost closure could occur. Owing to the scarcity of information as to actual cases of the occurrence of this phenomenon, it was proposed that, if possible, experiments be made to determine whether roof vents could be completely closed by frost under any reasonably conceivable conditions, and the Hydraulics Section of the National Bureau of Standards was asked to look into the matter.

Obviously it was impossible to conduct such a study on actual installations in the District of Columbia because of the mild winter temperatures that prevail here. However, the possibility of simulating actual service conditions by extending the roof vent of a laboratory plumbing stack up into a cold chamber in which low temperatures could be maintained was considered. Such an installation was constructed as shown in figure 4. It was necessary to use a blower to provide artificially the updraft of air in the stack that ordinarily would result from "chimney action" in an untrapped stack in winter. In the tests the updraft rate was adjusted to correspond to the rate computed for the assumed service conditions. This problem is analyzed in a later section of this paper.

Because of the limited purpose of the investigation when it was started, the desirability of simulating closely an actual installation, and the limited time and funds that were then available, the experimental investigation was of a practical nature rather than of a broad, scientific nature. However, it did demonstrate certain basic principles and pointed the way in which a more scientific study of the problem can be made at some later date.

Over a period of time subsequent to the experimental investigation, an analysis of the frost closure of vents was made on the basis of heat-transfer relationships at the vent section. The analysis yielded results in general agreement with observations of frost closure in the field, and is presented in some detail to indicate the nature of the phenomenon.

3. Previous Investigation of the Problem

The late Roy B. Hunter of the National Bureau of Standards considered the question of the effect of frost closure on trap seals in BH13 "Recommended Minimum Requirements for Plumbing" [2]. Tests simulating conditions of partial closure of roof vents by frost were made by reducing the openings in the tops of stacks and roof vents by replacing the topmost portion of the vents with pipes of smaller diameters. Thus, Hunter was interested in the effect of partial closure of the roof vent on the drainage system, not in how the phenomenon of frost closure occurs. Other unpublished material relating to later tests made at the National Bureau of Standards also deals with this effect. Hunter states: "Frost closure was simulated by setting sections of pipes of various diameters and lengths into the stack top. No measurable effect was produced by setting a 1½-in. pipe 20 in. long into the tops of the 3-in. stacks of the different systems. A 1-in. pipe 12 in. long set in the 3-in. stack only slightly increased the vacuum produced by a heavy discharge from the fixtures. No doubt the effect would be felt more with an increase in the volume of discharge. With a complete closure of the stack top, the water was sucked from one or more traps by the discharge of a single water closet on the system."

Tests made at a later date have confirmed these conclusions and have indicated that, if the top opening in a 3-in. stack is reduced to 1 in. in diameter, undesirable reductions in trap seal may occur in the fixture traps in a one- or two-story-and-basement installation.

Hunter states further: "Chief reliance for ventilation of the drainage system and for the relief of pressure changes set up by fixture discharge is placed upon a free course of air from street sewer to roof terminal. Effects of frost closure as determined by experiments apparently are so slight as to be negligible if a clear opening is left at the top of the stack equal in area to a circle of 1½ in. in diameter." It is assumed that the diameter of opening referred to applies in the case of a 3-in. stack.

A vent diameter of 4 in. at the roof line has been found adequate under most conditions, but, in some parts of the United States and in Canada, the severe climatic conditions encountered have led to the use of increasers 2 in. larger in diameter than the pipe below the roof. It has also been found that vent pipes that extend but a few inches above the roof are less subject to frost closure than longer lengths. This, however, may increase the effect of wind pressure on trap seals. Extension of such pipes above the elevation of possible snowdrifts has been found unnecessary, as the escaping warm air "honeycombs" the snow sufficiently to prevent serious obstruction.

Gray [3] states that a system connecting directly to the street sewer and having no trap in the house drain "favors high humidity and closure of vents by frost in winter". He also indicates that a system having back circuits or loop vents provides considerably greater heating surface for the air passing through it, which tends to make the temperature of the air higher as it passes through the roof vent than would be the case for a stack-vented system. His conclusion appears to indicate that a stack-vented system connected directly to the street sewer is more likely to be affected by frost closure than are other systems, other factors being equal.

Gray points out that heat from the roof may cause the temperature of the air surrounding the roof vent to be somewhat higher than the average outdoor air temperature on windless days. This heat may come either from the attic space (as, for example, from a heated attic) or from the absorption and reflection of the sunlight. Furthermore, he states that although at night the temperature of the air around the roof vent will usually be lower than in the daytime, the infrequent use of the plumbing fixtures during the late evening and early morning hours results in lower humidity of the air passing through the system. Gray suggests that it is desirable to enlarge the stack, not at the roof line, but at some distance below the roof, in order to take advantage of the large heating surface of the increaser below the roof line. Evidently he assumes here that the temperature of the air in the space immediately below the roof would be higher than the temperature of the air in the stack. If this were not true, it is obvious that heat would be lost by the air stream instead of gained.

The authors have received much interesting and significant information on the subject of frost closure from Canadian sources, and this is summarized later in the paper.

Valuable information on instances of frost closure has also been found in a report of the Canadian Institute of Sanitary Engineers [1]. This report contains a lengthy discussion of the problem of frost closure of roof vents in various parts of Canada and gives the results of observations at Winnipeg, Manitoba, during a cold spell in January and February of an earlier year. Figure 2 gives the daily minimum temperature at Winnipeg during this period and also the changes in closure of three stacks by frost, a 6-in. stack and an 8-in. stack at the Grain Exchange and a 6-in. stack at the Civic Curling Rink. Unfortunately, we do not know how the daily minimum temperatures had varied just prior to the period in question, nor do we know what fixtures discharged into the stacks, nor what wind velocities prevailed. It will be noted from figure 2 that the stack at the Curling Rink was enlarged from 4 to 6 in. in diameter just before passing through the roof, which in this case had a steep slope. This roof vent extended only 1½ in. above the roof on the high side. The other two stacks at the Grain Exchange were not enlarged before passing through the roof and extended 12 in. above the level of the flat roof. They were exposed on all sides.

The opening in the 8-in. roof vent was about 5 in. in diameter on January 24, the beginning of the period of observation, and the daily minimum temperature at this time was −25° F. Although the temperature rose shortly after this date,

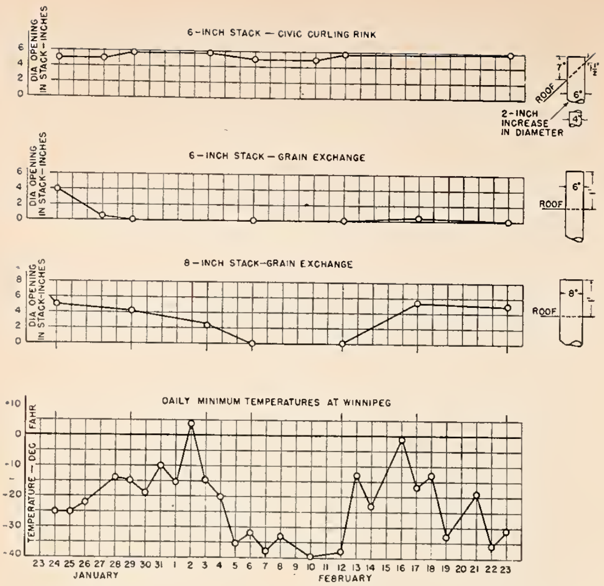

Figure 2. *Observations of frost closure at Winnipeg, Canada.*

reaching a value of +4° F on February 2, falling thereafter to −32° F on February 6, the vent continued to close up, until on February 6 it was completely closed. The daily minimum temperature remained below −30° F until February 12, when the stack was next observed and was found to be still completely closed.

Following this the temperature again rose, until on February 16 it was −1° F, when it again commenced to fall. The vent was observed on February 17 and was found to have opened partially, the diameter of the opening being about 5.4 in. Thereafter the temperature fell erratically, ending at −31° F on February 23, the last day of the period of observation. At this time the opening in the vent was about 5 inches.

The 6-in. roof vent at the Grain Exchange showed similar tendencies to those of the 8-in. vent, but it closed up sooner than the latter. It is, of course, possible that this vent might have opened up a little between the January 29 and the February 6 observations as a result of the warm spell during the latter part of this period.

The 6-in. roof vent at the Curling Rink, which was enlarged from 4 to 6 in. in diameter below the roof and which extended only a very short distance above the roof, did not close completely at any time during the period of observation, and the diameter of the opening in the vent followed in a general way the fluctuations of temperature.

These observations of the frost closure of roof vents are the most detailed of any that have come to the attention of the authors and tend to support the conclusions given later in this paper as to the behavior of roof vents in very cold weather.

Another unusual and interesting case of frost closure will be described here, although it relates to the closure of a smoke stack from a stove rather than the closure of a roof vent. The instance was brought to the attention of the authors by Robert F. Legget, Director, Division of Building Research, National Research Council of Canada. The following is quoted from a letter from Mr. Legget.

> Even though the record may sound fantastic, it may be of interest to you if I record the worst case that has come to my attention. The winter of 1945–46 was an unusually severe one in the North of Canada. At a small place called Baker Lake, which you will find at the end of Chesterfield Inlet on the West side of Hudson Bay, there are a few small buildings. One of these is occupied by a Roman Catholic mission. It is heated by an open stove with a metal smoke stack extending through the roof and protected outside the roof in the usual way by a caribou hide. This is especially effective against the high winds that always blow at this location.
>
> One night during this bad winter the combination of temperature and wind was such that the water vapor in the smoke stack coming from the fire started to freeze on the sides of the chimney. Once having started, it built up rapidly and eventually sealed the chimney tight, even though the fire was burning below. Two priests were severely gassed, but fortunately got out of the building in time.

In response to a further inquiry, Mr. Legget stated that this phenomenon occurred at least twice in this building and that the fuel being burned was coal.

Another example of frost closure has been called to the attention of the authors through L. Glen Shields, Chief Plumbing Inspector for the City of Detroit, Mich. This instance occurred at the Hotel St. James in Ironwood, Michigan. This hotel has 20 4-in. and 2-in. stacks of cast-iron soil pipe. The vents extend about 2 ft above a flat roof and are of the same diameter as the stacks. The building drain did not contain a house trap. On January 18, 1950, when the outside air temperature was −23° F, several of the 4-in. vents were observed to be completely closed by frost, and all of the 2-in. vents were completely closed. All of the other 4-in. stacks were partially closed. The inspector who made the observations estimated that at that time probably from 30 to 40 percent of all the vent stacks in Ironwood were partially or completely closed by frost (see fig. 1).

At the time of the observation the outside air temperature was −23° F, and the temperature on the preceding days had been as follows:

Preceding day	Maximum	Minimum
	° F	° F
1st	0	−20
2d	5	−15
3d	20	+5

The fixtures discharging into a typical 4-in. stack in the hotel were listed as follows: 4 bathroom groups and hot and cold process water.

Although much consideration has been given to the problem of frost closure of roof vents in Canada, and although the phenomenon has been observed, but not much commented upon, in the United States, apparently no laboratory tests have been made to study the problem previously, nor does any analysis of the physical factors involved appear to have been made. Perhaps this may be due in part to the fact that, where frost closure is frequent and severe, methods of minimizing it have been developed by empirical methods, some of which have proved very effective. Another reason may be the difficulty involved in simulating service conditions in a laboratory test. Some of these difficulties are not apparent at first sight, and the tests reported in this paper required a quite complicated setup before service conditions could be simulated successfully.

4. Analysis of Conditions in Service and Test Installations

The tendency for air to flow upward in plumbing stacks and vents in cold weather, at least when there is little or no water flowing down the stack, is due to the same principle as is involved in the action of a chimney. The phenomenon is due to the fact that the static pressure differential between the bottom and the top of the stack is greater outside of the building than it is inside of the stack, since the air temperature outside of the building is lower in winter than the temperature of the air inside the stack.

The static pressure difference outside of the building between the levels of the top and bottom of the stack is determined by the weight of an air column of unit cross section extending between these two levels outside of the building. The air inside of the stack, being at a higher temperature than the air outside of the building during cold weather, weighs less than the air outside of the building. Hence the column of air in the stack will exert a smaller pressure at the bottom of the stack than the column of air outside of the stack, or at least it would if it were stationary. The result is that this difference in pressure of the two columns, due to difference in density, is available to create an upward flow of air in the stack, and this flow is of such magnitude that the sum of the pressure losses within the stack due to wall friction to increases and decreases of diameter of the line, to bends in the line and to the creation of velocity of flow, is equal to this pressure difference.

In what follows it will be assumed that no water is flowing in the stack. This condition will exist in many buildings during a large part of the time. Any small flow of water down the stack will decrease the convective flow of air up the stack, and for larger flows the direction of the air current will be reversed, at least a portion of this air ultimately being carried out through the building drain and sewer to the street sewer. However, except in quite large buildings, the probability of finding an appreciable flow of water in the drainage stack at an arbitrarily chosen instant of observation is rather small.

In this paper no account is taken of the slight variation in density of the air vertically in a column of uniform temperature. Taking this variation into account would scarcely change the results and would complicate the computations. Since the tests conducted in this investigation showed that the air raising through the stack was nearly saturated with water vapor, the densities assumed for the relatively warm air inside the system were those given for saturated air. On the other hand, since air at temperatures far below the freezing point of water can contain only a negligible amount of water vapor, the densities assumed for the cold outside air were those given for dry air.

For the sake of simplicity it has been assumed that the building drain and the building sewer have the same diameter and the same coefficient of friction per unit length.[2]

4.1. Analysis of Service Installation

Figure 3 shows a stack with a short enlarged section at the top (the roof vent) and with a building drain and building sewer connecting to the street sewer. The building drain and sewer are assumed to be of the same diameter, so that no distinction is made between them in this drawing. The following considerations govern the assumptions made as to the different air densities involved.

It is assumed that the temperature of the atmosphere outside of the building is below freezing, so that the mass density ρ_{4s}[3] of the air outside of the building is relatively high. Actually, as has already been mentioned, the density varies a little from the level of the top of the stack to the ground level, but for simplicity an average value of ρ_{4s} is assumed to exist over this distance.

[2] According to the Report of tbe Coordinating Committee for a National Plumbing Code, the building drain extends from the base of tbe stack to a point 3 ft outside of the inner face of the building wall. The building sewer extends from this point to the street sewer.

[3] Tbe subscripts "s" and "t" will be used to distinguish between the *service* and the *test* systems discussed in tbis paper.

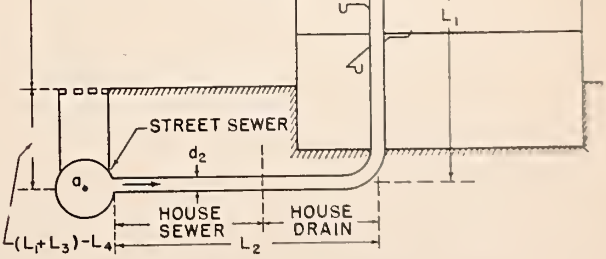

FIGURE 3. *Analysis of service installation*

The temperature of the air in the street sewer, the building sewer, and the building drain is assumed to be somewhat higher than that of the outdoor air. Actually it may increase a little as the air flows from the street sewer, through the building sewer and drain to the stack, but again for simplicity we assume that the mass density ρ_{2s} of the air in this part of the system is constant from the top of the manhole in the street sewer through the building sewer and drain to the base of the stack.

Similarly, as the air rises through the stack and roof vent, its temperature increases still further until it reaches the exposed part of the roof vent, where it will be cooled somewhat. However, for simplicity, it will be assumed that the mass density ρ_{1s} of the air in the stack and roof vent is constant.

With these assumptions in mind, one can easily see that the pressure increase outdoors from the level of the point "b" at the top of the roof vent to the point "a" in the street sewer is given by

$$p_{as}-p_{bs}=\rho_{4s}gL_{4s}+\rho_{2s}g(L_{1s}+L_{3s}-L_{4s})=\Delta p_s. \quad (1a)$$

But as

$$\Delta p=\rho_w g\Delta h, \quad (2)$$

where ρ_w is the mass density of water, and Δh is the height of water column in a manometer corresponding to the pressure Δp, eq (1a) may be expressed as

$$h_{as}-h_{bs}=\frac{\rho_{4s}}{\rho_w}L_{4s}+\frac{\rho_{2s}}{\rho_w}(L_{1s}+L_{3s}-L_{4s})=\Delta h_s. \quad (1b)$$

If r is used for the ratio of the air density to the water density, eq (1b) becomes

$$h_{as}-h_{bs}=r_{4s}L_{4s}+r_{2s}(L_{1s}+L_{3s}-L_{4s})=\Delta h_s. \quad (1c)$$

Now, as the air in the stack is at a higher temperature than the outside atmosphere, the pressure difference between points "a" and "b" under purely static conditions in the stack would be less than that which actually exists between these two levels in the outside atmosphere. As a result of this, air flows from the street sewer into the building sewer (if there is no house trap in the building drain), through the building sewer and drain, and up the stack at such a rate that the pressure loss h_{fs} due to wall friction, expansion and contraction, and the creation of velocity head, added to the static pressure difference between the points "a" and "b," measured inside the system, is equal to the pressure difference measured outside of the system.

Consideration of conditions inside the system indicates that

$$h_{as}-h_{bs}=h_{fs}+r_{1s}(L_{1s}+L_{3s}). \quad (3)$$

After substituting in eq (3) the value of $h_{as}-h_{bs}$ from eq (1c) and reducing, the following expression for h_{fs} is obtained:

$$h_{fs}=(L_{1s}+L_{3s}-L_{4s})(r_{2s}-r_{1s})+L_{4s}(r_{4s}-r_{1s}). \quad (4)$$

Thus we have derived formally the fact that could have been predicted a priori, that the head available to produce flow of air up the stack is determined by the difference in density of the two static air columns between points "a" and "b," one inside the stack and the other outside the building, and by the height of the system.

4.2. Test Apparatus

Figure 4 shows the arrangement of the test apparatus that was used for the experimental work. A 3-in. stack-vented, single-story-with-basement system was erected, complete with water closet, bathtub, lavatory, and kitchen sink. A pump supplied water for discharge through the bathtub at a constant rate and at any desired

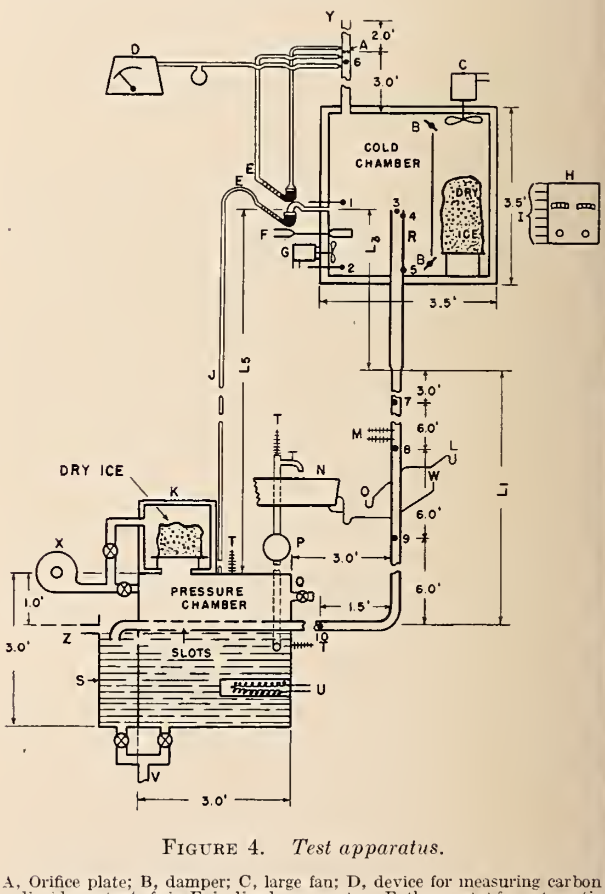

FIGURE 4. *Test apparatus.*

A, Orifice plate; B, damper; C, large fan; D, device for measuring carbon dioxide content of air; E, inclined manometers; F, thermostat for automatic control of large fan, C; G, small fan; H, remote temperature indicator; I, electrical connections to thermocouples at points 1 to 10; J, manometer tube; K, small ice chamber; L, lavatory; M, wet- and dry-bulb thermometers; N, bathtub; O, sink; P, water pump; Q, water supply; R, roof vent; S, spill basin; T, thermometer; U, immersion heater with thermostatic control; V, drain; W, water closet; X, air blower; Y, exhaust pipe; Z, overflow weir.

temperature. An automatic device connected to the water closet flushed the closet at regular intervals of time. At the top of the stack an insulated cold chamber in the form of a cube approximately 3 ft on a side (inside dimensions) surrounded the stack terminal or roof vent. This chamber was fitted with windows for making observations and with a door for maintenance of the test equipment located in the test chamber and for checking the accumulation of frost in the vent pipe. A rack was provided on which approximately 200 lb of "dry ice" (solid carbon dioxide) could be placed. This provided the means by which a very low temperature could be maintained in the chamber.

A fan mounted above the dry ice, actuated by means of a thermostatic control unit mounted near the terminal of the stack, circulated air in the chamber whenever required to maintain the temperature approximately constant at the value determined by the setting of the control unit. The control unit stopped the circulating fan whenever the temperature of the air in the chamber was reduced to the value to which the control unit was adjusted.

A smaller fan nearer the stack was run continually in order to simulate a breeze blowing over the rooftop and to cause a more nearly uniform temperature distribution along the portion of the stack inside the cold chamber. A section of 3-in.-diameter plastic pipe about 5 ft long was set in the top of the cold chamber to provide means by which the air from the stack and the gaseous carbon dioxide from the dry ice could pass freely from the cold chamber to the external atmosphere; otherwise the chamber was made as nearly airtight as possible in order to prevent undue heat loss and to make it possible to measure the flow of air in the stack. This section of pipe contained an orifice for the purpose of measuring the rate of air flow through the system; and, since the orifice could be observed through the transparent plastic pipe, it could be kept free of frost in order that the readings might be reasonably accurate.

A closed chamber surrounded a perforated section of the house drain. A blower discharged air through a valve into this chamber, and by appropriate adjustment of this valve the desired pressure differential could be maintained and the rate of air flow through the system could be controlled. The air entered the house drain through a number of ⅜-in.-diameter holes having a total cross-sectional area equal to the cross-sectional area of the 3-in. house drain. In this way the frictional resistance due to the air entering the drain was probably greater than if it had entered through an open end of the 3-in. drain, since the entrance was through a number of small orifices in a direction at right angles to the direction of flow in the drain. This, of course, resulted in a head loss as a result of the change in direction of the inflowing air through an angle of 90°, similar to the effect of introducing the air through a 90° elbow of small radius of curvature. In effect, this arrangement probably simulated a house drain and sewer of a length that might be expected in service, but which space limitations prevented in the test installation.

Water occupied the part of the chamber below the drain. The temperature of the water was controlled by means of an immersion heater, so that any desired temperature above room temperature could be maintained. Some of this hot water was pumped up to the bathtub from which it flowed in a steady stream at a rate of about 1.8 gal/min into the stack and returned through the drain to the supply chamber.

A slot was cut in the bottom of the drain, so that the flow of hot water from the bathtub would be returned to the supply chamber without loss, whereas a large flow of cold water, such as the discharge of the water closet, would for the most part pass on through the drain into the spill basin, so that there would be no great amount of cooling of the warmer water in the supply chamber due to the addition of relatively large quantities of cold water. The house drain terminated in a 90° bend turned downward into the spill basin to form a water seal, which prevented the escape of air from the drain by this route.

During very hot weather it was found that it was impossible to keep the average temperature of the air in the stack as low as was desired in some of the tests, and, if the weather turned hot during a test run, it was sometimes impossible for the existing apparatus to keep the stack temperature at the value selected at the beginning of a run. Hence an additional chamber was mounted near the blower and was filled with dry ice, so that by proper valve adjustment part of the air supplied by the blower passed through this chamber. By using this source of cooling, it was found possible to maintain the temperature of the air in the stack at the desired degree.

Inclined differential monometers were used to measure pressure differences between the pressure chamber enclosing the house drain and the chamber enclosing the roof vent and between opposite sides of the orifice plate in the outlet tube from the cold chamber.

The concentration of carbon dioxide in the mixture of air and carbon dioxide passing through the orifice was measured by a device that operated on the principle of absorption of the carbon dioxide from the mixture by means of a potassium hydroxide solution.

Temperatures inside the cold chamber, at five points in the air stream in the stack, at one point in the air stream passing through the orifice plate, and at two points in the wall of the section of vent pipe inside of the cold chamber, were measured by means of a remote recording device connected to thermocouples placed at the various points (see fig. 4). Temperatures of the room air surrounding the test setup and water temperatures were measured by means of ordinary mercury-in-glass thermometers. Humidity determinations inside the stack were based on wet- and dry-bulb thermometer readings taken at a point about 5 ft above the level at which the bathtub drain connected to the stack. These thermometers were fitted with rubber bushings, which were inserted into holes in the stack wall. Humidity determinations of the air in the room surrounding the installation were also based on wet- and dry-bulb thermometer readings.

In this connection, it is quite likely that the humidities obtained for the air in the stack were somewhat greater than the actual values, since the velocities in the stack probably were inadequate to lower the wet-bulb temperatures to their full extent. However, this possibility was overlooked at the time the tests were made.

4.3. Analysis of Test Installation

There are three sets of conditions to consider in connection with the test installation: (1) conditions outside of the system, (2) conditions inside of the system (i. e., inside of the stack and building drain), and (3) conditions in the manometer line (see fig. 5).

a. Conditions Outside of System

Corresponding to eq (1c) applying to the service system, the following equation applies to the test system:

$$h_{at}-h_{bt}=r_{4t}L_{4t}+r_{2t}(L_{1t}+L_{3t}-L_{4t})=\Delta h_t. \qquad (5)$$

However, in the tests made in this investigation the stack was mounted inside of a building at ordinary room temperatures and thus was not subject to as great a difference in static head as would exist under service conditions in cold weather between the outlet of the building sewer and the top of the roof vent, owing to the lesser density of the air at room temperature compared with that of air at, say, −30° F. Hence, to produce a flow of air through the test system comparable to that which would occur in actual winter service, it was necessary to create artificially an additional difference in pressure head, h_e, between points "a" and "b" through the stack. In the test installation this was done by means of a blower, as has been explained earlier. The head produced by the blower ranged from a few hundredths to a few tenths of an inch of water column. In order to produce the same difference in static pressure between points "a" and "b" as would exist in a similar installation in cold-weather service, the following relation must be satisfied:

$$h_{at}+h_e-h_{bt}=h_{as}-h_{bs}. \qquad (6)$$

b. Conditions Inside of System

Corresponding to eq (3) for the service installation, we have for the test installation:

$$h_{at}+h_e-h_{bt}=h_{ft}+r_{1t}(L_{1t}+L_{3t}). \qquad (7)$$

We can substitute in this the value of $h_{at}-h_{bt}$ from eq (5) and solve for h_{ft}, obtaining:

$$h_{ft}=(L_{1t}+L_{3t}-L_{4t})(r_{2t}-r_{1t})+L_{4t}(r_{4t}-r_{1t})+h_e. \qquad (8)$$

c. Conditions in Manometer Line

The auxiliary pressure created by the blower was measured by a manometer mounted on a level with the top of the roof vent. A relation between the reading h_m of the manometer and the pressure head h_e will next be derived. We can see intuitively that h_e must be approximately equal to h_m, but, if we wish to demonstrate this formally, we note from a consideration of figure 5 that the following relation holds for the manometer line:

$$h_{at}-h_{bt}+h_e=h_m+r_{4t}L_{4t}+r_{2t}(L_{1t}+L_{3t}-L_{4t}). \qquad (9)$$

Actually the value of r_{4t} inside of the manometer line will be a little greater than in the outside air because of the slightly higher pressure in the manometer line. Consideration of this pressure difference, using the gas law, shows, however, that the difference was not more than 0.1 percent in any of the tests, so the effect will be neglected. Hence, if we subtract eq (5) from eq (9), we obtain:

$$h_e=h_m. \qquad (10)$$

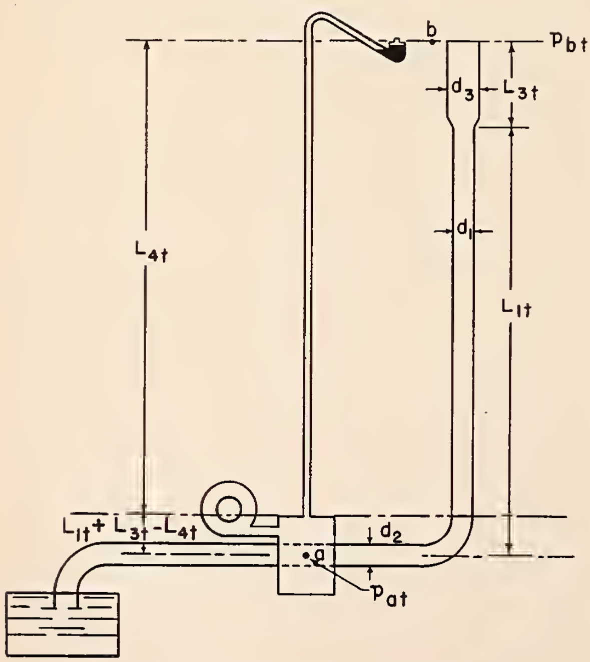

FIGURE 5. *Analysis of test installation.*

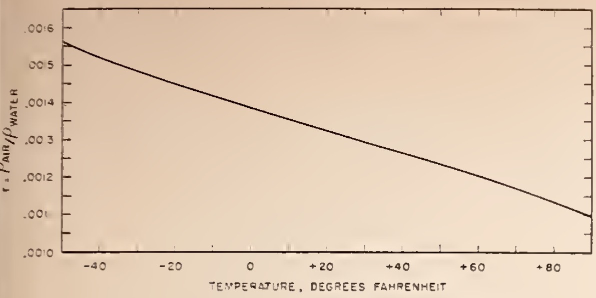

FIGURE 6. *Air-water density ratios for different temperatures.*

Figure 6, giving the values of r over the range of temperature in which we are interested, has been prepared for convenience in computing. As has been stated, for the lower temperatures the air was assumed to be dry, while for the higher temperatures inside the stack the air was assumed to be saturated.

5. Friction Losses Involved in the Upward Flow of Air in the System

In what follows it should be remembered that we are considering only the case in which no water is flowing in the drainage system. In order to evaluate the losses of head, h_{fs} and h_{ft}, it is necessary to consider the drainage system in detail (see fig. 3).

The head losses in the system can be considered as belonging to three classes: (1) losses due to the frictional resistance to flow in straight pipes; (2) losses due to change in direction or to changes in cross-sectional area; and (3) losses required to create velocity of the air in the system. The first of these can be computed from the Darcy-Weisbach equation:

$$\Delta h=f\frac{L}{d}\frac{v^2}{2g}, \tag{11a}$$

where

Δh=the head loss in terms of height of the fluid flowing—in this case, air
f=the dimensionless Darcy-Weisbach friction coefficient
L=the length of the pipe
d=the internal diameter of the pipe
v=the mean velocity of flow in the pipe
g=the acceleration of gravity.

In order that Δh may be measured in height of water column, it is necessary to multiply the right member by the ratio r of the density of air under the assumed conditions to the density of water, since a water manometer was used to measure values of Δh. Thus, when Δh is measured in height of water column, we have

$$\Delta h=rf\frac{L}{d}\frac{v^2}{2g}. \tag{11b}$$

The second class of losses can be expressed by a coefficient multiplied by the velocity head; so, again multiplying by r in order to obtain Δh in height of water column:

$$\Delta h=rK\frac{v^2}{2g}, \tag{12}$$

where K is a constant.

The third type of loss is that due to the kinetic energy of the air issuing from the roof vent and can be expressed by an equation similar to eq (12).

5.1. Head Loss at Transition From Street Sewer to Building Sewer

We assume that the energy loss, expressed as head of air, is equal to half the velocity head, as is customary where a square-cornered entrance is involved. The loss of head required to create the velocity v_2, the mean velocity of air flow in the building sewer and building drain, will not be added, since, if we take account of the energy losses (not transformations of energy) from point to point along the system, we need only to allow for the head loss required to create the velocity v_3 of the air issuing from the roof vent. Hence the loss of energy head at entrance to the building sewer is given by

$$\Delta h=\frac{1}{2}r_2\frac{v_2^2}{2g},$$

or, since we shall find it convenient to express all losses in terms of the velocity head in the stack:

$$\Delta h=\frac{1}{2}r_2\left(\frac{d_1}{d_2}\right)^4\frac{v_1^2}{2g}. \tag{13a}$$

5.2. Head Loss In Building Sewer and Drain

Usually the building sewer and building drain comprise a single line of the same diameter and slope, being physically indistinguishable from each other. The distinction is made solely for administrative purposes. Hence, in what follows, they will be treated as a unit, the line having the diameter d_2 and the length L_2. The loss due to friction in this line is given by

$$\Delta h=r_2f\frac{L_2}{d_2}\left(\frac{d_1}{d_2}\right)^4\frac{v_1^2}{2g}. \tag{13b}$$

5.3. Bend Loss at Entrance to Stack

$$\Delta h=r_2C_b\left(\frac{d_1}{d_2}\right)^4\frac{v_1^2}{2g}. \tag{13c}$$

5.4. Head Loss at Contraction, Upper End of Bend

In general the stack may be smaller in diameter than the building drain. Then the loss due to contraction is

$$\Delta h = r_1 C_c \frac{v_1^2}{2g}. \tag{13d}$$

C_c, the contraction coefficient, can be evaluated from tables given in various hydraulics textbooks, for example, Dodge and Thompson, *Fluid mechanics*, first edition, page 215.

5.5. Head Loss Due to Friction in Stack

$$\Delta h = r_1 f \frac{L_1}{d_1} \frac{v_1^2}{2g}. \tag{13e}$$

5.6. Head Loss at Transition to Roof Vent

The transition from the stack to the roof vent—if they are not both of the same diameter—may be either a contraction or an expansion. If it is a contraction, the loss is given by

$$\Delta h = r_1 C_c \left(\frac{d_1}{d_3}\right)^4 \frac{v_1^2}{2g}, \tag{13f}$$

and C_c can be evaluated as explained above. If it is an expansion, it is given by

$$\Delta h = r_1 C_e \frac{v_1^2}{2g}, \tag{13g}$$

where $C_e = [1-(d_1/d_3)^2]^2$.

5.7. Head Loss Due to Friction in Roof Vent

$$\Delta h = r_1 f \frac{L_3}{d_3} \left(\frac{d_1}{d_3}\right)^4 \frac{v_1^2}{2g}, \tag{13h}$$

where d_3 is the diameter of the opening in the vent, which depends on the thickness of the layer of frost, if such a layer is present.

5.8. Head Loss at Outlet of Roof Vent

Because the outlet is square-cornered, it will be assumed that all of the kinetic energy of the issuing air is lost. That is, there is no recovery of head at exit. However, we must include in the equation for the loss of head in the system the velocity head of the air issuing from the roof vent because a loss of head was required to create this velocity. Hence

$$\Delta h = r_1 \left(\frac{d_1}{d_3}\right)^4 \frac{v_1^2}{2g}. \tag{13i}$$

This procedure is not strictly correct because some of the changes of velocity in the system occur at the temperature θ_2 and some at temperature θ_1, under the assumptions made. However, the differences involved are so small as to be neglibible in the problem.

The total loss of head in the system is the sum of the above head losses, or

$$h_f = \Sigma \Delta h = \left[r_2 \left\{ \frac{1}{2} \left(\frac{d_1}{d_2}\right)^4 + f \frac{L_2}{d_2} \left(\frac{d_1}{d_2}\right)^4 + C_b \left(\frac{d_1}{d_2}\right)^4 \right\} + r_1 \left\{ C_c + f \frac{L_1}{d_1} + C_e + f \frac{L_3}{d_3} \left(\frac{d_1}{d_3}\right)^4 + \left(\frac{d_1}{d_3}\right)^4 \right\} \right] \frac{v_1^2}{2g}. \tag{14}$$

(In this equation, C_e is to be replaced by $C_c(d_1/d_3)^4$ if there is a contraction instead of an expansion. If neither, C_e and C_c are both equal to zero.)

Now, inserting the proper values for the density ratios, the lengths, the diameters, and the coefficients, and computing h_f from eq (4), we can solve eq (14) for v_1.

The following assumptions are made in the computations that follow: The diameters of the house sewer, the house drain, the stack, and the roof vent are all the same and will be represented by d_1. Of course, as the vent frosts up, its diameter will decrease, and, under these conditions will be represented by d_3. The total length of house sewer and drain is 50 ft. We adopt the following

TABLE 1. *Pressure differentials h_f in feet of water column tending to produce convection in stacks of different heights*

Height of stack L_1+L_3 [b]	[a] Temperature differences (°F)									
	110	100	90	80	70	60	50	40	30	20
ft										
20	0.0056	0.0050	0.0044	0.0039	0.0034	0.0030	0.0025	0.0020	0.0016	0.0012
30	.0093	.0082	.0072	.0064	.0056	.0048	.0036	.0033	.0026	.0019
40	.0130	.0115	.0100	.0089	.0077	.0067	.0056	.0045	.0035	.0026
50	.0166	.0147	.0128	.0114	.0099	.0085	.0072	.0057	.0045	.0032
60	.0203	.0179	.0156	.0139	.0120	.0104	.0087	.0069	.0054	.0039
70	.0239	.0211	.0184	.0165	.0142	.0122	.0103	.0082	.0064	.0046
80	.0276	.0243	.0212	.0189	.0163	.0141	.0118	.0094	.0073	.0053
90	.0312	.0276	.0240	.0214	.0185	.0159	.0134	.0106	.0083	.0060
100	.0349	.0308	.0286	.0239	.0206	.0178	.0149	.0119	.0092	.0066

[a] Temperature of the air in the stack and vent is taken as 60° F. Temperature of the air in the street sewer, manhole, building sewer, and building drain is taken as 50° F. The temperature difference is the algebraic difference between the temperature of the air in the stack and that of the outside air.
[b] $L_1+L_3-L_4=5$ ft.

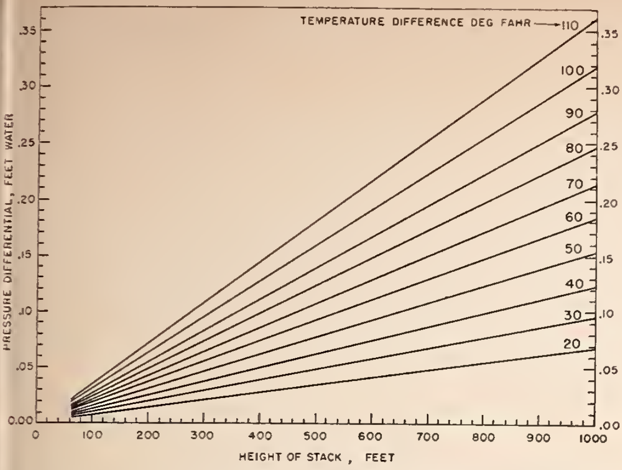

FIGURE 7. *Pressure differentials tending to cause convection due to temperature difference between outside air and air in stack.*

(See footnote to table 1 for air temperatures assumed.)

values: $f=0.03$, $C_b=0.23$, and $g=32.2$ ft/sec squared.

Values of h_t computed from eq (4) are tabulated in table 1 and are plotted in figure 7 for various differences in temperature between that of the outside air and the air in the stack and for heights of stack up to 1,000 ft.

Table 2 gives velocities of air flow in systems in which the building sewer, building drain, stack, and roof vent are all 3 in. in diameter for stacks up to 60 ft in height and for temperature differences ranging from 30 to 90 deg F. In this and all the following cases for which computed velocities are given, it is assumed that the total length of building drain is 50 ft. The temperature of the air in the building drain and sewer is assumed to be 50° F. and that in the stack is assumed to be 60° F. Outside air temperatures are selected to give the desired temperature differences.

Tables 3, 4, 5, and 6 give air velocities in 4-in., 6-in., 8-in., and 12-in. systems for stack heights up to 1,000 ft in the case of the 8-in. and 12-in. stacks.

TABLE 2. *Air velocities in stacks due to convection*

Pipe diameter throughout system, 3 in.[a]

Height of stack L_1+L_3	Temperature difference (° F)						
	30	40	50	60	70	80	90
ft	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*
20	2.9	3.2	3.6	3.9	4.2	4.5	4.8
40	3.8	4.4	4.9	5.3	5.7	6.1	6.5
60	4.4	5.0	5.6	6.1	6.5	7.0	7.4

[a] Length of house sewer and house drain, 50 ft.

TABLE 3. *Air velocities in stacks due to convection*

Pipe diameter throughout system, 4 in.[a]

Height of stack L_1+L_3	Temperature difference (° F)						
	30	40	50	60	70	80	90
ft	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*
20	3.2	3.6	4.1	4.4	4.7	5.1	5.4
40	4.3	4.9	5.5	6.0	6.4	6.9	7.3
60	4.9	5.6	6.3	6.9	7.4	8.0	8.4
80	5.4	6.1	6.8	7.5	8.0	8.6	9.2
100	5.7	6.4	7.2	7.9	8.5	9.1	9.7

[a] Length of house sewer and house drain, 50 ft.

TABLE 4. *Air velocities in stacks due to convection*

Pipe diameter throughout system was 6 in.[a]

Height of stack L_1+L_3	Temperature difference (° F)						
	30	40	50	60	70	80	90
ft	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*
50	5.5	6.3	7.0	7.6	8.2	8.8	9.4
100	6.8	7.7	8.6	9.4	10.1	10.9	11.5
200	7.7	8.8	9.8	10.8	11.6	12.5	13.2
300	8.1	9.3	10.4	11.3	12.2	13.2	13.9
400	8.4	9.6	10.7	11.7	12.6	13.6	14.4
500	8.5	9.7	10.9	11.9	12.8	13.8	14.6

[a] Length of house sewer and house drain, 50 ft.

TABLE 5. *Air velocities in stacks due to convection*

Pipe diameter throughout system, 8 in.[a]

Height of stack L_1+L_3	Temperature difference (° F)						
	30	40	50	60	70	80	90
ft	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*
50	6.1	7.0	7.8	8.5	9.1	9.9	10.4
100	7.6	8.6	9.7	10.5	11.4	12.2	13.0
200	8.8	10.0	11.2	12.2	13.2	14.2	15.0
300	9.3	10.6	11.8	12.9	13.9	15.0	15.9
400	9.6	10.9	12.2	13.4	14.4	15.5	16.4
500	9.8	11.1	12.5	13.6	14.7	15.8	16.7
600	9.9	11.3	12.6	13.8	14.9	16.0	17.0
700	10.0	11.4	12.8	13.9	15.0	16.2	17.1
800	10.1	11.5	12.9	14.0	15.1	16.3	17.3
900	10.1	11.5	12.9	14.1	15.2	16.4	17.4
1,000	10.2	11.6	13.0	14.2	15.3	16.5	17.5

[a] Length of house sewer and house drain, 50 ft.

TABLE 6. *Air velocities in stacks due to convection*

Pipe diameter throughout system, 12 in.[a]

Height of stack L_1+L_3	Temperature difference (° F)						
	30	40	50	60	70	80	90
ft	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*	*fps*
50	7.1	8.0	8.9	9.8	10.5	11.3	12.0
100	8.9	10.1	11.3	12.3	13.3	14.3	15.1
200	10.4	11.8	13.3	14.5	15.6	16.8	17.8
300	11.1	12.6	14.2	15.5	16.7	18.0	19.0
400	11.5	13.1	14.7	16.0	17.3	18.6	19.7
500	11.8	13.4	15.0	16.4	17.7	19.1	20.2
600	12.0	13.6	15.3	16.7	18.0	19.4	20.5
700	12.1	13.8	15.4	16.9	18.2	19.6	20.7
800	12.2	13.9	15.6	17.0	18.3	19.8	20.9
900	12.3	14.0	15.7	17.1	18.5	19.9	21.1
1,000	12.4	14.1	15.8	17.2	18.6	20.0	21.2

[a] Length of house sewer and house drain, 50 ft.

Table 7. *Air velocities in stacks due to convection*

Data from Gray

Temperature difference	Height of stack	Stack diameter (in.)				
		2	3	4	5	6
deg F	*ft*	*fps*	*fps*	*fps*	*fps*	*fps*
20	20	1.88	2.25	2.47	2.80	3.17
20	50	2.78	3.55	3.90	----	----
25	20	1.97	2.52	2.77	3.12	3.53
25	50	3.07	3.97	4.37	4.95	5.58
30	20	2.15	2.75	3.02	3.42	3.87
30	50	3.40	4.33	4.78	5.42	6.12

By comparison, the data given by Gray [3] on the velocity of flow of air in stacks due to convection are given in table 7. He does not state all of the assumptions he made in computing these values, but it will be observed that his results fit very well the results given in the tables referred to above.

It should be emphasized that the values given in tables 2 to 6, inclusive, apply only when no water is being discharged into the stack and when there is no closure of the vent by frost. In addition, these values have been computed on the assumption of straight stacks without horizontal branch or vent connections. Obviously these assumptions give computed velocities somewhat greater than those that occur sometimes in service. However, owing to the many variables inherent in the many types of plumbing drainage systems in service, it is necessary to make certain simplifying assumptions in connection with such computations. It is believed that the values in the tables above give at least a rough estimate of the maximum convective velocities to be expected in stacks.

6. Physics of Frost Closure of Roof Vents

6.1. General Considerations

The closure of a roof vent by the formation of a layer of frost on the inner surface of the vent is a complicated process which it is not feasible to discuss with any great degree of accuracy. However, the general physics of the process is quite clear and leads to certain conclusions, some of which are at variance with commonly accepted ideas today. The process will be discussed at considerable length here, therefore, both for the purpose of achieving a clear understanding of the principles involved in the process and for pointing out the way in which any further investigation might best be carried out.

The partial or complete closure of a roof vent by frost in cold weather requires that a more or less steady current of warm moist air flow up through the stack and roof vent. If the system does not contain a house trap, then this air comes from the street sewer and is relatively moist and warm. If there is a house trap in the building drain, then a fresh-air inlet is ordinarily required on the house side of the trap; and in this case the current of air flowing up the stack is much cooler than in the first-mentioned case and is less pronounced. It is also much drier when it enters the system.

When water is discharged intermittently from fixtures that drain into the stack, the upward current of air may become quite erratic, and, at times when considerable water is discharging, its direction may be reversed. However, during many hours of each day little or no use is made of the plumbing fixtures, and the upward current is fairly steady.

The air flowing upward through the stack, partially or completely saturated with water vapor, is chilled by heat loss to the cold interior surface of the roof vent. This causes condensation or deposition of water on or the adhering of ice particles to the surface. If the inner surface of the vent is below 32° F, the water freezes or the ice particles adhere, forming an ice or frost deposit; if it is above 32° F, the deposited water runs down the inner surface of the stack. The temperature of the inner surface of the vent, exposed to the current of air flowing upward in the stack, is thus a controlling factor in the formation of a frost deposit. Under steady conditions of outdoor weather and air temperature in the stack, the temperature of the inner surface of the vent depends on the temperature of the outside air and the wind velocity, on the insulating effect of the vent pipe and the frost deposit, and on the temperature and velocity of the air flowing in the vent pipe.

As the frost deposit builds up, it acts as insulation to reduce the flow of heat from the stack air to the outdoor air and consequently to raise the temperature of the frost deposit exposed to the stack air. If the ice-air surface rises in temperature to 32° F, further moisture deposits will remain liquid and will drain down the stack, and the frost deposit will not thicken any further. The calculations presented in this paper are for the purpose of estimating for any particular stack vent under steady temperature conditions the extent to which frost deposits may be expected to build up in the vent pipe.

The rate at which moisture or frost particles may be deposited, and, therefore, the rate at which a frost deposit may thicken, increases, other things being equal, as the humidity of the air stream increases. Whether a given vent will freeze closed during a particular spell of cold weather may thus depend on the rate of moisture deposition and so, to a considerable extent, on the humidity of the stack air.

The exposed length of the vent pipe is of obvious importance in connection with this phenomenon, since the available area for chilling the stack air and, therefore, for abstracting its accompanying moisture, is increased with increased length of vent, while the effect of conduction of heat upward in the wall of the vent pipe from the warmer length below is reduced.

6.2. Heat Transfer in a Roof Vent

It is assumed that warm air at the temperature θ_1, saturated with water vapor, is flowing upward through the vent with velocity v_3. From the standpoint of heat transfer, the general problem is that of a warm fluid flowing in a cylindrical pipe or shell, with heat transfer to the shell, and thence through the shell to the colder air or wind beyond it. The heat transfer phenomenon is a complicated one, partly because of the existence of a boundary layer near the pipe wall in the air stream and partly because changes of state occur in the air stream as it loses its moisture in passing through the vent.

It has already been stated that, as the saturated or nearly saturated air chills while passing up through the roof vent, some of the water condenses to form drops of moisture. Under some conditions some of this moisture may freeze while still in the air stream. As the layer of ice in the vent increases in thickness, the resistance that the vent offers to the flow of air increases, with the result that there is a decrease in the velocity of the air stream in the stack, but an increase in the velocity of the air stream in the vent (see fig. 8). When this happens, a smaller amount of moisture passes through the vent in a given time than when the latter is unobstructed, but, on the other hand, the area of the surface on which moisture can deposit is reduced to a greater extent than is the volume of flow.

Owing to these facts and to the further fact that there are two changes in state occurring in the vent pipe, i. e., from vapor to liquid and from liquid to solid, with consequent release of heat, it is obvious that it would be an extremely difficult and complicated task to compute accurately the rate of heat transfer from the air stream to the inner wall of the vent, nor do the practical aspects of the problem warrant such an attempt. However, formulas are available for the transfer of heat from an air stream to a chilled pipe wall when no changes of state occur, and one of these formulas will be used here, an estimate being included for the effect of the changes of state that occur. Figure 9, showing the cross section of a vent, gives the nomenclature used in what follows.

a. Transfer of Heat From Air Stream in Vent to Inner Wall of Vent

The general equation for the transfer of heat from the air stream to the wall is [4, p. 3]:

$$q=KS\Delta\theta, \tag{15}$$

where

q=the rate of heat transfer through the surface involved
K=the coefficient of heat transfer, which varies with the velocity of air flow and other quantities (see eq 17 and 24)
S=the area of the surface in question
$\Delta\theta$=the difference in temperature producing the flow of heat.

Applying this equation to the transfer of heat from the stream of air in the vent to the wall of the pipe or to the ice surface, as the case may be, we write eq (15) as follows:

$$q_{s3}=K_{s3}S_3\theta_{s3}=2\pi r_3K_{s3}\theta_{s3}, \tag{16}$$

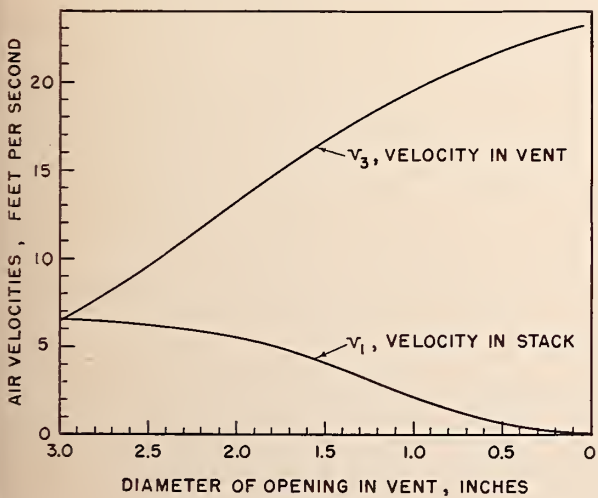

FIGURE 8. *Changes in air velocities in a 3-in. stack and vent as the vent freezes up.*

Height of stack, 40 ft; length of vent affected by frost, 1 ft; and temperature difference, 90 deg F. (See footnote to table 1 for air temperature assumed.)

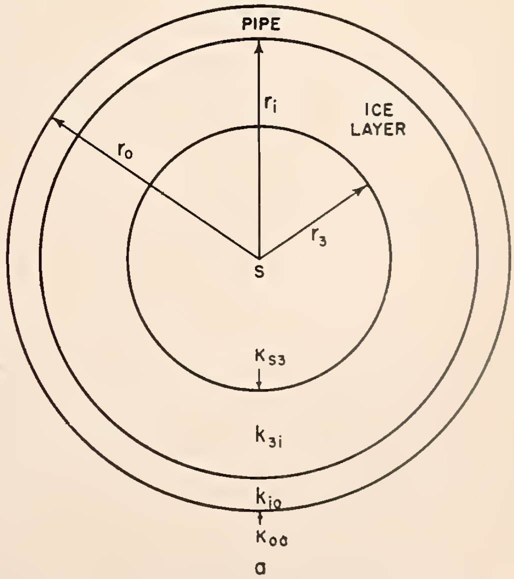

FIGURE 9. *Nomenclature used in heat transfer analysis.*

where

q_{s3} = the rate of heat transfer from the air stream to the wall

K_{s3} = the coefficient of heat transfer from the air stream to the wall

r_3 = the radius of the cylindrical opening in the vent

S_3 = the area of the inner wall $=2\pi r_3$, since unit length of vent is being considered

θ_{s3} = the difference in temperature between the wall and the air stream.

To evaluate K_{s3}, the equation given by McAdam applying to this case is used [4, p. 168]:

$$\frac{K_{s3}d_3}{k}=0.023\left(\frac{d_3\rho_1 v_3}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{0.4}, \qquad (17)$$

the notation being adapted to the present problem. In this equation

d_3 = the diameter of the cylindrical opening in the vent, in feet

k = the coefficient of thermal conductivity of the air, in Btu/(hr) (ft) (deg F)

c_p = the specific heat of the air at constant pressure, in Btu/(lb) air (deg F)

ρ_1 = the weight density of the air in the stack and vent, in lb/ft ^{3}

μ = the absolute viscosity of the air in lb/(hr) (ft)

v_3 = the velocity of air flow through the vent in ft/hr.

Equation 17 gives the value of the coefficient of heat transfer K_{s3} for the case of a fluid flowing through a chilled pipe, under the conditions that the viscosity of the fluid is not more than twice that of water and for Reynolds numbers exceeding 2,100, in other words, for turbulent flow. These two conditions are fulfilled in the problem under consideration, except that, for very low velocities in the smallest vents, the Reynolds number might be somewhat less than the value specified above.

A value of 0.78 can be taken as an average for $c_p\mu/k$. Substituting this in eq (17), we obtain

$$K_{s3}=0.027\frac{c_p(\rho_1 v_3)^{0.8}\mu^{0.2}}{d_3^{0.2}}, \qquad (18)$$

which is in agreement with McAdam [4, p. 174]. The coefficient 0.027 will be increased to 0.030 arbitrarily in an attempt to allow for heat generated by the changes in state referred to earlier. If this change is made, an average value of 0.0435 is assumed for μ, and a value of 0.25 is assumed for c_p, eq (18) reduces to the form

$$K_{s3}=\frac{0.004(\rho_1 v_3)^{0.8}}{d_3^{0.2}}. \qquad (19)$$

If this value of K_{s3} is substituted in eq (16), the following expression is obtained:

$$q_{s3}=0.004\,S_3\frac{(\rho_1 v_3)^{0.8}}{d_3^{0.2}}\theta_{s3}=0.004\pi(\rho_1 v_3 d_3)^{0.8}\theta_{s3}. \qquad (20)$$

This last equation gives the rate of heat transfer between the air stream in the vent and the inside surface of the vent (metal or ice) in British thermal units per hour per foot length of vent.

b. Transfer of Heat Through Ice Layer and Pipe Wall

The equation for the transfer of heat through a cylindrical shell is [4, p. 8]:

$$q=\frac{2\pi k_m L}{\ln(x_o/x_1)}\Delta\theta, \qquad (21)$$

where

k_m = the mean thermal conductivity of the material of the shell

L = the length of the cylindrical surface of the shell

x_o, x_1 = the radii of the outer and inner walls, respectively, of the shell

$\Delta\theta$ = the difference in temperature between the inner and outer walls of the shell.

Using eq (21), and taking the length of the cylinder, L, as unity, q_{31}, the rate of heat transfer through the ice layer, becomes, per unit length of cylinder:

$$q_{31}=\frac{2\pi k_{31}}{\ln(r_1/r_3)}\theta_{31}. \qquad (22)$$

Similarly, q_{1o}, the rate of heat transfer through the pipe wall, becomes

$$q_{1o}=\frac{2\pi k_{1o}}{\ln(r_o/r_1)}\theta_{1o}. \qquad (23)$$

c. Transfer of Heat From Outer Wall of Vent to Outer Air

The roof vent, extending vertically upward from a flat roof, may be looked upon as a single heated cylinder in a stream of cooler air flowing at right angles to its axis. The flow of air thus represents the wind blowing past the vent. For this condition McAdam [4, p. 221] gives a curve of the relation between Kd_o/k plotted against the Reynolds number, $d_o v_4\rho_4/\mu$, which applies to this case and extends to nearly the highest values of the Reynolds number that will be involved in the following computations. In the above Reynolds number, v_4 is the velocity of the wind in feet per hour, and ρ_4 is the weight density of the outdoor air in pounds per cubic foot. This curve was used in the computations that follow, and the relation that it gives can be represented by the equation,

$$K_{oa}=\frac{k}{d_o}\psi\left(\frac{d_o v_4\rho_4}{\mu}\right), \qquad (24)$$

where ψ is a functional symbol.

Substituting the value of K_{oa} given by eq (24) in eq (15), we have for the rate of heat transfer from the outer wall of the vent pipe to the outer atmosphere:

$$q_{oa}=S_o \frac{k}{d_o} \psi \left(\frac{d_o v_4 \rho_4}{\mu}\right) \theta_{oa}=2\pi r_o K_{oa} \theta_{oa}, \quad (25)$$

where q_{oa} and θ_{oa} are the rate of heat transfer per unit length of pipe, and the temperature difference between the outer wall and the air, respectively, S_o is the area of the surface of unit length of the outer wall of the vent, d_o is the outside diameter, and r_o the outside radius of the vent.

d. Computation of the Temperature of the Ice-Air Surface in the Vent

The problem is to compute the variation of the temperature of the ice-air surface in a given vent for any set of assumed conditions as the vent freezes up. If, at any stage of the icing process, the temperature of this surface rises to 32° F, the freezing will not continue further, and the pipe will remain only partly closed. If, on the other hand, the temperature of this surface does not rise as high as 32° F during the process of freezing, then the freezing will continue to complete closure, provided the conditions remain constant for a sufficiently long period.

The computations will be given in detail for a 3-in. vent in what follows. We assume a particular system in which the building drain and sewer, the stack, and the vent are all 3 in. in diameter. It will be assumed that the building sewer and drain together are 50 ft long and that the stack, including the roof vent, is 40 ft high. For the sake of concreteness, it will be further assumed that the vent projects 1 ft above the roof, although this assumption is not essential to the problem. The air temperature in the

TABLE 8. *Computation of coefficient of heat transfer from air stream in 3-in. vent to inner wall of vent*

Temperature of air in vent, 60° F; weight density of air in vent, ρ_1, 0.075 lb/ft³; $K_{a3}=0.004\frac{(3{,}600\rho_1 v_3)^{0.8}}{(d_3)^{0.2}}$.

Diameter opening in vent, d_3		Temperature of outside air	Velocity of air in vent	$3{,}600\rho_1 v_3$	$(3{,}600\rho_1 v_3)^{0.8}$	$(d_3)^{0.2}$	K_{a3}	$\frac{r_3}{r_o}$	$\frac{r_3}{r_i}$
in.	*ft*	*° F*	*fps*	*lb/ft²hr*					
3.07	0.256	−30	6.49	1,750	395	0.762	2.08	0.877	1.00
3.07	.256	−20	6.13	1,655	375	.762	2.00	.877	1.00
3.07	.256	−10	5.75	1,555	360	.762	1.89	.877	1.00
3.07	.256	0	5.31	1,435	335	.762	1.78	.877	1.00
3.07	.256	+10	4.90	1,325	315	.762	1.66	.877	1.00
3.07	.256	+20	4.35	1,175	285	.762	1.50	.877	1.00
2.5	.208	−30	9.23	2,490	520	.731	2.85	.714	0.814
2.5	.208	−20	8.80	2,375	500	.731	2.73	.714	.814
2.5	.208	−10	8.25	2,230	475	.731	2.60	.714	.814
2.5	.208	0	7.57	2,045	450	.731	2.44	.714	.814
2.5	.208	+10	6.92	1,870	415	.731	2.28	.714	.814
2.5	.208	+20	6.22	1,680	380	.731	2.08	.714	.814
2.0	.167	−30	12.85	3,470	680	.699	3.90	.571	.651
2.0	.167	−20	12.15	3,280	650	.699	3.72	.571	.651
2.0	.167	−10	11.30	3,050	615	.699	3.52	.571	.651
2.0	.167	0	10.50	2,835	580	.699	3.32	.571	.651
2.0	.167	+10	9.62	2,600	540	.699	3.09	.571	.651
2.0	.167	+20	8.63	2,330	495	.699	2.84	.571	.651
1.5	.125	−30	17.25	4,660	860	.660	5.20	.429	.489
1.5	.125	−20	16.15	4,360	820	.660	4.96	.429	.489
1.5	.125	−10	15.15	4,090	775	.660	4.68	.429	.489
1.5	.125	0	14.10	3,810	730	.660	4.42	.429	.489
1.5	.125	+10	12.90	3,480	680	.660	4.12	.429	.489
1.5	.125	+20	11.60	3,130	625	.660	3.88	.429	.489
1.0	.0833	−30	20.55	5,550	990	.608	6.51	.286	.326
1.0	.0833	−20	19.35	5,225	945	.608	6.21	.286	.326
1.0	.0833	−10	18.15	4,900	895	.608	5.88	.286	.326
1.0	.0833	0	16.80	4,535	845	.608	5.56	.286	.326
1.0	.0833	+10	15.40	4,160	785	.608	5.16	.286	.326
1.0	.0833	+20	13.75	3,720	720	.608	4.74	.286	.326
0.75	.0625	−30	21.40	5,780	1,025	.575	7.12	.214	.244
.75	.0625	−20	20.20	5,455	975	.575	6.78	.214	.244
.75	.0625	−10	18.75	5,065	920	.575	6.40	.214	.244
.75	.0625	0	17.55	4,740	875	.575	6.08	.214	.244
.75	.0625	+10	16.10	4,350	815	.575	5.68	.214	.244
.75	.0625	+20	14.30	3,860	740	.575	5.15	.214	.244
.50	.0417	−30	22.10	5,970	1,050	.530	7.92	.143	.163
.50	.0417	−20	20.80	5,615	1,000	.530	7.55	.143	.163
.50	.0417	−10	19.35	5,225	945	.530	7.12	.143	.163
.50	.0417	0	18.10	4,890	895	.530	6.75	.143	.163
.50	.0417	+10	16.60	4,485	835	.530	6.28	.143	.163
.50	.0417	+20	14.85	4,010	765	.530	5.76	.143	.163
.25	.0208	−30	22.60	6,100	1,070	.461	9.28	.0714	.0814
.25	.0208	−20	21.20	5,725	1,015	.461	8.82	.0714	.0814
.25	.0208	−10	19.95	5,390	965	.461	8.36	.0714	.0814
.25	.0208	0	18.45	4,985	910	.461	7.90	.0714	.0814
.25	.0208	+10	16.95	4,580	850	.461	7.36	.0714	.0814
.25	.0208	+20	5.35	4,145	785	.461	6.82	.0714	.0814

building sewer and drain will be taken as 50° F and that in the stack as 60° F.

With these assumptions we can compute the velocity of air flow upward through the vent for different degrees of closure of the vent, once we have assumed the temperature of the outdoor air. This temperature will be given successive values ranging from −30° F to + 20° F by 10-deg steps.

The first step in the computation is to determine values of v_3 for these different outdoor air temperatures for different degrees of closure of the vent. In order to do this we first compute the corresponding values of v_1 by using eq (14), which takes on the following simple form for the case assumed:

$$h_f=\left[r_2\left\{\frac{1}{2}+f\frac{L_2}{d_1}+C_b\right\}+r_1\left\{\frac{L_1+L_3}{d_1}+1\right\}\right]\frac{v_1^2}{2g}. \quad (26)$$

Once the value of v_1 has been computed, v_3 can be found from the relation:

$$v_3=\left(\frac{d_1}{d_3}\right)^2 v_1. \quad (27)$$

The results of this computation for an outdoor air temperature of −30° F are given in figure 8.

In computing the value of K_{s3} from eq (19), v_3 must be expressed in feet per hour, whereas in the computations dealing with pipe friction, the velocities have been expressed in feet per second. Hence we multiply the values of v_3 taken from figure 8 and similar figures not shown, by 3,600. The successive steps of the computation are given in table 8.

The value of k_{31}, the coefficient of thermal conductivity of the ice was taken as 1.0 Btu/(hr)(ft)(deg F) for ice that is assumed to be part granular and part solid. It seems probable that the layer of ice in the vent is neither entirely solid nor entirely granular; and a computation based on the assumption that the ice was solid, in which case k_{31} would be about 1.3 Btu/(hr)(ft)(deg F), gave temperature curves that seemed to be too low. Furthermore, a computation based on a value of $k_{31}=0.6$ Btu/(hr)(ft)(deg F), which would be approximately correct for granular ice, gave curves that were too high to agree well with the Winnipeg data used later in this paper as a check on the analysis. No allowance was made for the small effect of temperature on the value of k_{31}.

In order to compute K_{oa}, the coefficient of heat transfer from the outer wall of the pipe to the wind blowing past it, the curve given by McAdam [4, fig. 111] was used. Values of 3,600 $\rho_4 v_4$ were first computed for various wind velocities v_4 and outdoor temperatures θ_4 (or θ_o). Values of the Reynolds number, 3,600 $d_o\rho_4 v_4/\mu$), were next computed under the assumption that μ has the constant value, 0.0435 lb/(hr)(ft), regardless of the temperature. Next, values of $\psi(d_o\rho_4 v_4/\mu)$ were read from McAdam's curve and were multiplied by k/d_o. The values of k used for the different assumed air temperatures are indicated in table 9, together with the details of the computation of the values of K_{oa} for the 3-in. vent.

TABLE 9. *Computation of coefficient of heat transfer from outer wall of 3-in. vent to wind stream*

Outdoor air[a] temperature, θ_a	3,600 ρ_4	Wind velocity, v_4	3,600 $\rho_4 v_4$	$\frac{3,600\, d_o\rho_4 v_4}{\mu}=F$	$\psi(F)$	$\frac{k}{d_o}$	K_{oa}
°F	lb/ft³	fps					
−30	334.8	2	670	4,490	37.5	0.0429	1.61
−30	334.8	5	1,675	11,215	60.2	.0429	2.58
−30	334.8	10	3,350	22,430	88.0	.0429	3.78
−30	334.8	20	6,695	44,860	137.0	.0429	5.88
−30	334.8	40	13,390	89,725	227	.0429	9.75
−30	334.8	60	20,290	134,600	312	.0429	13.4
−30	334.8	100	33,480	224,310	470	.0429	20.1
−20	327.6	2	655	4,390	37.1	.0435	1.61
−20	327.6	5	1,640	10,975	59.5	.0435	2.59
−20	327.6	10	3,275	21,950	87.0	.0435	3.79
−20	327.6	20	6,550	43,900	134.0	.0435	5.83
−20	327.6	40	13,100	87,800	223	.0435	9.70
−20	327.6	60	19,660	131,700	307	.0435	13.4
−20	327.6	100	32,750	219,500	460	.0435	20.0
−10	320.4	2	640	4,295	36.8	.0442	1.63
−10	320.4	5	1,600	10,730	59.0	.0442	2.61
−10	320.4	10	3,205	21,470	86.1	.0442	3.81
−10	320.4	20	6,410	42,930	132.0	.0442	5.84
−10	320.4	40	12,820	85,870	220	.0442	9.72
−10	320.4	60	19,225	128,800	298	.0442	13.2
−10	320.4	100	32,040	214,670	453	.0442	20.0
0	313.2	2	625	4,195	36.4	.0453	1.65
0	313.2	5	1,525	10,500	58.3	.0453	2.64
0	313.2	10	3,130	20,980	84.7	.0453	3.83
0	313.2	20	6,260	41,970	131.0	.0453	5.93
0	313.2	40	12,530	83,940	215	.0453	9.74
0	313.2	60	18,800	125,900	294	.0453	13.3
0	313.2	100	31,320	209,850	443	.0453	20.1
+10	306.4	2	612	4,100	36.0	.0459	1.65
+10	306.4	5	1,530	10,250	57.5	.0459	2.64
+10	306.4	10	3,060	20,500	84.0	.0459	3.86
+10	306.4	20	6,120	41,000	128.0	.0459	5.88
+10	306.4	40	12,240	82,000	212	.0459	9.74
+10	306.4	60	18,360	123,000	290	.0459	13.3
+10	306.4	100	30,600	205,000	437	.0459	20.1
+20	298.8	2	598	4,005	35.6	.0470	1.67
+20	298.8	5	1,495	10,010	56.3	.0470	2.64
+20	298.8	10	2,990	20,020	82.8	.0470	3.88
+20	298.8	20	5,980	40,040	127.0	.0470	5.97
+20	298.8	40	11,950	80,080	208	.0470	9.77
+20	298.8	60	17,930	120,200	284	.0470	13.3
+20	298.8	100	29,900	200,200	430	.0470	20.2

[a] Assumed characteristics of outdoor air:

θ_a, (θ_4)	ρ_4	k	μ
°F	lb/ft³	Btu/(hr)(ft)(deg F)	lb/(hr)(ft)
−30	0.093	0.0125	0.0435
−20	.091	.0127	.0435
−10	.089	.0129	.0435
0	.087	.0132	.0435
+10	.085	.0134	.0435
+20	.083	.0137	.0435

d_o=3.5 in.=0.2917 ft; S_o=0.916 ft².

With the required values of K_{s3}, k_{31}, k_{10}, and K_{oa} determined,[4] the procedure of computing the temperatures of the ice-air surface under various assumed conditions is as follows: First, eq (20,

[4] Eq (19) and (24) give the methods for determining K_{s3} and K_{oa}, respectively. k_{3i} is assumed to be 1.0 Btu/(hr)(ft)(deg F) for partly granular ice. k_{io} is about 0.3 Btu/(hr)(ft)(deg F) for asbestos cement, and about 30 Btu/(hr)(ft)(deg F) for steel or cast iron.

22, 23, and 25) are adopted in the form

$$q_{s3}=2\pi r_3 K_{s3}\theta_{s3}, \tag{20a}$$

$$q_{31}=(2\pi k_{31})/\ln(r_1/r_3)\theta_{31}, \tag{22a}$$

$$q_{1o}=(2\pi k_{1o})/\ln(r_o/r_1)\theta_{1o}, \tag{23a}$$

$$q_{oa}=2\pi r_o K_{oa}\theta_{oa}. \tag{25a}$$

These equations are next written in the form

$$\frac{\theta_{s3}}{q_{s3}}=R_{s3}=\frac{1}{2\pi r_3 K_{s3}}, \tag{20b}$$

$$\frac{\theta_{31}}{q_{31}}=R_{31}=\frac{\ln(r_1/r_3)}{2\pi k_{31}}, \tag{22b}$$

$$\frac{\theta_{1o}}{q_{1o}}=R_{1o}=\frac{\ln(r_o/r_1)}{2\pi k_{1o}}, \tag{23b}$$

$$\frac{\theta_{oa}}{q_{oa}}=R_{oa}=\frac{1}{2\pi r_o K_{oa}}. \tag{25b}$$

Adding:

$$\sum\frac{\theta}{q}=\Sigma R=\frac{1}{2\pi}\left[\frac{1}{r_3 K_{s3}}+\frac{\ln(r_1/r_3)}{k_{31}}+\frac{\ln(r_o/r_1)}{k_{1o}}+\frac{1}{r_o K_{oa}}\right]. \tag{28}$$

Since $q_{s3}=q_{31}=q_{1o}=q_{oa}$ and $\theta_{s3}+\theta_{31}+\theta_{1o}+\theta_{oa}=\theta_{sa}=\theta_s-\theta_a$, then

$$\theta_{s3}=\theta_s-\theta_3=(\theta_s-\theta_a)\frac{R_{s3}}{\Sigma R}, \tag{29}$$

where

θ_s=the temperature of the airstream in the vent in degrees Fahrenheit

θ_a=the temperature of the outdoor air in degrees Fahrenheit ($=\theta_4$)

θ_3=the temperature of the ice-air surface in the vent in degrees Fahrenheit.

From eq (28) and (29) the following expression is obtained:

$$\frac{\theta_s-\theta_3}{\theta_s-\theta_a}=\frac{R_{s3}}{\Sigma R}=N$$

$$=\frac{1}{\frac{\ln(r_1/r_3)}{k_{31}}+\frac{\ln(r_o/r_1)}{k_{1o}}+\frac{1}{r_3 K_{s3}}+\frac{1}{r_o K_{oa}}}\cdot\frac{1}{r_3 K_{s3}}, \tag{30}$$

and

$$\frac{1}{N}=r_3 K_{s3}\left[\frac{\ln(r_1/r_3)}{k_{31}}+\frac{\ln(r_o/r_1)}{k_{1o}}+\frac{1}{r_3 K_{s3}}+\frac{1}{r_o K_{oa}}\right]$$

$$=\frac{r_3 K_{s3}}{k_{31}}\ln(r_1/r_2)+\frac{r_3 K_{s3}}{k_{1o}}\ln(r_o/r_1)+1+\frac{r_3 K_{s3}}{r_o K_{oa}}. \tag{31}$$

Then

$$\frac{1}{N}-1=\frac{\theta_3-\theta_a}{\theta_s-\theta_3}=(r_3/r_1)r_1 K_{s3}\left[\frac{1}{k_{31}}\ln(r_1/r_3)+\frac{1}{k_{1o}}\ln(r_o/r_1)+\frac{1}{r_o K_{oa}}\right], \tag{32}$$

since, from eq (30), $N=(\theta_s-\theta_3)/(\theta_s-\theta_a)$.

For a given θ_s and θ_a, freezing will continue, and r_3/r_1 will decrease, until θ_3 increases to 32° F. That is, the vent will continue to freeze up until N decreases below a value,

$$N=(\theta_s-32)/(\theta_s-\theta_a). \tag{33}$$

The temperature of the ice-air surface can now be computed from eq (32) for any assumed conditions. The results of this computation for a 3-in. metal vent are given in table 10 for a wind velocity

Table 10. *Computation of temperature of ice-air surface in 3-inch vent.*

r_o=1.75 in.=0.146 ft; θ_s=60° F; r_i=1.53 in.=0.128 ft; k_{3i}=1.0 Btu/(hr) (ft) (deg F); v_4=10 fps.

$2r_3$	θ_a	K_{s3}	K_{oa}	$\frac{\theta_3-\theta_a}{\theta_s-\theta_3}$	θ_3	r_3/r_1
in.	° *F*				° *F*	
3.07	−30	2.08	3.78	0.482	−0.7	1.00
3.07	−20	2.00	3.79	.463	+5.3	1.00
3.07	−10	1.89	3.81	.435	11.2	1.00
3.07	0	1.78	3.83	.407	17.4	1.00
3.07	+10	1.66	3.86	.377	23.7	1.00
3.07	+20	1.50	3.88	.339	30.1	1.00
2.50	−30	2.85	3.78	.600	+3.7	0.814
2.50	−20	2.73	3.79	.574	9.2	.814
2.50	−10	2.60	3.81	.543	14.6	.814
2.50	0	2.44	3.83	.508	20.2	.814
2.50	+10	2.28	3.86	.471	26.0	.814
2.50	+20	2.08	3.88	.428	32.0	.814
2.00	−30	3.90	3.78	.731	+8.0	.651
2.00	−20	3.72	3.79	.697	12.9	.651
2.00	−10	3.52	3.81	.651	17.6	.651
2.00	0	3.32	3.83	.617	22.9	.651
2.00	+10	3.09	3.86	.568	28.1	.651
2.00	+20	2.84	3.88	.520	33.7	.651
1.50	−30	5.20	3.78	.828	+10.8	.489
1.50	−20	4.96	3.79	.786	15.2	.489
1.50	−10	4.68	3.81	.738	19.7	.489
1.50	0	4.42	3.83	.692	24.6	.489
1.50	+10	4.12	3.86	.644	29.6	.489
1.50	+20	3.88	3.88	.601	35.0	.489
1.00	−30	6.51	3.78	.798	+9.9	.326
1.00	−20	6.21	3.79	.761	14.6	.326
1.00	−10	5.88	3.81	.715	19.2	.326
1.00	0	5.56	3.83	.675	24.2	.326
1.00	+10	5.16	3.86	.623	29.2	.326
1.00	+20	4.74	3.88	.569	34.5	.326
0.75	−30	7.12	3.78	.715	+7.5	.244
.75	−20	6.78	3.79	.681	12.4	.244
.75	−10	6.40	3.81	.642	17.4	.244
.75	0	6.08	3.83	.608	22.7	.244
.75	+10	5.68	3.86	.565	28.1	.244
.75	+20	5.16	3.88	.512	33.5	.244
.50	−30	7.92	3.78	.601	+3.8	.163
.50	−20	7.56	3.79	.571	9.1	.163
.50	−10	7.12	3.81	.536	14.4	.163
.50	0	6.74	3.83	.507	20.2	.163
.50	+10	6.28	3.86	.471	26.0	.163
.50	+20	5.76	3.88	.430	32.0	.163
.25	−30	9.28	3.78	.418	−3.5	.0814
.25	−20	8.82	3.79	.397	+2.7	.0814
.25	−10	8.36	3.81	.375	9.1	.0814
.25	0	7.90	3.83	.354	15.7	.0814
.25	+10	7.36	3.86	.329	22.4	.0814
.25	+20	6.82	3.88	.304	29.3	.0814

of 10 ft/sec and are plotted in figure 11. Similar temperature curves are shown in figures 10, 12, 13, 14, and 15 for 1½, 4, 6, 8, and 12-in. vents, respectively. The numbers appearing on the curves refer to the corresponding outdoor temperatures in degrees Fahrenheit. Because of the high thermal conductivity of a metallic vent and the negligible temperature drop through the wall of such a vent, the term $(1/k_{10})\ln(r_o/r_1)$ in eq (32) can be omitted without appreciable error. This has been done in computing the temperature curves shown in the above-mentioned figures. The heights of stack and vent assumed for diameters of 1½, 4, 6, 8, and 12-in. stacks were 30, 60, 100, 150, and 200 ft, respectively. The total length of the building sewer and building drain was taken as 50 ft in all cases. The assumed air temperatures in the building sewer, drain, and stack were the same as for the 3-in. stack.

Returning now to figure 11, it will be observed that the curve for an outside air temperature of 20° F crosses the line representing a temperature of 32° for the ice-air surface. Hence the vent would frost up until the diameter of the opening corresponds to the ratio, r_3/r_i, for which this occurs. The moisture deposited on the ice surface thereafter will not freeze but will run down the surface. Thus the dashed portion of the curve lying above the intersection of the 20° curve with the 32° line represents conditions that are physically impossible. In fact, the solid portion of the curve lying to the right of the dashed portion is also physically impossible for a vent that is freezing up. However, it may represent physical facts for a vent that is thawing.

To illustrate the effect of different wind velocities on the temperature of the ice-air surface as the vent freezes up, figure 16 was prepared for a 3-in. vent, an outside air temperature of −30° F and different wind velocities from 2 to 90 ft/sec

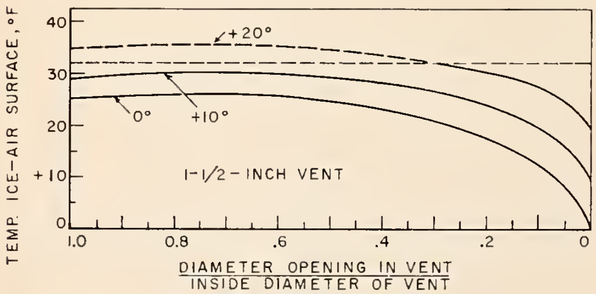

FIGURE 10. *Temperatures of the ice-air surface in a 1½-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec as the vent freezes up.*

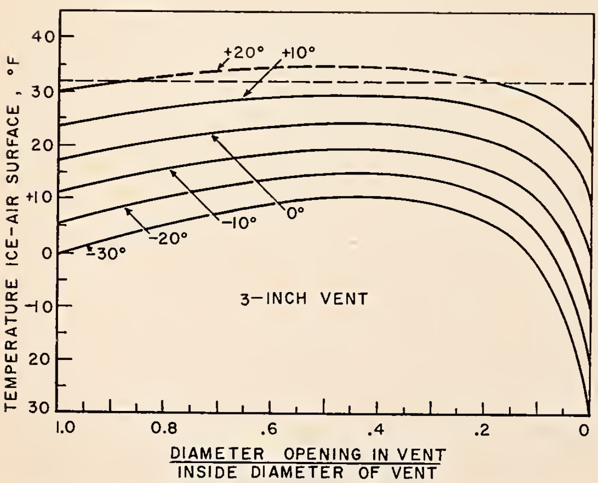

FIGURE 11. *Temperatures of the ice-air surface in a 3-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec as the vent freezes up.*

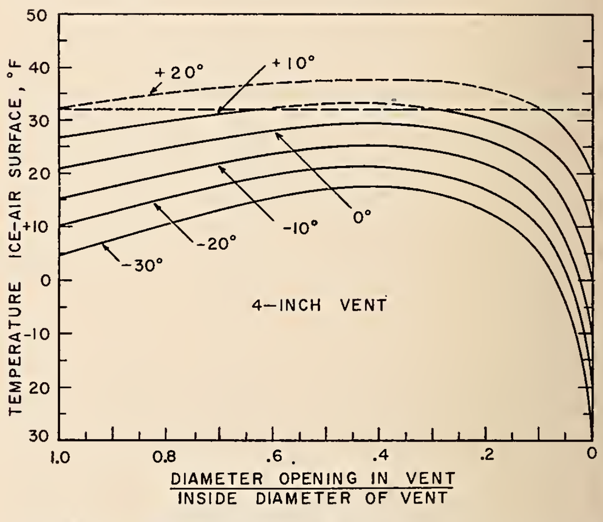

FIGURE 12. *Temperatures of the ice-air surface in a 4-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec as the vent freezes up.*

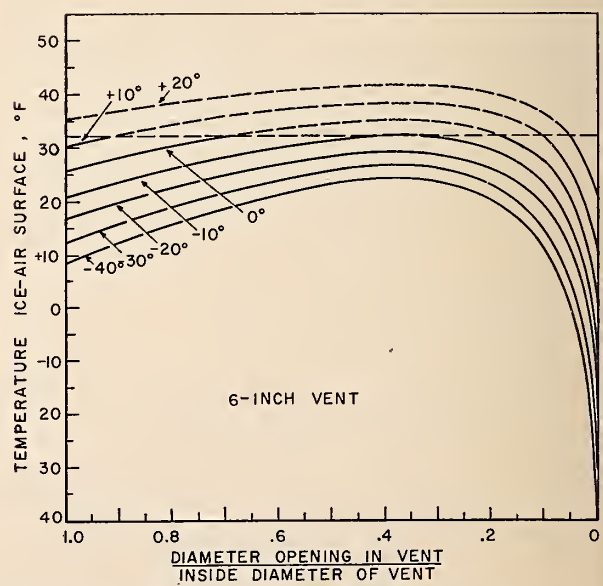

FIGURE 13. *Temperatures of the ice-air surface in a 6-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec as the vent freezes up.*

being assumed. None of these curves crosses the 32° F line; hence it is concluded that, given an outside air temperature of −30° F, a 3-in. vent will always freeze up solid, given sufficient time.

Finally, in order to show the effect of using for the vent pipe a material offering considerable resistance to the flow of heat, instead of the customary metal pipe, there are shown in figure 17 curves of the temperature of the ice-air surface in a 4-in. vent, first when the vent pipe is metal, and second when it is asbestos-cement. Asbestos-cement, having a thermal conductivity of 0.3 Btu/(hr)(ft)(deg F), was used for this comparison because this pipe is coming into use for dry vents. In computing the temperature curves for asbestos-cement, it was necessary to take into account the second term in the bracket in eq (32) involving the heat transfer through the wall of the vent pipe. The improvement in conditions attained by using this material in place of steel or cast iron (or any other metal) is definite. Evidently very heavy thermal insulation is necessary if complete protection against frost closure is to be achieved by this means, however.

The temperature curves bring out one puzzling feature of the phenomenon. The frost in a completely closed vent will presumably begin to thaw outward from the center when the outside air

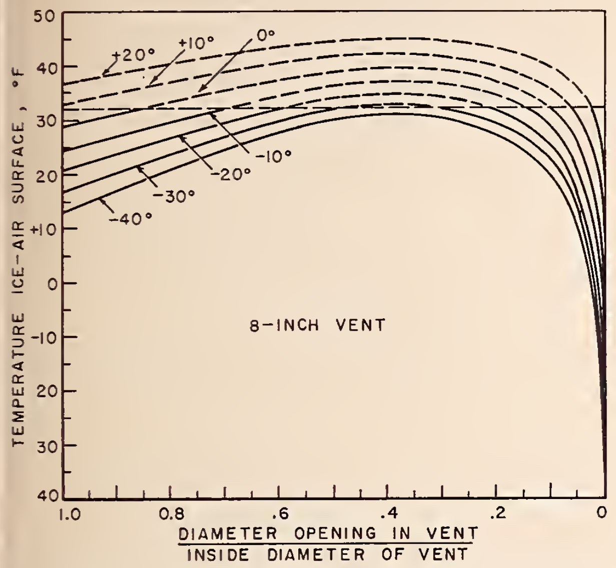

Figure 14. *Temperatures of the ice-air surface in an 8-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec as the vent freezes up.*

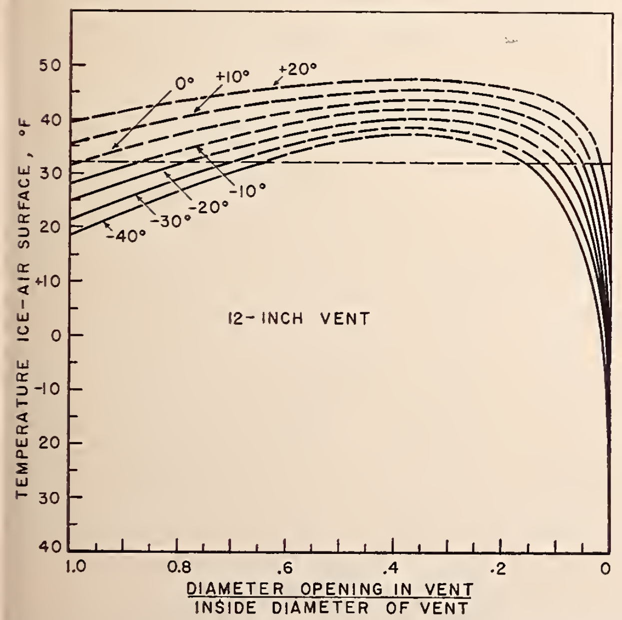

Figure 15. *Temperatures of the ice-air surface in a 12-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec as the vent ferezes up.*

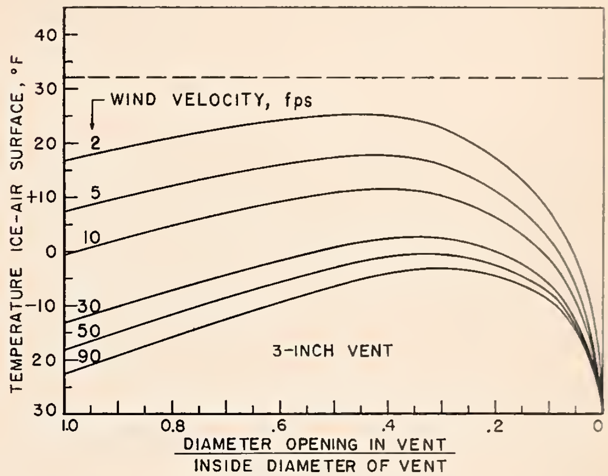

Figure 16. *Temperatures of the ice-air surface in a 3-in. vent for an outside air temperature of −30° F and for different wind velocities as the vent freezes up.*

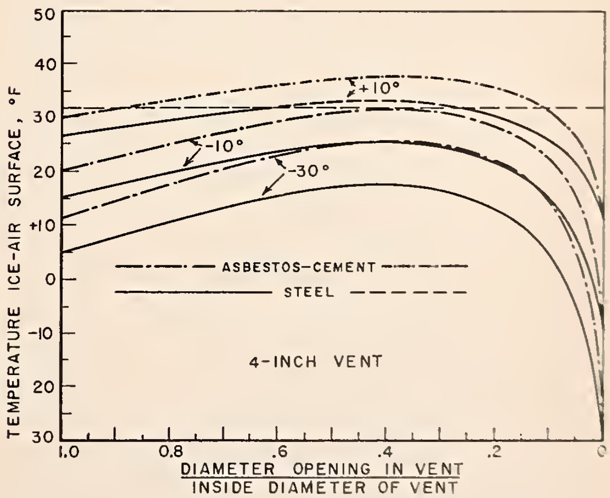

Figure 17. *Temperatures of the ice-air surface in a 4-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec.*

Comparison of steel and asbestos-cement vent pipes.

temperature rises. For example, referring to figure 12, which gives the temperature of the ice-air surface in a 4-in. vent for different outside air temperatures and for a wind velocity of 10 ft/sec, it is clear that, if the outside air temperature is −10° F, for example, frosting will continue until complete closure results, given sufficient time, because the temperature of this surface remains below 32° F for all degrees of closure of the vent.

Now suppose that the outside air temperature rises to and remains at 20° F. Since, when the vent is completely filled with frost, the temperature of the frost in the vent is equal to the temperature of the outside air, the temperature of the frost will rise with the outside air temperature to 20° F and should remain there. Thus it would seem at first sight as if the vent should not start to thaw out until the temperature of the outside air had risen above 32° F. Yet there is evidence that this is not the case. The data from Winnipeg, presented earlier in this paper, appear to contradict this.

Further consideration of the problem leads to a possible explanation of the phenomenon. It is very likely that there does not exist in the exposed part of the vent a layer of ice of uniform thickness. When the vent is completely closed for some distance down from the top, it is likely that the thickness of the layer of ice tapers off in the downward direction, as shown in figure 18. Whether there exists a very small opening through the vent when what has been assumed to be complete closure exists is not known. However, when the experimental vents that were presumably completely closed were inspected visually from the top, a small opening was seen, which apparently tapered off to zero a short distance down from the top. It may be, however, that this small opening merely deviated sidewise until it was lost to view.

If figure 18 represents the actual conditions, then there would be a current of warm air rising in the center of the vent, coming in contact with the ice, chilling, and then flowing downward in the neighborhood of the ice layer. A condition of approximate equilibrium would be attained as long as the outside air temperature remained low, say −10° F, with the ice in the portion of the vent that is frozen up completely attaining this same temperature.

Suppose now that the outside air temperature rises to 20° F. Then the ice in the completely frozen part of the vent would soon attain this latter temperature (see fig. 18). The condition of equilibrium that had been established would then be upset, and the current of warm air would begin to melt some of the ice with which it comes in contact. The upper point of the conical cavity shown in figure 18 would move upward until a clear opening might be established, air would then begin to pass upward and out of the vent, and the conditions assumed earlier for the freezing of vents in general would be established once more. Under these conditions, presumably the appropriate curve shown by the solid line at the right-hand edge of the appropriate figure (fig. 12 for a 4-in. vent) would be valid.

The Winnipeg data shown in figure 2 afford a rough check on the analysis made in this paper. The comparison is shown in figure 19. The curves in this figure were obtained as follows: From figure 11 we see that the 20° F curve for the 3-in. vent crosses the 32° F line at a value of the ratio r_3/r_i of approximately 0.86, or for a diameter of opening of 2.6 in. That is, if the outside air temperature is 20° F, the vent would freeze to this point and then stop. This establishes the point plotted on the line in figure 19 for the 3-in. vent. Furthermore, it is estimated from figure 11 that, if the temperature of the outside air should fall to about 14° F, the temperature curve (if plotted in figure 11) would just miss reaching a temperature of

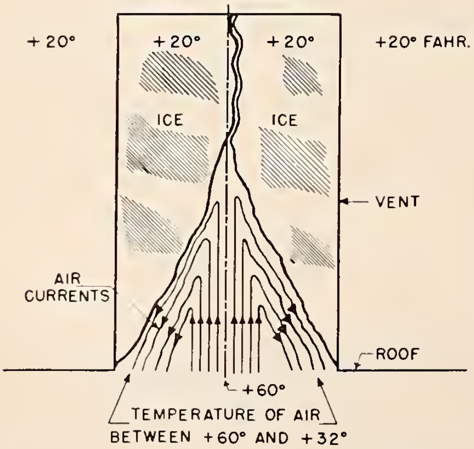

Figure 18. *Conjectured form of so-called complete closure of a roof vent by frost.*

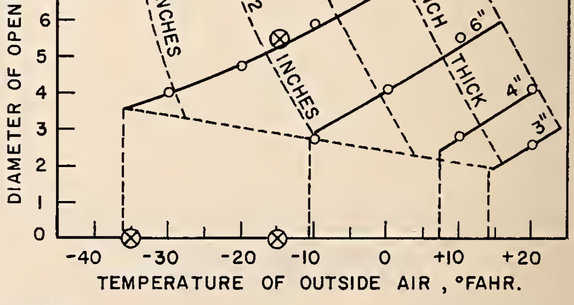

Figure 19. *Comparison of computed temperatures of ice-air surface with data from Canada for 6- and 8-in. vents.*

32° F at its highest point. In other words, the vent would freeze up completely for air temperatures of 14° F and below, given sufficient time. This is indicated by the vertical line drawn in figure 19 through a temperature of 14° F.

Similarly, we see from figure 12 for the 4-in. vent that the vent barely starts to freeze if the temperature of the outside air is 20° F. This establishes a point on the line for the 4-in. vent in figure 19. Another point is established by observing that, if the temperature of the outdoor air is 10° F, the vent will stop freezing when the ratio r_3/r_i takes on a value of about 0.73 (diameter of opening about 3.0 in.). This establishes the other point plotted in figure 19 for this diameter vent. We note also from figure 12 that the highest outdoor air temperature for which the curve (if plotted) would miss touching the 32° F line is about 8° F. This establishes the vertical line through the temperature of 8° F, connecting with the curve for the 4-in. vent. The significance of these vertical lines is that, as we move downward and to the left along the curve for any given vent, when the conditions corresponding to the intersection of the vertical line and the curve are reached, freezing will continue until complete closure results. The other curves for vents 6, 8, and 12 in. in diameter in figure 19 were obtained in this same way.

Now, considering figure 2, we note that the 8-in. stack on the Grain Exchange was found to be completely closed on January 6, when the minimum daily temperature was −35° F. This is represented by a large circle plotted on the base line of figure 19. Had the agreement been perfect, it would have coincided with the vertical line for the 8-in. vent. Obviously the agreement is quite good—better than might have been anticipated.

We next consider the observation of the same vent on February 17. On this date the opening in the vent was found to be about 5.5 in. in diameter, and the daily minimum air temperature at that time was about −15° F. It can be seen from figure 19 that this point also agrees very well with the computed curve.

We consider also the observation for the 6-in. stack at the Grain Exchange on January 29, at which time the stack or vent was observed to have closed up when the daily minimum temperature was about −15° F. This point, when plotted in figure 19, lies a little to the left of the line plotted for the 6-in. vent. Thus the agreement is still good, if not quite as satisfactory as for the 8-in. vent.

Although these three available observations show good agreement with the computed curves and hence will be taken as reasonably good justification for the computed temperature curves given in this paper, too much reliance should not be placed on the exactness with which the computed curves fit the actual conditions. It should be remembered that we do not have adequate information in regard to the Winnipeg data. We do not know the exact day on which the vents closed up because the observations were made only at infrequent intervals, and hence we are not sure of the daily minimum temperature on the actual day of closure. We do not know the daily average temperatures, but only the minimum temperatures. We do not know how the wind velocity varied during the period in question. Hence the comparison should be looked upon merely as a rough verification.

Curves similar to those shown in figures 10, 11, 12, 13, 14, and 15 were computed, using a value of 0.6 Btu/(hr)(ft)(deg F) for k_{3i} for the ice (corresponding to completely granular ice), and these curves looked more reasonable for the small-diameter vents than do those shown in the above-mentioned figures, but they did not agree at all with the Winnipeg data. Further experimental investigation and more detailed field data are needed to study the matter further.

7. Test Procedure

For the purpose of studying frost closure, plumbing systems may be considered as comprising two broad classes. The first class will include systems having a water seal in the drain downstream from the stack without a vent to the atmosphere on the house side of the water seal. This condition may exist if a running house trap without a fresh-air inlet is used (or in case the fresh-air inlet is plugged or closed off), or it may occur if the street sewer is so full that the outlet end of the house sewer is submerged. It is much more likely, however, that the second class of installation will be found in service. In this class the house drainage system is connected directly to the street sewer or a septic tank without any water seal in the horizontal drain from the base of the stack. Here the air and sewer gases may pass directly through the house drainage system in response to whatever forces are causing the flow to take place. An installation having a fresh-air inlet to the house trap might also be placed in this class, as far as the flow of air through the stack is concerned, although air entering through the house trap will have relatively low humidity, and hence in this respect it will tend to promote less frosting of the roof vent than if it were saturated. Also the air stream up through the system will be colder, and the rate of flow will be less than if there were a connection between the street sewer and the building system.

Tests were made by using the laboratory setup shown in figure 4, with the temperature of the air surrounding the top of the stack maintained at a constant value during each run. The temperature was about −30° F in most of the tests, although a few runs were made at a lower temperature.

For those tests in which the case of an unvented house trap was simulated, a trap was installed in the house drain near the base of the stack. Warm water was introduced through the bathtub at a rate of about 1.8 gal/min, and the water closet was flushed at regular intervals of time. The roof vent was observed periodically (once or twice daily) for evidence of frosting.

In most of the testing, however, no trap was used in the house drain, and air was forced through the system by a blower at the base of the stack, simulating the convective air current that would exist in a service installation.

An important consideration in connection with the tests was that of maintaining approximately a constant pressure differential available for producing air flow through the system. For a given height of stack in service and a given temperature difference between the air inside of the stack and the outside air, the differential can be approximated from table 1 or figure 7, or it can be computed from eq (4). In the test installation, it was possible to attain flow conditions approximating those that would be expected in service for the same stack by adjusting the blower so that a pressure reading ($h_m = h_e$) was obtained on the inclined manometer shown in figure 4, such that h_{ft} computed from eq (8) was equal to h_{fs} computed from eq (4).

It can be seen readily that, in order to simulate flow conditions closely, not only must the pressure differential for overcoming friction be maintained in the test setup at the same value as in the service installation simulated for the given temperature conditions, but also that the physical dimensions, or at least the overall flow resistance, of the setup must be the same as in the corresponding service installation. When these conditions are not attained, it may be that either more or less air flow is actually produced in the test installation than in any particular service installation, even though the pressure available for producing air flow be made the same in the two cases. In addition, for a given pressure differential h_f through the system and for a given roof vent, the greater the frictional resistance of the stack, building drain, and building sewer, the less will be the relative effect of a given degree of frosting of the roof vent on the volumetric rate of air flow through the system.

The importance of the factors mentioned in the above paragraph was not fully appreciated at the time when these tests were made. Actually, many of the tests were made using purely arbitrary settings for the pressure differential; hence it is unfortunate that flow conditions identical to those that would occur during frosting in service with the same setup were not produced.

It was necessary to make frequent calculations and adjustments in order to make available approximately a constant pressure differential for producing air flow as each test run progressed because the accumulation of frost and changes in room temperature would in a short time result in a differential differing from that which was desired. In making a complete cycle of computation, temperature and pressure differential readings, and adjustment every hour during the tests, it is believed that the effect of this tendency for the test setup to get out of adjustment was minimized, although it was soon evident that highly accurate control over the pressure differential could not be maintained with the test setup used.

Air and water temperatures were measured at points shown in figure 4. The water discharging into the stack was maintained at a constant temperature during each run, being as high as 120° F in a few runs, although a temperature of from 70° to 80° F was used in most of the tests, since higher temperatures were evidently not needed to maintain a high humidity in the air stream.

The average stack temperature was computed from readings of the air temperatures inside of the stack, these temperatures being measured by a remote-recording device. The average temperature in the stack was maintained as nearly constant as possible during each run. The temperature of the air around the roof vent was also maintained approximately constant.

The thickness of the accumulation of frost inside the vent was observed once or twice a day. Relative humidities in the stack and in the room in which the test installation was located were obtained from wet and dry-bulb temperature readings. The rate of flow of air through the system was determined from readings of the pressure drop across the orifice through which the mixture of air and carbon dioxide escaped to the atmosphere. The ratio of carbon dioxide to air was determined by the special device mentioned earlier and was taken into account when the rate of flow of air through the system was calculated.

During intervals when the apparatus was not in use overnight or on weekends, the top of the roof vent and the outlet to the cold chamber were plugged, and the chamber was filled with dry ice. In this way the accumulation of frost in the vent was apparently preserved fairly well in most instances until the next work day, when the test was continued. However, these interruptions may have changed the nature of the surface of the ice from a porous condition to a solid condition and hence may have influenced the further freezing of the vent. An effort was made to continue each test run until the vent ceased to accumulate frost. In some instances this meant carrying the test to complete closure of the vent.

The primary object of the tests was to ascertain if roof vents 1½, 3, and 4 in. in diameter could be frozen up completely. However, in some of the tests the effect of varying the rate of air flow through the vent was investigated, while in other tests the effect of varying the temperature inside the stack was studied. Maintenance of relatively low humidity in the stack was found to be too difficult to warrant an investigation of this factor; and, in any event, low humidity would tend to decrease the rate of frosting of the vent. The humidity in the stack approached saturation at all times during the tests, apparently because of the continual flow of water into the stack. However, as mentioned earlier in the paper, the humidity measurements made in the stack possibly indicated a greater degree of humidity than may actually have existed. Evidence has been found from observations in Canada that, when hot water is discharged into the stack, there is an increased tendency to frost closure, apparently because of the high humidity thus created.

The dimensions of the vent exposed to low temperature in the cold chamber were varied. In addition to tests on a 3-in. stack, which continued undiminished in diameter into the cold chamber, tests were run on the system with a 1½-in. vent pipe mounted on top of the 3-in. stack. The 1½-in. pipe was 38 in. long and extended 15 in. up into the cold chamber in most of the runs, but in a few tests only 6 in. of its length extended up into the chamber. A few runs were made on a 4-in. roof vent 38 in. long extending 15 in. into the cold chamber.

8. Test Results

8.1. Tests on System With House Trap

A few tests were made in which a house trap without a fresh-air inlet was installed in the house drain. In these tests no attempt was made to create a forced draft through the system. The unvented house trap eliminated the normal convective draft. The temperature of the air surrounding the upper 15 in. of the 3-in.-diameter roof vent was approximately −30° F in most of these tests, and the mean temperature of the air in the stack varied from 65° to 78° F. Runs varying in length from 3 to 24 hr were made. A constant flow of warm water was introduced to the stack throughout the tests, and the water closet was flushed at 1-hr intervals. In no case was there more than a slight surface coating of frost in the roof vent at any time.

8.2. Tests on System With Air Flow up Stack

This case corresponds to a service system in which there is free passage of air from the street sewer up through the stack and vent to the outer air. The tests were made on a test installation in which an upward flow of air in the stack was maintained by means of a blower at a rate reasonably representative of service conditions. In these tests partial or complete closure of the vent occurred in most instances. Four different vent conditions were tested: (a) 1½-in. vent on a 3-in. stack, with a length of 15 in. exposed to the low temperature, (b) the same, but with a length of 6 in. exposed to the low temperature, (c) the 3-in. stack unchanged in diameter and having a 15-in. exposure, and (d) the vent enlarged to 4 in. and extending 15 in. up into the cold chamber. The test data relating to temperature and flow conditions for the 1½-in. vent are given in table 11, and the data for the 3-in. and 4-in. vents are given in table 12.

TABLE 11. *Temperatures and flow conditions existing in frost-closure tests*

1½-in.-diameter vent exposed to temperature of approximately −30° F. Length of vent exposed to low temperature 15 in., except in runs 15, 16, and 17, in which the length was 6 in.

Run	Approximate head (in. of water) available for producing flow		Approximate air velocity in roof vent at beginning of run	Average temperature of air entering roof vent	Average temperature of air in stack
	At beginning of run	Average for entire run			
			fps	*°F*	*°F*
1	0.013	0.015	2.3	78	77
2	.018	.019	4.0	76	75
3	.020	.026	4.9	69	68
4	--------	.048		79	78
5	--------	.060	6.0	68	68
6	--------	.075	6.2	73	75
7	.072	.080	9.6	76	73
8	.066	.084	9.2	74	73
9	.070	.086	9.6	75	74
10	.083	.093	8.2	72	72
11	--------	.100	--------	68	68
12	.094	.102	9.4	72	72
13	.092	.102	10.2	72	71
14	.103	.106	9.4	66	66
15	.018	.024	5.3	78	75
16	.046	.042	6.4	74	72
17	.057	.056	8.3	70	68

TABLE 12. *Temperatures and flow conditions existing in frost-closure tests*

3- and 4-in.-diameter roof vents exposed for a length of 15 in. to a temperature of approximately −30° F.

Run	Approximate head (in. of water) available for producing flow		Approximate air velocity in roof vent at beginning of run	Average temperature of air entering roof vent	Average temperature of air in stack
	At beginning of run	Average for entire run			
3-in.-diameter roof vent					
			fps	*°F*	*°F*
18	--------	--------	--------	70	69
19	0.065	0.064	2.2	72	71
20	.136	.131	4.2	75	72
21	.129	.134	3.4	69	68
22	.137	.136	3.6	71	70
4-in.-diameter roof vent					
23	0.064	0.065	2.1	74	73
24	.066	.066	1.7	75	73
25	.105	.096	2.6	73	71

One interesting observation applying to most of the data obtained from tests in this investigation is that the freezing up of the vents—that is, the increase in thickness of the ice or frost layer—apparently was approximately linear with time. There is, however, no reason to believe that this would always be the case; in fact, there is reason to believe that, for certain temperature conditions, and especially for large stacks, there would be a decreasing rate of frost closure with increased thickness of the ice layer. Possibly it was merely a coincidence that the tests reported here yielded results indicating that closure is linear with time, or it may be that this is actually true generally in the case of small diameter roof vents. These matters have not been investigated adequately.

The data from the tests on 1½-in. vents are shown in figure 20. From this figure and the data in table 11, it is apparent that there is no consistent correlation of rate of freezing with stack temperature or rate of air flow. However, in this connection a number of runs (not shown in the above data) were made, using appreciably higher rates of air flow than existed in the tests shown in figure 20, other conditions being similar. In nearly all instances in which the mean air velocity in the 1½-in. vent at the beginning of a run exceeded about 10 ft/sec, little or no frost accumulation was noted. This was possibly due in part to the air stream not being cooled sufficiently when passing through the vent at high velocity to permit freezing in the vent to take place. Another explanation suggested by the operator of the test apparatus is that apparently a high-velocity air flow scours the frost accumulation off the wall as fast as it can form. It was noted in the tests at the higher air velocities that a more or less continuous spray of frost particles issued from the roof vent, indicating confirmation of one or both of the above suppositions.

Probably there is a gradual increase in rate of frosting with increase in rate of air flow, starting from zero flow and continuing up to a certain

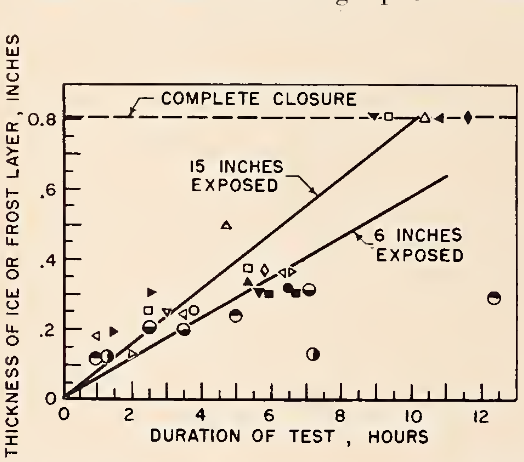

FIGURE 20. *Experimentally determined rates of frost closure for a 1½-in.-diameter roof vent exposed to outside air temperatures of approximately −30° F.*

Symbol	Run	Symbol	Run
○	1	◁	9
●	2	◀	10
□	3	▽	11
■	4	▼	12
△	5	◇	13
▲	6	◆	14
▷	7	◒	15*
▶	8	◓	16*
		◑	17*

*6-in. length of vent exposed. All other runs, 15 in. exposed.

intermediate range of flow rates, beyond which there is a sharp decrease in rate of frosting to near zero. Probably this curve is rather flat at intermediate flows, which may account for the fact that only inconclusive correlation of rate of frosting with air velocity was measured in tests at intermediate flows.

Summarizing the results on 1½-in. vents (fig. 20), we find that in the case of the 15-in. exposure, where all observations are given equal weight and the temperatures are averaged (stack temperature approximately 72° F, temperature of the air entering the roof vent approximately 73° F, and the temperature of the air surrounding the exposed portion of the roof vent approximately −30° F), the overall average rate of frosting was 0.080 in./hr. It is interesting to note that if only the 5 points that represent the runs leading to complete closure are considered, again an average rate of frosting of 0.080 in./hr is obtained. It will be explained here that by rate of frosting is meant the rate of increase in thickness of the frost or ice layer adhering to the inner surface of the roof vent, not the decrease in diameter, which would be double the rate specified. It is realized that this is not a definite dimension, but that the frost layer is very likely to be very irregular in thickness and in general will probably be thickest at some distance from the base of the roof vent, undoubtedly near the top in the case of a relatively short roof vent. In the data taken in the present investigation, an attempt was made to record the average thickness of the frost layer at the section of minimum opening. It is undoubtedly true that this method of estimating by visual inspection gave rise to appreciable errors.

The data obtained showed slightly better correlation of rate of frosting as affected by the temperature of the air entering the roof vent. The lowest air temperatures gave rates of frosting greater than did the highest air temperatures, there being a difference of about 8 to 10 deg F in the temperatures compared (comparison of runs 3, 5, and 11 with runs 1, 2, and 4). Nevertheless, because the results are so erratic in this respect, especially for the intermediate stack temperatures, little else can be inferred from the results. Probably the erratic nature of the phenomenon of frosting of vents, the unavoidable variations in flow and temperature conditions during the test runs, the limited range of stack temperatures and pressure differentials covered, the fact that partial loss of the frosted layer or changes in the nature of the layer took place in some of the runs when it was necessary to shut down the apparatus over night or over a holiday before continuing the run, and last, but not least, the very rough method employed in observing frost accumulation, all may have contributed to the inconclusiveness of the data on the effects of temperature and air flow.

Only limited data were obtained on the effect of roof-vent length on rate of closure. The data for the 6-in. exposure are shown in figure 20 as runs 15, 16, and 17. The data are badly scattered; hence detailed conclusions are not warranted. However, averaging all observations given, the average rate of closure was 0.059 in./hr, when the average stack temperature was approximately 72° F, and the average temperature of the air entering the roof vent was approximately 74° F. This rate is about 26 percent less than was obtained with a 15-in. exposure under substantially the same conditions.

The data for five tests on the 3-in. vent with a 15-in. exposure are shown in figure 21. For the only test that was carried to complete closure, run 19, the average rate of closure was 0.069 in./hr, which is about 14 percent less than the rate found for the 1½-in. vent having the same exposure length. In this run the average stack temperature was approximately 71° F. and the average temperature of the air entering the roof vent was approximately 72° F. It will be noted that figure 21 does not show run 19 going to complete closure but shows only the first two observations. The reason for this omission is that sometime after the 13th hr of the run, the temperature-control system failed, resulting in a partial loss of the ice layer in the vent. As the exact length of the period during which the ice layer had suffered reduction is unknown, we do not know just when the ice layer was restored to its original thickness, this having been accomplished after the apparatus was repaired. Thereafter apparent complete closure occurred within a few hours. The average rate of closure of 0.069 in./hr given above is based on the two observations shown in figure 21.

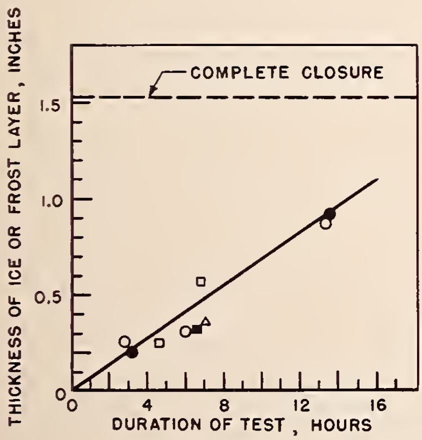

FIGURE 21. *Experimentally determined rates of frost closure for a 3-in.-diameter roof vent exposed 15 in. to outside air temperatures of approximately −30° F.*

Symbol	Run
○	18
●	19
□	20
■	21
△	22

Unfortunately none of the three runs shown in figure 22 for the 4-in. vent was carried to complete closure. Averaging all observations gives a rate of closure of 0.063 in./hr. The average stack temperature was approximately 73° F, and the average temperature of the air entering the roof vent was approximately 74° F. The rate of closure of 0.063 in./hr is about 21 percent less than was obtained in the case of the 1½-in. vent under similar conditions.

Plotting the rates of closure given above against values of l/d (where l is the exposed length of roof vent, and d is the full internal diameter of the vent, both in the same units) on logarithmic paper yields the interesting result that the data obtained in this investigation can be represented closely by the empirical relationship,

$$R_c = 0.04\left(\frac{l}{d}\right)^{0.3}, \tag{34}$$

where R_c is the rate of closure in inches per hour. Here R_c represents the rate of increase in thickness of the ice layer, not the rate of decrease of diameter of opening. Although this equation gives results that are generally in fair agreement with the average results obtained in the investigation, it is limited in application to the conditions existing in the tests and hence cannot be applied generally.

An attempt was made to compute rates of closure approximately, making use of the temperature curves for the ice-air surface given in the paper, but the number of unknowns was too great to permit any worthwhile attempt of this sort. Hence no attempt is made in the paper,

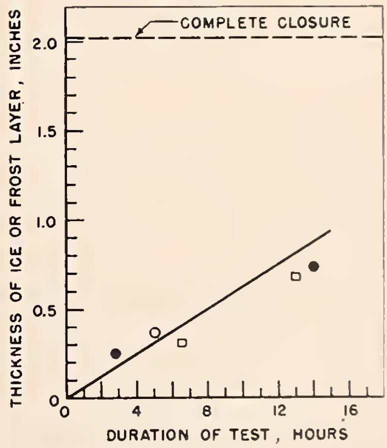

FIGURE 22. *Experimentally determined rates of frost closure for a 4-in.-diameter roof vent exposed 15 in. to outside air temperatures of approximately −30° F.*

Symbol	Run
○	23
●	24
□	25

other than the computations made in connection with figures 20, 21, and 22 to evaluate the time factor in the process of the freezing of a vent. The results presented purport to make it possible to predict roughly to what extent any given vent projecting above a roof will freeze up under given conditions, but not how fast it will freeze up.

9. Discussion of Frost Closure—Field Reports

There are two forms of frost closure that appear to occur in actual installations, provided the outside air temperature becomes and remains sufficiently low, say lower than perhaps 10° F. The first comprises a concentric layer of frost on the inside wall of the vent pipe that increases in thickness up to some particular value or to complete closure. It is this form that has been analyzed in this paper and that was observed in the laboratory tests. The second form comprises the building up of a frost cap on top of the roof vent, starting at the rim of the vent. There are several variations of this form of closure.

Field reports seem to indicate that this is the more common form of closure, but this may be due to the fact that it is the more easily observed of the two. One report from Canada indicates that both forms are likely to occur simultaneously.

Presumably the form first mentioned is more likely to occur when the exposed length of vent is relatively great. In this case the layers of air close to the cold wall of the vent commence to chill when the warm air is still a considerable distance from the outlet of the vent. This gives the drops of moisture more opportunity to come in contact with the wall of the vent and to freeze there than if the exposed length of the vent is short.

In the laboratory tests made in the investigation reported here, the exposed length of vent was 15 in. in the great majority of the cases tested. Thus the length/diameter ratios for the 1½, 3, and 4-in. vents were 10, 5, and 3.75, respectively, based on the nominal diameters. In all of the tests in which frost formed, it always occurred as a layer on the inner wall of the vent, although in a few instances it was observed that a cap also started to form over the top of the vent. In some instances it was noted that true ice, rather than frost, formed on the wall of the stack. Unfortunately not enough data were obtained to clarify this point.

The manner in which the second form of frost closure comes about seems to be fairly clear. Particles of water and frost are being carried upward out of the vent in the air stream. Some of the water particles strike the cold rim of the vent and freeze there. Other particles of frost and water strike the frost that has first formed on the rim of the vent and adhere, with the result that a porous mass of frost gradually builds upward and inward until a columnar mass roughly cylindrical in shape with an axial opening forms. In extreme cases this formation may possibly close completely at the top. Photographs of the development of such a frost cap in the Report of Proceedings, 1913 and 1914 Conventions of the Canadian Institute of Sanitary Engineers [1] for the 6-in. vent on the Civic Curling Rink in Winnipeg unfortunately are not clear enough to reproduce here.

The photographs in the reference [1] show that on February 3, following a period of weather with minimum daily temperatures ranging from −5° to −15° F, a rim of frost had started to build up around the upper edge of the vent, with a very ragged contour. The daily minimum temperatures then dropped steadily, reaching a low of about −40° F on February 10, then oscillated up and down during the remainder of the month. A photograph taken on February 10 showed that the body of frost had built up to a height of perhaps 6 to 8 in., but the opening had scarcely diminished in size. On February 25 this annular column of frost had grown to a height of about 18 in., but still the opening had not decreased perceptibly.

It will be noted from figure 2 that the exposed length of vent was very small, and it appears from the report that a special roof jack was installed around the vent in an attempt to retard frost closure. Unfortunately no information is available as to the type of closure that occurred with the other 6- and 8-in. vents shown in figure 2.

The Committee on Research of the American Society of Sanitary Engineering made a report [5] on the subject of frost closure in which it presented facts regarding the occurrence of frost closure and the means taken to combat it and gave information obtained from various cities in the United States. Excerpts that seem to be pertinent follow.

Elmira, N. Y. Considerable hoar frost. No knowledge of complete closure.

Sioux Falls, S. D. Some trouble with vents frosting but the city has no ordinance. Trouble occurs not more than 3 or 4 days at a time and only in very cold weather.

Milwaukee, Wis. During long stretches of very cold weather sometimes have many complaints. All vent pipes less than 4 inches in diameter must be increased to 4 inches and increaser must be about 18 inches below roof.

Springfield, Mass. In zero weather occasionally a stack closes. Require that no soil or vent pipe shall be smaller in diameter than 4 inches where it passes through the roof.

St. Joseph, Mo. Do not increase main vent stack through roof but permit nothing less than 2 inches internal diameter for any vent or revent pipe through roof. Top of vent stack rarely closes. When weather is above zero, no frost at all is noted.

Davenport, Iowa. Do not have any cases of frost closure. Increase stacks 2 inches where they go through roof.

Elizabeth, N. J. Have short cold spells when the temperature drops from 2 above to 4 below zero. Find that all pipes smaller than 4 inches were almost closed by frost. Specify that no vent pipe shall be smaller than 4 inches in diameter coming through roof.

Rock Island, Ill. Increase all vents going through roof 2 inches and do not allow them to extend more than 12 inches above the roof, so as to keep the length of the increaser below the roof. Very little trouble with frost closure and have no ordinance.

Columbus, Ohio. State Plumbing Code requires that all pipes be increased to 4 inches when passing through the roof. Obvious that in our northern cities all soil stacks should be increased one full size at least 1 foot below the roof.

Pittsburgh, Pa. Have a great deal of trouble in the Pittsburgh District from frost closure. No provision in code. Allowed to run pipes outside of buildings.

Dayton, Ohio. On very cold days the vent stacks above the roof have been closed by hoar frost to such an extent that it eventually formed a solid mass of ice, thereby closing the stack until the weather moderated and thawed it out. Has caused siphonage of traps in plumbing fixtures, causing sewer gas to permeate the interior of building. Law calls for all vent pipes to be increased through roof.

Buffalo, N. Y. No complaints. Ordinance requires all vent pipes to be increased one size or connected to main vent stack before passing through the roof.

Waterloo, Iowa. Require that no pipes less than 4 inches in diameter shall pass through roof. Pipes 4 inches and larger shall be increased two sizes. Even with this, find that many pipes freeze up if zero weather persists for several months without thawing spells in between.

Grand Rapids, Mich. Have no trouble with frost. Allow no increaser less than 4 inches, and every stack is increased one size at roof. Used to have trouble before fresh-air trap was abolished, but do not now, since warm air from sewer passes through.

Waterbury, Conn. Where the house trap is used, the liability of closure is reduced. Waterbury provides against the closure by installing the house trap. It is a matter of ordinance.

Recommendations of the Committee. Naturally in territories where climatic conditions are mild, the question of frost closure need not be considered. In many of our northern towns there are occasional cases of trouble from frost closure, but they do not seem to be sufficient to compel an ordinance on the subject. We believe it would be a good idea from the data contained in this paper to frame an ordinance concerning frost closure and methods of installation to prevent it which can be generally adopted throughout the country by towns and cities requiring this protection. There seems to be considerable agreement in the main points of installation, and it should not be difficult to construct such an ordinance. Some attention should be given also in the discussion as to whether the house trap should be considered a legitimate means of prevention or whether the remedy should in every case be found in the terminal construction of the vent line. If the vent line construction can be unanimously adopted as being satisfactory in it provisions against frost closure, we would suggest that a variation of the practice could be effectively done away with by dispensing with the suggested house trap remedy.

The following quotations in regard to the subject of frost closure have been drawn from various sources and are given, partly because of the factual information included and partly because of the suggestive ideas that some of them contain.

James Smith, Chief Plumbing Inspector, Winnipeg, Canada, [6], states:

In the Prairie Provinces of Western Canada we claim to have overcome this trouble to a very great extent at least by simply increasing the pipe before it passes through the roof and limiting the extent to which the pipe projects above the roof to a minimum of 1 inch and a maximum of 3 inches. This bold expedient was first suggested and experimented with by a very keen student of plumbing problems, the late plumbing inspector of Saskatoon, Saskatchewan. This method of treating pipe terminals has long passed the experimental stage and is now common practice in Western Canada. Frozen pipe terminals were at one time a very common condition, and while even the method I have described is subject to frost closure, it is only under very exceptional and unusually severe conditions. In this connection it may interest you to know that wherever possible we reconnect vent pipes to the stack before it passes through the roof and in this way provide a circulation of air throughout the system and so prevent syphonic action. In recent years we have gone a step further and required that the pipe terminal shall conform to the pitch of the roof, and for this purpose terminals are made having a 45° and 60° pitch, as well as the ordinary increaser used in a building having a flat roof. All increasers have hubs and are finished with a lead flashing.

The following opinions in regard to the use of increasers at the roof were expressed in discussion reported in the Proceedings of the 1913 and 1914 Conventions of the Canadian Institute of Sanitary Engineers [1]:

(1) When the diameter of the pipe is increased below the roof, the velocity of the outflowing air is retarded, and this promotes the deposition of moisture. The less metal in the increaser, the less is the tendency to freezing. (2) If the diameter of the pipe is increased at a considerable distance below the roof, the velocity of the outflowing air will be retarded, but, if the increaser is made as short as possible, the stream of air does not have an opportunity to expand fully within the increaser, and hence the moist air escapes without coming in contact with the wall of the pipe and this tends to prevent freezing. (3) The larger in diameter the increaser is made, the heavier the body of cold air that must be displaced by the warm air moving up the stack. (4) Experience at Edmonton, Canada, has shown that when the vent pipes are cut off at the roof complete frost closure did not occur. The results, when an increaser was used, have been practically the same. (5) In St. Boniface, Canada, it was found that increasing the exposed length of the vent terminal above the roof increased the trouble from frost closure. Their experience leads them to be heartily in favor of using increasers. (6) A great deal depends on the exposure of the terminal. Less trouble is experienced with southern exposures than with other exposures. Moisture that freezes falls over on the outside of the vent in the direction of the wind and builds up there. (7) At Winnipeg it was found that the increaser did not help matters any.

The following recommendations were submitted to the Convention referred to above and undoubtedly represent the thinking on the subject of frost closure prevalent in Canada at the time (1914).

Winnipeg Recommendations. All terminals of soil, waste, and ventilating pipes of 4 inches in diameter or less shall be increased 2 inches in diameter before passing through the roof of the premises, and all terminals of such pipes shall project to the outer air not less than 1 inch and not more than 2 inches above on the high side where passing through a pitched roof, and not less than 3 inches or more than 5 inches above where passing through a flat roof, provided that the portion of all such pipe terminals above the roof shall have a hub of a size in proportion to which the pipe is increased, and the same shall be made weatherproof by means of a lead flashing. All such lead used for this purpose shall be in weight at least 6 pounds per square foot and shall be worked over and into the hub with not less than 5 inches of cover on the roof on either side of the pipe terminal, and it shall be finished with a cast or wrought iron ring properly caulked into the hub which shall in no case project above such terminal.

All terminals of soil, waste, and ventilating pipes shall where passing through a pitched roof be carried to a point within 2 feet of the ridge or peak of the roof and shall be located not less than 10 feet from or 2 feet above any window, door, or other opening in the same or adjoining premises, provided that in all cases a roof with a pitch of 6 inches or more in 12 inches shall be considered as a pitched roof.

Saskatoon Recommendations. That all vent pipes terminate not more than 1 inch above the pitch of roof on the high side and have a lead flashing turned down 1 inch all around inside the top of pipe dressed in tight and secured with a malleable iron ring.

All vent pipes to be carried up to roof and to terminate the same size unless the vent line is less than 4 inches in diameter, when it shall be increased to 4 inches, at least 3 feet below roof.

We claim that by elimination of the roof jack and increaser and the consequent decreased surface, we lessen the radiation and therefore the deposition of moisture which congeals thereon.

All branch vents shall be carried back into the main stack before passing through roofs. This will reduce the number of roof terminals.

Edmonton Recommendations. All soil, waste, and ventilating pipes shall be located inside the premises; and all roof terminals of such pipes shall be located not less than 10 feet distant from any opening door, window, etc., in the same or any adjoining premises, nor shall a perpendicular from any roof terminal to the grade be nearer than 10 feet to the side line of the lot; the roof terminal shall project 1 inch and no more above the highest point on the roof where such roof terminal intersects the roof.

All vent pipes of 4 inch diameter or less shall be increased at least 2 inches before passing through the roof, and no roof terminal shall be less than 4 inches where the same passes through roof and shall terminate with a hub and shall be flashed with sheet lead turned down and caulked into the hub.

10. Methods of Retarding or Preventing Closure of Roof Vents by Frost

Experience and the principles presented in this paper indicate that means of retarding the closure of roof vents by frost include factors that affect the vent terminal itself and factors that are independent of the vent terminal.

Of the former, we may list (1) limit the height of exposed length of vent above the roof to the extreme minimum that can be permitted, (2) enlarge the vent just before it passes through the roof, (3) use a substitute material having a high resistance to the transfer of heat in place of the usual metallic vent pipe, (4) put thermal insulation around the exposed length of the vent, and (5) in extreme cases provide means for heating the outer surface of the exposed length of the vent electrically or by means of steam or hot water.

In the latter category we may list the use of a house trap, either with or without a fresh-air vent. If the discharge of hot water into the stack can be prevented, this should help reduce the occurrence of frost closure.

The simplest, most obvious, and probably most effective way of preventing or minimizing the frosting up of roof vents is to reduce the length of vent exposed to the low temperature to a minimum. In Canada it is quite customary to limit the length of vent projecting above a sloping roof to from 1 to 2 in. on the high side.

Figure 23 shows a typical design of roof terminal that has come into use at Saskatoon, Canada, and has been found successful in resisting frost closure [1]. Note that the terminal is a special pipe with the upper rim at an angle to fit approximately the slope of the roof. This pipe is 2 ft long measured from the rim on the lower side.

There seems to be no valid reason for objecting to a flush opening or a very short extension on a sloping roof. Snow may occasionally block a vent pipe, but the snow is porous and thus permits the passage of some air and furthermore such closure, which will occur only during heavy snow storms, is short-lived. It would seem that any amount of water that might enter a vent that is flush with the roof would be inconsequential. The situation on a flat roof, however, might be quite different, since, if the strainers at the storm leaders should become blocked with trash, the roof might become flooded, and hence discharge an undue amount of water down the roof vent.

Correspondence with various persons in Canada who have had experience with frost closure elicited considerable interesting information, the most pertinent of which follows:

Earle O. Turner of the University of New Brunswick, Fredericton, states:

> From my own experience, the only phenomenon of this kind in this climate is the formation of a frost cap over vents in soil pipes in buildings. This will only take place at temperatures below zero Fahrenheit and will not persist after the temperature rises.

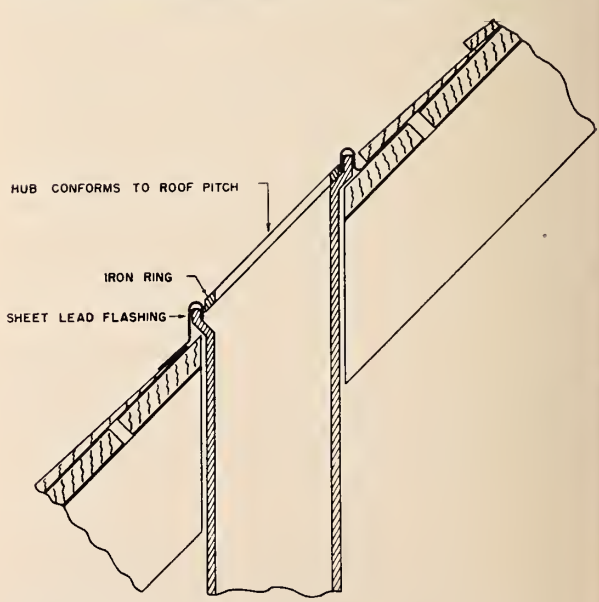

FIGURE 23. *Design of roof terminal used at Saskatoon, Canada.*

L. P. Cabana, Superintendent, Division of Sanitary Inspection, City of Montreal, Canada, writes:

> We have experienced the formation of ice at the outlet of vents on roofs, but not to the extent of complete closure. There is always in extreme cases a one-inch opening except during a snow storm, when this opening may be blocked temporarily with snow.

He states that the city does not permit house traps and that the vents are always 1 inch larger in diameter than are the stacks.

W. D. Cameron, Plumbing Inspector, Kirkland Lake, Canada, states:

> I must say we do have difficulty to some extent up here with vent stacks during the extreme cold weather which varies from zero to 55 degrees below during the winter months. We have made some experiments from time to time on this subject, and up to six years ago our code called for a 12-inch extension above the roof on the highest side. This was found to be too great an exposure, so we cut it down to 8 inches and insulated the vent pipe from the roof to the ceiling joists, which did help some, but in numerous cases could not be done where the stack was carried up the corner of the building and where it was impossible to extend the stack up the roof to any other point.
>
> We have come to the conclusion now, that by increasing all vent stacks to 4 inches from a point approximately 2 feet below the roof to 4 inches above on the highest side, we have gained the most satisfaction, and where necessary, insulate the 2 feet below the roof. Although this does not entirely eliminate the ice condition, it does not completely ice up solid under extreme conditions.
>
> I must mention with reference to our plumbing system here that we do not permit a main trap on the sewer line between the main trunk sewer in the street and the house, therefore, we have a straight vent line from the street through the roof on each building. We do not permit anything less than 2-inch extensions through the roof; this we find is the smallest size we can permit without completely icing up solid.
>
> This freezing or icing which occurs here only happens during the very lowest temperatures, perhaps from 15 to 45 degrees below zero and forms an icing on the side of the pipe to a depth of approximately 1 inch. Then there forms a cone or light ice cap somewhat heavier than a hoar frost and extends straight upwards to a height of from 6 to 8 inches and remains there until the temperature rises, which usually happens about noon each day, or more often until the heat from the building increases sufficiently to break this light ice cap and force an opening in the top, permitting the escape of the vapour. As for the wind extending this cone or ice cap to one side of the vent, we do not have the wind here when the temperature is at a low degree, for during such temperatures even the smoke from the chimneys rises straight up and a heavy fog occurs.

H. E. Roseborough, Building Inspector, Sudbury, Ontario, Canada, writes:

> Hoar frost very seldom extends more than 6 inches from the top of the vent stack and is of very even consistency. It generally forms in a cone shape above the top of the stack and extends some 4 or 5 inches. The wind seems to have very little effect on the shape of the cone of frost.
>
> During the second Great War restrictions were put on the use of 4-inch soil pipe, and at that time we changed our by-laws to permit the use of a 3-inch stack for a two-family house. We carry our vent pipe approximately 6 to 8 inches above the roof level, and we do not use any interceptor trap at the entrance to our building, therefore each stack is a partial vent to our main sewer.
>
> Previous to 1938 we have had an odd case of a 4-inch stack closing with hoar frost, but since using the 3-inch, only on one or two occasions, even with the temperature at 47 degrees below zero, have we had any trouble.
>
> During the past week our temperature ranged from 47 below to 26 below for four days, and not one case was reported to this office. We have had no trouble whatever with a 6-inch stack freezing over.

Gordon Park Jackson, Medical Officer of Health, Toronto, Canada, furnished the following information:

> The closure of vent stacks by frost in this City happens infrequently. In the very few places where this has occurred, it apparently was the result of the excessive use of hot water. For example, when there is a large fire in a heating furnace containing a domestic hot-water coil, the water becomes overheated and discharges into the drain. Winter temperatures in this City are usually below the freezing point, and we frequently have temperatures below zero extending over a period of three or four days. Vent stacks less than 3 inches in diameter where they extend through the roof are not permitted.

V. S. Baker, Secretary-Treasurer of the Ontario Association of Plumbing Inspectors and Affiliates writes (referring to the City of London, Ontario, Canada):

> In the City of London the average winter temperature is around 10 to 20 degrees, with occasional temperatures of 10 to 15 degrees below zero for a day or two. We receive a few complaints each winter from frost closure on 4-inch vents and also on 3-inch. On the average, the stacks that freeze are on the north or west sides of dwellings . . . We have also noted that the 1¼-inch sink vent in the cold portion of the attic space freezes when the building is insulated. In the western sections of the country increasers are used at the roof and very short terminals or nearly flush.

In reply to further questions Mr. Baker furnished the additional information that in the area referred to, in general, stacks freeze with frost caps. Also that in the case of the 1¼-in. vents in the attics of insulated homes, it was not certain whether the pipes froze solidly or whether they were filled with a spongy ice.

J. A. McDonald, City Engineer, Edmonton, Alberta, Canada, furnished the following information in response to specific questions:

> The City of Edmonton does not permit house traps to be installed. The stack is not permitted to extend more than 1 inch above the roof. Relatively few cases of frost closure have been experienced there, but those that have been observed were of the type that form on the interior wall of the pipe. No vent smaller than 4 inches is permitted, and in any case, the stack is increased a minimum of 1 inch in diameter where it passes through the roof. Edmonton frequently has periods of from one to three weeks when the temperature ranges from 20 to 50 degrees below zero continuously.

Guy S. Franks, Plumbing Inspector, Calgary, Alberta, Canada, states in response to specific questions:

A certain amount of frost closure is experienced. Every terminal of a soil, waste, or ventilating pipe three inches, four inches, or five inches, shall be increased one inch in diameter, and each under three inches shall be increased to four inches before passing through the roof, by means of an increaser and shall project to the outer air not less than 1 inch nor more than 3 inches above the roof and shall be made weatherproof by means of a lead flashing. All lead used for this purpose shall be in weight at 6 pounds per square foot and shall be worked over and into the hub of the increaser at least 1 inch with not less than 6 inches of cover on either side of the roof terminal, and it shall be finished with cast or wrought iron ring properly caulked with lead in the hub thereof . . . We have extreme low temperatures, lasting sometimes for days. Maximum 10 below zero and minimum of 30 below zero. Not the general rule.

An unusual type of frost closure, caused by moisture outside of the vent instead of moisture inside, is reported by R. E. Andrews, Sanitary Inspector, Niagara Falls City. He writes:

In view of the fact that Niagara Falls City is so geographically situated, we have practically no rimeing of vent stacks even in the 1½-inch size. We do, however, have an icing condition caused by spray from the Falls being carried over the City by a South or South-East wind. In that portion of the City and suburbs so affected, we stress the need for a 4-inch vent stack or the existing vent to be increased immediately below the roof and carried through by 6 inches. This serves the purpose in the majority of cases, but we have exceptions where we have had the vents encircled by ¼-inch copper pipe carrying hot water or steam and the whole installation lagged with hair felt and leaded over. This latter method has proved effective and we are able to prevent blocking by ice.

The following information was received from A. E. Berry, Director, Sanitary Engineering Division, Department of Health, Toronto, Canada:

We have been giving a good deal of consideration to the question you have submitted. It is a problem in this country, and unfortunately there are varying opinions regarding it. In some municipalities they report that closures do take place, while in others they find no difficulty, even with a 3-inch vent. Under extreme cold weather conditions there would probably be some closures, but even in the northern part of this province, where the temperature quite frequently goes down to 40 or 50 degrees below, no particular difficulty appears to be involved. Probably it is due to the fact that these cold spells do not last for any great length of time.

We have been giving consideration to the development of a plumbing code for the Province of Ontario, and the committee that was at work on this canvassed the situation somewhat carefully, with the result that they did not feel any special precautions were necessary to prevent closures.

Edward Pretious of the University of British Columbia, Vancouver, Canada, wrote as follows:

Prior to this arrangement (see figure 24A) there was no house trap, and the sewer cover was closed. The warm sewer gases escaped through the roof vent, and freezing was prevalent. The present scheme (shown in figure 24B) appears to obviate this condition.

He also remarks that when the roof vent is flush with the roof, freezing does not occur.

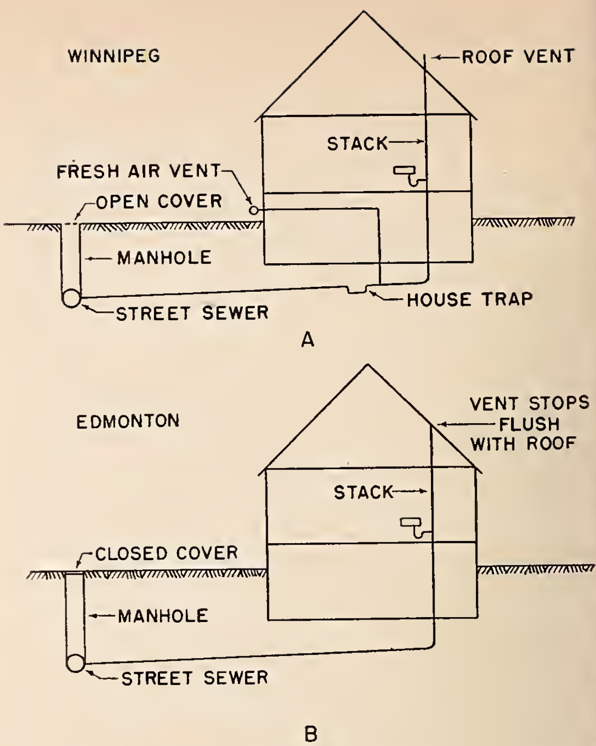

Figure 24. *Systems used at Winnipeg and Edmonton, Canada*

11. Conclusions

1. The roof vents of building drainage systems may become partially or completely closed by frost in very cold weather under certain conditions. Among the factors that affect frost closure are: (a) temperature of the outside air, (b) temperature and humidity of the air passing up the stack and vent, (c) wind velocity, (d) length of vent that is exposed to the outside atmosphere, (e) diameter of vent, (f) thermal insulation, if any, of the exposed part of the vent, or the use of a vent pipe of some material that is highly resistant to the transmission of heat, (g) whether or not a house trap is inserted in the building drain, either with or without a fresh-air vent, (h) whether or not the diameter of the vent is greater than that of the stack, and the distance to which such expansion extends below the roof, (i) the temperature conditions in the air space below the roof, (j) the exposure, whether northern, southern, etc., and (k) the velocity of air flow upward through the vent.

2. Frost closure has been observed in two general forms: (1) as a concentric layer that builds up on the inner wall of the vent, and (2) as a cap that builds up from the rim of the vent at its outlet. The latter form is the one that has been the more

frequently reported, possibly because it is the more easily observed of the two. Sometimes the two forms occur simultaneously.

3. In general, it appears that there is little likelihood of trouble from frost closure unless the outside air temperature falls below about 10° F and remains there for at least several days.

4. Reducing the length of the exposed portion of the vent as much as possible appears to be the most certain way of reducing or preventing frost closure.

5. Uninsulated small-diameter vents in unheated attics may freeze solid unless protected by insulation.

6. The discharge of hot water into the stack, particularly at night, when the upward convective air current is most pronounced, tends to increase the humidity of the air passing up the stack and thus increases the tendency to frost closure.

7. The larger the diameter of the vent, the less likely it is to close completely because: (1) a longer period of cold weather is required to create the necessary thickness of ice, and (2) because, with the larger diameter vents, the temperature of the ice-air surface in the vents is generally higher for a given thickness of ice layer than with the smaller diameter vents. (See figs. 10 to 15). Freezing stops when a temperature of 32° F is attained at the ice-air surface.

8. As the air from the street sewer is relatively moist and warm, the use of a house trap to prevent this moist air from passing up the stack should reduce the tendency to frost closure. Even if a fresh-air inlet is provided on the house side of the trap, this provides a source of relatively cold dry air that carries with it less moisture to condense out and freeze in the vent.

9. Snow storms may close the vent temporarily, but the snow is porous, and evidence seems to be available that this does not cause any serious difficulty.

10. Reconnecting vent pipes to the stack before it passes up through the roof has been found to reduce or prevent siphonage of trap seals when the vent was completely closed by frost.

11. Increasing the diameter of the vent above that of the stack may help in two ways: (1) It affords the advantage of a larger diameter of vent, so that it requires a longer time for the vent to freeze up completely, and (2) it would seem that, if the length of the expanded portion of the vent is relatively short, the stream of air passing up through the vent may not expand soon enough to reach the chilled wall of the vent, and hence less moisture reaches the wall than would otherwise be the case, so that the tendency to freeze is decreased.

12. The greater the wind velocity, the greater the tendency to closure. In general, however, the lower the temperature, the smaller is the wind velocity. Less trouble seems to be experienced when a vent has a southern exposure (in the northern hemisphere) than when it is exposed on the shady side of the roof.

13. The use of a material for the vent pipe that has a higher resistance to the flow of heat than does steel has a favorable effect.

14. As a rough estimate of the rate at which the thickness of the ice layer in a vent may increase in cold weather, we may take a value of 0.07 in./hr, or roughly 1½ in./day, assuming that the convective current of air persists during the greater part of the day. This value was obtained by laboratory experiments on 3-in. vents for an outdoor air temperature of −30° F and with the air passing up through the vent saturated with moisture at a temperature of about 70° F. Values of about 0.08 and 0.06 in./hr were obtained for 1½-in. and 4-in. vents, respectively.

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