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CONDENSATION ON A DOUBLE WOOD WINDOW

by

E. Nowak and A. Grant Wilson

Report No. 146

of the

Division of Building Research

Ottawa
August 1958

PREFACE

Windows are important components of almost all buildings. They pose many problems, as reflected by the numerous requests for assistance which have been received by the Division, beginning on the first day it was in operation. In common with almost all building components, windows are affected in service by conditions imposed upon them by the building of which they are a part. They cannot, therefore, be studied or assessed adequately by themselves but must be related to the building, particularly in respect of those important aspects of performance involving heat, moisture and air.

Experimental work on windows, though greatly needed, had to await the development of major test facilities within the Division. A good beginning has now been made on window work. This report describes the first major study on condensation on and between double windows. The extensive analysis of the problem which is presented will serve to confirm the complexity of the factors which enter into their performance.

Ottawa
August 1958

N.B. Hutcheon
Assistant Director

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CONDENSATION ON A DOUBLE WOOD WINDOW

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E. Nowak and A. Grant Wilson

This report covers a study of the condensation performance of a simple wood window having permanently installed outer glazing and removable inner glazing. With the window installed in the Building Services cold room, observations were made of surface and air temperatures and condensation on the inside surface of both inner and outer panes. These observations were made at different cold and warm room temperatures and warm room relative humidities. Variations were made in the tightness of the inner glazing and the degree of venting of the space between the panes to the outside. Laboratory results are compared with those predicted from simple theory.

I. ANALYSIS OF WINDOW CONDENSATION PROBLEM

The value of double windows in decreasing heat transmission through window areas and in reducing the condensation of water vapour on inside glass surfaces is well known. Some form of double-window arrangement is very common in Canadian homes. Double windows have also been in use for many years in most commercial buildings in areas having severe winters and are being used more and more in other parts of the country.

Regardless of the type of double window used, some condensation in the form of water or frost on the inside glass surfaces is common during the winter months. It is as likely to occur on expensive factory sealed double-glazed units as on standard wood window arrangements.

Condensation between the panes, on the inside surface of the outer pane, is also a common occurrence and is a potential problem with all window types except, perhaps, factory sealed double-glazed units.

Most people accept a small amount of window condensation as inevitable. When it begins to seriously obstruct the view through the window, however, or when the run-off wets the window sills or wall surfaces the problem assumes larger proportions. In modern dwelling units at Fort Churchill cases where ice filled the space between panes to considerable heights, have been recorded.

There are a number of factors that determine whether or not window condensation will occur. It is convenient when discussing these to consider condensation on the inside surface of the inner pane separately from condensation on the inner surface of the outer pane.

(a) Condensation on Inside Surface of Inner Pane

Condensation on the inside surface of the inner pane occurs whenever the window surface temperature at any point is below the dew point temperature of the air-water vapour mixture in the room.

It is usually observed just over the lower portions of the glass surface, suggesting vertical surface temperature gradients. The surface temperatures of windows for given inside and outside air temperatures can be calculated by using heat transmission coefficients for inside and outside air films and for air spaces. Such calculations are used as the basis for tables giving the maximum inside relative humidities that can be carried in buildings at different outside temperatures without creating window condensation. In making the calculations, uni-directional heat flow is assumed and no account is taken, therefore, of the effect of convection in the space between panes on vertical gradients in inside glass surface temperatures.

The practical solution to serious condensation on inside window surfaces is usually to reduce the relative humidity in the building through ventilation and the control of moisture sources. The only other possible course is to increase inside glass surface temperatures by increasing the inside air film heat-transmission coefficient or by direct heating. It is for this purpose that propellor fans are sometimes used to force air over the inside surfaces of display windows during cold weather. Such steps are not practical for most windows. However, the location of heating outlets may have a marked effect, both through increasing the film coefficient and through direct heating. One other influencing factor is the degree to which the inside glass surface is recessed within the window opening.

(b) Condensation on Inside Surface of Outer Pane

Condensation will occur on the inside surface of the outer pane whenever the temperature of that surface at any point is below the dew point temperature of the air-vapour mixture in the space between panes. This situation will ultimately occur with outside temperatures lower than inside, if the gain in water vapour to the space is greater than the loss.

Water vapour generally moves into and out of the air space under two forces. Vapour moves through the materials and cracks in the window assembly as a result of differences in partial pressure of the water vapour by the process usually referred to as diffusion. It is also transferred as a component of the air which flows through the cracks in the assembly under total air pressure differences.

(i) Water vapour transmission by diffusion

The equation used to express water vapour transmission through homogeneous materials under partial pressure differences is

$$W = \frac{u\ A}{l} \quad \Delta p \qquad (1)$$

where W = weight of water vapour transfer per unit time

A = area of cross section of flow path

l = length of flow path

Δ p = vapour pressure difference across flow path

u = coefficient of permeability.

The coefficient of permeability is not a constant for most materials but varies with temperature and humidity conditions. Most of the materials used in window construction are relatively impermeable, except for wood. Assemblies of wood, however, can be made relatively impermeable through painting.

Under these circumstances the cracks and openings in the assembly may provide the major paths for vapour flow by diffusion. The permeability coefficient for air-water vapour mixtures is independent of relative humidity at constant temperature but does vary somewhat with temperature, becoming smaller as the temperature decreases. If, as a first approximation, the coefficient of permeability is taken as a constant, the vapour flow by diffusion into and out of the air space will be directly proportional to the pressure differences across inner and outer panes.

The vapour pressure differences across inner and outer panes for different outside temperatures are given in Table I. These values have been calculated assuming that inside room and air space vapour pressures correspond to saturation at the temperatures of the inner surfaces of the inner and outer panes respectively. Outside vapour pressures were taken as those which corresponded to saturation at the outside air temperature. Surface temperatures were calculated for an inside air temperature of 70°F, assuming an over-all "U" value for the window of 0.53, and inside and outside film coefficients of 1.5 and 6.6 respectively. These coefficients are based on heat transmission data for windows in the 1957 ASHAE Guide.

The vapour pressure difference across the inner pane is several times greater in all cases than the vapour pressure difference across outer pane, the ratio of these pressure differences increasing with decreasing outside temperature. Thus, to maintain outflow equal to inflow, the effective resistance to vapour flow by diffusion of the inner glazing must be many times that of the outer glazing.

(ii) Air pressure differences due to wind

A number of factors may contribute to total pressure differences across windows. One of the most commonly recognized is wind. Air movement around a structure will result in a pattern of pressure variations at the surface of the structure. This pressure pattern will depend on the shape and size of the building, the influence of adjacent buildings or terrain and the direction and velocity of the wind. In the simplest cases it can be assumed that the pressures on leeward walls are below barometric while those on windward walls are above it. Pressures on the windward side may exceed barometric by approximately 0.7 to 0.9 of the wind velocity head while those on the leeward side may be of the order of 0.5 velocity heads less than barometric. Pressures inside the building resulting from wind action will depend on the air leakage of elements of the enclosure. If the leakage characteristics of all exposures are similar the pressures inside may be of the order of 0.2 to 0.3 velocity heads less than barometric. Inside pressures may be lower or higher, depending on the air leakage of windward and leeward exposures.

Thus, total air pressure differences across the windows on the windward side corresponding to approximately one velocity head can be expected, while pressure differences of 0.3 velocity heads can occur, on the leeward side. These pressure differences will be in opposite directions, that on the windward side leading to inflow and that on the leeward side leading to outflow. With heat loss the most significant flow results at the higher pressure difference - usually on the windward side. With condensation however, it is flow from inside to out that is undesirable since it results in a net gain in water vapour to the air space. Table II gives the possible pressure differences across a leeward window as a result of wind action, based on 0.3 velocity heads and with an air density of 0.075 lb/cu ft.

(iii) Air pressure differences due to chimney effect

A second major factor contributing to the total pressure difference across windows can be called stack or chimney effect. Pressure differences are created between two inter-connected columns of air at different temperatures as a result of differences

in density. Figure 1a represents an enclosed column of air with a single opening, at a higher temperature than the surrounding air. Under this condition the pressures inside and out will be the same at the level of the opening, but there will be pressure differences at other levels. These will depend on the distance from the level of no pressure difference (or neutral zone) and the difference in density of inside and outside air. Thus, the pressure inside will be less than outside below the opening and greater than outside above the opening.

Figure 1b represents an enclosed column of air at a higher temperature than the surrounding air and with openings at two different levels. In this case, the neutral zone will be somewhere between the openings, and closer to the opening having the least resistance to flow. If the openings have similar resistances the neutral zone will be midway between them. Again, the pressure inside will be less than outside below the neutral zone and greater than outside above the neutral zone. Thus, there will be inflow at the bottom and outflow at the top.

This situation is analogous to that which occurs in a heated building. Air will come in through openings below the neutral level and go out through openings above. The location of the neutral zone will depend on the vertical distribution of openings between inside and outside and their relative resistances. This suggests, that the neutral-zone location might be determined by the distribution of cracks in windows and doors. Any such simple calculation will usually lead to the conclusion that the neutral zone is below or in the vicinity of the first floor windows in a single story house with basement and, approximately at the level of the second floor in a two story house. Although there have been few experimental determinations of neutral zones in houses the data available (1) suggest that the actual levels are considerably higher than those predicted on the basis of window and door cracks alone. In single story houses the neutral zone may be above first floor windows, while in two story houses it may be at the level of the second story windows.

This can be explained, at least partly, by the effect of chimney draft on house pressures. Chimney draft tends generally, to lower inside pressures at all levels and therefore has the effect of raising the location of the neutral zone. The pressure difference between the base of the chimney and outside normally increases with inside-outside temperature difference at a greater rate than does the pressure difference between any point in the house and outside, since average flue gas temperatures are higher at lower outside temperatures.

Thus the effect of the chimney on the neutral zone location will vary, being least effective at small indoor-outdoor temperature differences.

Kitchen exhaust fans, when operating, will cause a lowering of inside pressures and will have the effect of increasing the height of the neutral zone. Any tendency to pressurize the house, such as would occur if an outside air supply duct were connected to the return side of a forced warm air furnace, will have the opposite effect. A fireplace with open damper or any similar stack terminating above house level, will result in an increase in the height of the neutral zone.

The location of the neutral zone in commercial buildings depends on these same factors. Again, few measurements have been reported. Unpublished work by the ASHAE laboratory on pressure differences across entrances of tall buildings, however, suggests that the neutral zone location in such structures is generally well above mid height.

The inside and outside pressure differences resulting from inside-outside temperature differences can be seen in Table III which gives pressure differences per foot at different outside temperatures. The values are based on an inside temperature of 70°F and a density of 0.075 lb/cu ft. To determine the actual pressure difference and its direction at any level the location of the neutral zone must be known.

(iv) Air flow characteristics of windows

The equation usually used to express air flow through windows under total pressure differences is:

$Q = C(\Delta p)^n$ where Q = volume rate of flow

Δp = pressure difference across window

C = air leakage coefficient

n = exponent of air flow

The passages through which air flows in windows are usually complex in form, often consisting of a variety of orifices, enlargements, contractions, bends, etc. Flow in these passages may be laminar or turbulent, depending on air flow rates. The exponent of air flow "n" therefore varies with window type and flow rate, having values between $\frac{1}{2}$ and 1, and must be determined by test. Over a considerable range in flow rates, however, "n" may be assumed constant for practical purposes. In double windows the resistance to air flow of the passages leading from inside the building to the air space may be different from that of the passages leading from the airspace to outside the building. This is not significant for

air leakage characteristics of windows with respect to heat loss, where over-all leakage values are important. The relative air leakage characteristics of passages into and out of the air space, however, may be highly significant for condensation between panes. This is apparent when the distribution of total pressures and resulting air flows across double windows are considered.

Figure 2 illustrates the variations in pressure with height across a double window subjected to a temperature gradient where the neutral zone occurs at mid-height. In representing the relative slopes of the pressure distribution curves it was assumed that the temperature of the air space was closer to outside temperature than to inside. The pressure distributions (Fig. 2a) will result whenever the resistance to flow above and below the neutral zone around either or both panes, is equal. For example, this will occur with the passages uniformly distributed around the periphery of one or both panes.

Under these circumstances the air space pressure is between inside and outside pressures at all levels. Thus inside pressure is higher than the air space pressure above the neutral zone and lower below the neutral zone. Similarly, the air space pressure is higher than the outside pressure above the neutral zone and lower below the neutral zone.

The air flows resulting from these pressure distributions will depend on the locations and resistances of the passages. Flow will vary from zero through passages located at the neutral zone to a maximum through passages at the top and bottom of the window. The air space can interchange air both with the inside and outside; the relative amounts depend on the relative resistance to flow of the passages. If the inside of the window were completely sealed the air space would interchange air with the outside only.

Figure 2b illustrates pressure distributions when passages of the outside pane at the bottom have much lower resistance to flow than other passages.

Similarly, Figure 2c shows pressure distributions with the low resistance passages at the top of the outside pane. For the situations illustrated in Figs. 2b and 2c appreciable air flow will occur when there are openings past both inner and outer panes, the flow being from inside to out in the former and from outside to in in the latter.

Figure 3 illustrates the variations in pressure with height across a double window subjected to a temperature gradient where the neutral zone is below the window, i.e., where the total pressure inside is greater than the total pressure outside at all levels.

Figure 3a represents the pressure conditions when the resistances to flow around both panes are equal. The air space pressure is approximately mid-way between inside and outside pressures and flow is from inside to out through all openings. The air space does not interchange air with the inside or outside. Figure 3 b represents the pressure distribution when the resistance to flow through passages of the inner pane is much greater than that for flow through passages of the outer pane these being evenly distributed above and below the mid-height of the window, i.e., with equal openings top and bottom. Under these conditions the pressure at the top of the air space is greater than outside and the pressure at the bottom is less. The air space can interchange air with the outside, all outflow passing through the upper passages of the outer pane. This includes both the inflow through the lower openings of the outer pane and the flow from inside to the air space through passages of the inner pane.

These conditions can only be approached if the pressure difference required to move all the air through the upper openings in the outer pane is less than that created by the difference in weight between the columns of air in the space between the panes and the outside. A more detailed discussion of air flow characteristics of the window is given in Appendix A.

Figure 3c represents the pressure distribution when the resistance to flow through the passages of the outer pane is much greater than through those of the inner pane, the passages of both panes being equally distributed above and below the mid-height of the window. Under this condition the air space will interchange air with the inside, the amount of air flow through the outer pane being equal to the difference in inflow and outflow past the inner glazing.

(v) Water vapour transmission by air flow

The foregoing discussion of pressure distributions across double windows has shown that, with the air-flow resistance of the inside pane sufficiently higher than the outside pane, and with the openings in the outside pane located at the top and bottom of the window, the air space can interchange air with the outside even when an over-all flow from inside to outside occurs. The relationship between these air flows and condensation can be shown by a simple mass balance.

If vapour flow by diffusion is neglected the net gain of water vapour by the air space as a result of air flow from the inside is given by the equation

$$Q_i d_i \ (\phi_i - \phi_s) \qquad (2)$$

where Q_i is volume rate of flow into the air space from the inside

d_i is the density of the inside air

ϕ_i is the specific humidity of the inside air

ϕ_s is the specific humidity of the air in the space between the panes.

The net loss of water vapour by the air space as a result of air flow from the outside is given by the equation

$$Q_o d_o (\phi_s - \phi_o) \tag{3}$$

where Q_o is the volume rate of flow into the air space from the outside

d_o is the density of the outside air

ϕ_s is the specific humidity of the air in the space between the panes

ϕ is the specific humidity of the outside air.

To prevent condensation the net gain in water vapour by the air space must equal the net loss of water vapour by the air space.

Equating equation (2) to (3) it can be shown that

$$\frac{Q_o}{Q_i} = \frac{d_i}{d_o} \frac{(\phi_i - \phi_s)}{(\phi_s - \phi_o)} = \frac{T_o (\phi_i - \phi_s)}{T_i (\phi_s - \phi_o)} \tag{4}$$

The minimum ratios of outside to inside air to prevent condensation at different outside temperatures are given in Table IV. These values have been calculated assuming specific humidities for inside room and air space corresponding to saturation at the temperatures of the inner and outer panes, respectively. Outside specific humidities were taken as those corresponding to saturation at the outside air temperature. Surface temperatures used were those given in Table I. The value of the minimum ratio increases with decreasing outside temperature.

Another factor which produces total pressure differences between the air space and outside is a change in its temperature. If the window is not sealed this pressure difference will cause air flow to or from the air space and the window is said to "breathe". The total amount of air interchange can be calculated from the simple Gas Laws and will depend on the magnitude of the temperature change and the volume of

the air enclosed in the space between the panes. Whether the air space will lose or gain water vapour as a result of this mechanism will depend on whether the major openings are around the outer or inner panes.

II. DESCRIPTION OF WINDOWS AND TEST INSTALLATION

All tests described in this report were carried out on three specimens of a window having inner and outer glazings in the same sash, details of which are shown in Fig. 4. The outer glazing was fixed and sealed to the sash with putty. The inner glazing was normally fixed but held in place on the wood sash with aluminum clips so that it could be removed for cleaning.

During the condensation tests variations were made in the inner glazing to alter the resistance to air and water vapour flow from the inside to the air space (Fig. 5). Figure 5a shows the inner glazing in a light stainless steel frame in direct contact with the wood sash. Figure 5b shows the inner glazing in an aluminum frame with a rubber gasket. Figure 5c shows the inner glazing in a stainless steel frame the perimeter of which is caulked. The resistance to leakage around the outer pane was altered by providing different numbers of $\frac{1}{4}$-inch vent holes in the top and bottom members of the sash as shown in Fig. 4.

During the investigation the windows were installed in a 4- by 8-ft insulated wood frame wall panel (Fig. 6). The spaces between the sashes of the windows and the frames of the openings were sealed with caulking compound as shown in Fig. 5.

Figure 7 shows the plan of the cold room. The wall panel formed part of a partition which divided the cold room into a large and small compartment. In this report the large and small compartments are termed cold room and warm room respectively. During the condensation and temperature measurement tests the cold room provided outdoor conditions while the warm room provided conditions inside buildings.

The main diffuser provided the cooling in the cold room for most of the tests. The diffuser contained the refrigeration evaporator coils and the electric reheat elements. A fan circulated air over the coils and reheaters. The air temperature variation at any point in the cold room did not exceed $\pm$ 0.25°F. The floor-to-ceiling air temperature gradient did not exceed 1°F. This was achieved by the use of a modulating temperature controller which regulated the electrical input to the heaters, with the refrigeration system operating continuously.

The air moved in a downward direction over the outer surface of the windows. The air velocity was not uniform being 7 mph for the top window, 6 mph for the centre window and 5 mph for the bottom window as measured by a velometer.

The warm room was heated by gravity baseboard convectors located approximately 9 in. from the floor on the wall opposite the partition. The electrical input to the convectors was regulated by a temperature controller. During some tests the air temperature at the centre of the room at a point 4½ feet from the floor was maintained at 70°F within ± 1°, while in other tests it was maintained at approximately 73°F.

A humidifying system and a dehumidifying system operated by a contact meter-type of electric hygrometer maintained the desired relative humidities in the room. Wet- and dry-bulb temperatures were observed with an aspirating psychrometer at a point near the thermostat location. The humidities determined from the observations of wet- and dry-bulb temperatures were maintained within ± 1 per cent during the tests.

III. DESCRIPTION OF TESTS AND RESULTS

(a) Air Infiltration Tests

Air infiltration tests were carried out on the double window shown in Fig. 5b to determine separately the characteristics of air flow around the inner and outer panes. The method of carrying out the tests was one commonly employed by other investigators. It consisted of sealing one side of the window into an air tight compartment and introducing or withdrawing air at such a rate as to maintain a given pressure difference across the window.

A large variable area flowmeter having a range of 0 to 33 cfm was used to measure air flow in one of the tests. It was calibrated against a laboratory orifice meter which was thought to have a possible error of -1 per cent. The air flow in all other tests was measured with a smaller flowmeter having a range of 0 to 2.1 cfm. The calibration supplied by the manufacturer of the small flowmeter was accepted. It was possible to read the large and small flowmeters to within ± 0.13 and 0.01 cfm respectively.

A displacement-type micromanometer in conjunction with a sensitive single-pan balance was used to measure pressure differences between 0 and 0.01 in. of water. A Betz micromanometer was used to measure pressure differences when they exceeded 0.01 in. of water. The displacement-type and Betz micromanometers were sensitive to pressure changes of approximately 0.0001 and 0.001 in. of water, respectively.

All the tests were carried out while the window was installed in the centre opening of the wall panel in the cold room. The air conditions in the cold and warm rooms were measured and controlled at approximately 72°F and 50 per cent R.H. The measured air flow was greater than the actual window leakage by the amount of leakage through the construction of the compartment. All air leakage figures have been corrected for the compartment leakage except those obtained in two tests where the measured pressure differences were less than 0.01 in. of water. In addition, air flows obtained under actual test conditions have been converted to flows which would occur with air at a standard density of 0.075 lb/cu ft, based on the flow equation for the window obtained by test.

Figure 8 gives the air-flow characteristics for the fixed outer glazing with 23 and 46 vent holes in the wood sash for the range of pressure differences between 0 and 0.01 in. of water. The pressure differences in the lower part of this range correspond to differences available to cause interchange of air by chimney action between the air space and outside. There are several reasons why the air flow through 23 vent holes is not exactly one-half the air flow through 46 vent holes at all corresponding pressure differences. Probably there were variations in the resistances to air flow of the vent holes since they were drilled by hand into the wood sash. The flowmeter calibration curve supplied by the manufacturer was thought to have a greater percentage error at the lower flows. Also, the percentage error in reading the flowmeter increases as the scale reading decreases. In addition to these sources of error the leakage through the construction of the compartment was neglected in these tests. This would result in a greater percentage of error in measured air flow through 23 holes than through 46 holes.

Figures 9 and 10 give the characteristics of air flow for the outer pane with one and 46 vent holes respectively in the wood sash for the range of pressure differences between 0 and 0.5 in. of water. The observed flow through one hole is not 1/46 of the flow through 46 holes because of the reasons just mentioned. The characteristics of air flow for the outer pane with one or more holes can be calculated with the least error from the characteristic curves for air flow around the outer pane with 46 vent holes in the wood sash.

A preliminary series of tests were carried out at a variety of pressure differences in the range between 0.315 and 0.788 in. of water to determine the characteristics of air flow for the entire window with from one to 46 vent holes in the wood sash. Figure 11 gives the results for the tests where the pressure on the inside was greater than that on the outside. At the maximum pressure difference used in the test, Fig. 11 indicates that the air flow did not increase after the number of vent holes exceeded 18. The results obtained with outside pressure greater than inside pressure showed that

the air flow did not increase after the number of vent holes in the wood sash exceeded 30 at the same pressure difference. At this point the pressure between the panes is the same as the outside pressure and the air flow is unaffected by the presence of the outer pane.

The air flows through the window with 46 vent holes obtained during the preliminary tests are given in Fig. 12. Curve A represents the air leakage characteristic of the inside glazing when flow occurs from the air space to the inside while curve B represents the characteristic of the inside glazing when flow occurs from the inside to the air space.

A second series of tests were carried out to determine the air leakage characteristics for the inner pane. In the interim, however, the inside glazing was removed and then refastened to the wood sash by the 6 aluminum clips. The air leakage characteristics of the inside glazing obtained in these tests are also given in Fig. 12. Curve C represents air flow from the air space to the inside while curve D indicates air flow from the inside to the air space. The difference between curves A and C, and curves B and D is attributable to the change of resistance of the inside glazing after being refastened to the wood sash. The curves also indicate that the resistance to air flow is greatest when it occurs from the inside to the air space.

(b) Temperature Measurements

Temperature measurements were made at a variety of inside-outside air temperature differences on windows installed in each of the three openings of the wall panel as shown in Fig. 6. All temperatures were measured with No. 30 B.S. copper-constantan thermocouples in conjunction with an electronic temperature indicator. The top window was the most fully instrumented and thermocouple locations are shown in Fig. 13. In the centre and bottom windows thermocouples were located at mid-height, at 10 inches above and below mid-height in the air space and on the inner and outer surfaces of the inner and outer panes.

It was difficult to obtain an accurate measurement of surface temperature. Two different methods of fastening the thermocouples were used without complete success. The surface temperatures reported in this section are the arithmetic mean of the measured temperatures at inner and outer surfaces obtained with thermocouples installed as shown in Fig. B1 method 2. Appendix B discusses the accuracy of this procedure. The thermocouples used in the measurement of air temperature were unshielded. The possible differences between measured and actual air temperatures are discussed in Appendix C.

All window temperatures reported in this section were obtained with the warm room being operated at low humidities to minimize surface condensation. At no time was there condensation on the inside surface of the inside pane; condensation on the inside surface of the outer pane first occurred at a cold room temperature of 0°F. Surface temperature measurements taken during condensation tests are discussed in Appendix D.

A vertical string of thermocouples was installed at the centre of the warm room and temperature gradients were obtained for each test. Typical gradients obtained at different cold room temperatures are given in Fig. 14. Some measurements were made of vertical air temperature gradients in the cold room, but these did not exceed one degree.

Figure 15 gives a typical set of vertical temperature gradients obtained for the top window at an inside - outside air temperature difference of 70°F. A large gradient in the air space is evident, indicating that convection is an important mechanism of heat transfer across the space. This air temperature gradient is reflected in the inside surface temperature of the inner pane, the surface temperature being approximately 34°F at the bottom and 44°F at the top. There is only a 3-degree variation in the inside surface temperature of the outer pane from top to bottom. This gradient is less than that on the inner pane since the outside film coefficient is higher than the inside one.

All these gradients are dependent on the inside - outside air temperature differences. Figures 16, 17 and 18 give the vertical temperature gradients for the inner pane, air space and the outer pane of the top window at a number of cold room temperatures with an inside air temperature of 70°F at the 4½-ft level. There were differences in the vertical temperature variations of the three windows. For the top, centre and bottom windows respectively, these gradients were 5, 8, and 14°F for the outer pane, 43, 51 and 40°F for the air space and 15, 20, and 20°F for the inner pane at an inside - outside air temperature difference of 100°F. Air temperatures 1 3/4 in. from the inside surfaces of the inner pane of the top, centre and bottom windows were 68, 66, and 65°F respectively. The variations in the vertical temperature gradients of the windows are perhaps attributable in part to variations in the convection coefficients with height on the surfaces facing the warm and cold rooms.

The effects of various amounts of air flow from the outside into the air space on the temperatures of the air space and inner and outer panes of the centre window were studied at cold room temperatures of 0 and -30°F. At both cold room temperatures measurements were begun with all the vent holes open in the top and bottom members of the wood sash. The number of open vent holes, top and bottom, was then

successively decreased. These tests (Table V) showed that the temperature at the top of the air space increased by approximately 3°F when the centre vent holes in the top and bottom members of the sash were closed. As more vent holes were closed the temperature at the top of the air space gradually increased. There was also some increase in the surface temperatures of both the inner and outer panes. When all the holes were closed the temperature at the top of the air space increased by approximately 10 and 16°F at cold room temperatures of 0 and -30°F respectively. Under these same test conditions there was an increase in surface temperature of approximately 2°F only. The increase in heat flow through a double window as a result of air interchange between the air space and outside is discussed in Appendix E.

A final test was carried out on the centre window at an inside-outside air temperature difference of 70°F to determine the effect of increasing the width of the sill from 1 3/4 to 4 3/4 in. Table VI gives measured temperatures for sill widths of 1 3/4, 2 3/4. 3 3/4 and 4 3/4 in. There was no appreciable change in the measured temperatures as a result of changing the sill width in the above range.

(c) Condensation Tests

Two series of tests were carried out to permit observation of the extent of condensation on the inside surfaces of the inner and outer panes under various test conditions. Figure 5c shows the bottom window and Fig. 5a is a cross section of the other two windows in the first series of tests. Some venting of the air space to outside was provided in the centre window. The tests revealed that it would be advantageous to modify the inner glazing to reduce the amount of water vapour being transferred to the air space. In the second series of condensation tests the bottom window had inner glazing as before while the centre and top had modified inner glazings as shown in Fig. 5b. Various degrees of venting of the air space to outside were provided in the bottom and centre windows.

In the two series of condensation tests the cold room temperature was cycled for a two-week period followed by steady state tests at different cold room temperatures and relative humidities in the warm room. The cycling tests were carried out to determine the effect of the "breathing action" of the air between the panes on the accumulation of condensation on the inside surface of the outer pane. During these tests the cold room temperature was cycled daily between +20 and - 20°F while a temperature of 70°F and 30 per cent R.H. were maintained in the warm room. A daily cycle consisted of lowering the temperature from +20 to -20°F in 8 hours, raising it from -20 to +20°F in 8 hours and finally maintaining +20°F for the remaining 8 hours.

During the steady state tests the temperature and relative humidity in the warm room were constant. The cold room temperature was also held constant but not the relative humidity. Two levels of relative humidity were maintained in the warm room at each of the cold room temperatures. The lower humidity was chosen to just cause condensation along the bottom of the inside surface of the inner pane while the higher humidity provided a more serious condensation condition.

No attempts were made to clear the frost from the inside surfaces of the outer panes in the intervals between various tests in the first series. The observations, therefore, were inconclusive. In the second series, however, the outer panes were cleared of condensation at the beginning of each cold room temperature condition.

Variations made in the inner glazing had no appreciable effect on the condensation on the inner surface. The observations of condensation on the inside surface of the inner pane reported here were made on the top window, which had inner glazing as in Fig. 5b, since it was most fully instrumented with thermocouples. There were no vent holes in the sash and the inside temperature was maintained at 70°F at the $4\frac{1}{2}$-ft level. The effect of venting the air space on the surface temperatures and on condensation on the inner pane is shown in Table V.

The condensation on the inside surface of the inner pane extended across the botton of the pane in a band of uniform width. Figure 19 gives the surface temperatures for the inner pane which were obtained at the various steady state test conditions. Table VII gives the test conditions and observations of the extent of condensation on the inner pane. The surface temperature at the upper boundary of condensation is equal to the dew point temperature in the warm room. Therefore, the extent of condensation can be predicted from the measured surface temperatures in Fig. 19 and the known warm room dew point. These predicted values of the extent of condensation are given in the table. An indication of the accuracy of surface temperature determinations can be obtained by comparing the measured values of temperatures at the upper boundary of condensation obtained from Fig. 19 and given in Table VII with the warm room dew point.

It is evident from the table that there is fair agreement between the measured and predicted amounts of condensation. Correspondingly, there is very good agreement between the surface temperatures determined from thermocouple readings and those predicted from observations of surface condensation and known room dew point temperatures.

The accumulation of condensation on the inside surface of the outer pane was affected by the variations made in the inner glazing and the venting of the air space as well as by the location of the windows with respect to the neutral zone. Measurements of the total pressure difference between the warm and cold rooms were made with a Betz micromanometer having a sensitivity of approximately 0.001 in. of water. Figure 20 gives the pressure difference across the partition at various heights. These pressure differences were produced by the differences in the density of the air in the cold and warm rooms.

It is evident that, during the tests, the centre window was near the neutral zone, the bottom and top windows being in regions where inflow and outflow of air to and from the warm room tended to occur. There was no significant inflow of air through the bottom window since the perimeter of the inner glazing was sealed with caulking compound. Also, there was no significant outflow of air through the top window since the vent holes in the sash were closed during tests.

The resistance to air flow of the inner glazing was many times that of the outer glazing with vent holes. Thus, the pressure at mid-height in the air space of the bottom window was close to that in the cold room at the corresponding level when equal numbers of vent holes were used at the top and bottom. Similarly, for the top window the resistance to air flow of the outer glazing without vent holes was many times that of the inner glazing. Therefore, the pressure at mid-height in the air space was the same as the pressure in the warm room at the same level (assuming that the resistance to air flow of the inner glazing was equally distributed above and below mid-height). If these conditions are met the location of the neutral zone has no effect on the condensation accumulation on the outer panes of the bottom and top windows.

The cycling tests in both series were preceded by tests in which window temperatures were measured at various cold room temperatures down to -40°F while the warm room humidity was continuously lowered from approximately 50 to 10 per cent. Condensation first occurred on the inside surfaces of the outer panes at a cold room temperature of 0°F.

The bottom and top windows had no vent holes while the centre window had two vent holes in the bottom throughout the first series of condensation tests. Figures 21, 22 and 23 give the frost patterns on the outer panes of the three windows prior to and following the cycling test in the first series. These indicate that the amount of water vapour

transferred into the air space of the centre window was greater than that for the top window. This may have been due in part to differences in resistances to air flow of the inner glazings of the windows. On the other hand the difference in condensation performance may have been partly due to differences in pressure distributions across the panes of the two windows.

Figure 3c shows the pressure distribution for the top window during condensation tests. The distribution for the centre window would be as in Fig. 2b or Fig. 3a depending on whether it was located at or above the level of the neutral zone. If the major mechanism of vapour transfer is by air flow, then during the cycling tests the centre window was located above the neutral zone with the pressure distribution as shown in Fig. 3a.

At the beginning of the cycling tests in the second series the bottom and centre window had two vent holes top and bottom. There were thin patches of frost at the top corners and specks of frost along the bottom of the outer pane of the top window. Thin patches of frost appeared at the corners and centre of the outer pane of the centre window while the outer pane of the bottom window was clear. After six days of cycling, the outer pane of the centre window had cleared while the outer pane of the bottom window remained clear. The patches of frost at the two top corners of the top window had increased in size.

For the remaining eight days of the cycling tests the centre window had one vent hole top and bottom while the bottom window had no vent holes. The amount of frost deposited on the outer pane of the top window continued to increase. At +20°F the outer pane of the centre window was clear while patches of frost formed on it at the centre and at the two right corners at -20°F. Similarly the outer pane of the bottom window was clear at +20°F but had a few specks of frost along the bottom and at the top corners at -20°F.

During the steady state tests in the second series the top window had no venting while the bottom and centre windows had different amounts of venting. Table VIII gives conditions of test, the venting arrangements, and the results for the steady state condensation tests of the second series. It was stated previously that the centre window was located in the vicinity of the neutral zone and that the condensation accumulation on the outer pane of the top window was not affected by the location of the neutral zone. Therefore, the frost pattern on the outer pane of the top window can be taken as that which would occur on the centre window if it had no vent holes since it can be assumed that the air leakage characteristics of the inner glazings of both windows were approximately the same.

During the first test at a cold room temperature of 20°F and 40 per cent R.H. in the warm room the centre window had two vent holes top and bottom. The observations of frost on the outer panes of the top and bottom windows were not recorded. At the beginning of the test the outer pane of the centre window was covered with large patches of frost at the sides and bottom. At the end of the test it was clear except for small patches of frost at the corners.

During the second test at 20°F, with 46 per cent R.H., the bottom window had no vent holes while the centre window had three vent holes top and bottom. The outer panes of all of the windows were clear at the start of this test. The frost patterns at the end of 48 hours are shown in Fig. 24.

During the final test at 20°F, with 44 per cent R.H., the centre window had eleven vent holes at the bottom only. At first the outer pane was clear except for patches of frost at the top corners and in 62 hours the patches had increased slightly. Additional frost patches developed at the centre and bottom of the outer pane of the centre window when the bottom venting was reduced from eleven to six holes. Observations of frost on the outer panes of the top and bottom windows were not recorded.

During the first test at 0°F, with 30 per cent R.H., the bottom window had one vent hole top and bottom while the centre window had three vent holes top and bottom. The frost patterns noted prior to and after 38 hours at the above conditions are shown in Fig. 25.

The humidity was then increased to 38 per cent and maintained for 124 hours. For the first 26 hours the bottom window had no vent holes while the centre window had three open top and bottom. The frost patterns on the outer panes at the end of this period are shown in Fig. 26.

During the last 98 hours the centre window had six vent holes top and bottom while the bottom window had one hole top and bottom. The frost pattern observed at the end of this period is given in Fig. 27. Light frost extended across the bottom and top of the inside surface of the outer pane of the top window. The inside surface of the outer pane of the centre window had cleared except for frost patches at the upper corners. The inside surface of the outer pane of the bottom window had cleared.

In the third test at 0°F with 38 per cent R.H., the centre window was tested with openings first at the bottom only then at the top for a total of 114 hours. At the start the outer pane was clear. For the first 90 hours the centre window had 23 holes open at the bottom. At the end of this time a thin band of frost extended from top to bottom at

both sides of the outer pane. The frost pattern did not change appreciably during the last 24 hours when the venting was changed to 23 holes at the top.

In the fourth test at 0°F with 38 per cent R.H., the centre window had 4 holes top and bottom. The outer panes were clear at the start. After 74 hours there were small patches of frost at the two upper corners and at the centre and bottom of the outer pane of the centre window. The condition of the outer pane of the top window was almost identical to that in Fig. 26. The number of vent holes in the top and bottom of the centre window was increased to five and after another 92 hours only the frost patches at the two upper corners remained. The condition of the outer pane of the top window was as shown in Fig. 27.

During the test at -20°F with 20 per cent R.H., the centre window had five vent holes top and bottom while the bottom window had two vent holes at the bottom only. The condensation conditions at the beginning and after 99 hours are shown in Fig. 28.

The test carried out at -20°F and 30 per cent R.H. was inconclusive for the centre and top windows as ice formed around the periphery of the inner sash altering its leakage characteristics. Two vent holes at the bottom kept the outer pane of the bottom window clear.

Under all conditions of test in the second series where observations were obtained on the top window there was progressive frost accumulation on the inner surface of the outer pane. The bottom window remained clear. Some venting was provided at cold room temperatures of 0°F and -20°F but it is not known if this was more than the minimum required.

The venting provided for the centre window under many of the test conditions, prevented condensation on the outer pane, except for small patches at the upper corners. Condensation in these stagnant areas could probably be eliminated by locating vents in this vicinity. If a small amount of condensation in the upper corners is acceptable, adequate venting arrangements under the test conditions were as follows: two holes top and bottom at 20°F., 40 per cent R.H.; three vent holes top and bottom at 20°F., 46 per cent R.H.; five holes and six holes top and bottom at 0°F, 38 per cent R.H. and; five holes top and bottom at -20°F, 20 per cent R.H.

The venting arrangements successful at 20°F and -20°F were probably more than adequate. At 0°F, however, four vent holes at the top and bottom did not provide sufficient air interchange but both five holes and six holes top and bottom did provide sufficient air interchange. Therefore, five holes top and bottom provided the minimum air interchange necessary to keep the outer pane clear.

Although the arrangement of eleven vent holes at the bottom at 20°F outside temperature and 44 per cent R.H. was almost sufficient to keep the outer pane clear, effective venting generally is not necessarily provided in this manner. Figure 20 shows that the centre window was near the neutral zone during the tests at 20°F. Figure 2 indicates that the vapour transfer from the inside to air space with holes at the bottom is likely to be much less than that with holes located top and bottom.

Figure 2 also shows that, with the window at the neutral zone, the vapour transfer from the inside to the air space is greater with vent holes at the top only than at top and bottom. This suggests that condensation conditions in the test at 0°F and 38 per cent R.H. should have been less severe with the holes at the bottom. The test with vent holes at the top only probably was too brief to point up any differences.

IV. DISCUSSION OF RESULTS

(a) Condensation on Inside Surface of Inner Pane

During the steady state tests, condensation on the inside surface always occurred first at the bottom in bands of uniform width. There was good agreement between the extent of condensation observed on the inner pane and that predicted from the measured vertical surface temperature gradients and the warm room dew point.

The ASHAE Guide and other engineering handbooks give tables based on simple heat-flow calculations, of the maximum inside relative humidities possible without condensation occurring on the interior surfaces of double windows at various outside temperatures. At an inside temperature of 70°F, values of the maximum relative humidity given in the 1957 ASHAE Guide for a double window with a U-value of 0.55 Btu/sq ft/hr/°F are 56%, 43% and 33% at outside temperatures of 20°F, 0°F and -20°F, respectively. If based on measured inside surface temperatures condensation would occur over almost the entire surface of the windows under test at these conditions. Some condensation occurred at the bottom of the inner pane at humidities as low as 46, 30 and 20 per cent at outside temperatures of 20°F, 0°F and -20°F.

Thus, condensation will occur on the inner panes of double windows at lower humidities than those predicted from calculations. The reason for this is that uni-directional heat flow does not occur, leading to vertical temperature variations in the air space and inner and outer panes.

(b) Condensation on Inside Surface of Outer Pane

The mechanisms which transfer water vapour to or from the air space of a double window have been discussed earlier in this report. Observations of condensation on the outer pane of the bottom window showed that the water vapour entering the air space as a result of vapour diffusion through the wood sash was negligible compared with the amount transferred through cracks and openings around the uncaulked inner glazings. In the condensation tests on the centre and top windows, therefore, cracks and openings around the inner glazings provided the major path for vapour transmission to the air space. It also follows that the vent holes provided the major paths for vapour transmission from the air space to the outside.

It would be useful to know the relative amount of vapour transfer through the openings of the inner and outer panes by vapour diffusion and air interchange under a given set of conditions. Equations 1 and 3 can be used to predict these rates provided the appropriate coefficients are known. If both mechanisms of vapour transfer are operating simultaneously there may be interaction and the simple equations may not be applicable. The equations, however, can be expected to give some idea of the relative importance of the two mechanisms.

The values for specific humidity and vapour pressure given in Tables I and IV can be used for evaluating the vapour transfer as a result of vapour diffusion and air flow. An approximate value of the permeability coefficient "α" for the vent holes can be calculated from the experimentally determined diffusion coefficient for water vapour through air in straight tubes. A value of 110 perm inches at 46°F is obtained for the permeability coefficients from the data given in the handbook of Chemical and Physical Constants (2). The coefficient increases with temperature but no further refinement is justified in view of differences in the data of investigators. The calculated vapour transmission by vapour diffusion through two vent holes (one top and bottom), is 0.1×10^{-2} grains/hr at 20°F and 0.05×10^{-2} grains/hr at 0°F.

The air flow through the vent holes at the appropriate pressure differences can be obtained accurately from Fig. 8. The air pressure differences across the vent holes due to buoyancy effects can be calculated from the air space temperatures obtained by simple calculation. These air space temperatures can be obtained by taking the mean of the temperatures for the inner and outer panes given in Table I. If the window is located at the neutral zone the air pressure differences due to buoyancy effects across the vent holes obtained by using equation 14 (Appendix A) are 0.0006 inches of water at 20°F and 0.0008 inches at 0°F. The corresponding air flows through one vent hole top and bottom are 0.57 and 0.76 cu ft/hr. The vapour transmissions past the outer pane

as a result of these air flows are 18 x 10^{-2} grains/hr at 20°F and 12 x 10^{-2} grains /hr at 0°F.

The calculations indicate that the vapour transfer through the vent holes by diffusion is negligible in relation to the vapour transfer by air flow. This was also borne out in part by tests in which the vent holes were located at either the top or bottom, where they proved to be relatively ineffective.

The passages past the inner glazing of the test window are complex in form. As stated previously they probably consist of a variety of orifices, enlargements, contractions, bends etc. The diffusion coefficients given in the Handbook of Physical Constants (2) are for vapour transfer through air in straight tubes and these cannot be applied directly to the passage of the inner glazing. Since the diffusion coefficient for the inner glazing was not measured it is not possible to calculate the vapour transfer by diffusion.

The vapour transfer past the cracks and openings of the inner pane as a result of air flow under a given set of conditions can be calculated from a knowledge of its air leakage characteristics. If the window is at or near the neutral zone the location of the openings of the inner pane must be known.

A relationship between the ratio of air flow from inside and outside to the air space and the occurrence of condensation was derived in the first part of this report. This relationship assumes that the vapour transfer by diffusion is insignificant in relation to that by air flow. Air flows into the air space from the inside and outside for given conditions of pressure can be determined from the air leakage characteristics of the inner and outer pane of a window. The ratio of outside to inside air can be compared with the minimum permissible ratios given in Table IV to determine the design temperature at which condensation will occur. Alternately, the air leakage characteristics of the outer pane required to prevent condensation can be determined.

Figure 17 indicates that the temperature of the air space is not uniform. Also, the mean air space temperature occurs above the mid-height of the window. The actual mean air space temperature corresponds closely to the calculated temperature obtained by averaging the temperatures given in Table I for the inside surfaces of inner and outer panes. These values can therefore be used to determine the average density of the air in the space.

The air flow through the vent holes at the appropriate pressure differences can be obtained accurately from Fig. 8. Unfortunately the air flow around the inner pane at pressure

differences present when the window is at or near the neutral zone can not be obtained accurately from Fig. 12 due to the limitations of the flow meter and manometer used in these measurements. The equations developed in Appendix A, however, can be used to overcome partially this limitation.

Equations 5 and 12 (Appendix A) define conditions required to prevent condensations on windows located above and at the neutral zone respectively. Assuming that the exponent in the air flow equation for the inner pane is at low pressure differences, equations 5 and 12 (Appendix A) can be simplified to:

$$Q_o = C_1 R \Delta P_a \tag{6}$$

and

$$Q_o = \frac{C_1 R \Delta P_i}{2} \tag{7}$$

These equations show that the air flow from the outside to the air space is equal to that which would occur through openings of the inner pane at pressure differences of $R\Delta P_a$ and $R\Delta P_1/2$ when the window is located above, and at the neutral zone.

It was previously concluded that during the cold room condensation tests, five holes top and bottom provided the minimum air interchange required to keep the outer pane clear of frost at a cold room temperature of 0°F and 38 per cent R.H. Reference to Fig. 20 indicates that the neutral zone was at the bottom edge of the inner glazing. During this test the cold room humidity was about 50 per cent.

Since the humidities in the cold and warm room were different than those used in the preparation of Table IV the minimum permissible ratio must be calculated from equation 4. If the specific humidity in the air space is assumed to correspond to the saturation value at the minimum temperature measured on the inner surface of the outer pane, a value of 6.2 is obtained for the minimum permissible ratio of outside to inside air.

If the neutral zone is at the bottom edge of the inner glazing, the average pressure difference across the inner pane "ΔP_a" at 0°F using equation 11 (Appendix A) is 0.002 inches of water. Using the value of 6.2 for the minimum permissible ratio R the air flow past the inner glazing at a pressure difference of $R\Delta P_a$ obtained from Fig. 12 is 3.6 cu ft/hr.

The pressure difference across the vent holes at 0°F under the above conditions using equation 10 (Appendix A) is 0.0008 inches of water. The corresponding air flow, through one vent hole top and bottom, obtained from Fig. 8 is 0.76 cu ft/hr.

Therefore, in order to provide the minimum permissible ratio, 6.2 of outside to inside air, five vent holes top and bottom are needed at 0°F.

Thus, there is good agreement between the actual and calculated amount of venting required to prevent condensation on the outer pane. This suggests that vapour transfer by diffusion can be neglected in determining the characteristics of a window required to control condensation on the inside surface of the outer pane.

During the cycling tests the breathing action of the air space contributed to the total vapour transfer to and from it. The calculated average rate of air flow into and out of the air space during a daily cold room cycle (as a result of the volume change corresponding to the air space temperature change) was 0.6×10^{-3} cu ft/hr.

During the test two vent holes top and bottom were needed to provide the minimum cold air required to keep the outer pane clear. The volume rate of air from the outside to the air space through two vent holes top and bottom at an outside temperature of 0°F, obtained from Fig. 8, is 1500×10^{-3} cu ft/hr. This assumes that the pressure at the mid-height of air space corresponds to the outside pressure at the same level. Based on the minimum permissible ratios given in Table IV the air flow from the inside to the air space is 85×10^{-3} cu ft/hr.

These calculations show that the water vapour transfer from breathing is insignificant compared to that of air flow from either inside or outside to the air space.

The condensation observations in the cold room were made with the windows located at or near the neutral zone. Calculations were made of the venting of the air space to the outside required to prevent condensation on the outer pane of the test window (inside glazing as in Fig. 5b) when subjected to different total pressures at outside temperatures of 20°F and 0°F. The results are given in Table IX. The procedures used were as previously outlined, using minimum permissible ratios of outside to inside air given in Table IV. Table IX also gives the volume rate of air flow from the outside to the air space along with the percentage increase and heat flow through the window by air flow (equation 9 - Appendix E).

The zero pressure difference refers to the condition where the window was located at the neutral zone. The remaining pressure differences were taken from Table II and correspond to those produced across a leeward window at wind speeds of 5, 10 and 15 mph respectively. These pressure

differences would be produced by buoyancy effect at an outside temperature of 20°F if the window was approximately 3, 9 and 21 feet above the neutral zone and at 0°F if the window was approximately 2, 6 and 15 feet above the neutral zone.

The calculated minimum permissible ratios given in Table IV were based on inside room and air space specific humidities corresponding to saturation at the temperatures of the inner and outer panes, and on outside specific humidities corresponding to saturation at outside temperature. The surface temperatures in Table IV were based on inside and outside film coefficients of 1.5 and 6.6.

Records of the actual levels of relative humidity in some typical Canadian dwellings indicate that inside relative humidities are generally lower than those corresponding to saturation at the calculated temperature on the inside surface of the inner pane of a double window. At an outside temperature of 0°F the inside humidity ranged from approximately 20 to 30 per cent while the calculated value was 42 per cent.

The climatological records for the various regions of Canada indicate that average winter outside relative humidities are below saturation. The average range at 0°F is approximately 70 to 94 per cent R.H. In the Ottawa valley 85 per cent might be taken as an average value at an outside temperature of 0°F.

The Climatological Atlas of Canada reports average wind speeds during the winter season in excess of 15 mph over the Gulf of St. Lawrence, and 15 mph over most of the Atlantic Coastal region of Canada. Elsewhere in Canada the mean winter wind speed is approximately 10 mph. Normally it would be expected that wind speeds over the leeward windows would be lower than the design values used for heat loss and surface temperature calculations.

The foregoing discussion indicates that the values of permissible ratios given in Table IV are conservative. If values of inside and outside film coefficients of 1.5 and 4.0 (based on a 10 mph wind) and inside and outside relative humidities of 25 and 85 per cent are used, a ratio of outside to inside air of 3.0 is needed to prevent condensation at an outside temperature of 0°F.

Using this value as a basis for calculation, the test window (inside glazing as in Fig. 5b) at 0°F would require one vent hole top and bottom when located at the neutral zone, five vent holes top and bottom with a 5 mph wind and sixteen vent holes top and bottom with a 10 mph wind. The corresponding venting areas are 0.05, 0.25 and 0.80 sq in. top and bottom. The resulting increases in heat flow are 0.07, 0.2 and 0.9 per cent.

The foregoing venting requirements apply to a specific window design of a particular size and shape. The cracks and openings past the inner glazing of the test window were assumed to be located principally along the top and bottom edges. Some windows have cracks and openings equally distributed around the periphery.

If the total pressure inside is greater than outside over the full height of the window, the over-all air flow rate past the inner glazing would be the same for either distribution of the cracks. If the windows are located at or near the neutral zone, however, the over-all air flow rate past the inner glazing does depend on the distribution of the openings. If these are uniformly distributed, the over-all air flow rate past the inner glazing can be obtained by integration around its periphery.

Windows with the same over-all air flow rate and height require the same venting irrespective of width. On the other hand windows with the same over-all flow rate but of different height require the same venting only when located at the neutral zone; when located above it the venting required decreases with increasing height.

The test window (inner glazing as in Fig. 5b) had an average leakage rate of approximately 0.04 cfm/ft of sash perimeter at an air pressure difference of 0.301 in. of water (velocity head of 25 mph). This leakage rate is probably of the same order as the sash leakage of other residential windows of the casement, awning or hopper type, and of some commercial windows with inner and outer glazing in the same sash. There are other window types which have a much higher leakage rate. For example, the maximum air leakage rate at a pressure difference equivalent to a 25 mph wind permitted for a double double-hung window in the specification of the Aluminum Window Manufacturers' Association is 0.5 cfm/ft of sash perimeter.

If it is assumed that the leakage characteristics of the inner and outer sash are similar and that the air leakage is proportional to the square root of the pressure difference it can be shown that the venting area required, for a 3- by 4-foot double double-hung window top and bottom, is approximately 9 sq in. with a 5 mph wind and 18 sq in. with a 10 mph wind. The corresponding increases in heat flow are 14 and 23 per cent. The basis of calculation was the same as that used in predicting the venting area requirement for the test window of 0.25 sq in. with a 5 mph wind and 0.80 sq in. with a 10 mph wind.

V. SUMMARY AND CONCLUSIONS

1. The measured values of inside surface temperatures for the inner panes were consistent with observations of the extent of condensation and measured warm room dew point to within better than 1°F.

2. There were appreciable vertical air temperature gradients in the air space under the conditions of test and these were reflected in vertical variations in temperature over the inner and outer panes. At a warm room - cold room temperature difference of 100°F these vertical gradients were 5°F, 43°F and 16°F for the outer pane, air space and inner pane. Temperature gradients of this magnitude can be expected in field installations involving windows of equal or greater height, except where direct heating beneath windows is employed.

3. The measured values of inside surface temperatures for the inner panes at the mid-height were lower by approximately 2°F than the values of surface temperatures obtained by the usual simple calculation.

4. Condensation occurred on the lower portions of the inside surface of the inner pane at considerably lower relative humidities than those predicted by calculation. At inside relative humidities corresponding to those at which visible condensation should just occur according to calculations, almost the entire inside surface of the inner pane would exhibit condensation.

5. There was no significant change in the measured temperatures of the inside surface of the inner pane as a result of increasing the sill width from 1 3/4 to 4 3/4 inches.

6. Further information is required on inside surface temperatures of double windows as affected by window height, air space thickness and method of heating.

7. A method has been developed for determining under what environmental conditions condensation will occur on the inside surface of the outer pane of double windows based on the relative air leakage characteristics of the openings around inner and outer panes. Alternately, with given air leakage characteristics of the inner sash the amount of venting of the air space to outside required to prevent condensation under different conditions can be determined. The method is based on the assumptions that vapour flow by diffusion is negligible in relation to that as a result of air flow.

8. It was evident from the condensation tests that the amount of water vapour entering the air space by vapour diffusion through the wood sash was insignificant in relation to the amount transferred through the cracks and openings around the inner glazing.

9. Calculations of the vapour flow through the $\frac{1}{4}$-inch diameter vents around the outer sash of the test window, based on diffusion theory and measured air leakage coefficients, indicate that with the vents located top and bottom the vapour transfer by diffusion is less than 1 per cent of that by air flow as a result of chimney action. The condensation tests showed that vents located top and bottom were definitely more effective than vents of the same total area located at either the top or bottom of the air space.

10. There was good agreement between the number of vents, around the outer sash at top and bottom, required to prevent condensation on the inside surface of the outer pane and the number determined by calculation, based on the measured air leakage characteristics of the openings around inner and outer panes. This indicates that for the test window the vapour flow by diffusion from inside to the air space was small in relation to that from air flow. A test is being planned to determine the actual coefficient of permeability for vapour diffusion of the inner sash.

11. By ignoring vapour flow by diffusion, it has been shown that the amount of air leakage between outside and the air space must be several times that from the inside to the air space to prevent condensation under winter conditions. The minimum permissible ratio of outside to inside air to prevent condensation increases with decreasing outside temperature. At a given outside temperature the ratio increases with increasing inside or outside relative humidity.

12. It has been shown that air interchange between the air space and outside as a result of chimney action can occur with openings top and bottom, even with inside air pressures greater than outside and with over-all air leakage from inside to outside, if the resistance to air leakage of the inner pane is sufficiently greater than that of the outer pane.

13. For the test window the amount of air interchange (and thus vapour interchange) between the air space and the environment induced by "breathing action" from a daily temperature cycle of 40°F is negligible in relation to the air flow through the inner glazing induced by chimney action at 0°F outside temperature, even with the window at the neutral zone. At pressure differences equivalent to a 10 mph wind the flow induced by "breathing action" is an even smaller proportion of the total. It follows that breathing action as a mechanism of vapour transfer is only important with windows having much tighter inner glazing than that of the test window.

14. If air interchange between the air space and outside is to be used to control condensation on the outer pane, the relative resistances to air leakage of the inner and outer panes depend on the minimum permissible ratios of outside to inside air and the outside temperature.

15. From calculations based on known air leakage characteristics and selected design conditions the amount of venting for the test window needed to prevent condensation results in an increase in heat flow of approximately 1 per cent. The average air leakage rate of the inside pane amounts to 0.04 cfm/ft of sash crack. For windows of the double-hung type having air leakage rates of 0.75 cfm/ft of crack similar calculations indicate that the amount of venting required to prevent condensation may result in an increase in heat flow of 15 to 25 per cent. There is, therefore, a practical limit to the leakage rate of the inner pane that can be tolerated if venting of the air space is to be used to prevent condensation on the outer pane of double windows. Similarly, when considering the application to a given window arrangement of venting the air space to outside as a means of controlling condensation on the inside surface of the outer pane, the possible effect of venting on the heat flow through the window should be determined by calculation.

16. There is a lack of detailed information on actual conditions in buildings which affect condensation on the inside surface of the outer pane. In particular, further details on total air pressure differences between inside and outside and inside relative humidities are desirable. For low buildings air pressure differences due to wind action appear to be the more important while for tall buildings those resulting from chimney effect may have to be considered.

Careful judgment should be used in selecting conditions for designing double windows to prevent condensation on the outer pane since extreme values may lead to unrealistic requirements for venting of the air space or for the tightness of the inner pane.

17. Unless conditions of test, including total air pressure differences, are similar to those expected in the field the results of observations of condensation on the outer pane in cold room studies are not directly applicable and are of doubtful value except for research purposes.

18. Further studies on other types of windows are required to determine the applicability of the approach developed in this report to the control of condensation on the inside surface of the outer pane of double windows.

ACKNOWLEDGMENTS

The authors wish to thank Dr. D.G. Stephenson for his assistance in the measurement of air pressure differences with the displacement type micromanometer. Grateful acknowledgment is also made to Mr. M.O. Pelletier who constructed the test installations and carried out most of the observations. Finally the authors wish to express their appreciation of the assistance and advice given by Mr. K.R. Solvason and Dr. N.B. Hutcheon.

REFERENCES

1. Bahnfleth, D.R., T.D. Moseley and W.S. Harris, Measurement of infiltration in two residences Part II: Comparison of variables affecting infiltration. Transactions, A.S.H.A.E., no. 1615, vol. 63, 1957, pp. 453-476.

2. Kaye, G.W.C., and T.H. Laby, Physical and chemical constants. Longmans, 10th edition, p.47.

TABLE I

Ratio of Vapour Pressure Differences across Inner and Outer Panes for Various Outside Temperatures

Outside Temperature t_o °F	Surface Temperatures: Inside of inner pane t_1 °F	Surface Temperatures: Inside of outer pane t_3 °F	Water Vapour Pressure Differences: Across inner pane $(P_i - P_s)$ inches H_g	Water Vapour Pressure Differences: Across outer pane $(P_s - P_o)$ inches H_g	$\frac{P_i - P_s}{P_s \quad P_o}$
40	59	43	0.225	0.0305	7
20	52	25	0.260	0.0276	9
0	45	6	0.249	0.0137	18
-20	38	-12	0.209	0.00715	29
-40	31	-30	0.165	0.00321	51

TABLE II

Pressure Differences across a Leeward Window as a Result of Wind Action

wind speed, mph	pressure difference across leeward window, inches of water
0	0
5	0.004
10	0.014
15	0.032
20	0.058
25	0.090
30	0.130

TABLE III

Pressure Differences due to Buoyancy of Inside and Outside Air

Outside Temperature	Pressure Differences per foot Above or Below Neutral Zone	
t_o °F	ΔP pounds per square foot	h inches of water
40	0.00451	0.000867
20	0.00783	0.00151
0	0.0114	0.00220
-20	0.0154	0.00295
-40	0.0197	0.00378

TABLE IV

Ratio of Outside to Inside Air for No Condensation at Various Outside Temperatures

Outside Temperature t_o °F	Surface Temperatures: Inside of inner pane t_1 °F	Surface Temperatures: Inside of outer pane t_2 °F	Difference in Specific Humidity: Between airspace and inside $(\phi_i - \phi_s)$ grains/lb of dry air	Difference in Specific Humidity: Between airspace and outside $(\phi_s - \phi_o)$ grains/lb of dry air	Ratio of absolute Values of Outside to Inside Temp. T_o/T_i	Ratio of Outside Air to Inside Air Q_o/Q_i
40	59	43	33.7	4.52	0.943	7
20	52	25	38.5	4.05	0.906	9
0	45	6	36.7	2.0	0.868	16
-20	38	-12	30.7	1.04	0.830	25
-40	31	-30	24.2	0.47	0.792	41

TABLE V

Effect of Various Amounts of Air-Interchange on Window Temperatures

Description	Temperature °F													
Cold Room	0	0	0	0	0	0	0	-30	-30	-30	-30	-30	-30	-30
Inside surface of outer pane 10" above mid-height	10	12	11	11	11	12	12	-15	-14	-13	-13	-13	-13	-13
Air space ½" from outer pane " " "	30	33	36	37	39	39	40	14	17	24	25	27	28	30
Inside surface of inner pane " " "	46	46	47	47	47	47	48	37	37	38	39	40	40	41
Inside surface of outer pane at mid-height	8	8	8	8	8	8	8	-18	-18	-18	-18	-18	-18	-18
Air space ½" from outer pane " "	22	24	25	25	26	24	24	2	3	4	6	7	5	3
Inside surface of inner pane " "	43	44	44	44	44	44	44	33	33	33	34	34	34	34
Inside surface of outer pane 10" below mid-height	7	7	7	7	7	7	7	-21	-20	-20	-21	-21	-21	-21
Air space ½" from outer pane " " "	12	16	13	12	12	12	+14	-14	-8	-12	-14	-14	-16	-17
Inside surface of inner pane " " "	34	35	35	35	35	35	36	19	20	20	20	21	21	21
Air Temperatures in Warm Room 102" from floor	70	-	-	-	-	-	-	71						
172" " "	70	-	-	-	-	-	-	70						
54" " "	70	-	-	-	-	-	-	70						
35" " "	68	-	-	-	-	-	-	68						
15½" " "	65	-	-	-	-	-	-	64						
7" " "	63	-	-	-	-	-	-	61						
Vent holes in top and bottom members of sash	All Open	12 Clsd	10-14 Clsd	8-16 Clsd	6-18 Clsd	4-20 Clsd	All Clsd	All Open	12 Clsd	10-14 Clsd	8-16 Clsd	6-18 Clsd	4-20 Clsd	All Clsd

TABLE VI

Temperature Measurements on Window with Various Lengths of Sill

Description	Temperature °F			
Inside surface of outer pane 10" above mid-height	12	12	12	12
Air space ½" from outer pane " " "	39	39	40	40
Inside surface of inner pane " " "	48	47	48	48
Inside surface of outer pane at mid-height	9	9	8	8
Air space ½" from outer pane " "	26	25	24	24
Inside surface of inner pane " "	47	46	45	45
Inside surface of outer pane 10" below mid-height	7	7	7	7
Air space ½" from outer pane " " ""	13	13	13	13
Inside surface of inner pane " " "	37	36	36	36
Air Temperatures in Warm Room 4" from floor	65	65	65	65
30" " "	67	67	67	67
54" " "	69	69	69	69
78" " "	71	71	71	71
102" " "	71	71	71	71
Length of sill in inches	$4\frac{3}{4}$	$3\frac{3}{4}$	$2\frac{3}{4}$	$1\frac{3}{4}$

TABLE VII

Observations of Condensation on Inside of Inner Pane

Cold room temperature (°F)	Warm room relative humidity %	Warm room dew point (°F)	Width of band of condensation (inches)	Measured surface temperature at upper boundary of condensation (°F)	Width of band of condensation, predicted from temp. measurements (inches)
20	40 46	44.5 48.5	0 2	- 48.5	0 2
0	30 38	37.5 43	1 7	37.5 43.3	1 6
-20	20 30	27.5 37.5	$\frac{3}{4}$ $10\frac{1}{2}$	28.2 37	$\frac{1}{2}$ 12

TABLE VIII

Results of Second Series of Steady State Condensation Tests

Cold room Temp. °F	Humidity in warm room % R.H.	Humidity in warm room dew point	Duration of test hours	Venting arrangement for centre window (vents)	Venting arrangement for bottom window (vents)	Adequacy of venting arrangement for the centre window	Adequacy of venting arrangement for the bottom window
20	40	44.5	168	2 top and bottom	-	adequate	-
	46	48.5	48	3 top and bottom	none	adequate	adequate
	44	47	62	11 bottom	-	almost adequate	-
			23	6 bottom	-	inadequate	-
0	30	37.5	38	3 top and bottom	1 top and bottom	inadequate	adequate
	38	43	124	6 top and bottom	1 top and bottom	adequate	adequate
			90	23 bottom	-	inadequate	-
			24	23 top	-	inadequate	-
			74	4 top and bottom	-	inadequate	-
			92	5 top and bottom	-	adequate	-
-20	20	27.5	99	5 top and bottom	2 bottom	adequate	adequate
	30	37.5	144	-	2 bottom	-	adequate

TABLE IX

Venting Required at Different Pressure Differences and Outside Temperatures

Outside temperature °F	Total pressure difference across window in. of water	Outside air flow to air space to prevent condensation cu ft/hr	Heat flow increase by outside air flow to air space %	Required number of $\frac{1}{4}$-in. dia. holes top and bottom	Equivalent venting area top and bottom sq in.
20	zero	1.2	0.1	3	0.15
20	0.004	10.5 to 11.5	1	15 to 25	1
20	0.014	25 to 35	2	55 to 65	3
20	0.032	55 to 65	4	125 to 135	6.5
0	zero	2.5	0.2	4	0.20
0	0.004	15 to 25	2	25 to 35	1.5
0	0.014	55 to 65	5	75 to 85	4
0	0.032	105 to 115	8	135 to 145	7

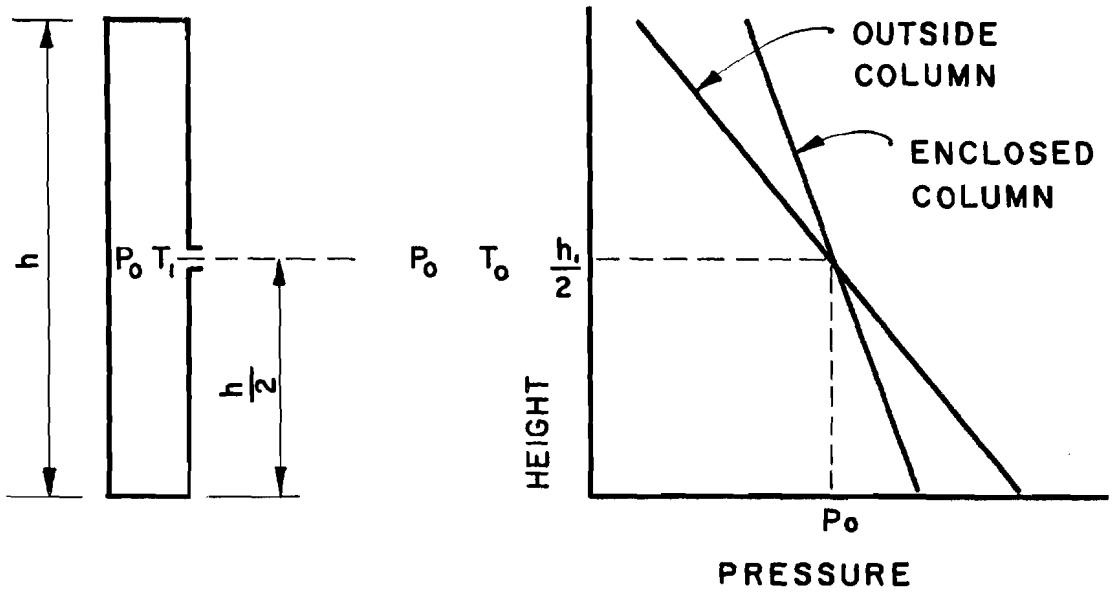


FIGURE I a

PRESSURE DISTRIBUTIONS FOR TWO COLUMNS OF AIR INTER CONNECTED AT THE CENTRE

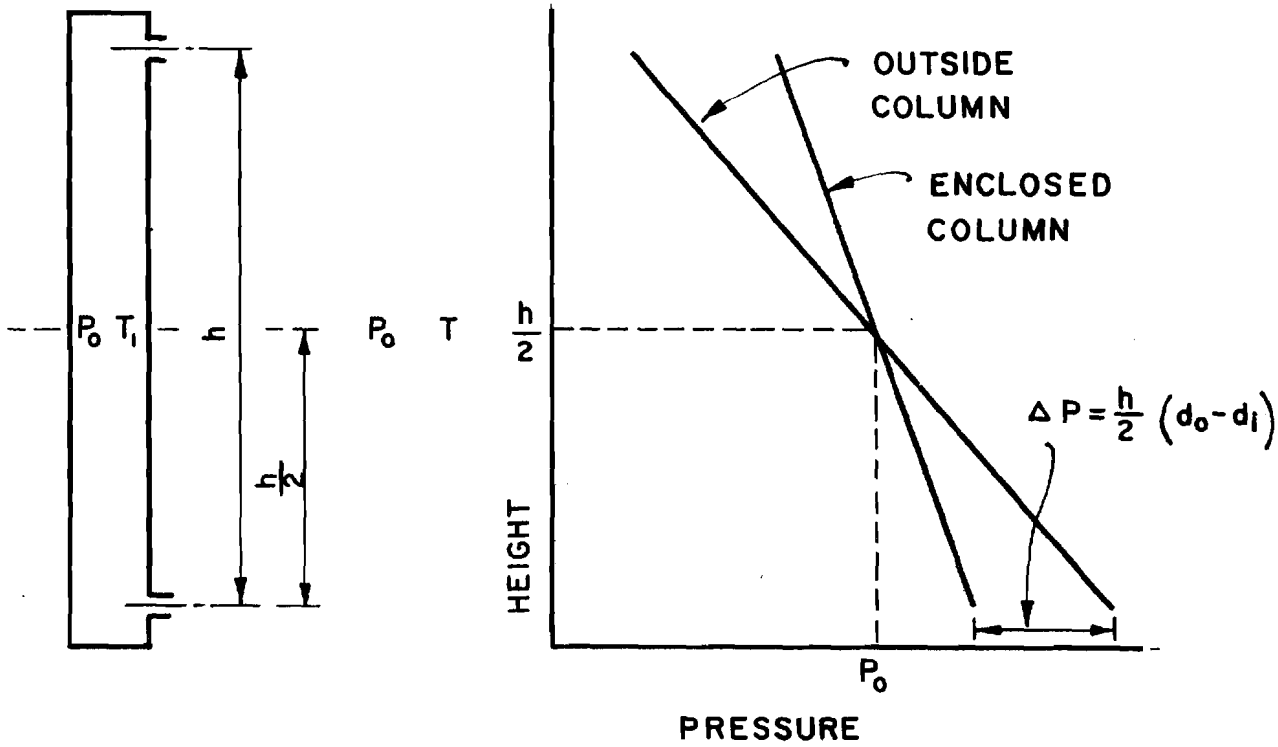


FIGURE I b

PRESSURE DISTRIBUTIONS FOR TWO COLUMNS OF AIR INTER CONNECTED AT TWO LEVELS

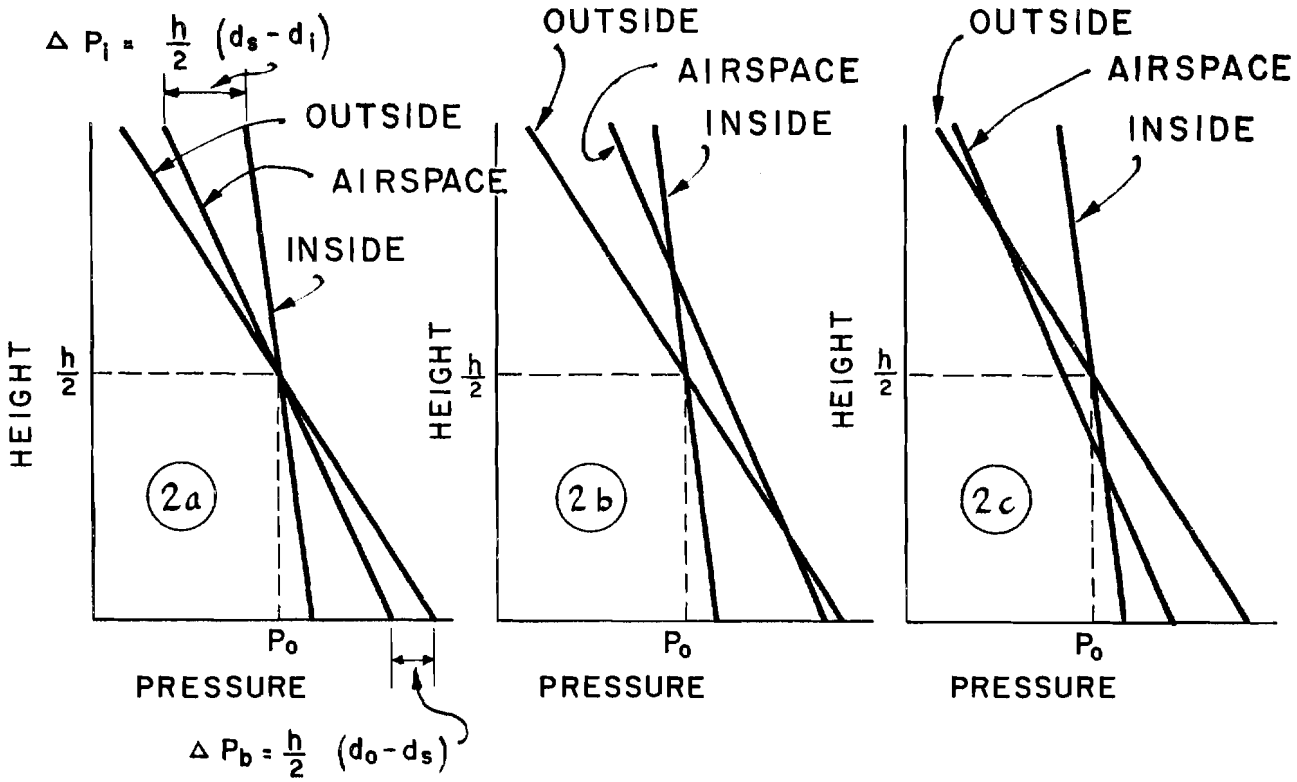


FIGURE 2 VERTICAL PRESSURE DISTRIBUTIONS FOR DOUBLE WINDOW AT THE NEUTRAL ZONE

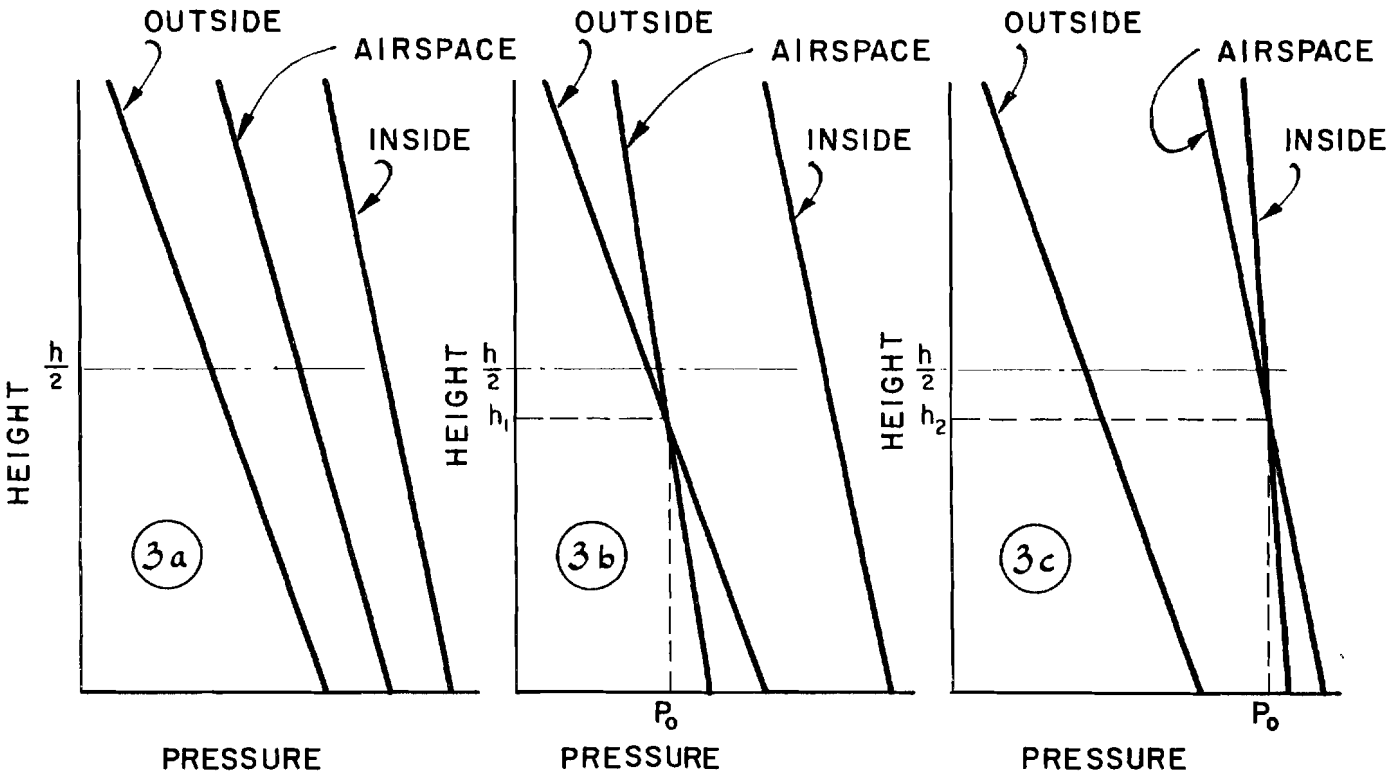


FIGURE 3 VERTICAL PRESSURE DISTRIBUTIONS FOR DOUBLE WINDOW ABOVE THE NEUTRAL ZONE

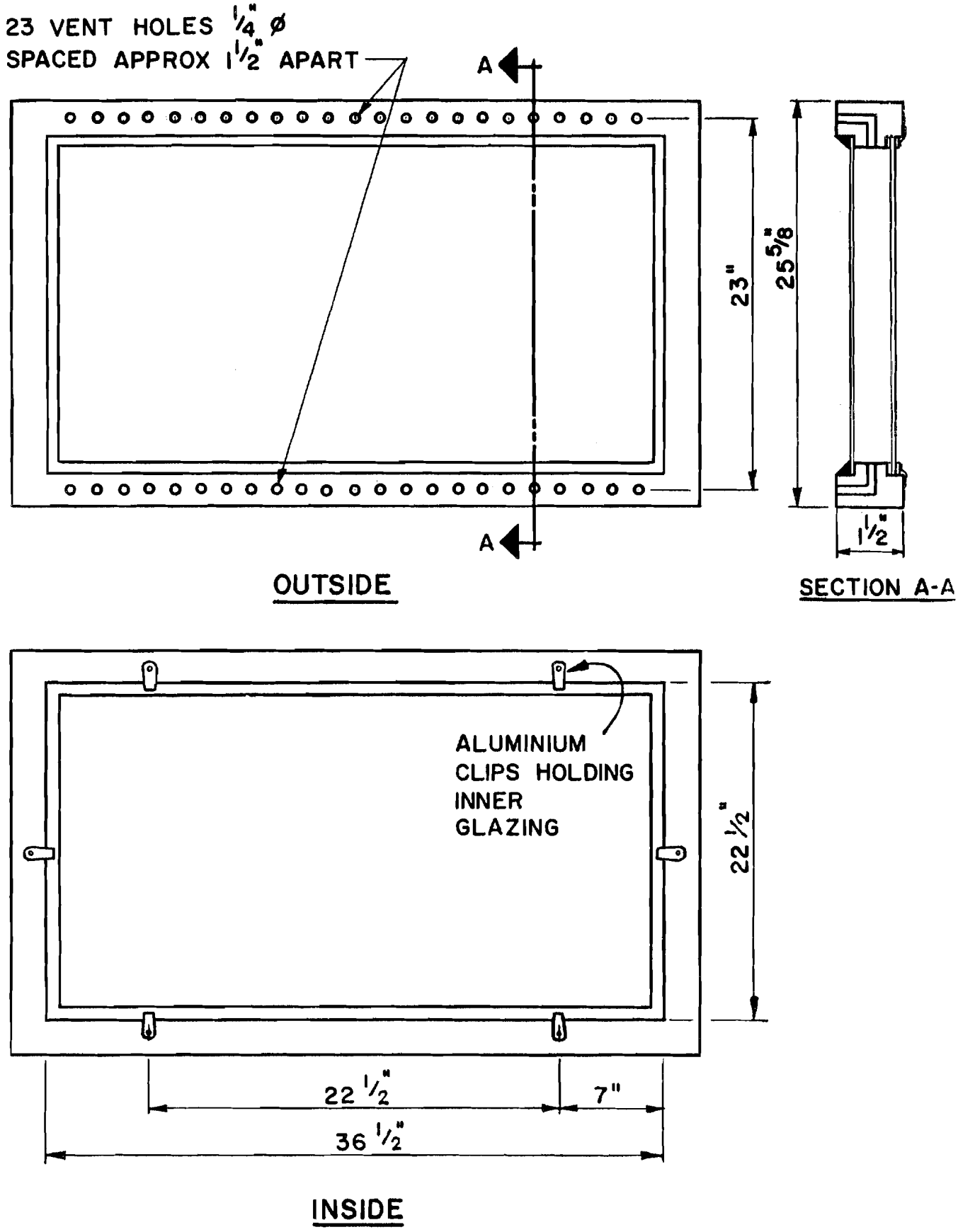


FIGURE 4

DETAILS OF CENTRE WINDOW

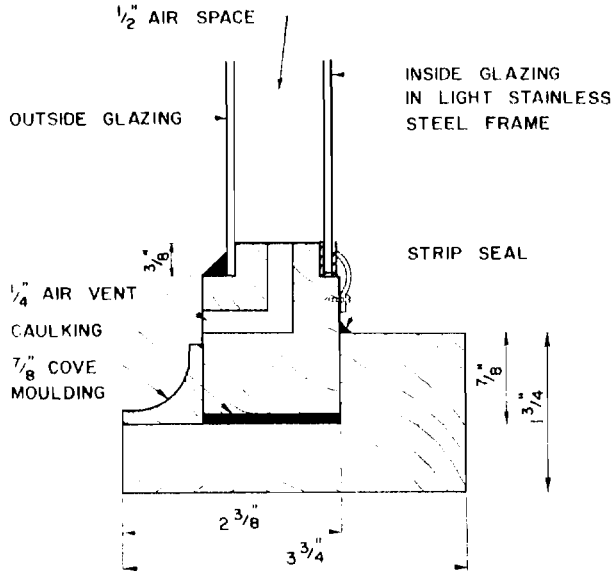


FIGURE 5a

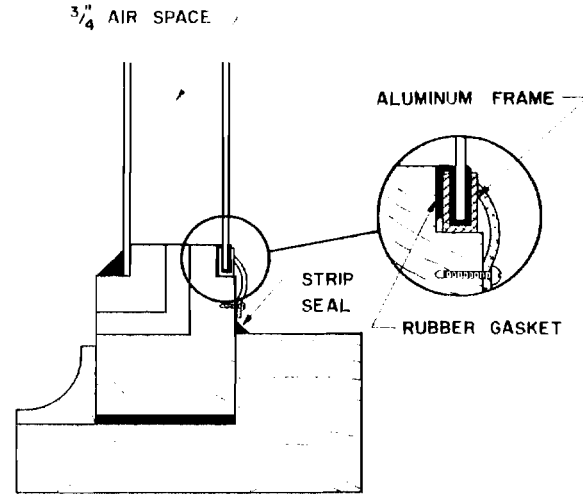


FIGURE 5b

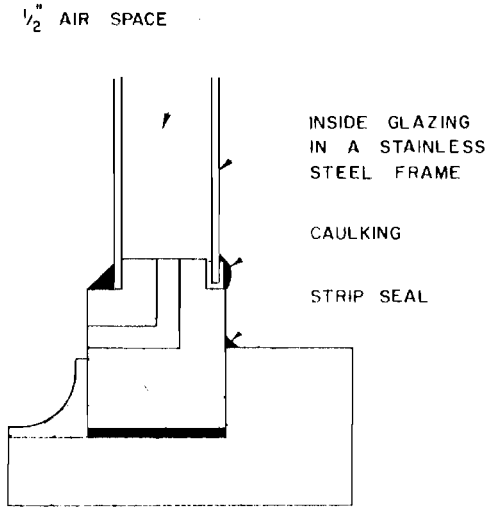
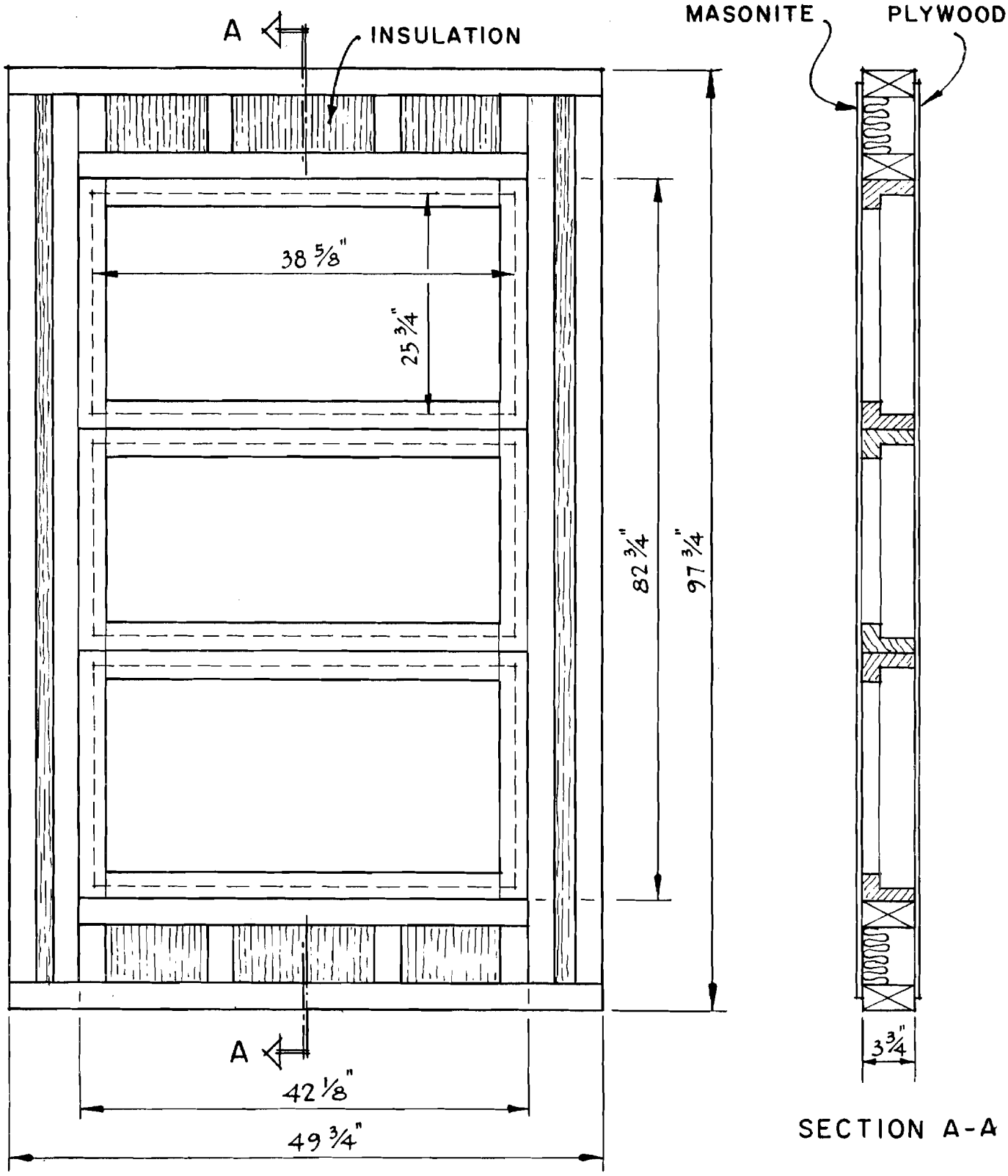


FIGURE 5c

FIGURE 5

SASH DETAILS OF TEST WINDOWS



NOT TO SCALE

ELEVATION WITH MASONITE REMOVED

FIGURE 6

WALL PANEL CONSTRUCTION DETAILS

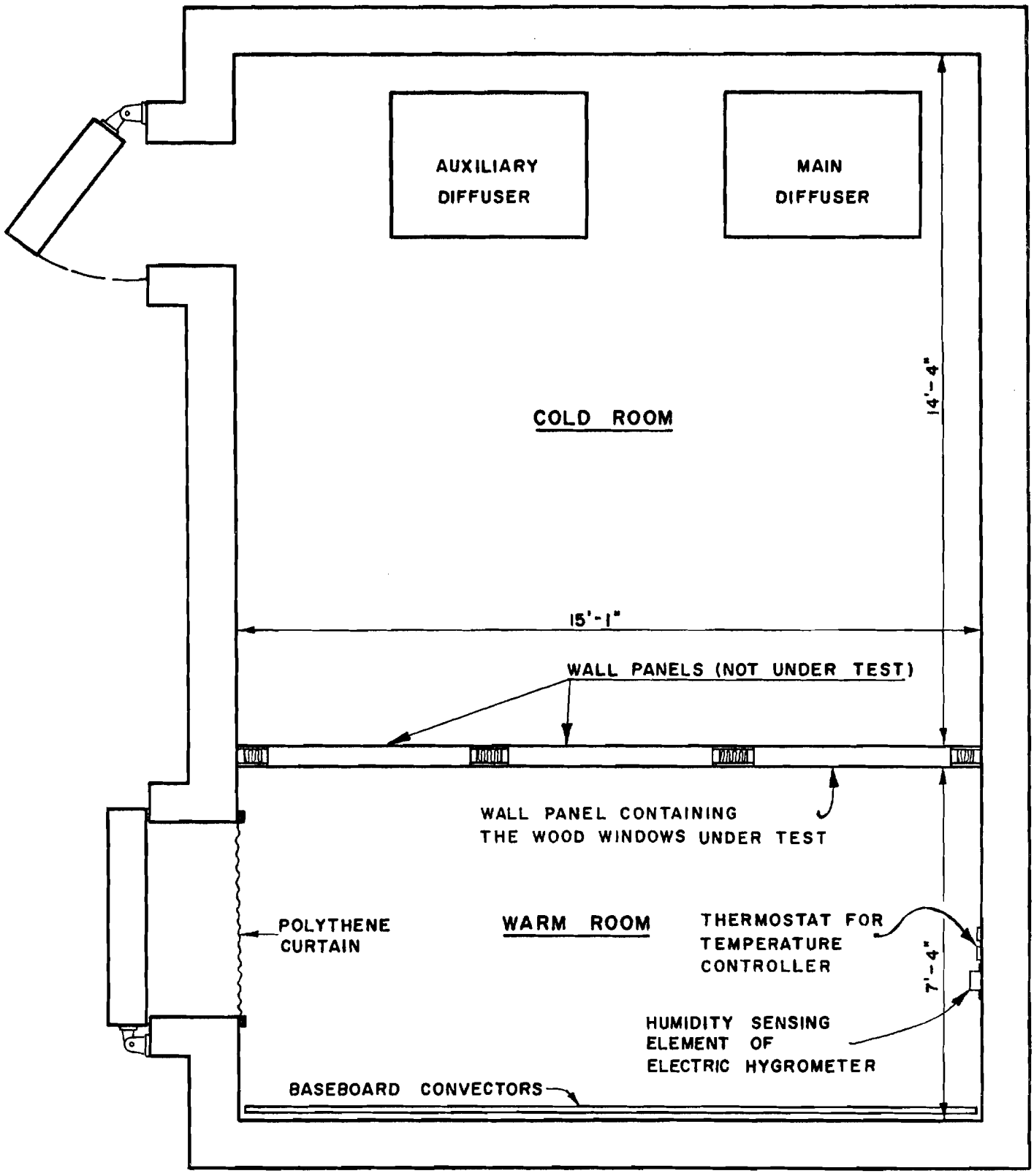


FIGURE 7 PLAN OF COLD ROOM

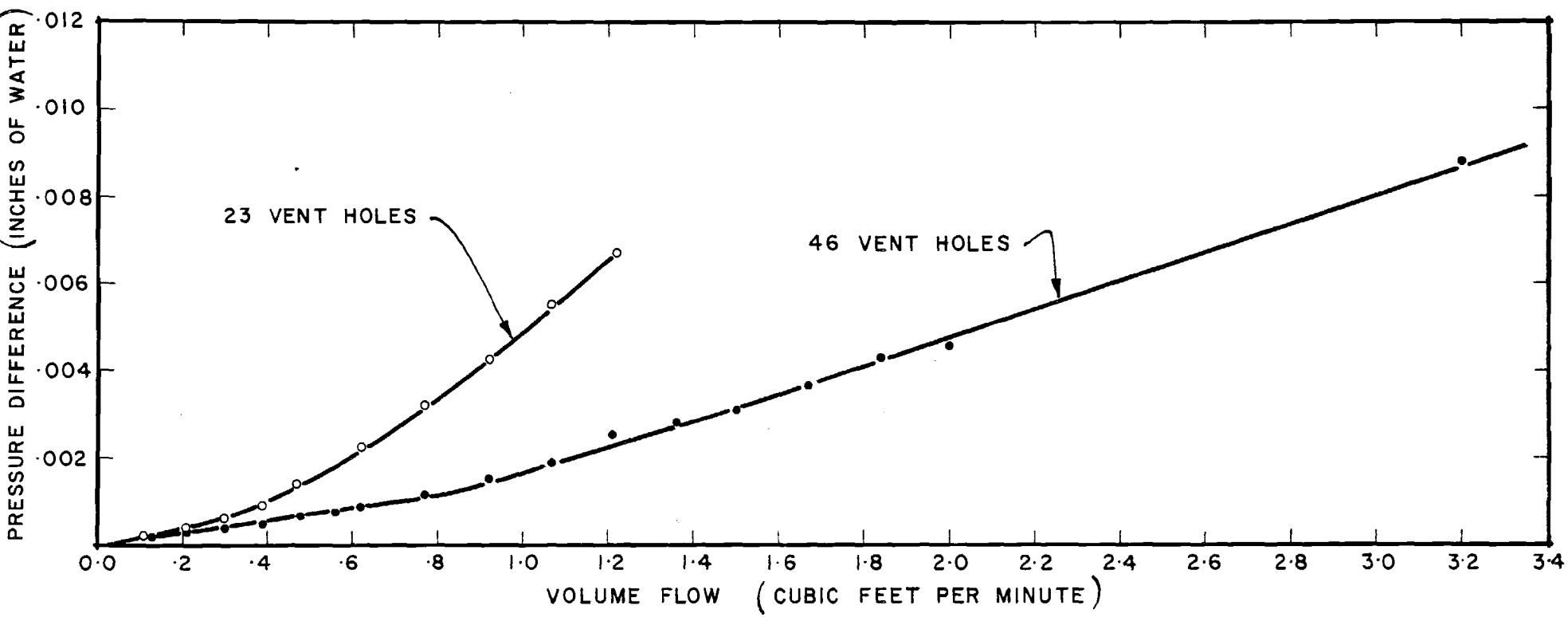


FIGURE 8

AIR FLOW VERSUS PRESSURE DIFFERENCE FOR OUTSIDE PANE WITH VENT HOLES

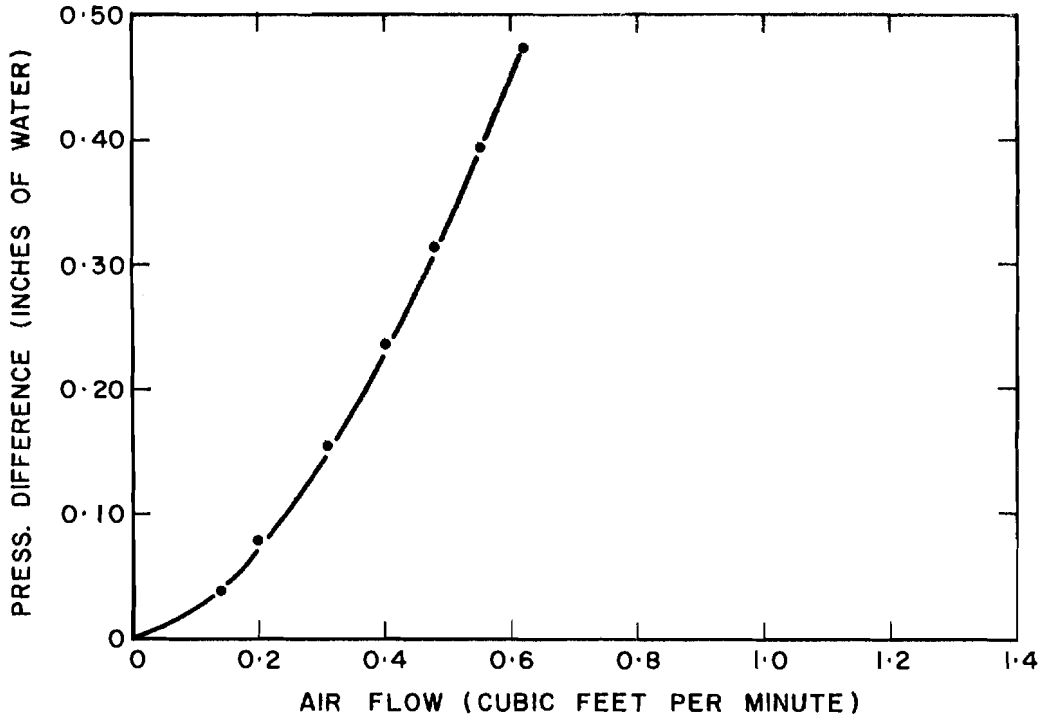


FIGURE 9
AIR FLOW VERSUS PRESSURE DIFFERENCE FOR OUTSIDE PANE WITH ONE VENT HOLE.

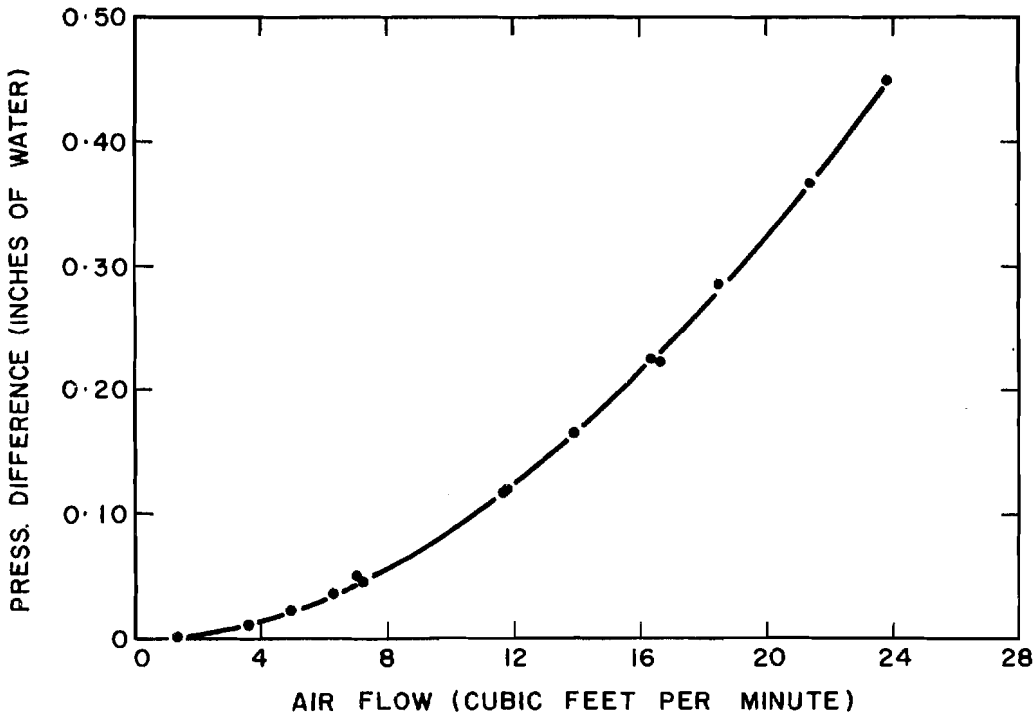


FIGURE 10
AIR FLOW VERSUS PRESSURE DIFFERENCE FOR OUTSIDE PANE WITH 46 VENT HOLES.

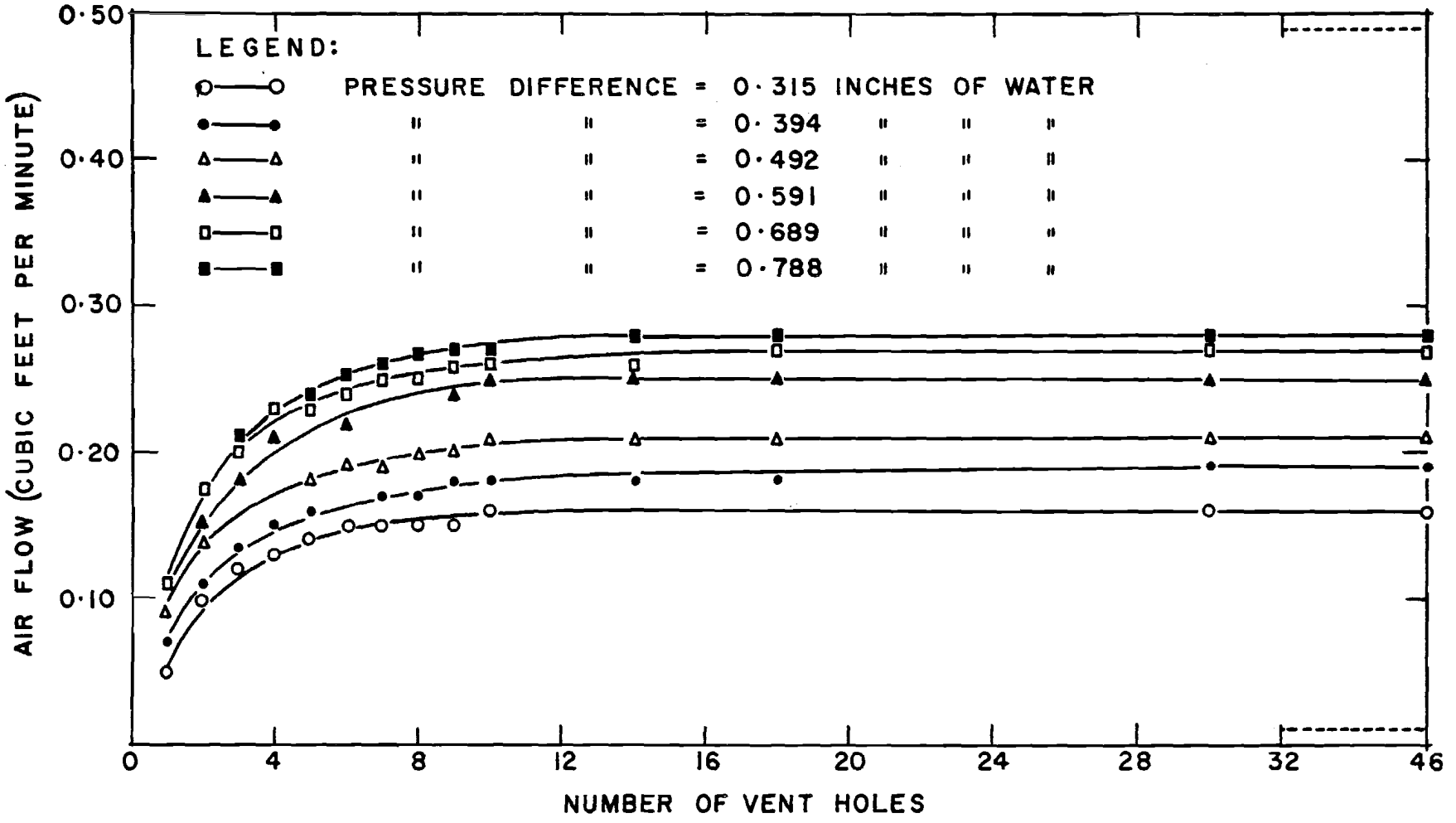


FIGURE 11

AIR FLOW THROUGH ENTIRE WINDOW VERSUS NUMBER OF VENT HOLES

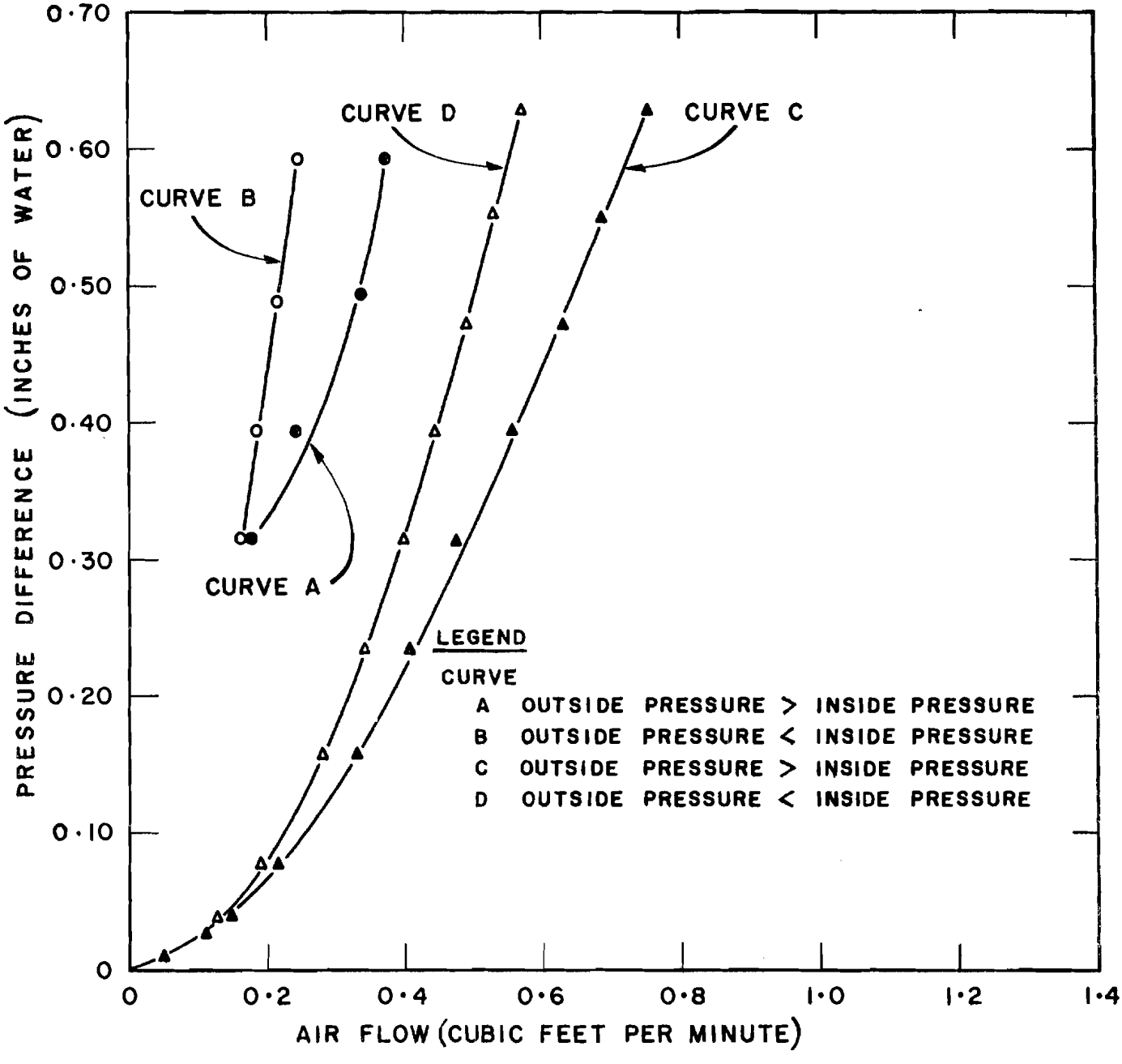


FIGURE 12

AIR FLOW VERSUS PRESSURE DIFFERENCE FOR INSIDE GLAZING

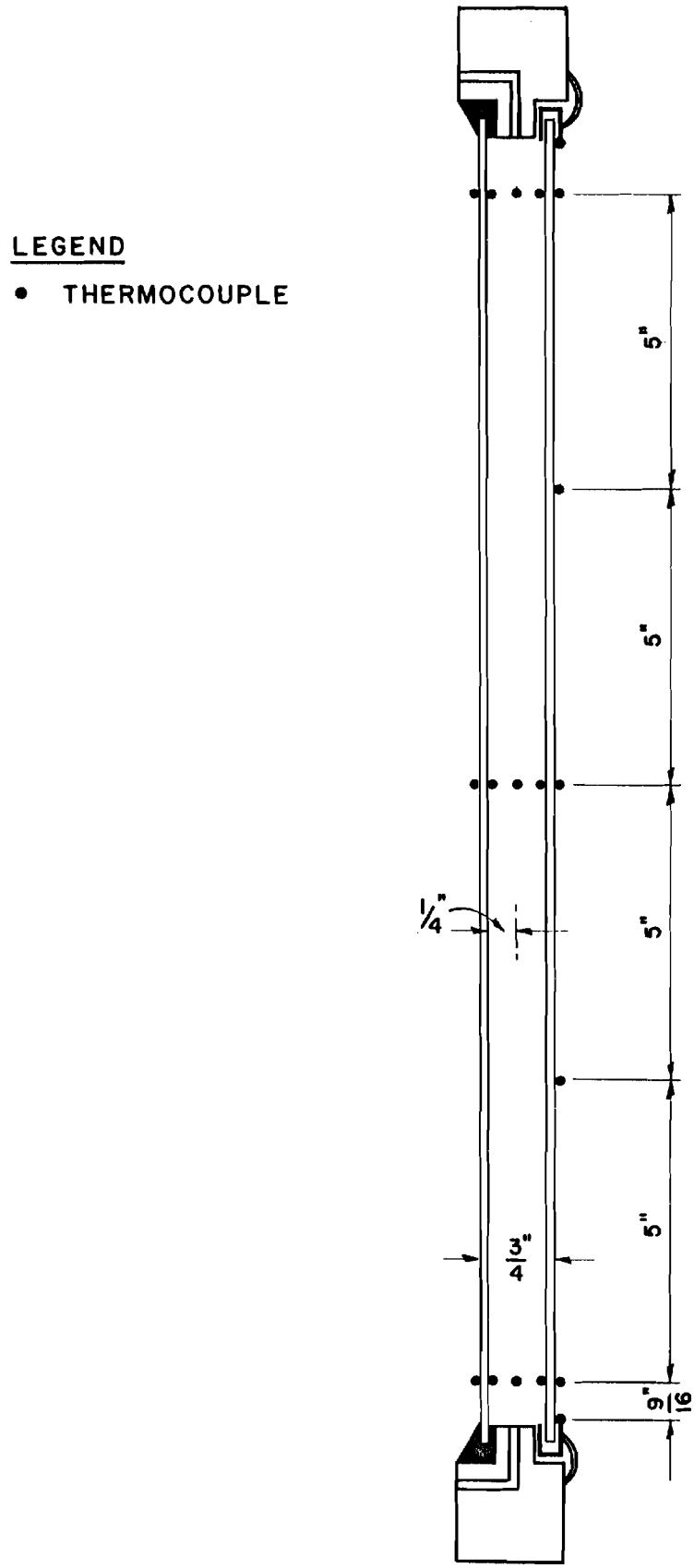


FIGURE 13

THERMOCOUPLE LOCATIONS FOR TOP WINDOW

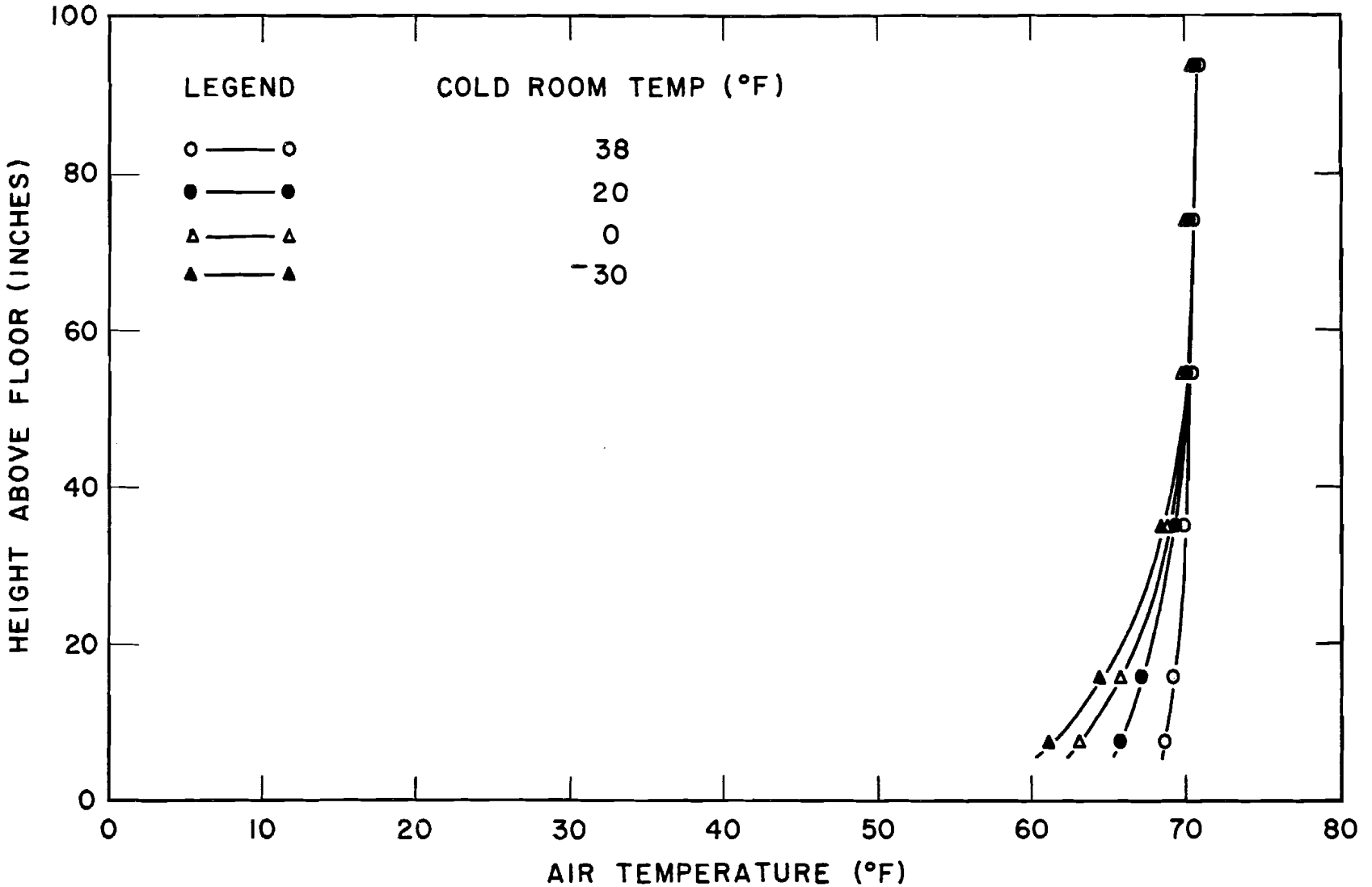
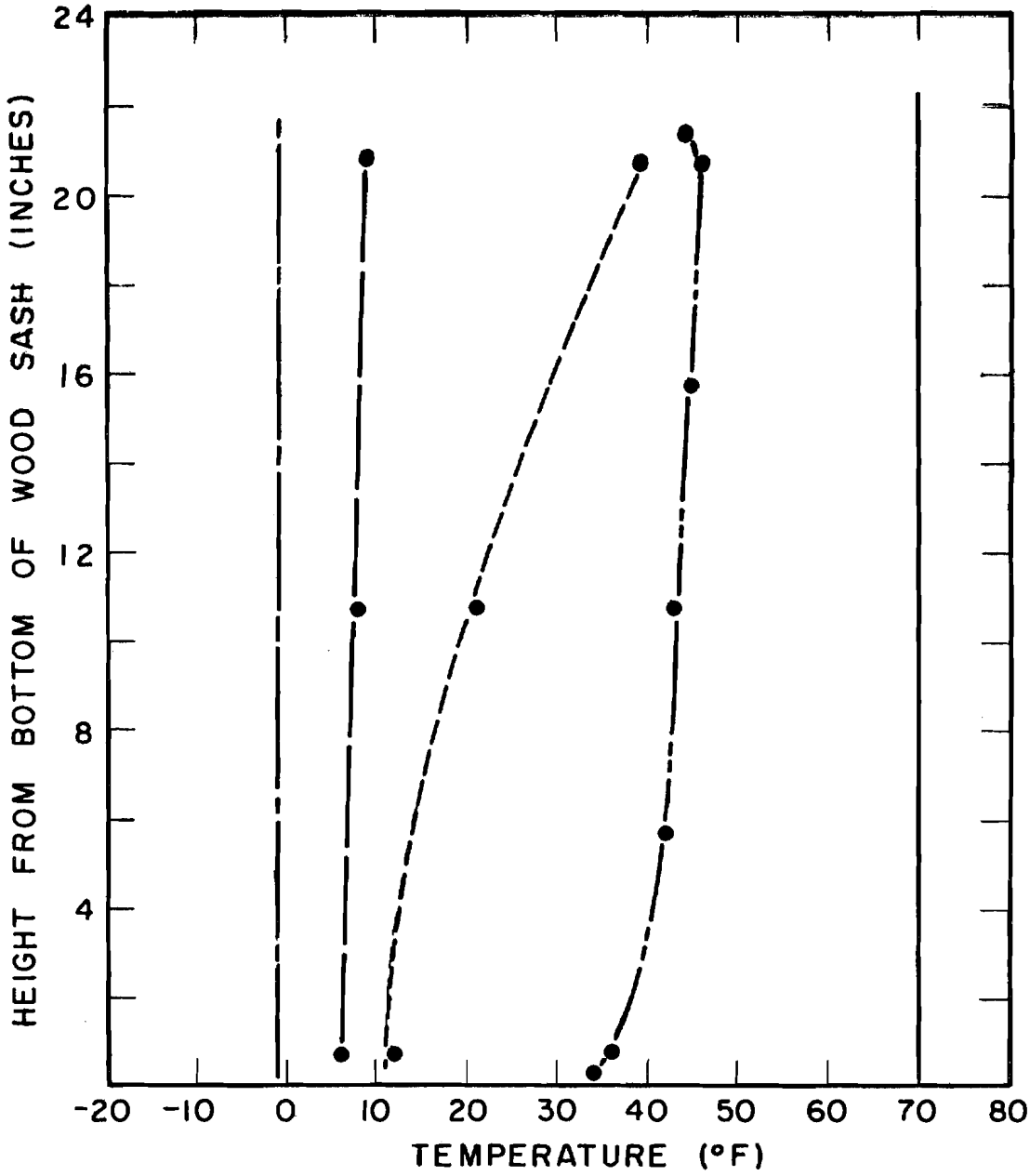


FIGURE 14

VERTICAL AIR TEMPERATURE GRADIENTS AT THE CENTRE OF THE WARM ROOM



LEGEND:

——— WARM ROOM AIR

—--— INSIDE SURFACE OF INNER PANE

------- AIRSPACE

— — INSIDE SURFACE OF OUTER PANE

—-— OUTSIDE AIR

FIGURE 15

VERTICAL TEMPERATURE GRADIENTS FOR WINDOW AT OUTSIDE TEMP OF 0°F

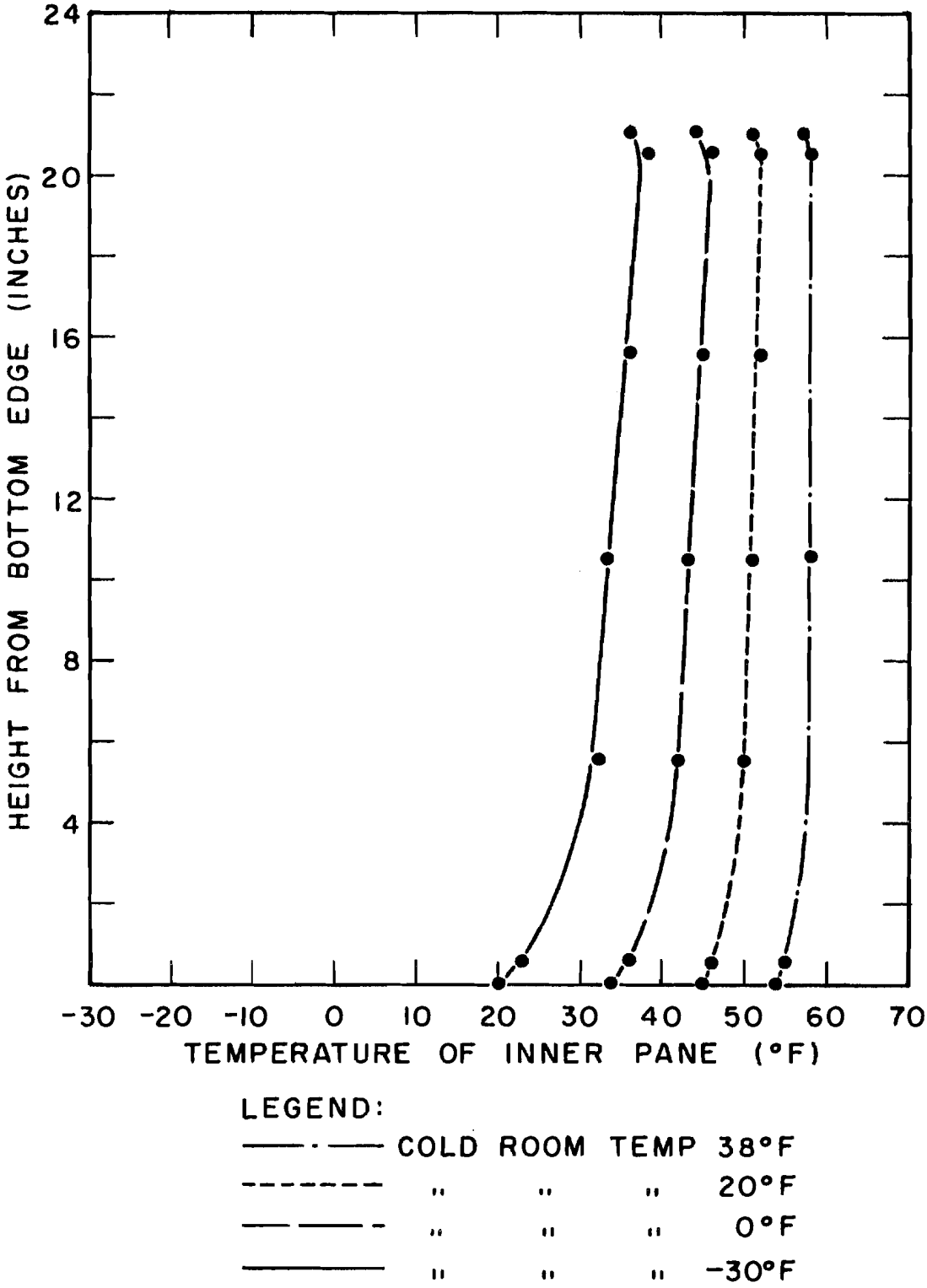
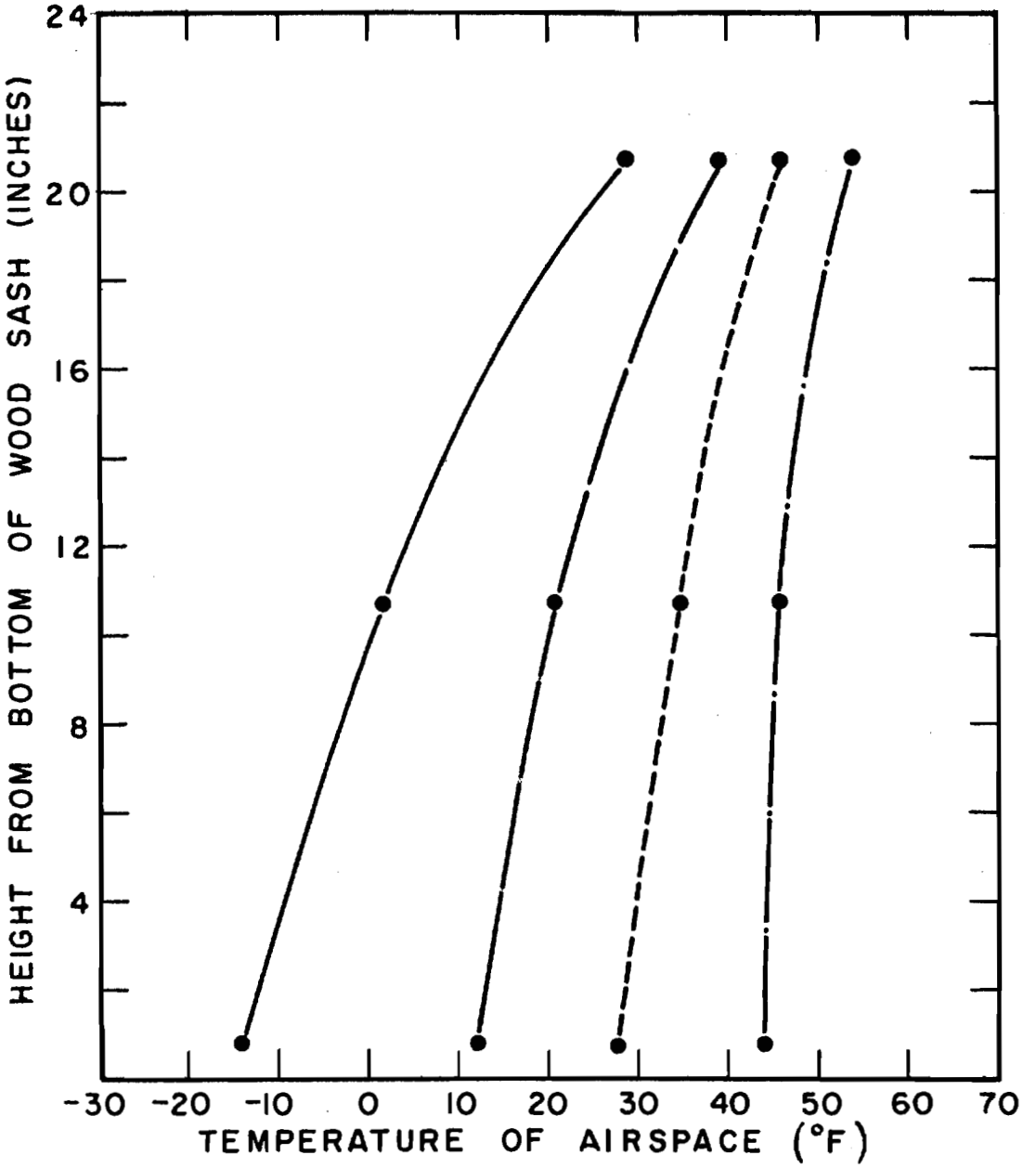


FIGURE 16

VERTICAL TEMPERATURE GRADIENTS FOR INSIDE SURFACE OF INNER PANE

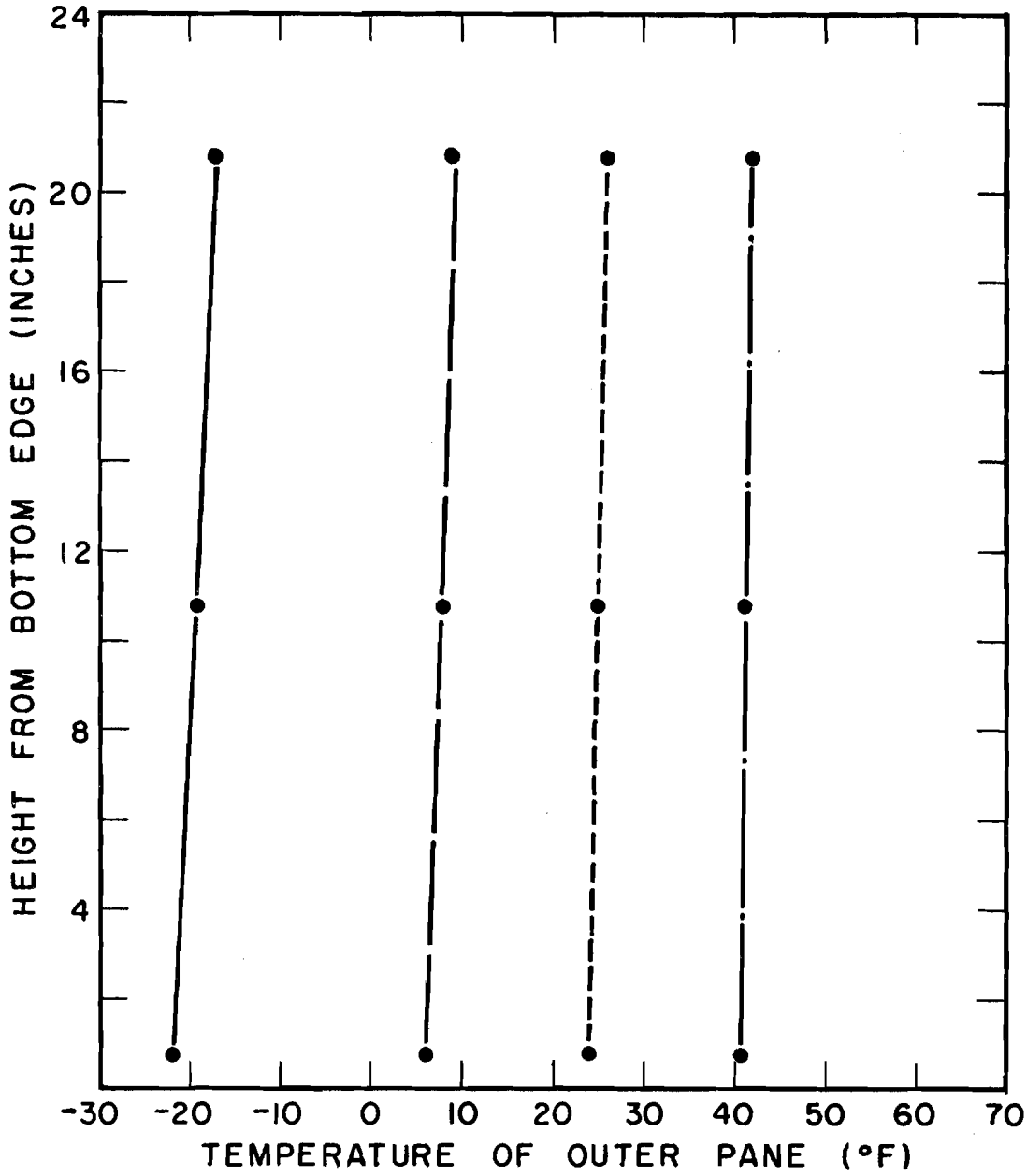


LEGEND:

——·——	COLD	ROOM	TEMP	38°F
- - - - - - -	"	"	"	20°F
—— —— –	"	"	"	0°F
————	"	"	"	-30°F

FIGURE 17

VERTICAL TEMPERATURE GRADIENTS FOR THE AIRSPACE

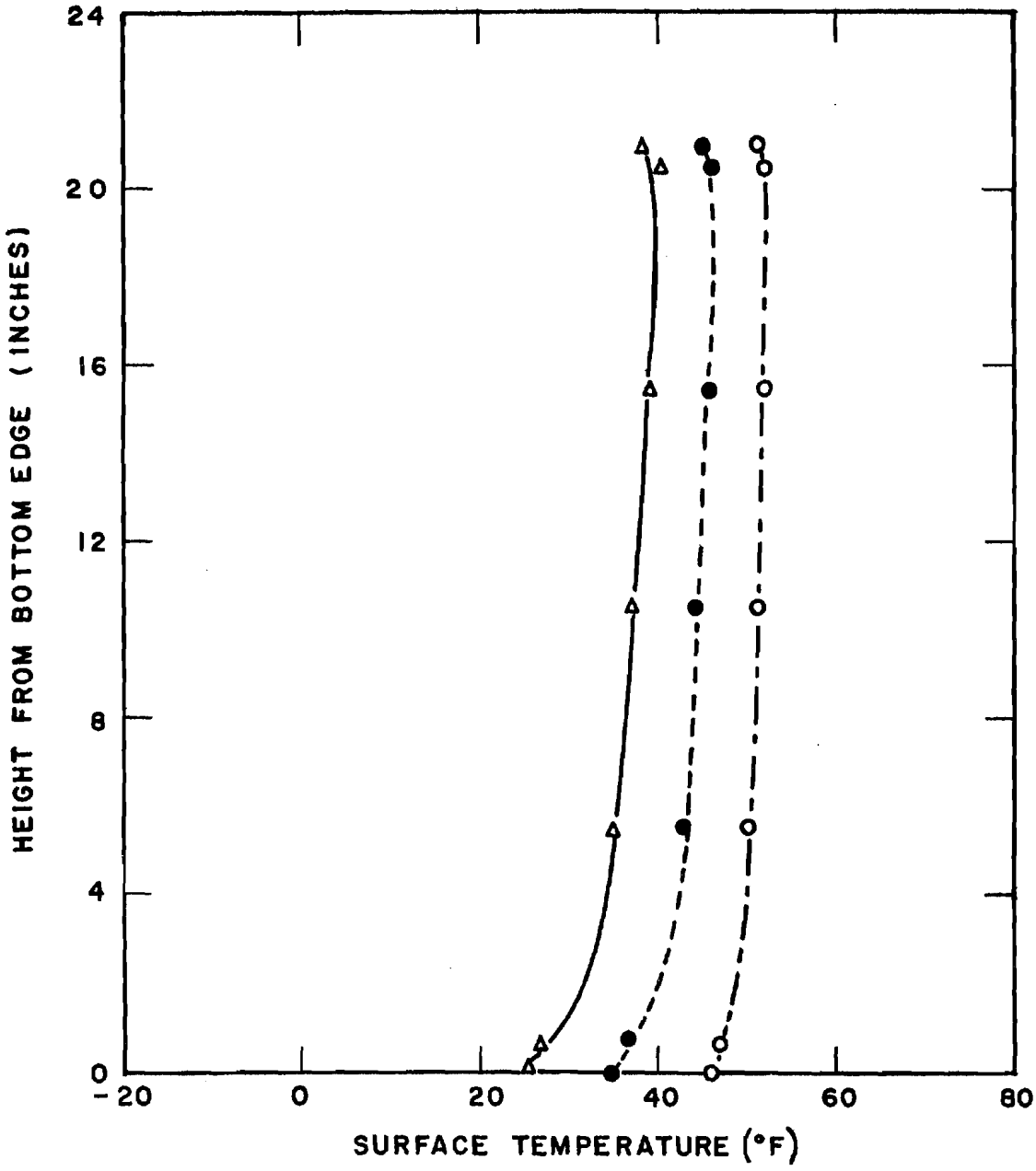


LEGEND:

——·——	COLD ROOM	TEMP		38°F
- - - - - - -	"	"	"	20°F
— — — —	"	"	"	0°F
————	"	"	"	−30°F

FIGURE 18

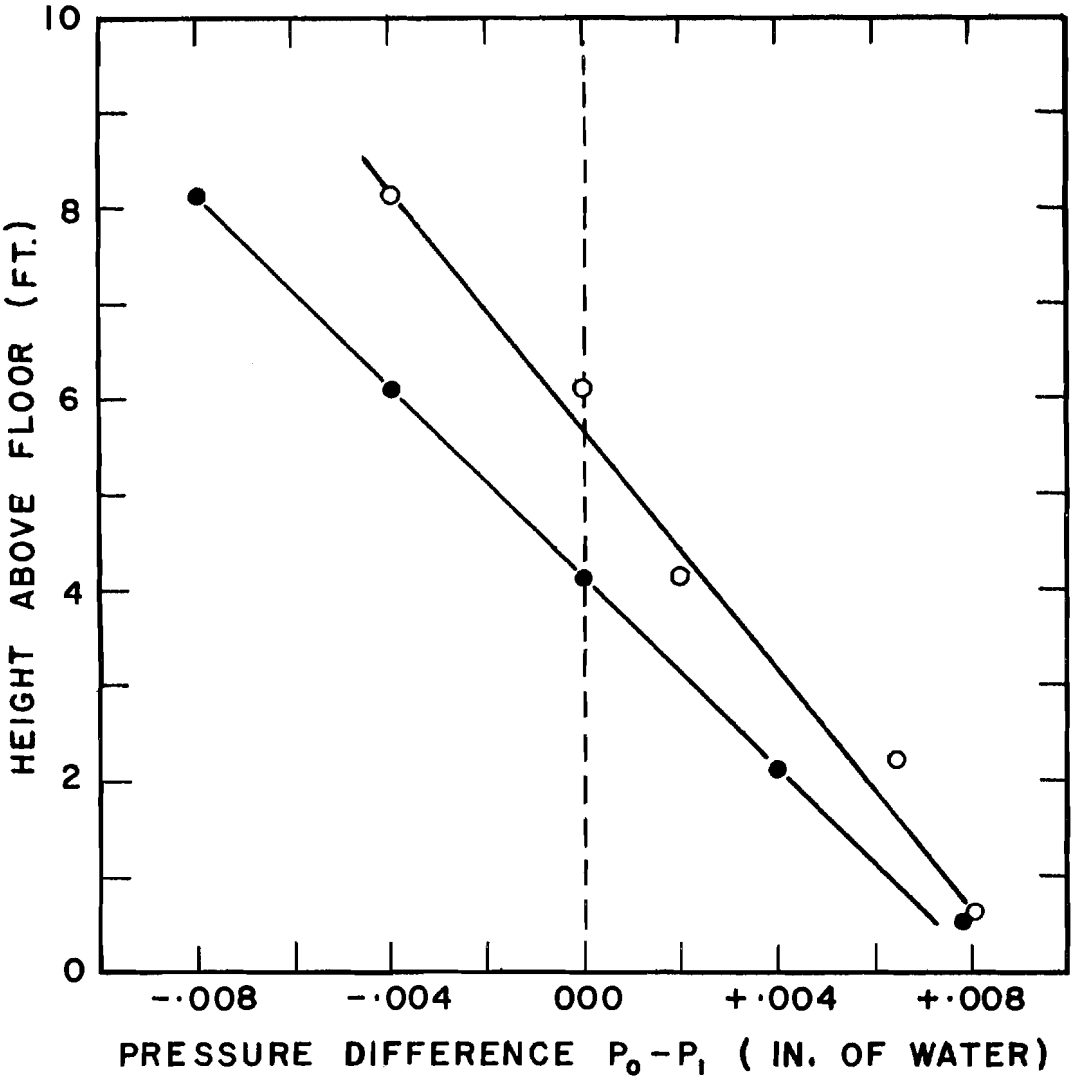
VERTICAL TEMPERATURE GRADIENTS FOR INSIDE SURFACE OF OUTER PANE



LEGEND	COLD ROOM TEMP.	DEW POINT TEMP.	TEMP. IN WARM ROOM 54" FROM FLOOR
o——o	20	48·5	70
●------●	0	37·5	71
Δ—-—-Δ	-20	27·5	69

FIGURE 19

VERTICAL TEMPERATURE GRADIENTS FOR INSIDE SURFACE OF INNER PANE



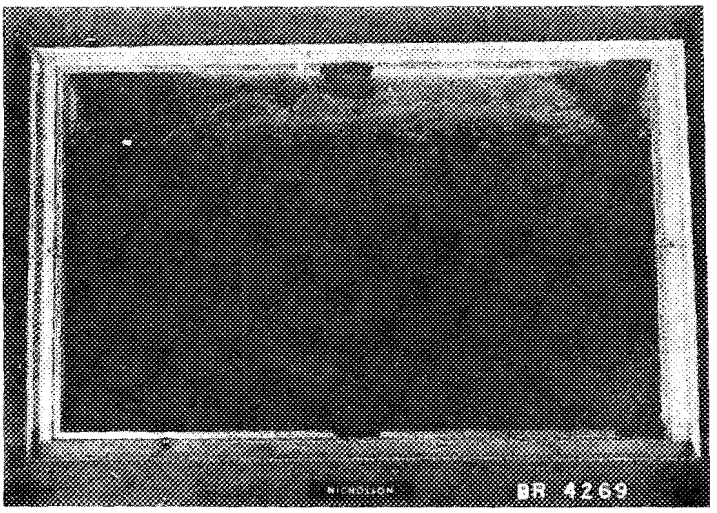
LEGEND:

○——○ INSIDE-OUTSIDE TEMP. DIFFERENCE OF 50° (ALL VENT HOLES CLOSED)

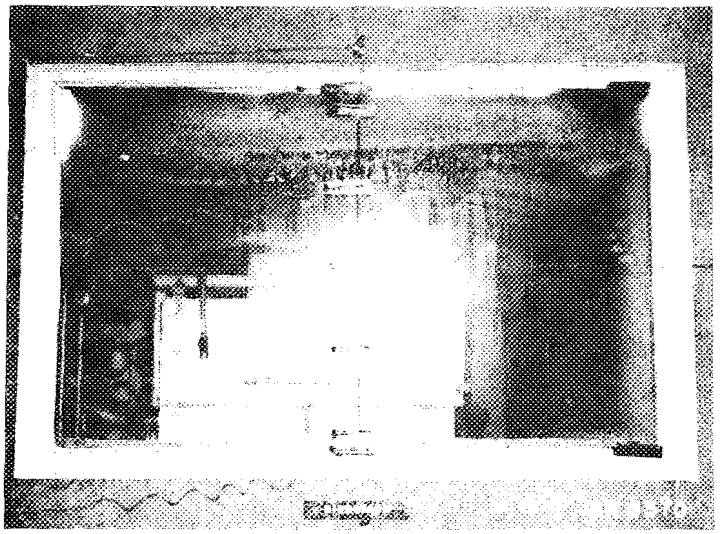
●——● INSIDE-OUTSIDE TEMP. OF 70° (ALL VENT HOLES OPEN IN THE CENTRE AND TOP WINDOWS)

FIGURE 20

PRESSURE DIFFERENCE BETWEEN WARM AND COLD ROOMS VERSUS HEIGHT

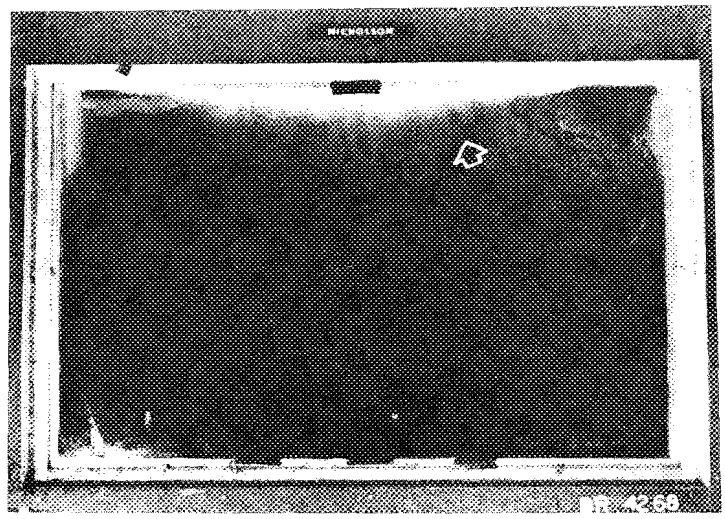


(a) Prior to cycling

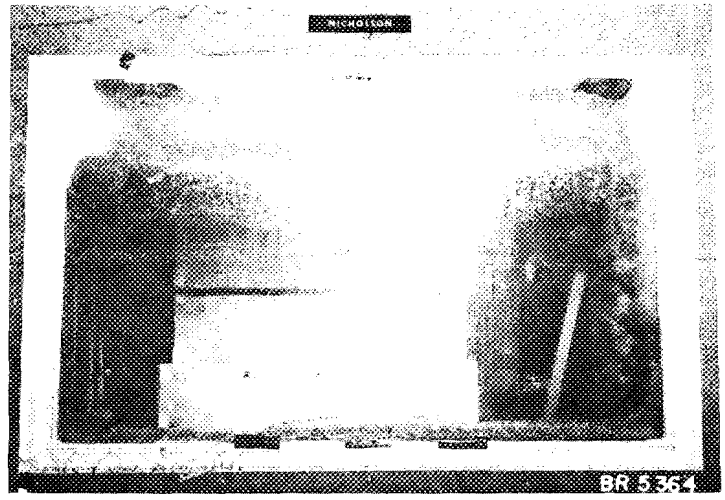


(b) Following cycling

Figure 21 Condensation on outer pane of top window in first series of condensation tests

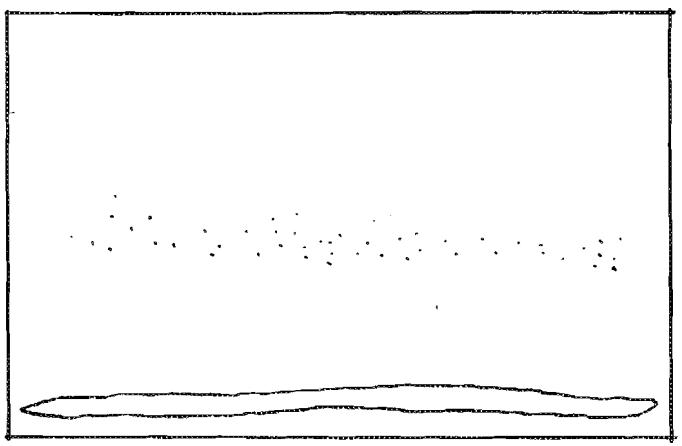


(a) Prior to cycling

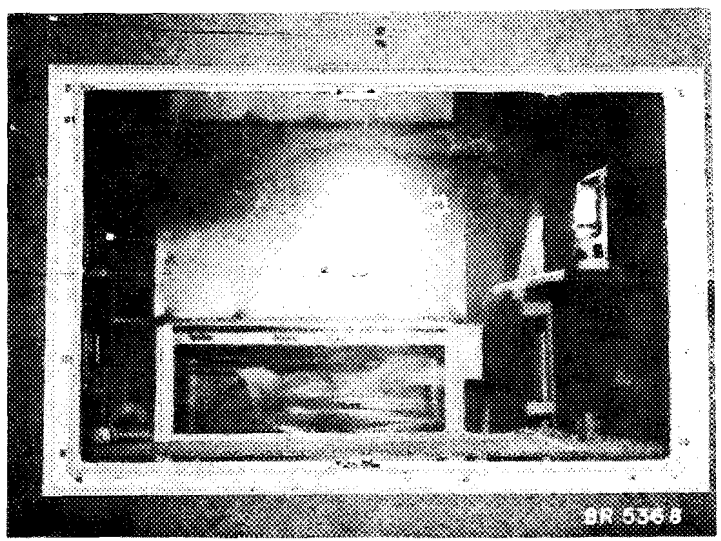


(b) Following cycling

Figure 22 Condensation on outer pane of centre window in first series of condensation tests

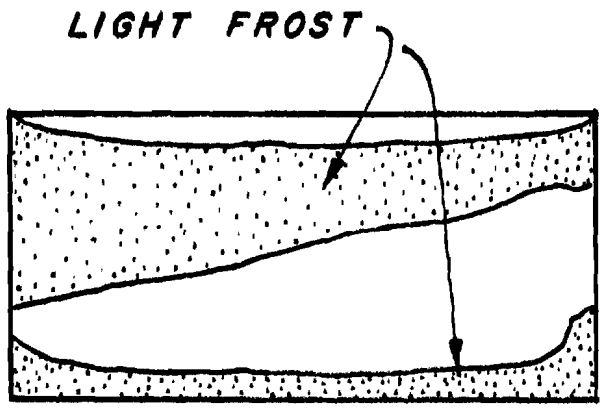


Prior to cycling



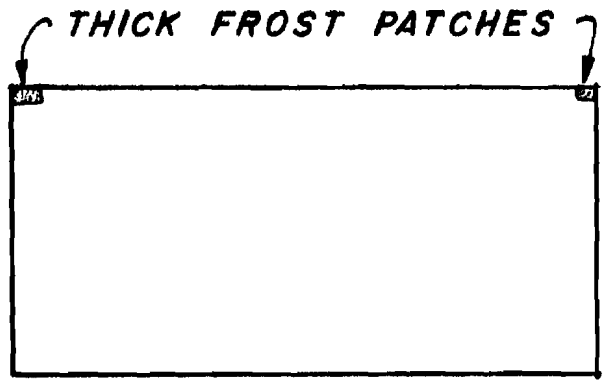
Following cycling

Figure 23 Condensation on outer pane of bottom window in first series of condensation tests



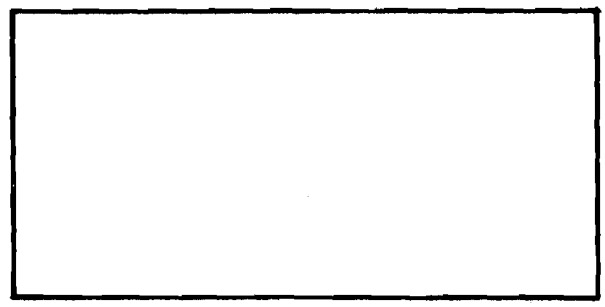
TOP

(NO VENTING)



CENTRE

(THREE HOLES AT TOP AND BOTTOM)



BOTTOM

(NO VENTING)

FIGURE 24

CONDENSATION ON OUTER PANES IN SECOND SERIES OF CONDENSATION TESTS AFTER 48 HOURS WITH OUTSIDE TEMP. OF 20°F AND INSIDE RELATIVE HUMIDITY OF 46%

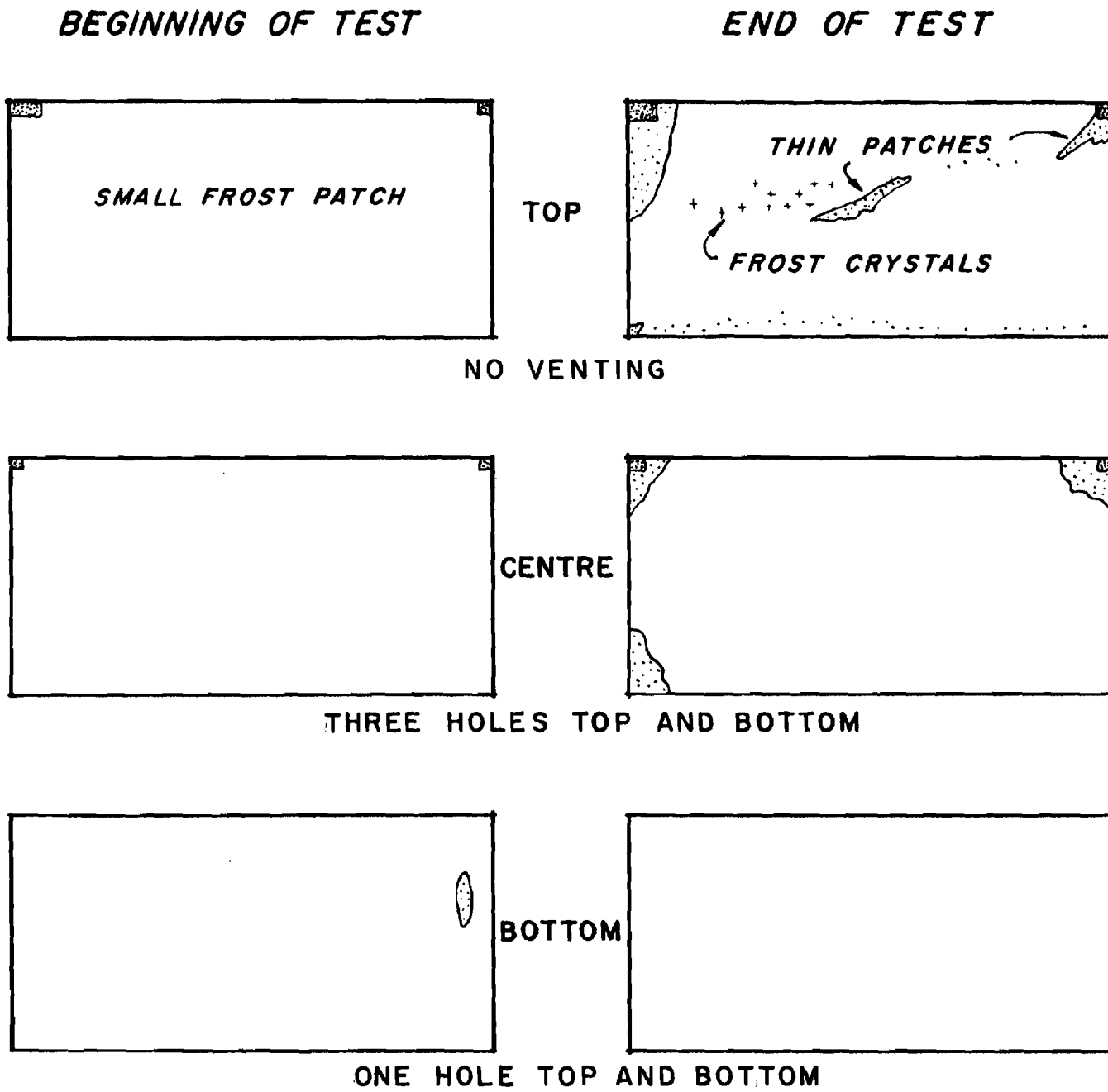


FIGURE 25

CONDENSATION ON OUTER PANES IN SECOND SERIES OF CONDENSATION TESTS BEFORE AND FOLLOWING 38 HR. WITH OUTSIDE TEMPERATURE OF 0°F AND AN INSIDE RELATIVE HUMIDITY OF 30%

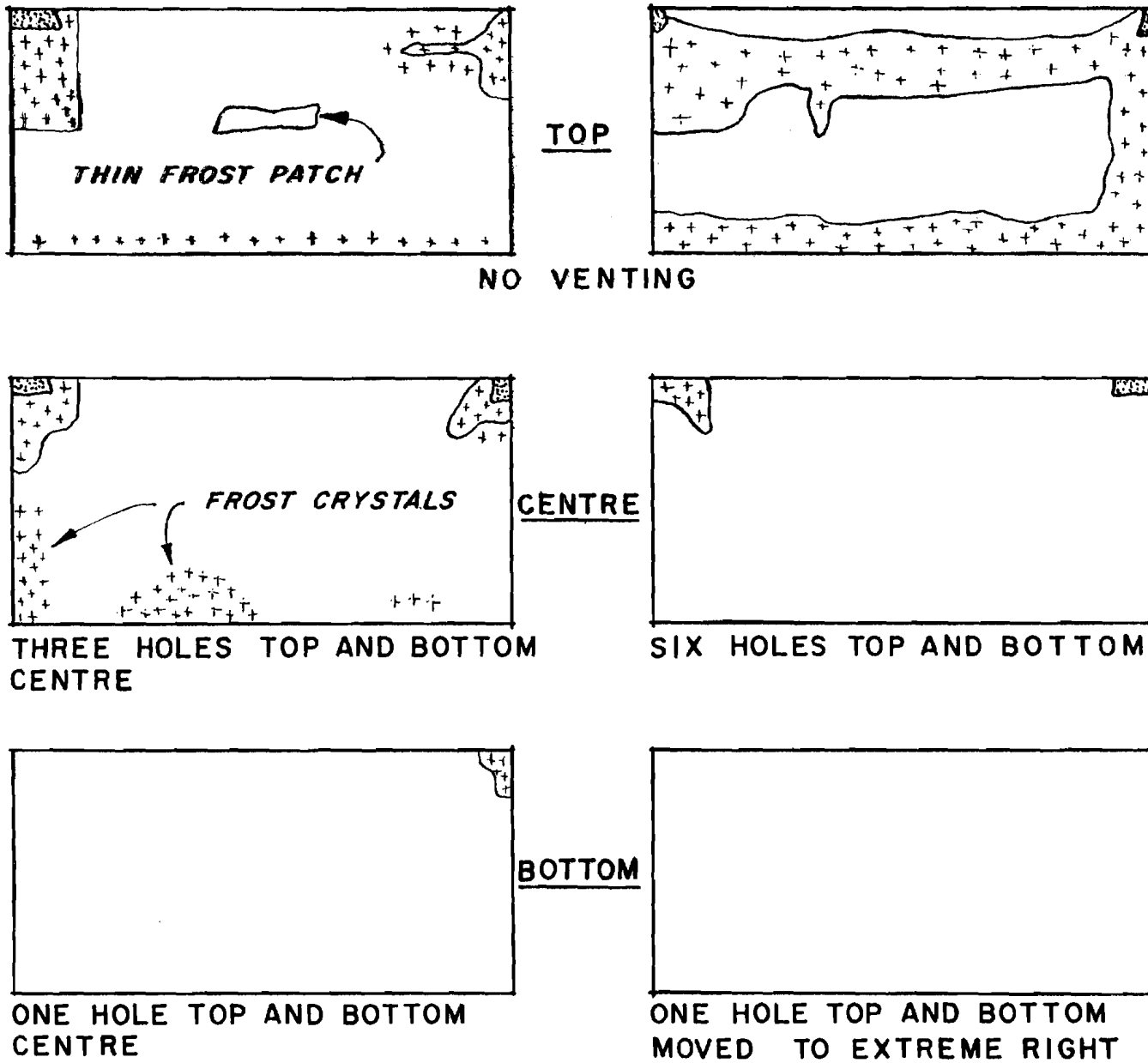


FIGURE 26

OUTSIDE TEMPERATURE = 0°F
WARM ROOM R.H. = 38%
DURATION = 26 HR.

FIGURE 27

OUTSIDE TEMPERATURE = 0°F
WARM ROOM R.H. = 38%
DURATION = 98 HR.

FIGS 26 & 27 SHOW CONDENSATION ON OUTER PANES IN SECOND SERIES OF TESTS

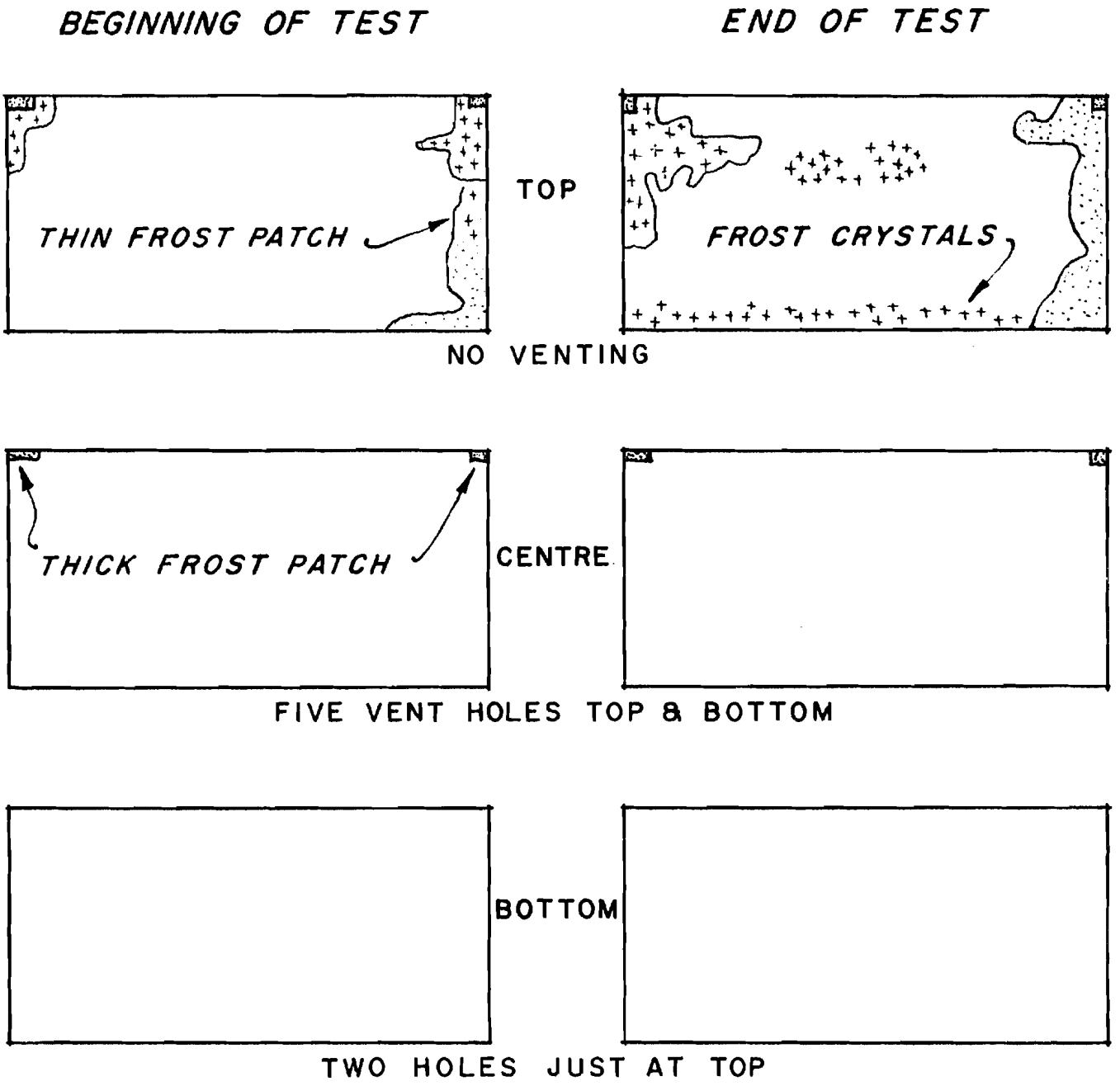


FIGURE 28

CONDENSATION ON OUTER PANES IN SECOND SERIES OF CONDENSATION TESTS BEFORE AND FOLLOWING 99 HR. WITH OUTSIDE TEMPERATURE OF -20°F AND INSIDE RELATIVE HUMIDITY OF 20 %

APPENDIX A

Air Flow Characteristics Required to Overcome Condensation Between Panes

Figure A1 illustrates variations in pressure with height across a double window subjected to a temperature gradient when the total inside pressure is greater than the outside. The outer pane is assumed to have openings top and bottom only, and to be much less resistant to air flow than the inner pane.

The air space pressure (the solid line) will result when the inner pane is completely sealed and openings around the outer pane are evenly distributed above and below the mid-height of the window. The pressure differences across the openings will result in an air interchange between the air space and outside dependent on the flow characteristics of the openings. As the resistance to flow of the inner pane is decreased the air flow from inside to the air space will increase. This air, together with that from the bottom openings of the outer pane, will flow through the top openings of the outer pane. The pressure difference across the top openings of the outer pane must therefore increase, with the line representing air space pressure in Fig. A1 moving to the right as indicated by the dotted line. With further reductions in the resistance of the inner pane a condition is reached when there is zero pressure difference across the bottom opening of the outer pane and no inflow occurs from the outside to the air space. Any further decrease in the resistance of the inner pane will result in a further shifting of the air space pressure to the right with air flow to the outside through both the top and bottom openings of the outer pane.

Table IV gives the minimum ratios of the volume rate of air flow from the outside to air space to that from the inside to the air space to prevent condensation on the inside surface of the outer pane. For the test window this condition can by written as:

$$Q_b = R\ Q_i \tag{1}$$

where

Q_b is the volume rate of air flow into the air space from the outside through the bottom openings of the outer pane

R is the minimum permissible ratio given in Table IV

Q_i is the volume rate of air flow into the air space from the inside

The volume rate of air flow past the inner and outer glazings of a double window located above the neutral zone can be defined by the following:

$$Q_i = C_i \ (\Delta P_a)^{n_i} \tag{2}$$

and

$$Q_b = C_o \ (\Delta P_b)^{n_o} \tag{3}$$

where Q_i is the volume rate of flow into the air space from the inside

Q_b is the volume rate of flow into the air space from the outside through the bottom openings of the outer pane

C_i is the air leakage coefficient for the inner pane

C_o is the air leakage coefficient for the outer pane with a given number of holes in the sash

ΔP_a is the average pressure difference across the inner pane

ΔP_b is the pressure difference across the bottom openings of the outer pane

n_i is the exponent of air flow for the inner pane

n_o is the exponent of air flow for the bottom openings of the outer pane

Substituting for Q_b and Q_i in equation 1

$$C_o \ (\Delta P_b)^{n_o} = R \ C_i \ (\Delta P_a)^{n_i} \tag{4}$$

Air leakage records given in Fig. 8 of this report indicate that at the small pressure differences set up by buoyancy forces the coefficient n_o is likely to be 1. If it is assumed that the flow exponent n_o is 1 at these small pressure differences equation 4 simplifies to

$$C_o \ \Delta P_b = R \ C_i \ (\Delta P_a)^{n_i} \tag{5}$$

Equation 5 gives the minimum permissible ratio in terms of the air leakage characteristics of the inner and outer glazings of the test window when located above the neutral zone. The pressure difference across the openings of the inner and outer pane can be determined with reference to Fig. A1, assuming that the air space pressure given by the dotted line represents the condition defined by equation 1. Under this condition the inflow and outflow through the bottom and top openings of the outer pane are given by the following equations:

$$Q_b = C_o\ (d_o - d_s)\ h' \tag{6}$$

$$Q_o = C_o\ (d_o - d_s)(h - h') \tag{7}$$

where Q_o is the volume rate of flow from the air space to the outside through the top openings.

d_o is the density of the outside air.

d_s is the density of the air between the panes.

h' is the vertical distance from the bottom openings of the outer pane to the level where the pressure in the air space equals the outside pressure.

h is the distance between the bottom and top openings of the outer pane.

The other symbols are the same as before.

Under these same conditions the outflow through the top opening of the outer pane is made up of the inflows into the air space through the bottom openings of the outer pane and the openings of the inner pane. This can be written as

$$Q_o = Q_b + \frac{Q_b}{R} \tag{8}$$

Substituting for Q_o in equation 7 and then solving for h' it can be shown that

$$h' = \left(\frac{R}{2R + 1}\right) h \tag{9}$$

Therefore the pressure difference across the bottom opening of the outer pane may be written as

$$\Delta P_b = \left(\frac{R}{2R + 1}\right) h\ (d_o - d_s) \tag{10}$$

On the other hand the average pressure difference across the inner pane can be written as

$$\Delta P_a = (P_i - P_o) - \left(\frac{h}{4R + 2}\right)(d_o - d_s) \tag{11}$$

If the window is located at the neutral zone and if it is assumed that openings of equal resistance are distributed at the top and bottom only of the inner and outer panes equation 5 is changed to

$$C_o \ \Delta P_b = \frac{R\ C_i\ (\Delta P_i)^{n_i}}{2} \tag{12}$$

The air pressure differences due to buoyancy effects across the top of the inner pane and the bottom of the outer pane of the window when located at the neutral zone are given by

$$\Delta P_i = \frac{h}{2}\ (d_s - d_i) \tag{13}$$

$$\Delta P_b = \frac{h}{2}\ (d_o - d_s) \tag{14}$$

Under this condition the inflow through the top openings of the inner pane is equal to the outflow through its bottom openings. For the outer pane, however, the inflow through its bottom openings is equal to the outflow through its top openings.

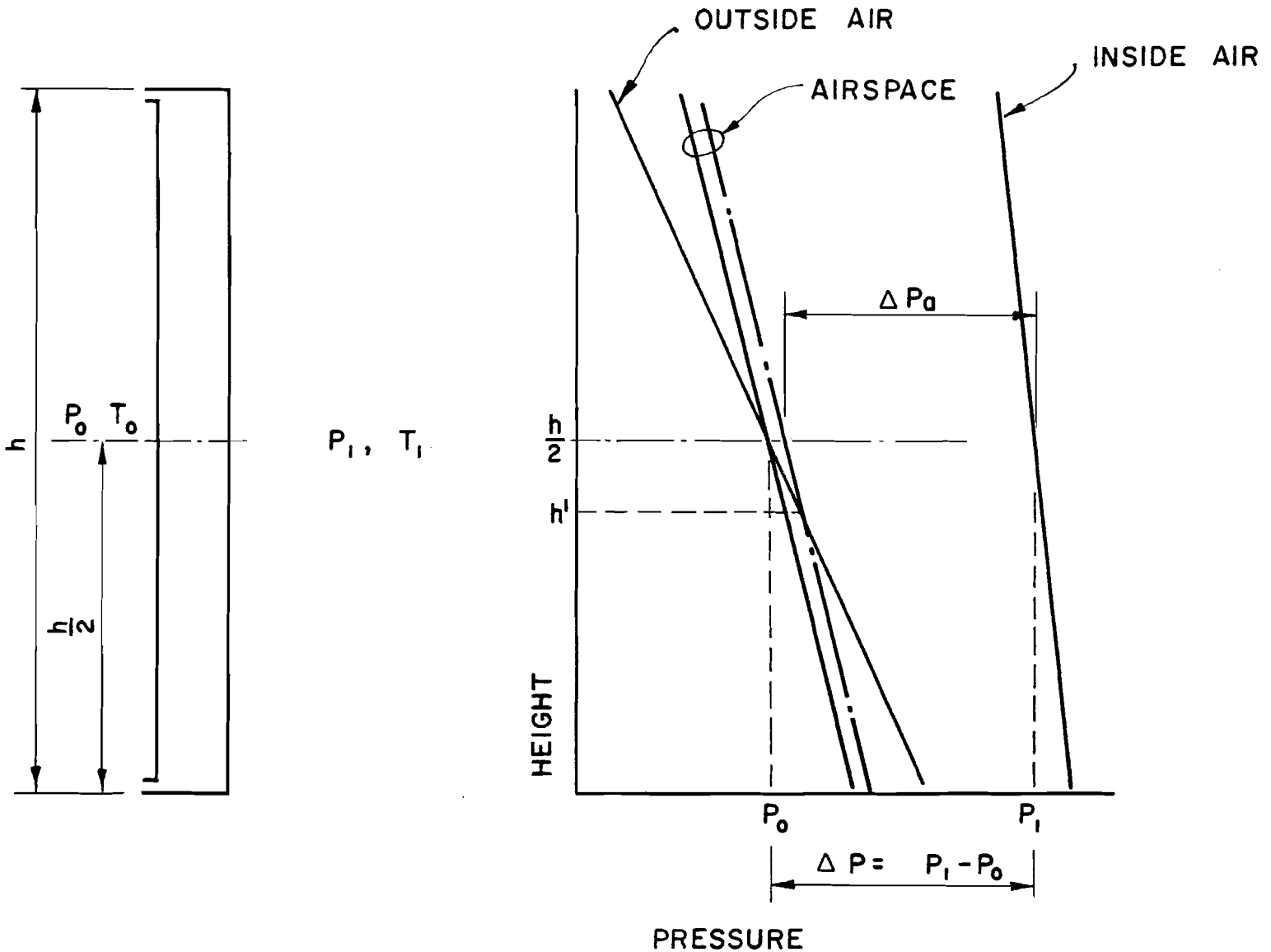


FIGURE A1

VERTICAL PRESSURE DISTRIBUTION FOR DOUBLE WINDOW WITH INSIDE PRESSURE GREATER THAN OUTSIDE

APPENDIX B

Errors in Surface Temperature Measurements

The measurement of surface temperatures is difficult and subject to much error and uncertainty. Kratz and Broderick (1-B) in their experiments showed that the apparent surface temperature was affected by the size of the thermocouple wire and the method of installation and that it was always between the actual surface temperature and the air temperature. They found that the best method of installing thermocouples on the surfaces of building materials was to embed the thermo-junction and a length of both lead wires flush in a shallow groove located along an isotherm.

It was not possible to put grooves in the surfaces of the window panes. Surface temperature measurements were obtained with two different methods of surface thermocouple installation (Fig. B1). Thermocouples were fastened to the inner and outer surfaces of the inner pane and the inner surface of the outer pane with black plastic tape and to the outside surface of the outer pane with Scotch tape. Scotch tape was used because of its better adherence to the glass under low temperature conditions.

Figures B2 to B5 give the surface-to-surface temperature differences measured at mid-height and 10 inches above and below it for both the inner and outer panes. These were obtained with the two methods of thermocouple installation. At any given inside-outside air temperature difference the surface-to-surface temperature difference measured with thermocouples as shown in method 2 is less than that measured with thermocouples as shown in method 1. The heat flow at each location at a given inside-outside air temperature difference is constant. Therefore, the error in the indicated temperature (method 2) is less than that measured in method 1.

Surface temperatures in this report were obtained by averaging the measured temperatures on both sides of the pane obtained with surface thermocouples (method 2). This procedure assumes that the convection coefficients and the air-to-surface temperature difference on either side of the pane at a given location are the same. It assumes also that the actual temperature difference across the pane is negligible.

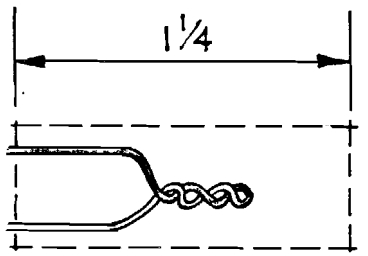
It is apparent from the vertical temperature gradients in Fig. 15 that the conditions of the first assumption are not completely realized. The worst possible situation would occur if the measured inside surface temperature corresponded to the actual inside surface temperature. Under this condition the error in taking the mean of the measured surface temperatures on either side of the pane as the inside surface temperature would be equal to one half the measured surface-to-surface temperature difference. If, however, the measured outside

surface temperatures of each pane corresponded to actual values, the errors in the reported inside surface temperatures would be somewhat smaller and of opposite sign. Values of the possible error in this case can be determined only if the actual temperature drop across the panes is known.

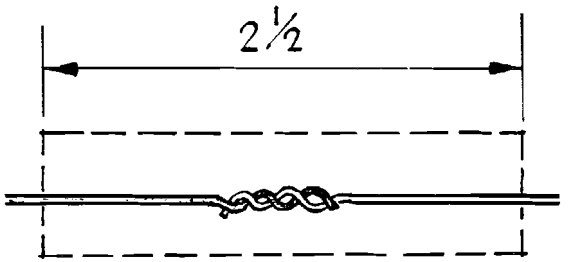
It is evident from the results given in Table VII that the errors in the reported inside surface temperatures for the inner pane are less than one degree. It can be safely assumed, therefore, that the actual errors in the reported inside surface temperatures for both panes are between those for the two limiting conditions.

Reference

1-B. Kratz, A.P., and E.L. Broderick, Study of the application of thermocouples to the measurement of wall surface temperatures. Transactions, A.S.H.V.E., no. 943, vol. 39, 1933. pp. 55-62.

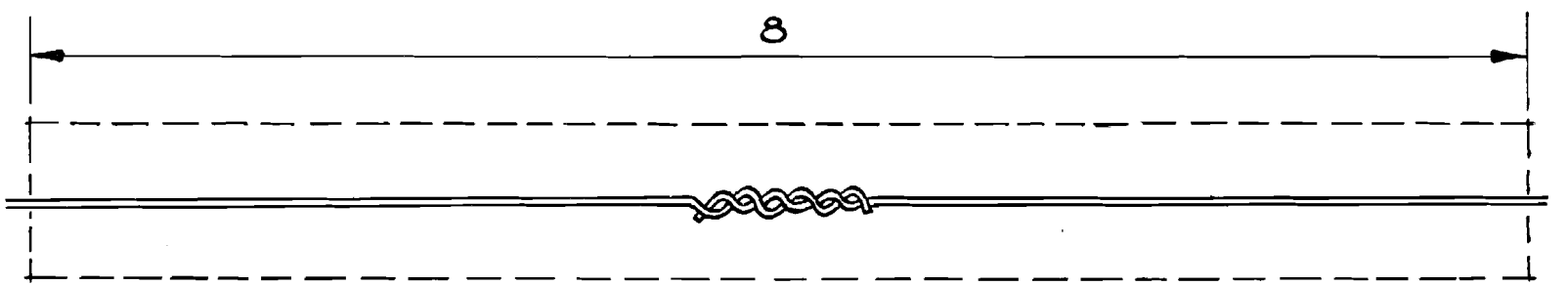


ON INSIDE SURFACE OF INNER PANE



ON OTHER GLASS SURFACES

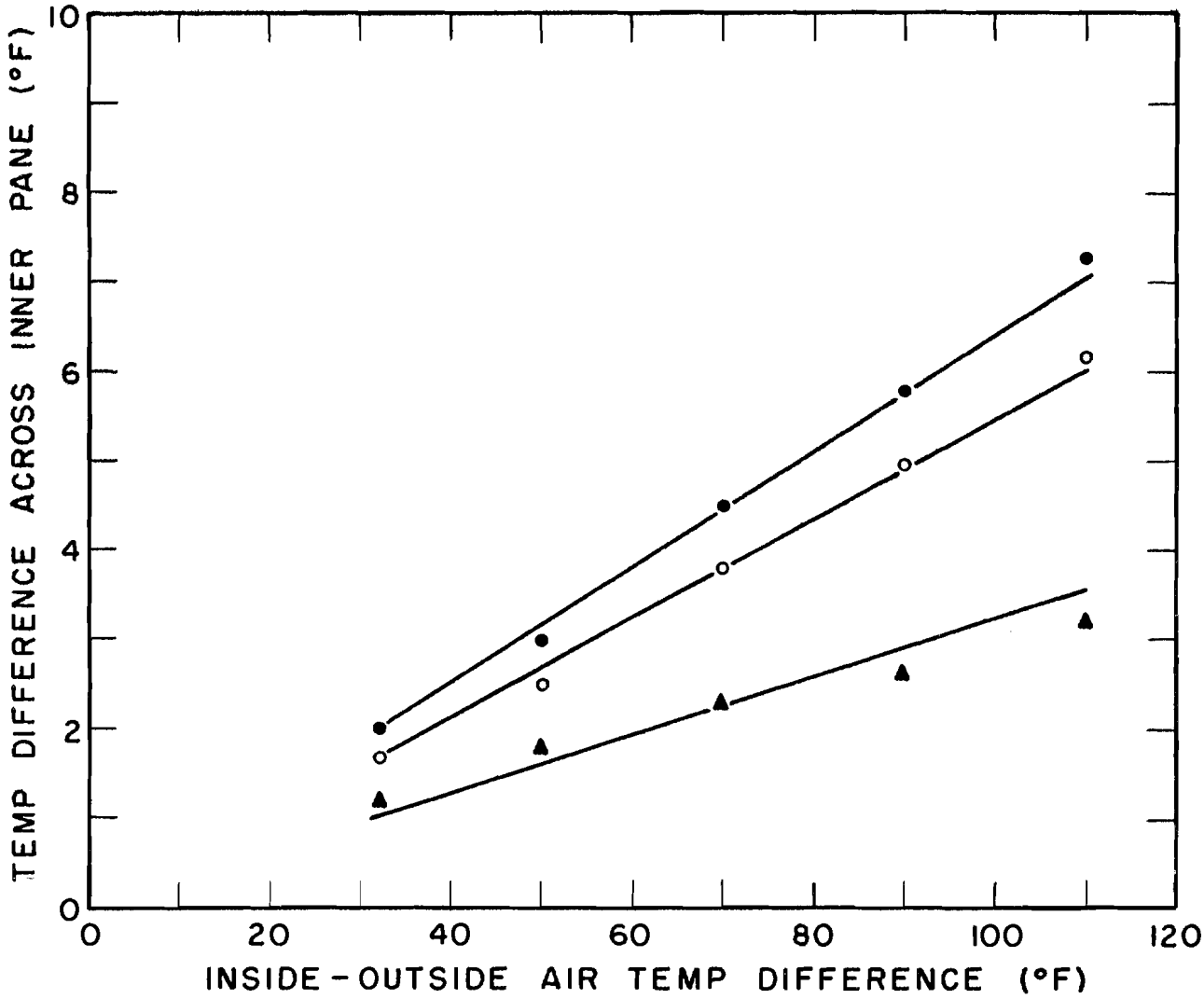
METHOD 1



METHOD 2

FIGURE B1

METHODS OF SURFACE THERMOCOUPLE INSTALLATION



LEGEND:

●——● 10" BELOW THE MID HEIGHT

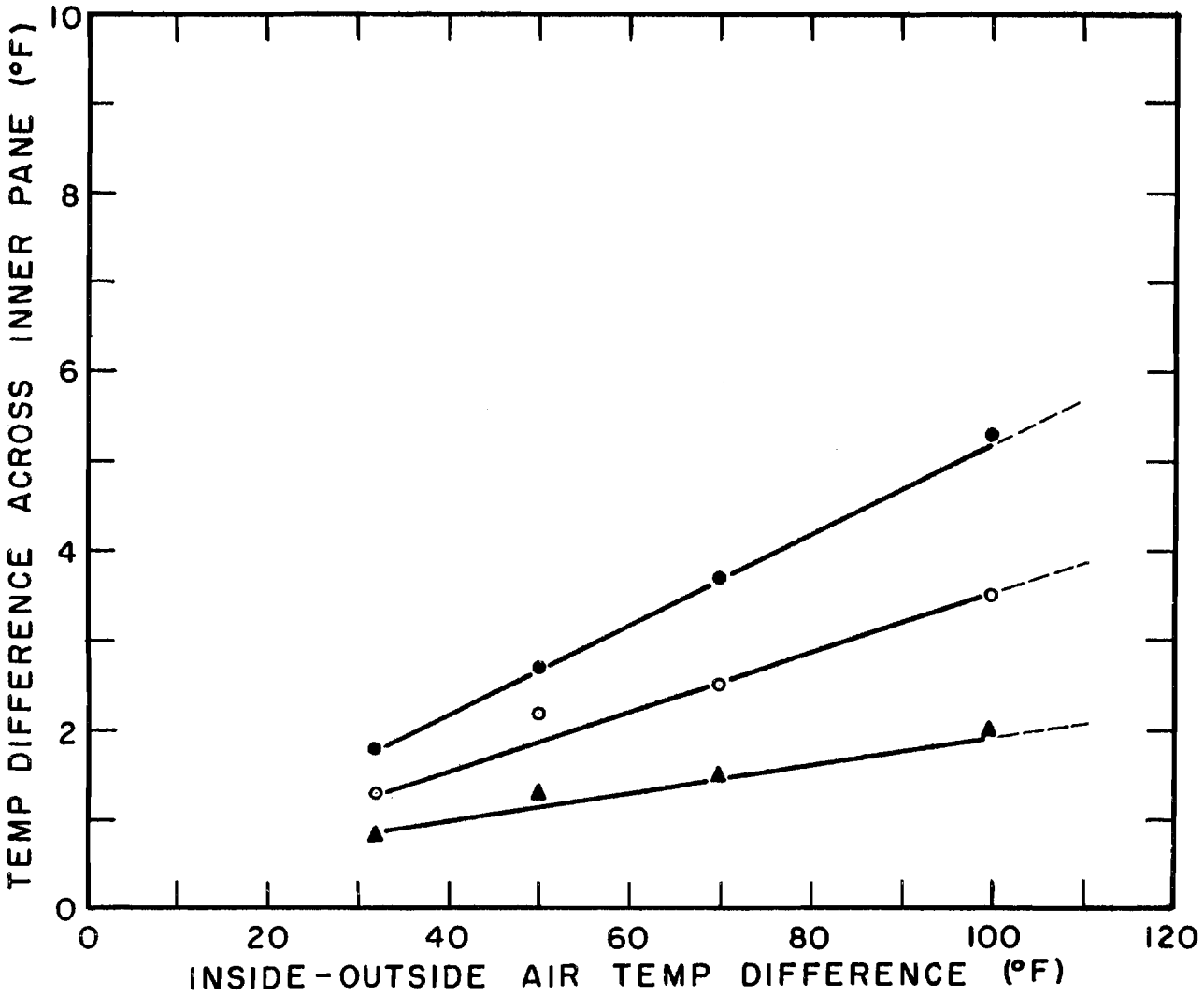
○——○ AT THE MID HEIGHT

▲——▲ 10" ABOVE THE MID HEIGHT

SURFACE THERMOCOUPLES AS SHOWN IN FIGURE B1, METHOD 1.

FIGURE B2

MEASURED TEMPERATURE DIFFERENCE ACROSS INNER PANE VERSUS INSIDE-OUTSIDE AIR TEMPERATURE DIFFERENCE.



LEGEND:

▲——▲ 10" ABOVE THE MID HEIGHT

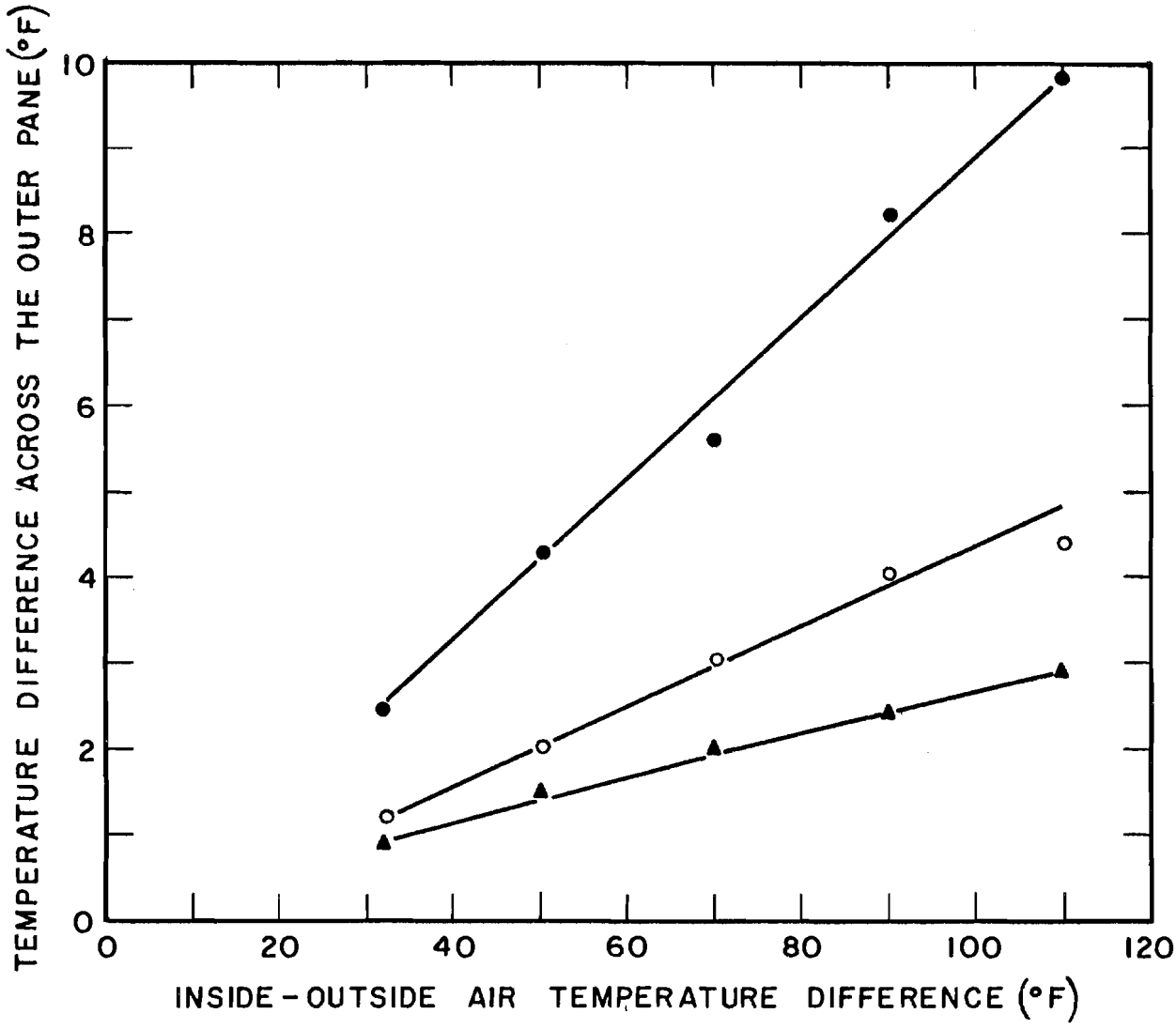
○——○ AT THE MID HEIGHT

●——● 10" BELOW THE MID HEIGHT

SURFACE THERMOCOUPLES AS SHOWN IN FIG. B1, METHOD 2.

FIGURE B3

MEASURED TEMPERATURE DIFFERENCE ACROSS INNER PANE VERSUS INSIDE-OUTSIDE AIR TEMPERATURE DIFFERENCE

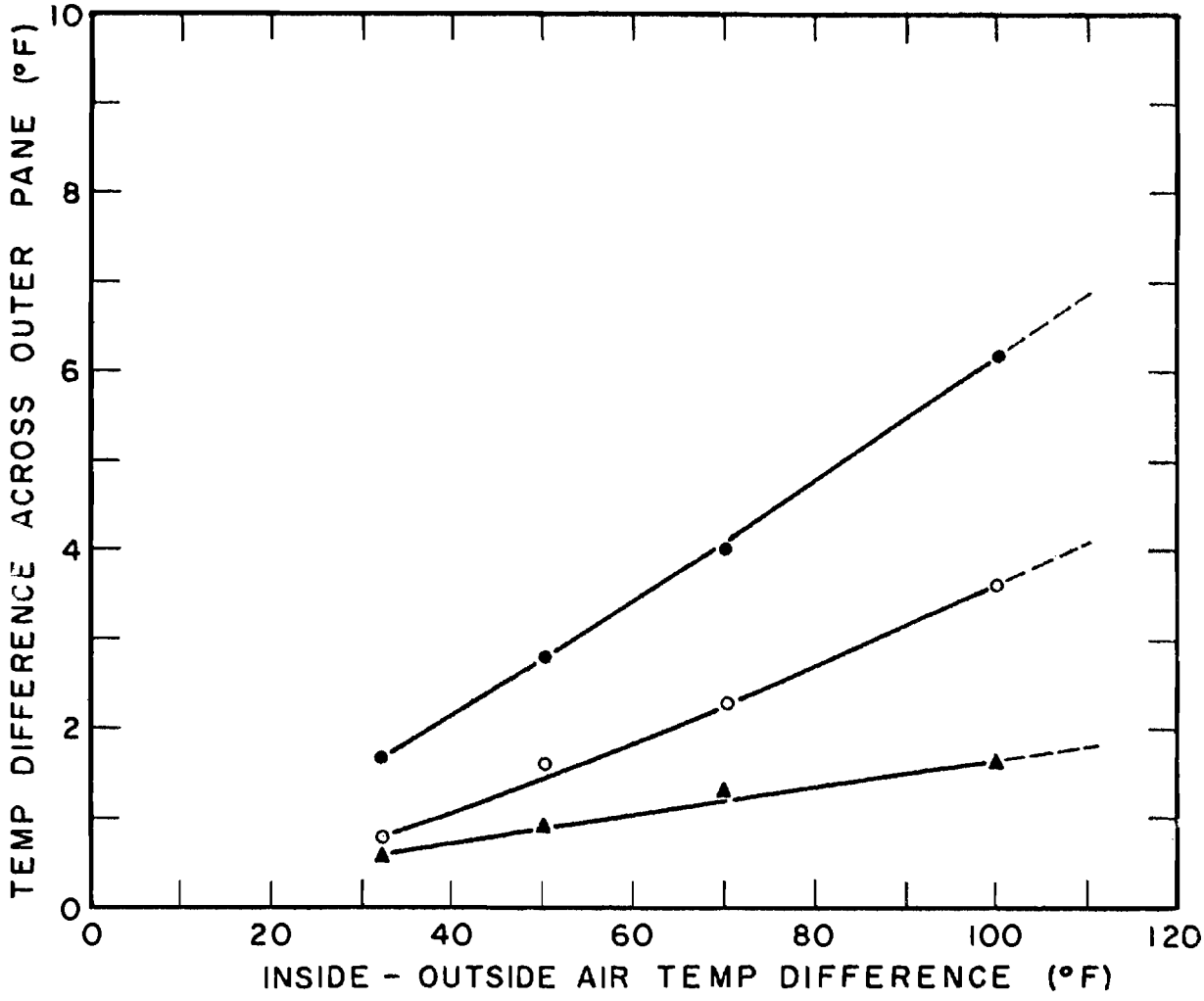


LEGEND:

- ●——● 10" ABOVE MID HEIGHT
- ○——○ AT THE MID HEIGHT
- ▲——▲ 10" BELOW MID HEIGHT

FIGURE B4

MEASURED TEMPERATURE DIFFERENCE ACROSS OUTER PANE VERSUS INSIDE-OUTSIDE AIR TEMPERATURE DIFFERENCE



LEGEND:

●——● 10" ABOVE MID HEIGHT

○——○ AT MID HEIGHT

▲——▲ 10" BELOW MID HEIGHT

SURFACE THERMOCOUPLES AS SHOWN IN FIG. B2

FIGURE B5

MEASURED TEMPERATURE DIFFERENCE ACROSS OUTER PANE VERSUS INSIDE-OUTSIDE TEMPERATURE DIFFERENCE

APPENDIX C

Errors in Air Temperature Measurements

The thermocouples used in the measurement of air temperature in this study were unshielded. The possible differences between the actual and measured air temperature can be calculated by equating the net radiant heat exchange to the heat exchange by convection. If it is assumed that the inside surfaces of the test panels are at window surface temperature and all other surfaces of the warm room are at the temperature of the thermocouple, the heat exchange at the thermocouple is given by the following equation:

$$(F_e\ F_a)(1.73 \times 10^{-9})(T_m^{\ 4} - T_1^{\ 4}) = h_c\ (T_a - T_m) \qquad (1)$$

where

F_e is the emissivity factor.

F_a is the form factor.

T_m measured air temperature in °F absolute.

T_1 inside surface temperature of the inner pane of a double window in °F absolute.

T_a actual air temperature in °F absolute.

h_c convective film coefficient of heat transfer in Btu/sq ft/hr/°F.

At an inside temperature of 70°F and a cold room temperature of -30°F the surface temperature at the centre of a window was approximately 34°F. The radiant heat exchange between the thermocouple and the surroundings was calculated by using values for the emissivity factor F_e of 1, and for the form factor F_a of 1/6 (for a small object at the centre of a cube). A value for $(T_m - T_a)$ of -1°F was calculated by using the convection coefficient h_c for horizontal cylinders obtained from Heat Transfer by Fishenden and Saunders (1-C). Although this value is only approximate, the calculations indicate that the errors in the measured warm room air temperatures were small. Errors in the cold room air temperatures were not calculated but probably would be less in view of the high air motion in the room.

The relation between the true and measured air temperature in the air space is given by the following equation:

$$(F_e\ F_a)(1.73 \times 10^{-9})(T_2^{\ 4} + T_3^{\ 4} - 2T_m^{\ 4}) = h_c\ (T_a - T_m) \qquad (2)$$

where F_e is the emissivity factor.

F_a is the form factor.

T_2 is the outside surface temperature of the inner pane °F absolute.

T_3 is the inside surface temperature of the outer pane °F absolute.

T_m is the measured air space temperature °F absolute.

T_a is the actual air space temperature in °F absolute.

Taking a value of 1 for F_e and $\frac{1}{2}$ for F_a the differences between the measured and actual air temperature of the air space (T_m - T_a) were calculated at three levels at a cold room temperature of -30°F. These differences were 2.6°F and 1°F at the bottom and centre and -2.4°F at the top. Thus, the actual vertical air temperature gradient in the air space was greater than that measured by approximately 5°F under these conditions. It can be assumed that the actual gradients at all inside-outside air temperature differences were somewhat greater than the measured gradients.

There were also fluctuations in the air temperature of the air space. At cold room temperatures of 0°F and -30°F there were fluctuations of 5°F in the measured air temperature at mid-height in the air space. There were no fluctuations in the measured air temperatures at the bottom and top of the air space.

Reference

1-C. Fishenden, M., and O.A. Saunders, An introduction to heat transfer. The Clarendon Press, Oxford 1950. p.91.

APPENDIX D

Effect of Condensation on Surface Temperatures

Condensation on a surface will occur whenever the temperature at any point on the surface is below the dew point temperature of the air-water vapour mixture. Under some test conditions a thin film of condensation formed on the inside surface of the inner pane. The order of the difference in temperature caused by this condensation can best be seen in Fig. D1 which gives corrected inside surface temperatures of the inner pane at a variety of inside-outside air temperature differences. The uncertainties of these temperatures were obtained as described in Appendix B. The total uncertainty of any temperature is indicated by the distance between the horizontal bars. A best line was drawn through these points.

At inside-outside air temperature differences of 51°F and 91°F temperature measurements were obtained with bands of condensation of 2 and 3/4 in. respectively at the bottom of the inside surface of the inner pane. Measurements were obtained at inside-outside air temperature differences of 71°F and 72°F with bands of condensation of 7 and 1 in.

The records indicate that condensation had no effect on the surface temperatures 10 inches above mid-height while it may have increased them at mid-height and bottom by about 1.5°F.

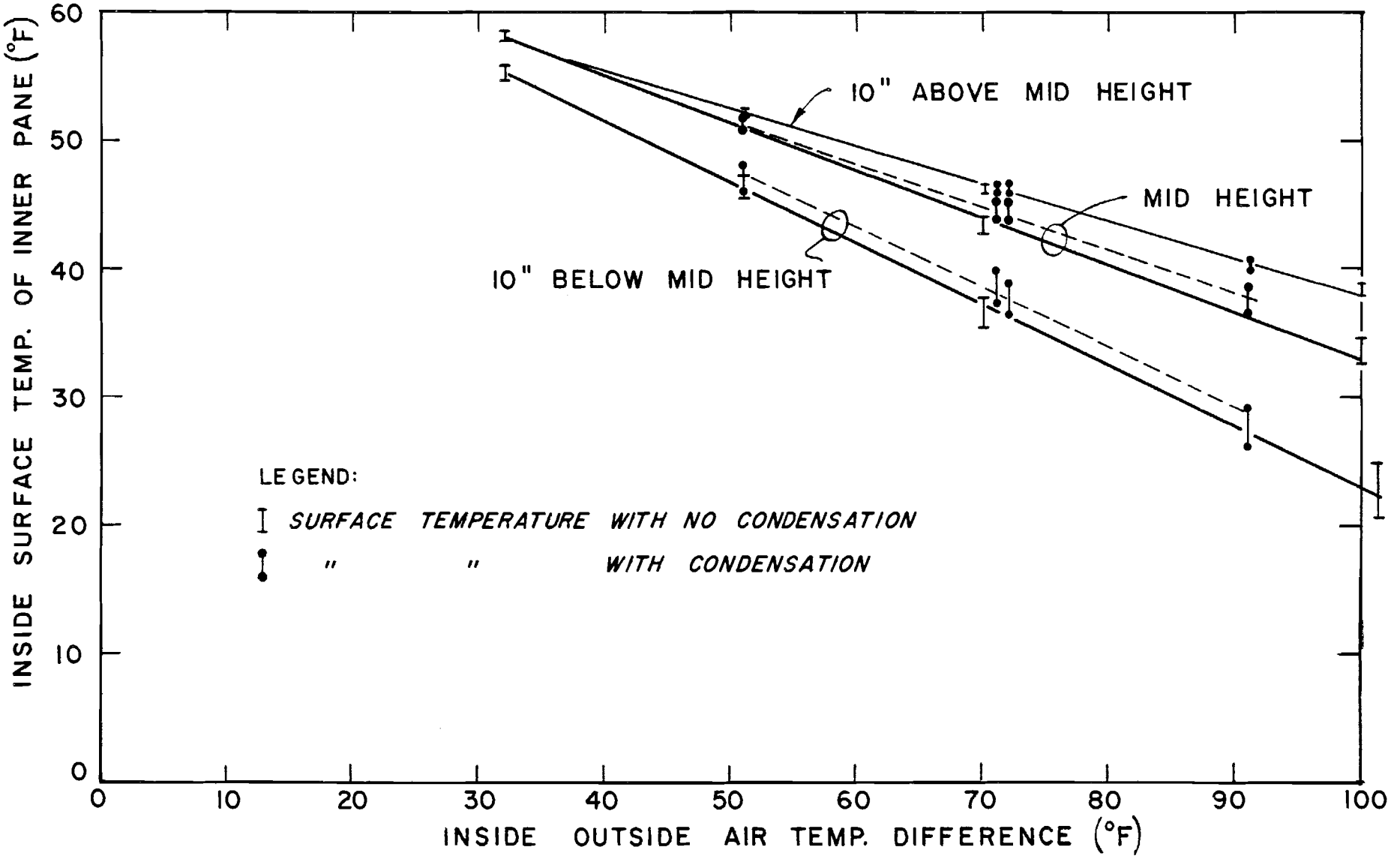


FIGURE DI

TEMPERATURES OF INSIDE SURFACE OF INNER PANE AT VARIOUS HEIGHTS WITH AND WITHOUT CONDENSATION

APPENDIX E

Effect of Venting on Heat Flow Through Double Window

The heat flow through the inner pane is in excess of that through the outer pane by that amount which is carried away as a result of the air interchange between the air space and the outside. Assuming that the inside film coefficient f_i is 1.5, that the outside film coefficient f_o is 6.0 and that the conductance of the air space can be taken as two film coefficients each equal to 2.0 Btu/sq ft/hr/°F., and neglecting the conductance of the glass, the following heat balance can be written with respect to the heat flow across the inner and outer panes

$$\frac{4}{7} f_i A (T_i - T') = f_i A (T' - T_o) + d_o Q_o C_p (T' - T_o) \qquad (1)$$

where

T_i is the inside temperature.

T' is the mean air space temperature with interchange.

T_o is the outside temperature.

A is the surface area of the window in square feet.

d_o density of the outside air.

Q_o amount of interchange of air in cu ft/hr.

C_p specific heat of the air, 0.24 Btu/lb/°F.

The over-all heat transfer coefficients for the window, without and with air interchange are given by equation 2 and 3

$$U = \frac{Q}{A \Delta T} \qquad (2)$$

$$U' = \frac{Q'}{A \Delta T} \qquad (3)$$

where

U is the apparent over-all heat transfer coefficient when there is no air interchange.

U' is the apparent over-all heat transfer coefficient when there is an interchange.

Q is the total heat flow through the double window when there is no interchange.

Q' is the total heat flow through the window when there is an air interchange.

A is the surface area of the window.

ΔT is the inside-outside air temperature difference.

Dividing equation 2 by 3 gives

$$\frac{U}{U'} = \frac{Q}{Q'} \tag{4}$$

The heat flow across the inner pane is equal to the total heat flow through the window as expressed by equations 5 and 6.

$$Q' = \frac{4}{7} f_i A \ (T_i - T') \tag{5}$$

$$Q = \frac{4}{7} f_i A \ (T_i - T) \tag{6}$$

where T is the air space temperature when there is no air interchange.

Substituting for the heat flows with and without interchange in equation 4 gives the following relationship between the over-all heat transfer coefficient and the air temperature difference across the inner pane

$$\frac{U}{U'} = \frac{T_i - T}{T_i - T'} \tag{7}$$

Substituting for T' in equation 1 and simplifying we have

$$\frac{U' - U}{U} = \frac{1}{\frac{2.6\ T_o}{Q_o} + 1.75} \tag{8}$$

Defining $\left(\frac{U' - U}{U}\right)(100)$ as $\Delta U\%$

equation 8 becomes

$$\Delta U\% = \frac{100}{\frac{2.6\ T_o}{Q_o} + 1.75} \tag{9}$$

Equation 9 gives the approximate relationship between the percentage increase in the over-all heat transfer coefficient and the volume rate of air interchange between the air space and the outside.