1 Basics of Contamination Control

Contaminants play an especially important role in the manufacture, manipulation or repair of such items as semiconductors, space vehicles, conventional and nuclear missiles, microbial cultures, ball-bearings, parenterals, vaccines and human organs.

While it may be unusual to think of the human body as a product, or the Operation Theatre as a factory, the same engineering principles of microcontamination control apply. The control of infectious airborne pathogenic organisms in hospital operating rooms and recovery wards can be achieved in a manner identical to that used to protect against airborne contaminants during pattern generation

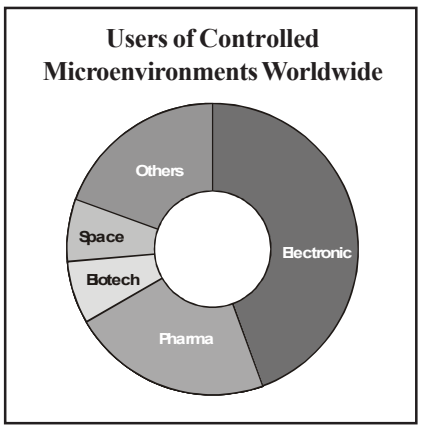


Fig. 1.1

of semiconductor devices, or during aseptic manipulations with thermolabile injectibles. The “risks” of manufacture, of course, are different since the loss of a human life has consequences beyond economics. But the technical approaches to solving the problem remain similar.

Contamination control is only a part of the larger Quality Assurance Initiatives that aim to minimise the risk of producing a defective, and maximise the probability of manufacturing a product "fit for use" or "fit for purpose". By this token, contamination control is best described as a set of systems, practices and procedures that aspire to minimise the introduction of a contaminant into a product or process.

Contamination control can be compared to providing the highest level of personal security to a VIP under threat. Depending on whether the VIP is the President of the United States of America, or of Sri Lanka, or of India, the group posing the threat differs. Once we know the identity of the VIP, we are better placed not only to anticipate the sources of the threat, but also to know more about their origin, locations, motives and modus operandi.

The security steps we normally take are:

1. Isolate the VIP
2. Minimise his exposure, both in terms of duration and frequency
3. Seek and destroy or immobilise those threatening his safety
4. If his enemies are outside, we make it difficult for them to penetrate the protective barriers
5. If they are already within, we flush them out
6. We monitor those in his immediate proximity
7. We advise the VIP not to antagonise anyone who may be around him, friend today, foe tomorrow (Don't *generate* enemies within)
8. Stay vigilant and cope

In the context of contamination control, a product or process is what we try to safeguard, and a contaminant is any substance or energy which produces an *adverse* effect on that product or process. Such a classification is purely contextual, without bearing on its absolute worth. Just as the enemy of one VIP may not necessarily be an enemy of the next VIP, so too in contamination control. Light is precious for all of us, but not for photoprocessing; gold, too, is precious, but not a speck is welcome in the wrong place on a wafer.

Contamination control measures make more sense once we understand contaminants and the contamination process.

Contaminant Classification

Regarded from the stand point of the 'type' of *damage* they do, contaminants may be divided into subgroups :

Table1.1

SUBSTANCE			ENERGY
Physical	**Chemical**	**Biologic**	
Dust Dirt Grit Fibre Lint Fly ash	Organic compounds Inorganic salts Vapour Mist Fume Smoke	Bacteria Fungus Spore Pollen Virus Human skin cells	Thermal Light Electromagnetic (EMI) Electrostatic (ESD) Radiation Electrical (RF)

- ***Physical :*** Particles that cause damage by virtue of their *physical properties* alone: for example, a grain of sand can score a bearing, or obstruct light in photoprocessing.
- ***Chemical :*** Organic chemicals such as oils, fats, waxes, fluxes, paints and plastics may *react chemically* with a product and change its properties, or simply insulate the product and interfere with its processing. Inorganic chemicals, being ionic by nature, modify the electrical characteristics of precision electronic products. Gases induce contamination (like oxidation) only in the gaseous phase. In contrast, vapours and mists contaminate in the vapour phase; on condensation, in the liquid phase (like oil films); and, on subsequent evaporation, in the solid phase (residues).
- ***Biological :*** Microorganisms are the critical contaminants in pharmaceuticals, biotechnology, food & beverage processing, cosmetics and patient care.
- ***Energy :*** Some products are thermolabile; some sensitive to electrostatic discharge (ESD); some are affected by RF & EMI.

Contaminant Pathway

If you were to ask any agency that provides security to VIPs they will tell you that the enemy may attempt a million times and fail; he needs to succeed just once. In contrast, they must succeed each time. This is just as true with contamination control.

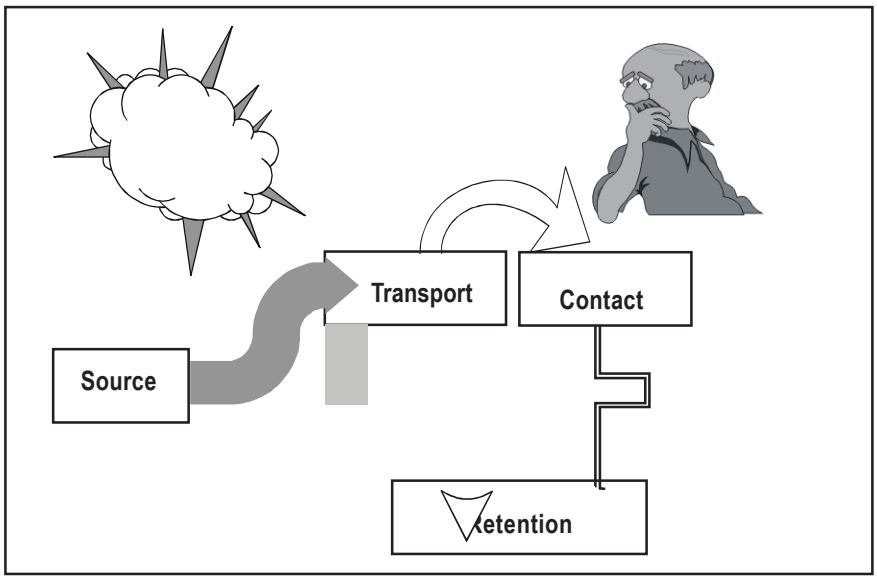


Fig. 1.2 The Contaminant Pathway

On the flip side, the mere presence of a contaminant does not automatically imply contamination. For contamination to occur, the contaminant must first have its *source*; must then be *transported* and reach the product site; must make *contact* with the product; and must be *retained* by the product.

If this process of contamination, known as the *contaminant pathway*, is broken at any stage, contamination does not occur.

For instance, if the source of the contaminant is absent; or, having a source, it is unable to access the product; or, having somehow managed to slip through, is prevented from making contact; or, even after having made contact, is not retained, or not allowed to be retained, *contamination does not take place*, and the product is safe.

Contamination control may then be viewed as an exercise that aims to break the contaminant pathway at one or more stages of the contamination process.

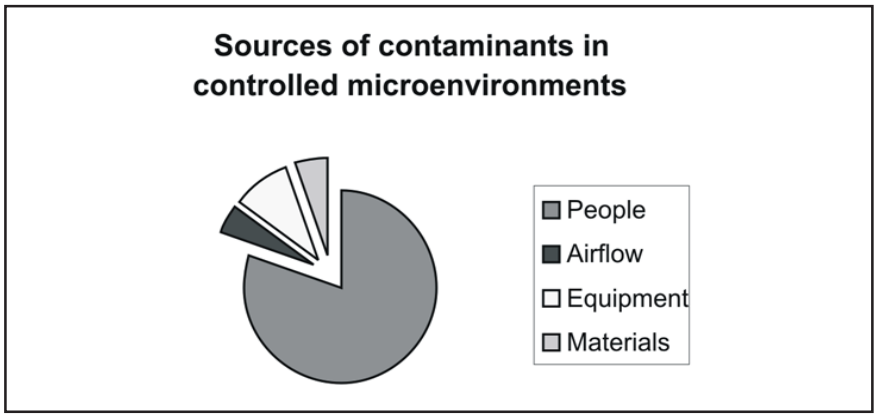


Fig. 1.3

Sources of Contaminants

Included contaminants emanate from raw materials and consumables; *fluidised* contaminants from utilities; *suspended* contaminants from the environment; *settled* contaminants from dust collecting surfaces; *emitted* contaminants from machinery, moving parts and surfaces; *shedded* and *transferred* contaminants from personnel.

In fact, research into a large number of reported occurrences of contamination in well-designed and maintained clean rooms reveals that in 5% of the cases it was due to *contaminated raw materials*; in 10% through *utilities* and *defective or soiled equipment, tools or implements*; in 5% due to *faulty air filtration;* and in 80% due to *breaches in the product-person interface*.

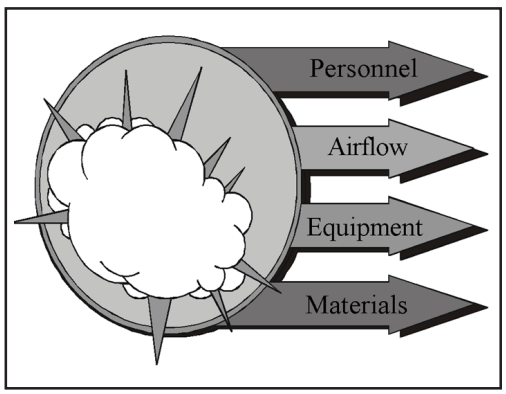


Fig. 1.4

Hence, contrary to popular belief, microcontamination control does not begin and end with air filtration: it is only one of many concurrent initiatives. Comprehensive microcontamination control requires a program that effectively integrates and orchestrates planned offensive

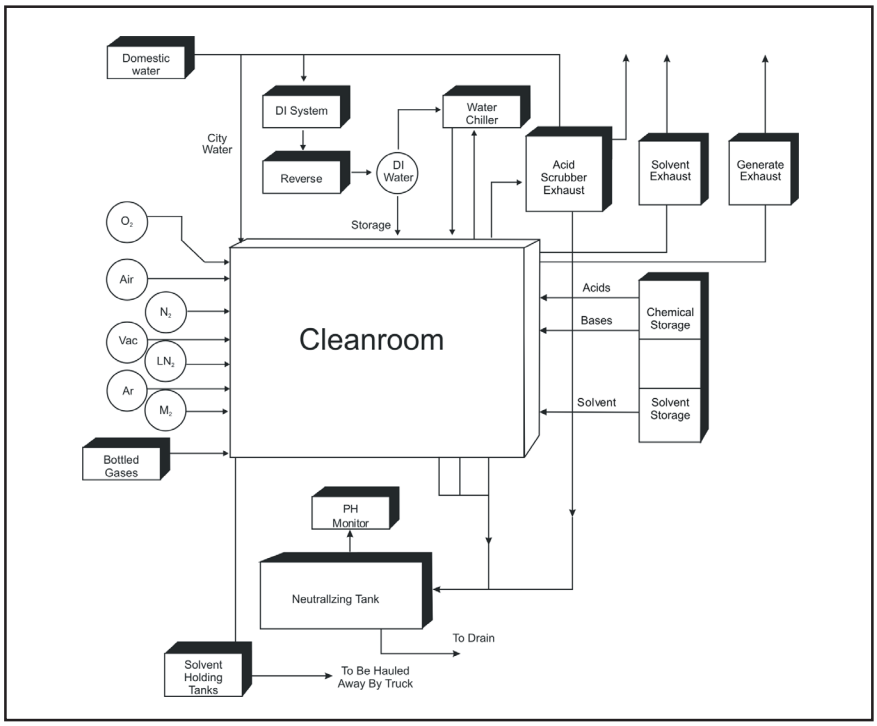


Fig. 1.5 Typical Semiconductor Processing Facility

measures on all four fronts. Pursuing one while ignoring others yields sub-optimal results.

I have personally seen many facilities where such "common sense" is conspicuous by its absence. The User forces me through a commendable decontamination entry regimen, only to leave me watch in amazement the impunity with which the trolley boy "gate crashes" from the material entry; double-doored and air locked. No decontamination protocols apply to him, his trolley or their dirt-laden wheels, except on some neatly typed SOP, stashed away in the recesses of a filing cabinet in the Production Manager's Office.

Controlling the quality of incoming raw materials, consumables, liquids and gases, and selection and use of equipment and accessories appropriate for the task are subjects beyond the scope of this book. They have been mentioned to record that these avenues too must be looked into as sources of contaminants while drawing up a program for microcontamination control.

We restrict our focus to the management of contaminants that are airborne, and those at the product-person interface.

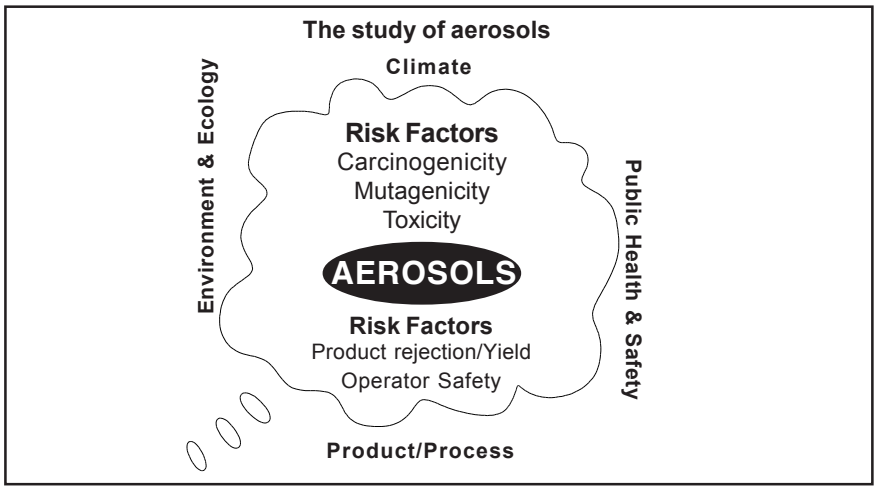


Fig. 1.6

Aerosols

The subject of aerosols has long interested researchers in pollution control as well as contamination control. In the former group are those in Public Health who worry about the risk factors associated with atmospheric pollution; environment scientists who are concerned about adverse ecological effects; and meteorologists whose interest is in determining the influence on climate

Table 1.2

Number of Particles/m^3 in Outdoor Air			
Size µm	Dirty	Normal	Clean
>0.1	1×10^{10}	3×10^{9}	5×10^{8}
>0.3	3×10^{8}	9×10^{7}	2×10^{7}
>0.5	3×10^{7}	7×10^{6}	1×10^{6}

and weather, as a consequence of which a wealth of data is available. Our interest is in examining their potential to compromise product yield and operator safety.

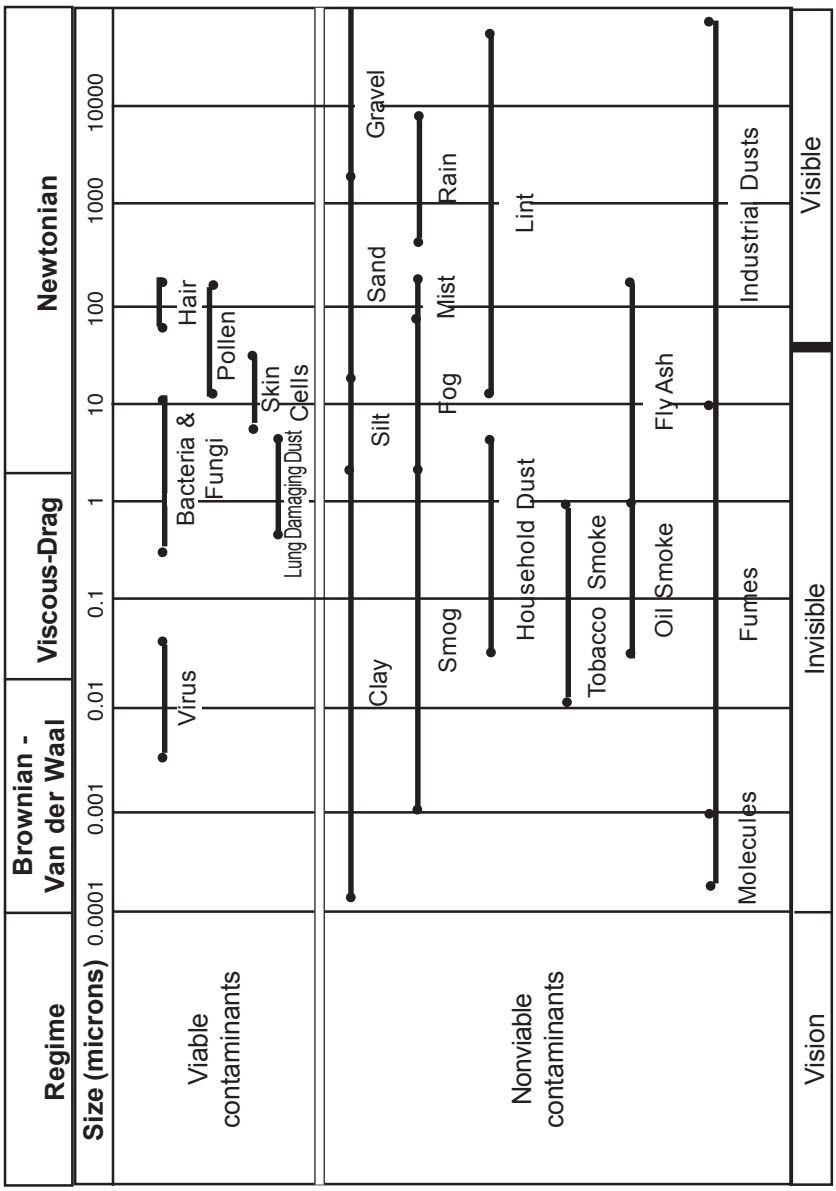


Fig 1.7 Size Distribution of typical suspended contaminants

The conventional unit of measurement for suspended particles is the micron (μ), or one-millionth part of a metre. To have some idea of the relative sizes, it may be noted that the diameter of average human hair is 100μ. Rain is a good example of 1000μ suspended droplets that settle out quickly, attaining a terminal velocity much before they reach ground level. Human vision with the unaided eye stops at 50μ.

Suspended Particulate Regimes

Larger particles have a relatively short "life" as *suspended* contaminants, and settle out rapidly. This is due to the fact that those in size above 20μ have sufficient mass to respond to gravity. Such particles are referred to, for the purpose of this discussion, as *Newtonian* particles or particles belonging to the *gravitational regime*. (Since our vision is limited to 50μ, this means that visible particles do not remain suspended in aerosols; in other words, the particles that do remain suspended in the aerosol are too small to be seen. Suspended contaminants are, therefore, by and large invisible. In fact, in an average cleanroom, 97% of suspended contaminants are sub-visible).

Particles in the size range 0.1μ to 10μ do not have sufficient mass for gravitational forces to be effective; they respond, instead, to *viscous drag forces* and move with air currents. We refer to these as *Stokes-Cunningham* particles or particles belonging to the *drag regime*.

Particles smaller than 0.1μ, and approaching molecular sizes, hardly have any mass, and are too small even for viscous pulls and pushes. They are in a constant state of Brownian motion, the irregular movement of suspended particles as a result of bombardment by atoms and molecules, Van der Waal forces, electrostatic attraction and repulsion. We call these *Brownian* particles or particles in the *diffusion regime*. As mentioned earlier, every single suspended contaminant in the aerosol is not necessarily a threat to the product. In order to contaminate, it must *first reach* the product. Let us therefore study the different mechanisms at play that can propel a contaminant toward the critical work area and precipitate the deposition process.

Gravitational Propulsion

If the particle is *newtonian*, gravity is probably the most recognised mechanism for particle movement and deposition. Particles in any liquid or gas of a lower density will settle out, reaching a terminal velocity determined by the balance between gravitational forces and the viscous drag of the fluid. Contaminants above the work site have the potential to reach the product while settling down. On the other hand, if the particle is below product datum level, it cannot cause harm as long as it remains at that level.

Table 1.3 Velocity of settling of typical suspended contaminants

Transport	Diffusion	Air currents	Gravity
Regime	Brownian-Van der Waal	Viscous-Drag	Newtonian

Diameter of particles (microns)	Velocity of settling		
	Feet per minute	Inches per hour	Centimetres per second
< 0.02	?	?	?
0.05	0.00003	0.022	0.000015
0.1	0.00016	0.115	0.000081
0.2	0.00036	0.259	0.00018
0.4	0.0013	0.936	0.00066
0.8	0.005	3.6	0.0025
1	0.007	5.04	0.0036
2	0.024	17.4	0.012
5	0.2	144	0.102
10	0.59	425	0.3
20	2.4	1,728	1.2
40	9.5	6,840	4.8
60	21.3	15,320	10.8
80	37.9	27,250	19.2
100	352	253,500	179
400	498	360,000	253

Similarly, a particle of sufficient mass moving in a fluid may find it difficult to negotiate deviating flow lines, specially when the fluid flows around obstacles in the course. In the process of bypassing the obstacle its momentum may cause it to veer out of control and cut across the flow to impinge and settle on the boundary wall. Or it may collide, lose momentum, and fall out. These are *inertial* mechanisms.

Sedimentation is a process triggered by the balance between gravity and forces of uniform fluid flow causing a suspended contaminant to settle out in a parabolic trajectory. The linear distance travelled is a function of fluid velocity and particle weight. The mass dependence of inertial forces reduces their influence in the sub-newtonian size range.

Drag Propulsion

Air currents are the principal cause of spread of suspended *Stokes-Cunningham* particles through their vigorous mixing action: the greater the air velocity and turbulence, the wider the range of spread. This phenomenon could facilitate drag regime particles to reach the product from any location or level in the room. (Liquids are more dense and viscous than air; hence fluidised particles are dragged over longer distances. If the contaminant dissolves, the dispersion and spread is even more pronounced).

Theoretical and experimental study of *turbulent* air currents is difficult, and little is known about the motion of particles suspended in turbulent flow. Particles will drop out no doubt; but the eddy currents present make it difficult to predict when, where or in which direction. All that can be said with any certainty is that the deposition rate will be an exponential decay function and that the velocity of any suspended particulate could be in any direction and of any magnitude.

Closely related to the concepts of turbulent flow are the *convection* currents in the environment. If there is a convective movement of gas containing suspended particles, there will be an interaction of forces between the gas medium and the particles tending to transport the particles on a bulk basis. Atmospheric clouds are examples of the convection phenomenon where droplets of water are transported great distances as a unit because of the temperature and concentration gradients between the cloud and the surrounding atmosphere.

Table 1.4

Regime	Brownian	Viscous-Drag	Newtonian
Propulsion medium	Assorted small particle effects	Air currents	Gravity
Regime-dependent deposition mechanism	Diffusion Electrostatic effects Capillary action Adsorption Van der Waal forces Coalescence Agglomeration	Surface tension	Sifting Sedimentation Inertial Forces
Regime-independent deposition mechanism	Impaction Interception Fibrillation Contaction	Impaction Interception Fibrillation Contaction	Impaction Interception Fibrillation Contaction

Artificial *agitation*, caused by personnel movements and process machinery motions, can, with the aid of the currents induced by the air distribution system in the room, transport suspended contaminants over considerable distances and precipitate deposition. The complex interplay of the mechanisms described above render it difficult to establish guidelines for the effects of 'artificially' induced agitation.

Diffusion Propulsion

Brownian motion causes spread of suspended ultrafines through diffusion: the higher the temperature, concentration, or diffusion coefficient, the larger the area of spread. The product could be compromised by a brownian particle from just about anywhere in the room.

Particles with diameter smaller than 0.1μ often grow in size till they assume a critical mass sufficient to settle out or be dragged away. Small particles tend to come together due to various mechanisms. Oppositely charged particles meet and become, neutral, but larger particles. While bombarding each other, two particles do not always rebound; if the Van der Waal force of intermolecular attraction is sufficiently strong, they stay bound together. In some cases a particle impinging on another loses its kinetic energy on impaction and remains loosely adhered at the surface. The first two are instances of *coalescence*

where particles fuse together to form a larger particle; the last is an example of *agglomeration*. Both phenomena lead to cluster formations, and the cluster behaves exactly as a single homogeneous particle of that size would: either respond to gravity or to viscous drag forces.

Electrostatic charge can influence particle transport and deposition depending on the type of charge carried by the particle and the intensity of the electric or magnetic field present.

Other Mechanisms

Some deposition mechanisms are independent of particle size or the regime generally governing their behaviour. One of them is *impaction*, where a particle collides with and deposits on the surface of an obstructing object. Or, a particle could be *entrapped*, *occluded* or *enmeshed*, when its physical size precludes its passage through a porous obstacle. Similarly, if a suspended particle in motion encounters a series of obstacles that "trip" it in succession, it may lose sufficient kinetic energy and settle out, a mechanism known as *interception*.

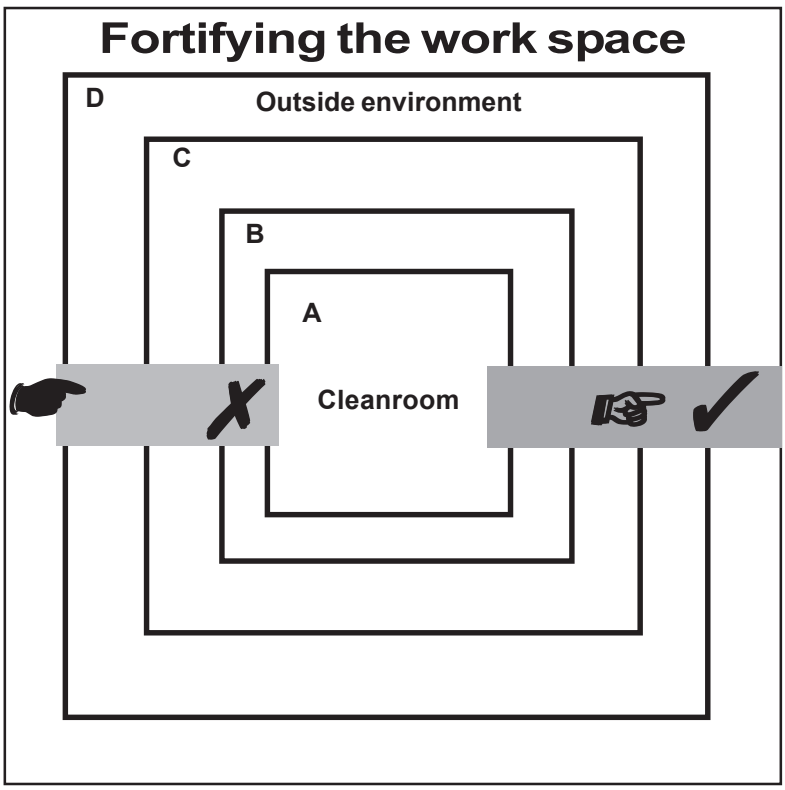
Perhaps the most commonly occurring deposition is through *contaction*. Settled contaminants reach the product through the operator or any article or implement that makes physical contact with it while working.

With so many diverse forces and mechanisms at play, the 97% of sub-visible suspended contaminants in aerosols, left to themselves, tend to move about randomly, in all directions. But once we fully understand these influences, we are better equipped to devise methods to control and direct their trajectories out of harm's way.

The techniques developed in this book are directed more towards control of suspended particulates and microflora. However, moisture and airborne molecular contaminants (AMC) are also airborne, but require very special techniques for their management. Humidity is relatively better known, understood and controlled, but here we pause to get acquainted with airborne molecular contaminants.

Molecular contaminants

Although AMC is most commonly associated with the microelectronics, it is a problem in other processes such as spray painting, which have embraced cleanroom practices. In microelectronics, the shrinking chip geometry with



1 Identify the contaminant
2 Anticipate the contaminant
3 Prevent ingress
4 Facilitate egress
5 Minimise internal generation
6 Control residual contaminants

Fig. 1.8: The master plan for contamination control

critical sizes approaching molecular sizes is driving the need for testing and minimising AMC.

The AMC in cleanrooms may be classified as A, B, C and D (Acids, Bases, Condensables, and Dopants). The levels at which they are present in cleanrooms are often at the detection limits of instruments. In microelectronics, limits for molecular contamination as low as 0.1 ppt are forecast.

Current practice for controlling AMC is cleanrooms has taken a dual track. One is traditional practice of removal with gaseous filters or scrubbers. The other approach is to minimize or eliminate the use of materials that out gas the undesirable AMC. This has required clean materials for filter manufacture such as PTFE membranes, non boron or phosphor containing products, inert sealing compounds, and separators.

Of the AMC, in microelectronics, boron and organophosphates and their compounds are of main concern. Both boron and organophosphates are semiconductor dopants, and can diffuse into the silicon causing changes to the dopant level and electrical properties of the semiconductor. In other applications such as spray painting, silicone is a major concern.

Microfiber glass is suspected to be the primary source of boron in cleanrooms. In many cases, concentrations of ambient boron are high enough to make it nearly impossible to measure levels of boron from cleanroom filter media. Currently, boron in glass media is measured by extraction in water and reported as bulk concentration.

In cleanroom filters, the sources of organic compounds are the potting compounds used to seal the filter media to the filter frame, materials used for pleat separation, gaskets, and materials used in the manufacture of the media. Organophosphates are common fire retardants and are used widely in many potting and sealing compounds.

Of the organics, only the semi volatile compounds (with boiling points approximately between 100 to 400 ^{0}C) are of concern in materials of construction of cleanroom filters. The low boiling point materials are volatile enough to be eliminated rapidly at room temperatures. The higher boiling point materials are for the most part not gaseous at operating temperatures and are not a problem.

The current consensus for measuring the off gassing of the medium boiling point materials is to collect the materials in ambient air sampling tubes. The sampling tubes contain appropriate adsorbents to trap the compounds of interest. The sampling tubes are then analyzed by thermal desorption GC/MS. This method is also known as dynamic head space analyses. The sample is

typically desorbed continuously at an elevated temperature while being purged by nitrogen. The out gassed compounds are then captured in a trap and analyzed by a GC/MS. The test provides only a relative abundance of the material in comparison to a reference. The temperature of the test can greatly affect the off gassing. It is a compromise between the higher temperatures needed to drive out more of the condensable from the material, and the lower temperatures needed to prevent the destruction of materials of interest. Currently, there is no consensus on the appropriate test temperature.

The master plan for contamination control

As mentioned at the outset, contamination control is much alike protecting a VIP, and the steps outlined for security apply here.

A product or process is susceptible to contamination during manufacture, assembly, testing, cleaning, transportation, storage or even while being used. Our objective is to minimise the risk of its being contaminated along the way.

Identifying the Contaminant

Our first exercise is in identifying the possible contaminants that threaten the product or process. We can then design a contamination control program that takes into account their characteristics and behavioural pattern.

Anticipting the Contaminant

Having identified the contaminants that are likely to compromise our product or process, we focus on the possible sources from where they could originate; and their mode of getting to the critical zone.

Preventing Ingress

Preventing ingress of contaminants into the selected work area. Since this book does not attempt to cover contaminants emanating from raw materials and utilities (*included* and *fluidised* contaminants), let us start with *suspended* contaminants. This is achieved by a combination of methods: controlling the particulate content through filtration of incoming air; isolating the product to the extent feasible from the harmful environment surrounding it; and entry restrictions with thorough decontamination of all materials, consumables, equipment, implements and personnel entering the zone. Where over pressurising is an available option, the balloon effect wards off incursions of suspended contaminants.

Table 1.5 : Basic microcontamination control checklist	
	Rigid inward Quality Control to check ingress of included contaminants through process raw materials/consumables, and fluidised contaminants through gases/liquids
Preventing Ingress	√ Select class of air cleanliness appropriate for the task √ Select location and layout optimising flowpaths for men, material and process ■ avoid loops in flowpaths ■ isolate through barriers ■ avoid direct / straight through access ■ stagger doorways ■ no windows on external wall ■ double-glazed view panels with breathers √ Sustain overpressure along clean-to-dirty axis, where not contraindicated √ Impose entry restrictions and thorough decontamination procedures for men, material and equipment
Facilitating Egress	√ Sustain overpressure along clean-to-dirty axis, where not contraindicated √ Avoid surfaces that can accumulate dust; where unavoidable, ensure easy accessibility to clean and disinfect √ Implement comprehensive sanitation plan
Minimising Generation	√ Select material and equipment that don't shed excessive particles or degas, especially walls, floor and ceiling √ Establish sound maintenance for upkeep of facility √ Operator training and discipline √ Good gowning
Coping with residual contaminants	√ Dilution of aerosol concentration by dilution: increase in air change rate √ Controlled velocity airflow without eddy currents to drag away suspended contaminants from critical zone: LAF √ Reduce product exposure time and exposure frequency

Since maintaining a high class of air cleanliness in the environment is always expensive, some designers advocate *task-specific* air cleanliness: a clean work bench in a cleanroom, where the air cleanliness at the work station is at least an order of magnitude higher than the surrounding environment.

Facilitating Egress

Facilitate egress of suspended as well as settled contaminants from within. The air distribution system should be designed to displace contaminated air to the exterior as directly and rapidly as possible. The principle of dilution can be employed: clean air can be passed through the given space in sufficient quantities to flush out as much of the contaminants generated within the space, and thinning out the concentration of the rest. An important corollary to control by dilution is an air distribution design that minimises recirculating eddy currents. An imaginative, effective and implementable sanitation scheme, closely supervised and monitored is another method of getting settled contaminants out of harm's way. Surfaces that gather dust should be avoided, or minimised where unavoidable; and all such surfaces should be smooth and accessible for thorough cleaning.

Minimising Internal Generation

Minimise generation of contaminants within. We start by reducing the number of operations, equipment, and personnel to the bare minimum. What can be done outside, must be done outside; what can be outside, should be outside; and who can be out side, should be outside. What remains inside is subjected to careful control: the process, equipment, operations and operator. As we shall see in a subsequent section, operator conduct and compliance often holds the key to successful contamination control.

Coping with Residual Contaminants

The last of the techniques relates to *coping with the residual contaminants*. Since deposition of suspended contaminants is a time dependent phenomenon, reducing *exposure frequency* and *exposure time* of sensitive products is an important form of control. Controlled eddy-free displacement of suspended contaminants, directed away from the critical site is another powerful method used to protect the product.