Invited Paper

Justifying a Continuous Monitoring System

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Abstract

It is often difficult to justify the large capital investment necessary to install a continuous contamination or electrostatic charge monitoring system. Often this is the result of faulty historical data, where sampling practices preclude obtaining a true characterization of the work place. There is a fear that hasty installation of a system will result in placement of sensors in locations where they are not needed. Finally, there often are questions about the types of sensors that should be used, the required resolution and other technical concerns that make decision making difficult. This paper describes a method to overcome these difficulties.

Several examples illustrate the method as applied to particle sampling. The first step in this method is installation of sampling hardware on workstations that conforms to the requirements for critical and busy sampling. Data is collected to determine if the traditional sampling method has determined an accurate measure of the conditions at the work station. Thereafter, sampling may continue using the manual optical particle counter, electrostatic charge monitor or other work station monitor, with a modified sampling protocol to collect comparative data. Sampling may also continue using the previous protocol to provide control data.

Data collected with the new protocol are then compared with the historical data base collected using the old protocol. Generally this uncovers a number of sample points where the old protocol grossly underestimates the particle concentrations or static charge levels present.

The new data are used to identify workstations that are out of compliance with contamination or electrostatic charge acceptance limits. An attempt can then be made to isolate and correct those items found to be contributing to the unacceptable conditions. Workstations that can be brought under control and maintained using a reasonable manual sampling frequency do not need continuous monitoring. Workstations that repeatedly show unacceptable conditions under manual sampling are candidates for continuous monitoring.

The manually collected data is examined for evidence of burst, trend and periodic contamination or electrostatic charge behavior. In addition, the results of modified manual sampling allow for the selection of contamination or electrostatic charge sensors with the optimum resolution, avoiding unnecessary costs associated with selecting sensors with unneeded resolution.

Examples will also illustrate the evaluation of the need for continuous horizontal flow monitoring in a vertical unidirectional flow cleanroom, electrostatic charge monitoring and continuous monitoring in cleaning machines.

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Introduction and Background

Traditionally, a variety of approaches have been taken to measure contamination or electrostatic charge in manufacturing areas. For example, it is universally recognized that a cleanroom must be positively pressurized with respect to the general factory environment in order to prevent the intrusion of contamination from uncontrolled adjacent factory areas. In most cleanrooms, a pressure gage or inclined tube manometer would be permanently installed on an outside wall. Once per day or once per shift the pressure would be read and the reading would be recorded. In this way, a variable that is important to the contamination performance of the cleanroom would be measured on a sampling basis.

Other examples can be sited. Rotating vane or hot wire anemometer measurements are taken near the face of HEPA filters to verify linear discharge velocities, verifying that the room air recirculation system is functioning correctly. This would involve taking a large number of measurements and so would be done infrequently. Often such a survey would only be taken as part of an annual room certification. Room air velocities at work station level would be collected for a smaller number of sampling points and are often manually surveyed less often than once per week. In cleanrooms with unreliable recirculation fan systems, air flow problems might go undetected for weeks at a time.

Surveys for ESD compliance are similarly troubled by inadequate data from manual sampling. Most ESD protected work areas are surveyed manually. These surveys are time consuming and occur infrequently. In addition, the duration of data collection in each survey can be quite short, so only a snapshot of charge generation and electrostatic discharge can be obtained. Activity in the area being surveyed often changes during the survey, so the data can further be distorted.

Some environmental conditions have been recognized to be more critical than room pressure or air velocity, and have been checked at least once per shift (for example, relative humidity) or as often as once per batch (for example, starting pH of a bath). For critical contamination parameters, often a continuous monitoring system would be build into the process equipment or its dedicated environmental enclosure (for example, temperature in a stepper). The continuous monitoring system could be easily justified, because a clear link between the process parameter and yield can be made.

Airborne particle contamination has long been considered an important factor to measure and control. As a consequence, many manufacturing processes would require airborne particle measurements be taken every day or every shift. However, the traditional methods used for sampling airborne particle contamination often produce erroneously low particle count results. In addition, the infrequency of particle count measurement makes it difficult or impossible to correlate with yield. These erroneous data are often used to justify minimizing the frequency of the manual survey and have been cited as evidence that automated continuous contamination monitoring is not justifiable.

Prior discussions of continuous contamination monitoring systems have tended to focus on the data management software (Pariseau, D., 1995) or make the tacit assumption that a system will be bought (Livingston et al.,1997), without a discussion of how to justify acquisition of a system to skeptical management. Occasionally clever methods have been developed for reducing the cost per sample point of a continuous monitor (Fardi, B., 1992), but still avoided discussing a method to demonstrate their necessity.

Traditional Airborne Particle Measurements

In the traditional approach to monitoring airborne particle contamination, an operator moves a conventional, self contained optical particle counter to the work station and places an isokinetic sample probe at some convenient location on the work station, usually held in place by a stand. The conventional self-contained optical particle counter usually contains a vacuum pump, power supply, display and often a printer. Inclusion of these features often results in a large and heavy particle counter. As a consequence, the conventional particle counters are mounted on a lab cart to facilitate moving about the cleanroom.

This is conspicuous to production personnel. In addition, the isokinetic probe and its stand are frequently bulky and difficult to locate close to the product or process. As a consequence, the probe is often arbitrarily placed on the work station in a location driven more by convenience than any other consideration.

Production personnel at the work stations almost invariably stop all activity and move away when the particle count sample is to be taken. This results in elimination of actions that may be generating contamination during normal production, thus lowering the particle count in the sample. More often than not, sampling via the conventional approach is only able to obtain contamination associated with the cleanroom or clean bench. This is often described as cleanroom idle sampling: sampling in which the contribution of equipment and personnel is not included in the total. Contamination associated with materials handling, load/unload operations, personnel generated contamination, etc. are seldom included in such sampling.

Improper Data Censoring

Improper censoring of data is often found to take place. The particle count operator observes the rate of particle count. So long as the counts arrive at a relatively steady rate, the count is allowed to proceed. However, the particle count operator will almost invariably terminate the count if a sudden burst of particles is observed to occur, especially if the particle count operator can associate the burst with some undesired activity, such as someone walking by. Improper data censoring will be repeated as often as is necessary until an acceptable result is obtained. Quite often the only count considered acceptable is one that is below the class limit for the area being sampled.

These two factors, sampling during work station idle periods and improper data censoring result in a historical particle count data base which makes the cleanroom and its work stations appear to be well in control with respect to particle count.

Adverse actions are generally taken using such data. First, there is a tendency to reduce the manual particle sampling frequency to reduce the labor cost associated with particle count sampling. It is difficult to justify sampling more often when the data indicates the areas are in control from a particle count perspective. It is not uncommon to see the facilities monitoring points divided into 2 or 4 subgroups, cutting in half or quartering the sampling frequency. In extreme cases of very large assembly operations, this may be carried to the extreme that each sample location is visited only once per month. Second, given the apparent compliance with airborne particle limits, all appears to be in control, and switching from a manual sampling protocol to a capital intensive continuous monitoring system simply can not be justified.

In order to correct the historical data base and develop a more accurate description of the work area a new sampling strategy must be developed. In the early stages of implementation, this strategy should be designed to minimize the expenditure of capital. The strategy must also deal with the two chief factors affecting the accuracy of the particle count: sampling the wrong place at the wrong time and improper data censorship.

Critical and Busy Sampling:

Here we introduce and define critical and busy sampling.

- Critical Location: as close to the product or process as possible, without physically interfering with the movement of product, the people or the process equipment.
- Busy Periods: during actual manufacturing operations, especially when product is exposed.
- Critical and Busy Sampling: sampling that satisfies the requirements of critical locations and busy periods.

The critical location often places the inlet to the particle counter in a place where laminar air flow does not exist. This works to great advantage, since the bulky isokinetic probe can be eliminated, allowing greater freedom in placement of the inlet near the product. The tubing for the inlet to the particle counter should then be fixed to the work station with brackets, tie wraps and other means. This ensures repeatability of the sample location and protects against the tubing getting loose to interfere with the process. Hardware needed to implement critical and busy sampling costs only a few dollars per work station and takes only minutes to install.

The particle counter outlet end of the tube should then be terminated at some point on the work station that allows the particle count operator to attach the conventional particle counter to the sample tube, without disturbing the process. This allows for sampling without stopping the process, referred to busy period sampling. Figure 1 shows a photograph of a critical and busy sampling tube installed on a work station.

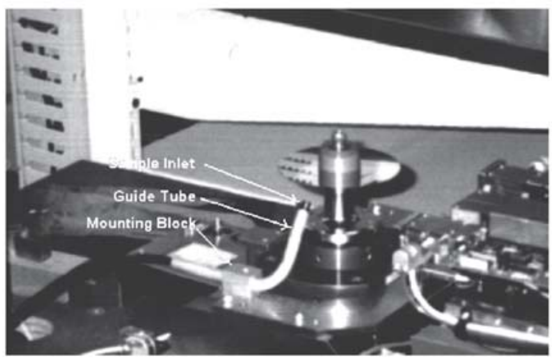


Figure 1. A critical and busy sampling tube installation on a work station.

Modified Data Collection Protocol

Once this low cost, critical and busy sampling hardware is in place, a new data collection protocol must be adopted. In the new protocol, data censoring is not allowed. The operator observes and records the activity at the work station during each sample.

- If no product is in production and the work station is unoccupied, the sample is labeled as taken during stage 1 operation, or a cleanroom idle sample.
- If product is being processed, but no production personnel are present, the sample is labeled as taken during stage 2 operation, or cleanroom and process tooling, but no personnel. This rule needs further discussion, covered below.
    - If the sample point is at a the load and materials handling location on the work station, table or cart, but the product is processed inside a tool or enclosure and no personnel are present, then the sample is labeled a stage 1 sample.
    - If the sample point is inside the tool and contamination from personnel are isolated from the sample/product location, then the sample is labeled a stage 2 sample.
- If product, people and tooling are present, the sample is labeled as stage 3 operation, fully operational and fully populated. Again, this rule requires further discussion.
    - If the process is within a tool or enclosure which effectively prevents contamination or electrostatic charge generated by the operator from getting on the product, the sample is labeled a stage 2 sample.
- If the inlet to the particle counter is scraped, the tubing is bumped or otherwise disturbed to invalidate the count, the sample is so annotated. Similarly, if charge sensors are disturbed in a manner that alters their readings in a way not representative of actual use conditions, these disturbances are noted.

These occurrences indicate the need to correct the installation of the critical and busy sampling hardware to assure the highest quality data.

By eliminating the option for data to be censored, we eliminate rejection of otherwise valid data. In addition, by labeling the stage of operation for each sample, it is possible to diagnose possible sources of the contamination or electrostatic charge. For example, if stage 1 particle counts are a significant fraction of stage 3 counts and the stage 3 counts are out-of-specification, the facility probably would be a fruitful place to begin searching for the source of contamination.

On-Going Use of Critical and Busy Sampling:

When a sample location is identified as out-of-specification with respect to contamination or electrostatic charge, a second stage of investigation is initiated. For example, a stand-alone particle counter may be used like a Geiger counter, sniffing out the individual particle generation points. If these can be located, fixed and kept under control by manually sampling at some tolerably low frequency, then a continuous monitor is not justifiable. However, the critical and busy sampling hardware and protocol should continue to be used.

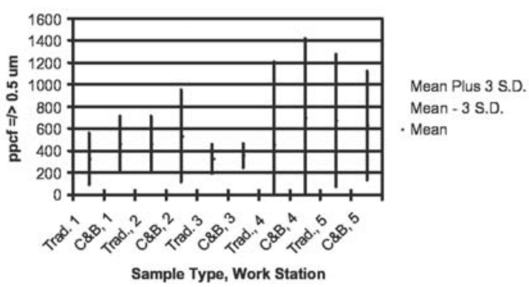
What if work stations are identified which require continuous monitoring? In this case, the continuous monitoring system is connected to the same critical and busy sampling system. Whenever an alarm is signaled, the manual sampling equipment is brought back to the location and is again used in the Geiger counter mode.

Case Studies of Traditional versus Critical and Busy Sampling for Airborne Particle Counts

Case Study 1 Work Stations in a Class 7 Mixed Flow Cleanroom:

Figure 2 shows the results of sampling two sets of data collection work stations in a class 7 mixed flow cleanroom. Data listed are the average and standard deviation of particle concentration, in particle per cubic foot, 0.5 mm in diameter and larger. All work stations previously had been found to comply with the airborne particle count requirements using the traditional manual sampling protocol. The particle count increases slightly using the critical and busy sampling protocol, but not enough to change the conclusion that all work stations are in compliance with Class 7 requirements. The general contamination in the room is dominant over the contamination generated at the individual work station. Data like these indicate a continuous monitoring system would not be necessary for these work stations.

Figure 2. Traditional vs. Critical and Busy Sampling in a Mixed Flow, Class 10,000 Room



Case Study 2 Class 5 Unidirectional Flow Benches in a Class 7 Mixed Flow Cleanroom:

Figure 3 shows comparative data for two identical sets of Class 5 work stations. These Class 5 work stations are located under unidirectional flow benches, effectively isolating each work station.

None of the work stations from either line A or line B exceeds Class 5 when sampled using the traditional approach. Conversely, the average and standard deviation of particle count increase for all work stations when sampled using the critical and busy protocol. In 7 cases, critical and busy sampling shows work stations far dirtier than Class 5. Also of interest is a comparison of work station number 6 on line A versus their identical counterpart on line B. The line B station is almost 10 times dirtier.

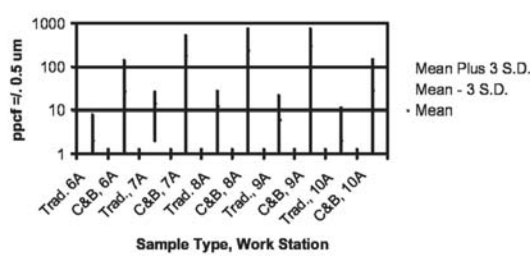
Airborne particle count data plotted in Figure 3 illustrates the difference in results obtained using traditional versus critical and busy sampling protocols. The Y axis lists the airborne particle concentration in particles per cubic foot of air, 0.5 µm diameter and larger. In Figure 3 the particle concentrations are plotted on a logarithmic scale, unlike Figure 2, to accommodate the broad data range. The tick marks on the vertical bars represent the average particle concentration. The upper and lower ends of the bars represent the mean plus 3 standard deviation and mean minus 3 standard deviation respectively. The bars are labeled along the X axis to indicate the sample location number and traditional versus critical and busy sampling protocol.

Case study 2 illustrates two common results of using critical and busy sampling in unidirectional flow work areas.

1. The emissions from the individual work stations are evident, because the mixing effects of the mixed flow cleanroom are eliminated.

2. Differences between pairs of otherwise identical work stations can be detected.

Figuer 3. Tradition versus Critical and Busy Sampling in Class 100 VLF Hoods in a Class 10,000 Ballroom



Case Study 3 Class 5 Unidirectional Flow Benches in a Class 6 Room:

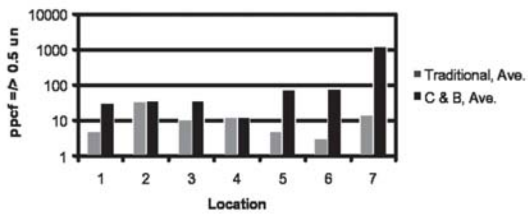
Case study 3 is for a set of operations under Class 5 unidirectional flow benches in a class 6 cleanroom. Here we show average values, omitting standard deviations, due to the limited sample size of the survey.

All 20 work stations sampled using the traditional approach easily meet Class 5. The boast in this facility was that most of the work stations would also meet or be better than class 4. The critical and busy samples indicate that most do not even satisfy class 5 requirements. The worst case discrepancy is found in location 18, where class 6 was exceeded. Note that using the critical and busy sampling approach, there are sufficient particles available to allow use of a 0.5 mm resolution, 0.1 cfm optical particle counter at nearly every work station. If the data collected using the historical approach was used, the particle counter chosen would probably have been either a 0.3 or 0.1 µm resolution particle counter, greatly increasing the cost of continuous monitoring.

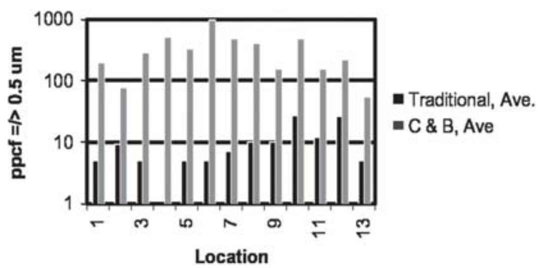
Figure 4 is a plot of traditional versus critical and busy sample averages for the fully automated work stations. It illustrates an important feature of the critical and busy sampling approach in work station 7. In order to sample using the traditional protocol the operator had to open the doors to the work cell. The safety interlock would stop the machinery inside, eliminating its contribution to contamination. The critical and busy sampling hardware was mounted so the operator could connect to the sample tube without having to open the enclosure. Thus, the machinery would continue operating, allowing its contribution to be detected.

Figure 5 is a plot of traditional versus critical and busy sampling in the hybrid work stations, where an operator and automated tooling work together. Comparison of Figures 4 and 5 illustrate a fairly widely held belief in a way seldom so clearly demonstrated: people are a major contributor to contamination.

Figuer 4. Fully Automated Class 100 VLF Work Stations in a Class 1,000 Room



Figuer 5. Hybrid Automation In Class 100 VLF In Class 1,000 Room



Trend, Cyclic and Burst Patterns of Particle Generation:

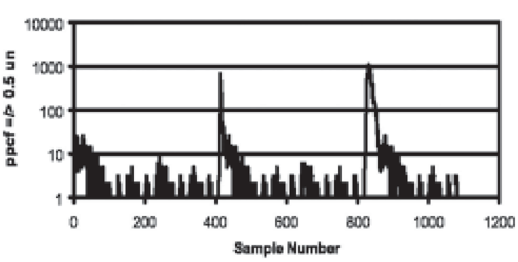
In addition to the average particle concentration prevailing at a work station, we must be concerned with trend, cyclic and burst patterns of particle generation(Bzik,T.J.,1985). Sampled over a long duration, the average particle concentration may appear to be within control limits. Looking at the data in more detail may reveal unwanted particle concentration behaviors.

Upward trends in particle count are considered undesirable because they may, at some future moment, exceed the control limits. Examples of upward trend are observed where work stations gradually become dirty between deep cleaning intervals. Since the rate at which work stations become contaminated is not perfectly constant, it is seldom easy to predict when the next deep cleaning should be scheduled. This is an example where a continuous monitoring system may provide a useful benefit.

Cyclic patterns of particle generation are a special case of burst pattern, where the bursts have a repeatable pattern. It is usually easy to associate these patterns with specific activities on the work station. If associations can be established, it is often easy to develop and implement fixes. Experience has shown that cyclic pattern of particle generation can usually be adequately controlled using manual monitoring and the critical and busy sampling hardware.

Random bursts of contamination are observed in nearly every cleanroom. These can be associated with sudden, catastrophic events. A good example is shedding from an electric motor: an example is illustrated in Figure 6. This stepper motor was continuously monitored for over a week. The counts down wind of the motor started out in the 15 to 30 ppcf range, but cleaned up within a short time to 1 to 3 ppcf. Two large bursts are seen. Each sample is the average over a 10 minute duration, collected at 0.1 cubic feet per cubic foot.

Figuer 6. Particle Bursts from an Electric Motor

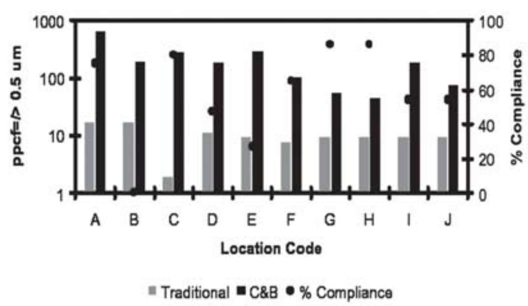


Averaged over the seven plus days, the electric motor produces only 16 ppcf. The second burst exceeded Class 5 for 25 hours. With a once per week manual sampling plan, the chance of detecting this burst is only one in seven. The first burst, with a duration over Class 5 for 5 hours, has only a 1 in 37 chance of being detected, sampling once per week.

Case Study 4 Extended Duration Manual Monitoring

Ten different Class 5 work stations were monitored using critical and busy sampling hardware (Query, C.F.). These data were also compared to traditional monitoring results. Sampling was of sufficient duration that the percent compliance could be calculated. Percent compliance is the percent of time that a work station is monitored that it is below its particle count limit. High percent compliance is considered to be good. Work stations with very low percent compliance are highly likely to be detected in a traditional, once per week particle sampling protocol. This is illustrated in Figure 7.

Figuer 7. Traditional versus Critical and Busy Sampling and Percent Compliance



Case Study 5 Extended Duration Manual Monitoring:

In this study, the manual optical particle counter was used to sample a work station using the critical and busy sampling hardware for several hours. The data was collected once per minute in a Class 5 unidirectional flow clean bench located within a Class 7 mixed flow cleanroom. The particle count operator observed and recorded the activities at the work station, but did not interfere with the actions of the production operators in any way.

The particle count operator's notes provide a very clear understanding of what is happening at the work station. Set-up or waiting for work generate little contamination. Assembly and especially soldering generate large quantities of airborne contamination. The arrangement of the items on the work station is not fixed. For convenience, the second operator moved the solder fixture and fume extraction system, with disastrous results. During soldering, the first operator averaged 370 ppcf =/> 0.5 mm: the 2nd averaged 746 ppcf =/> 0.5 mm.

This case study illustrates an example where a continuous monitoring system may be justifiable. Some flexibility in work station lay-out must be provided to accommodate the reach and comfort of the operator. A continuous monitoring system should be a useful tool to keep particle counts under control after such rearrangements.

Case Study 6 Continuous Electrostatic Charge Monitoring:

Magnetoresistive (MR) heads are among the most electrostatic discharge (ESD) sensitive devices in existence. Modern static safe facilities thus required many ESD protection tools to allow for safe manufacture. Among the more important tools provided for these static safe work areas are air ionizers.

The performance of air ionizers traditionally has been measured using charged plate monitors. During weekly audits the charged plate is used to measure discharge times and float voltages. In this procedure, the ESD technician places the sensor of the charged plate as close to the intended product location as possible. It is occasionally found that the air ionizer has drifted out of balance and needs service. Many times this consists of merely cleaning the emitter points on the air ionizer. Occasionally simply cleaning the emitter points is inadequate and the ionizer must be manually balanced.

One of the less well understood features of air ionizer performance is that they interact with their environment. That is, grounded objects on the work station below the ionizer tend to drain charge to ground. The polarity and amount of charge drained off is a function of the distance to and position below the emitter points on the ionizer. Relocating objects on the work station thus can change the balance of the ionizer. This can occur frequently in a development site, where tooling and work stations are often changed due to changes in products or process flow.

In order to more fully characterize these changes an electrostatic charge monitor equipped with a 20 picofarad plate was installed at a work station for four days. Each 10 minute sample was scanned for the maximum positive and negative voltage swing. Figure 9 shows the variation in float potentials measured for one work station in the development cleanroom. The layout of the work station was observed on a shift by shift basis and any changes were noted.

Figure 8. Extended Duration Manual Sampling

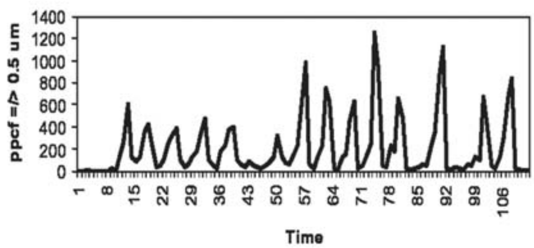
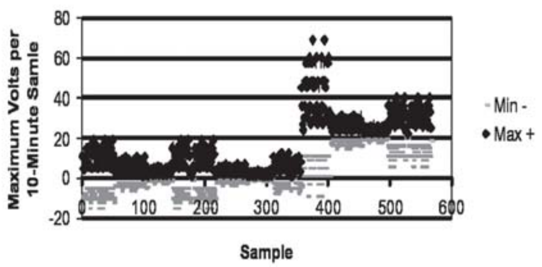


Figure 9. Charge Level in a Clean Room Static Safe Work Station



Inspection of Figure 9 shows the larger variations observed in the work station during first shift (observations 0 - 50, 160 through 210, etc.) than at other times of the day. The development cleanroom was being used for production on first shift, engineering on second shift and was practically empty at all other times. Note however, that an engineering experiment was performed on the 2nd shift of the 3rd day. In this experiment, a tall measurement stand was placed on the work station, nearly directly under the ionizer. The work station was rearranged to accommodate the stand. However, when the stand was taken away at the end of the second shift, the work station was not returned to its original layout. Hence on day 3 the balance in the work station has swung to a strong positive imbalance.

Case Study 7 Continuous Air Flow Monitoring

In this example a very large cleanroom was equipped with 54 modular unidirectional flow units. Once per week a cleanroom technician would do a velocity survey, measuring the linear air velocity discharged from the filters in each module. Approximately every other week, at least one of the modules would be found to have very low or no air velocity. The problem this creates in a unidirectional flow cleanroom is unwanted horizontal air flow. Clearly discovering this once per week is undesirable, but how would one design a cost effective continuous monitoring system to monitor for the condition.

The answer lies in the design of the cleanroom, as shown in the plan view in Figure 10. The design of the cleanroom lent itself to definition of 4 air flow zones, labeled A, B, C and D in Figure 10. These zones were supplied air from 10 to 16 unidirectional flow modules. It was immediately recognized that if air flow from any module would change the horizontal air flow through the restricted areas defined by the return plenums. In order to provide a module flow monitoring system, five hot wire anemometers were installed in the restricted locations numbered 1 through 5 in Figure 10. Hot wire anemometers are frequently used to measure air flow in cleanrooms. In this application though they were mounted to monitor horizontal flow, rather than vertical flow.

After installation of the horizontal flow monitor, no imbalance condition went unnoticed for longer than a single shift. Of course, the flow monitor would not tell the cleanroom technician which module had failed. But the monitor would tell which intersection between zones was out of control. The technician would then go to the out-of-control intersection and

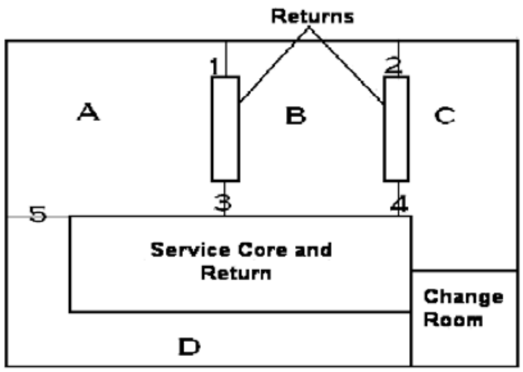


Figure 10. Plan view of a horizontal flow monitored, vertical unidirectional flow cleanroom.

determine the direction of the horizontal flow. This would then determine in which zone a module had failed, allowing the technician to quickly survey and identify the failed unit.

Case Study 8 Evaluation of an *In-situ* Monitor for Particles in an Aqueous Cleaner

The dominant cleaning process used in the cleaning of individual piece parts or sub-assemblies in precision assembly industries is aqueous cleaning. This process often involves initial cleaning by immersion in an ultrasonically agitated, deionized (DI) water/detergent mixture, followed by rinsing in multiple, consecutive, ultrasonic tanks of increasingly pure DI water.

Several approaches can be taken to monitor and control particle contamination on high technology products that are subject to cleaning. Among these are periodic sampling of liquids from the cleaning baths and periodic measurement of parts using direct or indirect particle measurement techniques. Periodic parts measurements are well supported by work reported by Nagarajan(1993) and Gouk (1997). The approach of periodic sampling of parts from production has historically satisfied the needs of the user.

Periodic sampling the bath fluids or parts from the bath suffer from several drawbacks, among which are:

- Manual bath sampling may interrupt production and can result in bath contamination.
- Parts sampled from on-going production may undergo recontamination in handling or packaging prior to analysis.
- Bath sampling and parts sampling are periodic and may involve a delay in obtaining results.
- Both techniques require off-line laboratory analysis, which may introduce procedural errors.

These drawbacks result in possible loss of data integrity and are unable to capture batches of parts that do not conform to particle cleanliness requirements on a real time basis. Knowledge of particle cleanliness for individual samples is excellent, but knowledge of the statistical cleanliness is poor, since sampling is infrequent. This makes it difficult to implement statistical process control. These difficulties were well articulated by Vargason(1990), who also described a multipoint ISPM for semiconductor acid processing baths.

Hess(1996) described the application of an ISPM for rapid optimization of a semiconductor cleaning bath. Later Hess (1997) described the application of the ISPM to a second semiconductor cleaning system, where an attempt was made to show correlation with direct surface inspection using a wafer scanner. The results showed an apparent negative correlation between the counts in the bath reported by the ISPM and surface counts of particles on the wafers. While these studies address many of the issues surrounding the application of ISPMs to monitoring process baths, all are focused on baths for processing semiconductor wafers.

Knollenberg (1998) reported on the use of an ISPM for monitoring particles in a cleaner for head stack assemblies, an important assembly for a hard disk drive. In this study the authors were able to show a strong positive correlation between particles in the final rinse overflow (i.e. sampling after the weir) and the residual particles ultrasonically extracted from the assembly and measured using a liquidborne optical particle counter (LPC). They were also able to show several applications of the ISPM for optimizing the performance of the cleaner and for monitoring for equipment failure modes. This study however does not address a far more complex problem, in that the cleaner is dedicated to cleaning a single part type.

The objective here is to determine the feasibility of using ISPM to monitor the performance of a cleaner where several different types of parts of variable incoming cleanliness levels are being cleaned. Further complicating this problem is the fact that the arrival rate, sequence of baskets and number of parts per basket was variable. This is considered an extreme challenge for the application of an ISPM, but one worthy of evaluation.

The Cleaning Process

The cleaner consists of five consecutive tanks. The first two tanks are prewash and wash tanks and the final three are rinse tanks. The tanks are made of stainless steel, with approximately 80 liter capacity and equipped with immersible ultrasonic transducers. All power generators were 1,000 watt units, operating at 95 % of full power, in the sweep frequency mode. The system was robotically loaded, although for certain tests described below, the cleaner was operated in the manual mode. Table 1 describes the important operating statistics for the system.

The system was operating in the following fashion. When baskets of parts were in each tank, the recirculation system was off but the ultrasonic power was on for a duration of 175 seconds. When baskets were entering or leaving the tanks, ultrasonic power was turned off, but the recirculation system was on, causing a relatively large volume of water to overflow the weir. If arrival rate of baskets was continuous, the recirculation was for a total of 35 seconds. If parts arrived at longer intervals, the recirculation system would remain on for longer periods of time. All baths were continuously fed,

Table 1. Description of the cleaning process

	Tank				
Parameter	1	2	3	4	5
Tank Name	Prewash	Wash	Rinse 1	Rinse 2	Rinse 3
Weir	Single sided	Single Sided	Four Sided	Four Sided	Four Sided
Fluid	DI Water	DI Water + 0.02 % Non-Ionic Surfactant	DI Water	DI Water	DI Water
Temp., °C.	45 + 7 − 3	45 + 7 − 3	45 + 7 − 3	45 + 7 − 3	45 + 7 − 3
Ultrasonic Frequency, kHz	40	40	75	75	75

independently, with approximately 4 liters per minute of fresh water. Approximately 4 liters per minute was drained continuously from each tank. The filtration system for recirculation and make-up water was via 5 μm and 0.2 μm filters.

The operating sequence, turning on and off the ultrasonic power and recirculation pumps, had a noticeable effect on the particle count signature, as will be seen in the results shown below.

The *In-situ* Particle Monitor and Installation

The in-situ particle monitor consists of a PMS model 900 CLS sampler equipped with a 0.3 μm resolution sensor. The output from the instrument was collected on a portable computer using the PMS Pharmacy View soft ware, although PMS Facility View software could have been used with the same results.

The in-situ particle monitor sampler draws a sample through the sample burette and an overflowing reservoir. In this installation approximately 2 meters of 3 mm inside diameter Teflon tubing connected the tank to the particle counter. The internal volume of the tubing was approximately 13 cubic centimeters. The total sample collected was approximately 4 times the volume contained within the sample tubing, assuring adequate sample flushing.

Particle were reported in particles per cubic centimeter (ppcc) equal to or larger than 0.3, 0.5, 0.7 1, 2, and 3μmm diameter.

Samples were collected in three different locations.

- In the overflow weir from tank 4 (rinse tank 2)
- In tank 4 (rinse tank 2).
- In tank 5 (rinse tank 3).

The desire was to obtain a comparison between the results measured in the weir for tank 4 and within tank 4, and also to compare results for sampling within tank 4 and within tank 5.

Description of the Particle Measurement Process

The operation of the ISPM was not triggered by the arrival of baskets in any particular tank. That is, the cleaner and ISPM operated independently. As a consequence, when in the sequence of events for the ISPM a basket of parts entered the tank being monitored was uncontrolled. This may affect the peak value for any basket load.

The sample process begins by drawing liquid from the sample tube through the sample burette and its attached overflow reservoir until liquid reaches a present limit. Pressure is then applied to force the sample liquid through the sensor to suppress bubble formation. At completion of the preset sample time, the liquid remaining in the sample burette and overflow reservoir is expelled to drain. Pressure in the apparatus is vented to atmosphere to prepare for the next sample.

Parts Cleaned During this Study

Twelve different parts were cleaned during this study. These parts ranged from: large surface area, electrophoretically painted, cast and machined aluminum parts; bare aluminum parts; cast plastic parts; stainless steel parts; and parts consisting of a combination of stainless steel and elastomeric plastic. The arrival frequency of these parts varied according to their size and consumption. Three generic descriptions can be used to combine these 12 different parts into sets: bare aluminum parts, plastic parts, and others. The type and number of parts entering the cleaner were recorded. This allows unique association of each peak recorded by the ISPM with the type of part being cleaned.

Effect of Sample Inlet Location

The study began with the sample inlet positioned in the liquid overflowing the sides of tank 4 into its weir (rinse tank 2). Figure 11 shows a representative plot of the particle counts recorded during a period of production in which parts were cleaned. This chart shows the cumulative particle counts in three size ranges versus time of day. The horizontal bars above the particle count traces indicate the approximate times for entry into and exit out of tank 4 for 11 different baskets of parts.

One feature is striking. Each basket of parts is apparently reported as two separate peaks, or as a peak preceded by a plateau. This can be explained by understanding the operation of the cleaner. As parts enter each tank, the recirculation/filtration system is operating. Thus, a large volume of liquid from the tank is overflowing the weir to the inlet to the particle counter. In 35 seconds after basket entry, the recirculation pump is turned off, so the flow rate overflowing the weir is that of the makeup flow rate, about 4 liters per minute. At the end of the cycle the ultrasonic agitation is turned off and the recirculation pumps are turned on again, increasing the flow rate from the tank over the weir. Thus we see an initial peak in particle counts when baskets first enter the tank (high overflow rate), a lower particle count during ultrasonic cleaning (low weir overflow rate) and finally a high particle count after ultrasonic agitation is turned off (high weir overflow). The rate of arrival of particles into the sampling location is thus affected by the operating cycle of the cleaning equipment.

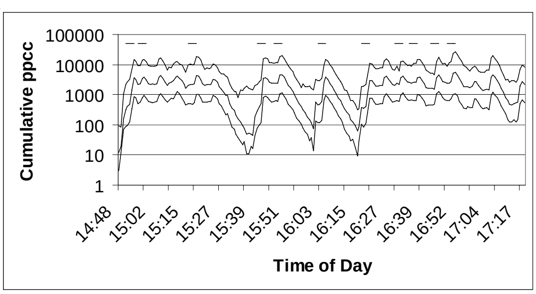


Figure 11. Jan. 25th, 1st shift, tank 4 weir

Relocation of the sample inlet to inside tank 4 eliminates this double peak effect, as shown in Figure 12. Horizontal bars indicate the periods in which baskets were in tank 4. A less ambiguous peak is recognizable. This allows a clearer interpretation of the particle count history during the cleaning process. A statistical comparison can be made of the location of the sample inlet outside the weir of tank 4 versus inside tank 4. However, this data illustrates one of the important considerations in the planning for an ISPM. The size resolution of the particle counter can often not be selected before some in-situ data has been collected. For the case under study here, the counts in the 0.3 μm and occasionally the 0.5 μm size channels exceed the 10,000 ppcc coincidence count limit. This leads to distortion of the size distribution and undercounting of small particles.

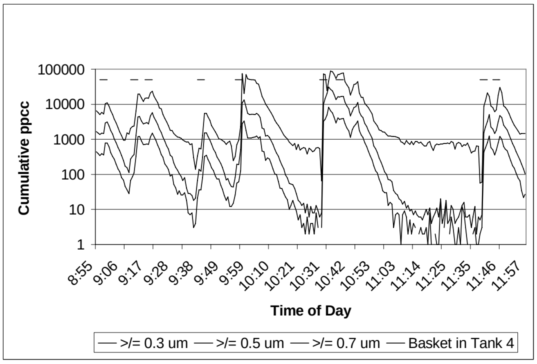


Figure 12. Jan 28th. 1st shift. Sample inside tank 4

These results show that sampling outside the weir significantly reduces the peak particle counts versus sampling within tank 4 for 4 out of 5 parts. The opposite result occurred for the small bare stainless steel parts: the particle count obtained in the weir is greater than that obtained in the tank. This result may be due to the small number of batches of these parts in the sample. Using Student's t test, only in the case of the bare aluminum and the small bare stainless steel parts are the comparisons statistically meaningful at the 95 % confidence level.

Table 3 summarizes the mean particle counts obtained for comparable baskets measured inside tank 4 and tank 5 for 4 parts with a high number of baskets.

These results show a surprise. In two cases the outcome is as anticipated: the average particle count in tank 4 is greater than the particle count in tank 5. For the other two parts, the reverse is evident: the particle count in tank 5 is higher than in tank 4. This may be an indication that the painted aluminum castings and bare aluminum parts may require longer rinse times. Again, using Student's t test the difference between particle count sampled within tank 4 and within tank 5 are statistically meaningful only for the bare aluminum parts.

Table 2. Comparison of ISPM results sampling in the weir from tank 4 or sampling within tank 4, ppcc ≥ 0.3 μm

Location		Painted Aluminum Casting	Bare Aluminum	Large Bare Stainless Steel	Stainless plus elastomer	Small Bare Stainless Steel
Tank 4 Weir	Mean	16433	34789	12506	7483	26641
	St. Dev.	3831	7959	4535	3998	5182
Within Tank 4	Mean	18400	57903	14037	17229	14200
	St. Dev.	6184	13196	7722	9905	5986

Table 3. Comparison of ISPM results sampling within tank 4 or sampling within tank 5, ppcc ≥ 0.3 μm

Location		Painted Aluminum Casting	Bare Aluminum	Large Bare Stainless Steel	Stainless plus elastomer
Tank 4	Mean	18400	57908	14037	17229
	St. Dev.	6184	19186	7722	9905
Tank 5	Mean	19280	77055	13366	13553
	St. Dev.	5198	9332	3479	9020

Effect of Part Arrival Rate and Sequence

Note that the arrival rate and sequence of baskets of parts is uncontrolled. As a consequence, a relatively clean part, such as the large bare stainless steel parts, may be preceded by a relatively dirty bare aluminum part. If this occurs over an interval too short for the rinse tank to recover to baseline, the starting value for each basket will be highly variable. This unpredictability of the baseline when a basket enters a rinse tank has a significant influence on the peak particle count achieved by any given basket of parts. One possible way to correct for this is subtract the lowest value of the baseline preceding entry of a basket from the peak value for that basket, regardless of whether the baseline has fully recovered or not. For the purpose of this analysis peak values sampled in tanks 4 and 5 are combined and compared to peak values corrected for the lowest value in the preceding 5 minutes of cleaner operation: the results are shown in Table 4.

In every case the mean value for a type of part is reduced by correcting for the preceding baseline. However, the amount of correction remains variable, as the type of part arriving in the preceding basket is not controlled. Hence, the starting point for the correction is variable. As a consequence, the coefficient of variability (the standard deviation times 100 divided by the mean) is not always improved for this method of baseline correction. This indicates that subtraction of the lowest value preceding a peak is not a viable way to correct for variable baseline in this study.

To determine if baseline correction might eventually be of value uncorrected peak values were compared to peak values that occur only after the cleaner has had an opportunity to essentially fully recover the baseline, that is, to less than 1,000 ppcc ≥ 0.3 μm. This comparison is shown in Table 5 for 4 types of parts.

Correcting the peak value for a fully recovered baseline improves the coefficient of variability of all four of these types of parts. The comparisons are statistically meaningful using Student's t test for bare aluminum, large bare stainless and stainless plus elastomer parts. In the management of the cleaner using the ISPM, allowing the cleaner to recover to a lower baseline would be beneficial. This could be accomplished by allowing a longer delay time between baskets, modifying the cleaner function to allow more rapid recovery or a combination of the two.

Effect of Basket Load (fill level)

In general, each basket would contain one or more inserts of parts. In general, each insert would be completely full. In a few cases, more than one type of part insert would enter the cleaner as a basket load. By noting the number and type of insert in each basket load, it is possible to determine if basket loading has a meaningful effect on the uncorrected peak value for the basket. The results are summarized in Table 6.

Table 4. Peak for each part type sampled in tank 4 and 5 compared to peak corrected for preceding baseline, ppcc ≥ 0.3 μm

Condition		Painted Aluminum Casting	Bare Aluminum	Large Bare Stainless Steel	Stainless plus elastomer	Small Bare Stainless Steel
Peak Value	Mean	18695	64665	13778	15595	14211
	St. Dev	5857	18607	6378	9434	5986
	CoV, %	31	29	46	60	42
Peak Corrected for Baseline	Mean	13519	64174	8758	6526	12294
	St. Dev.	5942	19227	4247	3036	3745
	CoV, %	44	30	49	47	30

Table 5. Peak for each part type in tank 4 and 5 compared to peak corrected for preceding, fully recovered baseline (i.e., less than 1,000, ppcc ≥ 0.3 μm).

Condition		Painted Aluminum Casting	Bare Aluminum	Large Bare Stainless Steel	Stainless plus elastomer
Peak	Mean	18695	64665	13778	15595
	St. Dev.	5857	18607	6378	9434
	CoV, %	31	29	46	60
Peak Corrected	Mean	18636	73171	11035	6073
	St. Dev.	5170	9881	4413	1073
	CoV, %	27	14	40	18

Table 6. Effect of basket load, as measured by number of inserts, in ppcc ≥ 0.3 μm.

Number of Inserts	Bare Aluminum		Large Bare Stainless Steel		Stainless Steel Plus Elastomer	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
1	28359	8747	12845	4354	5440	Note 1
2	39099	Note 1	17152	10371	11255	8946
3	70071	8578	na	na	17180	6242
4	74382	Note 1	na	na	na	na
5	68563	13308	na	na	na	na
6	79744	13013	na	na	na	na

Note 1. Only a single basket contained this number of inserts

The large painted aluminum castings do not appear in this analysis, as only one insert is cleaned at a time. This data shows that basket fill level has a significant effect on uncorrected peak value. In the management of the cleaner using the ISPM, basket fill level is clearly a variable that should be controlled.

Additional Observations

Additional test were run to determine the effect of the basket on the peak value during a rinse cycle. These tests indicate that some baskets for bare aluminum parts could have a significant influence on peak particle counts.

Management Using ISPM

Several objectives can be defined for use of the ISPM to assist management of cleaners. One of the most important of these is identification and isolation of batches of parts which do not meet statistical process control criteria for quality control requirements. Another objective is to collect data describing the cleanliness of parts in an automated fashion.

In this study, parts were cleaned that had a diverse range of surface cleanliness. In addition, the arrival rate and composition of baskets of parts were uncontrolled. This led to difficulty in interpretation of peak contamination values in rinse baths.

Several improvement can be suggested to improve the viability of the application of the ISPM evaluated for application with this cleaner:

- The cleaner cycle should be improved to get closer to the baseline for full operation. That is, the recirculation time and flow rate should be increased to allow the baseline particle counts to more nearly approach 1000 ppcc $\geq$ 0.3 μm between baskets.
- The loading of baskets should more closely controlled.
- The cleanliness contribution of inserts needs to be controlled, to prevent this from influencing the outcome of tests.

In this application, the operating cycle of the cleaner has a measurable influence on the results obtainable from the ISPM. First, the time for the cleaner to recover to baseline particle counts is significantly longer then the arrival interval for baskets of parts under fully loaded conditions. The arrival sequence of basket is unregulated so baskets of relatively dirty parts may immediately precede arrival of relatively clean parts. This, in combination with the long bath recovery time, interferes with interpretation of cleaner performance.

Summary and Conclusions:

An effective method has been developed to permit the assessment of the need for continuous contamination monitoring. Its use has been demonstrated for sampling and measurement of airborne contamination, for monitoring voltage balance in a static safe work area, and for monitoring the function of unidirectional flow modules. This method optimizes the placement of sample points to allow a correct characterization of the work place to be made.

The data obtained allows for the selection of a particle counter or other sensors using a lowest cost strategy.

In-situ particle monitoring is a well accepted technique in the semiconductor industry for vacuum processes. It has been demonstrated for wet process baths in applications in the semiconductor industry. It has also been shown to be feasible in the disk drive industry for head stack assemblies, where the identity of parts and contamination load in the cleaner are relatively tightly controlled.

The manufacture of disk drives represents a different problem. The range of cleanliness of parts, basket loading and sequence of arrival of parts in the cleaner are more or less random. As a consequence, control of cleaner performance requires modification of the management strategy for cleaners in order for application of the ISPM to provide full benefit as a process control tool.

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