Chapter 7
Classification of Air Cleanliness

With the fast development of semiconductor industry, pharmaceutical, food, and other industries, attention has been shifted from the particulate pollution in the past to the chemical pollution recently. For the control object related to the air cleanliness, it has been shifted from single object, i.e., particles in the past, to two objects which also include airborne molecular contaminant (AMC). In fact, standard related to air cleanliness and classification of air cleanliness has contained both the particle concentration level (customarily it is still called air cleanliness level) and the AMC concentration level. However, the air cleanliness specifically related to particle concentration level is still the core index to evaluate the air cleanliness of the environment.

7.1 Development of Air Cleanliness Standards (Classification)

The development process of national standards in different countries will not be introduced here, but it can be seen in the course of the development of air cleanliness standards (classification):

1. Due to the limit of the means to sample the dust and the limit of the depth of understanding of air cleaning technology in early times, either the particle counting concentration or the particle weight concentration has been used to describe the air cleanliness. For example, the former Soviet Union had made the following specification in national standards: particle concentration for level I is 0.00036 mg/m³, for level II is 0.5 mg/m³, and for level III is 0.8 mg/m³.

2. Because the characteristic of particle distribution in air was unknown in early times, it was confused even though the air cleanliness was classified with the particle counting concentration. For example, in the Technology Regulations T.O.00-25-203 published in the March of 1961 by US Air Force, particle concentration for level I is 8,834 pc/L (250,000 pc/ft³) for all the countable
particles, for level II is 3,004 pc/L (0.3–10 μm) (85,000 pc/ft³), for level III is 1,237 pc/L (0.3–10 μm) (35,000 pc/ft³), and for level IV is 353 pc/L (0.3–10 μm) (10,000 pc/ft³).

3. Due to the understanding of the characteristic of particle distribution on log-log paper, parallel lines on this kind of paper were used to distinguish between different places for the first time in the USA – levels of cleanliness for atmosphere, control area, standard cleanroom (equivalent to Class 8), and laminar flow devices (equivalent to Class 5). This was the revised air force technical order 203 published in July 1963. Even if it may be inspired by the distribution characteristic of atmospheric dust, it can be still considered as the first cornerstone of cleanroom technology.

4. Because “laminar” cleanroom (namely, unidirectional flow now) appears, air cleanliness can be classified into several classes according to the concentration level reached by unidirectional cleanroom and general cleanroom (namely, turbulent flow cleanroom or non-unidirectional flow cleanroom). This forms the classification or standard for air cleanliness, which will be introduced in the principle of cleanroom in Chap. 8. The class of air cleanliness is based on the corresponding measures of air cleaning technology. So the first scientific classification of air cleanliness standard was born, which was the US Federal Standard 209 published at the end of 1963. The concept of “laminar flow” cleanroom is the second cornerstone of cleanroom technology.

5. Due to the expansion of cleanroom applications, biological cleanroom standard appears which encompasses the control of inanimate particles and life particles. This is the standard published in August 1967 by US Aeronautics and Space Administration (in the past “the National Aeronautics and Space Administration”) (NASA) (it is customary to mention as aerospace standard for abbreviation, which is shown in Table 7.1). But later in the revised version of this standard US Federal Standard 209B amended in 1973, no requirement has been made for controlling the life particles. It is only mentioned that microorganism suspended in air is natural in the world, so they are included in the total number of particles in the air cleanliness classes. In 1978, the Fourth International Pollution Control Association has formally proposed the international standards (draft) including the control of life particles (see Table 7.2), but subsequently it was not implemented.

However, in US Federal Standard from 209C to 209E, it is clearly illustrated that the relationship between air cleanliness levels and biological particles has not been established. All these standards did not provide the specification of biological particle number corresponding to the number of particles.

6. For the need of production, a higher level than Class 100 appears since the outset of 209C, such as Class 10 and Class 1 for 0.5 μm or Class 10 and Class 1 for 0.1 μm.

7. Following with Europe, China, and Japan, the USA started to introduce the international system of units since 209E, but the British units still exist. The development process is shown in Figs. 7.1, and 7.2, Table 7.3.
As for the difference between 209E and its previous versions and as well as its specific application, please refer to other books [1].

8. In nature there is no difference between standards in other countries. The main difference is the expression of dust concentration: some adopts the metric system, while others used the approximated integer. For example, in the monograph “Air cleaning technology” published in 1979, the statistic results about the actual air cleanliness levels reached by the technical measures at that time were issued,

| Air cleanliness level (μm) | Particles | Maximum | Organism particles | Deposition |
|---------------------------|-----------|---------|-------------------|------------|
|                           | Maximum   |         |                   |            |
| 100                       | 0.5       | 100     | 3.5               | 1,200      | 12,900     |
| 10,000                    | 0.5       | 10,000  | 350               | 6,000      | 64,600     |
| 100,000                   | 5.0       | 65      | 0.5               | 30,000     | 323,000    |

| Air cleanliness level | Total number of airborne biological and nonbiological particles | Maximum number of ≥0.5 μm particles | Maximum number of airborne vital forming colony per unit volume air | Maximum number of deposition bacteria |
|----------------------|----------------------------------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 1                    | Not controlled                                                  | Not controlled                    | Not controlled                    | Not controlled                    |
| 2                    | 100,000                                                         | 3,500                             | 0.1                               | 12,900                            |
| 3                    | 10,000                                                          | 350                               | 0.5                               | 64,600                            |
| 4                    | 100                                                             | 3.5                               | 0.1                               | 12,900                            |
| 5                    | 10                                                              | 0.35                              | 0.04                              | 5,200                             |

Dec., 1963 F.S.209 Aug., 1966 F.S.209A Apr., 1973 F.S.209B May, 1976 F.S.209B revised version Dec., 1987 F.S.209C Jun., 1988 F.S.209D Sep., 1992 F.S.209E

British unit
Include all parameters in cleanroom

International unit
Mainly classification with air cleanliness level

Fig. 7.1 Development of US Federal Standard 209
which was carried out by 14 units including the former State Construction Committee Research Institute of Building Science. It forms the “3 series” air cleanliness levels. The first level is called Class 3 (equivalent to Class 100), the second level is called Class 30, and so on. In 1984 the national standard “Code for Design of Clean Room” (GBJ73-84) formally put forward Chinese classification of air cleanliness, which adopted the name from 209 with the international system of units in the content.

Other innovative classification of air cleanliness in cleanroom is the Japanese standard published in 1989, which is shown in Table 7.4. Since then, the European standard also provides a different method to classify the air cleanliness levels, which is presented in Table 7.5 [2].

It should be noted that the particle number in Tables 7.3, 7.4, and 7.5 means the sum of particle number whose diameter is equal to and larger than the corresponding size.

9. Little difference exists among standards about air cleanliness classification in different countries. Their expression for particle size 0.5 μm is consistent with US Federal Standard. So it is the trend to develop unified international standard. Therefore, International Confederation of Contamination Control Societies (ICCCS) organized a Standards Committee (ISO/TC 209) called “cleanroom and associated controlled environments” in 1993. ICCCS is composed of air cleaning technical societies (or associations) from 16 countries. There were
| Air cleanliness level | Upper limit of the corresponding concentration |
|----------------------|-----------------------------------------------|
|                      | 0.1 μm            | 0.2 μm            | 0.3 μm            | 0.5 μm            | 5 μm            |
|                      | Per unit volume   | Per unit volume   | Per unit volume   | Per unit volume   | Per unit volume   |
|                      | m³                | m³                | m³                | m³                | m³                |
|                      | ft³               | ft³               | ft³               | ft³               | ft³               |
| M1                   | 350               | 9.91              | 75.7              | 2.14              | 30.9              | 0.875             | 10.0              | 0.283             | –                 | –                 |
| M1.5                 | 1,240             | 35.0              | 265               | 7.50              | 106               | 3.00              | 35.3              | 1.00              | –                 | –                 |
| M2                   | 3,500             | 99.1              | 757               | 21.4              | 309               | 8.75              | 100               | 2.83              | –                 | –                 |
| M2.5                 | 12,400            | 350               | 2,650             | 75.0              | 1,060             | 30.0              | 353               | 10.0              | –                 | –                 |
| M3                   | 35,000            | 991               | 7,570             | 214               | 3,090             | 87.5              | 1,000             | 28.3              | –                 | –                 |
| M3.5                 | 26,500            | 750               | 10,600            | 300               | 3,530             | 100               | –                 | –                 | –                 | –                 |
| M4                   | –                 | –                 | 75,700            | 2,140             | 30,900            | 875               | 10,000            | 283               | –                 | –                 |
| M4.5                 | 1,000             | –                 | –                 | –                 | –                 | –                 | 35,300            | 1,000             | 247               | 7.00              |
| M5                   | –                 | –                 | –                 | –                 | –                 | –                 | 100,000           | 2,830             | 618               | 17.5              |
| M5.5                 | 10,000            | –                 | –                 | –                 | –                 | –                 | 353,000           | 10,000            | 2,470             | 70.0              |
| M6                   | –                 | –                 | –                 | –                 | –                 | –                 | 1,000,000         | 28,300            | 6,180             | 175               |
| M6.5                 | 100,000           | –                 | –                 | –                 | –                 | –                 | 3,530,000         | 100,000           | 24,700            | 700               |
| M7                   | –                 | –                 | –                 | –                 | –                 | –                 | 10,000,000        | 283,000           | 61,800            | 1,750             |
29 countries attending ISO/TC 209. After the formulation, the standard becomes one of the technical ISO standards. It was published on May 1, 1999, with the standard number ISO14644-1, which is shown in Table 7.6.

Compared with Japanese standard, ISO 14644-1 includes the particle size 1 μm and Class 9 which equivalents with Class 1000000. There is little difference about the particle number between them.

Now, the revised Code for Design of Clean Room in China (GB50073-2001) also adopts the same air cleanliness classification with ISO14644-1 [3].

### Mathematical Expression of Air Cleanliness Levels

As for the particle number mentioned in the classification of air cleanliness in the abovementioned countries, particle counting concentration in the cleanroom is approximated to be parallel lines on log-log paper. When the reference size of controlled particle is known, straight line parallel to the lines of atmospheric dust concentration can be obtained, and then the allowable particle number corresponding.
to other sizes can be determined (the rounding correction of integer is made). Formula can be used as follows:

$$\frac{N_D}{N_d} = \left( \frac{D}{d} \right)^{-n} \quad (7.1)$$

where \(d\) is the reference size, \(D\) is other size, \(N_d\) is the particle number for size \(d\) (i.e., \(\geq d\)), \(N_D\) is the particle number for size \(D\) (i.e., \(\geq D\)), and \(n\) is the exponential which is slightly different in various national standards.

It is obvious that this expression is exactly the same as Eq. (2.1).

Because of the rounding correction of integer, the value obtained by Eq. (7.1) is not exactly the same as that in classification table. Take Japanese standard as an example, 0.1 \(\mu m\) is the size of controlled particle. The particle number with size 0.1 \(\mu m\) in Class 3 is 10^3 pc/m^3 where 3 is the exponential.

So how much is the number of particles with size \(\geq 0.3 \mu m\) in Class 3?

With Eq. (7.1), the value of \(n\) in JIS, and the particle number of controlled size 0.1 \(\mu m\) \(N_{0.1}\) in Class 3, it can be written as:

$$N_{0.3} = N_{0.1} \times \left( \frac{0.3}{0.1} \right)^{-2.08} = N_{0.1} \times \left( \frac{0.1}{0.3} \right)^{2.08}$$

$$= 10^3 \times 0.10176 \text{ pc/m}^3 \text{ (set 101 pc/m}^3\text{)}$$

It is clear that this result is exactly the same as that in Table 7.4 for particle size 0.3 \(\mu m\) in Class 3.

But 0.1 \(\mu m\) can also be used as the control size for Class 3 in ISO14644-1. \(N_{0.3} = 102 \text{ pc/m}^3\). It is obvious that the calculated value of 0.10176 is approximated into 0.102. The difference between them by this rounding is little.

For another example,

Class 100 in 209E \(\rightarrow\) 100 pc/ft^3 \(=\) 3,530 pc/m^3 \(\approx\) 10^{3.548} pc/m^3 \(\approx\) 10^{3.5} pc/m^3

This is the integer rounding in the value of class. When another expression of class in 209E is used, the following equation can be obtained:
The particle number for particle size $D$ (such as 0.2 $\mu$m) in Class 3.5 is:

$$N_M = 10^3 \left( \frac{0.5}{D} \right)^{2.2} \text{ pc/m}^3$$

So it is smaller than the value 26,500 in Table 7.3. If the value of class without integer rounding is inserted into the expression to calculate the particle number corresponding to the control size, then:

$$N_M = 10^{3.548} \times \left( \frac{0.5}{0.2} \right)^{2.2} = 3,530 \times \left( \frac{0.5}{0.2} \right)^{2.2} = 26,500 \text{ pc/m}^3$$

It is exactly the same as that in the table. So 209E explains that the approximated particle number for various sizes can only be obtained by Eq. (7.2).

The only difference among various expressions for air cleanliness classification in various standards is the change of exponent $n$. $n = 2.2$ in 209E, $n = 2.08$ in JIS B9920 and ISO14644-1, and $n = 2$ in CEN/TC243. However, the value of $n$ is not directly given in the US 209 ~ 209B and GBJ73-84, but we can know that $n = 2.15$ by using the back calculation method (or based on the parallel characteristic to the standard distribution of atmospheric dust).

When the concentration for particle with size 0.5 $\mu$m is 1 pc/m³, the corresponding concentration for particle with size 0.1 $\mu$m can be calculated by Eq. (7.1):

For 209E

$$N_{0.1} = N_{0.5} \left( \frac{0.5}{0.1} \right)^{2.2} = 1 \times \left( \frac{0.5}{0.1} \right)^{2.2} = 34.49 \text{ pc/m}^3$$

For the Japanese standard

$$\frac{N_{0.5}}{N_{0.1}} = \left( \frac{0.1}{0.5} \right)^{2.08}$$

$$N_{0.1} = \frac{N_{0.5}}{\left( \frac{0.1}{0.5} \right)^{2.08}} = \frac{1}{\left( \frac{0.1}{0.5} \right)^{2.08}} = 28.43 \text{ pc/m}^3$$

For European standards

$$N_{0.1} = N_{0.5} \left( \frac{0.5}{0.1} \right)^2 = 1 \times \left( \frac{0.5}{0.1} \right)^2 = 25 \text{ pc/m}^3$$

The calculated results about the influence of $n$ on particle concentration are plotted on Fig. 7.3, which shows that the difference is not big.
7.3 Conversion Relationship of Particle Number for Different Sizes

According to the calculation equation \( n = 2.08 \) in ISO 14644-1, the conversion coefficient for particle number is presented in Table 7.7.

The value \( \phi \) of particle with diameter 0.1–0.007 \( \mu \)m is cited from Ref. [4] (it is based on the calculated result by Kazuya).

7.4 Parallel Lines for Air Cleanliness Levels

It is known from Fig. 7.3 that parallel lines representing in air cleanliness levels in various national standards have both the characteristic of particle distribution in cleanroom and the artificial factor. For example, according to US Federal Standard 209, the lines for \( n = 2.15 \) are plotted in order to be consistent with the distribution of atmospheric dust. While in Japanese and European standards, particle numbers of two particle sizes are considered (such as 0.1 and 0.5 \( \mu \)m or 0.5 and 5 \( \mu \)m). Therefore, it is not right to consider the parallel lines representing cleanliness levels as the characteristic of particle distribution in cleanroom directly. There is difference between the value of \( n \) in the actual indoor distribution and the value of \( n \) in Fig. 7.3.
parallel lines for corresponding class. It is only reasonable to state that the particle distribution in cleanroom is approximately straight in log-log paper. But the actual particle distribution for specific cleanroom is not exactly the same as that of parallel lines for corresponding class, and large difference may exist, which is similar as the relationship between the distribution feature of atmospheric dust and the measured data of atmospheric dust. Besides, there is artificial factor as mentioned before.

For example, some actually measured data shows that the distribution of the particle concentration in cleanroom has the characteristic of inclination and slow change, as shown in Figs. 1.24 and 7.4 [5]. For the latter case, \( n = 1.2467 \) for the

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**Table 7.7** Conversion coefficient of particle number for different sizes

| Particle size (μm) | 0.5  | 0.3  | 0.2  | 0.18 | 0.15 | 0.12 | 0.1  | 0.09 | 0.08 | 0.07 | 0.06 |
|--------------------|------|------|------|------|------|------|------|------|------|------|------|
| Conversion coefficient of particle number | 1    | 2.85 | 6.8  | 8.4  | 19   | 19.5 | 28.6 | 34   | 44.9 | 56.3 | 57.1 |

| Particle size (μm) | 0.05 | 0.04 | 0.035 | 0.03 | 0.025 | 0.02 | 0.018 | 0.015 | 0.013 | 0.01 | 0.007 |
|--------------------|------|------|-------|------|-------|------|-------|------|-------|------|-------|
| Conversion coefficient of particle number | 76.3 | 89.1 | 91.1  | 93.1 | 95.7  | 98.3 | 98.6  | 98.9 | 99.4  | 100  | 100.3 |

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**Fig. 7.4** Distribution of particle concentration in cleanroom on log-log paper (example 1)
average value of all the measured data. Obviously, if more measurement was performed, the average value is no longer 1.2467. Even for the unidirectional and non-unidirectional flow in the same measurement, the value of $n$ is different. In the above figure, $n = 1.1089$ for unidirectional flow and $n = 1.1778$ for non-unidirectional flow. However, there is other measurement that shows the different trend which has the characteristic of steeper inclination, which is shown in Fig. 7.5 [6]. But anyway it is a common feature that the particle distribution in cleanroom is approximately parallel straight lines on log-log paper.

Why this feature remains for the particles inside the cleanroom when they go through air filters? It is obvious that without particle generation inside the cleanroom, particle distribution through air filter is close to monodisperse or it has the feature of steep and short straight line (or polyline). It is because particles with larger diameter are captured by air filter. This can be proved by the measurement from high-grade as-built cleanroom without occupants. But there is particle generation in the operational cleanroom, and human is the main source. The particle distribution generated from human is straight on log-log paper and is very similar as that of typical atmospheric dust.
Polylines 1 to 7 in Fig. 7.6 show the particle generation characteristic from work clothes made of different materials [7]. Dashed line 8 shows the typical distribution of atmospheric dust. It is obvious that the trend between them is very similar.

Figure 7.7 is the measured data by author and others labeled with various symbols [8]. They are on behalf of the different amounts of particle generation with various activities. The amount of dust generated is approximately within the range sandwiched by the two straight lines. The dotted line is a typical distribution of atmospheric dust. It is clear that their trends are very close.

The above material shows that the particle distribution features in the operational cleanroom should be similar as that of particles generated by occupant (other kind of particles generated should also be included), which means it is similar as that of atmospheric dust. This can also been seen from the comparison among Figs. 7.8 [6], 2.28, and 2.29. The approximated linearity is mainly valid for particles with diameter larger than 0.1 μm. Therefore, another group of oblique lines parallel to that of atmospheric dust can be used to indicate different levels of air cleanliness. Of course, the smaller the amount of particles generated is, the higher the air cleanliness is, and the steeper the oblique line is. It should be noted that these parallel straight lines are obtained by statistical analysis. For one specific cleanroom, the distribution of particle concentration with size may deviate from this result.

7.5 Controlled Object for Corresponding Air Cleanliness

Two main objects are needed for air cleanliness. One is the minimum particle diameter in the air which may cause damage. The other is the particle counting number in the air which may also cause damage.
7.5 Control Object for Corresponding Air Cleanliness

### 7.5.1 Minimum Controlled Size

In the past, the requirement for minimum particle size was put forward to meet the need of precision machinery, especially from the aspect of mechanics such as blockage and abrasion which cause damage to the product. This minimum size should be less than certain geometric distance on the product – tolerance, gap, line spacing, line width between the components, and so on. Since it is possible that small particles could coagulate to be large particles or several small particles fell to the critical position of the product at the same time, the minimum controlled particle size is usually set to be between half and 1/3 of this geometric distance [9]. Since this kind of geometric distance can be as small as 1, 0.5 μm becomes the minimum controlled particle size in the air cleaning technology for a long time. In addition, when optical particle counter with light scattering is used to perform the measurement, only particles with diameter larger than 0.3 μm is in the area...
suitable for light scattering detection. But the sampling efficiency for 0.3 μm is lower than that for 0.5 μm (refer to Chap. 17); the minimum controlled particle size is limited, which is usually 0.5 μm.

However, due to the development of integrated circuits, higher requirement was needed for the minimum controlled particle size. From one hand, the geometric distance on integrated circuits becomes smaller. For example, the thickness of the coating or mask is only a few tenths even a few percent of microns. Before the appearance of VLSI, the distance between the conductive lines on the element, or the width of the metal line connecting elements (it is called the basic graphic size), or the characteristic size has reached to 1 μm, but now it has been reduced to be less than 0.1 μm. From the other hand, the minimum controlled particle size should be determined not only from a mechanical point of view but also from a physicochemical point of view. Even when a particle settles down within a certain geometric distance such as the thickness of a coating, pinhole and impurities source surface may be formed to destroy the product performance. Therefore, the minimum controlled particle size is further required to be between 1/10 and 1/3 or even less [10].

Table 7.8 shows a comprehensive literature survey on the relationship between the linewidth and the development trend of integrated circuits. It can be seen from the table that since 1970, the integration density has increased by four times every 3 years.
Table 7.8 Development of integrated circuit

| Year | Representative product DRAM | Silicon diameter/mm | Chip area (mm²) | Finest optically carved linewidth (μm) | Element number (#) |
|------|-----------------------------|---------------------|----------------|----------------------------------------|-------------------|
| 1970 | 1 K                         | 10                  | 2              | 2 × 10⁴                                |                   |
| 1975 | 16 K                        | 5                   |                |                                        |                   |
| 1980 | 64 K                        | 75                  | 3              |                                        |                   |
| 1983 | 256 K                       | 100                 | 40             | 2                                      | 5 × 10⁵           |
| 1986 | 1 M                         | 125                 | 50             | 1                                      | 2 × 10⁶           |
| 1989 | 4 M                         | 150                 | 90             | 0.8                                    | 8 × 10⁶           |
| 1992 | 16 M                        | 200                 | 130            | 0.5                                    | 10⁷–10⁹          |
| 1995 | 64 M                        | 200                 | 200            | 0.3                                    | 10⁷–10⁹          |
| 1998 | 256 M                       | 200                 | 300            | 0.2                                    | 10⁷–10⁹          |
| 2001 | 1 KM(G)                     | 300                 | 700            | 0.18                                   | 10⁷–10⁹          |
| 2004 | 4 KM(G)                     | 300                 | 1,000          | 0.113                                  | Possible 2 × 10⁹ |
| 2007 | 16 KM(G)                    |                     |                |                                        | 0.10             |
| 2010 | 64 KM(G)                    |                     |                |                                        | 0.07             |

Table 7.9 Requirement of integrated circuit on the controlled particle size

| Year | Integration degree | Controlled minimum size (μm) | Processing times β | Air cleanliness level (50 % yield) | Pure gas/water |
|------|--------------------|------------------------------|--------------------|------------------------------------|----------------|
| 1970 | 1 K                | 2                             | <100               | 100                                | ~10³ ppb       |
| 1975 | 16 K               | 0.4–1.3                       | <100               | 100                                | ~10³ ppb       |
| 1980 | 64 K               | 0.25–0.8                      | 100                | 100                                | 10³ ppb        |
| 1983 | 256 K              | 0.12–0.4                      | 140–160            | 100                                | 10³ ppb        |
| 1986 | 1 M                | 0.08–0.26                     | 160–200            | 10                                 | 500 ppb        |
| 1989 | 4 M                | 0.05–0.17                     | 200–300            | 1                                  | 100 ppb        |
| 1992 | 16 M               | 0.05                          | 300–400            | 0.1 or 10(0.1 μm)                  | 50 ppb         |
| 1995 | 64 M               | 0.035                         | 400–500            | 10(0.1 μm)                         | 5 ppb          |
| 1998 | 256 M              | 0.025                         | 500–600            | 10(0.1 μm)                         | 1 ppb          |
| 2001 | 1 G                | 0.018                         | 530–700            | 1(0.1 μm)                          | 0.1 ppb        |
| 2004 | 4 G                | 0.013                         | 600–700            | 0.1(0.1 μm)                        | 0.01 ppb       |
| 2007 | 16 G               | 0.01                          |                    |                                    |                |
| 2010 | 64 G               | 0.007                         |                    |                                    |                |

Table 7.9 shows the influence of the development of the integrated circuit in the literature on the requirement of controlled particle size and related contaminant control [11].

Except the integrated circuit, there is no requirement for such a small controlled particle size so far. Usually the limit is 0.5 μm. For example, the minimum controlled particle size is still 0.5 μm in pharmaceutical manufacturing cleanrooms and hospitals cleanrooms at home and abroad.
7.5.2 Number of Controlled Particles

Different processes have different requirement for the number of controlled particles (≥ controlled particle size). It will be very complicated if the standard of air cleanliness was made with these quantities. For example, the maximum allowable particle number per liter air for one process is 110 pc, while for another process it is 130pc, so little difference exists in the measures of air cleaning for these two cases, and it is not necessary to set different levels of air cleanliness. Therefore, the following principles should be followed during the development of controlled particle number in air cleanliness standards (level):

1. It can be achieved by current existing measures.
2. Economic difference is significant.
3. It is convenient for use. For example, it’s easy to keep in memory, which requires these controlled numbers are regular and integer.

It should be noted that in addition to “Air Clean Technology Measures” in China in the past, no other domestic and foreign standards set the requirement for the equivalent Class 1000000 in ISO/TC209. The above 209E and European air cleanliness level lists the minimum level whose particle concentration is 10,000 pc/L, which is equivalent to Class 300000. Now Chinese “Good Manufacture Practice” (GMP) has included Class 300000. Both “Implementation Details of Drug Packaging Materials, Container Manufacturing Practices” and “Architectural Technical Code for Hospital Clean Operating Department” include Class 300000, which is the base for the design of quasi-clean areas. It is sound to do so. Because with the expansion of service object by air cleaning technology, air cleanliness of many places need to be slightly lower than Class 100000. For example, in “Design Code for Electronic Computer Room” (GB50174-93), the particle concentration of the host room at-rest should be less than 18,000/L, which is equivalent to Class 500000. Some applications for transition to high-level cleanliness will need the so-called “quasi-clean” state. So it is necessary to set the appropriate level of cleanliness, and it is good for energy conservation and will promote the application of air cleaning measures in more departments. In order to meet this kind of need, the international standard IS014644-1 has formally set out Class 9 which is equivalent to Class 1000000.

7.6 Specific Conditions for Controlled Particle Concentration

When the controlled particle concentration corresponding to the air cleanliness level is considered, the following specific conditions must be also taken into account:

1. Which state is it under which the particle concentration is obtained?

   In US Federal Standard 209, the particle concentration is measured during the working time near the working place.
In Chinese standard, the particle concentration is also determined during the normal operation. This is called operational level, which is adopted by many countries before 209C.

It is found that the test result is affected by many actual conditions when the operational particle concentration is used to evaluate the air cleanliness level. It is difficult to accurately measure the concentration. It cannot reflect the problem of the project itself accurately and in time. So the air cleanliness level and state are separated since 209C, where only the particle number itself is mentioned.

In the last chapter about test technologies, the concept of operational, at-rest and as-built will be introduced.

2. Which area is it for measuring the concentration?

For the environment of a cleanroom, various standards have different specifications. Whether the particle concentrations in each area and every position meet the requirement or only the particle concentration in certain area meet the requirement. But practice has proved that the former is impossible, but also not necessary, especially in the past when the air cleanliness level is linked with operational state. Because in the vortex flow area, particle concentration is high near the particle source, but people is mainly concerned about the working area. In order to meet the cleanliness requirement and save energy, the particle concentration in the working area should be controlled. Therefore, air cleanliness levels in current standards are determined by the particle concentration in the working area.

The regional technical regulation for acceptance of Class 100 cleanroom has pointed out that the working area means the room space which is 3 ft (about 90 cm) below the ceiling and 30 in (about 76 cm) above the floor. In this region, “the measurement at any height must meet the requirements.”

In the past, when operational level is specified, the workspace or dust source is not included in this working area. It is the region near but outside the working position. In the abovementioned technical regulation, this concentration is measured at any place which is in the distance 24 in (about 61 cm) away from any pollution source. This specification is very scientific. Because near the dust source such as the lacquering machine, the grinding head, and the powder filling, the particle concentration must be very high. But this kind of high concentration does not make sense for the object itself which is spinned, grinded, and filled. So it is also unnecessary to keep high air cleanliness at the dust source for operational state.

In China’s “Air Clean Technology Measures,” the working area is defined as the region which is 0.8–1.5 m high from the floor, except the special requirement of some process. For the cleanroom with horizontal unidirectional flow, the first workspace is used as a representative which is a certain distance (usually it is 0.5 m) away from the outlet of the air filter.

To 209E, cleanroom is a “room” which includes one or more clean areas, and clean area means a certain space within which the air cleanliness with specific airborne particle is controlled. This means that the cleanroom includes many clean areas with different cleanliness. So “cleanroom with certain cleanliness” means the
main region of the cleanroom should reach this cleanliness level, and not all the cleanroom should control the particle concentration.

3. How is the particle concentration obtained including sampling times and sampling volume? These will be introduced in detail in the section about test techniques.

4. Is it the average, maximum, or other value of particle concentration?

Before 209C, the maximum particle concentration is generally used to assess the air cleanliness level, or the average is adopted but with some provisions at the same time (such as Chinese relevant standards). From 209C, the combination of statistical value and one maximum value is used, which will also be analyzed in the section about test techniques.

### 7.7 Theoretical Method to Determine the Yield by Air Cleanliness

#### 7.7.1 Influence of Air Cleanliness on Yield

It is a very complex issue to determine what kind of cleaning environment is needed for the production of each precision product. It is determined by many factors such as methods, tools, equipment, pure water, pure air, chemical reagents, processing times, and personnel who presides the process comprehensively. Traditional particle pollution should be controlled, and more attention has been paid on the influence of AMC on critical surface. Especially for the integrated circuit over 256M, the air component in the production workshop has almost become the monitoring object with the same importance of particles.

AMC include both the metal components at molecular level such as Na, K, Zn, Al, and Fe but also the gas-phase chemical contamination. Since in most countries there is no standard related to AMC, it is still the most basic problem for controlling the influence of particles in the cleanroom. In this section, only the influence of particle concentration on the yield is discussed. The probability of a product to be flawed by particle settling reduces with the decrease of the particle concentration, exposure area, and time. Of course, only these particles which can contact the product surface have the direct effect. Therefore, the following items must be investigated:

1. Which approach does the particle in air take to contact the product surface? How much is the probability for particles to deposit on surface? And how many particles?
2. What is the relationship between the deposition density onto the surface and the probability to cause the flow?
The first question has been discussed in Chap. 6 and will be discussed continuously in Chap. 9. Here the second problem will be discussed in detail.

Since particles are randomly distributed in air and their deposition is also random, the amount of particles deposited onto a surface with certain area is limited for a given time period, when the airborne particle concentration is known. For example, the number of particles deposited on the surface with area 1 m² during 1 h is 100 thousands, the average deposition density is 10 pc/(cm² · h). This does not mean the number of particles deposited onto each surface with area 1 cm² is 10 pc. Some is more, but other has less.

When particles are randomly distributed, the probability of a particle deposited onto a surface with a given area is fixed. Although the probability for the case of two particles is different from that of one particle, it is also fixed. It is the same for the case of \( n \) particles. The probability for the deposition of different number of particles follows the binomial distribution. As mentioned in Chap. 1, when the area of deposited surface is very small and the number of particles in this space is not large, the deposition density is very small. The probability of particle deposition can be approximated with Poisson distribution.

Taking the integrated circuit as an example, there are many graphics on the silicon chip with diameter 3 cm. The area of each graphic is termed as the area of chip. Figure 7.8 illustrates the chip areas and element number. With the increase of the chip diameter, the number of integrated elements is larger. Now the chip diameter increases from 30 cm towards 40 cm, so the chip area will further be increased. The chip area of ULSI (ultra large-scale integrated circuit) increases to several hundreds or thousands square millimeters from the initial 40–50 mm².

Metal wires are used to connect the elements on the integrated circuit. The whole circuit is made of complex electric net by multiply layers of these wires. Figure 7.9 is an enlarged figure of this kind of connected wires [12]. This kind of multiply layers is shown in Fig. 7.10, where the above is alumina wire, down the molybdenum wire and between isolated. Therefore, as long as one particle deposits on this complex wire net or any place on the element, break or shortcut of the electric circuit is formed, which makes the graphic flawed. This destroys the function of whole electric circuit, and thus this piece of chip is abolished.

Figure 7.11 is one example of the distribution of flawed chips on the silicon crystal wafer[13]. In the figure, the area with inclined lines represents the flawed chips by shortcut of the circuit. The graphic flaws on the observed chip are expressed by “●”.

Figure 7.12 shows the number of particles deposited onto a silicon crystal wafer with diameter 150 mm in a Class 1 level cleanroom for 0.1 \( \mu \)m particles. The data was obtained by placing the silicon wafer vertically with 1 m distance up from the roof for one week and people walk with 30 cm away from it. The value means the total particle number with diameter \( \geq \) the indicated particle size at the abscissa [13]. It is obvious that diffusional deposition is important for small particles. Before the measurement, the background number on the clean silicon wafer has been taken into account.
It is obvious that the higher the integrated intensity is and the larger the chip area is, the higher the probability of the damage caused by one particle deposition. Since the chip area is larger than any particle and the geometrical distance on the circuit (such as layer thickness and wire distance) is equivalent with the diameter of very tiny particle, the surface deposition density, which means the number of particles deposited, is much more meaningful than particle size for integrated circuit especially ULSI circuit. Normally this density has the similar implication as air cleanliness level, which is used to describe the particles with diameter \( \geq 0.5 \, \mu m \). The minimum diameter to cause damage on the manufacturing process can be adopted as the particle size for defining the deposition density.
7.7.2 Theoretical Expression for Yield

7.7.2.1 Yield of Single End Product

When an end product is not assembled by several parts, it can be considered as single manufacturing procedure, no matter how many steps it takes to manufacture.
It is the total exposure time that influences the yield. A typical example is the integrated circuit chip.

In order to get rid of the flaw caused by the deposition of particles on chips and to reduce the probability less than 10% or even 1%, the probability of the deposition of one and more than one particles onto the chip within the area of each graph is required to be 0.1 or 0.01.

Poisson distribution can be used to correlate the probability of particle deposition on the surface and the deposition density on this surface, i.e.,

\[ P(\xi \geq 1) = 1 - P(\xi = 0) = 1 - \frac{n_s^0}{0!} e^{-n_s} \]  \hspace{1cm} (7.3)

where \( n_s \) is the surface deposition density on the chip.

The probability without particle deposition is the minimum yield, i.e.,

\[ P' = P(\xi = 0) = e^{-n_s} \]  \hspace{1cm} (7.4)

Of course, the deposited particles may be removed by cleaning. But as mentioned before, there are other reasons to cause flaw except for the particles. In abroad, the total flaw number or flaw density \( D \) was proposed, where particles only cause partial flaw number \( \beta D \) [14]. But it is difficult to determine the value. So it is useful for comparison between two situations, while it is difficult to make calculation alone. Furthermore, as analyzed before, one flaw may be caused by the deposition of one particle, as well as the deposition of multiply particles, which makes it difficult to define the flaw number caused by particle deposition. In this book, only the reason of air cleanliness is considered for the minimum yield, which

![Fig. 7.12 Number of particles deposited on silicon circular wafer with diameter 150 mm which is vertically placed in the Class 1 level cleanroom for 0.1 \( \mu \)m particle](image)
is appropriate from the safety point of view. This concept is applied in the following explanation of yield.

When the yield of the chip is known, the maximum deposition density $n_s$ can be calculated, i.e.,

\[ n_s \leq 0.01 \text{ for yield } 99\% \]

\[ n_s \leq 0.1 \text{ for yield } 90\% \]

The value of $n_s$ is obtained for the whole expose time $t$ of the chip. With the known chip area (deposition area) and $t$, $n_s$ can be converted into the unit deposition density. At last, with the aforementioned method, the particle concentration in the air can be calculated. In the former two versions of this book, the graph for calculation was given while the equation was not presented. Here the derivation equation for big silicon circular chip with high degree of integration is presented.

As for the deposition quantity of particles onto the surface, although development has been made from some research report abroad, the deposition expression is still Eq. (6.27) without correction in Chap. 6, which does not include other deposition factors. As mentioned before, for particles with diameter less than 0.1 μm which are controlled in ULSI, diffusional deposition plays an important role in the deposition quantity. The deposition density of particles with diameter 0.08 and 0.05 μm onto the chip is 2–5 times for particles with diameter 0.1 μm [13].

As introduced in Chap. 6 that Eq. (6.31) should be used to calculate the deposition quantity on surface with unit area in the room with ventilation. Since the unidirectional flow velocity in the cleanroom is about 0.3 m/s, the velocity correction proposed in Chap. 9 can be omitted.

Therefore, the total deposition quantity $n_s$ onto one chip is:

\[ n_s = \alpha v_s t N f (\text{pc}) \quad (7.5) \]

The particle concentration (for the controlled size) in the air is:

\[ N = \frac{n_s}{\alpha v_s t f} \text{ (pc/cm}^3\text{)} \quad (7.6) \]

With Eq. (7.4), the minimum yield $\eta$ which is the minimum probability $P'$ that caused by particles (may be non-full deposition, washed out after deposition, or with the effect of coagulated deposition) can be expressed with decimal:

\[ \eta = P' = e^{-n_s} = e^{-\alpha v_s t f N} \quad (7.7) \]

\[ N = \frac{-\ln \eta \times 1,000}{\alpha D v_s D f} \text{ (pc/L)} \quad (7.8) \]
where

\( \alpha_D \) is found in Chap. 6 with the average area-weighted diameter \( D_s \) for particles with diameter \( \geq \) controlled size. While for vital particles, the equivalent diameter is used instead of the average area-weighted diameter. It is the same hereinafter; 

\( v_{s,D} \) is the deposition velocity for particles with the average area-weighted diameter \( D_s \) for particles with diameter \( \geq \) controlled size, cm/s; 

\( f \) is the chip area, cm\(^2\); 

\( t \) is the exposure time, s.

The relationship between \( D_s \) and \( v_s \) is presented below:

| Controlled particle size (\( \mu m \)) | \( D_s \) (the percentage above the controlled particle size is assumed 100 \%) (\( \mu m \)) | \( v_s \) (cm/s) |
|--------------------------------------|-----------------------------------------------|-----------------|
| 0.007                                | 0.132                                         | 0.0001          |
| 0.035                                | 0.14                                          | 0.0001          |
| 0.05                                 | 0.16                                          | 0.00015         |
| 0.07                                 | 0.194                                         | 0.0002          |
| 0.1                                  | 0.24                                          | 0.00035         |
| 0.12                                 | 0.3                                           | 0.00054         |
| 0.18                                 | 0.4                                           | 0.001           |
| 0.5                                  | 1                                             | 0.006           |

There are two methods to calculate the exposure time:

1. There is linear proportional relationship between the manufacturing times and the exposure time for chip. When the known exposure time for certain integrated circuit is set 1, the exposure time for other integrated circuit with known manufacturing times can be obtained by multiplying the time coefficient with the known exposure time.

The time coefficient \( l_t \) is shown in Table 7.9.

| Integrated circuit size | \( l_t \) |
|------------------------|----------|
| 256 K                  | 1        |
| 1 M                    | 1.2      |
| 4 M                    | 1.66     |
| 16 M                   | 2.3      |
| 64 M                   | 3        |
| 256 M                  | 3.7      |
| 1 G                    | 4.06     |
| 4 G                    | 4.3      |

For the exposure time of former integrated circuit before 256 K, the value used by author was 8 h [15].

2. The exposure time is directly adopted from the actual value. According to the report these years [16], among the exposure time of former 1 h in the cleanroom environment during 1/10 of the whole manufacturing times, such as the waiting time during the cleaning procedure, the chip is exposed in the environment, so the average waiting time can be set 1 h. With this estimation method, when the minimum manufacturing steps were 140 times for the 256 K integrated circuit, so 1/10 of the steps is 14 times, and the exposure time becomes 14 h.
For the same integrated circuit with certain integration level, the manufacturing times among different factories are different. Take the integrated circuit 64 M-1G DRAM as an example, the manufacturing steps usually arrives 500–600 times. Since the time limit for 64 M is about 2 months, the time for each procedure or each manufacturing step is about 2.5–3 h [13].

When the second method to calculate the exposure time is used, the equation to calculate the air cleanliness level based on the yield can be derived:

\[
N_{0.1} = \frac{-\ln \eta \times 1,000 \times 28.3 \times \phi_{0.1}}{\alpha_{D}v_{s,D}f \times 0.1 \beta \times 3,600 \times \phi_{1/10}} \left( \text{pc/ft}^3 \right)
\]

(7.9)

where

\(\alpha_{D}\) is the value of \(\alpha\) based on \(D_{s}\);

\(v_{s,D}\) is the value of \(v_{s}\) based on \(D_{s}\);

\(\phi_{0.1}\) is the value of \(\phi\) for 0.1 \(\mu\)m;

\(\phi_{1/10}\) is the value of \(\phi\) for the controlled particle size which is equivalent with 1/10 of the linewidth.

The calculation procedures are as follows:

1. Determine the controlled particle size.
2. Calculate \(D_{s}\) with the controlled particle size.
3. Calculate \(\alpha_{D}\) and \(v_{s,D}\) with \(D_{s}\).
4. Determine the manufacturing times \(\beta\) with the integration level, and 0.1\(\beta\) is used.
5. Multiply the concentration pc/L with 28.3, and the concentration pc/ft\(^3\) is obtained. \(N_{0.5}\) (pc/ft\(^3\)) is then obtained by dividing it with \(\phi_{1/10}\). The particle concentration (pc/ft\(^3\)) for 0.1 \(\mu\)m, which means the air cleanliness level corresponding to 0.1 \(\mu\)m, is obtained by multiplication between it and \(\phi_{0.1}\). The value with metric unit system can be obtained when it is multiplied with 1,000 instead of 28.3. For the convenience of comparison with results in the literature, the English system is still used.

Table 7.10 shows the summary of two calculation results for the yields 50 and 80 %. In the table, the controlled particle size is 1/10 of the linewidth. But recently the controlled particle size tends to be enlarged. For example, the Semiconductor Industry Association (SIA) adopted 1/5 of the linewidth as the controlled particle size in 1993, while 1/3 of the linewidth was proposed in 1994 [13].

Take 256 K with the yield 50 % in the table as an example, the particle concentration with the controlled particle size 0.18 \(\mu\)m is calculated as follows:

\[
N = \frac{-\ln 0.5 \times 1,000}{\alpha_{D}v_{s,D}f \times 0.1 \beta \times 3,600} = \frac{0.69 \times 1,000}{1.5 \times 0.001 \times 0.4 \times 14 \times 3,600} = 22.8 \text{ (pc/L)}
\]

\[
= 645 \text{ (pc/ft}^3)\]
Table 7.10  Air cleanliness level (pc/ft\(^3\) for particles with diameter \(\geq\) certain value)

| Integration degree of DRAM | 256 K | 1 M | 4 M | 16 M | 64 M | 256 M | 1 G | 4 G |
|----------------------------|-------|-----|-----|------|------|-------|-----|-----|
| Chip area/cm\(^2\)         | 0.4   | 0.5 | 0.9 | 1.3  | 2    | 3     | 7   | 10  |
| Controlled size (choose 1/10 of the linewidth) | 0.18  | 0.12| 0.08| 0.05 | 0.035| 0.025 | 0.018| 0.01 |
| Processing times \(\beta\) | 140–160| 160–200| 200–300| 300–400| 400–500| 500–600| 530–700| 600–700 |
| Time coefficient \(l_1\)  | 1     | 1.2 | 1.66| 2.3  | 3    | 3.7   | 4.06| 4.3  |
| Minimum yield (\(\eta = 50\%\)) | Controlled size level | 645  | 415 | 165 | 88  | 80   | 46  | 17   | 12  |
|                            | 1,129 | 727 | 289 | 155 | 141 | 81   | 30  | 21   |
| 0.5 \(\mu m\) level       | 77    | 21  | 3.7 | 1.1 | –   | –    | –   | –    |
|                            | 134   | 37  | 6.5 | 2   | (28.6)| (4.7)|     |     |
| 0.1 \(\mu m\) level       | –     | –   | –   | 33  | 25  | 14   | 5   | 3.4  |
|                            |       |     |     | 58  | 44  | 24   | 8.8 | 6    |
|                            |       |     |     | (28) | (21) | (11) | (4) | (2.6) |
| Minimum yield (\(\eta = 80\%\)) | Controlled size level | 206  | 132 | 52  | 28  | 26   | 15  | 5.5  | 3.8  |
|                            | 360   | 232 | 92  | 49  | 45  | 25.8 | 9.6 | 6.7  |
| 0.5 \(\mu m\) level       | 25    | 6.8 | 1.2 | 0.3 | –   | –    | –   | –    |
|                            | 13    | 12  | 2.1 | 0.6 |    | (9.1)| (1.5)|     |
| 0.1 \(\mu m\) level       | –     | –   | –   | 9.8 | 8   | 4.4  | 1.6 | 1.1  |
|                            |       |     |     | 17.2| 14  | 7.7  | 2.8 | 1.9  |
|                            |       |     |     | (16)| (6.5) | (3.8) | (1.4) | (0.83) |
When the air cleanliness level with 0.5 μm is needed, the particle concentration should be divided with the conversion coefficient $\phi_D$ for the controlled particle size of 256 K, which is shown in Table 7.7:

$$N_{0.5} = \frac{645}{\phi_D} = \frac{645}{8.4} = 77 \text{ pc/ft}^3$$

The equation to calculate the yield was given in the literature [13], i.e.,

$$\eta = \left(\frac{1 - e^{-fD}}{fD}\right)^2 \quad (7.10)$$

where

- $f$ is the chip area, cm$^2$;
- $D$ is the allowable concentration of the total flaw density (caused not only by particles), pc/cm$^2$, where the part caused by particles is defined as $\beta D$ and $\beta$ is unknown.

Since it is difficult to determine the value of $D$ and there’s no factor of time in the equation, it is not convenient to be used for calculation directly. With the condition that the actual yield arrives at 50% for 256 K in the Class 100 environment, the value of $D$ can be obtained. When the exposure time is assumed to be linearly proportional to the manufacturing times, both the value of $D$ and the yield or the air cleanliness needed can be derived with the relative relationship. It is shown in the bracket of row 3 in the air cleanliness part of Table 7.10, but the information about 256 K is missing in the original table.

In the table, row 2 in the air cleanliness part is obtained firstly for 256 K with 8 h exposure time. Air cleanliness level for other integration levels is calculated by multiplying the time coefficient with the basic value for 256 K. Row 1 is based on 14 h exposure time.

Literature [14] presents the estimation value of the yield for 4–256 M DRAM in Class 1 level cleanroom with 0.1 μm particles. It is the particle number deposited on the silicon wafer which was vertically placed in Class 1 level cleanroom for 0.1 μm particles after the 40 day (960 h) exposure time. The estimated controlled particle sizes chosen were 1/1, 1/2, and 1/3 of the graphic size. The detailed information of estimation method and parameters were not given. Figure 7.13 shows two estimation curves.

Calculation was performed with author’s method, when the controlled particle sizes were set 1/2 and 1/3 of the graphic size. Results are presented in Tables 7.11 and 7.12 and plotted in Fig. 7.13.

From Tables 7.10, 7.11, and 7.12, the following conclusions can be reached:

1. In China, the theoretical method to determine the air cleanliness level corresponding to the minimum yield was proposed in 1981. When further correction was made on this method, the result agrees well with that of the calculation result abroad.

Figure 7.14 shows the calculation curve with author’s method. From the comparison of the methods between home and abroad, it is known that the accuracy of the curve is good, and author’s method is convenient to use.
2. The minimum air cleanliness for 0.5 μm is Class 134 (it is temporarily called with the number) for 256 K integration level and 8 h exposure time, when the yield can be reached 50 %. It is not surprised that the yield reached 50 % in Class 100 cleanroom for 0.5 μm in the early report. While the exposure time becomes 14 h, the air cleanliness level needed should be Class 77. Since the actual air cleanliness level is far lower than the cleanliness upper limit, it is natural that the yield reaches 50 % in Class 100 level cleanroom corresponding to 0.5 μm.

3. Even for 256 K, Class 268 is needed for exposure time 4 h, and Class 67 is needed for exposure time 16 h. But the cleanroom for manufacturing process should still be designed with Class 100 level (the yield is 50 %).

4. For 256 M, Class 14 level is needed corresponding to 0.1 μm, and it is obvious that the environment with air cleanliness Class 10 corresponding to 0.1 μm should be provided. For 1G, Class 5 corresponding to 0.1 μm is needed, so it is unsafe to provide the environment with air cleanliness Class 10 corresponding to 0.1 μm. It is only practical to design the environment with air cleanliness Class 1 corresponding to 0.1 μm (the yield is 50 %).

5. When the yield is 97 % for 4 M and 20 % for 256 M, Class 1 corresponding to 0.1 μm is needed when the exposure time is assumed to be 960 h. When the actual exposure time is used and 1/3 of the graphic size is considered, Class 50 for 0.1 μm or Class 1 for 0.5 μm is enough.

6. Taking the integrated circuit as an example, the air cleanliness improves by ten times every 10 years.
Table 7.11 Calculation results with controlled particle size equivalent with 1/3 of the graphic size

| Integration degree | Graphic size (μm) | Controlled size (μm) | $D_s$ (μm) | $v_s$ (cm/s) | $\alpha$ | $f$ (cm$^2$) | $\eta$ (%) | 1/10 of the processing steps exposed with 0.1 μm level | Entire exposure with 0.1 μm level |
|--------------------|-------------------|----------------------|-------------|--------------|---------|----------------|---------|------------------------------------------------|----------------------------------|
| 256 M              | 0.25              | 0.25/3 = 0.08        | 0.194       | 0.0002       | 8       | 3              | 20      | 55                                                | 30.5                             |
| 64 M               | 0.35              | 0.35/3 = 0.12        | 0.3         | 0.00054      | 2.3     | 2              | 65      | 45                                                | 44.4                             |
| 16 M               | 0.5               | 0.5/3 = 0.17         | 0.4         | 0.001        | 1.5     | 1.3            | 88      | 35                                                | 35.1                             |
| 4 M                | 0.8               | 0.8/3 = 0.27         | 0.55        | 0.0018       | 1.3     | 0.9            | 97      | 25                                                | 33.7                             |
Table 7.12  Calculation results with controlled particle size equivalent with 1/2 of the graphic size

| Integration degree | Graphic size (μm) | Controlled size (μm) | $D_s$ (μm) | $v_s$ (cm/s) | $\alpha$ | $f$ (cm²) | $\eta$ (%) | 1/10 of the processing steps exposed with 1 h for each step | 0.1 μm level | Entire exposure with 40 (day/h) | 0.1 μm level |
|--------------------|-------------------|----------------------|------------|-------------|----------|-----------|-----------|-------------------------------------------------|--------------|-----------------------------|-------------|
| 256 M              | 0.25              | 0.25/2 = 0.125       | 0.31       | 0.0006      | 2.3      | 3         | 65        | –                                               | –            | 960                         | 1.3         |
| 64 M               | 0.35              | 0.35/2 = 0.18        | 0.4        | 0.001       | 1.5      | 2         | 80        | –                                               | –            | 960                         | 2.1         |
| 16 M               | 0.5               | 0.5/2 = 0.25         | 0.53       | 0.0017      | 1.4      | 1.3       | 93        | –                                               | –            | 960                         | 1.1         |
| 4 M                | 0.8               | 0.8/2 = 0.4          | 0.8        | 0.0038      | 1.1      | 0.9       | 98.5      | –                                               | –            | 960                         | 0.5         |
### 1960s–1970s
- Small- and middle-scale integrated circuits
  - Class 100 for 0.5 μm

### Late 1970s
- Large-scale integrated circuit
  - Class 10 for 0.5 μm

### Late 1980s
- ULSI
  - Class 1 and Class 0.1 for 0.5 μm
  - (or Class 10 for 0.1 μm)

### Late 1990s
- ULSI
  - Class 0.1 for 0.5 μm or Class 1–Class 10 for 0.1 μm

### Beginning of this century
- ULSI
  - Class 0.1–Class 1 for 0.1 μm

### The first decade of this century
- ULSI
  - Class 0.1 for 0.1 μm

**Fig. 7.14** Air cleanliness curve calculated based on the yield of integrated circuit

![Air cleanliness curve](image-url)
Since the cleanrooms with air cleanliness Class 10 and Class 1 for 0.1 μm have been available for many years, it is very like to build a cleanroom (clean space) with air cleanliness Class 0.1 for 0.1 μm. In this way, the manufacturing requirement for 64G DRAM will be met in 2010.

7.7.2.2 Yield for Composite End Product

Although there are hundreds of procedures to manufacture the integrated circuit chip, they are completed on the same chip. But the process is less for the drug filling and potting. And it is completed on different objects. Such as the cleaning of penicillin bottle, waste product may be generated when pollution leaves inside it without complete cleaning. When the environmental air cleanliness in the process of bottle filling and potting is not good enough, it will be polluted during this process, which will also cause waste product. When the plug for bottle potting is not completely disinfected, it will contact the medicine and cause waste product. The end product of this kind is called composite end product, which will be made through many individual procedures.

Now taking the bottle filling and potting of sterile powder medicine (which cannot be disinfected at last) as an example, the bottle of the medicine will be discarded if one bacterium drops into during the process, which cannot be disinfected. This is similar as the waste product resulted from the deposition of one particle onto the chip.

After being cleaned and disinfected, the penicillin bottle will be open and delivered to the production line of bottle filling and potting. Let’s assume the open area of exposure $f = 1 \text{ cm}^2$. It usually takes about 20 s to arrive at this production line for bottle filling and potting. The whole process of bottle filling and potting takes about 12 s. Therefore, the exposure time during the whole process of bottle filling and potting can be assumed to be 30 s.

The difference between medicine and chip is that for medicine, it should not be infected with bacteria absolutely. It is not a problem of economical benefit affected by the yield but a safety problem of 100 % for the patient. It is obvious from the expression to calculate $N$ that if the yield is required to be $\eta = 100 \%$, the number of particles which carry bacteria should be $N = 0$. In practice this is impossible. Therefore, we need to consider the situation when the deposition probability is extremely low.

Usually the output of the penicillin bottles can reach more than 10,000 bottle/(turn · people). If the probability of the deposition of particles carrying bacteria is as small as 1/10,000 for bottles delivered to the bottle potting after cleaning (e.g., the number of bottles on the turntable is only 200), which means the contamination of one bottle is likely to happen if the exposed bottles increase by 50 times, the number of particles carrying bacteria deposited under the original manufacturing situation is regarded as “0.”

Suppose there are $n$ procedures during the process of manufacture and the qualified ratio of the semifinished products for each procedure is $P_1, P_2, \ldots, P_n$, so the qualified ratio, i.e., the yield of the end product is $\eta_\Sigma$, can be obtained.
Since the incidence of the waste product in each procedure is independent from each other, “the product is qualified” ($\eta\Sigma$) means “the first procedure is qualified” ($P_1$), “the second procedure is qualified” ($P_2$)… until “the n procedure is qualified” ($P_n$). With the multiplication law of probability, we can obtain the yield from many individual procedures:

$$\eta\Sigma = E \prod_{i=1}^{n} P_i$$ (7.11)

When all the semifinished products are qualified, the final qualified ratio, i.e., the yield, will be decreased during the influence of reliability of whole manufacturing process. This can be reflected with a coefficient $E$ in the above equation, where $E$ is between 0.1 and 1.0. Since this is also one kind of probability concepts, one more procedure may be added for the convenience of discussion. Therefore, the above equation is converted into

$$\eta\Sigma = \prod_{i=1}^{n+1} P_i$$

For the assumed values of $n$ and $P_i$, the results (the yield $\eta\Sigma$ of composite product) can be obtained which are shown in Table 7.13.

It is shown from Table 7.13 that:

1. When there are many procedures, the final yield is also very low even though the yield of each procedure is high.
2. When there are many procedures, the final yield is greatly affected even if only the yield of one procedure is very low. Therefore, not only the air cleanliness level for critical procedure should be guaranteed but also that of the ordinary procedure must be guaranteed.
3. The yield of composite product with few procedures can be easily improved.

Taking the bottle filling and potting of sterile medicine as an example, three procedures including cleaning, canning, and potting are necessary. The composite yield of these three procedures should be 0.9999 (the defect rate is 1/1,000), which means with the above equation the yield of each procedure is 0.99997. Therefore, the concentration of airborne bacteria is

$$N = \frac{-\ln 0.99997 \times 1,000}{1.2 \times 0.09 \times 30 \times 1} \approx 0.01 \text{ pc/L}$$

where

1.2 is the value of $\alpha_D$ obtained with the equivalent diameter 3.9 $\mu$m of the bacteria, which is shown in Chap. 9.

0.09 is the value of $v_{S,D}$. 

7.7 Theoretical Method to Determine the Yield by Air Cleanliness 371
From the bacteria concentration required for bottle filling and potting of sterile product in Table 7.14, the following conclusions can be reached:

1. Because with unidirectional flow, the standard for dynamic state should be 2–3 times higher than static state (please refer to Sect. 17.5.2). So when the bottle filling and potting process of sterile powder is carried out in the class 5 environment with Chinese GMP standard published in 1998, the airborne bacteria concentration with dynamic state for GMP class 5 space should be \(0.005 \times (2/C)^{3} = 0.01–0.015\) pc/L, which is slightly higher than that of the needed value 0.01 pc/L. So it is basically feasible. If the defect rate was increased to 1/1,000, namely the comprehensive yield increases to 0.99999, the yield for each procedure should be increased by 10 times, which is 0.999997. In this case, \(N\) should reach 0.001 pc/L, i.e. 1 pc/m³. The current GMP specifies the environmental bacteria concentration for sterile bottle filling process to be less than 1 CFU/m³, which meets this requirement. If the defect rate of each procedure increased to 1/1,000,000, \(N\) should be reduced to 0.3 pc/L.

2. If measures can be taken to reduce the number of exposed bottles for filling and potting, such as shorten the route, reduce the turntable area, and use the clean tunnel on the turntable or the conveying line like in the manufacture of integrated circuit, the requirement on the air cleanliness level can be reduced, which reduces the investment of cleanroom accordingly.

### 7.8 Level of AMC in Clean Environment

Airborne molecular compound (AMC) includes the following kinds:

1. Acid gas, such as HF, NOₓ, SO₂, SO₃, H₂S, Cl₂, and HCl
2. Alkaline gas, such as NH₃
3. Condensation organic compound, such as HCHO and HMDS(C₆H₁₉Si)
4. Mixture compound, such as BF₃ and B(OH)₃
5. High volatile organic compound (VVOCs), such as NHHC
6. Molecular metal, such as Fe, Na, K, Ca, Zn, and Al

These contaminants do not only come from the manufacture process itself but also from the building decoration material in the cleanroom. For the former case, the representative includes the disinfection agent from solvent vapor, phenol, and

| \(n + 1\) | \(P_i\) | 10 | 9  | 8  | 11 | 6  | 5  | 4  |
|----------|-------|----|----|----|----|----|----|----|
| 0.8      | 0.107 | 0.134 | 0.168 | 0.21 | 0.262 | 0.328 | 0.41 |
| 0.9      | 0.349 | 0.387 | 0.43 | 0.478 | 0.531 | 0.59 | 0.656 |
| 0.95     | 0.599 | 0.63 | 0.663 | 0.699 | 0.735 | 0.774 | 0.815 |
| 0.99     | 0.904 | 0.914 | 0.923 | 0.93 | 0.94 | 0.95 | 0.96 |
| 0.999    | 0.99 | 0.991 | 0.992 | 0.993 | 0.994 | 0.995 | 0.996 |
| 0.9999   | 0.999 | 0.9991 | 0.9992 | 0.9993 | 0.9994 | 0.9995 | 0.9996 |
ether from anesthetic. For the latter case, the representative includes NH₃ and Ca from the concrete; siloxane from the aquaseal, PH₃, PF₃, Na, Ca, and Fe from the anti-static material; metal ion, toluene, and dimethylbenzene from the painting; NOₓ, SOₓ, Na, and Cl from the fresh air; B, DOP, Na, and Cl from the interior of cleaning air-conditioning system such as HEPA filter; and NH₃, Na, Cl, and various organic materials from people, costume, and cosmetic.

As for the TVOC (total volatile organic compound) from building decoration material only, the concentration measured was 3,500 μg/m³ in a newly decorated cleanroom performed by Osaka University from Japan. After operation for 1 month, it reduced to 500 μg/m³, while it kept at 200 μg/m³ stably after operation for 4 months [17].

It is increasingly important to control AMC in cleanroom. This has already become an essential condition especially for ULSI.

Table 7.15 lists the source of AMC during the manufacture of ULSI [18].

In 1995, International Association of Semiconductor Equipment and Material proposed the classification standard for AMC in clean environment: SEMI F21-95.

### Table 7.14 The airborne bacteria concentration required for bottle filling and potting of sterile product

| Standard                                      | Airborne bacterial concentration with air cleanliness level Class 8 (CFU/L) | Airborne bacterial concentration with air cleanliness level Class 7 (CFU/L) | Airborne bacterial concentration with air cleanliness level Class 5 (CFU/L) | Airborne bacterial concentration with air cleanliness level Class 4 (0.5 μm) (CFU/L) |
|-----------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| US NASA                                       | 0.0884                                                                      | 0.0176                                                                      | 0.0035                                                                      | 0.0014                                                                      |
| EU GMP (operational state)                    | 0.1                                                                         | 0.01                                                                        | 0.001                                                                       | –                                                                           |
| China GMP (1998) (at-rest state)              | 0.5                                                                         | 0.1                                                                         | 0.005                                                                       | –                                                                           |
| China GMP (2010) (operational state)          | 0.1                                                                         | 0.01                                                                        | 0.001                                                                       | –                                                                           |
| China Standard: architectural technical code for hospital clean operating department (at-rest state) | 0.15                                                                        | 0.05                                                                        | 0.005                                                                       | –                                                                           |

7.8 Level of AMC in Clean Environment 373
The maximum allowable concentrations for four kinds of contaminants were given in this standard, which is shown in Table 7.16. The magnitude of pptM in the table means \(1 \times 10^{-12}\).

In 2000, Air Cleaning Association of Japan proposed the draft “Label and test method for air cleaning level about AMC in cleanrooms and related controlled environment” [19], which proposed the expression method for the AMC cleanliness level, i.e.,

\[
N = \lg \left(1/C_{AMC}\right) \quad (7.12)
\]
where $C_{AMC}$ is the allowable upper limit of concentration for specific AMC and its derivation. The unit for volumetric concentration is $g/m^3$, while for surface concentration $g/cm^3$. It is shown in Table 7.17.

Compared with the standard SEMI, the item about high volatile organic material is added, but not metal content is included.

This standard specified to use the following method to make the label, which starts from $X$:

$$Xa(b;c);[d;e]$$

where

- $a$ is the symbol representing the contaminant in Table 7.17. For example, HCl is expressed with A;
- $b$ is the specific name of the contaminant, such as DOP and HCl;
- $c$ is the air cleanliness level $N[-]$, such as the value shown in Table 7.17;
- $d$ is the test method;
- $e$ is the exposure time (when the surface concentration is used).

Furthermore, the operational state and related parameters (such as temperature, humidity, and pressure drop) should be recorded.

### Table 7.17 Classification of air cleanliness for AMC (Japan)

| Pollutant                              | Volumetric concentration $(\times 10^{-N}g/m^3)$ | Surface concentration $(\times 10^{-N}g/cm^2)$ |
|----------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Acid gas (expressed with A)            | $N = 9 \cdots 2$                                | $N = 11 \cdots 5$                             |
| Alkali gas (expressed with B)          | $N = 9 \cdots 2$                                |                                               |
| Coagulative organic matter (expressed with C) | $N = 9 \cdots 2$                        |                                               |
| Dopant (expressed with D)              | $N = 9 \cdots 2$                                |                                               |
| High volatile organic compound (expressed with V) | $N = 9 \cdots 2$                 |                                               |

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