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Air Inleakage Due to Door Opening and Closing

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ABSTRACT

With the recent interest in a more accurate assessment of inleakage into operating nuclear power plant control rooms, the question of the actual inleakage due to door opening and closing has come under scrutiny. SRP 6.4 recommends 10 CFM of additional inleakage for those control rooms that do not have airlock-type double doors. The 10 CFM value does not appear to have any theoretical or experimental basis. For many plants this additional inleakage does not pose difficulties in achieving compliance with the safety criteria included in the plant control room habitability analysis. However, for a number of plants, the 10 CFM value may represent a significant challenge to the attainment of a suitable habitability analysis.

This paper provides a review of the basic physics involved in air interchange into a room caused by door opening and closing. During door movement an amount of air is entrained in the door wake. This entraining action can pump a quantity of air out of the room initially as the door opens and then pump a quantity of outside air back into the room as the door closes. Additionally, the temperature difference between air inside and outside of the room can influence the air interchange during door movement. A theoretical and empirical format for estimating actual air interchange (inleakage) due to opening and closing of a single door is provided for non-pressurized control rooms.

For pressurized control rooms, sufficient empirical data do not exist to allow a complete analysis to be undertaken. Data on the quantity of air entrained by door movement apparently have not been generated for the case of a pressurized room. However, air exchange volume for buoyancy induced flow can be calculated. Air exchange volumes for several makeup flowrates are calculated as a function of differential temperature. The limiting flow rate necessary to eliminate buoyancy-induced door inleakage is calculated also.

1.0 INTRODUCTION

With the recent interest in a more accurate assessment of inleakage into operating nuclear power plant control rooms, the question of the actual inleakage due to door opening and closing has come under scrutiny. SRP 6.4 recommends 10 CFM of additional inleakage for those control rooms that do not have airlock-type double doors. The 10 CFM value does not appear to have any theoretical or experimental basis. For many plants this additional inleakage does not pose difficulties in achieving compliance with the safety criteria included in the plant control room habitability analysis. However, for a number of plants, the 10 CFM value may represent a significant challenge to the attainment of a suitable habitability analysis.

This paper provides a review of the basic physics involved in air interchange into a room caused by door opening and closing. The flow through a doorway may be caused by a number of mechanisms [1]:

density difference between inside and due to outside temperature differences

door swing pumping action

pressure differences due to mechanical ventilation

passage of personnel through the doorway

The temperature difference between air inside and outside of the room or building creates a density difference between the inside and outside air. This density difference results in a hydrostatic pressure difference that can cause air exchange during door movement.

During door movement, an amount of air is entrained in the door wake. For a door that opens out of the room this entraining action can pump a quantity of air *out* of the room initially as the door opens and then pump a quantity of outside air back *into* the room as the door closes.

For some operating conditions mechanical ventilation of a room can overcome the hydrostatic pressure difference created by temperature effects and thereby eliminate thermally induced air exchange. However, mechanical ventilation will not eliminate air exchange caused by door swing pumping.

A small amount of data has been published on the effects of personnel passage through an open doorway. These data were for passage through a fully open sliding door in a non pressurized room (recirculation flow only) and ranged from 3 to 10 cubic feet of air exchange per passage [2]. As such, they may not be relevant to air exchange induced by passage through a swinging door. Apparently, no data have been published for passage through a swinging door. Accordingly, the contribution of personnel passage through a doorway will be ignored in the following discussion.

2.0 FLOW THOUGH A DOORWAY

The basic physics of airflow through a doorway can be described by reference to Figures 1 and 2. The derivations that follow all assume only a single door opening at any one time. We also assume that the temperatures in the two rooms are different but uniform, i.e. we do not consider the existence of temperature gradients in the following.

In most circumstances within the power plant environment, the control room will be cooler than the adjacent room. Thus, opening a door results in a flow of the relatively denser cool air along the floor that is replaced by an inflow of less dense air across the upper portion of the door opening.

In Figure 1, we provide the basic parameters that will describe the flow for a single doorway that separates two rooms. The derivation that follows is based on taking the outside temperature as the temperature of air at the top of an opening and taking the inside temperature as the temperature at the base of the opening. This temperature difference creates a density (and a hydrostatic pressure) difference along the plane of the opening.

2.1 BUOYANCY DRIVEN FLOW: NON PRESSURIZED ROOM

When there exists a difference in air density across an opening, a buoyancy driven counterflow will result. In the inside room, the pressure P, at a level Z below the centerline will be

$$P_i = P_C + \rho_i g Z \qquad (1)$$

and the pressure in the outside room at the same level will be

$$P_o = P_C + \rho_o g Z \qquad (2)$$

The pressure difference in the two rooms at the same level is thus

$$P_i - P_o = (\rho_i - \rho_o) g Z \qquad (3)$$

This pressure difference can be expressed as the height h_a of a column of air where

$$h_a = \left(\frac{\rho_i - \rho_o}{\rho_{av}}\right) \bullet Z = \left(\frac{\Delta\rho}{\rho_{av}}\right) \bullet Z \qquad (4)$$

where ρ_{av} is the mean density given by

$$\rho_{av} = \frac{\rho_i + \rho_o}{2} \qquad (5)$$

If we assume ideal flow, we can use the Bernoulli equation to calculate the velocity v of air flowing across one half of the door opening height

$$v = (2gh_a)^{1/2} = \left(2g\left(\frac{\Delta\rho}{\rho_{av}}\right) \bullet Z\right)^{1/2} \qquad (6)$$

The flowrate through the opening is given by

$$Q = K \bullet A \bullet v \qquad (7)$$

where K is the orifice coefficient, A is the area of the opening and v is the velocity of air flowing through the opening. The total volumetric flow through half of the opening can be written as

$$Q = \int_o^{H/2} W\left(2g\left[\frac{\Delta\rho}{\rho_{av}}\right] \bullet Z\right)^{1/2} dZ \qquad (8)$$

Integrating this expressions, the total volumetric flow through one half of the opening is given by

$$Q = \frac{KW}{3} \bullet \left[gH^3 \bullet \left(\frac{\Delta\rho}{\rho_{av}}\right)\right]^{1/2} \qquad (9)$$

where W is the door width [2].

Equation (9) applies to an opening of fixed dimensions at a time when steady flow is fully established. If we assume that the flow is quasi-steady, we can account for door opening and closing by imposing a time variation on W.

Referring now to Figure 2, the minimum opening width is given as

$$W' = W \cos\theta \tag{10}$$

where θ is the angular position of the door. Treating the flow as quasi-steady allows equation (9) to be written in integral form over the total opening time t_{tot}, which is the sum of the opening time t_o, the fully open hold time t_h and the closing time t_c.

Thus, the net volume of air exchanged due to buoyancy effects, V_n, is given by,

$$V_n = \int \frac{KW}{3} \bullet \left[gH^3 \bullet \left(\frac{\Delta\rho}{\rho_{av}} \right) \right]^{1/2} dt \tag{11}$$

where equation (11) is a definite integral from t=0 to $t=t_{tot}$.

Assuming that the orifice coefficient does not vary significantly with door position and that the door swing speed is constant, one obtains equation (12),

$$V_n = Q_n \bullet \left[t_h + \frac{2t_o}{\pi} + \frac{2t_c}{\pi} \right] \tag{12}$$

where Q_n is given by equation (9). By integrating over time the value calculated in equation (12) is a *per opening* value and not a rate.

Note that the assumption of a constant orifice coefficient is not unreasonable since the orifice edge geometry does not vary significantly with door position. The assumption of quasi-steady flow implies that the flow instantaneously adjusts to the changing opening size while the door is moving. In practice, however, the flow adjustment will lag the door position. Thus, the actual air exchange volume will be *less* than that predicted by equation (12).

Experimental data for a non-pressurized room have been obtained using both full scale and fluid modeling techniques and are documented in reference [3]. It was found that the orifice coefficient, K, was a weak function of temperature and showed no dependence on door opening width. Equation (13) provides this dependence.

$$K = 0.4 + 0.0075 \bullet \Delta T \tag{13}$$

This equation agrees well with other published data on flow through vertical openings.

2.2 PUMPED FLOW AT ZERO DENSITY DIFFERENCE

At a zero temperature difference, there will be no buoyancy effects and flow will be dominated by door pumping alone. Referring again to Figure 2, as the door begins to open, air is drawn in behind the door at a velocity that is proportional to the average speed, U_d of the center of the door, therefore

$$U_d = \theta_0 \bullet \left(\frac{\frac{W}{2}}{t_0} \right) \tag{14}$$

where t_0 is the opening (or closing) time and θ_0 is the final opening angle. The volume swept by the door, V_d, is then

$$V_d = A \bullet t_0 \bullet U_d = A \bullet \left(\frac{W}{2} \right) \bullet \theta_0 \tag{15}$$

where A is the area of the door.

In reference [2] it was found from both full-scale mockup tests as well as 1/20 scale liquid model tests that the pumped volume V_p was linearly related to the mean door velocity in meters per second for $\theta_0 = 90$ degrees.

$$V_p = 2.3 \bullet U_d \tag{16}$$

Because this is a dimensionally inconsistent equation, it should be noted that equation (16) is only valid over a limited range of door sizes and opening velocities that do not differ significantly from those used in generating equation (16).

2.3 COMBINED BUOYANCY AND PUMPING EFFECTS

In most practical cases both pumping and buoyancy driven exchange will occur. It is unlikely that the two effects can be simply added to estimate their combined effects because each mechanism tends to interfere with the other's ability to promote air exchange. For a given door velocity, buoyancy forces will dominate at large temperature differences and the flow will be that predicted by buoyancy alone. At small temperature differences, door swing pumping will dominate. Between these two extremes the exchange flow that results depends on the combined effects of the two mechanisms.

An empirically determined equation that reproduces the observed air exchange behavior due to door swing is given in reference [3] as

$$V_p = \frac{2.3 \bullet U_d}{1 + \left[45 \bullet \left(\frac{\Delta\rho / \rho_{av}}{U_d} \right) \right]^4} \tag{17}$$

These authors note that their results are valid only for doors of approximately the same size as that used in the tests (0.91 m by 2.06m) since this equation is not properly non-dimensionalized. Further they note that their results are valid for door speeds in the range of 0.2 m/sec and less.

Thus, by combing equation (12) and (17) and making use of equation (13) it is possible to estimate the air exchange volume for door opening in a non pressurized control room (i.e. a control room with recirculation air flow only). Equation (18) below forms the basis of the calculations for a non-pressurized control room presented in section 3.

$$V_{tot} = V_n + V_p \tag{18}$$

Note that this value of air exchange is a *per opening* volume.

2.4 BUOYANCY DRIVEN FLOW: PRESSURIZED ROOM

For the case of a pressurized room, the basic geometry of Figure 1 still applies. The difference is now that the flow velocity vectors will be biased due to the existence of bulk airflow out of the room induced by the pressurization flow. The sole substantive difference is the inclusion of a term v_x that corresponds to the average linear velocity of air through the door opening. Note that v_x is given by the ratio of the makeup flowrate ($Q_{m/u}$) to the area of the opening (A).

For the inside room the pressure P at the centerline is given by

$$P_i = P_C + \rho_i g Z + P_x \tag{19}$$

where P_x is the additional pressure within the room due to the makeup flow and P_C is now the pressure at the level of the neutral plane.

The pressure in the outside room at the same level is

$$P_o = P_C + \rho_o g Z \tag{20}$$

The pressure difference between the two rooms at the same level is

$$P_i - P_o = (\rho_i - \rho_o) g Z - P_x \tag{21}$$

The pressure difference and makeup-induced room pressure can be expressed as the height h_a of a column of air where the pressure due to temperature differential is

$$h_T = \left(\frac{\rho_i - \rho_o}{\rho_{av}} \right) \bullet Z = \left(\frac{\Delta\rho}{\rho_{av}} \right) \bullet Z \tag{22}$$

and the makeup induced room pressure is

$$h_m = \frac{P_x}{\rho_{av} g} = \frac{v_x^2}{2g} \tag{23}$$

Thus using equation (21)

$$h_a = h_T - h_m \tag{24}$$

Using the Bernoulli equation once again, one obtains

$$v = \left[2g \left(\frac{\Delta\rho}{\rho_{av}} \right) \bullet Z - v_x^2 \right]^{1/2} \tag{25}$$

If we define Q_L as the inleakage flow against the makeup-induced outflow we can write

$$Q_L = K \bullet A \bullet v \tag{26}$$

Thus,

$$Q_L = K\int_{L2}^{L1} W\left[2g\left(\frac{\Delta\rho}{\rho_{av}}\right)\bullet Z - v_x^2\right]^{1/2} dZ \qquad (27)$$

where the limit L1 represents the bottom (or top) of the door and equals H/2 since the centerline of the door has been used as the reference point, and L2 is the level of the neutral plane where supply pressure equals buoyancy pressure, i.e. when the pressure due to the temperature differential equals the makeup-induced room pressure:

$$P_T - P_x = 0 \qquad (28)$$

Equation (27) reduces to

$$Q_L = \frac{KW}{3}\bullet\left(\frac{1}{g\left(\Delta\rho/\rho_{av}\right)}\right)\bullet\left[g\left(\Delta\rho/\rho_{av}\right)\bullet H - v_x^2\right]^{3/2} \qquad (29)$$

An immediate consequence of equation (29) is that there exists a linear flow velocity (and hence a makeup flowrate) for which the buoyancy induced air exchange volume is zero.

B imposing a time variation on W in a manner similar to that used to obtain equation (12) we arrive at an equation for air exchange volume in a pressurized room due to door opening and closing,

$$V_n = Q_L \bullet\left[t_h + \left(\frac{2\bullet t_o}{\pi}\right) + \left(\frac{2\bullet t_c}{\pi}\right)\right] \qquad (30)$$

Note that in this equation, the exchange volume is a *per opening* value.

Experimentally K was found to be the product of two coefficients that incorporate the effects of temperature (C_T) and flow velocity v_x (C_V) on the overall orifice coefficient [5]. Plots of these coefficients are provided in Figures 3 and 4.

This is as far as our calculational effort can proceed. Unfortunately it appears that no data have been published on door pumping exchange effects for a pressurized room similar to those published for door pumping in a non-pressurized room. Thus, it is not possible at present to formulate a relation analogous to equation (18) for non-pressurized rooms. However, equation (29) provides a bound on buoyancy induced air exchange in a pressurized room. Equation (30) can be used to estimate the contribution of buoyancy induced flow on the air exchange volume due to door opening in a pressurized room.

3.0 CALCULATIONAL RESULTS

By using typical door dimensions and reasonable values for door movement times, it is possible to generate graphical data that illustrate the range of door induced air exchange volumes in a non-pressurized room. All calculations in the following assume a door with a width of 3 feet (0.91 m) and a height of 7 feet (2.06 m). Door open and close times are assumed to be equal for ease in calculation. Door open times are taken as 3, 5, and 10 seconds. Door hold times are taken as 1, 2, 3, and 5 seconds. These values span those observed in a variety of plants by the author.

Figures 5, 6 and 7 illustrate air exchange versus inside-outside temperature difference for 3, 5, and 10 second door opening times. On each graph the calculated air exchange for door hold times of 1, 2, 3, and 5 seconds is plotted.

For relatively low temperature differences, air movement generated by door movement dominates the flow. For higher temperature differentials, buoyancy effects dominate the flow. Of course for relatively long door move (or hold) times, buoyancy flow will eventually dominate the air exchange no matter what the temperature differential. As the differential temperature increases, the air exchange volume also increases reflecting the dominance of buoyancy effects.

In Figure 8 we compare air exchange volume for a 2 second hold time (typical of door ingress and egress) for three open (and close) times. Below a temperature differential of approximately 2 degrees F, all three plots show that approximately 30 cubic feet of air (or less) is exchanged. As temperature differential increases, the air exchange volume changes relatively slowly for 3 and 5 second move times, but the 10 second move results in a smoothly increasing air exchange volume. The air exchange volume at the 3 and 5 second hold times reflect the fact that at low differential temperatures (here less than 5 degrees F) the major contribution to air exchange volume is door movement. At the longer hold time the effect of the density-induced pressure differences dominates the flow.

For a 20 degree F differential, a 3 second move time with a 2 second hold time results in an air exchange volume of approximately 55 cubic feet of air. For a 5 second move time the corresponding volume is approximately 90 cubic feet.

In the case of a pressurized control room, it is not possible to undertake as complete a calculation as for the un-pressurized control room. However, equation (29) does provide useful information about the effects of pressurization flow on room air exchange volume.

In this figure, we plot makeup flow as a function of temperature difference required to overcome the effects of buoyancy induced air exchange. The plot suggests that some buoyancy induced air exchange may occur for even relatively modest temperature differentials. In Figures 10 and 11 we provide plots of buoyancy induced air exchange volume for door open times of 3 and 5 seconds with a door hold time of 2 seconds. Plots are provided for makeup flow of 500, 000 1500 and 2000 CFM.

4.0 CONCLUSIONS

The calculated air exchange volumes for a non-pressurized room experiencing a single door opening range from approximately 10 to 90 cubic feet depending on the differential temperature. This calculated value overestimates the actual value due to the assumptions made in generating the controlling equations. However, the value is probably realistic to within a factor of 2.

Recirculation (non-pressurized) control rooms account for approximately 20% of the existing nuclear power plant inventory when radiation accidents are considered. However, control rooms that recirculate under accident conditions represent virtually 100% of the inventory for toxic gas incidents. Thus, it may be prudent to initiate a modest experimental program to refine the knowledge base used to generate equations (12), (13), and (17).

For pressurized rooms, the buoyancy induced air exchange volume varies from approximately 10 to 160 cubic feet and depends both on the inside-outside temperature difference and on the makeup flowrate. The calculated values presented in this paper overestimate the actual value due to the assumptions made in generating the controlling equations. However, the value is probably realistic to within a factor of 2.

Additional experimental data for pressurized control rooms would allow a complete analysis analogous to that leading to equation (18) to be undertaken by incorporating the effects of door pumping on the overall air exchange volume. Such an effort would allow a critical evaluation of the veracity of the 10 CFM inleakage estimate.

The engineering knowledge base at the preset time is not complete enough to allow incorporation of door induced air exchange into habitability analyses in a defensible manner. The calculations do however, suggest that an inleakage contribution of 10 CFM is a reasonable (and probably a conservative) estimate of the contribution of actual door induced air exchange.

What is clear from these admittedly crude attempts to quantify door opening induced air exchange is that for those plants that require very low values of inleakage to satisfy habitability considerations, it may be prudent to entertain the option of adding a second door and a simple vestibule to each control room entry door. Such an addition would eliminate the possibility of door opening induced air exchange contributing to unfiltered inleakage into the control room envelope.

5.0 REFERENCES

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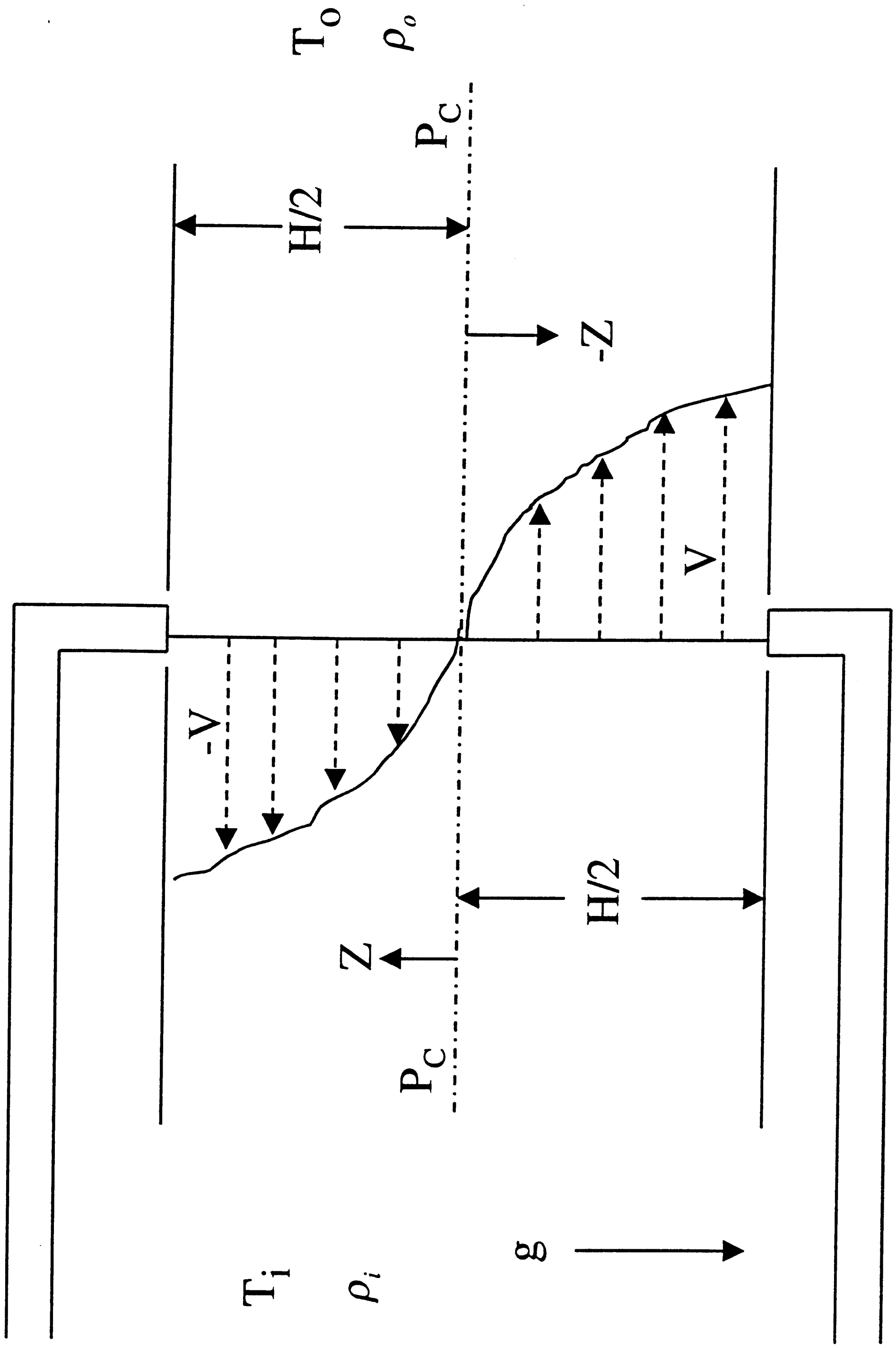

Figure 1. Parameters for Door Opening Air Exchange Calculation

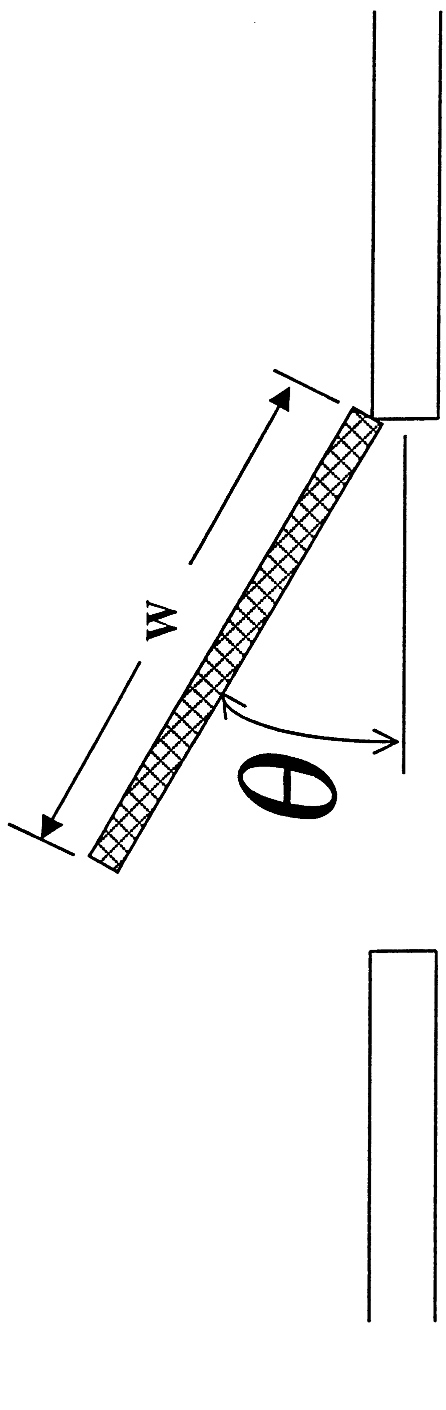

Figure 2. Geometry of Swinging Door

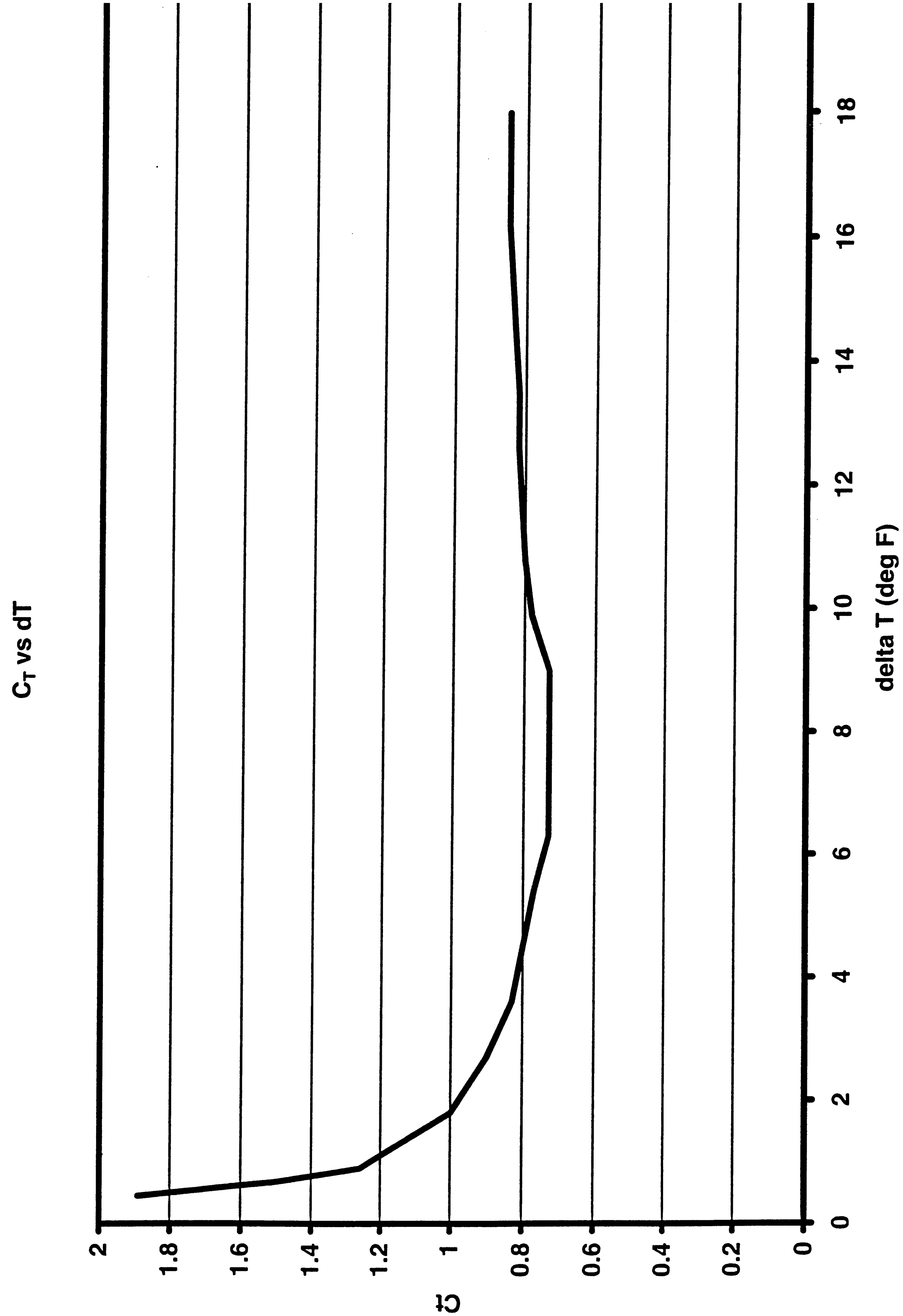

Figure 3. Plot of coefficient C_T versus differential temperature

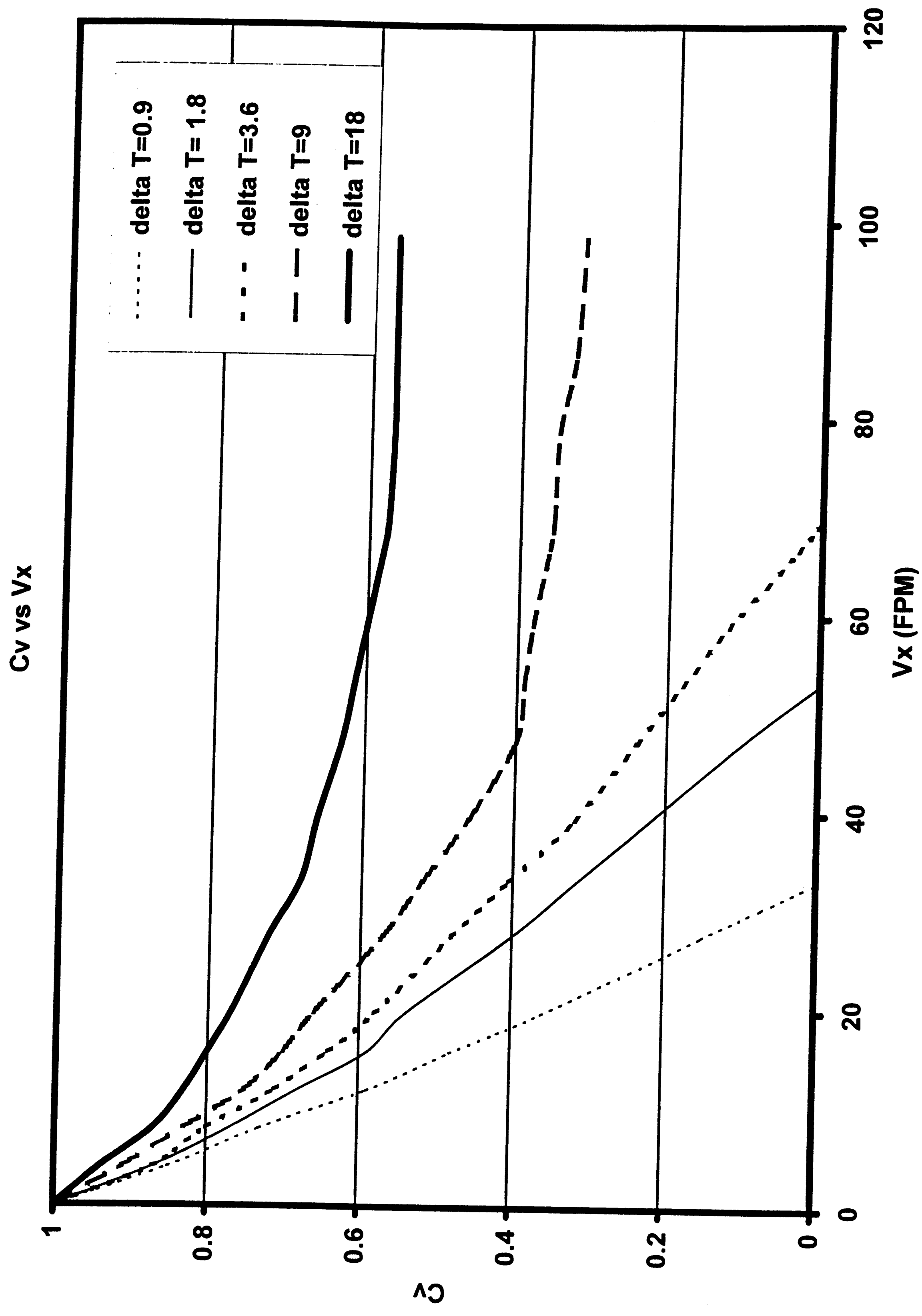

Figure 4. Plot of coefficient C_V versus v_x.

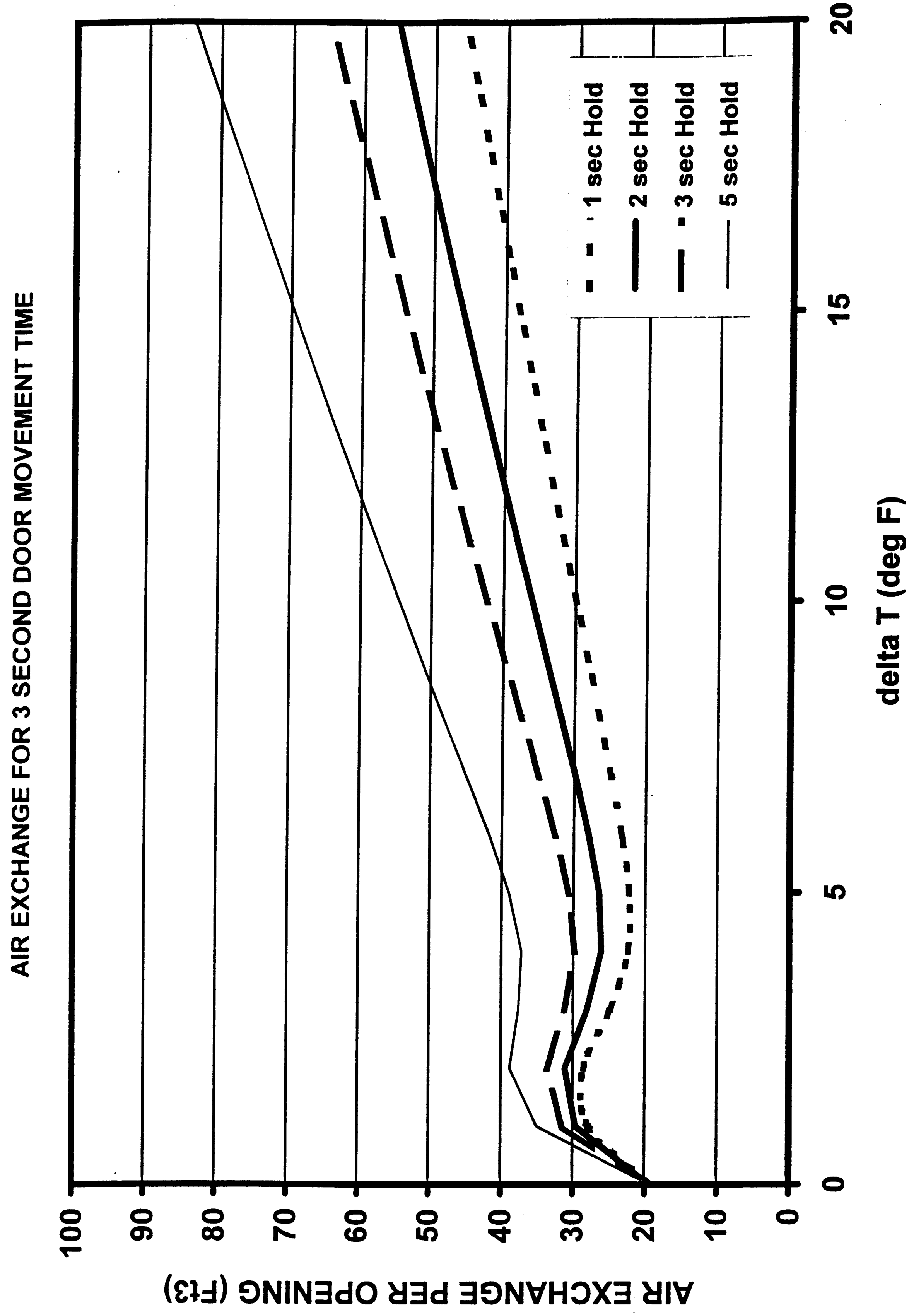

Figure 5. Air Exchange Volume for 3 second door movement time.

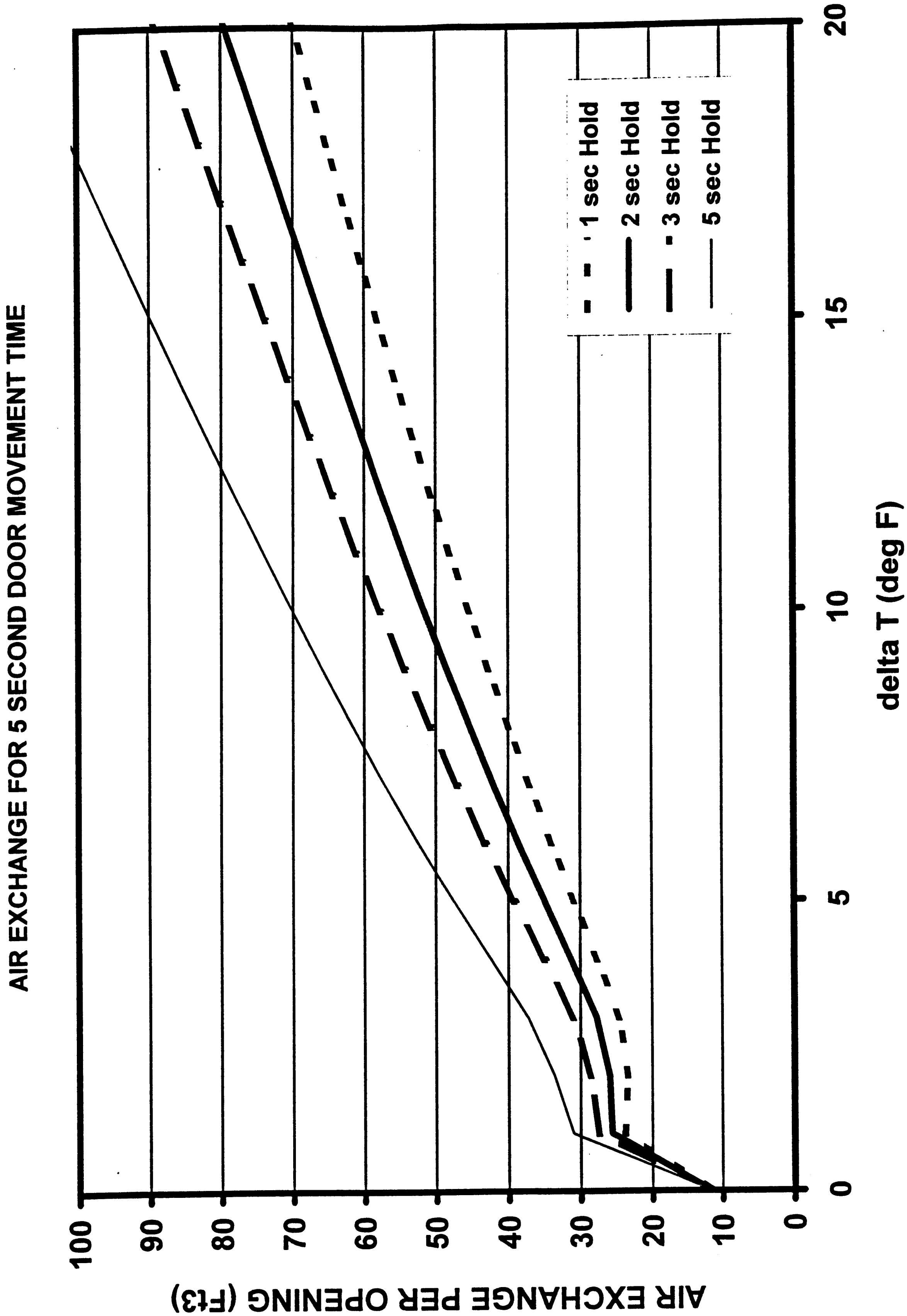

Figure 6. Air Exchange Volume for 5 second door movement time.

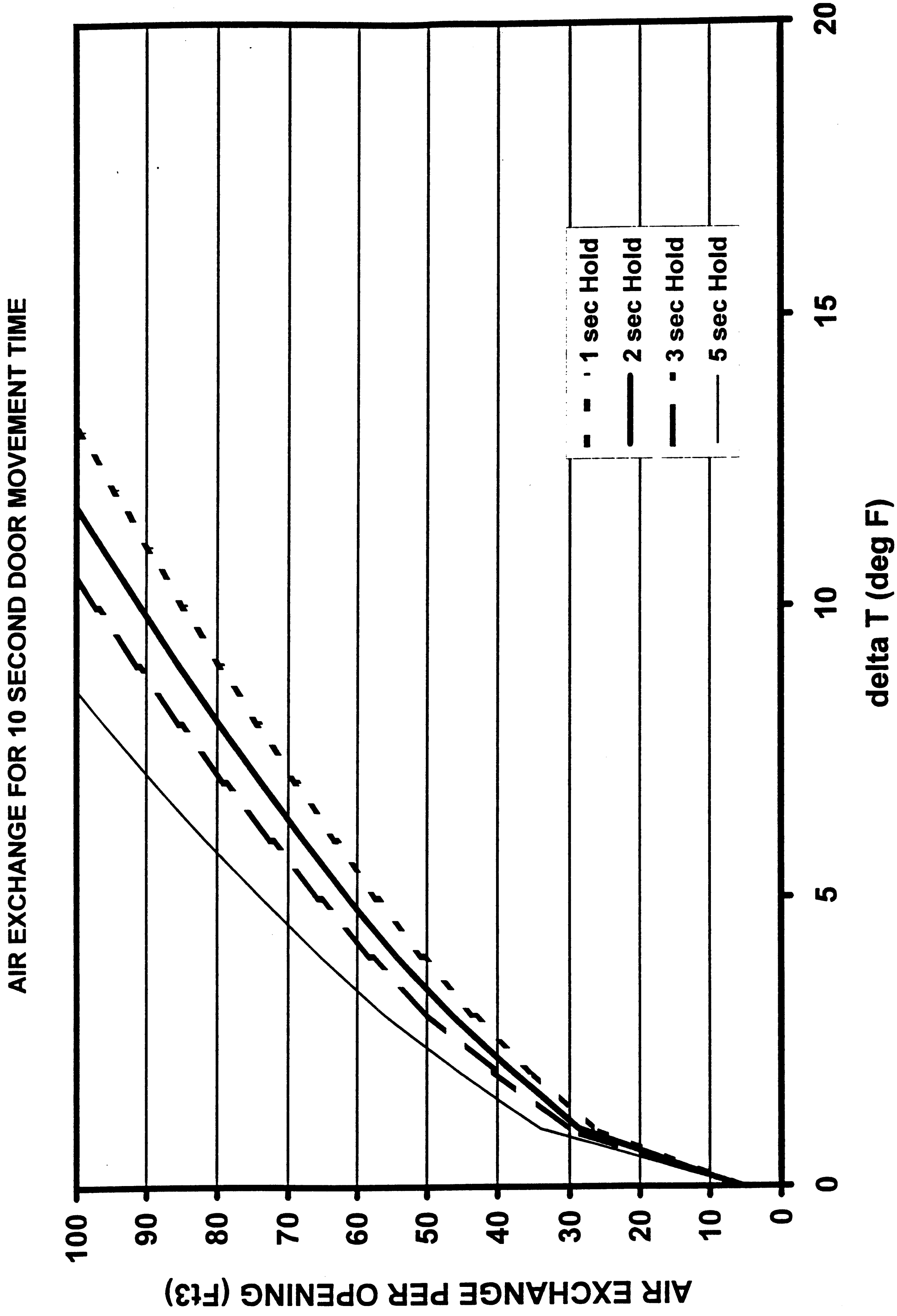

Figure 7. Air Exchange Volume for 10 second door movement time.

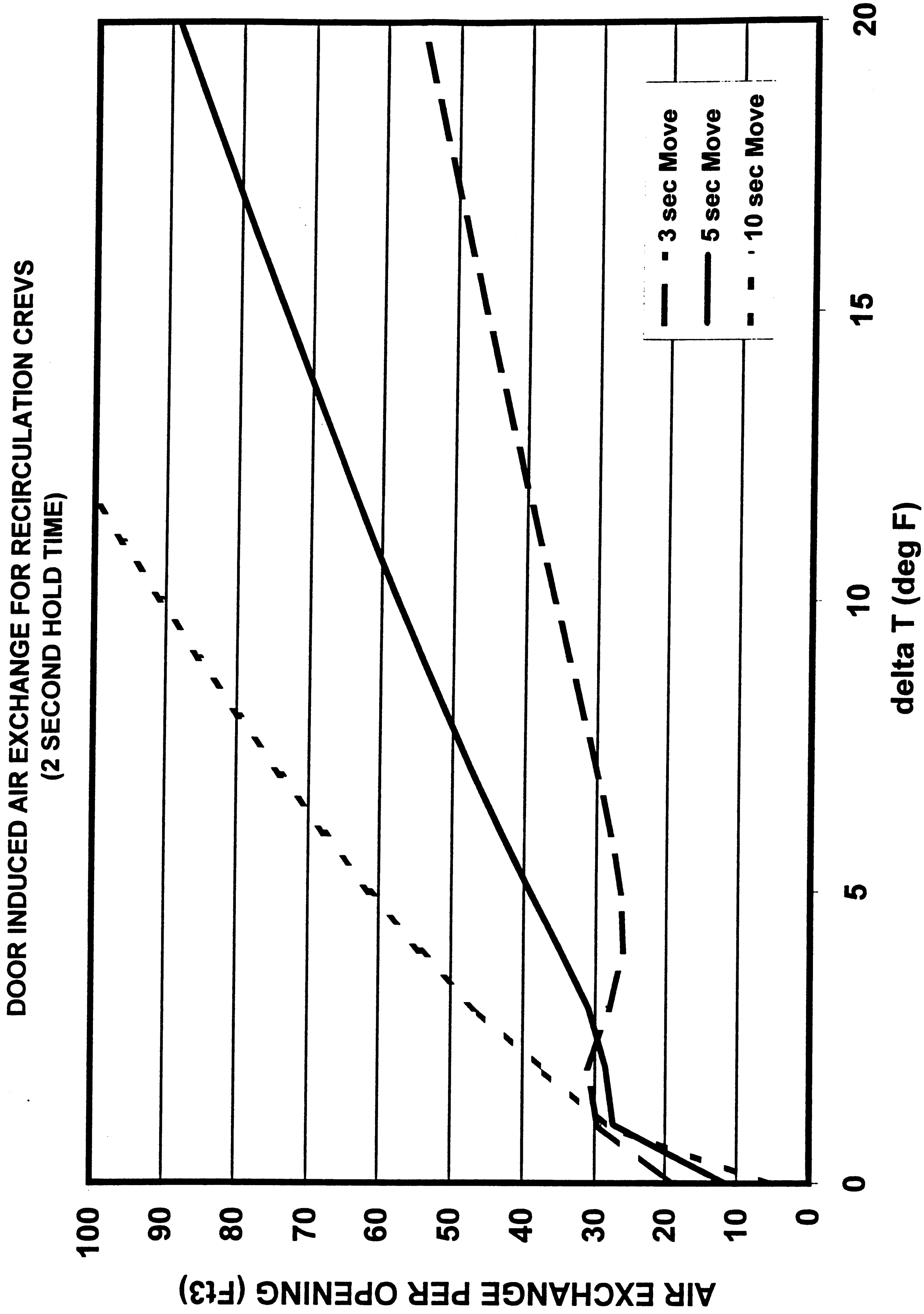

Figure 8. Air Exchange Volume for 2 second door hold time.

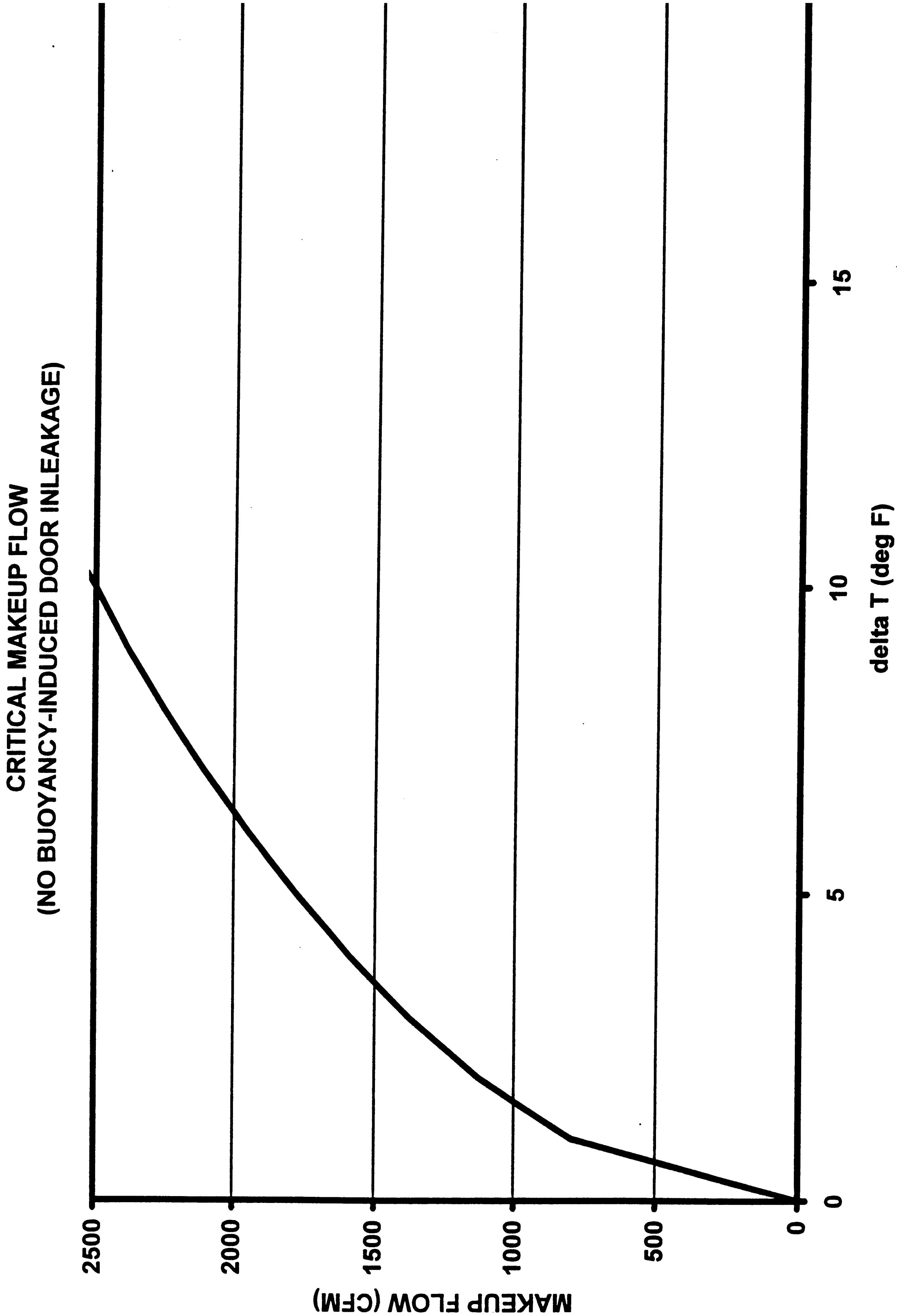

Figure 9. Makeup flowrates required to suppress buoyancy induced air exchange.

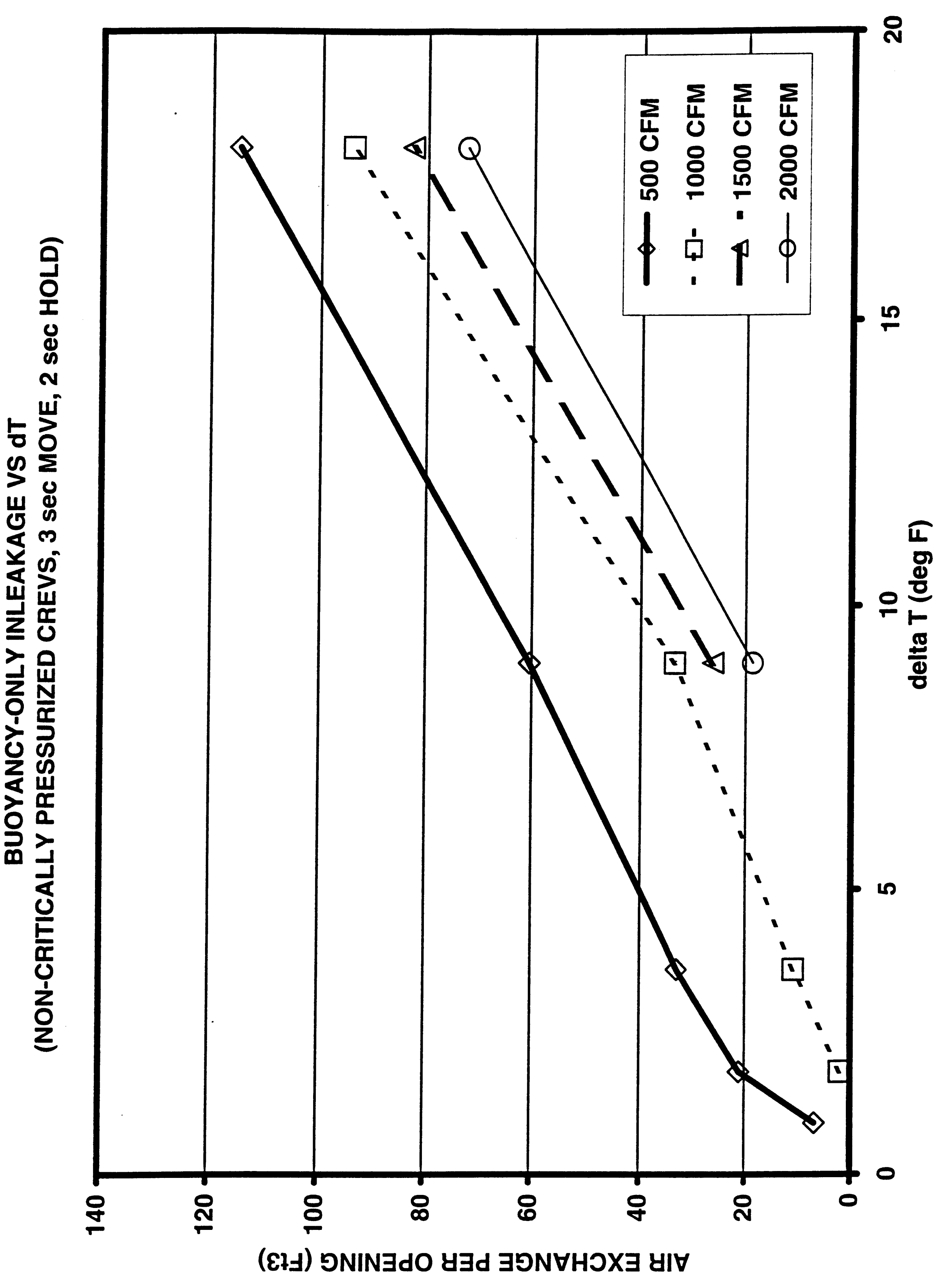

Figure 10. Air Exchange Volume with a 3 second open time for Pressurized Room

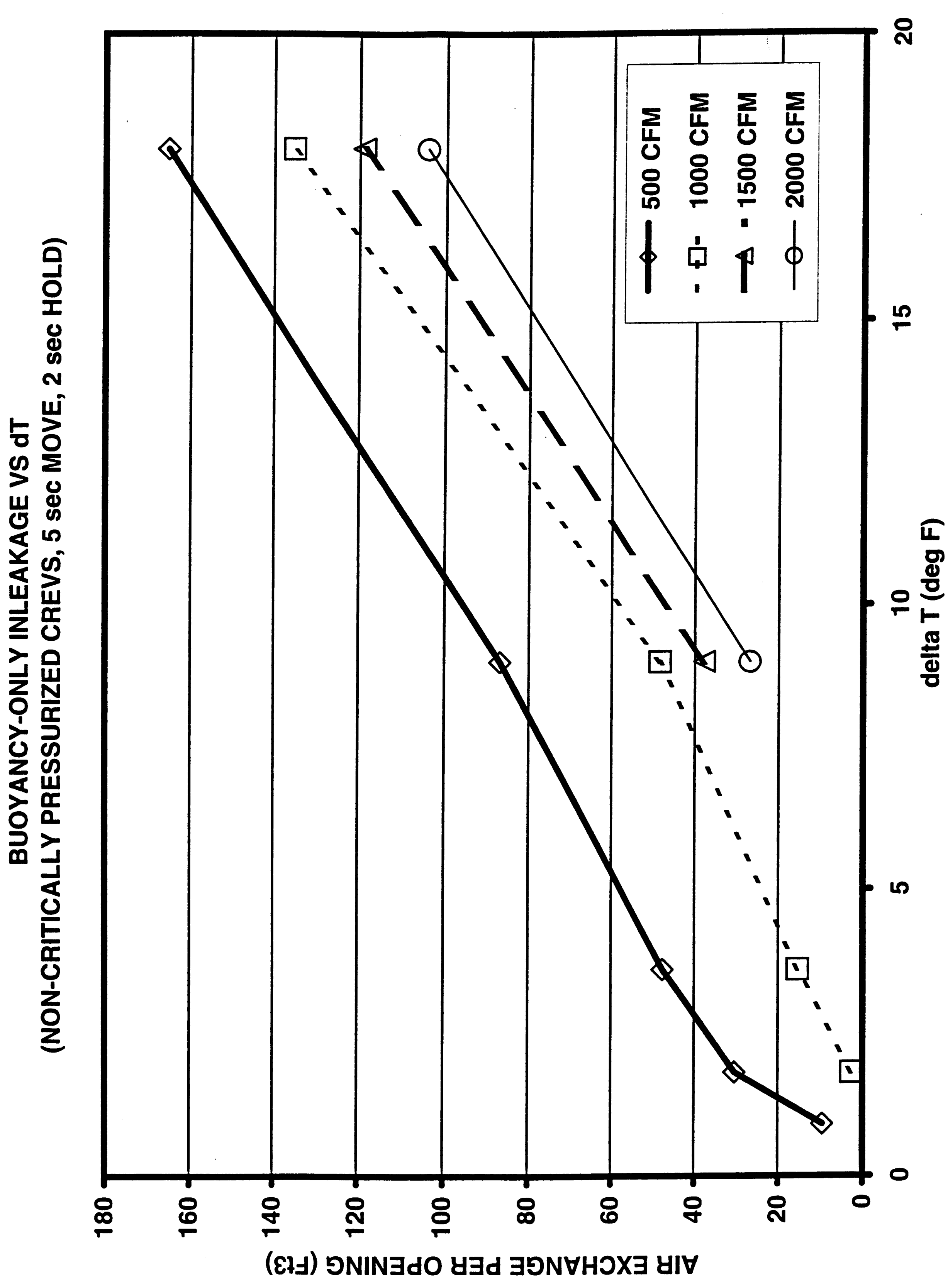

Figure 11. Air Exchange Volume with a 5 second open time for Pressurized Room