IDENTIFICATION OF ENVIRONMENTAL SENSORS FOR CLEANROOM MONITORING AND CONTROL STRATEGY

Aurelia MEGHEA, H. WEISSIEKER*

Camerele curate şi mediile curate sunt din ce în ce mai necesare în fabricarea unui mare numar de produse. Dispozitivele semiconductoare şi chip-urile pentru calculatoare, mediile optice, medicamentele, dispozitivele medicale, sateliții, alimentele şi băuturile sunt produse şi procesate în facilități curate. Camerele curate trebuie să fie monitorizate conform cerințelor ghidurilor standard şi să corespundă aspectelor de control al calității. Selectarea setului optim de senzori şi a sistemului de monitorizare este o sarcină complexă. În acest sens, analiza datelor nu se poate realiza numai pe baza instrumentelor statistice standard. În plus, controlul camerelor curate nu se poate realiza cu sistemele de monitorizare existente în prezent pe piață. În această lucrare este prezentată o nouă abordare privind strategia de monitorizare şi control a camerelor curate.

Clean rooms and clean environments are more and more needed to manufacture a large variety of products. Computer chips and semiconductor devices, optical media, drugs, medical devices, satellites, food and beverages are produced and handled in clean facilities. Cleanrooms have to be monitored as requested by standard guidelines and to comply with quality control aspects. The selection of the right set of sensors and the monitoring system is a complex task. In this respect, the analysis of the data cannot be done with standard statistical tools alone. Moreover, the control of the cleanroom system with the cleanroom monitoring system cannot be done with today systems on the market. In this paper a new approach for clean room monitoring and control strategy is described.

Keywords: contamination continuum, cleanrooms, environmental sensors, monitoring, statistical analysis, control strategy

Introduction

Cleanrooms and clean environments are the technical base of all high tech industries as well as absolutely required for the life science industries to protect the product or the people involved in the production or as a consumer of the goods. In the fields of "Contamination Control" not only the clean air or the clean rooms are considered, but also the cleanliness of all kind of medias like purified

* Prof., Eng., Dept. of Applied Physical Chemistry and Electrochemistry, University POLITEHNICA of Bucharest, Romania

water, clean gases or the influences of other parameters like electrostatic discharge, vibration and much more.

Even there may be a some thousand year old history of contamination control in special applications, cleanrooms and contamination control in the today world have only a 50 year old history.

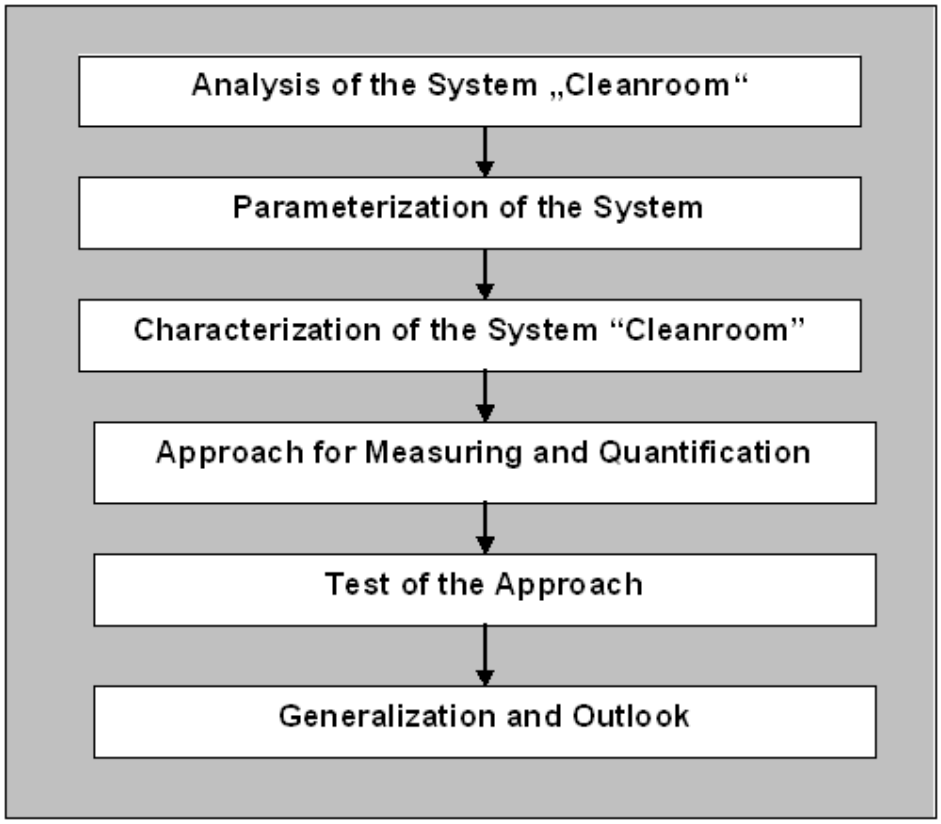

Fig. 1. Approach for the procedure

In Fig. 1 the approach or the procedure for deriving the approach to identify the necessary and sufficient set of environmental sensors for monitoring and control is given. The necessary cleanroom parameters are derived from the cleanliness requirements of the product in the different production steps [1-11]. The necessary machines and equipment for manufacturing define the general layout of the cleanroom. The transport logistics is connecting the different production zones furthermore defining the “slope” of the cleanroom. The space for the necessary production facilities (clean air, purified water, gases) and

utilities (steam, waste water, etc.) has to be added to the space requirements of the total production fabricator. In other words, in the first step the fabricator is designed from inside - out.

In the next step these requirements are mapped in a feasibility study with the conditions of a possible green field construction site. Depending on the meteorological (radiation, temperature, humidity, wind, contamination etc.), geographical (earthquake risk, soil, vibration etc.) and some other baselines the original design is redesigned from outside - in, to address the outside conditions [12-16].

One part of the following design phase is to identify the necessary and sufficient set of environmental sensors for the monitoring of the outside and inside cleanliness situation of the fabricator.

The new approach described in this article is the approach not only to monitor the given situation, but to develop a control strategy to actively control the cleanliness for the single given cleanroom.

Since the standard statistics is not sufficient for the control strategy, supplementary investigations have to be made in the statistical analysis of the data.

1. Experimental

The contamination continuum from the gas phase, nowadays nominated as *Airborne Molecular Contamination* (AMC) to the particle phase and the interactions of molecules and particles - the contamination dynamics have to be understood, analyzed and controlled for fulfilling cleanroom requirements. These subjects are illustrated in Figs. 2 and 3 [17-25].

For the particle regime three single distributions can be identified and best described through the log-normal distribution $C_l(D_p)$, [26-30] and equation (1):

- Primary aerosols out of condensation, combustion
- Secondary aerosols
- Mechanically generated airborne particles

$$C_1(D_P)=\frac{1}{D_P\sqrt{2\pi}\ln\sigma_g}e^{-\frac{(\ln D_P-\ln CMD)^2}{2(\ln\sigma_g)^2}} \quad (0<D<\infty) \tag{1}$$

with:

CMD - count median diameter,
D_p - particle diameter,
σ_g - geometric standard deviation.

The sum of the primary, secondary and mechanically generated particles results in the so-called *Junge distribution* of airborne particles.

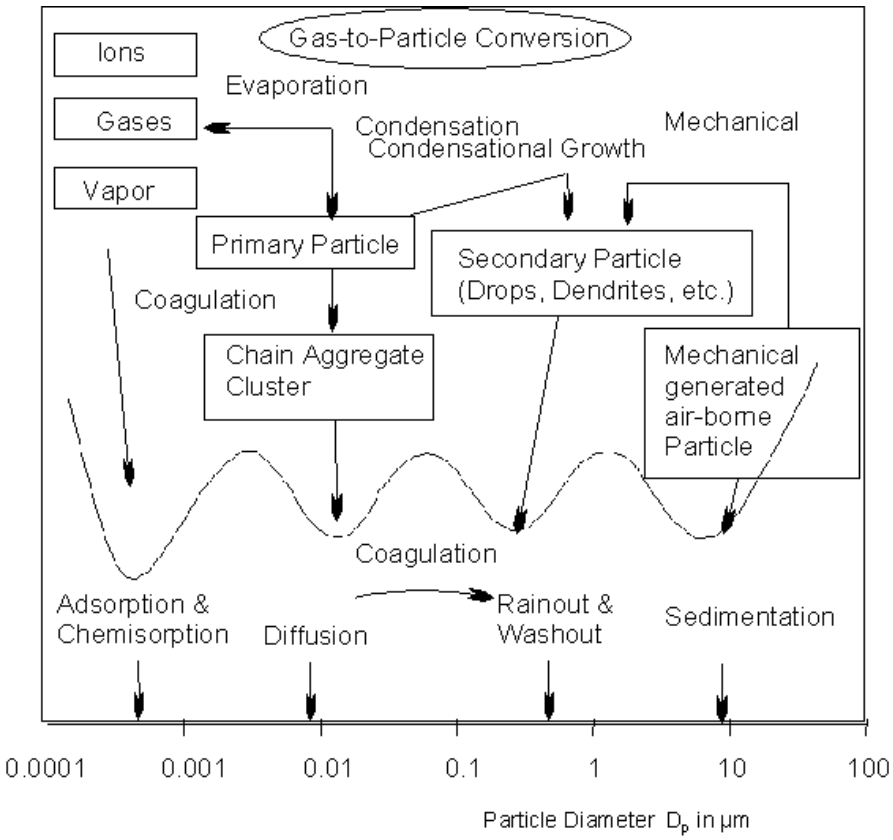

Fig. 2. Contamination continuum for the airborne phase

The cleanliness classes according to ISO 14644-1 [23, 24], (Fig. 3) have a similar slope as the Junge distribution.

It can be also derived from this that the measurement of 3 to 4 particle sizes representing these 3 major particle distributions may be sufficient to cover the total particle spectrum for monitoring purposes.

Out of the cleanliness requirements of the semiconductor chips it can be derived that the cleanliness classes of the ISO 14644-1 may be extended also to the molecular regime (Fig. 3) and [22, 31]. It has to be stated that the cleanliness classes are normally calculated out using the given formula and not represented by the straight lines in the graph.

To achieve the particle cleanliness classes of air depending on the outside conditions typically three stages of air filtration are needed, (Fig. 4).

For an ISO class 5 generally a F7, F9 as pre-filters and H13 or H14 as final filter are sufficient for the cleanliness class and a suitable life time of the final filter of larger than 3 to 5 years. Due to the outdoor pollution and the amount of air recirculation possible life times of more than 10 years for the final filters may be achieved [9, 32].

For some applications where higher air cleanliness is required for the manufacturing of the finest structures so-called *minienvironments* [11] or enclosed spaces are built in the cleanroom with additionally filtration of airborne molecular contaminations (AMCs) and particles.

Depending on the specific requirements of production AMC filters may have to be included in the make-up air, recirculation, minienvironment or also in the exhaust air.

For the derivation whith sensors and monitoring and control necessities have to be regarded additionally to the outdoor and filtration mechanisms the aerosol and AMC generation and dynamics in the cleanroom have to be described and understood.

As shown in equations 2 and 3 and as derived in aerosol physics and chemistry it has to be expected that the gaseous contaminations ($\boldsymbol{C}_n$) are correlated with particle regime and not only in the outdoor environment but also in the cleanroom systems and subsystems.

$$C_n = 10^N \times \left[\frac{0.1}{D_P}\right]^{2.08} \tag{2}$$

with: N - cleanliness class; 0.1- reference particle diameter.

$$\begin{array}{llll} C_P^O \Rightarrow C_P^R & \Leftrightarrow C_P^C & \Leftrightarrow C_P^L \\ \Updownarrow \quad \Updownarrow & \Updownarrow \quad & \Updownarrow \quad & \Updownarrow \\ C_G^O \Rightarrow C_G^R & \Leftrightarrow C_G^C & \Leftrightarrow C_G^L \end{array} \tag{3}$$

The following symbols were used: P- Particle, G - Gases / Airborne Molecular, Contamination, O - Outdoor, R – Recirculation, C – Cleanroom, L - Local Environment.

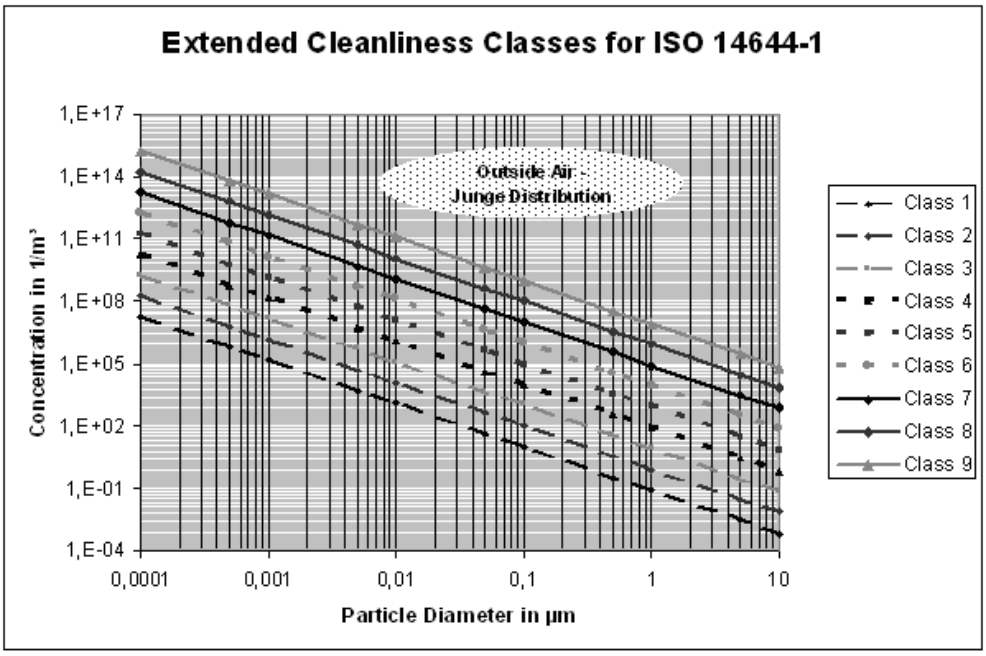

Fig. 3. Air cleanliness classes in accordance with ISO 14644 extended to Airborne Molecular Contaminations (AMCs)

The allowable defect rates, either for microelectronic requirements or for pharmaceutical sterility, have to be close to zero (*e.g.* 10^{-6} and better) [11, 31, 33-42]. Such defects rates have to be measured and proved. For example it can be shown that, to certify to Class 5, ISO 14644-1, under operating manufacturing conditions, at least four to six weeks of continuous data are needed, and to certify to higher air cleanliness classes even longer monitoring timescales are necessary. However, not only the particle air cleanliness, but also the cleanliness of process materials and many other parameters are important.

For this reason a total contamination control strategy should be developed to map the whole process flow of material and personnel from outside the cleanroom to the interior and back again.

The major requirements for a cleanroom monitoring system are:

- To define for the correct design of cleanrooms the outdoor environmental conditions where the cleanroom is going to be build up,
- To define the dependencies of the cleanroom conditions from the outdoor conditions for a better control of the cleanrooms,
- To define a general understanding of contamination continuum.

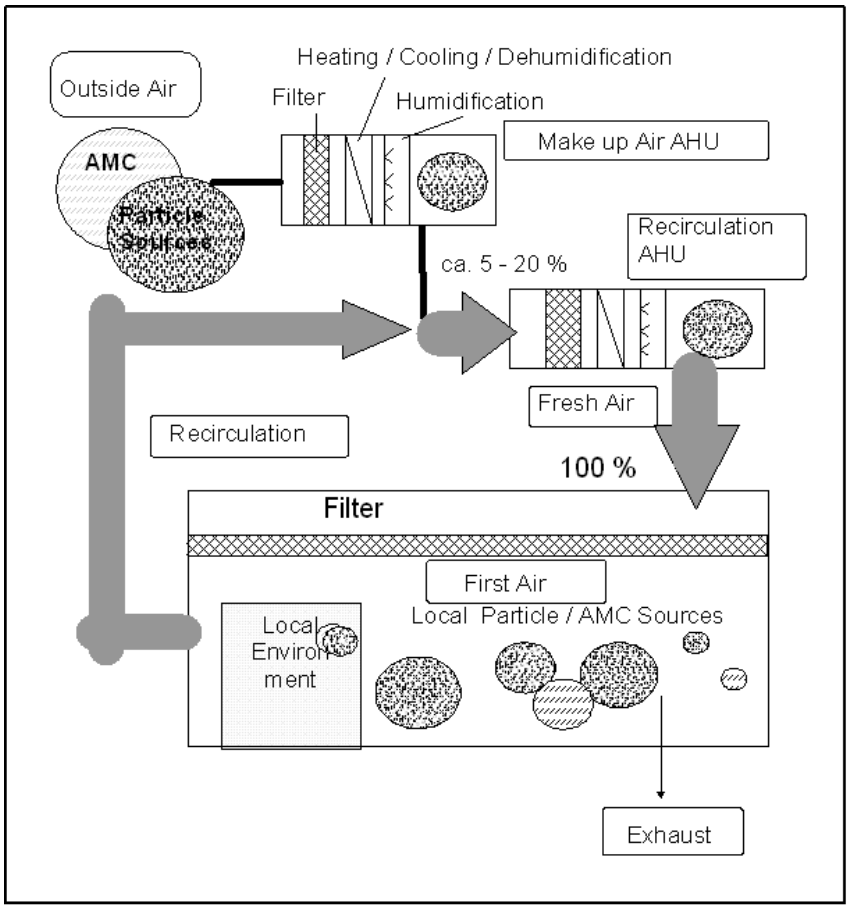

Fig. 4. Cleanroom systems with sources and sinks of contaminations

- To define the monitoring requirements for the control of cleanrooms:
  - from the measurement technologies;
  - from the monitoring requirements;
  - from the side of statistics and analysis.
- To develop an approach for the data analysis applicable for the non-linear dynamic data.
- To develop a control approach for the above.

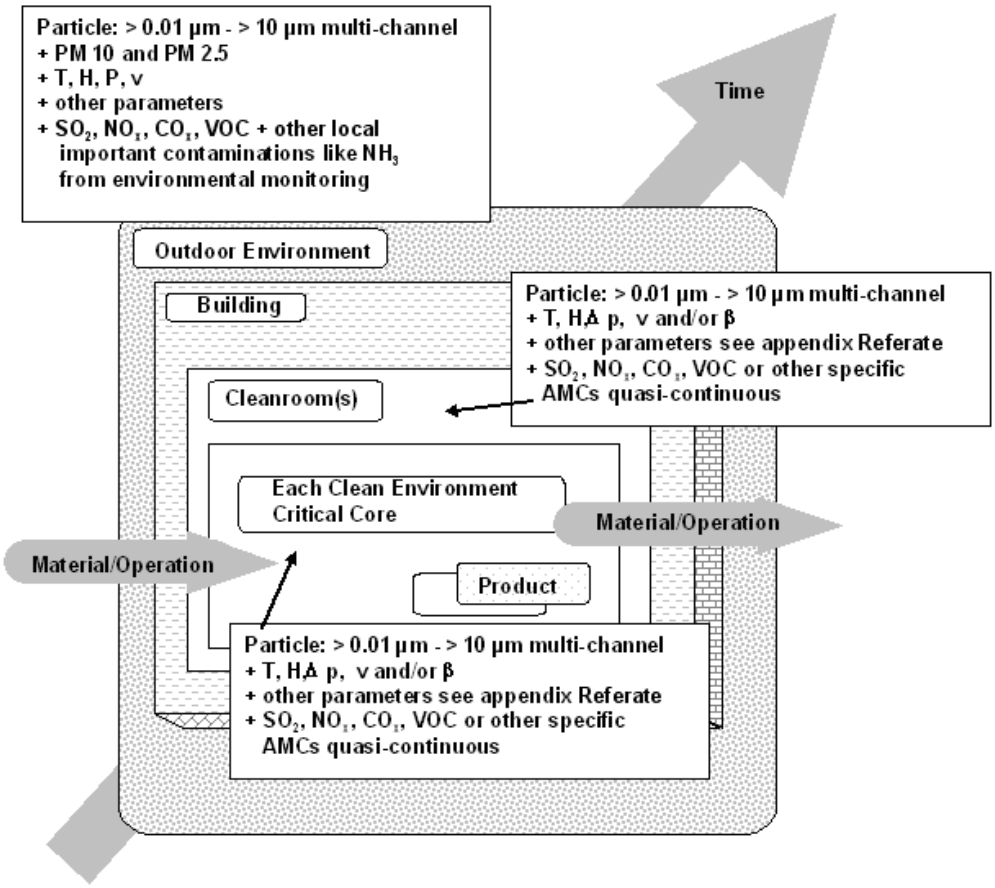

Fig. 5. Example monitoring for semiconductor cleanrooms

When deciding the site for the manufacturing line and specifying the technical requirements of the plant, the transport mechanisms and local concentrations of contaminants have to be investigated. Particles and critical contaminant gases can be transported over long distances with high efficiency and short time frames (a matter of weeks for continental-scale problems, such as large-scale atmospheric pollution). The concentrations of contaminants may vary in a matter of seconds by several orders of magnitude. Possible interactions of chemicals also have to be taken into account (ozone etc). All these have to be included in the monitoring requirements and disaster procedures, as Fig. 5 shows.

Also, for a stable manufacturing environment, the outdoor parameters should be monitored over the specified measurement intervals.

Summarizing all the parameters yields a characteristic function of all critical parameters for a specific manufacturing line. By the Hazard Analysis of Critical Control Points (HACCP), the characteristic monitoring functions result. Not all parameters have to be monitored continuously. For some parameters, discontinuous data acquisition may be sufficient.

For pharmaceutical applications, the contamination risk definitions are dominated by microbes. In Table 1 a set of monitoring parameters is given for comparison. The requirements of the different applications and related cleanliness classes result in a complex list of parameters.

Table 1

Particle monitoring proposal (pharmaceutical)

Class	Description	Frequency Documenting	Alarming
A (ISO 5 LF)	Manufacture or open handling of aseptic products: continuous single particle counting	1/min	> 50/cf
B (ISO 5 Turbulent) -at rest (EC-Guide)	Continous particle counting	1/min	>100/cf
- in operation		1/min	>100/cf
C (ISO 7)	Continuous particle counting, multiplex system	1/15min	>5000/cf
D (ISO 8)	Discontinuous particle counting	2/week	>50,000/cf
General	Discontinuous particle counting	1/month	>100,000/cf
Special	Discontinuous particle counting – no Class	1/6months	>200,000/cf

(cf: cubic foot, particles equal or larger than 0.5 µm)

In general, if the product requires also the monitoring of the very small particles, the following particle sizes should be monitored, (Fig. 5 was given as an example):

- 0.01 µm with a condensation particle counter, flow rate 0.1 cfm;
- 0.2 µm with a laser particle counter with flow rate 1 cfm;
- 0.5 µm with a laser particle counter with a flow rate of 1 cfm;
- 5 µm with laser particle counter with a flow rate of 1 cfm.

The particle sampling at a representative location is a very important factor and may be a source of failures and deviations in monitoring if not carefully designed and installed.

2. Monitoring system requirements

For a successful monitoring not only the measurement techniques like condensation particle counter, laser particle counter etc. are important but also the computer hard- and software, networking, data acquisition, analysis, as follows:

- *automated data acquisition* (also see Table 1) of heterogenic sensors for air/gas-borne and liquid borne particles, environmental parameters and, in particular, differential pressure, GCMS (gas chromatography coupled with mass spectrometry), HPLC (high pressure liquid chromatography), surface particle counters, microbiological monitoring, and others with different types of monitoring:
  - sporadic monitoring - after changes of cleanroom and/or process;
  - quasi-continuous monitoring - once a day or week;
  - discontinuous monitoring - *e.g*. after failures and/or alarms (less critical parameters);
  - continuous monitoring - for parameters critical to the yield;
- *automated data analysis for alarms and warnings*, actions such as shutdown operations, automated `fire brigade' callout, and automated documentation of alarms and warnings;
- *cross-link* to possible direct digital control *(DDC)* and/or facility automation systems, if not included in the monitoring system (note of caution: for pharmaceutical applications the monitoring should be clearly separated from DDC and/or facility automation systems);
- *automated data storage*, including eventual data compression, because some continuous signals may only be stored for further analysis every minute or at other time intervals (see Table 1);
- *automated documentation*, such as batch and shift analysis, weekly and monthly reports, yearly trend analysis, including data from possible *DDC* and/or facility automation systems, on a graphical and tabular basis compressed by normal and specific cleanroom-applicable statistics;
- *general data handling* - saving and storing data at different types of media such as hard discs, optical discs, and magnetic tapes for future documentation needs,
- *cross-link* to implemented standard process control *(SPC)* for correlation with the yield of the manufactured product with a feedback loop to the monitoring.

A more detailed control strategy for the cleanrooms consists out of:

- monitoring;

- on-line control of warning and alarms including documentation of the alarms and alarming (mostly optical and audible) as well as acknowledging of the alarms and warning and setting them back;
- event detection (outside meaning in the environment and inside the building/cleanrooms);
- analysis of the data for example size distribution, time series analysis for all parameters as identified for source detection or detecting long term influences;
- analysis of ultra-clean cleanrooms [43-47];
- active control of air conditioning and cleanliness in reacting to either outside environmental conditions - for example reducing or enhancing the amount of outdoor air - or the inside cleanroom conditions - for example reducing or enhancing the volume of air transported to the cleanroom in conjunction with the degree of cleanliness, manufacturing activities or requirements;
- forecasting and trend analysis of cleanroom variables and parameters like cleanliness and filter life time for guiding preventive maintenance cross correlation to process control systems for correlation of cleanroom parameters and data with the process yield.

3. Data Analysis and Control Strategy

Looking onto Fig. 6 and Fig. 7 and the analysis of the data, (that will be presented in Fig. 10), it can be seen that the standard statistical analysis, trend analysis and time series analysis are not delivering values for the mean or the periodicity with acceptable standard deviations or variations. The standard deviations are 10 times (and more) higher than the averages for the particle data, but also the other environmental sensors show large variations.

Not only the data for the outside parameters (see Fig. 6) show the very noisy behavior on nearly every time scales and resolutions but also the data for the cleanrooms (see Fig. 7) cannot be predicted by the standard statistical analysis. Even for the cleanest cleanrooms the data show noise and events (as Fig. 10 has shown).

For a control strategy a new approach has to be developed. This approach should be able to handle the large amount of data to be analyzed, correlated etc., derive describing control parameters and last but not least affordable from the money point of view.

As shown in Fig. 8 the monitoring data are used for setting up the analysis parameters for the fractal analysis *via* the box count methodology. The data of the fractal analysis and the cross correlation analysis are used for the control matrix, see Fig. 9.

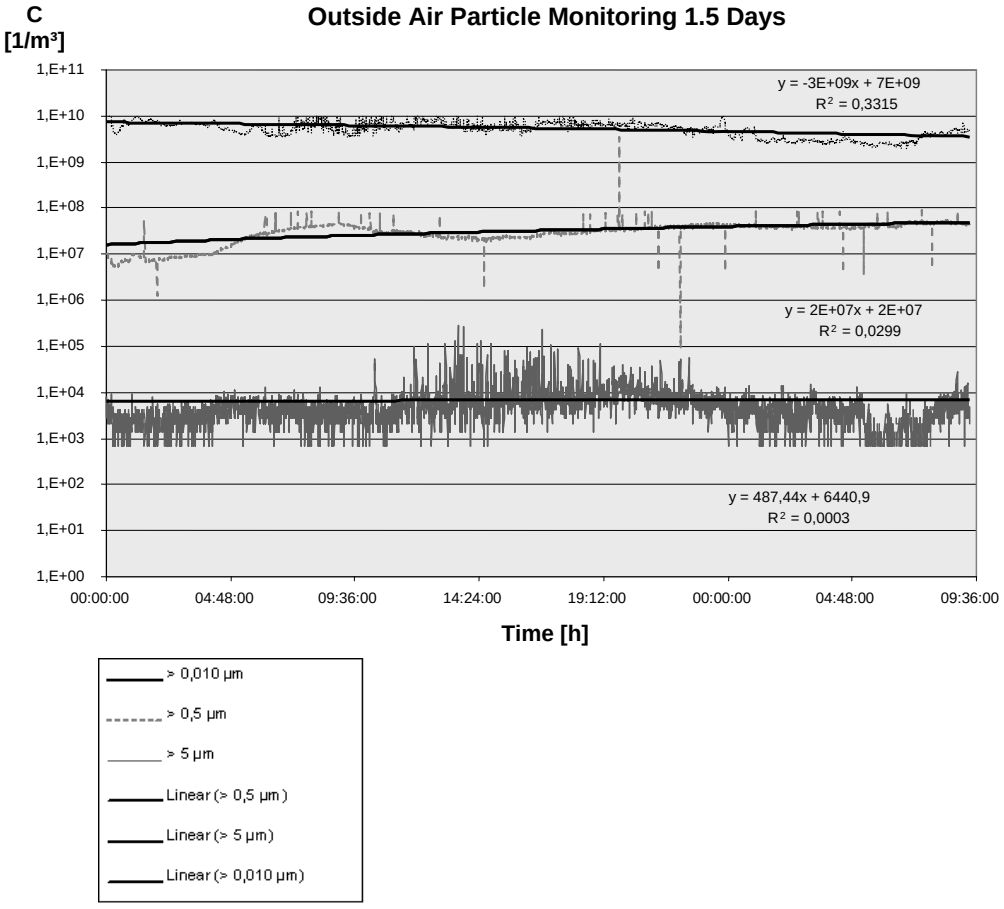

Fig. 6. Outside air particle monitoring

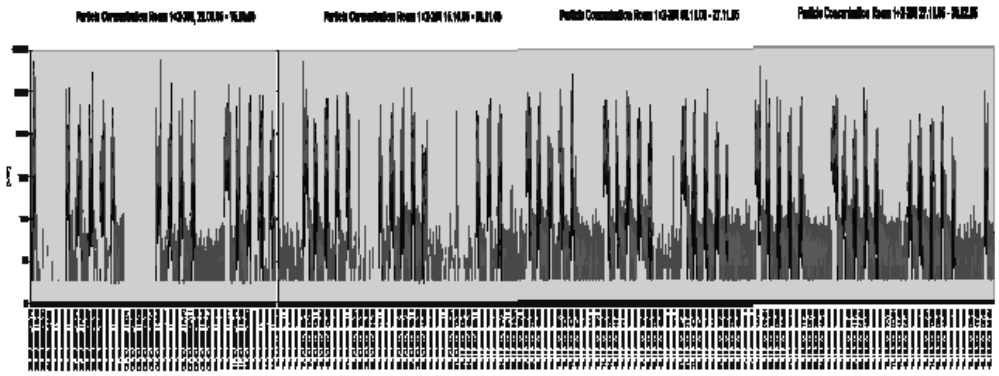

Fig. 7. Particle monitoring in a parenteral manufacturing for 4 months in 2005

In Fig. 11 an example of the box count analysis is given together with the correlation coefficient of a straight line fit to the data. This figure shows a fairly good correlation coefficient, > 0.9, and the data are lying in the main area of the graph roughly within the +/- sigma range showing the applicability of the control approach.

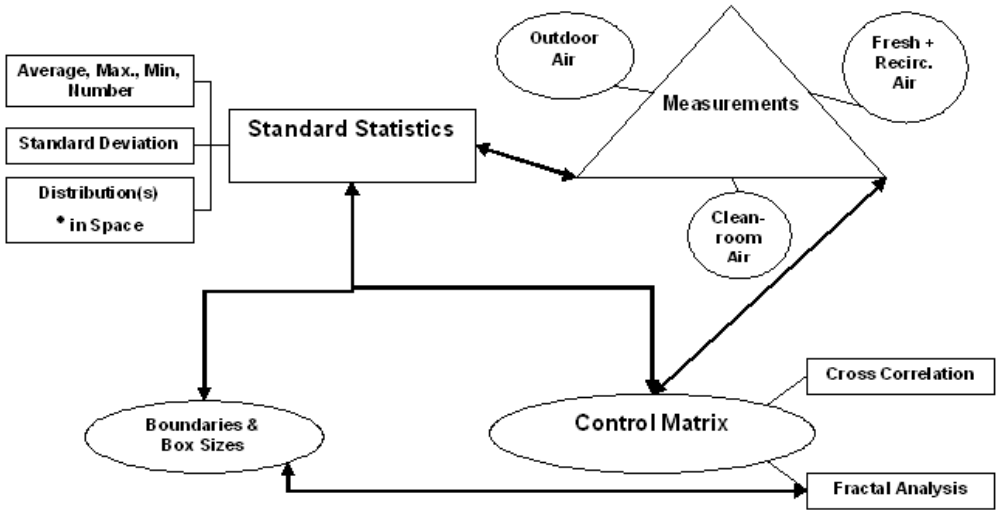

Fig. 8. The approach for the derivation of a control strategy.

Control Matrix

	Parameter 1	Parameter 2	Parameter 3	Parameter .	Parameter .	Parameter j
Parameter 1	Correlation Fractal Coeff.					
Parameter 2	Correlation Fractal Coeff.	Correlation Fractal Coeff.				
Parameter 3	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.			
Parameter .	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.		
Parameter .	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	
Parameter j	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.	Correlation Fractal Coeff.

Fig. 9. The generalized control matrix for the cleanroom control

Parameter	Particle Room 2 2.64 0.5 µm (1/m³)	Particle Room 1 2.64 0.5 µm (1/m³)	Particle Machine 1 Room 2.64 0.5 µm (1/m³)	Particle Machine 1 Room 2.64 5.0 µm (1/m³)	Diff. Pressure Room 2.64 (Pa)	Particle Room 2.62 0.5 µm (1/m³)	Particle LF 1 Room 2.62 0.5 µm (1/m³)	FFU-Velocity LF 1 Room 2.62 (m/s)	Diff. Pressure Room 2.62 (Pa)	Humidity Room 2.62 (% r.F.)
Average	2570	5100	822	1	36.72	341	0	0.449	35.56	40.44
Standard Deviation	28774	41750	17262	122	4.08	8657	21	0.114	3.75	4.24
Number of Points (2.591.516)	259198	259198	259174	259174	259129	259127	259129	259129	259129	259129
Correlation										
Particle Room 2 2.64 0.5 µm (P/m³)	1.00									
Particle Room 1 2.64 0.5 µm (P/m³)	0.59	1.00								
Particle Machine 1 Room 2.64 0.5 µm (P/m³)	0.00	0.00	1.00							
Particle Machine 1 Room 2.64 5.0 µm (P/m³)	0.00	0.00	0.39	1.00						
Diff. Pressure Room 2.64 (Pa)	0.01	0.01	0.00	0.00	1.00					
Particle Room 2.62 0.5 µm (P/m³)	0.05	0.04	0.00	0.00	0.01	1.00				
Particle LF 1 Room 2.62 0.5 µm (P/m³)	0.00	0.00	0.00	0.00	0.00	0.00	1.00			
FFU-Velocity LF 1 Room 2.62 (m/s)	0.04	0.06	0.01	0.00	0.05	0.02	0.00	1.00		
Diff. Pressure Room 2.62 (Pa)	0.01	0.01	0.00	0.00	0.79	0.01	0.00	0.07	1.00	
Humidity Room 2.62 (% r.F.)	0.00	0.01	0.01	0.00	-0.05	0.01	0.00	-0.04	-0.05	1.00

Fig. 10**.** Results of cross correlation and standard statistical analysis for parenteral data (see also Fig. 8).

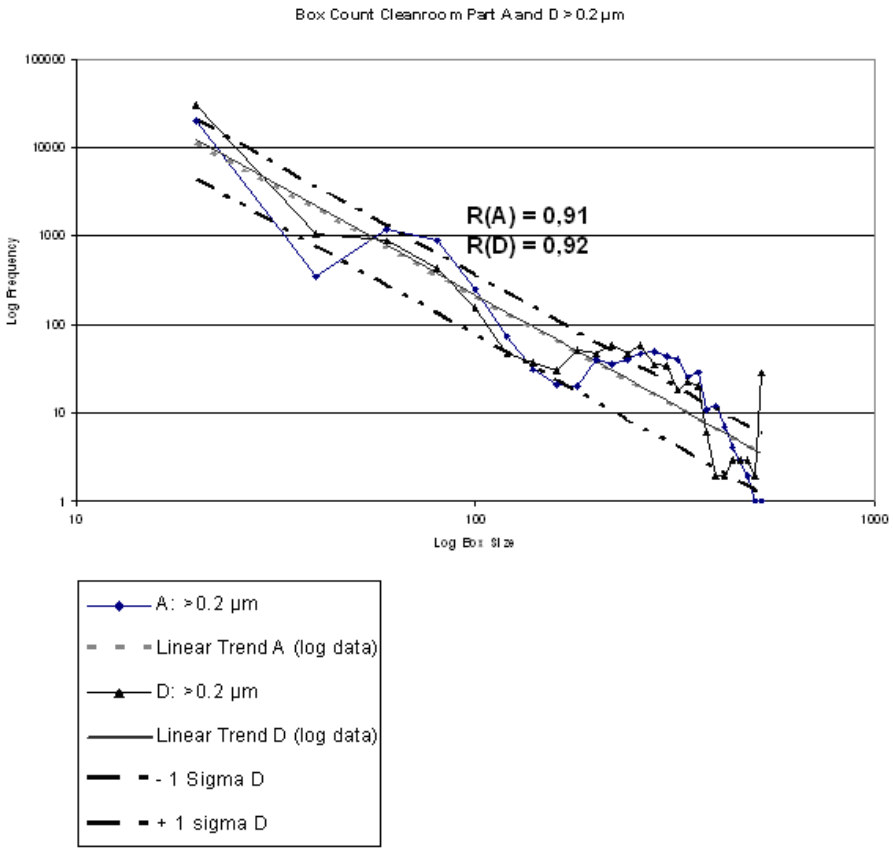

Fig. 11: Results of box count analysis with indication of correlation coefficient and ± 1 sigma

Conclusions

Based on aerosol and contamination control physics and chemistry a necessary and sufficient set of measurement technologies and requirements for monitoring systems could be derived. The frequency of measurements should be as close to continuous sampling as technically possible with the different counting devices. If discontinuous measurements or averaging is chosen as a monitoring strategy the results are less good or even not usable for the following analysis steps.

The standard statistical analysis is not able to describe the monitoring data sufficiently. The cross correlation analysis may not show "good" correlation coefficients as used in the standard statistical analysis but can be used to show general dependencies as long as equally spaced and enough data are available for analysis. With the box count methodology a good description of the data can be achieved with sufficient correlation coefficients.

The box counting methodology offers possibilities not only to investigate particle distribution and time series but with minor transformations of the data to develop a description also for ultra-clean cleanroom environments.

With the new approach the cleanroom can be controlled actively and the cleanroom design can be optimized.

With the planned cleanroom for the ICP-MS instrument at the University POLITEHNICA of Bucharest it should be possible to prove and extend the approach to the molecular regime, too.

R E F E R E N C E S

1 *Belew, B. et al.* High-yield manufacturing: Particle monitoring in minienvironments, Cleanrooms, **4**, (2004)
2 *Flickinger, B.* Contamination control in space, Cleanrooms, **5**, 10 – 11, (2006).
3 *Mosley, G.* Managing Product and Environmental Microorganisms in Your Facility, Controlled Environments, **6**, 21 – 26, (2006).
4 *Muller, C.* The ITRS and AMC: More control on the way? Cleanrooms, **5**, 4 – 21, (2006).
5 N.N. ITRS Roadmap, 2005, Sematech
6 N.N. EU GMP, Emea,(2005)
7 *Seyfarth, H.* Überprüfung der mikrobiologischen Qualität von nicht- sterilen Produkten nach den international harmonisierten Vorschriften, Pharm. Ind., **68** (8), 995 – 1004, (2006).
8 *Tolliver, D.L.* Handbook of Contamination Control in Microelectronics (Principles, Applications and Technology), (1988).
9 *Weißsieker, H.* The Filtration Dynamics of Glas Fiber Filters and Practical Applications in the Food Industry, ICCCS-Conf. Proceedings, Bonn, (2004).
10 *Weißsieker, H.* Clean Air Purifications for the 64 MB Chip Generations to Come, 12th ICCCS Conf., Yokohama, 373 – 400, (1994).
11 *Weißsieker, H., Ludwig, J. and Warnecke, H.-J.* Einschlußtechniken zur Qualitätssicherung in der Reinraumtechnik (Teil 1), Reinraumtechnik, 4, 24 – 30, (1993).
12 *Davies, C.N. ed.* Aerosol Science, Academic Press, New York, *(*1966).
13 *Friedlander, S.K. and Pui, D.Y.H.* Emerging Issues in Nanoparticle Aerosol Science and Technology (NAST), University of California, Los Angeles, (2003).
14 *Hinds, W.C.* Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, John Wiley, New York, (1982).
15 *Hussein, T. et al.* Urban aerosol number size distributions, Atmos. Chem. Phys., **4**, 391 – 411, (2004).
16 *Niessner, R.* The chemical response of the photo-electric aerosol sensor (PAS) to different aerosol systems, J. Aerosol Sci., **17** (4), 705 – 714, (1986).

17 *Allendorf, S.W.* et al. Optical Sensors for Process Control and Emissions Monitoring in Industry Sandia Report, Sand, 99 – 8424, (1999).

18 *Fister Gale, S.* Monitoring AMC, Cleanrooms, **5**, 22 – 28, (2006).

19 *Horn, H.G. and Weißsieker, H.* Arbeitsprinzip und Aufbau moderner, kontinuierlich arbeitender Kondensations-Partikelzähler und ihre Einsatzmöglichkeiten in der Reinraumtechnik, Fortschritt-Berichte Reihe 19: Wärmetechnik/Kältetechnik, **38**, 47, (1990).

20 *Koch, W.* Das dynamische Verhalten von ultrafeinen Aerosolen, BIA- Report **7**, 89 – 132, (2003).

21 *Liu, B.Y.H.* Fine Particles - Aerosol Generation, Measurement, Sampling, and Analysis Academic Press, New York, (1976).

22 *Muller, C.* A look at the future of reactivity monitoring for cleanroom AMC, Cleanrooms, **5**, 29 – 33, (2006).

23 N.N. ISO 14644, Part 1 - 8 "Contamination Control", Beuth Verlag, Berlin, (2006).

24 N.N. VDI-Richtlinie 2083, Blatt 1 - 16, Reinraumtechnik, Beuth Verlag Berlin, (2006).

25 *Wang, H.C. and Kasper, G.* Filtration Efficiency of Nanometer-Size Aerosol Particles, J. Aerosol Sci., **22**(1), 31-41, (1991).

26 *Ensor, D.P., Donovan, R.P. and Locke, B.R.* Particle Size Distributions in Clean Rooms, J. Env. Sciences, **5**, 44 – 49, (1987).

27 *Epstein, B.* The Mathematical Description of Certain Breakage Mechanisms Leading to the Logarithmico-Normal Distribution, J. Franklin Inst., **244**, 471 – 477, (1947).

28 G*albas, H.G.* Schätz- und Testmethoden für den Erwartungswert einer log-normal verteilten Grundgesamtheit, Staub - Reinhaltung Luft, **35**(12), 448 – 452, (1975).

29 *Kottler, F.* The Distribution of Particle Sizes, J. Franklin Inst., **250**, 339 – 356, (1950).

30 *Raabe, O.G.* Particle Size Analysis Using Grouped Data and the Log-Normal Distribution, Aerosol Sci., **2**, 289 – 303, (1971).

31 *Dance D., Collica R. and Jenson D.* Developing Yield Modeling and Defect Budgeting for 0.25 µm and Beyond, MICRO, **16**(3), 51-61, (1998)

32 G*ail, L. and Hortig, H. ed.* Reinraumtechnik, Springer Verlag, Berlin, 2. ed, (2004).

33 *Hitschfeld, R.* Computergestütztes Umgebungsmonitoring in der pharmazeutischen Parenteralia-Produktion, Freie Universität Berlin, (2005).

34 *Holtz, K.v.* (2006) Preparing of cleanroom certification and validation, Cleanrooms, **5**, 34.

35 *Markle, R.L., Dance, D.L. and Menon, V.B.* Employing Yield Models, In-Situ Monitoring to Predict and Achieve Defect Density Goals, MICRO, **2**, 37 – 41, *(*1992).

36 *Tolliver, D.L.* The Need for Real-Time Automated Monitoring Technology, MICRO, **5**, 12 – 15, (1984).

37 *Weißsieker, H.* Prozessüberwachung in Reinräumen in: Handbuch der Reinraumpraxis, (Ed. by Hohmann R. and Hauptmann G.), Ecomed, Landshut, (1992).

38 *Weißsieker, H.* Einsatz der Meßtechnik bei Abnahme und Überwachung von Reinraumtechnischen Anlagen, VDI-Berichte, **919**, 25-45, (1991).

39 *Weißsieker, H.* First Results of Monitoring Clean Room Parameters in HDA Line, Swiss Cont. Control, **3**, Nr. 4a (Proceedings of the 10th ICCCS-Conference), 281-284, (1990).

40 *Weißsieker, H.* Echtzeit-Reinraumüberwachung, 6. Fachtagung Granulometrie, (3), 30-36 (1989).

41 *Welker, R.* Justifying a continuous contamination monitoring system, MICRO, **15** (9), 113 – 123, (1998)

42 *Weyrauch, K., Kerkmann, B. and Weißsieker, H.* (1991) Auswertung von Daten eines Monitoring-Systems – Neuer Ansatz, Reinraumtechnik, 5, 35 - 39.

43 *Bzik, T.J.* Statistical Analysis of Data for Ultraclean Systems, Microcont. Conf. Proc., 49 – 61, (1986).

44 *Bzik, T.J.* Statistical Management and Analysis of Particle Count Data in Ultraclean Environments, Microcont. Conf. Proc., 49 – 61, (1985).
45 *Cooper, D.W.* Sequential Sampling Statistics for Evaluation Low Concentrations, J. Env. Sciences, **16**(5),. 33 – 36, (1988).
46 *Fujii, P. et al.* Monte Carlo Simulation to Characterize a Sequential Sampling Method for the Evaluation of Low Concentrations, Swiss Contamination Control, **3**(4a), 433 – 436, (1990).
47 *Preining, O.* Optical Single-Particle Counters to Obtain the Spatial Inhomogeneity of Particulate Clouds, Aerosol Science and Technology, **2**, 79-90, (1993).