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# Development of an Empirical Model to Aid in Designing Airborne Infection Isolation Rooms

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*Airborne infection isolation rooms (AIIRs) house patients with tuberculosis, severe acute respiratory syndrome (SARS), and many other airborne infectious diseases. Currently, facility engineers and designers of heating, ventilation, and air-conditioning (HVAC) systems have few analytical tools to estimate a room's leakage area and establish an appropriate flow differential ($\Delta Q$) in hospitals, shelters, and other facilities where communicable diseases are present. An accurate estimate of leakage area and selection of $\Delta Q$ is essential for ensuring that there is negative pressure (i.e., pressure differential [$\Delta P$]) between an AIIR and adjoining areas. National Institute for Occupational Safety and Health (NIOSH) researchers evaluated the relationship between $\Delta Q$ and $\Delta P$ in 67 AIIRs across the United States and in simulated AIIR. Data gathered in the simulated AIIR was used to develop an empirical model describing the relationship between $\Delta Q$, $\Delta P$, and leakage area. Data collected in health care facilities showed that the model accurately predicted the leakage area 44 of 48 times. Statistical analysis of the model and experimental validation showed that the model effectively estimated the actual leakage area from −39% to +22% with 90% confidence. The NIOSH model is an effective, cost-cutting tool that can be used by HVAC engineers and designers to estimate leakage area and select an appropriate $\Delta Q$ in AIIRs to reduce the airborne transmission of disease.*

**Keywords** airborne, infection control, isolation, pressure difference, ventilation

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## INTRODUCTION

The occurrence of airborne nosocomial transmission of tuberculosis (TB) from an infectious patient to health care workers and other patients is well documented.[1−6] Many health care facilities use airborne infection isolation rooms (AIIRs) to reduce airborne transmission of TB and other infectious agents. For an AIIR to fulfill this function, however, it must be properly designed. Several studies have shown that AIIRs are often not under continuous negative pressure (NP) with respect to surrounding areas.[7] For example, one study showed that of 30 rooms housing patients with active pulmonary tuberculosis, only 2 were under negative pressure, and more than 75% of the rooms had inadequate air changes per hour.[8] Another study evaluated a total of 129 AIIRs at 13 different hospitals.

Of the 34 AIIRs in one hospital included in the study, only 53% (18/34) were under negative pressure. Another hospital in this study had 26 AIIRs, only 58% (15/26) of which were effective. Among all 13 hospitals, AIIR effectiveness ranged from 44% to 100%.[9] Establishing an appropriate flow differential ($\Delta$Q) in hospitals, shelters, and other facilities where airborne infectious diseases are present is essential for specification of an effective NP (i.e., negative pressure differential [$\Delta$P]) between an AIIR and the adjoining areas.

In theory, an AIIR should prevent the escape of infectious aerosols into the general hospital environment.[10] Because air moves from areas of high to low pressure, the lower pressure room is at NP with respect to the higher pressure, general hospital environment. The general ventilation system of an effective AIIR must be balanced to ensure that a greater volume of air is exhausted from rather than supplied to a room. The required difference between exhaust and supply air flows is directly related to the total leakage area in an AIIR.

## NOMENCLATURE

| | |
|---|---|
| A | leakage area |
| $A_{True}$ | true leakage area |
| $A_{Est}$ | estimated leakage area calculated from model |
| $I_U$ | upper limit of inaccuracy |
| I | actual inaccuracy |
| PL | perimeter length of the leakage area |
| a | exponent of leakage area, empirically determined |
| b | exponent of ΔQ, empirically determined |
| c | exponent of ΔP, empirically determined |
| d | exponent of PL, empirically determined |
| n | experimentally determined flow exponent (range of 0.5 to 1.0) |
| ΔQ | mechanical flow differential, $ft^3$/min |
| ΔP | pressure differential between AIIR and surrounding areas |
| $\alpha$ | leak coefficient |

*Note:* The parameters a, b, c, d, and alpha will have values that depend on the units of measurement used for the other factors in each equation.

Because AIIRs are constructed using a variety of techniques and materials, significant differences exist from one room to another. These variations make direct application of standard ventilation equations difficult at best. As a result, facility engineers and AIIR designers have few analytical tools at their disposal when establishing, validating, certifying, or balancing ΔQs. A good estimate of leakage area and an accurate ΔQ is essential to achieve NP between an AIIR and the surrounding hospital environment. HVAC technicians may face many challenges in determining whether an AIIR is operating efficiently and effectively. When AIIR ventilation parameters are designed for and balanced under static conditions, pressure changes outside the AIIR and variations in AIIR leakage area will each influence the attainable ΔP. Common AIIR leakage areas include cracks near doors and door frames, construction joints, electrical and plumbing penetrations, and degradation of airtight seals due to aging. Changes in leakage area may result from movement of elevators, the opening and closing of doors or windows in areas contiguous to the AIIR, and changes in weather.

The empirical relationship between ΔQ, ΔP, and leakage area (A) for air infiltration into a building is:[11]

$$A = \frac{\Delta Q}{\alpha(\Delta P)^n} \tag{1}$$

where $\alpha$, the leakage coefficient, depends on the leakage area geometry and the air velocity flowing through it;[12] n equals 1.0 when airflow through the leakage area is laminar and 0.5 when the airflow is turbulent.

Usually, airflow is neither completely laminar nor completely turbulent, and n is assigned a value between 0.5 and 1.0. Hairline cracks tend to have values of n equal to 0.8 or 0.9. Because airflow through cracks larger than 1/8 in. (3.18 mm) is often completely turbulent, leakage areas of this size are assigned an n value of 0.5.[11]

Equation 1 can be expanded to include interactions between perimeter length of leakage area (PL), ΔP, ΔQ, and A in AIIRs. Analytically, this relationship can be shown as:

$$A = \alpha^a \Delta Q^b \Delta P^c PL^d \tag{2}$$

where

PL = perimeter length of the leakage area
a = exponent of leakage area
b = exponent of ΔQ
c = exponent of ΔP
d = exponent of PL

Note that a, b, c, and d are all empirically determined. Equation 2, however, is not easily applied, and the data or models needed to optimize ventilation parameters for a specific NP in an isolation room are lacking. One problem is that PL or the geometry of leakage area into a room cannot be easily measured in the field. This absence of needed information has resulted in many poorly designed AIIRs in health care facilities. At best, a poorly designed AIIR may be a waste of energy; at worst it is not continuously under negative pressure and represents a risk for nosocomial disease transmission to health care workers.[7–9,13,14] In this article, a mathematical model is developed that describes the relationship between leakage area and ΔP and ΔQ. This model can be used to assist HVAC engineers in designing AIIRs.

## METHODS

Initial field studies were performed to measure ΔQ and ΔP in 67 AIIRs, at six different U.S. hospitals.[15–19] These data were used to determine proper evaluation conditions during the study's laboratory phase. The effect of leakage area on both ΔQ and ΔP was systematically examined. Data collected from a simulated AIIR were used to develop an analytical model describing total room leakage area based on ΔQ and ΔP. This analytical model was validated by subsequent field studies.

### Collection of Initial Field Data

A TSI, Inc. (St. Paul, Minn.) Model 8370 balometer was used to measure exhaust and supply airflow rates in AIIRs and adjoining bathrooms. ΔQs for each AIIR were determined using the following equation:

$$\Delta Q = \sum \text{Exhaust Flowrates} - \sum \text{Supply Flowrates} \tag{3}$$

A Neotronics (Gainsville, Ga.) Model MP20 electronic digital micromanometer was used to measure the ΔPs for the gap beneath closed doors. This instrument has a range of 0.000 to 2.000 $''H_2O$ (0.0 to 498.0 Pa) with a resolution of 0.001 $''H_2O$ (0.249 Pa).

### Collection of Laboratory Data

An experimental AIIR was constructed having a wooden frame covered by plywood sheets. The walls and ceiling were sealed with plastic film (vapor film) to minimize air infiltration.

**TABLE I. Geometric Parameters of Known Leaks**

| Configuration | Description | Area (in.$^2$) | Perimeter Length (in.) | Panel Thickness (in.) |
|---|---|---|---|---|
| 1 | Round—5.75 in. dia. | 26.0 | 18.8 | 0.20 |
| 2 | Round—6.00 in. dia. | 28.3 | 18.9 | 0.20 |
| 3 | Round—6.50 in. dia. | 33.2 | 20.4 | 0.20 |
| 4 | Round—7.00 in. dia. | 38.5 | 22.0 | 0.20 |
| 5 | Multiple (34) holes 1.15 in. diameter | 35.3 | 122.8 | 0.20 |
| 6 | 0.07 in. wide slots | 19.1 | 554 | 0.03 |
| 7 | 1/8 in. wide slots | 33.5 | 536.5 | 0.03 |
| 8 | 3/16 in. wide slots | 11.7 | 123.5 | 0.05 |
| 9 | 3/8 in. wide slots | 22 | 125.2 | 0.05 |
| 10 | Door-to-floor slot | 29.4 | 85 | 1.75 |

*Note:* The leakage areas were cut into the panels, providing measurable geometric characteristics of leakage area for the study.

The room, similar to many AIIRs, was 14 ft$^2$ (4.3 m) and had an 8-ft (2.4-m) ceiling. Areas near light fixtures, construction joints, and electrical penetrations were sealed with caulk. A 42 in. × 80 in. (1.1 m × 2.0 m) door was centered in one wall. The door was closed and sealed with duct tape. There was a gap under the door's lower edge of approximately 0.7 in.× 42 in. (0.02 m × 1.1 m).

The effect of door-slot leakage was determined by taking $\Delta$Q and $\Delta$P measurements with and without duct tape on the door's lower edge. Additional known leakage areas ($A_{True}$) were created by mounting thin aluminum panels (12 in. × 12 in. × 0.125 in. [0.30 m × 0.30 m × 0.00318 m]) in a wall opening near the door. The panels were machined to provide varying shapes and sizes of leakage areas into the AIIR. The aluminum panel's geometries are described in Table I.

## Experimental Equipment

Phoenix Controls (Newton, Mass.) Models MAV 110M and EXH 110M linearized Venturi valves automatically controlled the supply and exhaust flow rates for the AIIR in a range of 60 ft$^3$/min to 900 ft$^3$/min (28 to 430 L/sec). Centerline supply and exhaust duct velocity pressures were measured 7.5 duct diameters downstream of the nearest air disturbance with pitot tubes and a Setra (Acton, Mass.) Model 264 differential pressure transducer. The Setra pressure transducer was calibrated with a 10-point pitot traverse of the 10 in. (0.25 m) diameter supply and exhaust ducts at four volumetric flow rates.[20]

Pressure differential between the experimental AIIR and the surrounding area was measured by five Setra Model 264 differential pressure transducers having a range of ±0.100 ″$H_20$ (±24.9 Pa) $\Delta$P and an accuracy greater than 0.001 ″$H_20$ (0.2 Pa). An MKS (Andover, Mass.) Type 698 pressure transducer was used periodically to verify the results obtained by the Setra transducers and to gather data outside the range of the Setra. The MKS unit had a range of 0 to 0.535 ″$H_20$ (0 to 133 Pa), and a sensitivity of 0.0005 ″$H_20$ (0.1 Pa) per millivolt.

The low pressure side of the Setra pressure transducers was connected with 0.188 in. (4.76 mm) diameter Tygon tubing to the five locations shown in Figure 1. The ends of the tubes were enclosed in double-baffled cylinders made of perforated steel sheets (0.05 in. [1.3 mm] thick) to prevent air currents from affecting the static pressure measurements. The high-pressure ports of all transducers were interconnected and routed to the area outside of the AIIR that was maintained at atmospheric pressure. Data gathered over approximately 12 days during a 2-month period showed no bias or precision errors resulting from pressure variations in the building. These data points were collected by a Keithley Metrabyte (Taunton, Mass.) Model DAS20 data acquisition system (DAS) controlled by Labtech (Wilmington, Mass.) Notebook Pro software. Signals from the five Setra $\Delta$P transducers were averaged at a 4-Hz rate using a 45-sec time constant (900 data points averaged per $\Delta$P reading between the AIIR and surrounding area).

## Experimental Design

Based on model errors at low $\Delta$Q and upper limits of the pressure transducers, only $\Delta$Q values greater than 40 ft$^3$/min (19 L/sec) and leakage areas larger than 10$^2$ in. (6500 mm$^2$) were used to develop and evaluate the model.

Three sets of leakage area experiments were performed (Table II). Using a blocked, high/low experimental design with repetition, the empirical equation describing the relationship between $\Delta$Q and $\Delta$P was developed from the first set of experimental data. Data from the second and third sets of experiments were used to evaluate the model. The first set of experiments (see Table II) were used to examine leakage area configurations at a supply rate of 100 ft$^3$/min (47.2 L/sec) and four replicates of four exhaust settings with eight leakage areas for a total of 128 observations, ($4 \times 4 \times 8 = 128$ observations).

The second experiment was divided into five replicate blocks of two flow rates and eight leakage areas ($5 \times 2 \times 8 = 80$ observations). Within each block, the supply air was 95 ft$^3$/min (45 L/sec), and the exhaust was either 215 ft$^3$/min (102 L/sec) or 335 ft$^3$/min (158 L/sec), giving $\Delta$Q of 120 (56.6 L/sec) and 240 ft$^3$/min (113 L/sec), respectively.

The third experiment examined 10 leakage area configurations (the original eight configurations, plus two additional

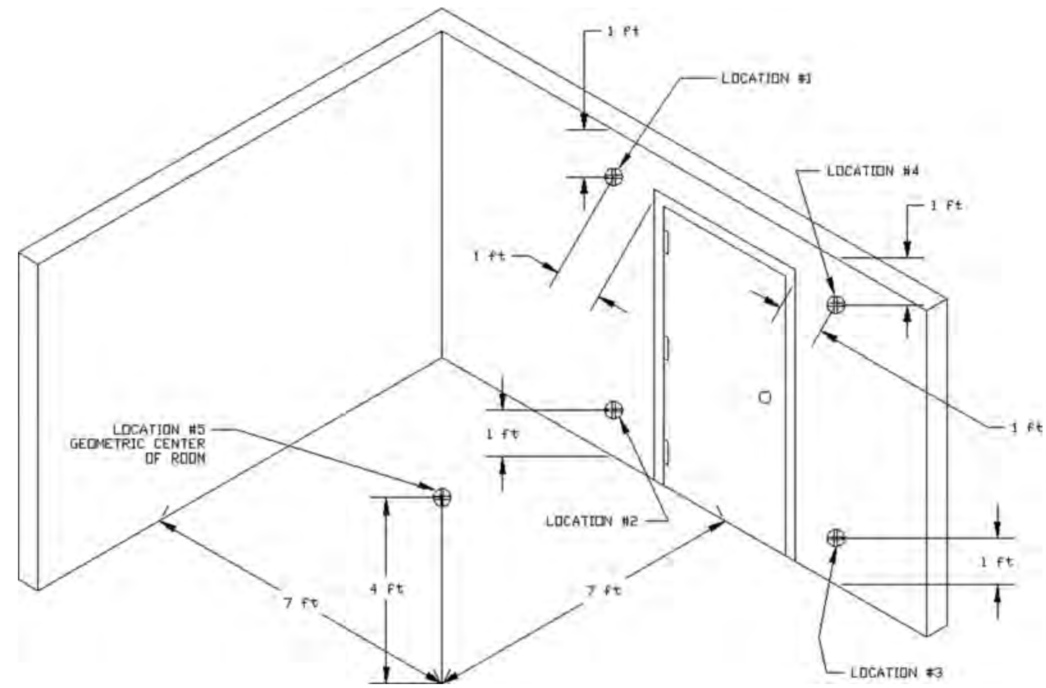


**FIGURE 1.** Differential pressure sensing location within the AIIR

configurations) at the same flow rates used in the first set of experiments. This experiment consisted of two replicate blocks: in each block the 10 configurations at the four ΔQs used in the first experiment ($2 \times 4 \times 10 = 80$ observations) were examined.

The ventilation parameters studied included

1. ΔQs from 42 $ft^3$/min to 249 $ft^3$/min (20 L/sec to 118 L/sec)
2. ΔPs from 0.001 ″$H_2O$ to 0.200 ″$H_2O$ (0.2 Pa to 50.0 Pa)
3. True or measured leakage area ($A_{True}$) from 11.7 $in.^2$ to 38.5 $in.^2$ (75.5 $cm^2$ to 248 $cm^2$)
4. Measured perimeter length from 19 in. to 554 in. (0.48 m to 14.1 m)

## Model Validation in Hospital AIIRs

Validation of the empirical model took place in 12 AIIRs located in two different hospitals.

- In Hospital A, the model was validated in six rooms (three rooms each in two unoccupied wings). The AIIRs had a multizone, constant-volume ventilation system. Each AIIR and bathroom combination had a dedicated exhaust system (100% exhaust to outside). Each was adjacent to the corridor (i.e., no anteroom or buffer zone).
- In Hospital B, the model was validated in six rooms (two rooms on each of three floors) of one unoccupied wing. All six AIIRs had constant-volume, general supply ventilation systems with dedicated constant volume exhaust systems (100% exhaust to outside). Each AIIR was adjacent to the corridor.

The NIOSH empirical model was applied to each AIIR and evaluated regarding its ability to accurately predict the estimated leakage area ($A_{Est}$). To assess the validity of the model, several steps were performed to: (1) gather baseline information, (2) seal large leakage areas of unknown magnitude,

**TABLE II. Leakage Area Experiments**

| Experiment | Leakage Configuration$^A$ | Experimental Flow Differentials ($ft^3$/min)$^B$ |
|---|---|---|
| Experiment 1—model development | 1, 2, 3, 4, 6, 8, 9, 10 | 50, 70, 90, 110 |
| Experiment 2—model evaluation | 1, 2, 3, 4, 6, 8, 9, 10 | 120, 240 |
| Experiment 3—model evaluation | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 | 50, 70, 90, 110 |

*Note:* The first experiment was used to develop the model, whereas the second and third experiments were used to evaluate the model.
$^A$See also Figure 2 and Table I.
$^B$Approximate.

and (3) introduce leakage areas of known magnitude. For each step, $\Delta Q$ and $\Delta P$ were measured.

**Step 1**. Each AIIR door leading to the corridor was closed, and the supply and exhaust flow rates in the AIIRs and adjoining bathrooms were measured using a TSI Model 8370 balometer. $\Delta Q$s were calculated using Eq. 3. Pressure differential across the closed door was measured at the door bottom with a Neotronics Model MP20 micromanometer.

**Step 2**. The side and top edges of each closed AIIR door was sealed with duct tape to eliminate large leakage areas into the AIIRs. $\Delta Q$ and $\Delta P$ were again obtained as described in Step 1.

**Steps 3–6**. With the door fully open, each AIIR doorway was sealed with a wood/plastic fixture. A leakage area panel was mounted to the fixture to introduce known leakage areas of 10 in.$^2$, 33 in.$^2$, 45 in.$^2$, and 127 in.$^2$ (65 cm$^2$, 210 cm$^2$, 290 cm$^2$, and 819 cm$^2$) near the doorway. For each of these four leakage areas, $\Delta Q$ and $\Delta P$ were measured, as described in Step 1 ($\Delta P$ measured through the sealed bottom of the fixture).

The model was used to estimate leakage area ($A_{Est}$) for each of the six steps. The $A_{Est}$ calculated in Step 1 gave an estimate of the total leakage area into each room from leakage around the door and unidentified sources, such as plumbing pass-throughs and small cracks. The $A_{Est}$ from Step 2 gave an estimate of the leakage areas from the unidentified sources. The difference between the $A_{Est}$ in Step 1 and $A_{Est}$ from the unidentified sources in Step 2 equaled the estimated leakage area ($A_{Est}$) around each door. Steps 3–6 compared the estimated leakage area for each door with the estimated leakage area from unidentified sources (found in Step 2). Thus, the known leakage area ($A_{True}$) was found by adding Step 2 $A_{Est}$ to the leakage area introduced at the door. The percent inaccuracy (%I) of the model was determined using the following equation.

$$\%I = \frac{A_{Est} - A_{True}}{A_{Est}} 100\% \quad \textbf{(4)}$$

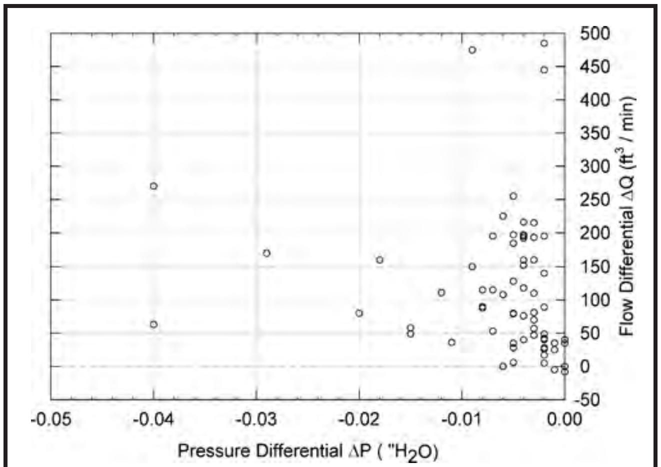


**FIGURE 2.** Pressure differential vs. flow differential scatterplot showing results of examination of AIIRs in a field study

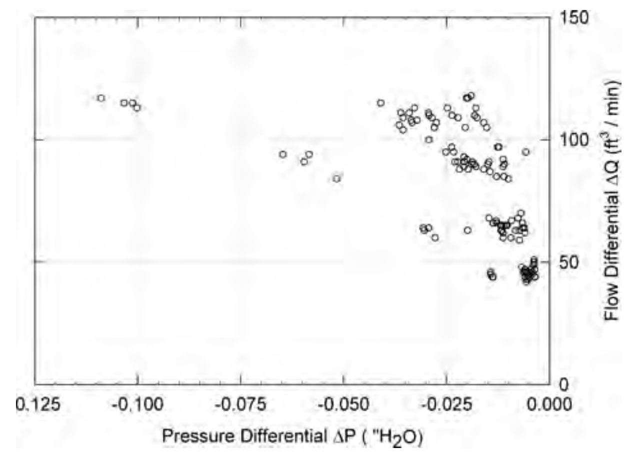


**FIGURE 3.** Scatterplot of data used to develop leakage area model

## RESULTS

### Initial Field Data Results

Values of $\Delta Q$ and $\Delta P$ measured in 67 AIIRs (as described in the Methods section) are shown in Figure 2. For all 67 AIIRs examined, the average $\Delta Q$ was 114 ft$^3$/min (54 L/sec), having a standard deviation of 105 ft$^3$/min (49.6 L/sec) over a measured range from 0 to 270 ft$^3$/min (0 to 130 L/sec). The average $\Delta P$ was equal to –.006 $''H_2O$ (–1 Pa) with standard deviation of 0.008 $''H_2O$ (2 Pa) over a measured range from 0.000 to –0.040 $''H_2O$ (0 to –10 Pa).

### Experimental Laboratory Results

Figure 3 shows the data used to develop the model, and Figure 4 shows the data used to evaluate the model accuracy. Note that the data used to assess the accuracy of the model included $\Delta Q$ and $\Delta P$ ranges outside those used to develop the model. By so doing, the scope of applicable $\Delta Q$ and $\Delta P$

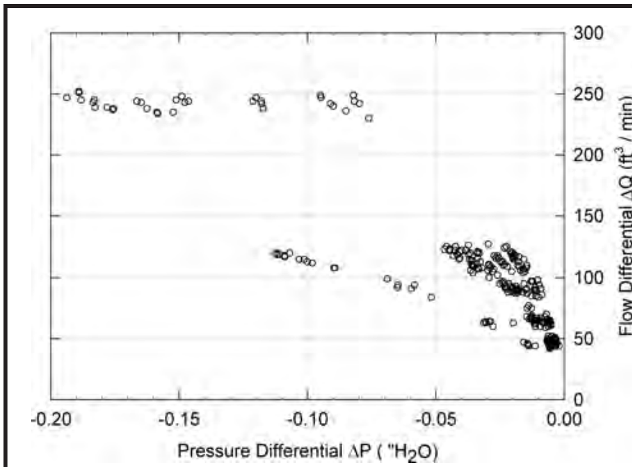


**FIGURE 4.** Scatterplot of data used to determine inaccuracy of the model

**TABLE III. Field Test of Model, Hospital A**

| Room | Step | $\Delta$P, ″$H_2O$ | $\Delta$Q($ft^3$/min) | $A_{Est}$ (in.$^2$) | Leakage Area at Door (in.$^2$) | $A_{True}$ (in.$^2$) | % Inaccuracy |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.011 | 199 | 84 | | | |
| | 2 | 0.02 | 204 | 60 | | | |
| | 3 | 0.011 | 204 | 87 | 45 | 105 | −22 |
| | 4 | 0.006 | 209 | 128 | 127 | 187 | −46 |
| | 5 | 0.015 | 204 | 72 | 10 | 70 | 2 |
| | 6 | 0.012 | 205 | 83 | 33 | 93 | −13 |
| 2 | 1 | 0.012 | 215 | 87 | | | |
| | 2 | 0.022 | 207 | 58 | | | |
| | 3 | 0.014 | 217 | 81 | 45 | 103 | −28 |
| | 4 | 0.007 | 223 | 126 | 127 | 185 | −47 |
| | 5 | 0.017 | 209 | 69 | 10 | 68 | 0.7 |
| | 6 | 0.014 | 218 | 81 | 33 | 91 | −12 |
| 3 | 1 | 0.008 | 196 | 100 | | | |
| | 2 | 0.015 | 196 | 69 | | | |
| | 3 | 0.009 | 200 | 95 | 45 | 114 | −19 |
| | 4 | 0.006 | 204 | 125 | 127 | 196 | −57 |
| | 5 | 0.014 | 195 | 71 | 10 | 79 | −11 |
| | 6 | 0.013 | 196 | 75 | 33 | 102 | −36 |
| 4 | 1 | 0.006 | 192 | 116 | | | |
| | 2 | 0.01 | 177 | 78 | | | |
| | 3 | 0.006 | 187 | 113 | 45 | 123 | −9 |
| | 4 | 0.004 | 204 | 159 | 127 | 205 | −29 |
| | 5 | 0.009 | 177 | 83 | 10 | 88 | −6 |
| | 6 | 0.007 | 187 | 103 | 33 | 111 | −8 |
| 5 | 1 | 0.006 | 221 | 137 | | | |
| | 2 | 0.01 | 217 | 99 | | | |
| | 3 | 0.007 | 220 | 124 | 45 | 144 | −16 |
| | 4 | 0.004 | 223 | 177 | 127 | 226 | −28 |
| | 5 | 0.01 | 218 | 99 | 10 | 109 | −10 |
| | 6 | 0.007 | 222 | 126 | 33 | 132 | −5 |
| 6 | 1 | 0.012 | 225 | 92 | | | |
| | 2 | 0.018 | 219 | 70 | | | |
| | 3 | 0.012 | 226 | 93 | 45 | 115 | −24 |
| | 4 | 0.008 | 251 | 134 | 127 | 197 | −47 |
| | 5 | 0.017 | 224 | 74 | 10 | 80 | −8 |
| | 6 | 0.014 | 231 | 87 | 33 | 103 | −19 |

ranges for the model were expanded, providing a conservative estimate of the model accuracy. Any trends noted in Figure 4 are the result of changing leakage areas for different test runs using the same $\Delta$Q.

## Model Development

Measured values of $\Delta$Q and $\Delta$P from the first experiment were log-transformed to provide a normal data distribution. A backward regression analysis was performed on the log-transformed data to determine $A_{Est}$. The model must be sensitive and specific, that is, it should estimate the leakage area and be sensitive to only leakage area and no other variable. This was tested by fitting the "best" model of known leakage area, known perimeter length, and known flow and pressure differential to predict the estimated leakage area. The method of selecting the "best" model was by the Mallow's $C_P$ method. This method provides a convenient criterion for determining whether a model is improved by adding or removing predictor variables.[21] This method was used to determine and subsequently drop insignificant variables such as air changes per hour early in the analysis. The model was then solved for log($A_{Est}$) so that the right-hand side included only observable variables (the exception being the perimeter length of the leakage area [PL], which cannot be observed or found in the field). The anti-log, or exponent of the variable, was then solved to produce the leakage area model, which can

**TABLE IV. Field Test of Model, Hospital B**

| Room | Step | ΔP, ″$H_2O$ | ΔQ ($ft^3$/min) | $A_{Est}$(in.$^2$) | Leakage Area at Door (in.$^2$) | $A_{True}$(in.$^2$) | % Inaccuracy |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.008 | 165 | 82 | | | |
| | 2 | 0.018 | 170 | 52 | | | |
| | 3 | 0.017 | 165 | 52 | 10 | 62 | −19 |
| | 4 | 0.011 | 168 | 69 | 33 | 85 | −23 |
| | 5 | 0.01 | 225 | 103 | 45 | 97 | 6 |
| | 6 | 0.003 | 173 | 156 | 127 | 179 | −15 |
| 2 | 1 | 0.011 | 122 | 47 | | | |
| | 2 | 0.019 | 106 | 29 | | | |
| | 3 | 0.014 | 119 | 40 | 10 | 39 | 2 |
| | 4 | 0.008 | 134 | 64 | 33 | 62 | 3 |
| | 5 | 0.008 | 134 | 64 | 45 | 74 | −15 |
| | 6 | 0.003 | 160 | 143 | 127 | 156 | −9 |
| 3 | 1 | 0.014 | 146 | 51 | | | |
| | 2 | 0.028 | 105 | 23 | | | |
| | 3 | 0.023 | 125 | 31 | 10 | 33 | −4 |
| | 4 | 0.013 | 148 | 54 | 33 | 56 | −4 |
| | 5 | 0.012 | 148 | 56 | 45 | 68 | −2 |
| | 6 | 0.004 | 178 | 136 | 127 | 150 | −1 |
| 4 | 1 | 0.007 | 136 | 71 | | | |
| | 2 | 0.009 | 123 | 54 | | | |
| | 3 | 0.008 | 133 | 64 | 10 | 64 | −1 |
| | 4 | 0.005 | 139 | 89 | 33 | 87 | 2 |
| | 5 | 0.005 | 140 | 90 | 45 | 99 | −11 |
| | 6 | 0.003 | 152 | 134 | 127 | 181 | −35 |
| 5 | 1 | 0.007 | 128 | 66 | | | |
| | 2 | 0.01 | 116 | 47 | | | |
| | 3 | 0.008 | 126 | 60 | 10 | 57 | 5 |
| | 4 | 0.006 | 141 | 81 | 33 | 80 | 1 |
| | 5 | 0.006 | 133 | 76 | 45 | 92 | −21 |
| | 6 | 0.003 | 153 | 135 | 127 | 174 | −29 |
| 6 | 1 | 0.005 | 135 | 86 | | | |
| | 2 | 0.008 | 146 | 71 | | | |
| | 3 | 0.007 | 140 | 73 | 10 | 81 | −11 |
| | 4 | 0.005 | 140 | 90 | 33 | 104 | −16 |
| | 5 | 0.004 | 141 | 103 | 45 | 116 | −13 |
| | 6 | 0.002 | 158 | 179 | 127 | 198 | −11 |

be stated as:

$$A_{Est} = 0.00888\frac{\Delta Q^{1.278}}{\Delta P^{0.658} PL^{0.0916}} \quad \textbf{(5)}$$

having an adjusted coefficient of determination, $R^2$, of 0.90. Units for $A_{Est}$ are in square inches. The constant, 0.00888, is a combination of unit conversion factors (for British units) and leakage coefficient effects, where ΔQ, ΔP, and PL are in $ft^3$/min, ″$H_2O$, and inches respectively.

Although Eq. 5 has four variables (ΔP, ΔQ, leakage area, and perimeter length), an assumed value for PL (in the form of a PL to $A_{Est}$ ratio) was used because only two of the variables (ΔP and ΔQ) were measured in the field. The PL/$A_{Est}$ ratio was used to increase model accuracy. The model is valid for perimeter length to area (PL/$A_{Est}$) ratios of 0.5 in.$^{-1}$ to 29 in.$^{-1}$, which is within the range of the 10 tested configurations and reasonable for most applications.(11) Substituting PL=6$A_{Est}$ (6 in.$^{-1}$ is the arithmetic average of the ΣPL/Σ$A_{True}$ used in the model development) in the model and solving for $A_{Est}$ yields:

$$A_{Est} = 0.01138\frac{\Delta Q^{1.170}}{\Delta P^{0.602}} \quad \text{British Units} \quad \textbf{(6)}$$

$$A_{Est} = 4.891\frac{\Delta Q^{1.170}}{\Delta P^{0.602}} \quad \text{SI Units} \quad \textbf{(6a)}$$

**TABLE V. Comparison of Ranges of %I**

| | Lower Limit of %Inaccuracy | Upper Limit of %Inaccuracy | Number of Tests Within Reported Range/Number of Tests Performed |
|---|---|---|---|
| Reported range[A] | −38 | +22 | |
| Hospital A | −57 | +2 | 20/24 |
| Hospital B | −35 | +7 | 24/24 |

*Note:* Model % inaccuracy when applied to field environment in comparison with the %I developed in the statistical evaluation of data obtained in the laboratory environment.
[A]As developed in the statistical evaluation of the model.

where SI units of $A_{Est}$, $\Delta Q$, $\Delta P$ are $cm^2$, L/sec, and Pa, respectively.

### Statistical Evaluation of the Model

Statistical evaluation of the model was conducted for the $\Delta Q$, $\Delta P$, and leakage area values shown in Tables I and II and Figure 4. All data used to evaluate the model were independent of those used to develop the model. Estimated leakage areas were compared with known leakage areas.

NIOSH accuracy criteria (NAC) describe methods for establishing and interpreting the inaccuracy of an analytical model.[22–25] Inaccuracy (I) is a combination of bias and precision errors.[26] Ten configurations established the upper limit of leakage area inaccuracy ($I_U$) as 28% (Eq. 3 had an $I_U \leq$ 26%), having a 95% upper confidence limit.

The relationship of $A_{Est}$ to $A_{True}$ is

$$A_{True}(1 - I) \leq A_{Est} \leq A_{True}(1 + I) \tag{7}$$

which, for $I = 0.28$ and multiplying respective probabilities ($0.95 * 0.95 = 0.90$), gives:

$$\frac{A_{Est}}{1.28} \leq A_{True} \leq \frac{A_{Est}}{0.72} \tag{8}$$

with 90% probability. Hence, there is 90% confidence that the true leakage area is at least 78% and no more than 139% of the estimate (i.e., if $A_{Est} = 10$, then $7.8 \leq A_{True} \leq 13.9$, with 90% confidence).

### Field Use of the Model

Tables III through V provide data that shows how the model is used to estimate leakage area. Table III shows measured $\Delta Q$ and $\Delta P$, calculated $A_{Est}$, magnitude of the leakage area introduced at the doorway, calculated $A_{True}$ ($A_{Est}$ from Step 2 plus leakage area introduced at the door), and calculated %I of the model, for each of the last four steps of the evaluation, for the six AIIRs examined at Hospital A. At Hospital A, the field verification of the model yielded %I within the range expected in 20 of the 24 tests. Table IV shows similar results from Hospital B, where field verification of the model yielded %I within the range expected in 24 of the 24 tests. Table V provides the ranges of %I at each hospital in comparison with the expected range of %I found in the statistical evaluation (using lab data) of the model.

### Curves of Constant Leakage Area

Equation 6 was used to plot the constant leakage area curves shown in Figure 5. The scatterplot overlay gives the data points used to develop and evaluate the model in the laboratory. The shaded portion of the graph illustrates the general range of the leakage areas, $\Delta Q$, and $\Delta P$ that were examined in the laboratory. Most of the field data (Tables III, IV) used to validate the model was outside of the shaded area, and the model still performed well. If values outside the shaded area are used, the model will likely be less accurate than using operational values from inside of the shaded area.

## DISCUSSION

Data collected during the initial field surveys were consistent with previous studies indicating problems with AIIRs. The initial surveys revealed that approximately 4 of 67 AIIRs (6%) were not under negative pressure. The flow differential was below 50 $ft^3$/min (24 L/sec) in all 4 AIIRs not under negative pressure. The 63 AIIRs that were under NP had a wide range of $\Delta P$ and $\Delta Q$ values, thus indicating additional ventilation balance problems. Some rooms had a high $\Delta P$ and a low $\Delta Q$; others had a low $\Delta P$ and a high $\Delta Q$. Ideally, AIIRs should have as small a $\Delta Q$ as possible yet operate with a $\Delta P$ of at least 0.01 ″$H_2O$ (2 Pa) to operate effectively.[10] If AIIRs have a low $\Delta Q$ with a corresponding high $\Delta P$, they must have relatively small leakage areas in order to be operating that efficiently. American Institute of Architects currently recommend a $\Delta P$ of 0.01 ″$H_2O$ (2 Pa).[27] Likewise, CDC has revised their guidelines to recommend operation of AIIRs with an increased $\Delta P$ of 0.01″$H_2O$ (2 Pa).

The model accurately predicted the leakage area in 44 of 48 cases. As the door's leakage area increased, the model became less accurate and underestimated the true leakage area. The four cases where the model did not accurately predict the leakage area involved relatively large leakage areas where use of the balometer may have accounted for the discrepancy. One study shows that field use of the balometer can account for flow rate measurement errors on the order of 30–40%.[28]

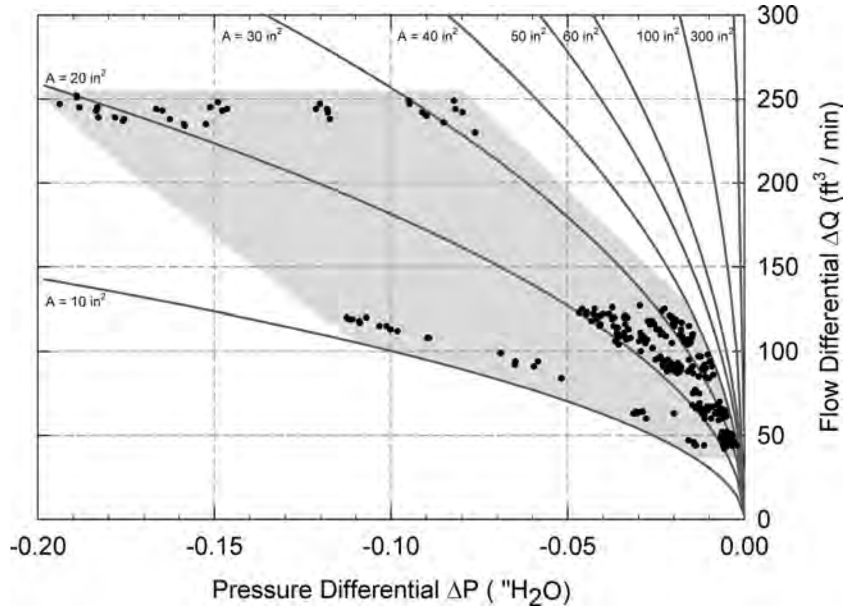


**FIGURE 5.** Curves of constant leakage area on a pressure differential vs. flow differential. *Notes:* (1) Do not decrease exhaust flow rate to less than recommended ACH rate, regardless of flow differential. (2) Shaded portion of the graph illustrates the range within which actual values ΔQ, ΔP, and leakage (A) were examined.

Statistical analysis of the model showed that as much as 26% of the 28% model error was likely due to errors in the flow rate measurements. This is likely a result of the large variation in field measurements made using the balometer.

Table V shows that the model tends to underestimate the leakage area. This may be caused by large leakage areas dominating the smaller ones as more leakage is introduced (in the final four steps of the field evaluation). Leakage area thickness, or depth, may have influenced the model. However, this effect on the leakage area calculation was probably small in comparison to the effect of ΔP, ΔQ, and PL.

## CONCLUSIONS AND RECOMMENDATIONS

The current CDC guidelines recommend a minimum ΔP of 0.01 ″$H_2O$ to maintain proper directional control of airflow into an AIIR. Wind effects, elevator movement, or even the eddies caused by a person passing outside an AIIR door could alter this ΔP.[9,11] Intuitively, the larger the ΔP, the more effective the AIIR ventilation will be in containing airborne contaminants within a room, as the ΔP is less likely to become neutral or positive in response to the external events. However, increasing ΔP may also increase operating expenses. Reducing leakage areas could help to minimize the economical impact of increased ΔP and will certainly increase the effectiveness of the AIIR to prevent airborne contaminants from escaping from the room.

Identification and elimination of excessive leakage areas will decrease the operating expenses incurred by a facility. The ventilation parameters selected for efficient operation of an AIIR ventilation system are subjectively determined on the basis of regional climate, type of HVAC system, energy costs, etc. Reducing the volume of makeup air required by lowering exhaust flow rates will save money. Even more money may be saved when considering the increased effectiveness of the AIIR in preventing the transmission of airborne disease and the cost associated with treating even one preventable disease. These decisions must be made with a thorough understanding of the relationships between leakage area, ΔP, and ΔQ. Similarly, the air changes per hour (ACH) in a room must meet the current guidelines of $\geq$12 mechanical ACH with $\geq$2 ACH from outdoors.[29]

The model should be used to estimate and change leakage areas when designing, constructing, or renovating AIIRs. It can also be used to examine the effects of building aging, including settling and degradation of airtight seals, and the degree of wear on ventilation equipment and control systems. When the model is used to periodically evaluate AIIR ventilation systems, a constant flow differential should be established prior to changing leakage areas. Automatic flow rate controls and variable air volume systems should be overridden to provide constant volume ventilation rates.

Diffuser, grill size, and its location in an AIIR should be compatible with standard field measuring devices (e.g., flow hoods). Installation of radiators, recirculation units, and other equipment that may hamper airflow measurements should be avoided in the area of the diffuser/grill. If this is not possible, in-duct and permanently mounted ventilation flow rate equipment should be used. By examining methods for establishing the magnitude of leakage areas, corrective action may be taken to minimize the ineffective and inefficient effect of these leakage areas in AIIRs. Reducing leakage areas in the AIIR will minimize the effect of elevator movement, or opening and closing of doors or windows, or weather effects on ΔP.

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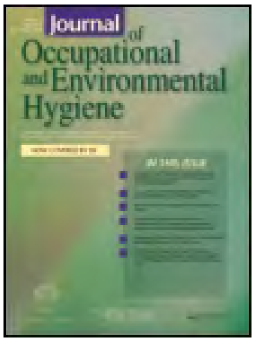

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# Development of an Empirical Model to Aid in Designing Airborne Infection Isolation Rooms

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