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Characterization of Minienvironments in a Cleanroom: Design Characteristics and Environmental Performance

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1. Abstract

A minienvironment is normally used to maintain a level of stringent cleanliness through controlling particle concentrations within a tightened volume of clean spaces. Because minienvironments are expected to locally achieve a higher level of cleanliness than their adjacent cleanroom, it is important to understand the characteristics of their design and operation and effectiveness in environmental control. This paper presents findings from a field study on a group of minienvironments, with the focus on characterizing and evaluating environmental performance of the minienvironments as part of a large-scale of field investigation into the total performance of the minienvironments operating in a cleanroom. In particular, this paper summarizes design and operating characteristics and presents measured environmental performance of five minienvironments and the cleanroom that housed them. The study discovers that pressure differentials as low as under 0.2 Pa can be sufficient for achieving a high level of air cleanliness to meet environmental control expectation and requirements. Comparisons with relevant industry standards show that existing standards or guidelines may have been suggesting thresholds that are higher than necessary at least in some minienvironment applications. The

paper suggests potential benefits from identifying and optimizing the required range of pressure differentials, and likely opportunities and challenges in improving the system's total performance through further studies and refining relevant standards.

2. Keywords

Minienvironment, cleanroom, airflow, pressure differential, environmental performance, cleanliness, particle concentration

3. Background

A minienvironment is a type of separate device mainly used in microelectronics industry to maintain a level of stringent cleanliness in a tightened volume of clean spaces. It is a localized environment created by an enclosure to isolate or separate a product or process from the surrounding environment [1] [2]. The purpose of a minienvironment is to achieve effective control of particle concentration in a localized space, often through maintaining desired pressure differential or supplying unidirectional airflows needed for maintaining cleanliness levels within the space.

Some minienvironments provide various device and physical configurations to actively or passively direct air from the surrounding cleanroom to and from the minienvironments. Some other minienvironments include independent systems to accommodate specific requirements for temperature control, humidity control, and chemical filtration as part of their operation. With the demand for better contamination control in specific applications, e.g., higher cleanliness within a localized and relatively small space, it is important to understand minienvironments' characteristics and effectiveness in particle control, and to optimize planning and design of clean spaces so that contamination control effectiveness is attained or improved.

The ISO and IEST publish the methods or protocols on construction and operation of minienvironments and cleanrooms [3][4][5]. Previous investigations or guidelines focused on

design optimization of minienvironments mainly through simulation and modeling and some experiments [6][7][8][9][10]. Other studies or benchmarking activities addressed the impact of production yields by adopting minienvironments [11][12]. Recent field evaluations quantified the energy performance of a minienvironment as a function of airflows and pressure differential under various operation conditions [13][14][15]. Overall, very limited field data was available or published to quantify the characteristics of environmental performance of minienvironments in their actual operation. For example, a field study on minienvironments provided performance data on yield but excluded quantitative information on the particle concentrations in the enclosing cleanroom facility [11]. Prior to this study, virtually no published data associated with the use of minienvironments in operation was available to quantify their characteristics including both environmental performance and energy-savings potential.

In order to further understand the benefits of minienvironments in contamination control and total performance of minienvironments in cleanrooms, it is necessary to review the characteristics and to quantify the magnitude of environmental performance of minienvironments. This paper will focus on characteristics and environmental performance of the minienvironments and the surrounding cleanroom. Evaluations and discussion about their energy performance and energy-saving implications from applying the minienvironments in traditional cleanrooms is presented in a separate paper [16].

4. Scope and objectives

This paper presents the measured results from a field characterization to understand design characteristics and environmental control in a group of minienvironments housed in a cleanroom.

The objectives of this paper include the following: 1) review and evaluate the design and operation characteristics of minienvironments in operation; 2) measure and evaluate environmental performance of the minienvironment systems; and 3) understand the key factors and measures that may influence the effectiveness in particle control within minienvironments

5. Methods

Reviews of open literatures and a field investigation were carried out to assess the characteristics and to quantify environmental performance of minienvironments. Normally, dimensions of the minienvironment spaces may vary depending on specific applications. Some of advantages in using minienvironments include creating cleanliness-class upgrade, better contamination control, and process integration; and maintaining better contamination control by controlling pressure differentials or providing unidirectional airflows.

In the cleanroom studied, there were various activities that required different environmental conditions depending on the process or locality within an ISO-Cleanliness-Class-4 cleanroom, i.e., ISO-Cleanliness-Class-3 and/or ISO-Cleanliness-Class-4 localized spaces. A number of minienvironments with a cleanliness level designated to be equivalent to ISO-Cleanliness-Class-3 spaces in the cleanroom were installed in the facility. In this study, the measured parameters included airflow speeds, airflow rates, static pressures, and particle concentrations in the minienvironments under their normal operating conditions, and concurrent electric power demand (representing energy end-use). Key parameters were measured to characterize the environmental performance of the minienvironments. When appropriate, comparisons are made to evaluate the performance of the five minienvironments with that of the enclosing cleanroom and other cleanrooms that were previously studied. Based upon analyses of the measured data,

this paper discusses the important factors for consideration in achieving effective particle control in minienvironments.

5.1 Measuring Airflows and Pressure Differential

A backpressure-compensated device attached to an electronic micro-manometer [17] measured the average speeds of the airflow delivered out of the face of the fan-filter units, which were installed at the top of the stand-alone minienvironments. The actual sizes of individual fan-filter units (FFUs) and HEPA filters varied from minienvironment to minienvironment.

The measurement uncertainty in airflow speeds was $\pm 3\%$ of reading plus ± 7 fpm (3.5 cm/s) from 50 to 2500 fpm (0.25 m/s to 12.5 m/s). An airflow measurement device was used to sample 16 points over a 1 ft x1 ft (30 cm x 30 cm) area to determine average airflow speeds at a distance of 2.5 inches (6.3 cm) downstream away from the face of the filter frames. Airflow-speed readings were automatically corrected for the density effect of barometric pressure and temperature. Readings were displayed as local density and true air speeds.

Air pressures were measured using a Pitot tube with a multi-meter. The multi-meter is capable of measuring a wide range of air pressures from 0.0001-inch-water column (0.025 Pa) to over 60.00-inch-water column (15,000 Pa), with a measurement uncertainty of $\pm 2\%$ of reading plus 0.001-inch-water column (0.25 Pa) from 0.05-inch-water column to 50.00-inch-water column (0.125 Pa to 12,500 Pa). The air pressure differential between the space inside the minienvironment and the space surrounding the minienvironment was recorded for each of the minienvironments, concurrent to the airflow measurements under the normal operating conditions.

5.2 Measuring Particle Concentration

In addition to measuring the airflow speeds out of the fan-filter units, air pressure differential between the space inside the minienvironments and the space surrounding the minienvironments, particle concentration levels were measured concurrently to evaluate environmental performance of the minienvironments..

According to the definition of Airborne Particulate Cleanliness Classes in ISO Standard 14644 [18], the classification of air cleanliness in cleanrooms and associated controlled environments is defined in terms of concentration of airborne particles within the space. Equation 1 shows the relationship among maximal permitted particle concentration that is allowed, ISO cleanliness class, and the associated diameter of the particles of concern.

$$C_n = 10^N (0.1 / D)^{2.08} \quad \text{Eq. (1)}$$

Where

- C_n is the maximum permitted number of particles per cubic meter equal to or greater than the specified particle size (D), rounded to whole number.
- N is the ISO cleanliness class number, which must be a multiple of 0.1 and be 9 or less
- D is the particle size in micrometers (μm).

For example, a cleanroom with an ISO-Cleanliness-Class-4 level (N) corresponds to no more than 10^4 (10,000) counts of particles per cubic meter (C_n) with particle sizes of 0.1- μm or larger (D), or 352 counts of particles per cubic meter with particle sizes of 0.5- μm or larger, in the space of concern. Using this concept, a minienvironment with an ISO-Cleanliness-Class-3 level (N) corresponds to no more than 10^3 (1,000) counts of particles sizing 0.1- μm or larger per cubic

meter (Cn), or 35 counts of particles sizing 0.5- μm or larger per cubic meter, of the minienvironment space.

According to the ISO standard [19], laser particle counters [20] were used to measure the particle concentration within the minienvironments. The laser-based particle counter discriminated and counted particles with sizes of 0.1- μm , 0.2- μm , 0.3- μm , 0.5- μm , and 1.0- μm . The airflow rate used for particle sampling was 2 cfm (56.6 Liter/min) supplied by an internal carbon-vane pump in the counters. In general, a higher airflow rate for particle sampling in the chamber of a particle counter indicates higher capacity of sensing particles traveling into the particle counter and better accuracy in particle counts during transitional (or unsteady-state) sampling .

6. Findings

6.1 Characteristics of the Cleanroom

The cleanroom housing the minienvironments in this study was located on the second floor of a two-story semiconductor manufacturing facility in Southern California. The ISO-Cleanliness-Class-4 cleanroom had a total floor area of 4,065 ft² (378 m²) with a ceiling height of 10 ft (3.0 m), and operated 24 hours a day and 365 days a year. In addition to one make-up air system, two types of recirculation air systems served the cleanroom: ducted-HEPA-filter and pressurized-plenum.

The fans in the recirculation air-handling units for the cleanroom were originally designed to deal with possible future expansion, which was expected during the original design and installation. For example, in the original design, airflow rates for recirculation consisted of a) 216,000 cfm (6,120m³/min) to be supplied through a total of four air-handling units connected to

the ducted-HEPA filters, and b) 131,000 cfm (3,710 m³/min) to be supplied by a total of three additional air-handling units connected to the pressurized plenum.

The air-handling units connected to the ducted-HEPA-filter systems were designed to cover approximately 2,290 ft² (213 m²) of the primary cleanroom space, while the other three-air-handling units serving the pressurized plenum covered approximately 1,390 ft² (129 m²) of the primary cleanroom space. The total floor area of the primary cleanroom space was 3,680 ft² (or 342 m²). The cleanroom had a secondary space for return air, which covered a floor area of approximately 385 ft² (36 m²).

Table 1 shows the physical size of the cleanroom, airflow rates, airflow speeds, and air-change rate for the air-recirculation systems, and make-up-air systems in its normal operation.

Table 1 Cleanroom airflow system characteristics

ISO Class 4 Cleanroom	Units	Recirculation Air (Ducted HEPA Filters)	Recirculation Air (Pressurized Plenum)	Recirculation Air (Combined)	Make-up Air
Floor Area Served	m ²	213	129	342	342
	ft ²	2,290	1,390	3,680	3,680
Airflow Rate	m ³ /min	2,700	1,810	4,510	424
	cfm	95,400	64,000	159,400	14,960
Average Cleanroom Airflow Speed	m/s	0.21	0.23	0.22	-
	feet per minute (fpm)	42	46	43	-
Air-change Rate	m ³ air/(hr-m ³ room)	250	276	260	24
	ft ³ air/(hr-ft ³ room)	250	276	260	24

In actual operation, the airflow rates from the ducted-HEPA-filter systems and the pressurized-plenum systems were measured to be 95,400 cfm (2,700 m³/min) and 64,000 cfm

(1,810 m³/min), respectively. The total of the actual recirculation airflow rate was 159,400 cfm (4,510 m³/min), which was approximately 46% of the design airflow rate (347,000 cfm, or 9,830 m³/min).

6.2 Characteristics of the Minienvironments

Two types of minienvironments were located within the ISO-Cleanliness-Class-4 cleanroom in this study: 1) a stand-alone minienvironment with an open-loop air system, and 2) a passive minienvironment to which no additional fans were attached.

In the stand-alone minienvironments, airflow was drawn from the surrounding cleanroom space through fan-filter units that were attached at the top of the minienvironments. The air was filtered through localized High-Efficiency-Particulate-Air (HEPA) filters or Ultra-Low-Penetration-Air (ULPA) filters at certain airflow speeds for various activities. The filtered air was then supplied into the minienvironments to maintain a higher cleanliness level (i.e., lower level of particle concentration) within the localized space. They were intended for achieving ISO-Cleanliness-Class-3 space, i.e., fewer than 1000 particles sizing 0.1- μ m or larger per cubic meter, or fewer than 35 counts of particles sizing 0.5- μ m or larger per cubic meter, of the minienvironment space,

as shown in Figure 1.

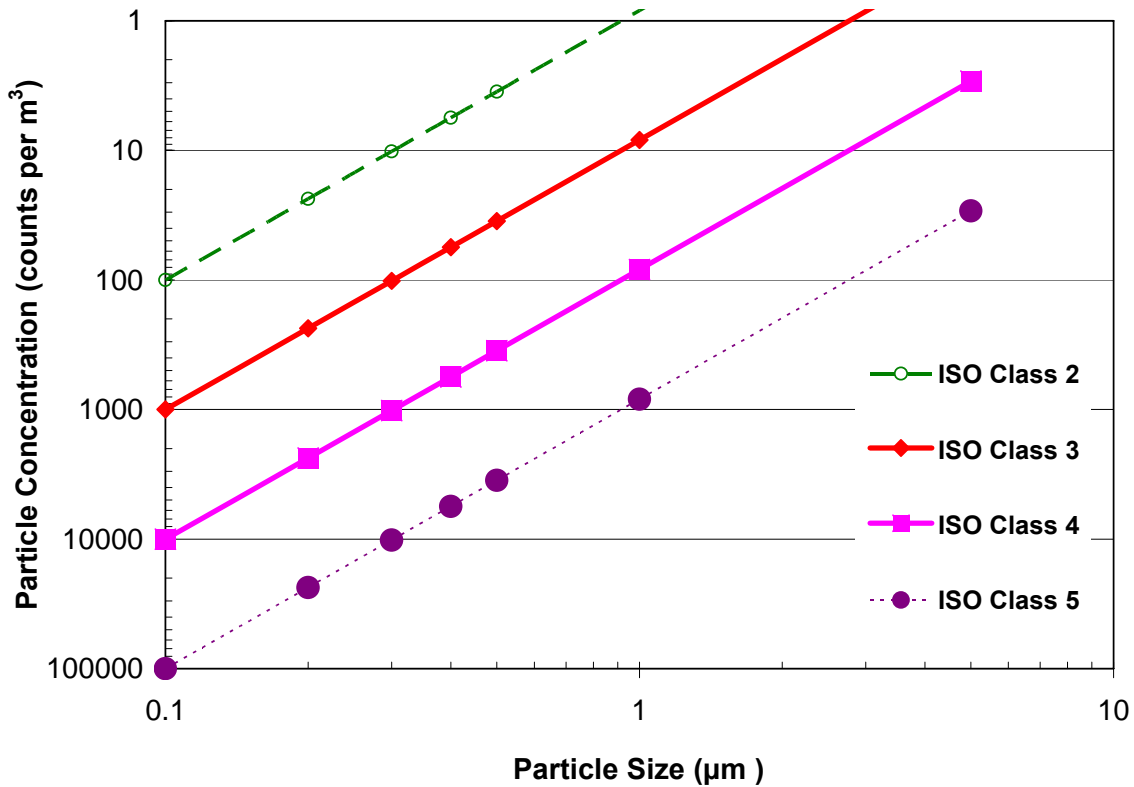


Figure 1 Cleanliness classes of the minienvironments and cleanroom in the study

Without containing any fan-powered device such as fan-filter units on top of the minienvironment, a passive minienvironment mainly served as physical barriers to provide a buffer zone from the surrounding space to lower the risk in contamination due to unexpected changes in ambient conditions, local disturbance of airflow patterns, or pollutants from the human occupants. Normally without additional filter, the passive minienvironments were used to maintain a cleanliness level equivalent to ISO-Cleanliness-Class-4, i.e., fewer than 10,000 particles sizing 0.1-µm or larger per cubic meter, or fewer than 352 counts of particles sizing 0.5-µm or larger per cubic meter, of the minienvironment space. A schematic diagram of the minienvironments in the cleanroom is included in Figure 2. In a stand-alone, open-loop

minienvironment, the supply air was filtered through FFUs located on top of the minienvironment. Additional flow shields were installed underneath the HEPA/ULPA filters of the FFUs to create downward unidirectional airflows inside the minienvironment. The outgoing airflows from the minienvironment may then mix with the surrounding air within the cleanroom space.

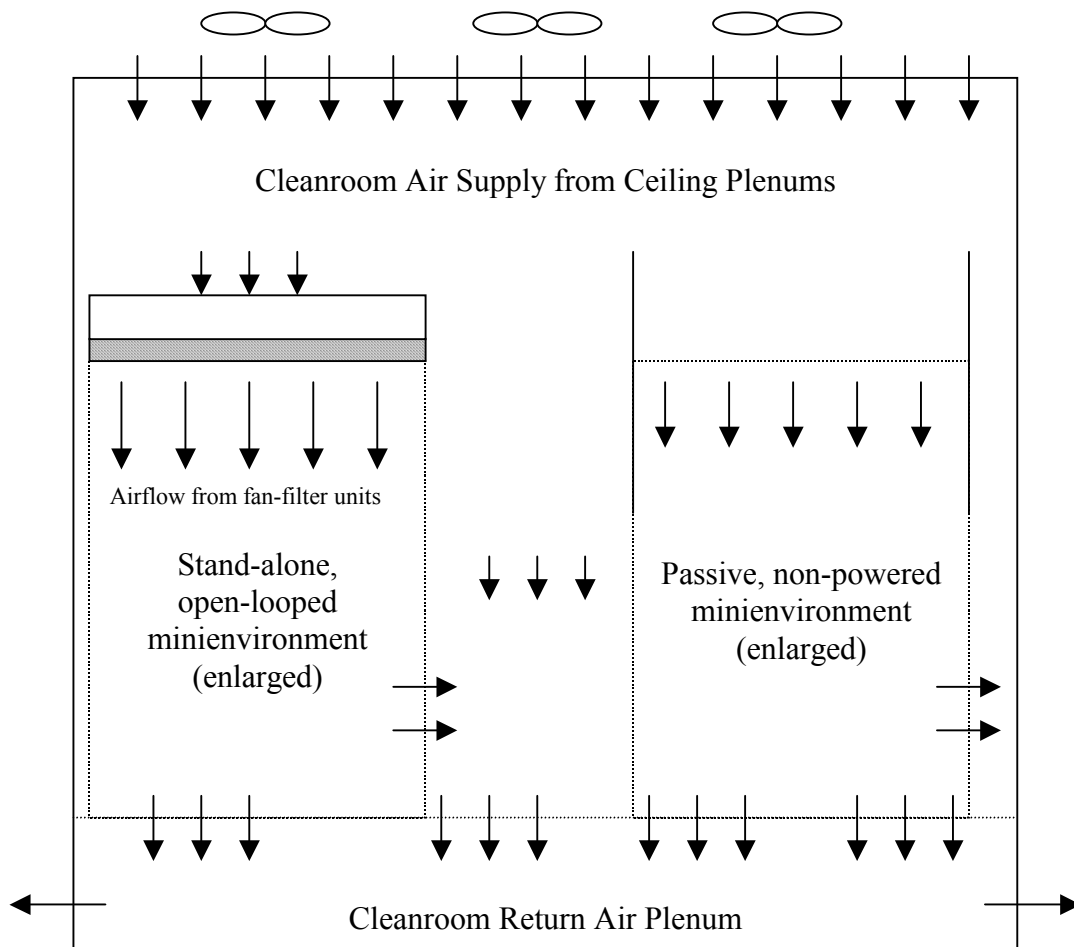


Figure 2 Schematic diagrams of open-loop and passive minienvironments

Table 2 shows the physical size of the inner-space of the five stand-alone, open-loop minienvironments that were selected and measured in this study.

Table 2 Characteristics of Sample Minienvironments

Minienvironments	Units	A	B	C	D	E
Floor Area	m ²	6.3	1.2	1.7	0.7	4.1
	ft ²	68	13	18	8	44
Height	cm	178	259	230	216	240
	inch	70	102	91	85	95

Overall, eight minienvironments with a size equivalent to that of “A” listed in the table were located in the cleanroom. Among these, five minienvironments were stand-alone, open-looped systems that were designed to create ISO-Cleanliness-Class-3 spaces, while three others were passive minienvironments without fans to deliver the airflow from the cleanroom into the minienvironments. Additional minienvironments, including minienvironments B, C, D, and E, were located within the same cleanroom. The total of net floor area of the stand-alone, open-looped minienvironments was approximately 424 ft² (39 m²), which represented approximately 12% of cleanroom’s primary floor area.

6.3 Environmental Performance of the Minienvironments

The purpose of a minienvironment is to provide contamination control through creating physical barriers and using filtration to locally control the particle concentration below a certain level within the minienvironment space. It is important to ensure that the enclosed space achieves the required cleanliness class. The key factors for achieving effective control of particle concentration include 1) design characteristics of the minienvironments and the surrounding space, 2) operating airflows and air-change rates, 3) pressure differential, and 4) filtration efficiency. The filtration efficiency of HEPA/ULPA filters used in the minienvironment could be

affected by airflow speeds, the design, geometry, and material of filters [14]. Given a certain HEPA/ULPA filter, optimal particle control for minienvironments can be realized by regulating airflow rates and air pressure differentials between the minienvironment space and its surrounding space. The benefits of optimal environmental control may include improved filtration effectiveness particulate filtration control and enhanced energy efficiency of airflow circulation in the entire building systems.

6.3.1 Airflows and Air-Change Rates

Table 3 shows that the minienvironments in this study exhibited a wide range of airflow rates, namely, ranging significantly from 750 cfm to 4,990 cfm (21 m³/min to 141 m³/min). The wide range was in part due to the variations in the floor area of the minienvironments that ranged from eight ft² to 68 ft² (0.7 m² to 6.3 m²). It is also affected by the different airflow speeds from minienvironment to minienvironment. The average airflow speed inside each minienvironment ranged from 52 fpm to 99 fpm (0.27 m/s to 0.50 m/s), with an average of 73 fpm (0.37 m/s). The airflow speeds were generally higher than the average airflow speed in the surrounding cleanroom, which was 43 fpm (0.22 m/s) as shown in Table 1. In addition, Figure 3 shows the air change rates as they related to airflow speeds in the five minienvironments, as compared to the enclosing cleanroom and other cleanrooms described in a previous study. The trend line shows the trend of variations for the minienvironments.

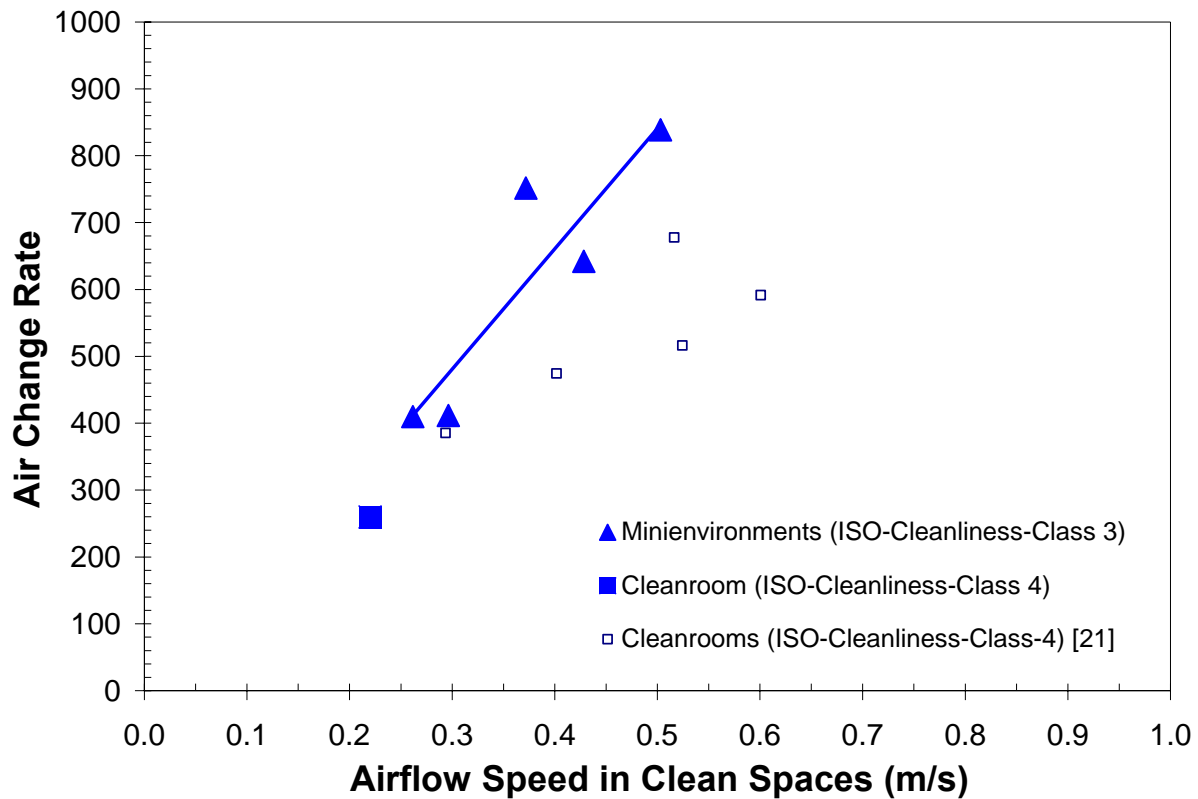


Figure 3 Air change rates and airflow speeds in minienvironments and cleanrooms

Table 3 Magnitudes of airflows and air-change rates of the five minienvironments

Units	A	B	C	D	E	A-E Sum	Average
m ³ /min	141	21	26	22	106	317	-
cfm	4,990	750	930	790	3,730	11,200	-
m/s	0.37	0.30	0.26	0.50	0.43		0.37
fpm	73	58	52	99	84	-	73
m ³ air/(hr-m ³ room)	752	412	410	839	642	-	611

The air-change rates of the five minienvironments ranged from 410 m³air/hr-m³room to 752 m³air/hr-m³ room, exhibiting a similar range to the operating range of a typical stand-alone, open-looped minienvironment in a previous study [14]. In that study, the operating range of

air-change rates for the minienvironment was between 480 m³air/hr-m³room and 800 m³air/hr-m³room, corresponding to airflow speeds ranging from 60 fpm to 100 fpm (or 0.30 m/s to 0.50 m/s) in the minienvironment.

When compared with the average airflow speeds in other ISO-Cleanliness-Class-4 cleanrooms from a previous study [21], the magnitude of airflow speeds from these minienvironments generally exhibited a similar or lower range (Figure 3). In addition, within a similar airflow speed range, the air-change rates of the five minienvironments exhibited a slightly wider range than that of ISO-Cleanliness-Class-4 cleanrooms that were studied previously. The narrower range of the cleanrooms was between 385 and 680 m³air/hr-m³room, corresponding to airflow speeds ranging from approximately 60 fpm to 120 fpm (or 0.30 m/s to 0.60 m/s) [21]. In general, the HEPA/ULPA filter coverage in ceilings of the minienvironments was 100% while the ISO-Cleanliness-Class-4 or ISO-Cleanliness-Class-5 cleanrooms normally have lower ceiling coverage [22].

In summary, the air-change rates of the five minienvironments in this study were significantly higher than that of the ISO-Cleanliness-Class-4 cleanroom housing the minienvironments, i.e., 260 m³air/hr-m³room. It is clear that higher average airflow speeds, higher HEPA/ULPA filter coverage in the five minienvironments (i.e., 100%), and lower ceiling heights of the minienvironments collectively contributed to the higher air-change rates within the minienvironments than that of the surrounding cleanroom.

6.3.2 Pressure Differential

The pressure differential is the static pressure difference between the internal space of a minienvironment relative to the air in the surrounding space may prevent the surrounding air

with higher particle concentrations from being transported into the minienvironment. By adjusting the airflow rates, a positive pressure differential for minienvironments may be created to prevent introduction of potential contaminants from the surrounding cleanroom.

In the five minienvironments studied, the pressure differential and particle concentration was measured. Table 4 shows that the measured pressure differential ranged from 0.025 Pa to 0.175 Pa among the five minienvironments. This was lower by several levels of magnitudes when compared to the recommended ranges [1][10], which recommend a typical process-bay pressure exceeding the service-chase pressure by approximately 0.01- to 0.05-inch-water column (or 2.5 Pa to 12.5 Pa) in microelectronic minienvironments. In addition, the measured pressure differential was also much lower than the rule-of-thumb pressure differential with a minimal value of 0.01- to 0.03-inch-water column (or 2.5 Pa to 7.5 Pa), or 10 Pa as the minimum pressure differential between classified area and adjacent areas of lower classification specified in British Standard 5295 [23].

Table 4 Minienvironment Environmental Performances

Minienvironments	Units	A	B	C	D	E
Pressure Differential	Pascal	0.15	0.15	0.025	0.025	0.175
	Inch water column	0.0006	0.0006	0.0001	0.0001	0.0007
Space Volume	m ³	11.3	3.1	3.8	1.6	9.9
	ft ³	398	109	136	57	348
Particle Concentration within Minienvironment	Particle count per cubic meter	0	0	0	0	0

In a recent minienvironment study, the pressure differential ranged from 0.003-inch-water column to 0.024-inch-water column (0.75 Pa to 6 Pa) [13], corresponding to airflow speeds ranging from 32 fpm to 95 fpm (or 0.16 m/s to 0.48 m/s). In another computer modeling analysis, a positive pressure differential of less than 1 Pa was suggested as a requirement to

provide contamination control requirements in one application [9]. It is apparent that the actual pressure differential between each minienvironment and the enclosing cleanroom was much lower than the recommended range or the rule of thumb, while the minienvironments have maintain satisfactory particle concentration controls. The observed effective operation was largely dependent on the function or design of the minienvironment, e.g., large open areas for outgoing airflows through the minienvironments. Less opening area could be achievable by the use of closeable doors at the local area but it was not adopted at the facility site studied.

6.3.3 Effectiveness of Particle Control

Maintaining the particle concentration within the prescribed cleanliness level is the key of effective particle control. Particle concentration was measured for particles with the sizes ranging from 0.1 μm to 3 μm within the five minienvironments studied. The particle counter was set to run 30-second samples with a 3-second delay between samples. The sampled particle counts per space volume were then averaged as reported in Table 4. The measured concentration during normal operation was all less than one and was rounded as zero. This was below the particle concentration thresholds for minienvironments with ISO-Cleanliness-Class-3 rating, i.e., no more than 1,000 counts of 0.1- μm particles per cubic meter, or 35 counts of 0.5- μm particles per cubic meter, of the minienvironment spaces [18]. This indicates that all five minienvironments that were tested in this study have satisfied or even surpassed the minimal environmental requirements for ISO-Cleanliness-Class 3 at the time of particle measurements.

In this study, supplying and controlling the airflows through the HEPA/ULPA filters of the fan-filter units in the minienvironment was sufficient to maintain particle concentration within the required range for the ISO-Cleanliness-Class 3 spaces, even though the actual pressure

differential between each minienvironment and the enclosing cleanroom was much lower than the IEST recommended range or the rule of thumb.

7. Conclusions and Recommendations

By building protective enclosures that are combining this with other design elements within cleanrooms, it is feasible to create minienvironments that are much cleaner than common cleanrooms by several levels of magnitudes. This study investigated the characteristics and environmental performance of ISO-Cleanliness-Class-3 minienvironments that was designated, housed, and operated within a traditional, larger ISO-Cleanliness-Class-4 cleanroom. The field measurements included pressure differential, airflow rates, particle concentration, in addition to concurrent electric power demand for minienvironments and the cleanroom.

Based upon the field measurements, analyses, and comparisons with cleanrooms with less-cleanliness, the following conclusions are drawn:

- Minienvironments in this study appeared to be effective in maintaining particle-concentration levels well below what was designated. In addition, the minienvironments exhibited large variations in physical sizes, airflow speeds, and air-change rates.
- The air-pressure differentials between minienvironment space and its surrounding space appeared to be very low, ranging from 0.025 Pa up to 0.175 Pa. The measured pressure differentials were considerably lower than the standards adopted in the industries (ranging from 2.5 Pa to 12.5 Pa pending various applications). This indicates opportunities and challenges in improving the guidelines and environmental control for

minienvironments through optimizing design, regulating airflow rates, and air-pressure differentials between minienvironment and its surrounding space.

This field study provides quantitative data to characterize the environmental performance of minienvironments that were in operation at a steady state. Additional investigations would be needed for further evaluating acceptable ranges of airflow speeds and air-change rates in minienvironments, pressure differential between minienvironments and the surrounding spaces, and their association with cleanliness levels under various operational stages, e.g., as-built, at-rest, operational, and unexpected disturbance or interruptions. Finally, there is a need to further investigate and address airflow control parameters in guiding documents in future editions, such as ANSI-accredited IEST RP 28.1 – Minienvironments, in order to maximize its usefulness in the case by case situations, and to benefit sustainable development of the industries using minienvironments.

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