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Site Comparison of Selected Aerosol Samplers in the Wood Industry

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Several samplers (IOM, CIP 10-I v1, ACCU-CAP™, and Button) were evaluated at various wood industry companies using the CALTOOL system. The results obtained show that compared to the CALTOOL mouth, which can be considered to be representative of the exposure of a person placed at the same location under the same experimental conditions, the concentrations measured by the IOM, CIP 10-I v1, and ACCU-CAP™ samplers are not significantly different (respectively, 1.12, 0.94, and 0.80 compared to 1.00), the Button sampler (0.86) being close to the ACCU-CAP™ sampler. Comparisons of dust concentrations measured using both a closed-face cassette (CFC) and one of the above samplers were also made. In all, 235 sampling pairs (sampler + CFC) taken at six companies provided us with a comparison of concentrations measured using IOM, CIP 10-I v1, ACCU-CAP™, and Button samplers with concentrations measured using a CFC. All the studied samplers collected systematically more dust than the CFC (2.0 times more for the IOM sampler, 1.84 times more for the CIP 10-I v1 sampler, 1.68 times more for the ACCU-CAP™ sampler, and 1.46 times more for the Button sampler). The literature most frequently compares the IOM sampler with the CFC: published results generally show larger differences compared with the CFC than those found during our research. There are several explanations for this difference, one of which involves CFC orientation during sampling. It has been shown that concentrations measured using a CFC are dependent on its orientation. Different CFC positions from one sampling session to another are therefore likely to cause differences during CFC–IOM sampler comparisons.

Keywords: ACCU-CAP™; button sampler; CALTOOL; CIP 10-I; closed-face cassette; inhalable fraction; IOM sampler; wood dust

INTRODUCTION

Exposure to wood dust is commonplace. A recent European study indicating that 3.6 million employees are occasionally exposed in 25 Member States of the European Union (Kauppinen *et al.*, 2006) clearly confirms this. Naso-sinusal cancer, respiratory tract attacks, and skin irritations can originate from the wood dust, to which subjects are exposed, and this has led the International Agency for Research on Cancer (IARC) to class wood dust as carcinogenic for man based on epidemiological studies (IARC, 1995). At European level, work involving exposure to hardwood dusts has been classed carcinogenic (European Directive 1999/38). This same directive has established an exposure limit value of 5 mg m^{-3} for hardwood dust, while emphasizing that it is the inhalable fraction that must be sampled and that this limit value applies to all combined wood dust, in the event that hardwood dust is mixed with other wood dust. In France, this limit value has been adopted in a regulation of 26 October 2007.

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The applicable binding limit value is 1 mg m^{-3} for unrestricted wood types. French regulation of 20 December 2004 defines the measuring method to be applied for controlling wood dust concentration compliance in workplace atmospheres. Sampling is performed using a closed-face cassette (CFC) (Association Française de Normalisation, 2008) and the wood dust concentration is calculated from the mass of dust deposited on the cassette filter and the sampled air volume. Dusts deposited on the internal walls of the cassette are not taken into account. This method was subsequently termed the 'closed-face cassette' or 'CFC' method and it corresponds to the term 'total dust sampling' sometimes used in the literature.

The CFC in its closed configuration, i.e. with a 4-mm inlet orifice, has been widely used to measure industrial exposures for many years. This cassette has in no way been designed to sample an aerosol conventional fraction (inhalable, thoracic, or respirable), even though it is mainly used in practice for assessing exposure risk in situations in which the aerosol-relevant fraction is the inhalable fraction. Moreover, the study of inhalable fraction samplers by Kenny *et al.* (1997) showed that the CFC underestimates significantly the inhalable fraction, when the aerodynamic diameter of the aerosol particles exceeds ~20 to 25 μm. More or less extensive dust deposits on the cassette internal walls, depending on conditions, have also been observed (Demange *et al.*, 1990, 2002; Harper and Demange, 2007). This has led some analysis methods to consider these deposits, when this is technically possible. This is the case for metals, which can be put into solution right inside the cassette (Institut National de Recherche et Sécurité, 2005). Puskar *et al.* (1991) have also referred to dust deposition on cassette internal walls in a series of sampling operations performed in the pharmaceutical industry, in which on average only 22% of dust was collected on the filter due probably to the presence of electrostatic charges.

Publication, in the mid-1990s, of aerosol-standardized conventional fractions [Comité Européen de Normalisation (CEN), 1993; International Organization for Standardization (ISO), 1995] led to development of or encouraged the use of many samplers specially designed for sampling a given aerosol conventional fraction. In particular, we could mention the CIP 10-I inhalable fraction sampler, developed from the CIP 10-R model, which was initially designed to sample the respirable fraction (Courbon *et al.*, 1988), the IOM sampler (Mark and Vincent, 1986), or the GSP sampler (Ströhlein GmbH & Co., Kaarst, Germany). The Button sampler was not initially designed to sample the inhalable fraction (Kalatoor *et al.* 1995) but its successful implementation as a personal inhalable aerosol sampler has been demonstrated (Aizenberg *et al.* 2000). Another sampler was developed in parallel from the CFC to take into account wall deposits during gravimetric analyses. This sampler comprises an accessory, which is inserted into the cassette, allowing capsule collection of all dust particles entering through the CFC inlet orifice. Originally quoted in an Occupational Safety and Health Administration (OSHA) method (OSHA method PV2121) and made of aluminium (Puskar *et al.*, 1992), this device was then manufactured in plastic and marketed under the name ACCU-CAP™. It could be expected that this modification would correct, at least in part, the observed underestimation in dust concentrations, measured with the CFC, in terms of the inhalable conventional fraction and this has indeed been confirmed by preliminary research (Demange *et al.*, 2003).

The sampling efficiency of personal inhalable aerosol samplers is usually determined using laboratory-based facilities such as wind tunnels in which idealized conditions such as uniform airflow and uniform aerosol concentration are employed (Kenny *et al.*, 1997, 1999; Li *et al.*, 2000; Aizenberg *et al.*, 2001). In order to ensure that the performance testing is relevant to real workplace conditions, a system known as CALTOOL was developed. The CALTOOL system is a manikin which was designed for site assessment of sampler performance (Mark *et al.*, 2004) and whose initial application involved the rubber industry (de Vocht *et al.*, 2006). This system enables the response of the tested samplers to be compared with that of the manikin mouth, which can be considered to be representative of the exposure of a person placed at the same location under the same experimental conditions. Moreover, it was shown that CALTOOL gave results that are close to the calm air inhalability criterion proposed by Aitken *et al.* (1999).

In anticipation of possible developments in French regulations resulting from the European directive requirement for sampling the inhalable convention for wood dust, dust concentrations measured using these different samplers (CFC, IOM, CIP 10-I, ACCU-CAP™, and Button) were evaluated at various industrial woodworking facilities using the CALTOOL system to determine which of them complies best with the calm air inhalable criterion. The limited choice of test samplers was due only to limited laboratory capacity and in no case implies that others would not have been

of interest. In a second set of experiments results obtained with IOM, CIP10-I, ACCU-CAP™, and Button samplers were compared with those measured using the CFC. This does not mean that the CFC is considered a reference sampler, but it simply enabled us to evaluate to what extent a sampler change will impact measured concentrations.

The purpose of this paper is to detail the results obtained. Document appendices include references to additional results, also obtained during this study, which are potentially helpful to the discussion. These involve the influence of CFC orientation and flow rate on measured concentration (Appendix 1) and comparison of two versions of the CIP 10-I sampler (Appendix 2).

METHODOLOGY

Samplers used

Sampler characteristics and conditions of usage were as follows:

IOM (SKC, SKC 22570): sampling flow rate = 2 l min^{-1} on 25-mm diameter polyvinyl chloride (PVC) membranes (Gelman, GLA 5000 66466) and pore diameter = 5 µm, housed in metal cassettes (SKC 22575).

CIP 10-I v1 (Arelco, ARC 10 010 I SP): sampling flow rate = 10 l min^{-1} on foams housed in cups (ARC 10-007).

ACCU-CAP™ (Omega, OMEM083760CP): sampling flow rate = 2 l min^{-1} on mixed cellulose ester membranes and pore diameter = 0.8 µm, housed in 37-mm two pieces CFCs.

Button (SKC 225-360): sampling flow rate = 4 l min^{-1} on 25-mm diameter PVC membrane (Gelman, GLA 5000 66466) and pore diameter = 5 µm.

CFC (Millipore, MOOO 037 A0): three pieces, 37 mm diameter, CFC, sampling flow rate = 1 l min^{-1} on 37-mm diameter PVC membrane (Gelman, GLA 5000 66469) and pore diameter = 5 µm.

A standard aerosol sampling head (Millipore, XX5004700) was used to sample air at the mouth position of the CALTOOL system: sampling flow rate = 20 l min^{-1} on 47-mm diameter PVC membranes (Gelman, GLA5000 66468) and pore diameter = 5 µm.

The ACCU-CAP™ sampler and the CFC were mounted in a special device (Arelco, ARC 8507) such that their inlet orifices were oriented forwards (filter in a vertical plane).

Sampling

Evaluation of the samplers using the CALTOOL system. CALTOOL (Calibration Tool) is an idealized manikin, designed to assess sampler performance on site (Mark *et al.*, 2000; Fauvel *et al.*, 2003).

It comprises a stainless steel cylindrical head (diameter 175 mm and height 200 mm) mounted on the top face of a stainless steel volume of elliptical cross section (diameters 420 and 240 mm), which models a human torso (Fig. 1). The head incorporates an aspiration orifice at its 'mouth', connected via a cylindrical tube to a 47 mm diameter filter holder located behind the device. The 15-mm diameter orifice is positioned 10 cm from the bottom horizontal plane of the head. The suction flow rate of 20 l min^{-1}, used to sample the aerosol, is delivered by a volumetric pump. Personal samplers, connected via critical orifices to the volumetric pump, can be fitted to the torso. The CALTOOL system is designed to be used in a fixed configuration at the workplace.

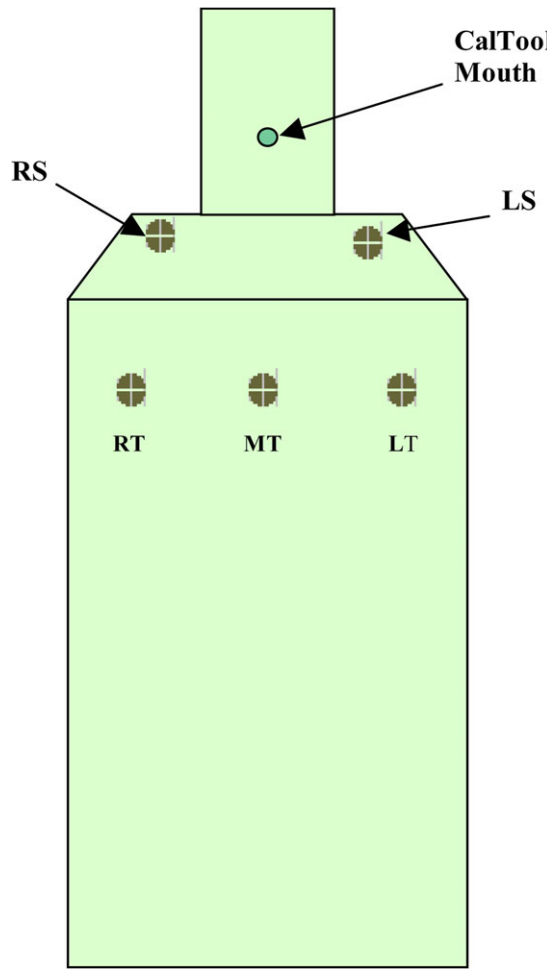

Fig. 1. Representation of CALTOOL system.

Five sampler placement positions were identified for this study: two positions on the shoulders (left LS and right RS) and three positions on the upper torso (left LT, middle MT, and right RT). The IOM, ACCU-CAP™, Button samplers, and the CFC were randomly placed at positions LS, RS, LT, and RT. The CIP 10-I v1 sampler was always placed at position MT. Using this system, samples were taken at five wood industry factories.

Soap film flowmeters (Gilian, Gilibrator) were used to measure the critical orifice flow rates. CIP 10-I sampler flow rates were measured and adjusted in the laboratory on a bench using pressure drop compensation, the cup rotational speed being checked on site using a tachometer (Arelco, ARC 8527).

Comparison of the samplers with the CFC cassette. Samples were either individual or static samples. For individual samples, the employee was fitted with two samplers: the CFC and one of the four samplers used for comparison. A number of studies (Golle and Paik, 1985; Vaughan *et al.*, 1990) have shown that the ratio between dust concentrations measured simultaneously on opposite lapels may be very different (more than a factor of 2), so we were careful to position the CFC as many times on the right-hand side of the employee's body as on the left-hand side to prevent any bias related to sampler position. Static sampling involved several samplers (no more than four), including the CFC, which were simultaneously positioned on supports ~1.6 m above the workplace floor.

Portable pumps were used for sampling (Gilian Gilair 3 model for the IOM, ACCU-CAP™ samplers, and the CFC and Gilian Gilair 5 model for the Button sampler).

As for samples taken on the CALTOOL system, soap film flowmeters (Gilian, Gilibrator) were used to measure pump flow rates and CIP 10-I sampler flow rates were measured and adjusted in the laboratory on a bench using pressure drop compensation, the cup rotational speed being checked on site using a tachometer (Arelco, ARC 8527).

Gravimetric analysis

Substrates were weighed on balances accurate to the micrograms (Mettler MX5 model for filters, IOM, and ACCU-CAP™ cassettes and Mettler AX26 model for CIP 10-I cups). Field blanks (usually six) were associated with each set of substrates (~20 to 25). Substrates were weighed before and after sampling. Prior to weighing, the substrates were dried in an oven at 50°C for at least 4 h and were then left for at least one night in the weighing room. Weight differences between second and first weighing operations were corrected for weight variations in the field blanks. The standard deviation for mass variation was determined for the different substrates used based on the requirements of Standard NF ISO 15767 (ISO, 2003). Table 1 provides the corresponding data.

Knowing the number of field blanks used, these data allow us to compute the variance associated with each sampled dust mass measurement (difference between second and first weighing).

Data processing

In this paper, data processing is most often aimed at establishing a correlation between the concentration (Y) measured by one of the samplers designed to collect the aerosol inhalable fraction and the concentration (X) measured by the CFC. Assumptions made for deriving the supposed linear relationship between Y and X are especially significant, when there is a fairly high dispersion of graphically plotted experimental points; this is often the case for samples taken on site. Figure 2 illustrates all the experimental points Xi and Yi obtained for a specific sampler tested during this study.

If no assumption is made, the least squares regression line will be biased by the high concentration extreme values and will then pass to one side of most of the plotted experimental points (regression line of slope 1.00 not shown on Fig. 2). We can consider that the most dispersed points are outliers in order to remedy this situation. If, for example, we discard the experimental points, for which the Student residual standard deviation exceeds 3, from the least squares computation, the regression line of slope 1.77 is more representative of the experimental points, but at the expense of discarding nine data pairs (shown lightly in Fig. 2). However, discarding these data does raise a problem because they do not

Table 1. Standard deviation (SD) in mass for different blank substrates used

Type of substrate	SD (σ) in µg
IOM sampler cassette	39
CIP 10-I sampler foam + cup	46
ACCU-CAP™ sampler cassette	13
25-mm PVC filter for Button sampler	3
37-mm PVC filter for CFC	6
47-mm PVC filter for the standard aerosol sampling head	4

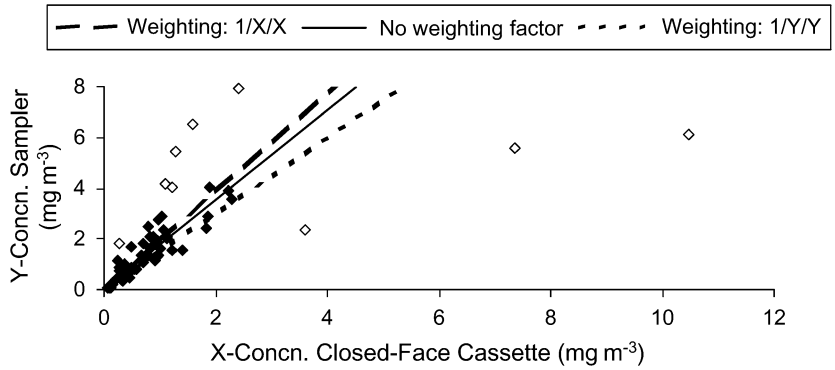

Fig. 2. Relationship between concentrations measured using sampler (*y*-axis) and concentration measured using CFC (*x*-axis). The lightly represented points are data excluded from the least squares regression line computation, without weighting based on a Student residual SD > 3. Different regression lines depend on the chosen weighting factor.

necessarily represent unrealistic points and may simply reflect the variability of samples taken on site.

It was this idea that was taken into account in data processing by Martin and Zalk (1998), who implemented the method proposed by Tsai *et al.* (1995). To take into account the fact that experimental point variability is all the greater when concentrations are high, these authors suggested introducing a weighting factor equal to $1/X^2$ (weighting by inverse of the square of the concentration measured using the CFC) into the regression line computation. This led to a weighted regression line with a slope of 1.93. There are considerably less data, for which the Student residual standard deviation exceeds 3, than in the previous method (their number is reduced from nine to two), showing that this model takes into account a greater number of data. However, this approach is really no more satisfactory because it is too dependent on the choice of weighting factor. We can easily convince ourselves of this by choosing to take the other axis as weighting factor ($1/Y^2$). A regression line with a slope of 1.49 is then obtained without any justification for choosing one axis or the other for weighting the data. The regression lines obtained on the basis of these three assumptions are plotted in Fig. 2.

A more detailed model was implemented for data processing to avoid these drawbacks. For each measurement, this model takes into account both analysis and sampling errors. The analysis error specific to each measurement result is characterized by a relative error modelled by a log-normal distribution. This relative error was determined from errors in the collected dust mass and the sampled air volume. The sampling error is characterized by an identical variation coefficient for all samplers, all samples, and all companies. This variation coefficient and the regression lines are determined by statistical analysis based on Bayesian methods (WINBUGS software).

For each sample p taken with sampler e (e varying from 0 for the CFC to 4):

$$Y_{pe} \sim LN\left(Y_{pe0}, eg_{pe}\right),$$
$$Y_{pe0} \sim LN\left(\beta_e \times Y_p, eg_P\right).$$

Y_{pe} = measurement result for sample p taken with sampler e,
Y_{pe0} = 'true' measurement value for sample p taken with sampler e,
eg_{pe} = standard deviation for analysis error,
Y_p = 'true' concentration value for sample (personal or static sampler),
β_e = regression coefficient between sampler-measured concentration e and CFC-measured concentration (by agreement, $\beta_0 = 1$ for CFC),
eg_P = geometric standard deviation characterizing sampling error.

RESULTS

All the experiments were conducted at seven companies. Table 2 shows the activity of these companies.

Evaluation of the samplers using the CALTOOL system

Samples were taken at five wood industry factories (Factories B, D, E, F, and G from Table 2). The mean concentration measured at the mouth position was 1.4 mg m^{-3} (range between 0.15 and 6.1 mg m^{-3}).

For each set of samples (usually three per factory, except four for Factory G), the particle size distribution was assessed by applying the Coulter counting method to the sampling filters downstream of the CALTOOL mouth. The corresponding results are given in Table 3 and Fig. 3.

As the volume equivalent median diameters measured on samples taken at Factory G (22.2—66.8 μm) were very different from those obtained at the other factories (13–28 μm), the results obtained at Factory G are separately described. Table 4 gives the mean ratio R of the concentration measured by each sampler to the concentration measured from the CALTOOL mouth, as well as its standard deviation. For each measurement, this table also shows the upper and lower limit values of the confidence interval and the variation coefficient of ratio R.

Figure 4 illustrates the same data shown as a classic box and whisker plot.

Table 5 consolidates the results obtained at the fifth factory (Factory G) in the same form as above.

Figure 5 illustrates the same data shown as a classic box and whisker plot.

Table 2. Main company activities

Company	Main activity
A	Door and window manufacturing
B	Door manufacturing
C	Sawmill
D	Furnishings production
E	Door, staircase, etc. manufacturing
F	Furnishings production
G	Sawmill

Table 3. Volume equivalent median diameter (range) determined by the Coulter technique in companies B, D, E, F, and G

Company	Volume equivalent median diameter (range in μm)
B	17–23
D	19–21
E	17–28
F	13–17
G	22–67

Comparison of the samplers with the CFC

In all, 235 sample pairs (sampler + CFC) were obtained at six companies (A to F from Table 1).

Table 6 indicates the number of sample pairs taken by sampler type and their division between static and personal samples.

Table 7 provides the regression line slope determined from the statistical model described in the data processing section for the different samplers studied. For each sampler, these data are expressed not only as combined results but also separately for static and personal sampler measurements. The sampling error determined by the statistical model was evaluated at 27%.

Figures 6–9 illustrate the relationship between the concentration measured by one of the samplers and

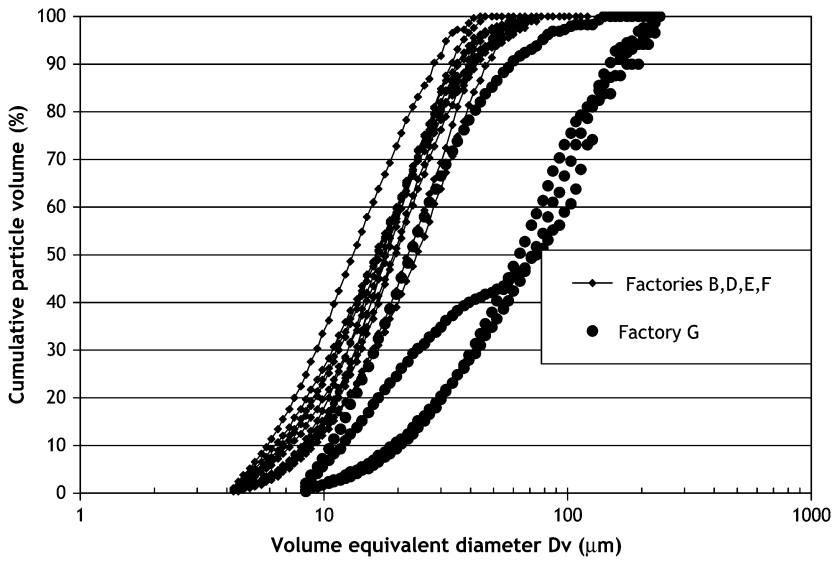

Fig. 3. Cumulative particle volume distribution in relation to the volume equivalent diameter for factories B, D, E, F, and G.

Table 4. Ratio of sampler-based measured concentration to CALTOOL system mouth-based measured concentration (factories B, D, E, and F)

Sampler	Number of measurements	Ratio *R*: sampler concentration/CALTOOL mouth concentration				
		Mean	SD	Lower limit	Upper limit	Variation coefficient (%)
IOM	12	1.12	0.17	0.86	1.43	15.3
CIP 10-I v1	12	0.94	0.11	0.78	1.15	12.2
ACCU-CAP™	12	0.80	0.14	0.64	1.17	17.1
Button	12	0.86	0.08	0.74	0.97	8.9
CFC	12	0.62	0.13	0.42	0.88	21.5

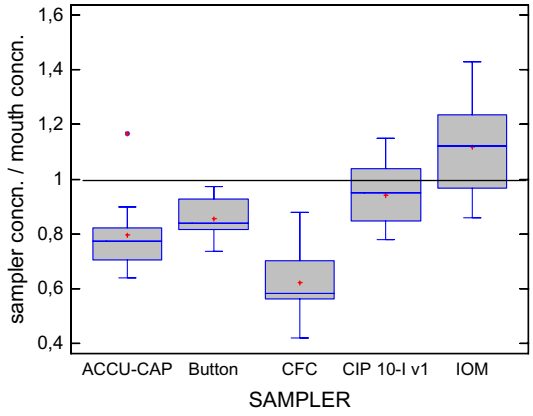

Fig. 4. Box and whisker plot of ratio of sampler-based measured concentrations to CALTOOL system mouth-based measured concentration (factories B, D, E, and F) '+' symbol shows the mean..

the CFC for the IOM, CIP 10-I v1, ACCU-CAP™, and Button samplers, respectively. Axial scaling is such that the ratio of the vertical scale to the horizontal scale remains constant (1.5), allowing slopes to be directly compared.

DISCUSSION

Evaluation of the samplers using the CALTOOL system

The data shown in Table 4 show that the concentrations measured by the IOM, CIP 10-I v1, and ACCU-CAP™ samplers are not significantly different from the reference concentration (respectively, 1.12, 0.94, and 0.80 compared to 1.0), while this is not the case for the Button and CFC samplers. In fact, ACCU-CAP™ (0.80) and Button (0.86) samplers are close together, but the Button sampler is probably penalized by its low variation coefficient, which allows a better differentiation from the reference concentration. The measurement variation coefficient ranges from 9 to 21% for the different samplers. The highest variation coefficient occurs for the CFC, perhaps reflecting the additional variability between the deposit proportions on the filter and on the cassette internal walls introduced for the CFC.

The data shown in Table 5 were obtained under particular conditions; the CALTOOL system being positioned very close to a dust emission source, below a wood trimming workstation. Its orientation with respect to the wood dust source was slightly altered during the course of the four experiments, which led to it measuring very different median particle diameters (22.2, 52.8, 61.2, and 66.8 µm). Results obtained under these conditions, in which the risk of direct projections was very high, are different to those obtained previously. We observe right away the almost general increase in the measured variation coefficients (13–104%). The IOM sampler gave the highest dispersion coefficient. This is probably because of its wide orifice, which encourages inclusion of direct projections, although drawing conclusions from a limited number of data is invariably delicate.

Comparison of the samplers with the CFC

We have ∼50 comparative data on sampler and CFC concentration measurements for the IOM, CIP 10-I v1, ACCU-CAP™, and Button samplers. These results are for both static and personal samples. Those given in Table 7 show that overall (static and personal samples combined), all the studied samplers collect statistically more dust than the CFC (2.0 times more for the IOM sampler, 1.84 times more for the CIP 10-I v1 sampler, 1.68 times more for the ACCU-CAP™ sampler, and 1.46 times more for the Button sampler). Each sampler's ratios (sampler-measured concentration/CFC-measured concentration) are statistically similar for static and personal samples.

Numerous papers focussing on comparison of the concentration measured by a sampler likely to collect the inhalable fraction and the concentration measured by the CFC have been published in the

Table 5. Ratio of sampler-based measured concentration to CALTOOL system mouth-based measured concentration (Factory G)

Sampler	Number of measurements	Ratio *R*: sampler concentration/CALTOOL mouth concentration				
		Mean	SD	Lower limit	Upper limit	Variation coefficient (%)
IOM	4	4.53	4.71	1.22	11.5	104
CIP 10-I v1	4	0.704	0.18	0.50	0.87	25.3
ACCU-CAP™	3	0.62	0.08	0.57	0.71	12.7
Button	4	0.55	0.22	0.35	0.81	38.8
CFC	4	0.31	0.14	0.16	0.49	43.6

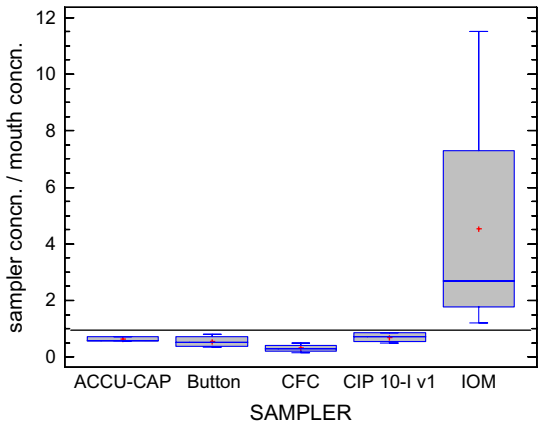

Fig. 5. Box and whisker plot of ratio of sampler-based measured concentrations to CALTOOL system mouth-based measured concentration (Factory G).

Table 6. Number of static and personal samples for different samplers studied

Sampler	Number of sample pairs	
	Static	Personal
IOM	37	28
CIP 10-I v1	36	25
ACCU-CAP™	36	26
Button	23	24

literature. We can quote Lamont Moore *et al.* (1990), Perrault *et al.* (1996, 1999), Martin and Zalk (1998), Tatum *et al.* (2001), and Harper and Muller (2002), if we limit ourselves to those in which this comparison was performed in the wood industry.

The paper by Harper and Muller (2002) compares mass concentrations obtained from personal samples taken in parallel, associating in pairs the IOM and Button samplers and the CFC. The published results reveal that the IOM sampler and the CFC measure statistically different wood dust concentrations. The same observation is made for the IOM and Button samplers. On the other hand, the Button sampler and the CFC measure statistically similar wood dust concentrations. Mean and median IOM/CFC ratios are 5.5 and 3.3, respectively [data calculated from Table 1 in the Harper and Muller (2002) paper]. Similarly, the mean and median Button/CFC ratios are 0.93 and 0.87, respectively [data also calculated from Table 1 in the Harper and Muller (2002) paper].

In the study by Tatum *et al.* (2001), static samples were compared for IOM, conical inhalable sampler (CIS, a plastic version of the GSP), 7-hole (multi-orifice) samplers, and the CFC. In this case, the experimental design was elaborated to provide data on both the relative performance and the accuracy of these different samplers. Concentration ratios range from 0.6 to 3.7 (mean 1.85) for IOM/CFC, from 0.7 to 2.8 (mean 1.34) for 7-hole/CFC, and from 1.0 to 2.7 (mean 1.46) for CIS/CFC. For each sampler, the variation coefficient varies between 2.8 and 20% for the CFC, between 1.9 and 29.7% for the CIS sampler, between 14.4 and 52.8% for the IOM sampler, and between 11.6 and 40.6% for the 7-hole sampler. This leads the authors to suggest that CIS samplers and the CFC could be more reproducible than the IOM and 7-hole samplers.

Based on a series of 17 personal samples, Martin and Zalk (1998) show that the IOM/CFC ratio ranges from 1.8 to 4.1 (mean 2.8), when the concentration measured by the CFC is >0.5 mg m^{-3}, and from 2.1 to 71 (mean 22.9), when the concentration measured by the CFC is lower than 0.5 mg m^{-3}. The reason given for the highest values of the IOM/CFC ratio is the larger IOM sampler orifice, which makes it possible to collect projected large diameter particles. Phase contrast optical microscope observation confirms the presence of particles with diameters >100 μm in samples taken using the IOM sampler.

Perrault *et al.* (1999) have published other comparative measurements of wood dust concentration

Table 7. Regression line slope for different sampler and sampling types: combined data, static, and personal samples

Sampler	Sampler/CFC regression line slope		
	All points (CI)	Static (CI)	Personal (CI)
IOM	2.02 (1.83–2.22)	2.01 (1.78–2.26)	2.09 (1.75–2.47)
CIP 10-I v1	1.84 (1.67–2.01)	1.76 (1.57–1.97)	2.01 (1.73–2.34)
ACCU-CAP™	1.68 (1.53–1.84)	1.74 (1.54–1.95)	1.57 (1.34–1.83)
Button	1.46 (1.32–1.62)	1.54 (1.34–1.77)	1.36 (1.16–1.59)

The 95% confidence intervals (CIs) are given for the data.

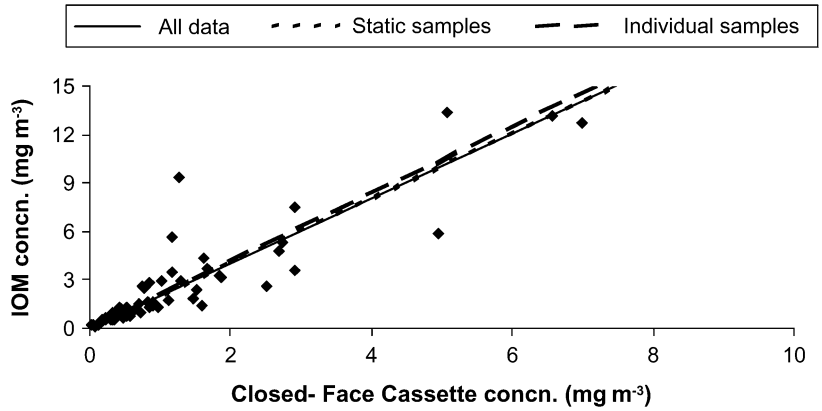

Fig. 6. Relationship between concentrations measured by the IOM sampler and the CFC.

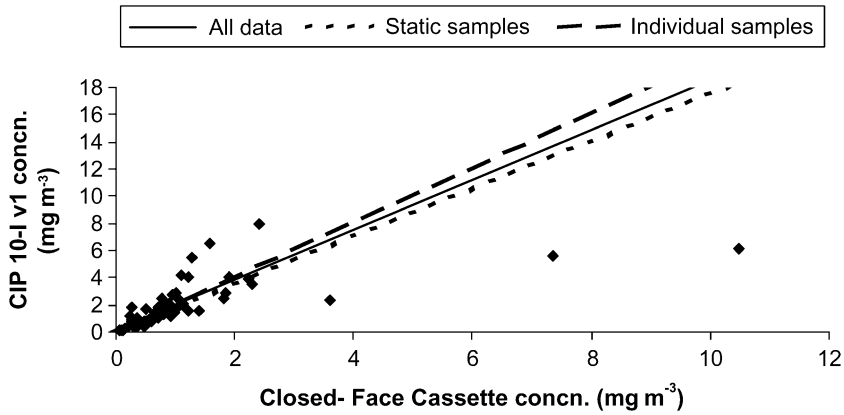

Fig. 7. Relationship between concentrations measured by the CIP 10-I v1 sampler and the CFC.

based on the IOM sampler and the CFC. These measurements correspond to samples taken in a furniture factory, three sawmills, and three paper mills. A total of 205 samples were taken. Mean values of the IOM/CFC ratio, based on sampling type (static or personal) and location, range from 2.25 to 4.29 (mean 2.75). Perrault in collaboration with other authors (Perrault *et al.*, 1996) also compared at a sawmill and three paper mills wood dust concentrations measured using a CFC, including a cap (a system probably similar to the ACCU-CAP™) and an IOM sampler. Only static samples were taken. Mean values varied between 1.86 and 3.27 (mean 2.45) for the CFC (with a cap)/CFC ratio and between 2.63 and 4.74 (mean 3.68) for the IOM/CFC ratio, depending on sampling location.

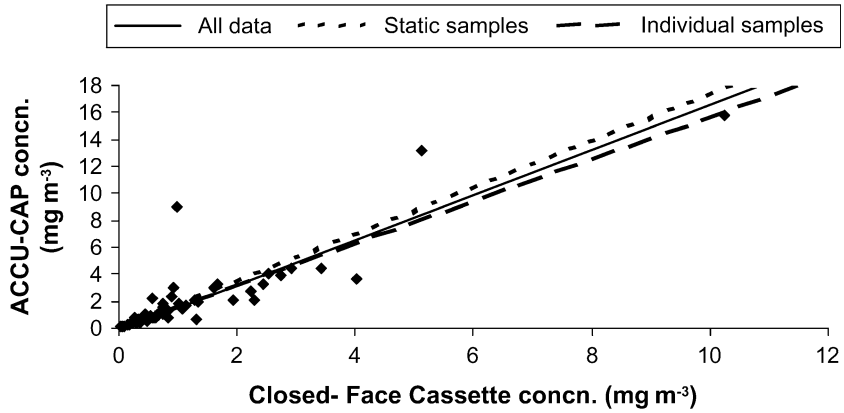

Fig. 8. Relationship between concentration measured by the ACCU-CAP™ sampler and the CFC.

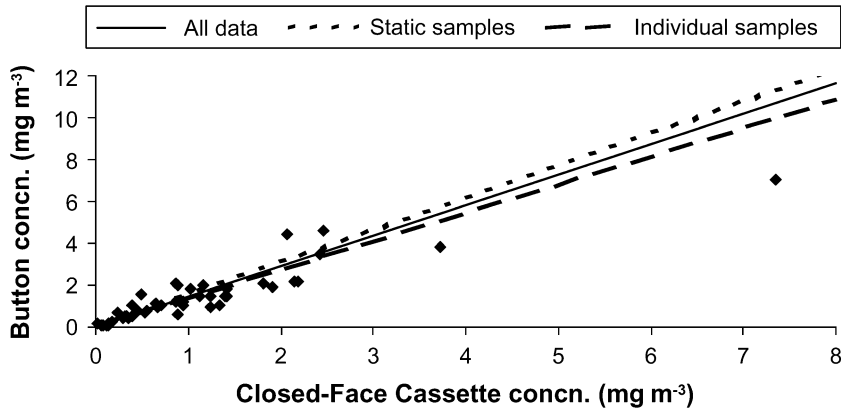

Fig. 9. Relationship between concentration measured by the Button sampler and the CFC.

Lamont Moore *et al.* (1990) have obtained another set of comparative samples. Their comparison was based on 17 personal samples taken with a CFC and a sampler marketed by MSA (cassette containing an aluminium cap). The mean concentration measured by the MSA device was 3.48 mg m^{-3} and that measured by the CFC was 1.60 mg m^{-3}, giving a value of 2.2 for the MSA cassette with cap/CFC ratio.

Table 8 consolidates the mean values for the IOM/CFC, cassette with cap/CFC, and Button/CFC ratios. The so-called cassette with cap device includes not only the ACCU-CAP™ sampler but also other devices such as the MSA cassette.

On reading Table 8, we note a high degree of variability in the ratios of IOM sampler-measured concentrations to CFC-measured concentrations quoted by different authors. The 2.02 coefficient obtained in our study lies fairly far down the variation range. There are several possible explanations for the high variability in the different research results.

The first explanation relates to sampling circumstances. Measurements were taken in different countries and industries and for different woods be worked; manufacturing processes could also differ widely.

A second explanation would be the IOM sampler's wide orifice (15 mm) compared with the CFC orifice (4 mm). Under certain circumstances (coarse particle size dust and dust source near), this wide orifice may favour inclusion of large-size directly projected particles (diameters $>$ 100 μm) in the sample. In a comparative study of particle distributions for wood dust collected by several samplers, Harper *et al.* (2004) state that particles with aerodynamic diameters exceeding 100 μm were found in 65% of samples taken with the IOM sampler, in 42% of samples taken with the CFC, and in 32% of samples taken with the Button sampler. These very large particles represent, on average, 53% of the total mass collected, although the variability around this mean

Table 8. Concentrations measured using IOM sampler, CFC with cap, and Button sampler compared with concentrations measured using the CFC

Authors	IOM sampler/CFC		Closed cassette with cap/CFC		Button sampler/CFC	
	Number of measurements	Mean ratio	Number of measurements	Mean ratio	Number of measurements	Mean ratio
Kauffer *et al.* (this study)	65	2.02	62	1.68	47	1.46
Harper and Muller (2002)	16	5.5			23	0.93
Tatum *et al.* (2001)	70	1.85				
Martin and Zalk (1998)	17	22.9[a]				
		2.8[b]				
Perrault *et al.* (1999)	54	3.68	54	2.45		
Perrault *et al.* (1996)	250	2.75				
Lamont Moore *et al.* (1990)			17	2.2		

Compilation of published results.
[a]When CFC-measured concentration < 0.5 mg m^{-3}
[b]When CFC-measured concentration > 0.5 mg m^{-3}

is itself high (10–95%). Presence of large diameter particles has also been reported by Martin and Zalk (1998), as highlighted above.

A third possible explanation concerns CFC orientation during sampling and its operating flow rate. Among all the samplers tested, the CFC and obviously the ACCU-CAP™ were the two devices that offered the most options in terms of sampler orientation. In our study, these two samplers were mounted in a special fitting to ensure that their inlet orifices were facing forward (filter in vertical plane), which is the accepted practice in France. The design of the IOM and Button samplers naturally leads their installation in this position, when fixed on an employee. Based on the observation that, in the European study (Kenny *et al.*, 1997), the inlet orifice of samplers with the lowest sampling efficiencies with respect to large particles was oriented downwards, Baron (1998) emphasizes the importance of orienting the sampler inlet orifice forward. This information is rarely available. Among the previously quoted publications, only the paper by Perrault *et al.* (1999) states that the inlet orifice of the CFC was oriented downward in their study. The effect of this downward orientation was to maximize the sampler/CFC ratio. For information, experiments conducted during the present study (see Appendix 1) revealed that a cassette with its inlet orifice oriented 45° downward collects, on average, 1.35 times less than a cassette, whose inlet orifice is oriented forward. With regard to the CFC operating flow rate (1 l min^{-1} was used during this study, while 2 l min^{-1} is most frequently used), the experiments described in Appendix 1 show that there is no influence on concentrations measured within the 1–2 l min^{-1} range.

There are fewer references comparing wood dust concentrations measured using the CFC with those obtained using a cassette with a cap or the Button sampler. Concentrations measured, when a cap is used, are approximately twice as high as when a conventional cassette is used, which shows that inclusion of wall deposits does significantly alter the measured concentrations. There is less variability in the CFC with cap/CFC ratio (1.68–2.45, Table 8) than in the IOM sampler/CFC ratio. This may be due to the smaller inlet orifice than that of the IOM sampler, making directly projected deposits less likely. Moreover, sampler orientation is probably less significant to the extent that the CFC and the CFC with a cap are probably similarly oriented in the same experiment. Our results show that the Button sampler collects significantly more dust than the CFC. However, these results are not confirmed by Harper and Muller (2002), although no plausible explanation is given for this.

Field results compared with laboratory results

In a companion paper, Görner *et al.* (2010) provide a description of the laboratory determination of the sampling efficiency of several devices likely to sample the wood dust inhalable fraction, depending on the aerodynamic diameter of particles in both moving (1m s^{-1}) and calm air. These devices are mainly the same as those studied in the present study (IOM, CIP 10-I, ACCU-CAP™, and Button). However, for the CIP 10-I sampler, versions v1 and v2 of the device were investigated in the laboratory, while evaluation of the CIP 10-I sampler with the CALTOOL system or its comparison with the CFC in the field study only involved version v1 of CIP

10-I sampler because an insufficient number of version v2 was available.

Data comparing the concentrations measured using the different samplers with the concentration measured using the CFC (concentration ratios) are consolidated in Table 9 to further the discussion on comparing results obtained in the laboratory and in the field. The slopes of the regression lines included in Table 7 have been recorded for all samples (static and personal) taken during the field study. The data shown for the laboratory study correspond to measurements taken in both moving air and calm air [from Table 3 in Görner *et al.* (2010), this issue]. The field and laboratory measurements are in fact complementary. The laboratory measurements allow us to compare the efficiency of the different samplers with the inhalable fraction conventional efficiency curve for moving air (CEN, 1993; ACGIH, 1994-1995; ISO, 1995) or the efficiency curve proposed by Aitken *et al.* (1999) for calm air. The field measurements allow us to adjust the laboratory results by taking into account the specific type of dust or ventilation conditions in a given industry.

Overall, these data show that the results obtained in the field are closer to the laboratory data for calm air experimental conditions than for moving air experimental conditions. This would seem logical to the extent that the air velocities measured in the field were low (accurate to a few tenths of a metre per second).

Only version v1 of the CIP 10-I sampler was compared with the CFC in the field. Unlike the other samplers, sufficient numbers of version v2 (Görner *et al.*, 2010, this issue) were in fact unavailable at the time for comparison with the CFC. CIP 10-I versions v1 and v2 could nevertheless be directly compared in the field. In this case, the results included in Appendix 2 show that no difference between the two versions of the sampler is observed for the specific case of wood dust. We might therefore consider that, if the CIP 10-I version v2 could have been compared with the CFC, the results would have been identical to those obtained for version v1. However, the laboratory results for the two versions were fairly different for both moving air and calm air. The reason for the differences of the two CIP 10-I's behaviour between laboratory and field measurements may be due to different particle size distribution between laboratory and field measurements, laboratory data being collected over a biggest range of particle size than the field data. The difference in behaviour of the two CIP 10-I versions during the field study and during the laboratory study may also be due to the type of dust collected. The two CIP 10-I versions have different dust transmission systems between their aspiration slots and collection devices as detailed in Görner *et al.* (2009). In the laboratory study, glass microspheres were used in the different tests. In the CIP 10-I version v1, whose design favoured wall deposition, it was probably more difficult for the airflow to re-entrain these glass particles in suspension once they had been deposited than wood particles, which catch the air stream more readily because of their morphology. The morphology of wood dust particles is very irregular and offers a large surface to the air stream, which facilitate the removing of the particles previously deposited on the sampler inner wall.

Table 9. Ratios of concentrations measured using different samplers and the CFC during the Field study and for laboratory study experimental conditions (Moving air and Calm air)

Sampler	Ratio of concentrations measured using sampler and CFC		
	Field study	Laboratory study	
		Moving air	Calm air
IOM	2.02	1.57	2.21
CIP 10-I v1	1.84	1.06	1.25
CIP 10-I v2		1.48	1.81
ACCU-CAP™	1.68	1.23	1.46
Button	1.46	1.19	1.88

Concerning the CIP 10-I sampler, again, the laboratory measurements revealed that the responses of its version v2 and of the IOM sampler were similar for measurements taken in moving air, yet much more dissimilar for measurements taken in calm air. The explanation offered by Görner *et al.* (2010) for these differences would be the presence of the CIP 10-I protective cowl, which masks part of the circular orifice. This effectively reduces the sampling efficiency for the largest particles in strictly calm air, in which these particles move from vertically downward under laboratory conditions. This difference in the behaviour of the IOM and CIP 10-I samplers is not encountered in the field, when they are compared with the CFC. Clearly, the movement of all particles is different to the prevalent behaviour during the laboratory study in this case.

The particular morphology of wood dust may also explain the differences in Button sampler behaviour under calm air conditions in the laboratory and in the field, when this device is compared with the CFC (ratio 1.46 compared with 1.88, Table 9). We may in fact consider that, in this case, the multiple orifices

on the Button sampler surface (∼400) encourage more the deposition of highly irregular particles, such as wood dust, than that of spherical particles, such as glass microspheres. This would effectively reduce its efficiency when sampling wood dust.

CONCLUSION

The results obtained show that compared to the CALTOOL mouth, which can be considered to be representative of the exposure of a person placed at the same location under the same experimental conditions, the concentrations measured by the IOM, CIP 10-I v1, and ACCU-CAP™ samplers are not significantly different (respectively, 1.12, 0.94, and 0.80 compared to 1.00), the Button sampler (0.86) being close to the ACCU-CAP™ sampler. Of course this evaluation has to be weighted by the limited data obtained during this study. The accumulation of data by others authors will only make a better discrimination possible.

Ratios of the concentrations measured by these samplers to the concentration measured by the CFC turn out to be close (2 to 1.5). All the samplers studied collect systematically more dust than the CFC (2.0 times for the IOM sampler, 1.84 times for the CIP 10-I v1 sampler, 1.68 times for the ACCU-CAP™ sampler, and 1.46 times for the Button sampler). The IOM sampler has been most often compared with the CFC in the literature. The published results usually reveal greater differences with respect to the CFC than those obtained during our study. Two explanations have been advanced concerning this difference. The first is the inclusion of large directly projected particles, when sampling with the IOM device. This possibility, which is favoured by the wide IOM sampler orifice, is all the more probable when the sample is taken near to the dust source. The second explanation is associated with CFC orientation during sampling. The more the CFC is oriented downward, the greater the difference with respect to the IOM sampler.

When comparing laboratory and field studies, differences are inevitable. The advantage of laboratory studies is to take into account precisely a lot of different parameters but at the expense of idealized conditions such as uniform airflow and uniform aerosol concentration. Field studies allow us to adjust the results obtained, when considering the specific type of dust for a given industry. Possible explanation has been given to explain differences observed in the behaviour of different samplers between the laboratory (Görner *et al.*, 2010) and the field study, especially for the CIP 10-I and Button samplers.

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APPENDIX 1

Influence of CFC flow rate and orientation on measured concentration

An experiment was conducted in one of the wood industry factories visited during the study to examine the influence of CFC flow rate and orientation on the measured concentration. For this experiment, a specially designed device took simultaneously 18 static samples. Figure A1 provides a diagrammatic view of this device comprising two aluminium bars spaced at 13 cm and positioned ∼160 cm above the floor.

A single pump (VCA15 model made by Rietschle, Schopfheim, Germany) connected to a series of critical orifices delivered the sampling flow; each sampling head being connected to one critical orifice or to two such orifices combined to ensure the nominal sampling flow rate of 1 or 2 l min^{-1}.

Three different types of sample, identified by the letters A, B, or C were collected. Sampling characteristics were as follows:

A—Flow rate 1 l min^{-1}. Cassette inlet orifice positioned along a horizontal axis (filter in vertical plane).

B—Flow rate 1 l min^{-1}. Cassette inlet orifice positioned at 45° (cassette oriented downward).

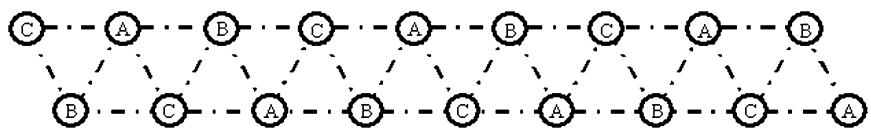

Figure A1. Experimental device used.

C—Flow rate 2 l min^{-1}. Cassette inlet orifice positioned along a horizontal axis (filter in a vertical plane).

The experiment described was repeated twice. The concentration measured by each cassette was divided by the mean concentration derived from the 18 sampling cassettes to standardize the results for each experiment (three in all). A total of 54 relative concentrations around the value 1 were obtained. If we now calculate the relative concentrations for each type of sample, we obtain the following results:

A—mean concentration = 1.06, confidence interval = 0.93–1.19
B—mean concentration = 0.81, confidence interval = 0.76–0.86
C—mean concentration = 1.13, confidence interval = 1.07–1.20

These results show that:

- there are no significant differences between Type A and Type C samples. The difference in flow rate (1 or 2 l min^{-1}) has no effect on the measured concentration.
- Type B samples are significantly different to Type A or Type C samples. Cassette orientation has an influence on the measured concentration. A cassette oriented downward (at 45°) samples on average 0.74 of the concentration measured by a cassette with its inlet orifice positioned horizontally.

APPENDIX 2

Comparison of CIP 10-I sampler versions v1 and v2

It was version v1 of the CIP 10-I (CIP 10-I v1) sampler that was compared with the CFC in the field study and it was both versions v1 and v2 (CIP 10-I v1 and CIP 10-I v2) that were studied in the laboratory programme (Görner *et al.*, 2010, this issue). Version v2 of this sampler could not be used in the field because an insufficient number of these devices were available. However, a prototype was available and this enabled us to undertake limited comparison of versions v1 and v2.

In all, 36 sample pairs (CIP 10-I v1 and CIP 10-I v2) were taken and these were divided as follows:

- 18 static sample pairs (Factories A to F).
- 18 personal sample pairs (Factory G).

Figure A2 illustrates the relationship between the concentrations measured using the two CIP 10-I versions (v1 and v2).

One point plotted as a square is obviously separated from all the other points on this graph. This untypical point represents a personal sample. A possible, but as yet unconfirmed, explanation for this anomaly is that one of the CIP10-I samplers was partially covered by the employee's work jacket. This hypothesis is all the more plausible since these samples were taken in January, when it was cold. If we exclude this point, the regression line gradient is then calculated at 0.99 and the upper and lower limits of the 95% confidence interval are 0.93 and 1.06, respectively. The sampling error determined using the statistical model is 13% (see the data processing section).

Unlike the experiments conducted in the laboratory, these field tests show that the two CIP 10-I sampler versions (v1 and v2) are equivalent for the specific case of wood dust. It is therefore reasonable to consider that the derived relationships between the concentrations measured using version v1 of the CIP

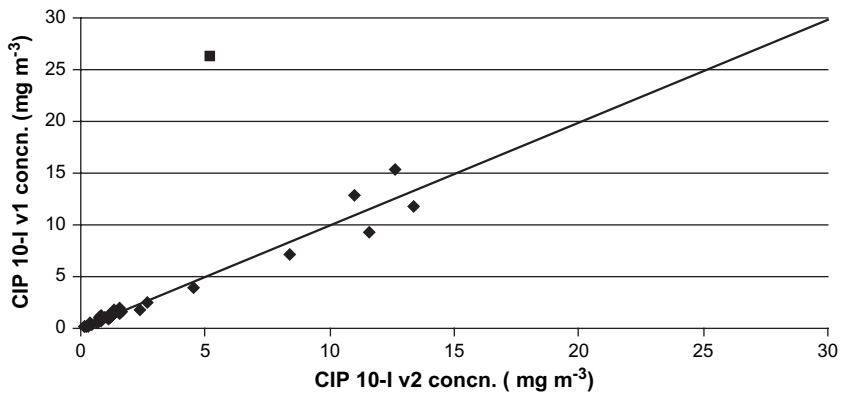

Figure A2. Relationship between concentrations measured by the two CIP10-I versions.

10-I sampler and the other samplers would be identical for the CIP 10-I version v2 sampler when used in the wood industry.

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