# PREVENTING TRANSMISSION OF TUBERCULOSIS IN HEALTH CARE FACILITIES: AN ENGINEERING APPROACH


## ABSTRACT

*In recent years, the transmission of tuberculosis in health care facilities (nosocomial transmission) has reached epidemic proportions. These transmissions have included outbreaks of multidrug-resistant strains of Mycobacterium tuberculosis that have produced many deaths. Preventing transmission of TB in health care facilities requires a comprehensive program including effective identification, isolation, and treatment of infected persons, specific ventilation, general ventilation, personal respiratory protection and surveillance of health care workers. Epidemiology, transmission and pathogenesis of TB are discussed to provide a framework for understanding the disease. The engineering aspects of hospital facility design related to controlling TB are outlined including general and specific ventilation, air filtration, ultraviolet germicidal irradiation, isolation suite design and room pressure control strategies. For engineers and other professionals not directly related to the medical profession, definitions are included as an appendix to familiarize the reader with the terminology found in the extensive references.*

## INTRODUCTION

Tuberculosis, the *White Plague* or *Consumption* was almost unheard of in the United States for over thirty years. Although TB was responsible for as many as one third of the deaths of U.S. citizens between the ages of 25 and 45 at the turn of the century, steady declines in the number of reported cases of the disease between 1953 and 1964 has led many to believe that this disease had been eradicated from the country.[1] Indeed, many young people these days have not even heard of TB and the memory of TB sanitariums remains a distant memory to those in the baby boomer generation. Globally, TB still has a higher mortality rate than any other single infectious disease and is responsible for approximately 3 million deaths per year.[2] In developing nations, 26% of avoidable adult deaths are attributed to TB. Recently, even in the U.S., reported cases of TB are on the rise for the first time in a generation. More alarmingly, the percentage of multidrug-resistant strains of the disease is also increasing.[3]

Old prevention and treatment practices are being relearned, and new practices, techniques and technologies are being brought to bear against this disease. The engineering community is playing an increasingly important role in the fight against the spread of TB, especially in health care facilities. This paper is intended as an overview of the disease and the engineering practices and technology required for control of it. The references and bibliography contain many citations worthy of study by those intending to engage this enemy.

## JUST HOW BAD *IS* THE SITUATION?

The following quotes from medical and scientific journals reveal that TB, and especially multidrug-resistant TB, is a clear and present danger in health care facilities, especially to susceptible patients and health care workers.

> "A 1992 study found that 10% of patients in a large hospital's HIV unit had TB, and that *half had acquired the infection since admission.* More than half the nurses working on the same floor had a positive tuberculin test, indicating they were infected with the bacterium. *The study also found inadequate air flow in the unit, which would spread the bacterium to other patients*...Some

of these outbreaks have involved multidrug-resistant strains of TB with *extremely high mortality*" (emphasis mine).[4]

"In May 1989, *all 17 [Health Care Workers]* who worked in the HIV unit [of a large public teaching hospital in San Juan, Puerto Rico], who by verbal history had a negative purified protein derivative (PPD) tuberculin skin test at the time of employment, reportedly tested positive. *This finding suggested that TB transmission was occurring at the hospital* (emphasis mine).[5]

"The CDC found up to 15% of TB cases resistant to at least one antituberculous drug. Up to 4% of cases may be resistant to isoniazid and rifampin, the top two choices in treating TB."[6]

"One-third of all cases tested in a New York City survey in 1991 were resistant to one or more drugs. The case fatality rate for TB resistant to two or more major antibiotics (multidrug resistance) is 40 to 60%, *equivalent to untreated TB* (emphasis mine).[7]

## TB: AN OVERVIEW

### What is TB?

TB is bacterial infection caused by rodlike organisms called *Mycobacterium tuberculosis, Mycobacterium bovis, and Mycobacterium africanum,* also called tubercle bacilli. It is most often found in the lungs, although the bones and other organs may also be affected.

### Who is at risk of TB infection?

Certain groups of people are more likely to contract TB than others due to demographics or other factors. These include HIV infected individuals, health care workers, persons living in the same households or in frequent contact with TB infected individuals or individuals from certain demographic groups that have a high incidence of TB. These groups include Blacks, Asians, Pacific islanders, native Americans, Alaskan natives, Hispanics, current or past prison inmates, alcoholics, intravenous (IV) drug

users, the elderly, and foreign born persons from areas of the world with a high prevalence of TB (e.g., Asia, Africa, the Caribbean, and Latin America).[8,9]

### Who is at risk of progression from a latent TB infection to active TB?

Like above, certain groups of people are more likely to progress to an active TB infection from a latent condition once the disease is contracted. These include individuals with the following conditions: HIV infection, silicosis, status post gastrectomy or jejuno-ileal bypass surgery, being more than 10 pounds below ideal body weight, chronic renal failure, diabetes mellitus, immunosuppression due to receipt of high-dose corticosteroid or other immunosuppressive therapy, some malignancies, recent infection with TB (in the last two years), fibrotic lesions on chest radiograph, and children under the age of 5 years.[8,9]

### TB Transmission:

TB is transmitted via the air through inhalation. *Mycobacterium tuberculosis* is carried in airborne particles known as droplet nuclei that can be generated when persons with pulmonary or laryngeal tuberculosis sneeze, cough, speak, spit, or sing. Droplet nuclei may also be generated by medical procedures such as respiratory therapy (AP), bronchoscopy, endotracheal intubation, open abscess irrigation, and autopsy. The droplet nuclei are so small (1-5 μm) that they can be suspended indefinitely in the air and be spread throughout a facility by the HVAC system. The probability that a susceptible person will become infected with *Mycobacterium tuberculosis* depends primarily upon the concentration of infectious droplet nuclei in the air and the exposure duration. Unlike other airborne diseases (such as Legionella pneumophilla) which require large aerosolized colonies of bacteria to produce an infection, TB exposure has no TLV. It has been demonstrated that one TB bacillus is enough to infect humans.[8,9]

### Environmental factors that enhance the likelihood of TB transmission:

There are three major environmental factors that can facilitate TB transmission. The first is exposure of susceptible persons to an infectious person in relatively small enclosed spaces like hospital patient or treatment rooms. The second is inadequate local or general ventilation that results in

insufficient dilution and/or removal of infectious droplet nuclei. The third is recirculation of air containing infectious droplet nuclei without adequate filtration or disinfection. Eliminate these, and the risk of transmission of TB is significantly reduced.[8,9]

## METHODS OF INFECTION CONTROL

The Centers for Disease Control acknowledge four major methods of TB infection control.

**Early identification, isolation and treatment of persons with active TB.** This is the foundation of all infection control programs. Isolation and treatment are impossible without proper (and early) identification of those infected.[9]

Engineering Controls: These are the engineering methods, systems, and equipment required to accomplish the *isolation* mentioned above and usually involve the following five areas: source control (during procedures that can produce large quantities of droplet nuclei, i.e., sputum induction chambers); directional airflow to provide continuous flow from the *cleaner* to the *dirtier* parts of the facility; room pressure controls to prevent contamination of areas adjacent to infection sources; general ventilation to dilute and remove contaminated air; air cleaning via HEPA filtration; and ultraviolet germicidal irradiation (UVGI).[9] All these will be covered in more detail to follow.

**Personal respirators:** These are special valveless filtered face masks which prevent the passage of particles larger than one µm. They are required by OSHA, under certain circumstances, to protect health care workers exposed to patients with active TB during high-risk medical procedures such as sputum induction. They may also be used for "isolation" of TB patients during intra- and inter-facility transport when outside infectious isolation facilities or when they are unavailable.[9,10]

**Surveillance of health care workers for TB infection.** This is a necessary part of all TB infection control programs. It can indicate the spread of infection throughout a facility and indicate closer surveillance of workers who have positive TB tests.[9]

## SOURCE CONTROL

The use of local exhaust ventilation to remove airborne contaminants at or near their source is an effective infection control measure and should be used whenever possible. There are four types of source control ventilation devices that are commonly used. Two are capture-type, and two are the enclosing type of hood.

Figure 1A shows a capture device that is designed to intercept infectious nuclei expelled from an infected person before it can escape into the room air. This device is a classical rectangular opening type of capture hood, its characteristics and design information can be found in Ref. 12. In the configuration shown in the figure, it is similar to a laminar-flow hood only operated in reverse. Instead of the filtered air being forced through HEPA filters, over the work surface and out of the hood, air is drawn into the hood, through the filters and then exhausted by a fan either back into the room or outside the building. The longer the top and sides of this device, the better it will work. Ideally the top and sides should extend far enough that, when seated, the head of the person using the hood is inside the device. In this case, the contaminant is already "captured" as it is released and containment is all that is necessary. If the top and sides of this device are omitted, the volume and face velocity required are much higher to overcome room air currents and capture the droplet nuclei as they are released.

Figure 1B shows a typical laboratory fume hood. These capture devices should be used in clinical laboratories when working with BLII level materials such as *Mycobacterium tuberculosis*. Information about the design, application and use of laboratory fume hoods can be found in Refs. 18-19.

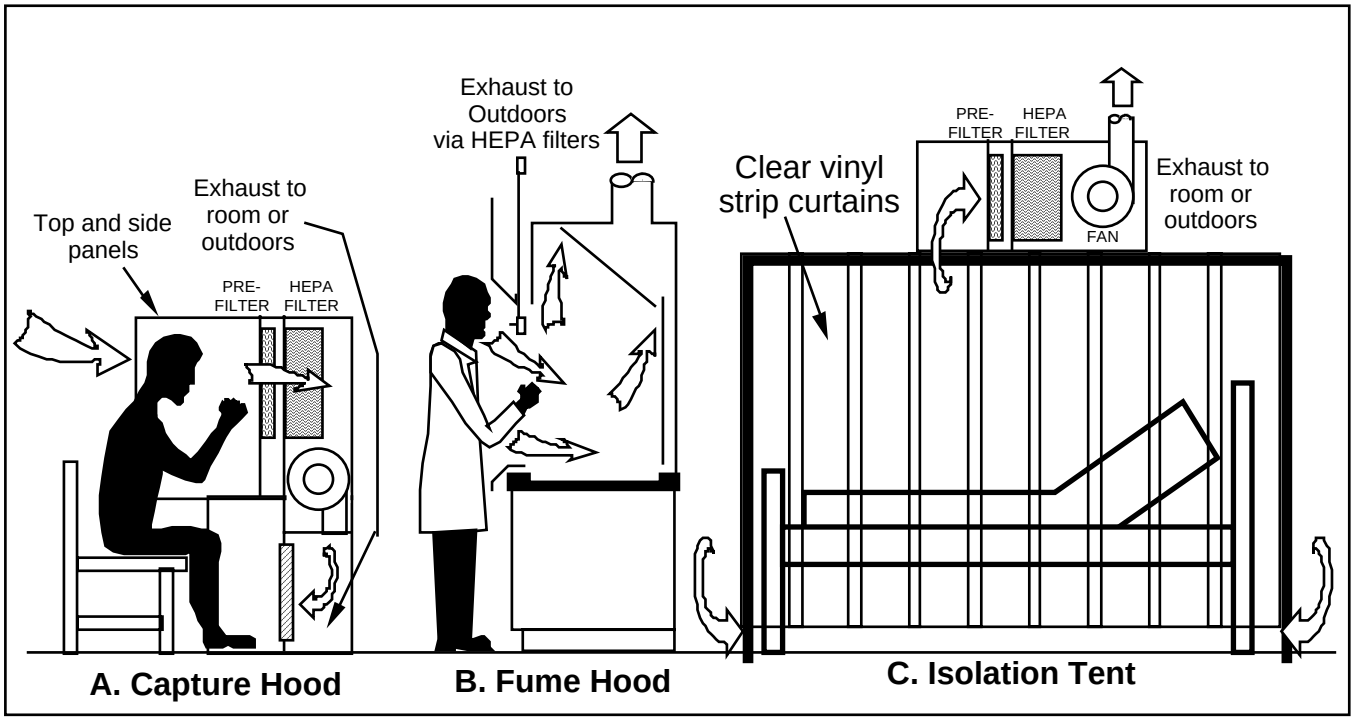


***Figure 1*** Three methods of source control via specific ventilation

Figure 1C shows an isolation tent which is an enclosing type of source control device. This is usually a plastic enclosure with a metal frame to support the tent and air moving equipment. They have an arrangement similar to negative-pressure enclosures that are used for asbestos abatement. They are similar also to soft-side clean room enclosures except that the airflow is reversed. They are used most often around the patient's bed or other areas for use during high-risk procedures.

Figure 2 shows two different configurations of enclosing type devices called sputum induction chambers or AP administration booths. These are enclosures in which the infected subject sits to undergo certain cough-inducing procedures such as sputum induction or AP administration. They are to be maintained at a negative-pressure with respect the surrounding area at all times. The top figure shows an upflow arrangement where fresh air is drawn into the enclosure through filters in the side of the chamber, up through the cabinet, through HEPA filters and is exhausted. The bottom figure shows a downflow arrangement where fresh air enters the cabinet through filters at the top, down past the patient and is exhausted near the floor of the cabinet. The air exhausted can be discharged into the room or outside the building.

Sputum induction chambers are manufactured by several companies as an engineered product. Most are completely self-contained. Some have wheels that allow easy relocation and their size permits them to be moved through standard doorways. Power is usually provided to the unit through a chord that plugs into an outlet in the room in which the chamber is located. Most have gauges and other diagnostic devices to evaluate the performance of the fan and filter system. Some have auxiliary power outlets and fold out tables on the outside of the unit to facilitate the use of the medical equipment required for the procedure.

The exhaust volume of the enclosing type devices should be designed to remove 99% of the airborne particles during the interval between the departure of one patient and the arrival of the next. See Table 1 which shows air change rates for removal of particulates from a space.

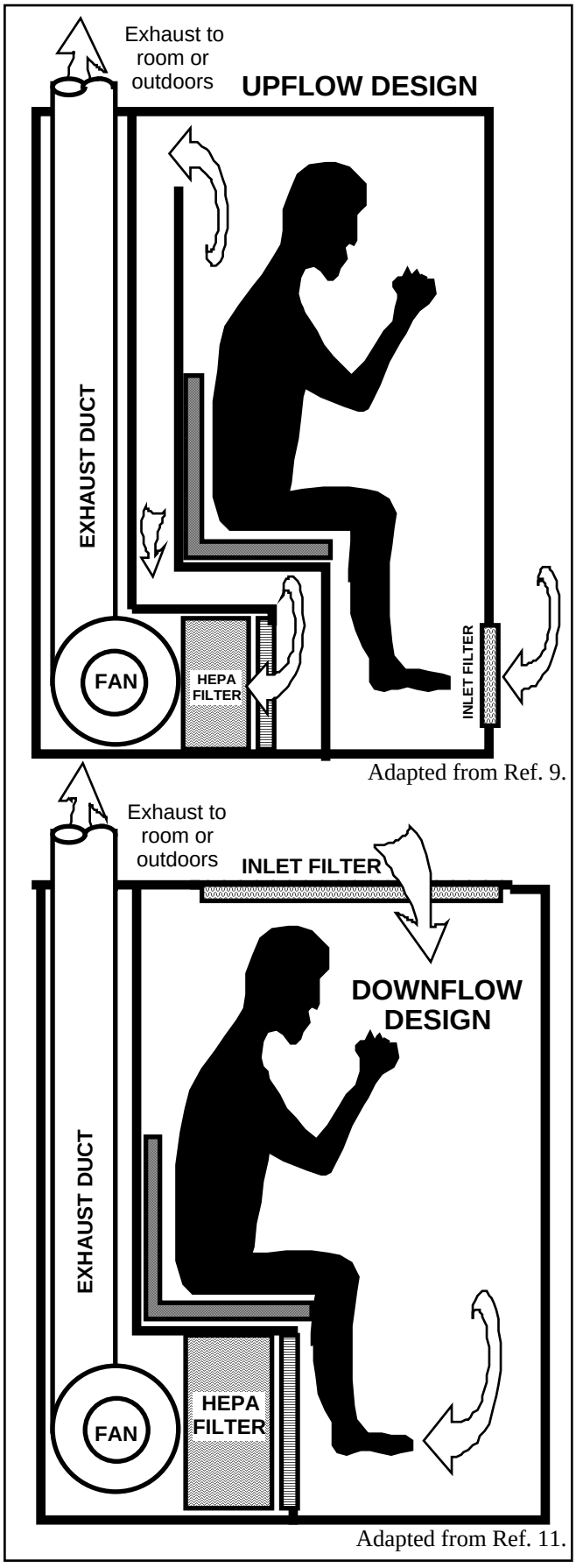


***Figure 2*** Sputum induction chamber designs

## TABLE 1
## Air Change Rates and Removal Efficiencies of Airborne Contaminants

| Air Changes Per Hour | Minutes Required For: 90% Removal | 99% Removal | 99.9% Removal |
|---|---|---|---|
| 1 | 138 | 276 | 414 |
| 2 | 69 | 138 | 207 |
| 3 | 46 | 92 | 138 |
| 4 | 35 | 69 | 104 |
| 5 | 28 | 55 | 83 |
| 6 | 23 | 46 | 69 |
| 7 | 20 | 39 | 59 |
| 8 | 17 | 35 | 52 |
| 9 | 15 | 31 | 46 |
| 10 | 14 | 28 | 41 |
| 12 | 12 | 23 | 35 |
| 14 | 10 | 20 | 30 |
| 16 | 9 | 17 | 26 |
| 18 | 8 | 15 | 23 |
| 20 | 7 | 14 | 21 |
| 25 | 6 | 11 | 17 |
| 30 | 5 | 9 | 14 |
| 40 | 3 | 7 | 10 |
| 50 | 3 | 6 | 8 |

This table was prepared according to the following formula:

$t_2 = (-\ln(C_2 / C_1) \cdot (V / Q) \cdot (60) \cdot (k)$

It is an adaptation of the formula for the rate of decay of airborne contaminants where:

time $t_1 = 0$

time $t_2$ = minutes to achieve x% dilution

mixing constant k = 1 (assumes perfect mixing.)

$C_2 / C_1 = 1 -$ (removal efficiency / 100)

V = volume of room

Q = ventilation rate

Adapted from Refs. 9,12.

Autopsy procedures can generate infectious droplet nuclei. The use of an isolation type autopsy room with differential pressure controls, an isolation tent enclosing the autopsy table, or the combination of personal respirators and a ventilated downdraft table is recommended when performing autopsies on decedents who had active TB.

As mentioned previously, when moving an infected patient from one location to another in the hospital, a personal respirator may be used to capture droplet nuclei exhaled or expelled through coughing. This method, however, has very limited uses and is not recommended for long periods or as a substitute for other types of engineered isolation.

## GENERAL VENTILATION

The classical purpose of general ventilation is to dilute and remove contaminants generated in the space. For hospital isolation rooms, this rate is usually measured in air changes per hour (ACH). Recommended ventilation rates and pressure relationships for hospital isolation rooms is shown in Table 2. Information has been taken from several sources, and the recommended ventilation specifications vary depending upon the reference. Note that in all cases, these ventilation rates assume perfect (ideal) mixing in the space. This actually never occurs under actual conditions. The mixing constant (k) in the equation shown in Table 1 is usually in the range of 1- to- 10.[12] Proper selection and location of the room supply diffusers and exhaust grilles can enhance room convection and ventilation effectiveness. Computer tools such as computational fluid dynamics (CFD) can be used to optimize room convection and capture of contaminants in an isolation suite and should be considered during design. The actual mixing constant may be approximated by this technique as well.

## TABLE 2

## Isolation Room Ventilation Rates

| CDC Guidelines [9] | Pressure Relationship to Adjacent Spaces | Minimum Air Changes of Outdoor Air Per Hour | Minimum Total Air Changes Per Hour | All Air Exhausted Directly to Outdoors? | Recirculation of Air Within Rooms Allowed? |
|---|---|---|---|---|---|
| **Infectious Isolation Room** (in existing facilities) | ⊖ | — | 6 | YES | OPT [C] |
| **Infectious Isolation Room** (in new facilities) | ⊖ | — | 12 | YES | OPT [C] |
| **ASHRAE '95 Appl. Hbk.** [13] | | | | | |
| **Infectious Isolation Room** [A] | ⊖ | 2 | 6 [B] | YES | NO |
| **Protective Isolation Room** [A] | ⊕ | 2 | 15 | YES | OPT [C] |
| **Isolation Room Anteroom** [A] | ± | 2 | 10 | YES | NO |
| **AIA/DHHS Guidelines** [14] | | | | | |
| **Infectious Isolation Room** [A] | ⊖ | 1 | 6 | YES | NO |
| **Protective Isolation Room** [A] | ⊕ | 1 | 6 | — | NO |
| **Isolation Room Anteroom** [A] | ± | — | 10 | YES | NO |
| **CA Mech. Code '93 Rev.** [15] | | | | | |
| **Neg. Press. Isolation Room** [A] | ⊖ [D] | 2 | 10 | YES | NO |
| **Neg. Press. I/R Anteroom** [A] | ⊕ [E] | 2 | 10 | YES | NO |
| **Pos. Press. Isolation Room** [A] | ⊕ [F] | 2 | 15 | — | NO [C] |
| **Pos. Press. I/R Anteroom** [A] | ⊖ [G] | 2 | 15 | — | NO [C] |

[A] Consult the references for a more detailed treatise on this type of isolation room.

[B] Where highly infectious respirable diseases such as TB are to be isolated, increased air changes should be considered.

[C] Recirculation of air within these rooms may be allowed if it is HEPA filtered.

[D] The isolation room shall be negative to the anteroom and positive to adjoining toilet room.. The suite shall be neutral to the corridor.

[E] The anteroom shall be positive to the isolation room.

[F] The isolation room shall be positive to both the anteroom and toilet room. The suite shall be neutral to the corridor.

[G] The anteroom shall be positive to the isolation room.

## DIRECTIONAL AIRFLOW

This is a technique of isolating an entire area of a building from the rest of the facility. This is usually used for a group of isolation rooms or a ward for infectious patients. A net negative air balance is established in the *dirty* area causing airflow to move in the direction from the *clean* to the *dirty* area. If the two areas can be physically separated by a set of doors, or even a double set of doors, this barrier effect is further enhanced. See figure 3 which shows this concept.

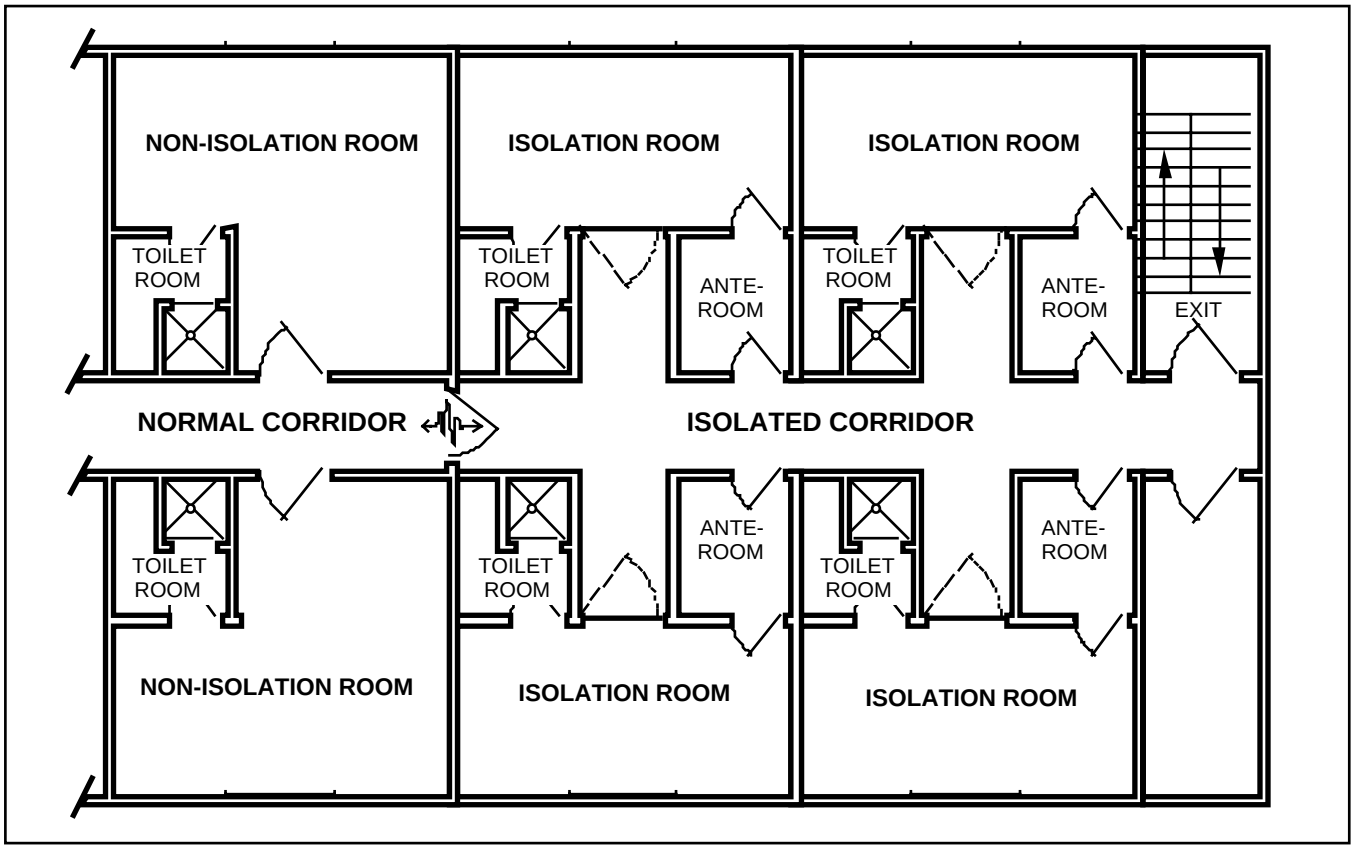


***Figure 3*** Isolation ward with directional airflow

## NEGATIVE ROOM PRESSURE

Like directional airflow, this technique protects clean areas from isolation rooms or other areas by establishing a pressure differential between the spaces and forcing air to flow from the protected space to the area being isolated.

## AIR FILTRATION

HEPA Filters are designed to capture at least 99.9% of all particles greater than or equal to 0.3µm in diameter. For droplet nuclei, which are considerably larger, the capture efficiency is virtually 100%. Where recirculation of room air for isolation rooms is allowed, the return air should be HEPA filtered. For protective isolation, the supply air should also be HEPA filtered. For recirculated air, the filters should be located as close as practical to the return/exhaust grille to minimize the length of potentially contaminated duct. HEPA filters should be contained in a "bag-in, bag-out" type of housing to allow removal and replacement of the filter while keeping the entire operation sealed and minimizing the risk

of exposure of the maintenance personnel to potentially infectious materials. When designing these systems, special attention should be given to providing active volume control to compensate for increasing pressure drop over the life of the filters. A CAV box or other constant volume control method is advisable. Providing a constant (and stable) volume of supply air will make isolation room pressure control much easier and accurate. Measurement of filter pressure drop and monitoring using a building automation system is also recommended. Establish rigid filter replacement criteria and make sure that the maintenence personnel change the filters when required.

Higher ventilation rates and special filtration are recommended for areas of the hospital not covered by HEPA filtration requirements such as waiting rooms, examination rooms, and emergency room areas such as treatment rooms where persons with undiagnosed TB may be found. Filtering all recirculated air from these areas using 90-95% (arrestance rating) filters will remove most (³99%) droplet nuclei. Again, provision for maintaining a constant flow as filter pressure drop increases is recommended but is not as critical unless room pressure control is being attempted. Also, monitoring of pressure drop, "bag-in, bag-out" capability and regular replacement are recommended just as with HEPA filters.

## ULTRAVIOLET GERMICIDAL IRRADIATION (UVGI)

Evidence indicates that UV irradiation provides protection against transmission of TB and other bacteriological infections.[9] The type of UV radiation that is effective against bacteria is UV-C which includes the range of 100-290 nanometers. UV-C radiation is relatively harmless to humans unlike UV-A radiation (400-320 nm) which can cause skin cancer and UV-B radiation (320-290 nm) which is known to cause cataracts. Still, special safety precautions are indicated when using UV-C radiation including proper clothing and glasses for regular lamp inspections and maintenance. This wavelength of light may cause reddening of skin or conjunctivitis during prolonged high-intensity exposure, but both of these effects are temporary. Other side effects of UV-C radiation include fading of colored paints and fabrics and damage to plants.

UVGI may be applied in one of two general ways: upper-room irradiation and duct irradiation.

## UVGI by Upper Room Irradiation

The second method of germicidal disinfection using UV radiation is achieved by installing UV lamps near the ceiling of a room and creating a UV radiation field at the ceiling level as shown in Figure 4. Convection (natural or induced) in the room causes a certain portion of the room air to circulate through this field and be disinfected. Note that the location and type of lamps (wall mounted vs. ceiling mounted) is only an example. There are many effective lamp installation configurations for a typical room and these depend upon the lamp and fixture design, power, etc. The UV field strength curve shown is only an example as well and will vary with these criteria. Application of these devices should conform to the manufacturer's recommended installation criteria. Water vapor absorbs significant quantities of UV-C radiation and high humidities will impair the efficiency of these units.[16] Lamp tube wall temperature also affects the efficiency of the lamp. When sizing these units, be sure to derate the output intensity caused by these two factors so that the actual UV intensity under operating conditions is sufficient to accomplish the desired disinfecting efficiency (usually 99.9%).

The effectiveness of upper room UV irradiation is usually expressed in equivalent air changes per hour, i.e., quantified by citing the amount of ventilation required to provide the same reduction in the number of tubercle bacilli as are killed by the UV radiation. UV radiation has been found to provide the equivalent of 20 ACH for surrogate bacteria that are less susceptible to the effects of UV radiation than tubercle bacilli. Optimizing convection through the radiation field may double this effect.[9] Note that optimizing convection does not mean maximizing convective current velocities through the radiation field, which can reduce residence time in the field and reduce killing efficiency, but attempting to induce the greatest percentage of the room air volume to flow through the radiation field at a velocity that provides sufficient residence time. This depends upon the room configuration, lamp design and configuration, lamp power, etc. As mentioned previously, CFD tools can be used to model a space and strike a balance between mixing, convective velocities, and residence time of particles in the radiation field.

When comparing installation and operating costs for UVGI, the cost per equivalent air changes is much lower than mechanical ventilation. Caution should be exercized, however. UVGI has its

limitations and should not be used as a substitute for recommended ventilation rates or pressure differentials between spaces.

Likely applications of upper room UVGI include; isolation and treatment rooms, to augment recommended ventilation and negative pressure controls; laboratories, waiting rooms, examination rooms, emergency rooms, corridors and central areas of facilities where people with undiagnosed TB may be found.

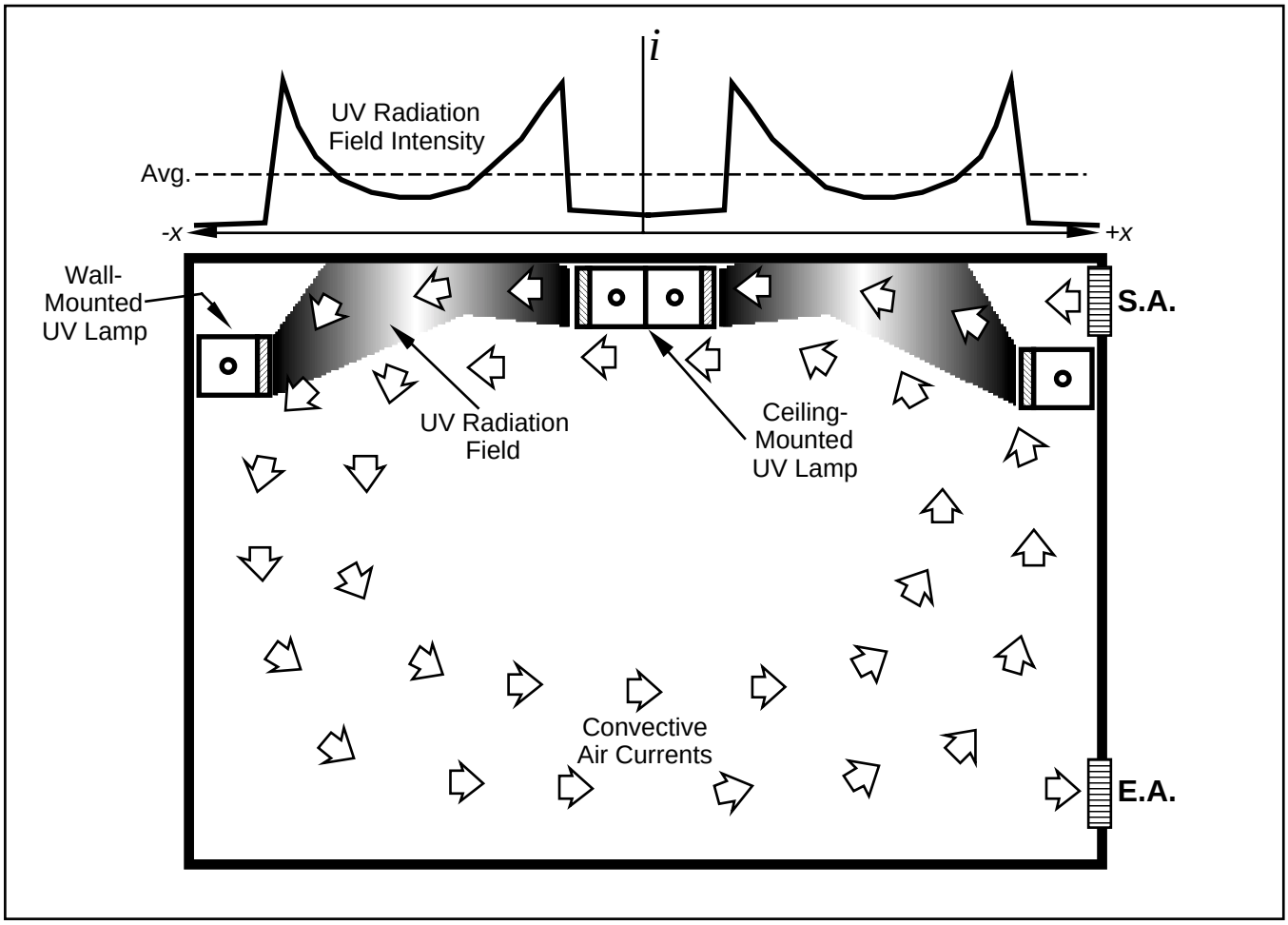


***Figure 4*** Upper room UVGI arrangement

## UVGI by Duct Irradiation

This technique involves the installation of UV lamps directly in the airstream in the ductwork. Figure 5 shows a typical UV lamp installation. The lamp arrangement is installed in the duct, perpendicular to the flow. The number of lamps and their wattage are selected to provide enough intensity over the entire cross section of duct to kill TB bacteria in droplet nuclei. Note that particle

residence time the radiation field and field intensity are both related to the efficiency of this device in killing bacteria. Duct velocity should, therefore, be low enough to provide adequate residence time. Since dirt on the lamps significantly reduces the field intensity, the lamps should be located downstream of an efficient filter bank and be cleaned regularly. Access doors in the ductwork are required for maintenance and for lamp inspection and field intensity measurement. Proper warning labels and interlocks are required on the access doors to prevent exposure to the UV radiation. Consult the manufacturer for proper application of these devices.

Please note that duct UVGI should not be substituted for HEPA filtration if the air is to be recirculated.

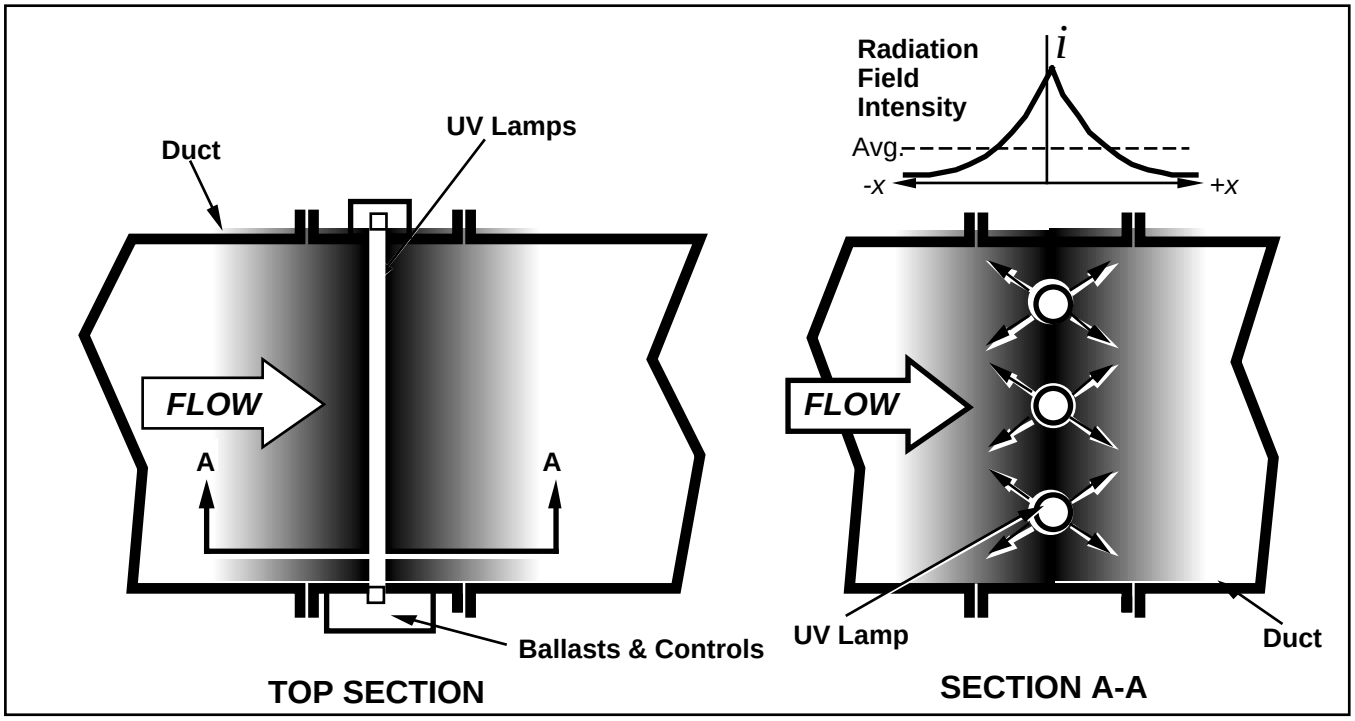


***Figure 5*** Duct mounted UV lamp arrangement

## ISOLATION SUITE DESIGN

There are two types of isolation rooms: *infectious isolation rooms* which are negatively pressurized to prevent exfiltration of infectious organisms produced by an infectious patient located inside the room; and *protective isolation rooms* which are positively pressurized to prevent infiltration of infectious organisms and protect a susceptible patient located in the room. An isolation suite, for purposes of this

paper, consists of the isolation room, the attached toilet room and the isolation room anteroom. The anteroom (also *alcove* or *vestibule*) connects the isolation room with the corridor and serves as a buffer. Anterooms are not required in all cases but are recommended as the level of protection increases with the presence of the anteroom.

Figure 6 shows an example of an isolation suite layout. Note that many configurations are possible, and the sizes of the rooms may vary depending on the level of care required in the suite. In this case, in order to eliminate the need for supply air in the toilet room, it was located adjacent to the hallway to eliminate heating and cooling loads. The anteroom must be located along the corridor for access. To eliminate a "T" or "L" shaped isolation room, which might cause stagnant areas and prevent good air mixing and convection, the inset was required. If the suite is located on a corner with corridor access to two sides, the inset can be eliminated and the configuration simplified. The patient sink was located in the toilet room to eliminate the airflow blockage that would occur if it were in the isolation room. Furniture and other objects that will block convection currents in the room are discouraged. Those that must be used, i.e., the bed, a tray stand and perhaps a television can be included in a CFD model to allow optimization of ventilation effectiveness through location of the supply diffusers, exhaust grilles and those objects.

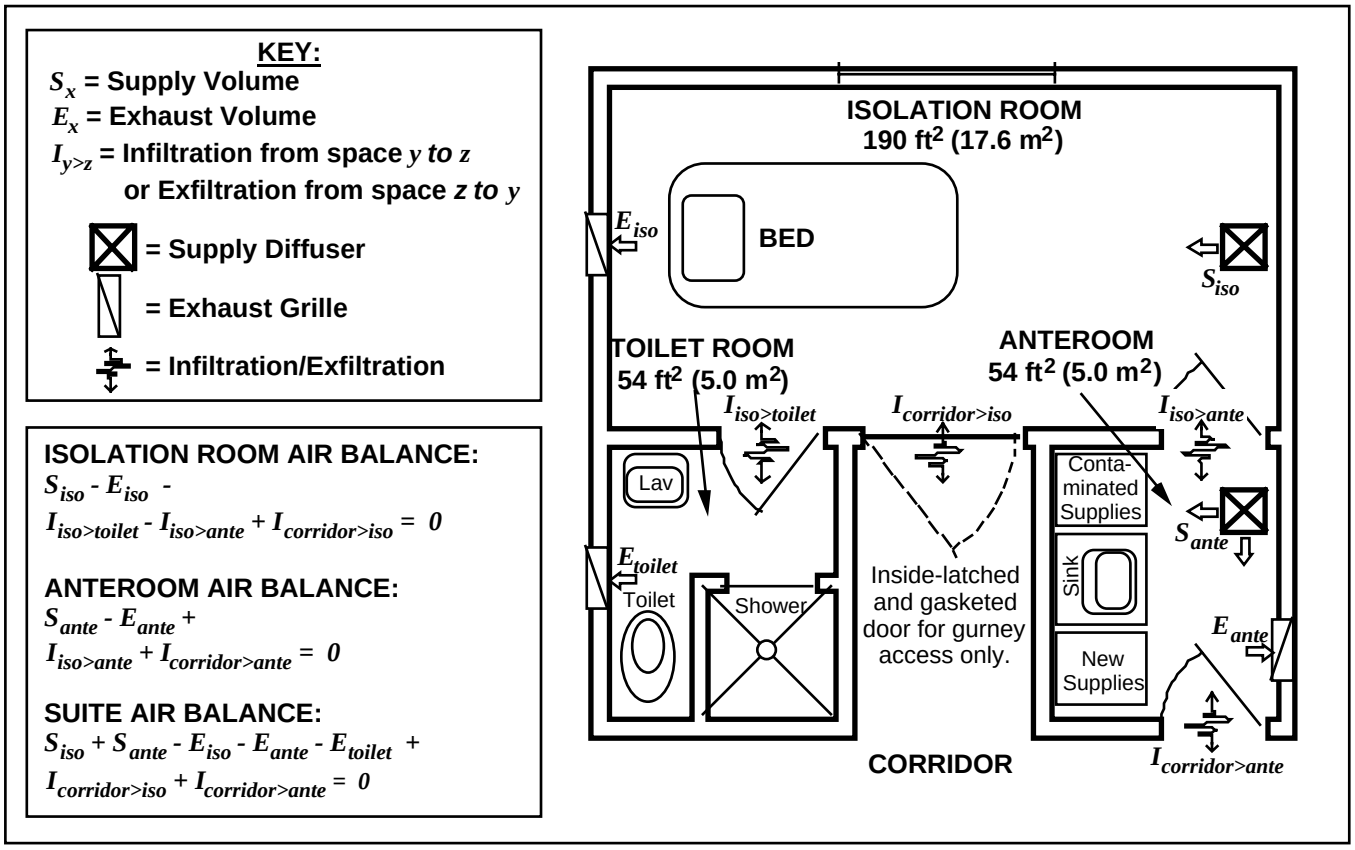


***Figure 6*** Isolation room arrangement

It is recommended that the walls of the suite extend all the way to the deck above and be sealed to produce a *very* tight envelope. All component interfaces should be sealed, i.e., walls to walls, walls to floor, walls to deck. Architectural and mechanical design of the suite should reduce the number of penetrations through this envelope, and those that *are* required should be well sealed. An expandable firestop foam works well for this purpose. Windows in the isolation room should have fixed sash. The gurney access door into the isolation room should be gasketed. The access door from the corridor to the anteroom should provide a good seal also. The door between the anteroom and the isolation room may or may not be sealed depending upon the airflow design chosen. Sealing of the rooms in the suite is necessary to prevent undesired infiltration/exfiltration and will greatly enhance the ability of the room pressure controls to function properly without large volume offsets.

## Room Air Distribution

Figure 7 shows two possible room air distribution methods adapted from the CDC guidelines.[9] It is easy to draw arrows on a diagram of this type to predict air flow patterns, but the author has found that this is naive. The original sketches in the reference use much longer arrows implying nice, near-horizontal or near-vertical streamlines. Do not be fooled by these predictions. Even the short arrows in Figure 8 near the sources, sinks and boundary are probably unrealistic, but they *do* show what the designer should *try* to accomplish.

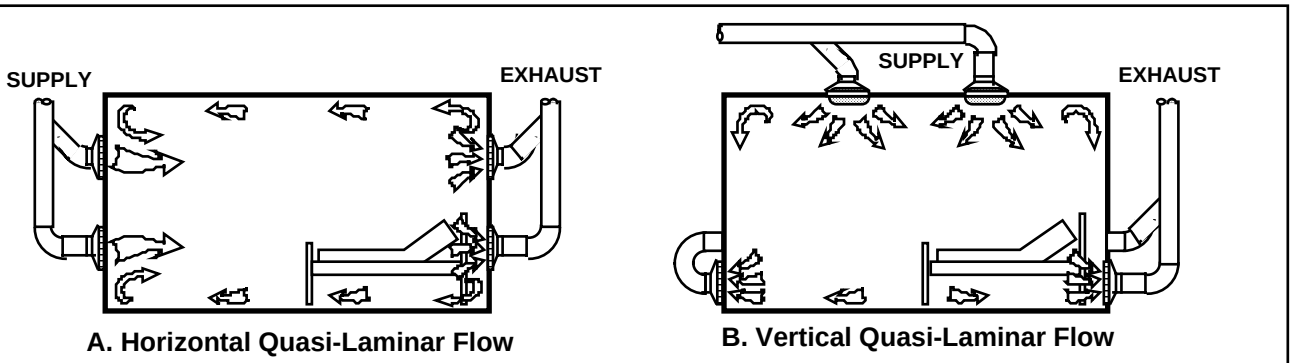


***Figure 7*** Room air distribution in isolation rooms

Experience has shown that air often ignores diagrams like these and does whatever it wants to in spite of your best intentions. Note also that these are only two-dimensional representations showing a plane through the diffusers and grilles. Since these devices do not extend completely across the room, aspiration and vortexes are almost certain to occur in the third dimension not shown in the figure. That is why computational fluid dynamics is such a powerful tool in designing isolation rooms, laboratories, operating rooms, and clean rooms where laminar or quasi-laminar flow is desired.

The type of exhaust grille will have almost no effect on the room air distribution as this effect is very localized. They should, therefore, be selected to meet reasonable pressure drop, noise and aesthetic criteria. Their location in the room, however, will affect the room air patterns greatly and their placement should be carefully studied.

The supply diffusers should be a relatively low velocity, non-aspirating type diffuser if quasi-laminar flow is desired. If necessary, architectural and other mechanical design should accommodate optimal placement of the exhaust grilles and supply diffusers.

These diagrams may not apply if upper room UVGI is planned. Room convection is then a desired effect and an arrangement similar to that in Figure 4 might be considered.

## Infectious Isolation Rooms

These suites are also called negative pressure isolation suites due to the pressure relationship of the isolation room to the corridor. It is recommended that anterooms be used, but they are not required.

There are three commonly used airflow/control designs which can be used with both infectious or protective isolation suites. The difference between them is the pressure relationship of the anteroom to the isolation room and the corridor. They are not the only designs possible. The method shown in Table 3 to calculate air flow rates for these designs is based on the supply volume to each space being equal to the desired or required air change rates and the room pressure being established using the exhaust flow rates. This is not the only way to determine flow rates for these spaces, but it is a reasonably conservative one. All three designs have special advantages and disadvantages that are enumerated in the descriptions below. These options should be discussed with the health care facility staff before committing to a design.

All three designs outlined here include anterooms. If an anteroom is not included you can use the exhaust and supply information for the isolation room and the toilet room from Design #3.

**Design #1I: Anteroom negative to isolation room and corridor.**

This design has two advantages: there is no need to supply air to and delicately balance the anteroom, and if the anteroom becomes contaminated there is still a pressure buffer between the anteroom and the corridor. The disadvantage is: since the anteroom is negative with respect to the isolation room, the chance of contaminating the anteroom is higher. A variation of this design adds

supply air into the anteroom. If this is done, the exhaust flow from the anteroom must be increased to maintain the desired pressure relationship.

**Design #2I: Anteroom net neutral; positive to isolation room and negative to corridor.**

This design incorporates the best features of the previous two designs. The advantages are: since the anteroom is positive with respect to the isolation room, the chance of contaminating the anteroom is lower, *and* if the anteroom becomes contaminated there is *still* a pressure buffer between the anteroom and the corridor. The disadvantage is increased cost and complexity of the controls and balancing. These are small drawbacks, however, if a good airflow controls manufacturer is selected. This design is recommended over the previous two.

**Design #3I: Anteroom positive to isolation room and corridor.**

This design also has two advantages: there is no need to exhaust air from and delicately balance the anteroom, and since the anteroom is positive with respect to the isolation room, the chance of contaminating the anteroom is lower. The disadvantage is: if the anteroom *does* become contaminated, it is likely that the corridor will become contaminated as well. **For this reason, this design is not recommended.** A variation of this design adds exhaust air from the anteroom. If this is done, the supply flow to the anteroom must be increased to maintain the desired pressure relationship.

# TABLE 3

# A Design Method for Infectious Isolation Room Airflows

| RELATIVE PRESSURE RELATIONSHIPS | Design #1I<br>Anteroom Negative to Isolation Room and Corridor | Design #2I<br>Anteroom Net Neutral; Positive to Room, Negative to Corridor | Design #3I<br>Anteroom Positive to Isolation Room and Corridor |
|---|---|---|---|
| Isolation Room to Corridor: | ⊖ | ⊖ | ⊖ |
| Anteroom to Corridor | ⊖ ⊖ | ⊖ | ⊕ |
| Toilet Room to Corridor | ⊖ ⊖ | ⊖ ⊖ | ⊖ ⊖ |

| AIRFLOW FORMULAE | Design #1I | Design #2I | Design #3I |
|---|---|---|---|
| Isolation Room Supply: | | | $S_{iso} = \frac{(A_{iso} \bullet H_{room} \bullet ACH_{iso})}{60}$ |
| Isolation Room Exhaust: | $E_{iso} = S_{iso}$<br>(See note 1) | $E_{iso} = S_{iso}$<br>(See note 3) | $E_{iso} = S_{iso} + S_{ante}$<br>(See note 2) |
| Anteroom Supply: | N/A | | $S_{ante} = \frac{(A_{ante} \bullet H_{room} \bullet ACH_{ante})}{60}$ |
| Anteroom Exhaust: | | $E_{ante} = S_{ante}$ | N/A |
| Toilet Room Exhaust: | $E_{toilet}$ = [3]75 cfm (35 L/s) | $E_{toilet}$ = [3]75 cfm (35 L/s) | $E_{toilet}$ = [3]75 cfm (35 L/s) |
| Infiltration from Corridor into Anteroom: | Assume:<br>$I_{corridor>ante} = E_{ante}$ | Assume:<br>$I_{corridor>ante} = E_{toilet}/2$ | Assume:<br>$I_{corridor>ante}$ = Zero |
| Infiltration from Isolation Room into Anteroom: | Assume:<br>$I_{iso>ante}$ = Zero | Assume:<br>$I_{iso>ante} = -(E_{toilet}/2)$ | Assume:<br>$I_{iso>ante} = -(S_{ante})$ |
| Infiltration from Corridor into Isolation Room: | Assume:<br>$I_{corridor>iso} = E_{toilet}$ | Assume:<br>$I_{corridor>iso} = E_{toilet}/2$ | Assume:<br>$I_{corridor>iso} = E_{toilet}$ |
| Infiltration from Isolation Room into Toilet Room: | $I_{iso>toilet} = E_{toilet}$ | $I_{iso>toilet} = E_{toilet}$ | $I_{iso>toilet} = E_{toilet}$ |

## EXAMPLE DESIGN DATA FOR NP ISOLATION ROOM CONFIGURATION IN FIGURE 5:

| | Design #1I | Design #2I | Design #3I |
|---|---|---|---|
| Isolation Room Area: $A_{iso}$ | 190 ft$^2$ (18m$^{2)}$) | 190 ft$^2$ (18 m$^{2)}$) | 190 ft$^2$ (18m$^{2)}$) |
| Anteroom Area: $A_{ante}$ | 54 ft$^2$ (5.0 m$^{2)}$ | 54 ft$^2$ (5.0 m$^{2)}$ | 54 ft$^2$ (5.0 m$^{2)}$ |
| Toilet Room Area: $A_{toilet}$ | 54 ft$^2$ (5.0 m$^{2)}$ | 54 ft$^2$ (5.0 m$^{2)}$ | 54 ft$^2$ (5.0 m$^{2)}$ |
| Room Heights: $H_{room}$ (all) | 9 ft (2.7 m) | 9 ft (2.7 m) | 9 ft (2.7 m) |
| Isol. Rm. Air Changes: $ACH_{iso}$ | 12 | 12 | 12 |
| AntRm Air Changes: $ACH_{ante}$ | 10 | 10 | 10 |
| Isolation Room Supply: | 342 cfm (161 L/s) | 342 cfm (161 L/s) | 342 cfm (161 L/s) |
| Isolation Room Exhaust: | 342 cfm (161 L/s) | 342 cfm (161 L/s) | 423 cfm (200 L/s) |
| Anteroom Supply: | N/A | 81 cfm (38 L/s) | 81 cfm (38 L/s) |
| Anteroom Exhaust: | 81 cfm (38 L/s) | 81 cfm (38 L/s) | N/A |
| Toilet Room Exhaust: | 75 cfm (35 L/s) | 75 cfm (35 L/s) | 75 cfm (35 L/s) |

[1]This formula assumes conservatively that all the anteroom exhaust air is drawn from the corridor and none from the isolation room. Negative pressure is established in the isolation room using the toilet room exhaust volume.

[2]This formula assumes conservatively that all the anteroom supply air is drawn into the isolation room and none goes to the corridor. Negative pressure is established in the isolation room using the toilet room exhaust volume.

[3]This formula assumes (not conservatively, but reasonably) that half of the isolation room net negative air balance is drawn from the corridor directly into the isolation room and the other half of the net negative air balance is drawn from the corridor indirectly into the isolation room through the anteroom. It is impossible to determine the actual ratio of direct vs. indirect infiltration into the isolation room. If a more conservative approach is desired to assure larger indirect infiltration into the isolation room from the anteroom, it is suggested

that special care be given to making the isolation room as tight as possible and increasing the toilet room exhaust or the isolation room exhaust rate to achieve the desired results. Negative pressure is established in the isolation room using the toilet room exhaust volume.

## Protective Isolation Rooms

These suites are also called positive pressure isolation suites due to the pressure relationship of the isolation room to the corridor. It is recommended that anterooms be used, but they are not required.

The method shown in Table 4 to calculate air flow rates for these designs is based on the exhaust volume from each space being equal to the desired or required air change rates and the room pressure being established using the supply flow rates. Again, this is not the only way to determine flow rates for these spaces, but it is a reasonably conservative one. All three designs have special advantages and disadvantages that are enumerated in the descriptions below. These options should be discussed with the health care facility staff before committing to a design.

All three designs outlined here include anterooms. If an anteroom is not included you can use the exhaust and supply information for the isolation room and the toilet room from Design #3.

**Design #1P: Anteroom negative to both isolation room and corridor.**

This design has two advantages: there is no need to supply air to and delicately balance the anteroom, and if the anteroom becomes contaminated there is still a pressure buffer between the anteroom and the isolation room. The disadvantage is: since the anteroom is negative with respect to the corridor, the chance of contaminating the anteroom is higher. A variation of this design adds supply air into the anteroom. If this is done, the exhaust flow from the anteroom must be increased to maintain the desired pressure relationship.

**Design #2P: Anteroom net neutral; negative to isolation room and positive to corridor.**

This design incorporates the best features of the previous two designs. The advantages are: since the anteroom is positive with respect to the corridor, the chance of contaminating the anteroom is lower, *and* if the anteroom becomes contaminated there is *still* a pressure buffer between the anteroom and the isolation room. The disadvantage is increased cost and complexity of the controls and balancing. These

are small drawbacks, however, if a good airflow controls manufacturer is selected. This design is recommended over the previous two.

**Design #3P: Anteroom positive to both isolation room and corridor.**

This design also has two advantages: there is no need to exhaust air from and delicately balance the anteroom, and since the anteroom is positive with respect to the corridor, the chance of contaminating the anteroom is lower. The disadvantage is: if the anteroom *does* become contaminated, it is likely that the isolation room will become contaminated as well. **Therefore, this method is rarely used and is not recommended.** A variation of this design adds exhaust air from the anteroom. If this is done, the supply flow to the anteroom must be increased to maintain the desired pressure relationship.

# TABLE 4

# A Design Method for Protective Isolation Room Airflows

| RELATIVE PRESSURE RELATIONSHIPS | Design #1P<br>Anteroom Negative to Isolation Room and Corridor | Design #2P<br>Anteroom Net Neutral; Negative to Room, Positive to Corridor | Design #3P<br>Anteroom Positive to Isolation Room and Corridor |
|---|---|---|---|
| Isolation Room to Corridor: | ⊕ | ⊕ ⊕ | ⊕ |
| Anteroom to Corridor | ⊖ | ⊕ | ⊕ |
| Toilet Room to Corridor | ⊖ | ⊖ | ⊖ |

| AIRFLOW FORMULAE | Design #1P | Design #2P | Design #3P |
|---|---|---|---|
| Toilet Room Exhaust: | $E_{toilet}$ = ³75 cfm (35 L/s) | $E_{toilet}$ = ³75 cfm (35 L/s) | $E_{toilet}$ = ³75 cfm (35 L/s) |
| Isolation Room Offset: | $Offset_{iso}$ = ³75 cfm (35 L/s) | $Offset_{iso}$ = ³75 cfm (35 L/s) | $Offset_{iso}$ = ³75 cfm (35 L/s) |
| Isolation Room Exhaust: | | | $Eiso = \frac{(A_{iso} \bullet H_{room} \bullet ACH_{iso})}{60}$ |
| Anteroom Exhaust: | | | N/A |
| Anteroom Supply | N/A | $S_{ante} = E_{ante}$ | $S_{ante} = \frac{(A_{ante} \bullet H_{room} \bullet ACH_{ante})}{60}$ |
| Isolation Room Supply: | $S_{iso} = E_{iso} + E_{toilet} + E_{ante} + Offset_{iso}$. (See note 1) | $S_{iso} = Ei_{so} + E_{toilet} + Offset_{iso}$. (See note 3) | $S_{iso} = E_{iso} + E_{toilet} + Offset_{iso}$. (See note 2) |
| Infiltration from Corridor into Anteroom: | Assume: $I_{corridor>ante}$ = Zero | Assume: $I_{corridor>ante} = -(Offset_{iso})/2$ | Assume: $I_{corridor>ante} = -(S_{ante})$ |
| Infiltration from Isolation Room into Anteroom: | Assume: $I_{iso>ante} = E_{ante}$ | Assume: $I_{iso>ante} = -(Offset_{iso})/2$ | Assume: $I_{iso>ante}$ = Zero |
| Infiltration from Corridor into Isolation Room: | Assume: $I_{corridor>iso} = -(Offset_{iso})$ | Assume: $I_{corridor>iso} = -(Offset_{iso})/2$ | Assume: $I_{corridor>iso} = -(Offset_{iso})$ |
| Infiltration from Isolation Room into Toilet Room: | $I_{iso>toilet} = E_{toilet}$ | $I_{iso>toilet} = E_{toilet}$ | $I_{iso>toilet} = E_{toilet}$ |

**EXAMPLE DESIGN DATA FOR PP ISOLATION ROOM CONFIGURATION IN FIGURE 5:**

| | Design #1P | Design #2P | Design #3P |
|---|---|---|---|
| Isolation Room Area: $A_{iso}$ | 190 ft² (18m²)) | 190 ft² (18 m²)) | 190 ft² (18m²)) |
| Anteroom Area: $A_{ante}$ | 54 ft² (5.0 m²) | 54 ft² (5.0 m²) | 54 ft² (5.0 m²) |
| Toilet Room Area: $A_{toilet}$ | 54 ft² (5.0 m²) | 54 ft² (5.0 m²) | 54 ft² (5.0 m²) |
| Room Heights: $H_{room}$ (all) | 9 ft (2.7 m) | 9 ft (2.7 m) | 9 ft (2.7 m) |
| Isol. Rm. Air Changes: $ACH_{iso}$ | 15 | 15 | 15 |
| AntRm Air Changes: $ACH_{ante}$ | 15 | 15 | 15 |
| Toilet Room Exhaust: | 75 cfm (35 L/s) | 75 cfm (35 L/s) | 75 cfm (35 L/s) |
| Isolation Room Offset: | 75 cfm (35 L/s) | 75 cfm (35 L/s) | 75 cfm (35 L/s) |
| Isolation Room Exhaust: | 428 cfm (202 L/s) | 428 cfm (202 L/s) | 428 cfm (202 L/s) |
| Anteroom Exhaust: | 122 cfm (57 L/s) | 122 cfm (57 L/s) | N/A |
| Anteroom Supply | N/A | 122 cfm (57 L/s) | 122 cfm (57 L/s) |
| Isolation Room Supply: | 700 cfm (330 L/s) | 578 cfm (273 L/s) | 578 cfm (273 L/s) |

[1]This formula assumes conservatively that all the anteroom exhaust air is drawn from the isolation room and none from the corridor.

[2]This formula assumes conservatively that all of the anteroom supply air is drawn into the corridor and none goes to the isolation room

[3]This formula assumes (not conservatively, but reasonably) that half of the isolation room offset is drawn into the corridor directly from the isolation room and the other half of the offset is drawn from the isolation room indirectly into the corridor through the anteroom. It is impossible to determine the actual ratio of direct vs. indirect exfiltration from the isolation room.

## RENOVATIONS:

### Creating isolation rooms from existing patient rooms

When renovating existing patient rooms, there may not be enough space available to create an anteroom if one is desired. A method used successfully in the past is to create two isolation rooms and a common anteroom from three existing patient rooms. Figure 8 shows a possible layout for this conversion. Controlling the space pressures in this configuration is more complex than the previous designs with an anteroom for each isolation room. Envelope leakage must be virtually eliminated. Transfer grilles, or large undercuts in the doors between the common anteroom and the isolation rooms coupled with large offsets are necessary to prevent one isolation room from affecting the other. Very stable performance from the airflow controls is necessary to make this operate correctly.

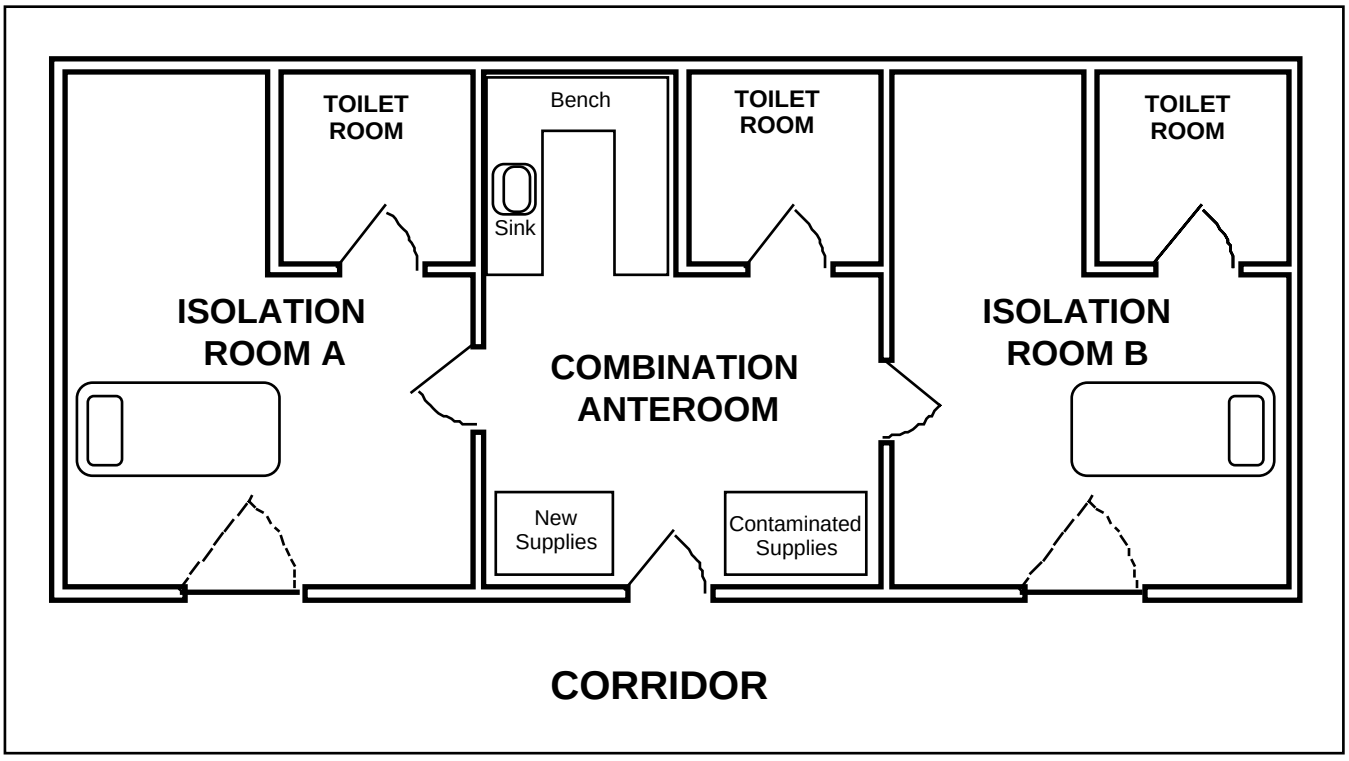


***Figure 8*** Creating isolation rooms using regular patient rooms

## ROOM PRESSURE CONTROL STRATEGIES:

A detailed treatment of this subject is beyond the scope of this paper. Reference 20 explains these systems in more detail than is possible here. The reference deals with space pressure controls for laboratories, but the principles are exactly the same for isolation rooms. In fact, most manufacturers of laboratory airflow control systems also market similar products (sometimes even the same product) for isolation facilities.

### Differential Pressure Systems

This control method measures the actual differential pressure between the isolation room and the corridor (classic ÆP method) or measures the velocity of air induced through a hole in the envelope between the isolation room and corridor created by the differential pressure (Pseudo-ÆP method). A schematic of this type of system is shown in Figure 9B.

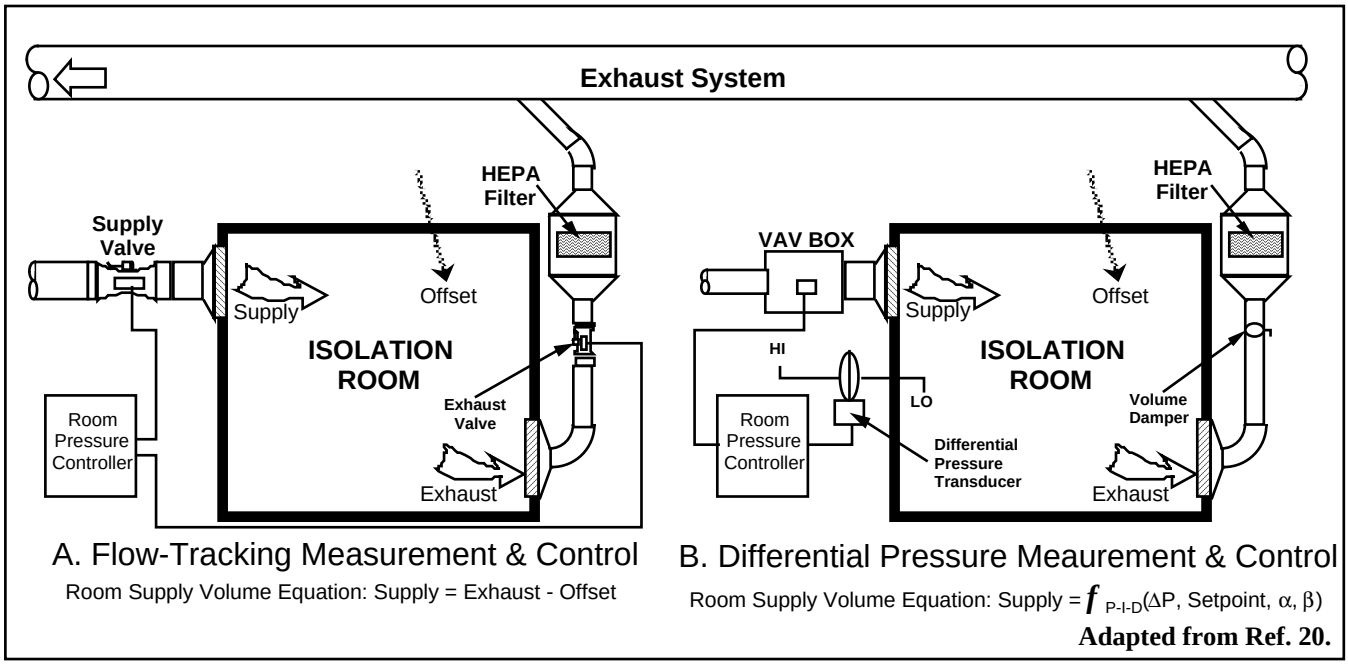


***Figure 9*** Two methods of isolation room differential pressure control

Although it may appear that measuring the variable (or an analog of the variable in the case of the Pseudo-ÆP method) is a wise thing to do, there are some difficulties with this particular method. First,

the differential pressure to be measured and controlled is extremely small, on the order of $^{1}/_{100}$ in. wg (2.5 Pa). To put this in perspective, this same pressure is 0.00036 psi (0.0025 kPa).

Measuring pressures of this magnitude accurately is *extremely* difficult. There *are* accurate ultra-low-differential pressure transducers on the market that cost several thousand dollars, and if simply sensing and controlling a stable, low-noise pressure signal of this magnitude was all that was necessary, then this method would work fine (and be very expensive). However, in real health-care facilities there are factors which greatly affect the pressure signals to be sensed. Some of these factors are foot traffic past the sensor, building stack effects, elevator effects, wind, etc. When these other effects, which can be much larger in magnitude than the differential pressure signal, are introduced, the resulting signal is so noisy that it becomes even more difficult. The Pseudo-*Æ*P method improves the signal to noise ratio by a factor of about three, but the SNR is still less than unity.

The health-care application is a little more forgiving, however, than a VAV laboratory. For instance, in a VAV lab the exhaust and supply airflows in the controlled space a very dynamic and some classic *Æ*P or Pseudo-*Æ*P systems may not even stabilize between upsets. An isolation room is a much more steady-state application and, if applied correctly, tuned properly, maintained frequently and selected with care, *may* function adequately.

## Flow-Tracking Systems

The other method of room pressure control is called flow-tracking or differential-volume control. In this method, the exhaust and supply flow rates from the space are measured and controlled to produce a desired infiltration or exfiltration. If the space is to be maintained negative with respect the adjoining area, more exhaust is drawn out of the room than supply air provided to it. The difference between these two flows is called the *offset.* A schematic of this type of system is shown in Figure 9A.

Since the signals are large and the noise is small, in comparison, these systems tend to be inherently more stable than the *Æ*P systems. However, specifying a reputable airflow controls manufacturer is still very important. It is a good idea to build a mock-up and test equipment from several different

manufacturers before making a purchase. A consultant can also make recommendations based on experience.

## EMERGENCY ROOMS & RECEPTION AREAS:

Public areas of a health-care facility such as emergency rooms and reception areas provide another challenge to preventing transmission of infectious diseases such as TB. In these areas, persons with undiagnosed active-TB can come in contact with and infect others prior to examination and treatment. Some additional precautions are, therefore, prudent in these areas.

Proving negative pressure in waiting areas, treatment rooms and examination rooms can prevent contaminated air from reaching sensitive areas or susceptible people in the facility.

Providing sectional waiting areas with partitions or cubicles can provide a physical barrier between infected persons and those at risk.

HEPA filtration or 95% filtration of return air from these areas will remove all or most of the infectious droplet nuclei as mentioned before and is recommended for these areas.

Upper room UVGI in waiting areas, hallways, treatment rooms, etc., is also a low-cost precaution that may yield significant benefits.

## CDC RECOMMENDATIONS REGARDING ENGINEERING EXPERTISE:

It is important to have qualified staff or consultants design, specify, recommend, and commission the systems described herein. This technology and the proper application of it is well beyond the general-practitioner of HVAC design. It should not be done by operating "engineers" or maintenance people but by qualified, experienced staff or consultants. The CDC says it even better:

Staff of inpatient facilities should either include an engineer or other professional with expertise in ventilation or industrial hygiene, or the facility should have this expertise available from a consultant. These persons should work closely with the infection-control committee in the control of airborne infections.[8]

## CONCLUSION:

TB is posing an ever increasing threat, especially in health-care facilities. Preventing the transmission of this disease requires the use of both old, proven methods as well as new technology. When these are applied prudently and correctly, the risk of transmission can be significantly reduced.

## APPENDIX 1: DEFINITIONS

Since the target audience of this paper is not people in the medical profession but engineers, and since understanding the subject and the references cited require the knowledge of many medical terms, it is necessary to define them here.

***AFB:*** Acid-fast bacilli. Organisms that retain certain stains even after washing with acid alcohol. Most are Mycobacteria. The presence of AFB indicates a tuberculosis diagnosis.

***AIDS:*** Acquired Immune Deficiency_ Syndrome, caused by HIV.

***AP:*** Aerosolized pentamidine. A drug given to HIV patients to treat or prevent *Pneumocystis carinii* pneumonia (PCP). The drug is suspended in a solution that this aerosolized and inhaled.

**Bronchoscopy:** A diagnostic technique involving a bronchoscope which is inserted into the patient's lungs allowing visual inspection of the tissue.

***Conjunctivitis:*** Irritation of the eyes.

***Droplet Nuclei:*** A small drop of liquid (1-5μm in diameter). An *infectious droplet nucleus* contains viable organisms.

***Endotracheal Intubation:*** A medical procedure involving the insertion of a tube into the trachea to assist breathing or allow sampling of tissue.

***HEPA:***: High-efficiency particulate air filter. Capable of trapping 99.97% of all particles greater than 0.3μm in diameter.

***HIV:*** Human immunodeficiency virus. The virus that causes AIDS. A person can be infected with HIV and not yet have full blown AIDS.

***Immunosupressed:*** Those having a damaged or non-functioning immune system including patients with AIDS, leukemia, cancer undergoing certain chemotherapies, certain other medical conditions.

***Latent Tuberculosis Infection:*** A condition in which tuberculosis organisms *(M. tuberculosis, M. bovis, or M. africanum)* are present in the body, but no active disease is present. People with latent tuberculosis infection are not infectious. Infected persons have a 10% probability of progression to active TB in their lifetime. The risk is the greatest in the first two years post infection, but some risk persists for decades.

***MDR-TB:*** Multidrug-resistant strains of *Mycobacterium tuberculosis.* Caused by incomplete regimes of self-administered, unsupervised antibiotic therapies in TB patients.

***Nosocomial:*** Pertaining to a hospital, infirmary or other health care facility; i.e., a nosocomial infection is an infection acquired in a hospital.

***Open Abscess Irrigation:*** A medical procedure in which an exposed abscess is flushed with a liquid for cleaning or medication.

***PCP:*** *Pneumocystis carinii* pneumonia. This organism does not produce pneumonia in persons with a normal immune system but is frequently contracted by HIV infected individuals.

***PR:*** Personal Respirator (valveless). A disposable, particulate respirator (respiratory protective device or face mask) designed to trap particles greater than one micron in diameter, a.k.a. one micron mask.

***Sputum Induction:*** A procedure where the patient is induced to cough to collect diagnostic sputum samples.

***TB:*** Tuberculosis. An infection or active disease caused by *Mycobacterium tuberculosis, Mycobacterium bovis, or Mycobacterium africanum.* It is considered extremely communicable. The multidrug-resistant strains of *Mycobacterium tuberculosis* (MDR-TB) are of particular concern due to their resistance to normal treatments and serious pathology, i.e., death.

***UV:*** Ultraviolet. A non-visible part of the spectrum that damages or kills living cells and is used to disinfect air in HVAC systems.

***UVGI:*** Ultraviolet Germicidal Irradiation. It is used to describe the method of air disinfection using UV radiation. A.K.A. UVGDI, ultraviolet germicidal disinfection.

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