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Cleanroom Pressurization Strategy Update—Quantification and Validation of Minimum Pressure Differentials for Basic Configurations and Applications (Part 1)

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This paper is based on findings resulting from ASHRAE Research Project RP-1344.

ABSTRACT

Pressurization technology utilized in cleanroom facilities is typically used to minimize airborne contamination from less-clean rooms entering into cleaner rooms. Pressurization design has traditionally been based on intuitive suggestion instead of well-established guidelines. A pressure differential (PD) of 0.05 in. (12.5 Pa), as a single and uniform criterion, has been used for many years since it was adopted into Federal Standard 209 and the "Clean Spaces" chapter of ASHRAE Handbook—HVAC Applications *(2011). This criterion is believed to be oversimplified and no longer precise for more complex conditions.*

The research illustrates that the air leakage rate (in relation to not only pressure differential but also room airtightness, which has not been well understood and is often ignored) is a critical variable in determining the flow offset value (the difference between room incoming and leaving airflows). The lab testing further revealed the impact of barrier's leakage opening size on particle migration. Particle exchanges from a dirtier room into a cleaner room are not only driven by a pressure differential that is well known but also by particle concentration differential, also called mass diffusion. Under the same positive pressure differential and other conditions, a cleanroom could receive more migrated particles if it is surrounded by a heavily contaminated area than by a less-contaminated area. The research establishes new terminologies and mathematical definitions such as contamination ratio, daily accumulated contamination ratio, barrier effectiveness, etc.

The recommendations from the research include a table of minimum PD requirements across cleanroom enclosures grouped by cleanliness class difference across a barrier. This PD table is intended to replace the existing single pressure differential criterion.

BACKGROUND

Room Pressurization

Pressurization is normally used to direct desired flow patterns and to minimize airborne particle and biological contaminations from less clean rooms entering into cleaner rooms. It is defined as a technique in which air pressure differences are created mechanically between rooms to introduce intentional air movement through room leakage openings. These openings could be either designated, such as doorways, or undesignated, such as air gaps around door frames or cracks of duct/pipe wall penetrations. Pressurization is often achieved by HVAC systems by properly arranging the controlled flow rates of supply, return, and exhaust airstreams to each room within the space.

Shortcoming of Existing Single Criterion for Pressurization

Pressurization control technology utilized in cleanroom facilities has been traditionally based on intuitive suggestion instead of well-established guidelines. A pressure differential (PD) of 0.05 in. (12.5 Pa), as a single and uniform criterion, has been used since it was adopted into Federal Standard 209, *Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones* (IEST 1992), and the Clean Spaces chapter of *ASHRAE Handbook—HVAC Applications* (2011).

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It had been assumed that when a closed-door cleanroom enclosure can maintain 0.05 in., then during door operation, although the pressure differential will decrease significantly, the desired flow patterns between two rooms can still be maintained and contamination caused by air backflow from less-clean surrounding areas into the cleanroom can be minimized. The criterion of 0.05 in. for each PD step is believed to be oversimplified and no longer precise, especially when a cleanroom is surrounded by less-clean adjacent area which could be one, two, three or more cleanliness classes dirtier.

Current ISO Standard on Pressure Differential Range

The recent ISO Standard 14644-4 *Cleanrooms and Associated Controlled Environments – Design, Construction and Start-up* has already allowed a PD range from 0.02 to 0.08 in. (5 to 20 Pa) (ISO 2001). However, which value to specify and what could be the resulting decontamination effectiveness is still left to designers' intuition to decide. Besides, decontamination barriers such as clean benches (laminar hoods), airlocks or mini-environments, which practically impose an extra level of resistance to airborne contamination, have not been credited quantitatively. Furthermore, the airtightness level of room enclosures, which is a critical element in design consideration, has for decades often been ignored during pressurization designs.

No Standard or Guideline for Door-In-Operation Conditions

Cleanroom pressurization defines a desired flow pattern and performs as a particle migration barrier. A certain pressure differential across a closed door between two rooms of different air cleanliness normally can prevent airborne cross- contamination from the less clean room into the cleaner room, since if there are some cracks along the door frame, the openings will be small and the leakage air velocities through these cracks will be very high to prevent backflows. However, when the door is opened, the established pressure differential will drop quickly and then the barrier's functionality will be questionable. Currently no standard or guideline has indicated the minimum required pressure differential or additional treatment at door-in-operation conditions to prevent backflow.

Research Objective and Advancement

This research illustrates the air leakage rate in relation to not only pressure differential but also room airtightness, which is a critical variable in determining the flow offset value. The lab testing further reveals the impact of the barrier's leakage opening size on particle migration. Most of the tests were conducted at door-closed conditions to test particle migration into a cleanroom under various differential pressures and/or particle challenges, while others were tested at "door opened with a series of minor gaps" conditions to simulate room leakage sizes that impact particle migration. The entire research mainly focuses on the migration of nonviable particles into the cleanrooms under various pressure differentials or particle challenges. However, the results could be a good reference for those industries with similar concerns on airborne microbial migration. The research objective is to establish a table of minimum PD requirements across the cleanroom enclosures. This PD table is intended to replace the existing single pressure differential criterion.

THEORETICAL AND MATHEMATICAL DEVELOPMENT

Room Pressurization Scenarios and Variables Relationships

Room pressurization variables and their relationships are illustrated in Figure 1.

Traditional Rules-of-Thumb Methods in Determination of Flow Offset Values

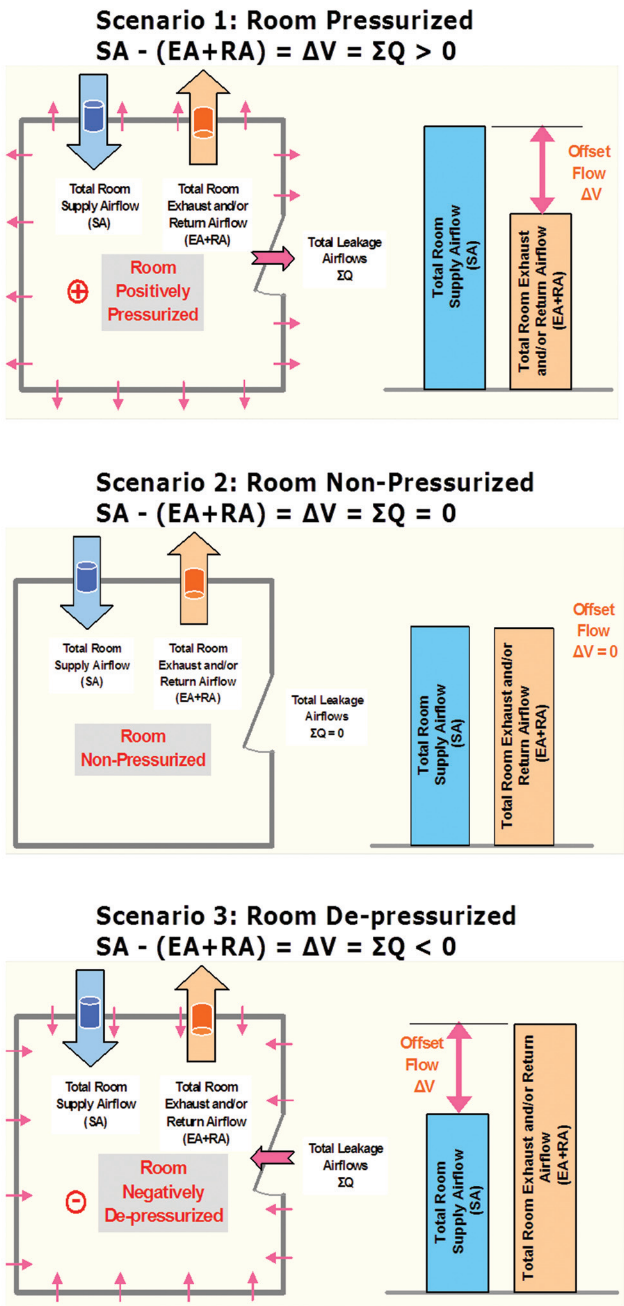
Many rules-of-thumb opinion-based approaches have been utilized in determination of the absolute or relative offset values during room pressure design. Typical examples are:

- Flow Percentage Offset Method: An example of this approach is the method recommended in the VA *HVAC Design Manual for Hospitals* (2008).
- Flow Differential Offset Method: An example of this approach is the method recommended by the CDC guideline (2003).
- Leakage Equation Based Method: An example of this approach is the method recommended by ASHRAE Standard 170 (2008).

The CDC approach advanced from the Flow Percentage Offset Method, and it indicated the requirement for the airtightness of the room envelope. However, the method to estimate the leakage area was not addressed or provided in the guideline. Also, the pressure differential at 0.01 in. (2.5 Pa) seems well below the recommended levels from other guidelines and standards. ASHRAE Standard 170 uses the quantified method and lists the leakage equation; however, how to apply this equation for design purposes is not adequately discussed (ASHRAE 2008).

Contamination Rate (CR)

An aerosol particle sensing method is developed to measure the degree of containment in an experimental cleanroom lab. The risk level of cleanroom particle



Note:

1. SA is Supply Air, RA is Return Air, EA is Exhaust Air
2. SA is the total entering air, (EA+RA) is the total leaving air
3. ΔV - Room Offset Flow
4. ΣQ - Total Leakage Flow which is a mathematic sum with possible leak-in air and leak-out airs

Figure 1 *Room pressurization scenarios.*

contamination can be expressed as a new terminology called *contamination rate* (CR) as follows:

$$CR = \frac{(P_C - P_B)}{P_O}$$

Or,

$$CR = \frac{P_C}{P_O} \qquad \left(\text{when } \frac{P_B}{P_O} < 0.1\%\right)$$

where

CR = particle contamination rate, or particle contamination ratio if $\frac{P_B}{P_O} < 0.1\%$ in percentage

P_C = particle concentration inside cleanroom behind door under challenge

P_B = initial background particle concentration inside cleanroom behind door without challenge

$P_C - P_B$ = particle concentration gain inside cleanroom behind door under challenge

P_O = particle concentration in corridor, or in front of cleanroom entrance door as contamination challenge

Contamination rate is defined as the airborne particle concentration gain above the initial background concentration in a protected cleanroom over the particle concentration outside the corridor that is the source of particle challenge. When initial background concentration before particle challenge is significantly lower than the corridor, say less than 0.1%, or three classes cleaner, then the particle concentration in the contamination ratio between two rooms can be used as a simplified method to calculate the contamination rate.

In this paper, CR primarily refers to contamination rate, it can be replaced with contamination ratio if

$$\frac{P_B}{P_O} < 0.1\%$$

or if the initial cleanroom background concentration is not available, such as during design stage. Therefore, CR is a criterion to quantify the effectiveness of a cleanroom barrier in preventing particle migration into a cleanroom. Obviously, under various scenarios, the lower the CR level, the better the performance of the barrier's effectiveness. This criterion can be generally applied for a "barrier device" or a "mechanism" in a general term. For example, a single door can act as a simple form of a barrier, a two-door in-series airlock is a more complex and advanced barrier, so as a mini-environment, a glove box, or an entire sealed enclosure with the common goal to minimize particle migration into a protective or clean space.

The locations of the particle sensors inside a protected cleanroom and in the corridor across the barrier door are important. If the locations are not clearly defined, the CR value could vary even if all other conditions are kept identical. In order to compare the relative contamination levels in terms of contamination rates for future tests by others, the sensors' locations must be in a defined protocol or standardized. The research team for this project selected a typical scenario that could satisfy the majority of applications, as the standardized sensors' locations show below:

- Sensor height: Half of door height. If a door is 84 in. (214 cm) tall, the height for sensors is 42 in. (107 cm).
- Sensor distance from wall: 12 in. (30 cm) from both sides of the wall that holds the door frame.
- Sensor distance from door edge (next to traffic path): 12 in. (30 cm)

Figure 2 shows the sensing locations for CR definition in relation to average room concentration sensing. The reasons to define the sensors' positions as indicated above are as follows: First, the vicinity around the door opening is the most sensitive area to study particle migration, as the dirty particles have to pass through this area to impact the rest of the cleanroom space. Second, typically it is rare for equipment to be placed so close to a door for undisrupted traffic. Last, the mid-height can be easily identified for a door of any height or size.

This contamination rate or contamination ratio criterion is obviously a function of pressure differential applied across the door. This expression can be also applied for airborne microbial migration, in which the particle counts are replaced with the counts of colony forming units (CFUs).

$$\mathrm{CR} = \frac{(M_C - M_B)}{M_O}$$

Or,

$$\mathrm{CR} = \frac{M_C}{M_O} \qquad \left(\text{when} \quad \frac{M_B}{M_O} < 0.1\% \right)$$

where,

CR = microbial contamination rate, or microbial contamination ratio if $\frac{M_B}{M_O} < 0.1\%$, in percentage

M_C = microbial count (CFUs) inside cleanroom behind door under challenge

M_B = initial background microbial counts (CFU) inside cleanroom behind door without challenge

$M_C - M_B$ = microbial counts (CFU) gain inside cleanroom behind door under challenge

M_O = microbial counts (CFU) in corridor, or in front of cleanroom entrance door as contamination challenge

Here, CR is defined as the gain of airborne microbial counts (CFUs) above the initial background CFU counts in the protected cleanroom over the CFU counts outside the corridor, which is the source of microbial challenge. Here, CR is a criterion to quantify the effectiveness of cleanroom airborne microbial containment in preventing microbial migration into a cleanroom through a barrier device, such as a single door, a double-door airlock, a biosafety cabinet, etc.

Barrier Effectiveness (BE) Against Particle Migration

Related to contamination rate, barrier effectiveness (BE) is defined as the percentage of airborne particles (expressed in concentrations) that is blocked from entering the protected cleanroom from the outside corridor. BE is a criterion to quantify the effectiveness of cleanroom particle containment in

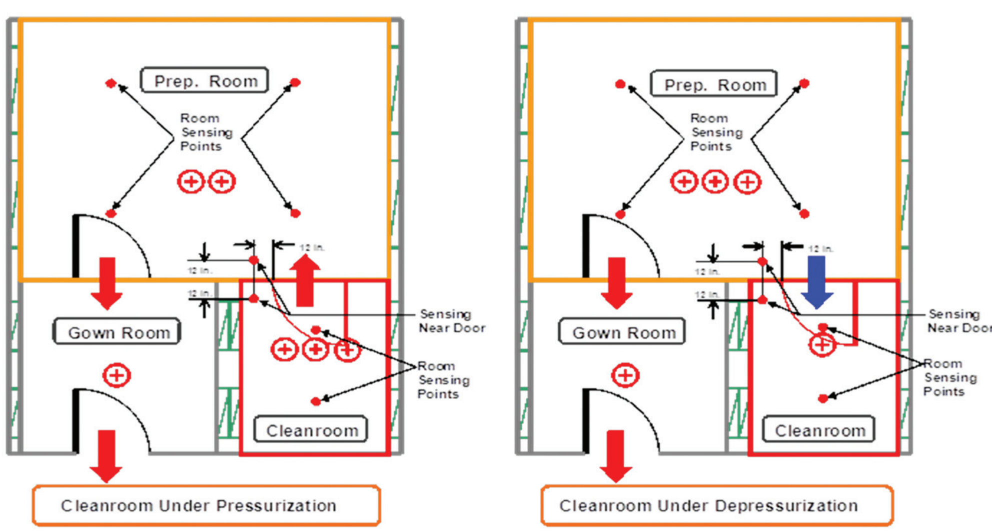


Figure 2 *Protocol of particle sensors' locations in the study (suite of three cleanrooms).*

preventing the particles' migration into the cleanroom through a barrier device, such as a single door, a double-door airlock, etc.

$$BE = 1 - CR$$

where,

BE = barrier effectiveness against particle migration under challenge, in percentage.

Contamination Ratio Versus Concentration Ratio, Cleanliness Class Ratio, and Cleanliness Class Difference

Based on ISO Standard 14644-1, cleanroom cleanliness is represented by the average particle concentration that is measured at multiple, evenly spaced locations inside a cleanroom (1999). The number of measuring or sampling points depends on the size of the cleanroom. Average room particle concentration can be considered a continuous variable as long as it can be sampled continuously at a certain time interval. The ratio between the average cleanroom concentration and the average corridor concentration can be called *concentration ratio between rooms*.

ISO Standard 14644-1 defines the cleanliness class based on the maximum allowable particle counts in each particle size range (channel), and each class is about × 10 of particle counts apart in each channel (1999). Therefore, cleanliness class is not defined as a continuous variable but as a fixed and step value. The cleanliness class ratio between two adjacent cleanrooms is typically at 1, 10, 100, 1,000...10^N. N=0, or ratio=1, means zero-class difference, N=1, or ratio=10 means one-class difference; and so on. Therefore, cleanliness class ratio and cleanliness class difference are virtually telling the same thing. The first terminology is expressed in 10^N, and the second is expressed in continuous numbers—1, 2, 3, and so on.

Contamination rate measures the relative particle gain due to the next door challenge. To examine the true contamination across the door, either in door-closed or door-in-operation conditions, the sensors are intentionally placed at the vicinity across the door. Therefore, CR is aimed at particle exchanges from the unclean area into a cleanroom. For a large cleanroom, the particle contamination inside the cleanroom near the entrance door has less impact on, or takes a long time to reach, the most remote corners of the cleanroom. Therefore the CR is uniquely defined to measure the relative contamination from a contaminated space to its adjacent cleanroom, as shown in Figure 3.

CR Value During a Door Operation Cycle Under Various Initial ΔPs

As a part of the ASHRAE RP-1431 research, it was found that the CR value is much higher during door-in-operation (one opening and closing cycle) conditions than at the door-closed condition during the door operation as shown in Figure 4 (2012). It was also found that the CR value increases suddenly at the time when the door returns almost to the closed position. Furthermore, the CR value increases when the cleanroom pressure differential in respect to the less-clean corridor increases. Figure 5 is a summary chart that combines all the individual charts in Figure 4. Figure 5 also illustrates the impact of human

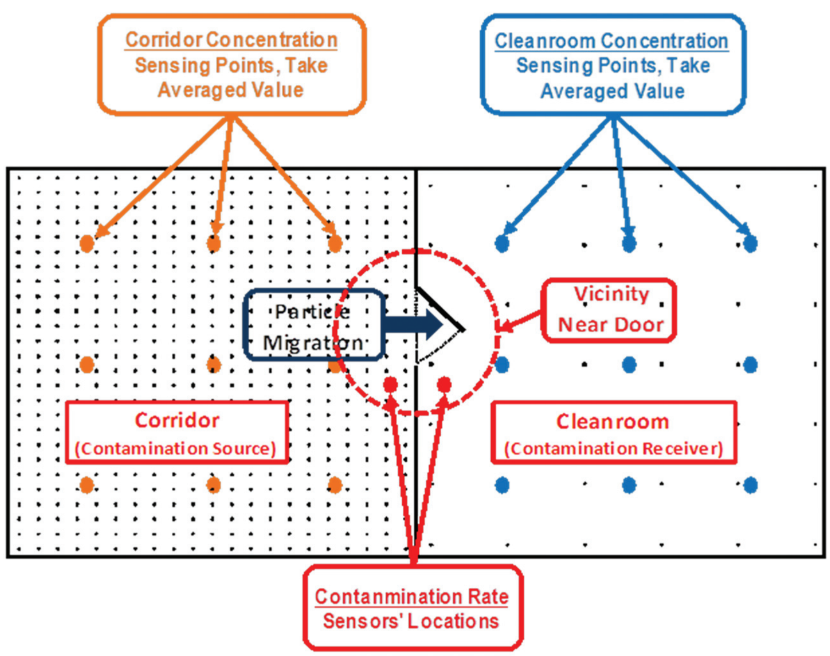


Figure 3 *Contamination ratio versus concentration ratio.*

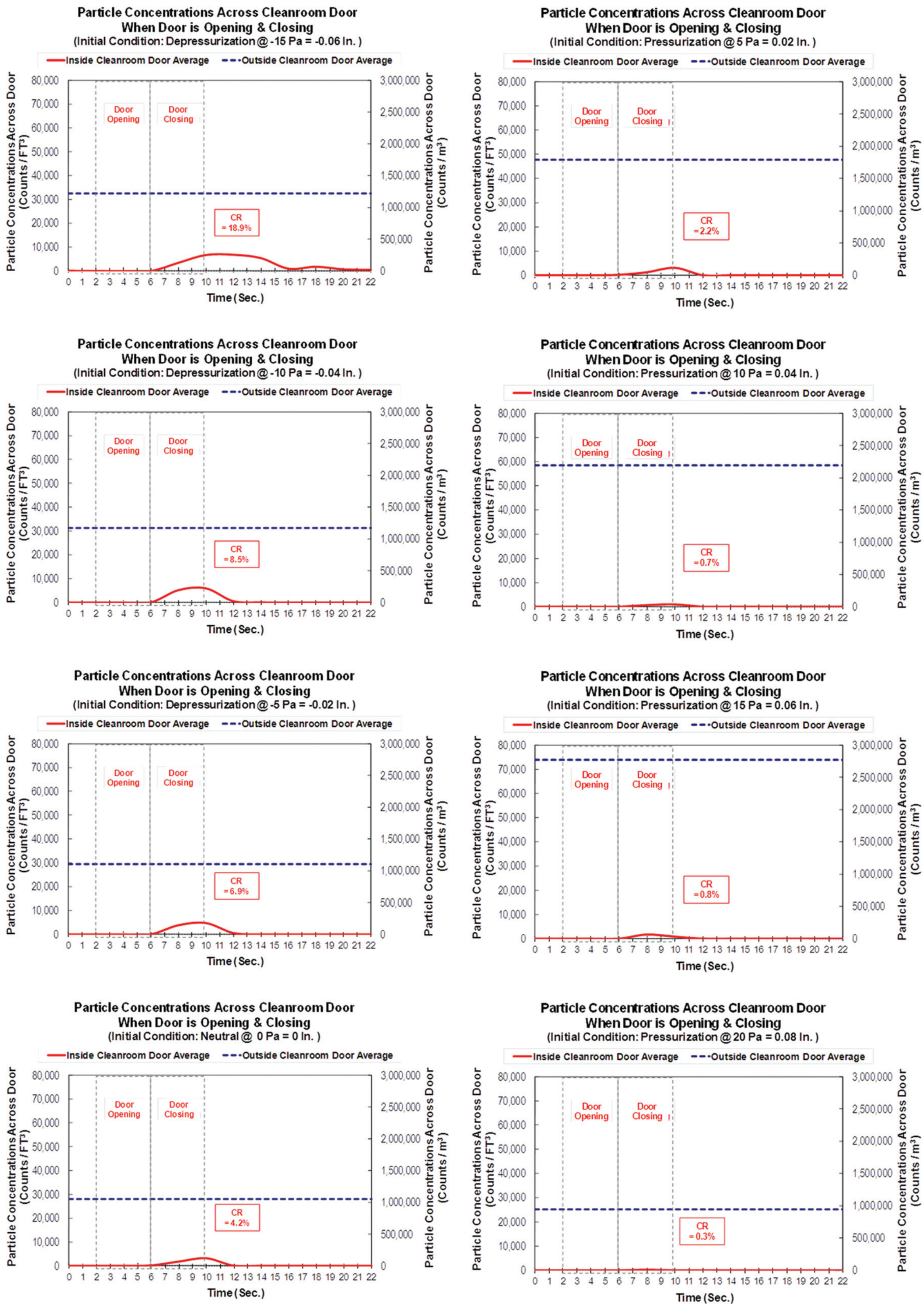


Figure 4 *The CR value during door-in-operation conditions is much higher than in door-closed conditions. Higher initial* Δ P *could decrease the CR value (Sun 2012).*

walk-through influence during door operation—it was found that human traffic could decrease the CR value slightly when the cleanroom is under negative pressure and increase the CR value slightly when the cleanroom is under positive pressure.

Why Both Static and Dynamic Contamination Controls Need to Be Considered in Design

A typical cleanroom door could be operated many times a day. Test data shows that the contamination ratio at door-opened conditions is much higher than at the door-closed conditions, although its duration is much shorter. Many factors such as pressure differential, cleanliness class difference, leakage conditions, etc., could impact the daily accumulated contamination results greatly. Figure 6 illustrates that the impacts from both static (door-closed) and dynamic (door-in-operation) conditions could be equally important based on practical applications. The daily frequency of door operation is also a key element in overall daily contamination. It is recommended in this research that a daily door operation more than 30 times is considered

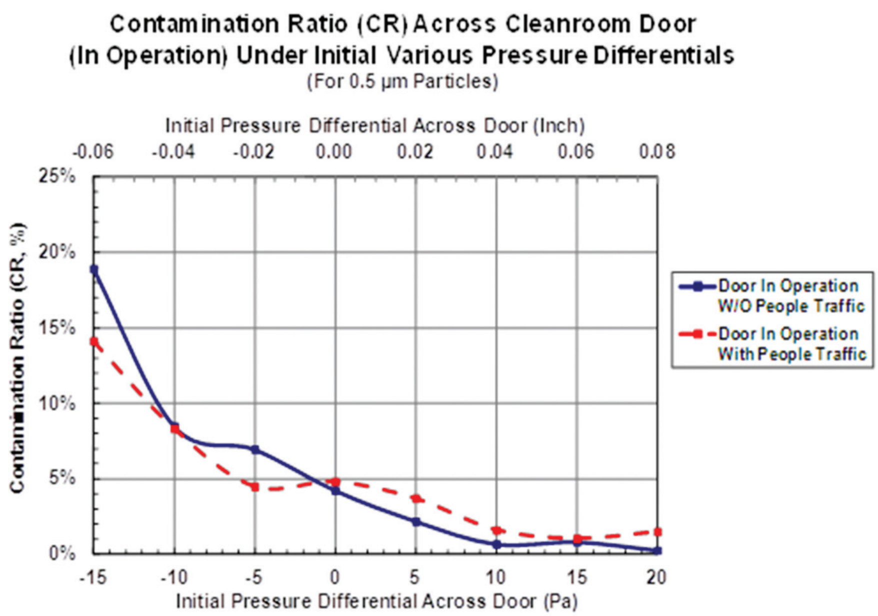


Figure 5 *The CR value during door-in-operation conditions under initial pressure differentials, with and without people traffic (Sun 2012).*

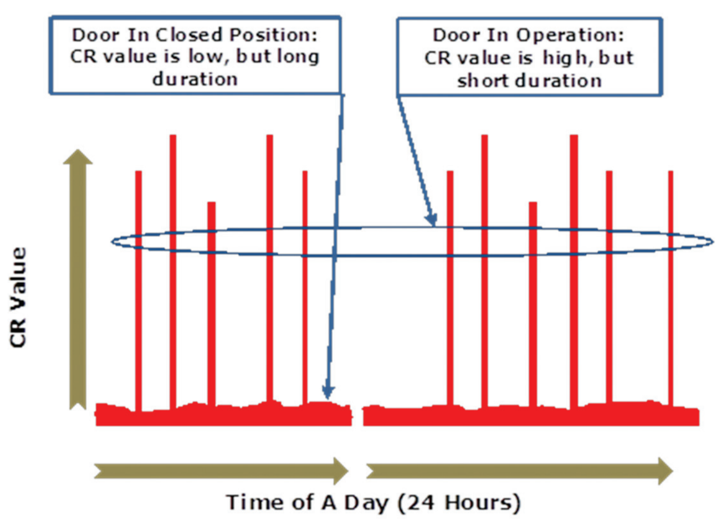


Figure 6 *Daily accumulated contamination during door-closed and door-in-operation conditions.*

"frequent operation" and dynamic contamination control should be considered.

Time-Averaged Contamination Rate and Daily Accumulated Contamination Rate

Contamination rate values vary between door-closed and door-in-operation conditions, and the value in the later situation usually is much higher. To analyze the overall contamination over a period of time that also counts the frequency of door operations, a new terminology called *time-averaged contamination rate* is defined as follows,

$$CR_T = \frac{\int_0^T CR \cdot dt}{T} = \frac{\int_0^T \left(\frac{P(t)C - P_B}{P(t)O}\right) \cdot dt}{T}$$

$$= \frac{\int_0^T \left(\frac{P(t)C}{P(t)O}\right) \cdot dt - \int_0^T \frac{P_B}{P(t)O} \cdot dt}{T}$$

where

CR_T	=	time-averaged contamination rate over a time period, dimensionless
$CR(t)$	=	contamination rate at any time, dimensionless
T	=	time period under consideration, s
$P(t)C$	=	particle concentration in cleanroom near door at any time, counts/ft^3 (counts/m^3)
$P(t)O$	=	particle concentration at corridor near door at any time, counts/ft^3 (counts/m^3)
P_B	=	cleanroom initial background particle concentration, counts/ft^3 (counts/m^3)

Typically, an initial background concentration reading, P_B,is taken without corridor particle challenge, so $P_B < P_C \ll P_O$ When P_C is less than 0.1% of P_O, then the term of $\frac{P_B}{P(t)O}$ can be ignored, so,

$$\mathrm{CR}_T = \frac{\int_0^T \mathrm{CR} \cdot dt}{T} \approx \frac{\int_0^T \left(\frac{P(t)C}{P(t)O}\right) \cdot dt}{T}$$

$\int_0^T \mathrm{CR} \cdot dt$ can be called the *accumulated contamination rate during a time period*. If 24 hours (one day) is used as the time period, then we can call it *daily accumulated contamination rate*. Daily accumulated contamination rate can be taken during a typical operational day, which is a good representation to analyze the overall contamination over an extended time period. This value includes the scenarios not only at door-closed and door-opened conditions but also the frequency of door operations.

DATA RESULTS, ANALYSIS, AND FINDINGS

Test Floor Plan, Setup and Photos

Figure 7a shows the cleanroom test lab configuration, and Figures 7b through 7g illustrate the test equipment and preparations. In this research, to achieve a certain PD in a room, a supply air (SA) rate remained constant to maintain the same air changes per hour (ACH). Only the return air (RA) rate was adjusted through a manual damper. Once the needed PD was obtained, then the SA and RA flow rates were measured manually by a flow hood that was calibrated routinely with ±3% error in accuracy. Tests were repeated for other PDs as well. High-precision pressure differential sensors were in ±0.5 Pa (±0.002 in.) accuracy in the measured flow range. Multiple-channel particle counters were used from several manufacturers. Some latest models have 6 channels (0.1, 0.2, 0.3, 0.5, 1.0, and 5.0 μ m), while others have 5 channels. Sampling speed with the time indicator was set at 1s for dynamic testing and 10 s for static testing. Particle measurement accuracies from various manufacturers were within 10%. All test data have at least three replicas. Data accusation software was utilized for dynamic testing on particle count and pressure differential readings and on flowrate readings as well during blower door tests.

Data Treatment

Figure 7h is a typical particle concentration data collection chart. Multiple particle-count readings (replicas) were collected over the entire measurement time duration T with a specific sampling time interval. Particle concentration between two sequential readings can be linearly extrapolated. Then particle-count reading at any time, P_i, can be mathematically treated as a continuous function, therefore average particle concentration P_A can be expressed as

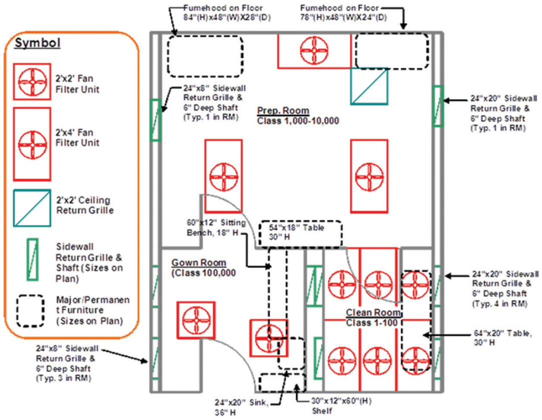
$$PA = \frac{\int_0^T P_i \, dt}{T}$$

If a counter's sampling speed is S, and the time recording interval is consistent (equal), and the total number of readings is N, then,

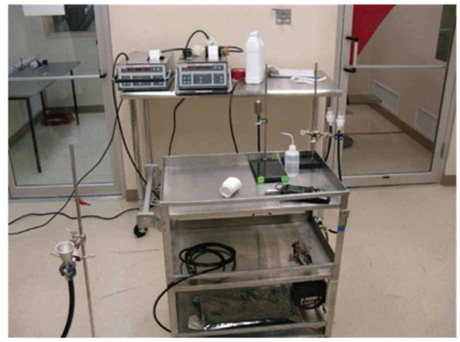
$$T = S(N-1)$$

$$P_A \approx \frac{\sum_{i=1}^{N} (SP_i)}{S(N-1)} = \frac{\sum_{i=0}^{N} (SP_i)}{SN} = \frac{\sum_{i=0}^{N} P_i}{N}$$

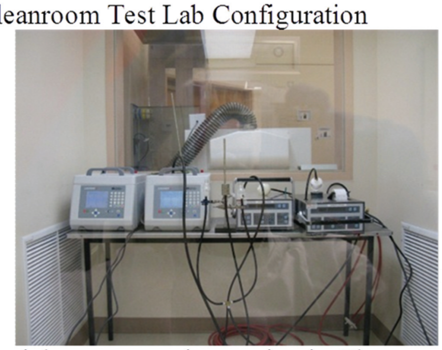
For an automatic pre-manufactured swing or sliding door, each door opening/closing cycle T_D typically ranges from 6 to 10 s and is adjustable in the field. In this project, 8 s was used as an average cycle. For the particle contamination test during the door-in-operation conditions, it is



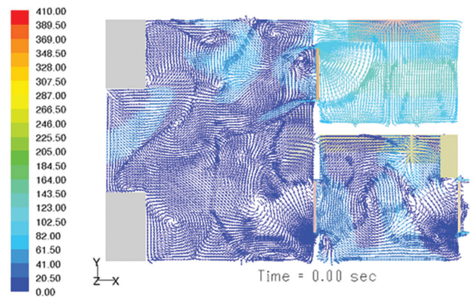
a Cleanroom Test Lab Configuration



b. In Prep. Rm.: Gown Rm. (right), Cleanroom (left)

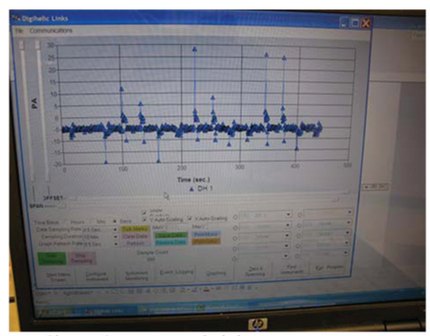


c. Particle concentration testing in Cleanroom



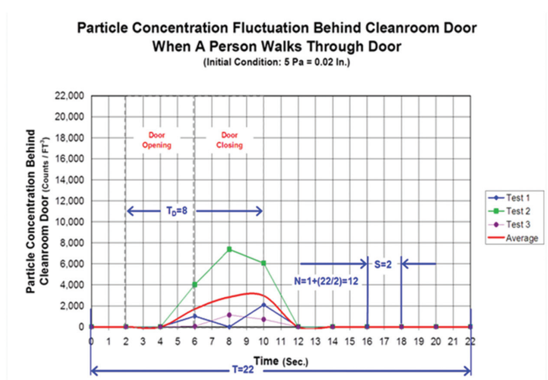
d. CFD to analyze particle distribution and migration

e. Room background leakage testing by airflow control devices when ceiling and door are sealed



f. Fast sampling data acquisition system to analyze pressure fluctuations

g. Cleanroom "background leakage" test with blower door to identify initial room leakage before pressurization tests by HVAC system.



h. Sample of Collected Data (Similar In SI Units)

Figure 7 *Lab floor plan, photos, and sample data.*

recommended that the entire test (sampling) duration T be set around three times of door-opening/closing cycle times, T_D.

Based on contamination rate (CR) determination, then:

$$CR = \frac{P_C - P_B}{P_O} = \frac{\dfrac{\sum_{i=0}^{N} P_{Ci}}{N_C} - \dfrac{\sum_{i=0}^{N} P_{Bi}}{N_B}}{\dfrac{\sum_{i=0}^{N} P_{Oi}}{N_O}}$$

Further, if a cleanroom background particle concentration is extremely low compared with the concentration after the challenge is imposed, then the contamination rate becomes the contamination ratio:

$$CR = \frac{P_C}{P_O} = \frac{\dfrac{\sum_{i=0}^{N} P_{Ci}}{N_C}}{\dfrac{\sum_{i=0}^{N} P_{Oi}}{N_O}}$$

Where N_C, N_B, and N_O refer to particle sampling numbers for the cleanroom background, cleanroom under challenge, and corridor, respectively, and they can be set at an identical sampling speed so that $N_C = N_B = N_O$.

CR Value Across a Closed Door Under Various ΔPs

Figure 8 shows that at door-closed conditions that the CR value decreases significantly for both 0.5 and 1.0 μm sizes when the cleanroom pressure differential ΔP changes from negative to positive and further increases. However, when ΔP is above 0.04 in. (10 Pa), the CR may not decrease much further. Also, similar to what is shown in Figure 6, the CR level is much lower when the door is in the closed position than the open position. Therefore, from both static (door closed) and dynamic (door-in-operation) analysis, a minimum of 0.04 in. (10 Pa) for room pressure differential is adequate. Anything below that level could be risky. Also, the benefit to setting pressure differential high above 0.04 in. (10 Pa) is not very significant.

Impact on CR Value when Contamination Level Increases in Adjacent Area

If a cleanroom is adjacent to a less-clean or a contaminated space separated by a door as a physical barrier, whether the door is in closed, slightly opened, or in-operation conditions, the cleanroom is challenged by the high-concentration particles from the other side of the door. In the tests, as shown in Figure 10a, the cleanroom, which has an average of 430 counts/ft^3 (15,179 counts/ m^3) concentration, was adjacent to a less-clean room (prep room) at an averaged 4663 counts/ft^3 (164,604 counts/ m^3) concentration, which is about one class dirtier. Over a wide range of pressure differentials and door gaps, when the average concentration in the prep room is raised to 47,144 counts/ft^3 (1,664,183 counts/ m^3) (an increase of 10.1 times, about two classes dirtier), then the concentration in the cleanroom responds and increases to 508 counts/ft^3 (17,932 counts/ m^3) (an 18% increase). When the prep room is further raised to 480,351 counts/ft^3

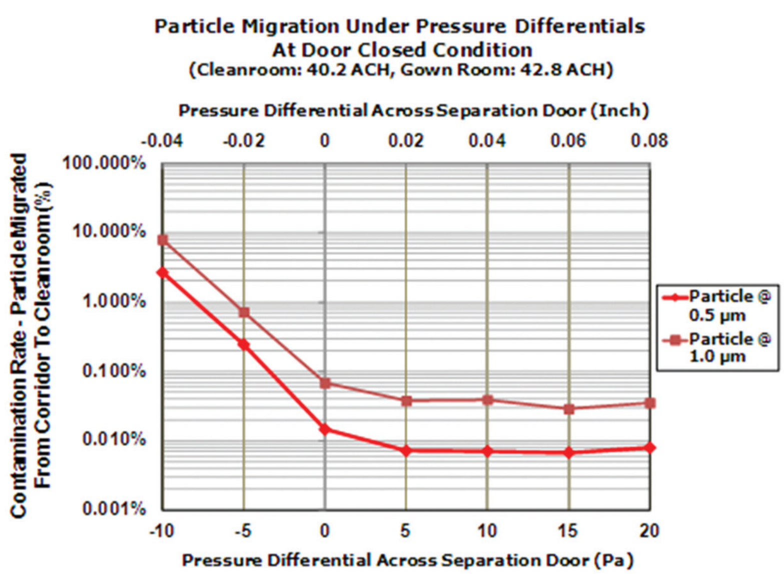


Figure 8 *CR values across a closed door under pressure differentials.*

(16,956,390 counts/ m^3) (a further increase of 10.2 times, about three classes dirtier), then the concentration in the cleanroom increases to 625 counts/ft^3 (22,063 counts/ m^3) (a further 22% increase, or an accumulated 45% increase).

From this set of tests, it is found that when the surrounding particle challenge increases, a cleanroom that typically is not 100% airtight could receive more particles from the other side by particle migration though minor cracks. In other words, the absolute contamination in the cleanroom increases. However, the interesting phenomenon is that the relative contamination, measured by contamination rate, actually decreases. Therefore, the resulting particle concentration in the cleanroom near the door does not proportionally respond to the increase of particle challenge on the other side of the door.

From the tests, about a 20% (ranged from 18% to 22%) particle concentration increase in the cleanroom near the door is noticed for each cleanliness-class reduction in the surrounding area. Of course, this percentage could be lower or higher under other conditions with different room airflow rates and room airtightnesses.

If a particle gain of around 20% to a cleanroom when challenged by a two-class-dirtier surrounding space with frequent door operations is not acceptable, or a particle gain of around 45% to a cleanroom when challenged by a three-class-dirtier surrounding space with less frequent door operations is not acceptable, then a single door alone as a particle barrier may not be adequate to defend the particle challenge disregard the pressure differential. In another ASHRAE project RP-1344 study on airlocks, it was found that airlock is possibly the most effective mechanism to minimize particle migration not only during door operation (dynamic conditions) but also in the door-closed situation (static conditions) since a time delay between two doors could allow the contaminated air entered the airlock space (after the first door operation) to be replaced by the clean supply air. Therefore, it is suggested to utilize a two-door airlock to replace a single door when a cleanroom is adjacent to a less-clean space of two-class cleanliness dirtier with frequent door operation or of three-class cleanliness dirtier with less frequent door operation.

A typical cleanroom door could be operated many times a day. Test data show that the contamination rate at the door-opened conditions is much higher than at the door-closed conditions, although its duration is much shorter. It is illustrated that the impact of contamination in both static (door-closed) and dynamic (door-opened) conditions could be equally important for design consideration. During the RP-1431 airlock study (see Figure 9), four typical airlock types are listed—cascading, bubble, sink and dual-compartment—based on pressure differential arrangements among corridor, airlock and cleanroom (Sun 2012). Although detailed research on airlocks is not a scope of this research, it is further found in the RP-1431 research that once an adequate time delay is provided, the benefit of having a pressure differential over 5 Pa (0.02 in.) across each airlock door may not be significant. Therefore, a minimum of 5 Pa (0.02 in.) across each airlock door is recommended, as shown in Figure 9.

It is very important to understand that in addition to the PD that can force a desired airflow carrying particles, the particle concentration differential can also force an airflow to allow the concentrations in both rooms to reach an equilibrium due to the mass diffusion if the time is long enough and the path of the particle exchanges is through the connecting cracks or openings. In a typical pressurized cleanroom case, these two particle flow paths (by pressure differential and concentration differential) are in the opposite directions, the sum of two opposite flows is the net leakage flow, and the net particle exchange is that typically a cleaner room gains more particles from the less clean side even if the cleaner room's pressure is higher, since the Δ P brings fewer particles to the less clean room while the less clean room releases many more particles to the other side due to mass diffusion, as illustrated in Figure 10b.

Air Change Rate Impact (Low ACH versus High ACH) on Particle Migration

If a cleanroom is initially under the fixed offset flow value (SA-RA value remains constant for all rooms) and under positive pressure, and a cleanroom door opens slightly to create an air gap between the door and its frame, when the air gap widens, the leakage area of the door gap increases, the pressure differential across the door decreases, and CR increases at all particle sizes tested (0.3, 0.5, and 1.0 μm).

Comparing between Figures 11a and 11b, one can see a cleanroom with higher ACH has a lower CR value when all other variables remain the same. However, using higher ACH is not a cost-effective option to achieve a lower CR value, in comparison with using higher ΔP value. In a higher ACH cleanroom, 1.0 μm particles do not impose more contamination than the 0.3 μm and 0.5 μm particles, until the door is opened to 30 degrees and wider.

When a cleanroom door is opened 30 degrees and wider, although the ΔP value drops to zero, the CR value increases continuously, because the air velocity through the door opening is getting lower under the same offset flow.

Impact of Temperature Differential on Particle Migration

It is found that when the cleanroom is at neutral or positive pressure in respect to the surrounding area (gown room was used), a 5°F or 10°F (2.5°C or 5.0°C) colder cleanroom than surrounding does not have any noticed impact on particle migration, as shown in Figure 12a. However, when the cleanroom is at negative pressure in respect to the surrounding area, a 5°F or 10°F (2.5°C or 5.0°C) colder cleanroom could actually slightly reduce particle migration. It is believed that colder air in a cleanroom has higher density than the air in the warmer gown room, which generates an opposite flow direction (due to mass diffusion to even out the particle concentration differential on both sides) against the leakage airflow caused by depressurization, thus slightly reducing particle migration. A warmer cleanroom has not been tested since more often a cleanroom is colder and dryer than the surrounding areas.

Impact of Relative Humidity Differential on Particle Migration

It is found that when the cleanroom is at neutral or positive pressure in respect to the surrounding area (gown room), a 5% or 10% (in relative humidity) dryer cleanroom than surrounding does not have any noticed impact on particle migration, as shown in Figure 12b. However, when the cleanroom is at negative pressure in respect to the surrounding area (gown room), a dryer cleanroom (5% or 10% dryer) could actually slightly increase particle migration. It is believed that wetter air has higher water content and higher air density, which has a tendency to even out the moisture imbalance (water vapor density differential) with dryer room air through connecting openings. This natural force generates a reinforced flow following the leakage airflow direction caused by depressurization, thus slightly increasing particle migration. A wetter cleanroom has not been tested since more often a cleanroom is colder and dryer than the surrounding areas.

Discussion on Airtightness Requirement for Cleanroom Envelope

Sun (2003) analyzed the power equation and orifice equation, which are commonly used by building leakage and airtightness researchers, and illustrated the relationship between Equivalent Leakage Area (ELA) and leakage flow rate Q and further indicated that the room flow offset value ΔV is the mathematical summation of all leakages, $\sum Q$, in the room, which is also indicated in Figure 1. Either the power equation or the orifice equation indicates that a larger room ELA causes a higher leakage rate Q under the same pressure differential ΔP and a higher overall leakage rate, $\sum Q$, in a room would require more offset flow ΔV between the room's incoming air (SA) and leaving airs EA+RA (combined exhaust and return air).

Higher offset flow ΔV could create challenges in design. The room SA rate is typically determined by heating/cooling load calculations and set to be controlled by room thermostat

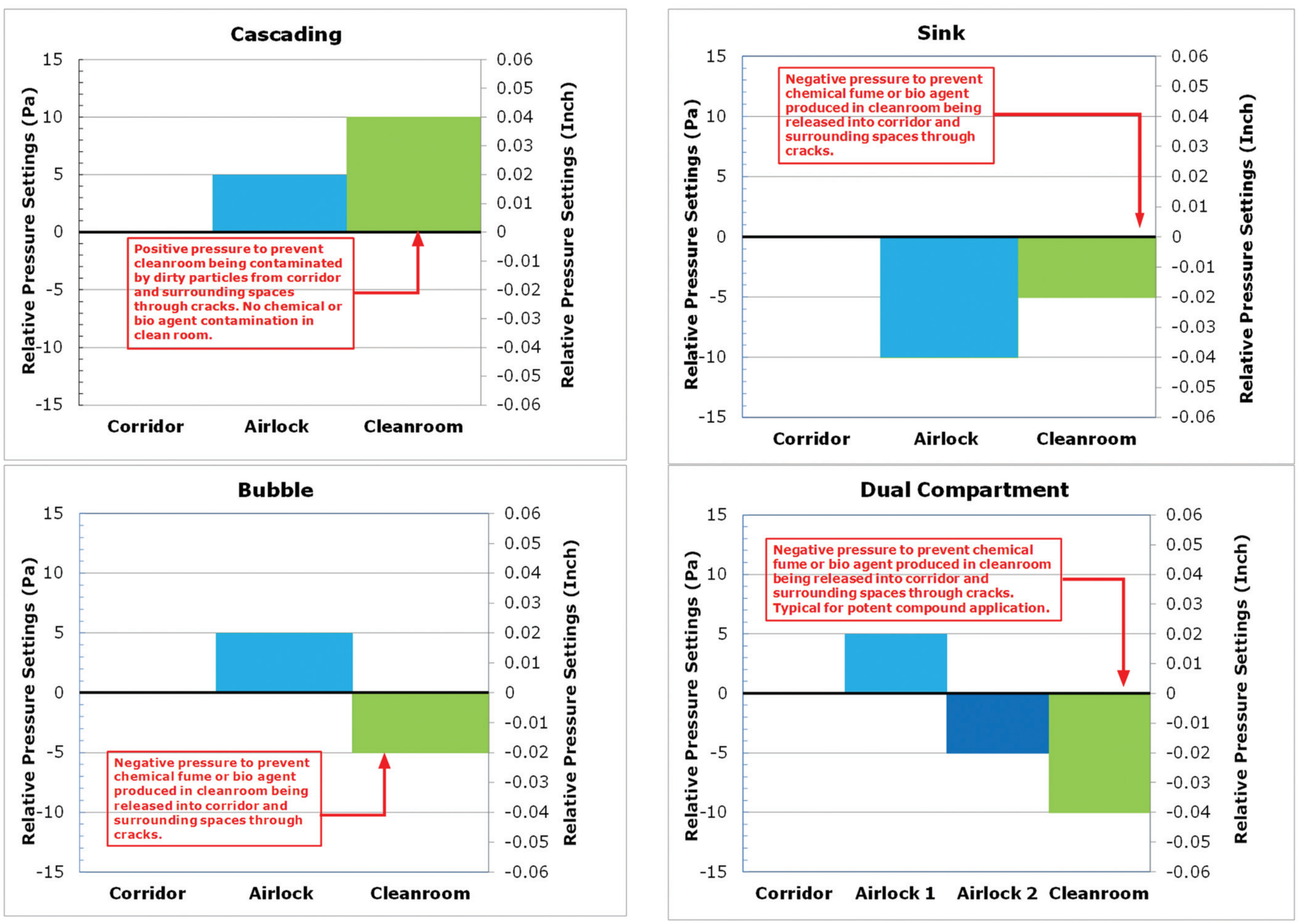
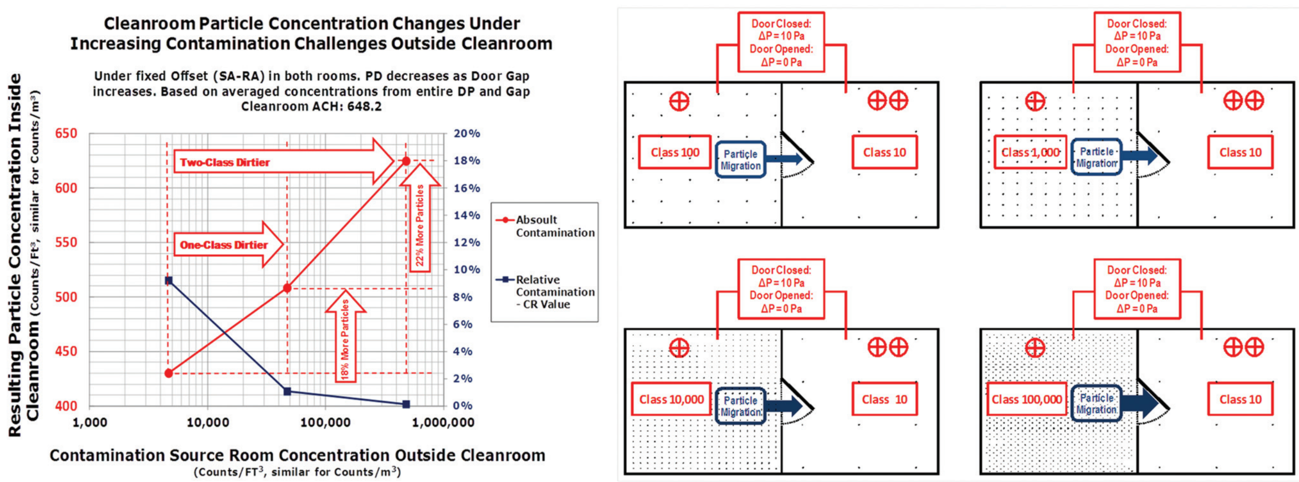


Figure 9 Minimum pressure differential values for airlock rooms (Sun 2012).

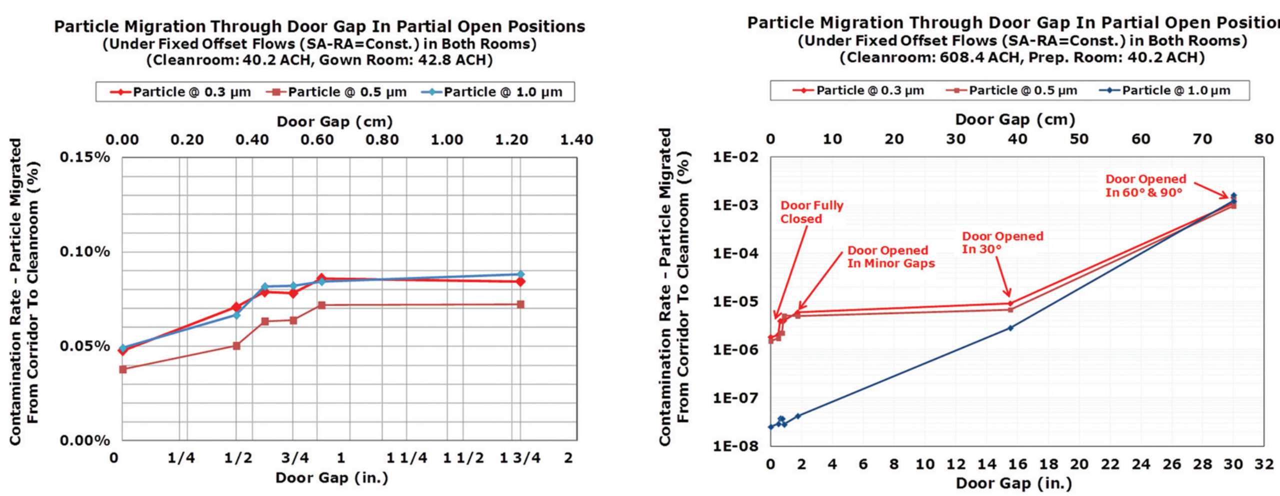
and sometimes with a minimum ACH requirement. For a pressurized room, the total exhaust and return air flows, EA+RA, need to be lower to allow a higher ΔV. For a small and leaky room, sometimes even with no return and no exhaust air, the entire SA amount still may not be adequate to create the needed ΔV. For a depressurized room, the EA+RA rate needs to be significantly higher than SA to allow a higher ΔV, since SA can only be altered by temperature control, not typically used for room pressure control, as SA is often and mainly to meet room temperature, plus possibly ACH and humidity, requirements. Sun (2005) further analyzed the energy impact: when a higher offset ΔV is required for each of the pressure-controlled rooms served by a common air-handling unit (AHU), then more outdoor air (OA) needs to be brought in and treated with heating or cooling in the AHU, which often consumes more energy.

A cleanroom enclosure (room envelope) typically is constructed of architectural components such as walls, ceiling, floor, doors, and windows, etc. If a cleanroom is required to have room pressure controlled, the cleanroom shall be designed, constructed, and maintained in such a manner that the room enclosure is relatively airtight. The airtightness of the entire room envelope, in terms of ELA, has often been ignored by design professionals since most published design standards and guides do not, or at least do not adequately, address this issue. Although room airtightness study is not a part of the research scope, further research is needed to quantify and



(a) (b)

Figure 10 *(a) Cleanroom particle concentration change when contamination level increases in adjacent area across door and (b) transport of more particles (mass diffusion) into cleanroom when adjacent area is much dirtier.*



*(**a**: Low ACH)* *(**b**: High ACH)*

Figure 11 *CR value when cleanroom door is partially opened with a small air gap.*

propose a cleanroom envelope airtightness design criterion for design professionals.

To obtain the same pressure differential, it is more cost-effective to make a room tighter (by better sealing), which requires a smaller flow offset between incoming (supply) and leaving (return or exhaust) airflows, than a looser room, which requires a larger flow offset—a larger imbalance between incoming and leaving airflows in rooms typically requires bringing more treated (heated/cooled and filtered) outdoor air to AHU units, which uses more energy and makes the task of HVAC design and air balance more complicated.

CONCLUSION

Airtightness of Cleanroom Envelope

Slightly tighter room envelope construction is recommended by providing necessary architectural details. This effort can make room air balance and pressure control more achievable and can save operational cost and energy. Quantitative cleanroom envelope airtightness value(s) as a minimum requirement should be further studied.

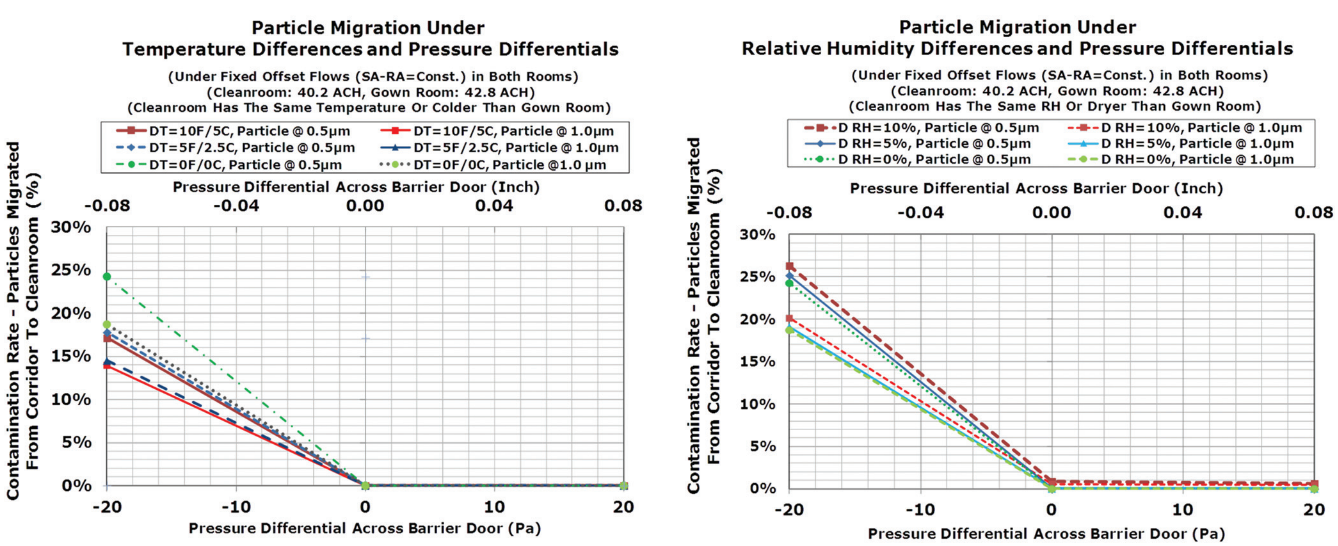
Pressure Differential (ΔP) Across Cleanroom Envelope

A cleanroom envelope (including doors) is a natural barrier to contain particle migration. However, when a door is opened for traffic, the initial pressure differential across the door/envelope disappears quickly (typically less than 0.25 s) before the door is closed (typically 6–10 s), much more quickly than any airflow control devices (such as air valves) to modulate from prior flow positions to the new positions (1–2 s).

The magnitude of particle migration is much higher at the door-in-operation (dynamic) conditions than at the door-closed (static) conditions. Additional treatment is required and associated design criteria need to be considered in door-in-operation conditions.

An effective mechanism to tackle the issue is to install a two-door airlock with a proper time delay. A time delay between two doors can allow the airlock room air to be fully or partially replaced by filtered clean air supplied to the room. An airlock can reduce particle migration not only during door operations but also in door-closed conditions.

Table 1 shows the recommended minimum pressure differentials (ΔP) across the cleanroom envelope and is a summary of this research. The table is intended to be used for cleanroom design professionals for convenience without utilizing calculation tools. For example, cleanliness class difference instead of particle concentration ratio is used in the table since the latter would require particle measurement to obtain it; Figure 5 shows that a minimum PD of 0.04 in. (10 Pa) is required to minimize particle migration under door-in-operation conditions, while Figure 8 shows that under door-closed conditions a PD over 0.02 in. (5 Pa) does not bring extra reduction of particle migration. In other words, if a door is never opened then a PD of 0.02 in. (5 Pa) is adequate. However, a door is purposely for traffic for people, materials, or products; therefore, particle migration under door-in-operation conditions becomes the dominant factor and 0.04 in. (10 Pa) is selected as the minimum requirement. Figure 10a indicates that each additional cleanliness class difference between the cleanroom and adjacent area will cause about 20% more particle gain into the cleanroom from these tests. Therefore, the



(a) (b)

Figure 12 *Impact on particle migration (a) under temperature differential across cleanroom wall and (b) under relative humidity differential across cleanroom wall.*

consideration of door operation frequency is included and an airlock may need to be used over the established threshold.

It should be noted that Table 1 only applies for controlling the nonviable particle migration between a cleanroom and adjacent areas, as the test findings were conducted for nonviable particle contamination only. Additional research on microbial migration under various pressure differentials needs to be conducted in the future. Obviously if both particle and microbial migrations across a room envelope need to be considered and controlled, then the worse of the two may be the dominating criterion.

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Table 1. Recommended Minimum Pressure Differential (ΔP) Across Cleanroom Envelope to Control Nonviable Particle Migration from Adjacent Less-Clean Area

Cleanliness Class Difference Between Cleanroom and Adjacent Less-Clean Area	Door Closed (Static)	Door In Operation (Dynamic)
	Minimum Pressure Differential (ΔP) Between Rooms	Installation of Airlock
One-Class Difference (e.g., ISO Classes 7 and 8 adjacent rooms across door)	10 Pa (0.04 in.)	Not Required
Two-Class Difference (e.g., ISO Classes 6 and 8 adjacent rooms across door)	10 Pa (0.04 in.)	Required if door operation is frequent (more than 30 times daily) (1) Install a two-door airlock to replace single door that separates two areas. (2) Minimum 5 Pa (0.02 in.) across each door of the airlock. (3) Time delay between two doors in airlock . Not Required if door operation is not frequent (30 times or less daily).
Three or More Class Difference (e.g., ISO Classes 5 and 8 adjacent rooms across door)	10 Pa (0.04 in.)	Required (1) Install a two-door airlock to replace single door that separates two areas. (2) Minimum 5 Pa (0.02 in.) across each door of the airlock. (3) Time delay between two doors in airlock.
Cleanroom Surrounded by Non-Cleanroom Areas		

Note: Refer to Figure 9 for detailed pressure differential arrangement for various airlocks.

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