Available online at www.sciencedirect.com

ScienceDirect

Building and Environment 42 (2007) 2993–3000

BUILDING AND ENVIRONMENT

www.elsevier.com/locate/buildenv

Characterization of minienvironments in a clean room: Design characteristics and environmental performance

Tengfang Xu*

Building Technologies Department, Lawrence Berkeley National Laboratory, One Cyclotron Road, Bldg. 90R3111, Berkeley, CA 94720, USA

Received 1 June 2006; accepted 19 October 2006

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 clean room, it is important to understand the characteristics of their design and operation and effectiveness in environmental control. This paper presents findings from an in-situ 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 in-situ investigation into the total performance of the minienvironments operating in a clean room. In particular, this paper summarizes design and operating characteristics and presents measured environmental performance of five minienvironments and the clean room 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.

Keywords: Minienvironment; Clean room; Airflow; Pressure differential; Environmental performance; Cleanliness; Particle concentration

1. 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 clean room 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 clean rooms [3–5]. Previous investigations or guidelines focused on design optimization of minienvironments mainly through simulation and modeling and some experiments [6–10]. Other studies or benchmarking activities addressed the impact of production yields by adopting minienvironments [11,12]. Recent in-situ evaluations quantified the energy performance of a minienvironment as a function of airflows and pressure differential under various operation

---

*Tel.: +1 510 486 7810; fax: +1 510 486 4089.
E-mail address: ttxu@lbl.gov.

0360-1323/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2006.10.020

conditions [13–15]. 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 clean room 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 clean rooms, 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 clean room. Evaluations and discussion about their energy performance and energy-saving implications from applying the minienvironments in traditional clean rooms is presented in a separate paper [16].

2. 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 clean room.

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.

3. 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 the 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 clean room studied, there were various activities that required different environmental conditions depending on the process or locality within an ISO-Cleanliness-Class-4 clean room, 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 clean room 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 clean room and other clean rooms 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.

3.1. 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 (FFUs), which were installed at the top of the stand-alone minienvironments. The actual sizes of individual FFUs and High-Efficiency-Particulate-Air (HEPA) filters varied from minienvironment to minienvironment.

The measurement uncertainty in airflow speeds was ±3% of reading plus ±7 feet per minute (fpm) (3.5 cm/s) from 50 to 2500 fpm (0.25–12.5 m/s). An airflow measurement device was used to sample 16 points over a 1 ft × 1 ft (30 cm × 30 cm) area to determine average airflow speeds at a distance of 2.5 in. (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-in.-water column (0.025 Pa) to over 60.00-in.-water column (15,000 Pa), with a measurement uncertainty of ±2% of reading plus 0.001-in.-water column (0.25 Pa) from 0.05-in.-water column to 50.00-in.-water column (0.125–12,500 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.

3.2. Measuring particle concentration

In addition to measuring the airflow speeds out of the FFUs, 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 clean rooms and associated controlled environments is defined in terms of concentration of airborne particles within the space. Eq. (1) shows the relationship among maximal permitted particle concentration that is allowed, ISO cleanliness class, and the associated diameter of the particles of concern.

$$C_{\mathrm{n}} = 10^{N}(0.1/D)^{2.08}, \tag{1}$$

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 clean room 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 (1000) counts of particles sizing 0.1-μm or larger per cubic meter (C_{n}), 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, 0.2, 0.3, 0.5, and 1.0-μm. The airflow rate used for particle sampling was 2 cfm (56.6 L/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.

4. Findings

4.1. Characteristics of the clean room

The clean room 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 clean room had a total floor area of 4065 ft^2 (378 m^2) with a ceiling height of 10 ft (3.0 m), and operated 24 h a day and 365 days a year. In addition to one make-up air system, two types of recirculation air systems served the clean room: ducted-HEPA-filter and pressurized-plenum.

The fans in the recirculation air-handling units for the clean room 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 (6120 m^3/min) to be supplied through a total of four air-handling units connected to the ducted-HEPA filters, and (b) 131,000 cfm (3710 m^3/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 2290 ft^2 (213 m^2) of the primary clean room space, while the other three-air-handling units serving the pressurized plenum covered approximately 1390 ft^2 (129 m^2) of the primary clean room space. The total floor area of the primary clean room space was 3680 ft^2 (or 342 m^2). The clean room had a secondary space for return air, which covered a floor area of approximately 385 ft^2 (36 m^2).

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

In actual operation, the airflow rates from the ducted-HEPA-filter systems and the pressurized-plenum systems were measured to be 95,400 cfm (2700 m^3/min) and 64,000 cfm (1810 m^3/min), respectively. The total of the actual recirculation airflow rate was 159,400 cfm (4510 m^3/min), which was approximately 46% of the design airflow rate (347,000 cfm, or 9830 m^3/min).

4.2. Characteristics of the minienvironments

Two types of minienvironments were located within the ISO-Cleanliness-Class-4 clean room in this study: (1) a

Table 1
Cleanroom airflow system characteristics

ISO Class 4 clean room	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	2290	1390	3680	3680
Airflow rate	m^3/min	2700	1810	4510	424
	cfm	95,400	64,000	159,400	14,960
Average clean room airflow speed	m/s	0.21	0.23	0.22	—
	feet per minute (fpm)	42	46	43	—
Air-change rate	m^{3}air/h-m^{3}room	250	276	260	24
	ft^{3}air/h-ft^{3}room	250	276	260	24

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 clean room space through FFUs that were attached at the top of the minienvironments. The air was filtered through localized 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-μm or larger per cubic meter, or fewer than 35 counts of particles sizing 0.5-μm or larger per cubic meter, of the minienvironment space, as shown in Fig. 1.

Without containing any fan-powered device such as FFUs 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 clean room is included in Fig. 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 clean room space.

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.

Overall, eight minienvironments with a size equivalent to that of "A" listed in the table were located in the clean room. 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 clean room into the minienvironments. Additional minienvironments, including minienvironments B–E, were located within the same clean room. The total of net floor area of the stand-alone, open-looped minienvironments was approximately 424 ft^2 (39 m^2), which represented approximately 12% of clean room's primary floor area.

4.3. 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

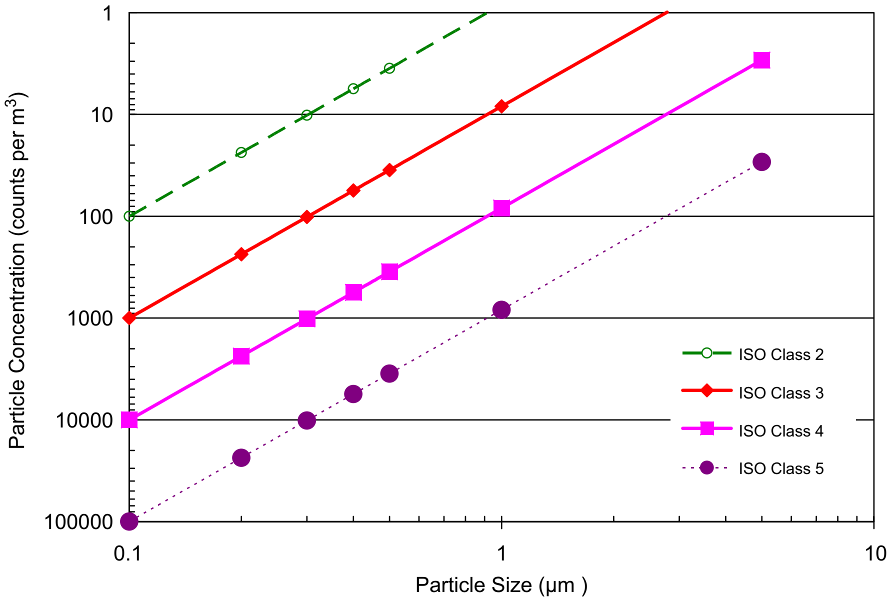

Fig. 1. Cleanliness classes of the minienvironments and clean room in the study.

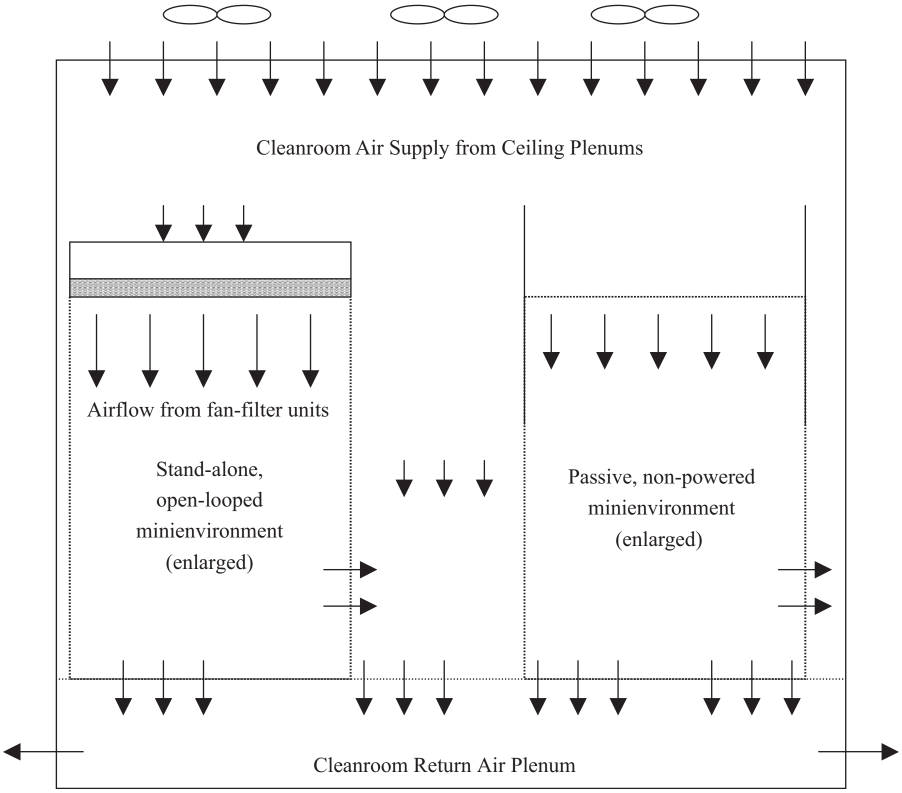

Fig. 2. Schematic diagrams of open-loop and passive minienvironments.

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
	In.	70	102	91	85	95

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	4990	750	930	790	3730	11,200	—
m/s	0.37	0.30	0.26	0.50	0.43		0.37
fpm	73	58	52	99	84	—	73
m^3air/h-m^3room	752	412	410	839	642	—	611

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.

4.3.1. 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 to 4990 cfm (21–141 m^3/min). The wide range was in part due to the variations in the floor area of the minienvironments that ranged from 8 to 68 ft^2 (0.7–6.3 m^2). It is also affected by the different airflow speeds from minienvironment to minienvironment. The average airflow speed inside each minienvironment ranged from 52 to 99 fpm (0.27–0.50 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 clean room, which was 43 fpm (0.22 m/s) as shown in Table 1. Air-change rate is defined as the airflow rate supplied to the minienvironment divided by the actual volume of each minienvironment. In addition, Fig. 3 shows the air-change rates as they related to airflow speeds in the five minienvironments, as compared to the enclosing clean room and other clean rooms described in a previous study. The trend line shows the trend of variations for the minienvironments tested.

The air-change rates of the five minienvironments ranged from 410 to 839 m^3air/h-m^3room, 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 and 800 m^3air/h-m^3room, corresponding to airflow speeds ranging from 60 to 100 fpm (or 0.30–0.50 m/s) in the minienvironment.

When compared with the average airflow speeds in other ISO-Cleanliness-Class-4 clean rooms from a previous study

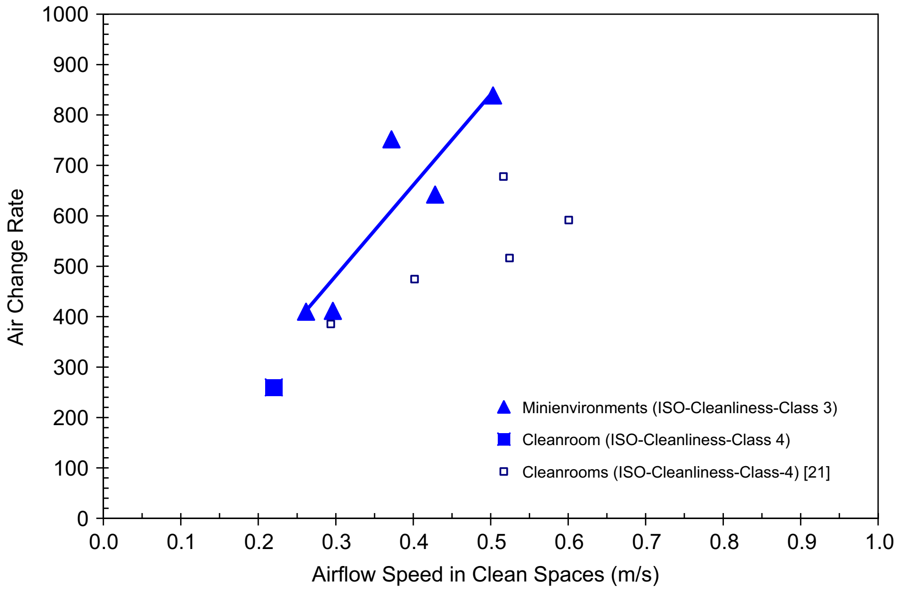

Fig. 3. Air-change rates and airflow speeds in minienvironments and clean rooms.

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
	in. 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

[21], the magnitude of airflow speeds from these minienvironments generally exhibited a similar or lower range (Fig. 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 clean rooms that were studied previously. The narrower range of the clean rooms was between 385 and 680 m^3air/h-m^3room, corresponding to airflow speeds ranging from approximately 60 to 120 fpm (or 0.30–0.60 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 clean rooms 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 clean room housing the minienvironments, i.e., 260 m^3air/h-m^3room. 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 clean room.

4.3.2. 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 clean room.

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 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 0.01–0.05-in.-water column (or 2.5–12.5 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 0.01–0.03-in.-water column (or 2.5–7.5 Pa), or 10 Pa as the minimum pressure differential between classified area and adjacent areas of lower classification specified in British Standard 5295 [23].

In a recent minienvironment study, the pressure differential ranged from 0.003-in.-water column to 0.024-in.-water column (0.75–6 Pa) [13], corresponding to airflow speeds ranging from 32 to 95 fpm (or 0.16–0.48 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 clean room 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.

4.3.3. *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 to 3 μm within the five minienvironments studied. The particle counter was set to run 30-s samples with a 3-s 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 1000 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 FFUs 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 clean room was much lower than the IEST recommended range or the rule of thumb.

5. Conclusions and recommendations

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

Based upon the measurements, analyses, and comparisons with clean rooms 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 up to 0.175 Pa. The measured pressure differentials were considerably lower than the standards adopted in the industries (ranging from 2.5 to 12.5 Pa pending various applications). This indicates that there are opportunities and challenges in improving the guidelines and environmental control for minienvironments. The opportunities lie in optimizing design, regulating airflow rates, and air-pressure differentials between minienvironment and its surrounding space.

This 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.

Acknowledgments

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program (http://www.energy.ca.gov/). This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the US Department of Energy under Contract No. DE-AC02-05CH11231.

References

[1] International Organization for Standardization (ISO). ISO 14644-7, Cleanrooms and associate controlled environments—Part 7: Separative devices (clean air hoods, glove boxes, isolators and minienvironments). The Institute of Environmental Sciences and Technology (IEST), 5005 Newport Drive, Suite 506, Rolling Meadows, IL 60008, USA, 2004.

[2] The Institute of Environmental Sciences and Technology (IEST). IEST-RP-CC028.1: Minienvironments. Handbook of recommended practices. Contamination Control Division, 5005 Newport Drive, Suite 506, Rolling Meadows, IL 60008, USA, 2002.

[3] International Organization for Standardization (ISO). ISO 14644-1, Cleanrooms and associate controlled environments—Part 1—classification of air cleanliness. The Institute of Environmental Sciences and Technology (IEST), 5005 Newport Drive, Suite 506, Rolling Meadows, IL 60008, USA, 1999. 18pp.

[4] International Organization for Standardization (ISO). ISO 14644-4, Cleanrooms and associate controlled environments—Part 4: design, construction and start-up. The Institute of Environmental Sciences and Technology (IEST) 5005 Newport Drive, Suite 506, Rolling Meadows, IL 60008-3841, USA, 2001. 54pp.

[5] International Organization for Standardization (ISO). ISO 14644-3, Cleanrooms and associate controlled environments—Part 3: metrology and test methods. The Institute of Environmental Sciences and Technology (IEST), 5005 Newport Drive, Suite 506, Rolling Meadows, IL 60008-3841, USA, 2002. 65pp.

[6] Tannous G. Airflow simulation in a minienvironment. Solid State Technology 1996;July:201–7.

[7] Tannous G. Optimization of a minienvironment design using computational fluid dynamics. Journal of the IEST 1997;40(1):29–34.

[8] Hu SC, Chuah YK, Yen MC. Design and evaluation of a minienvironment for semiconductor manufacture processes. Building and Environment 2002;37(2):201–8 [February 2002, Elsevier Science].

[9] Hu SC, Tong RH. Particle dynamics in a front-opening unified pod/load port unit minienvironment in the presence of a 300 mm wafer in various positions. Aerosol Science and Technology 2005;39(3):185–95.

[10] International SEMATECH. Integrated minienvironment design best practices, technology transfer # 99033693A-ENG. Austin, TX, USA: International SEMATECH, Inc.; 1999.

[11] Rothman L, Miller R, Wang R, Baechle T, Silverman S, Cooper D. SEMATECH minienvironment benchmarking project. Journal of the IEST 1995;38(3):36–41.

[12] Shu S. The impact of minienvironment of Fab capacity and yield. In: Proceedings of the 41st annual technology meeting. Anaheim, CA: The Institute of Environmental Sciences and Technology (IEST); 1995. p. 118–23.

[13] Xu T. A study on the operation performance of a minienvironment system. Journal of the IEST 2006;49(1):63–71 LBNL 58743. Berkeley, Calif., USA.

[14] Xu T. Opportunities for sustainable design and operation of clean spaces: a case study on minienvironment system performance. LBNL-56312. Berkeley, CA, USA, 2005.

[15] Xu T. Investigating the performance of a minienvironment system. In: Proceedings of 51st ESTECH conference, Schaumburg, Illinois. Berkeley, CA, USA: The Institute of Environmental Sciences and Technology (IEST). LBNL-56767. 2005.

[16] Xu T. Characterization of minienvironments in a cleanroom: assessing energy performance and its implications. Building and Environment. LBNL-60437 II. Berkeley, CA, USA, submitted for publication.

[17] ADM-860C. Airdata multimeter—backpressure compensated air balance system. Shortridge Instruments, Inc., 7855 East Redfield Road, Scottsdale, Arizona 85260. 〈http://www.shortridge.com〉.

[18] International Organization for Standardization (ISO). ISO 14644-1, Cleanrooms and associate controlled environments—Part 1: classification of air cleanliness, 1999.

[19] International Organization for Standardization (ISO). ISO 14644-2, Cleanrooms and associate controlled environments—Part 2: specifications for testing and monitoring to prove continued compliance with ISO 14644-1, 2000.

[20] MetOne laser airborne particle counter, Hach Ultra Analytics 〈http://www.particle.com/〉.

[21] Xu T. Performance evaluation of cleanroom environmental systems. Journal of the IEST 2003;46(1):66–73 [Institute of Environmental Sciences and Technology (IEST), Rolling Meadows, Illinois. LBNL-53282. Berkeley, CA, USA].

[22] Xu T. Considerations for efficient airflow design in cleanrooms. Journal of the IEST 2004;47(1):24–8 [LBNL-55970. Berkeley, CA, USA].

[23] British Standard 5295. BSI Standards, 389 Chiswick High Road, London W44 AL, UK, 1989.