

Workshop Announcement
Calibration Standards for Indoor Material/Product Emissions Assessment

The National Institute of Standards and Technology (NIST) and ASTM are co-sponsoring a workshop on Calibration Standards for Indoor Material/Product Emissions Assessment. The purpose of this workshop is to discuss the current state of building material and product emissions testing, the sources of emission testing inconsistencies, and potential strategies to improve measurement reliability. Specific topics to be discussed during the workshop will include current emissions testing calibration methodologies and associated standardization needs, sources of emissions testing uncertainties, and development of reference materials for assessment of chamber performance.

For more background regarding product emissions testing variability, I've attached a paper titled "Developing a Standard Reference Material for VOC Emissions Testing" that was recently presented at the Environmental Protection Agency/Air & Waste Management Association's *Conference on Indoor Environmental Quality: Problems, Research and Solutions*. This NIST/ASTM workshop will also serve as a follow-up meeting to the Environmental Protection Agency's Green Building Products Forum that was held in Research Triangle Park, NC on July 19, 2006.

The NIST/ASTM workshop will be held at the Hyatt Regency in Atlanta, Georgia during ASTM's Committee Week on Monday, October 23, 2006 (1:30 pm to 5:30 pm). Participants will include representatives from industry, commercial testing laboratories, product labeling programs, government agencies, academia and other stakeholders interested in product emissions testing.

For more information, please contact Cindy Reed at (301) 975-8423, chreed@nist.gov or Andy Persily at (301) 975-6418, andrew.persily@nist.gov. Additional information on the workshop and the general ASTM meeting can be found on the ASTM website (www.astm.org) under committee D22.

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Developing a Standard Reference Material for VOC Emissions Testing

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ABSTRACT

Manufacturers of building materials and furnishings are increasingly using emission rate testing to demonstrate low volatile organic compound (VOC) emissions from their products and to qualify for “green” certification/labeling programs. To date, however, there are no consensus U.S. standard test methods applicable to these measurements. There are several guides, such as ASTM D 5116 Standard Guide for Small-Scale Environmental Determinations of Organic Emissions from Indoor Materials/Products, which provides useful information regarding the measurement of VOC emission rates in small chambers, but not a specific procedure to produce a test result. Nor does it address all of the quality assurance issues specific to the determination of emission rates. As a result, there are significant inconsistencies in VOC emission rate results between different testing laboratories. The limited “round robin” testing that has been completed to date has revealed wide variations in the measurement results (coefficient of variation often greater than 40 %). To address these interlaboratory discrepancies, the National Institute of Standards and Technology (NIST) is starting a project to develop reference materials and associated test methods for calibration of VOC emission rate test facilities. The first phase of this project, and the focus of this paper, includes the identification of issues facing the consistency of small-scale chamber emissions testing and important characteristics of a reference material. The development of such reference materials and standard test methods have the potential to significantly improve competitiveness in the building materials and products industries as well as commercial test laboratories and will potentially improve consumers’ quality of life.

INTRODUCTION

Indoor air exposure to the volatile organic compounds (VOCs) present in thousands of indoor materials and products (*e.g.*, paints, flooring materials, wood products, *etc.*) has been linked to a number of adverse health effects, including upper respiratory irritation, neurological symptoms, and cancer¹ as well as reduced productivity.² Reducing the emissions of VOCs indoors has the potential to save the U.S. billions of dollars in reduced healthcare costs and improved worker productivity.³ As a result, there is increasing government and market pressure on U.S. manufacturers to monitor and reduce the emissions of VOCs from their products. In 1989, the State of Washington required emissions testing for all products to be used in a state office building being built in Olympia.⁴ Since then, several government agencies have increased regulations regarding the procurement of products that may emit VOCs.⁵⁻⁷ In recent years, there has also been an emergence of several “green” certification/labeling programs targeting products that emit VOCs.^{8,9}

To verify low VOC emission rates for their products and qualify for “green” certification/labeling programs, manufacturers have them tested in commercial laboratories.

Often, these laboratories conduct emissions tests on portions of products in small scale chambers with environmental conditions similar to a real building. To date, however, there are no consensus standard test methods developed by voluntary consensus standard bodies for measuring VOC emission rates in small test chambers, which has resulted in significant inconsistencies in VOC emission rate results between different testing laboratories. Even in round robin tests with a prescribed test method, there have been wide variations in VOC emission profiles with no indicator of accuracy.¹⁰⁻¹²

To address these interlaboratory discrepancies and improve the consistency of product emissions testing, the National Institute of Standards and Technology (NIST) has started a project to develop reference materials and associated test methods for calibration of VOC emission rate test facilities. This past year, NIST started the initial research phase of the project by consulting with several materials and indoor air experts from other NIST laboratories, several universities, U.S. Environmental Protection Agency, product manufacturers and commercial emissions testing laboratories. These discussions resulted in the identification of important emissions testing issues and potential approaches to developing reference materials, both of which are discussed in this paper. The next phase of this project will be the production of prototype reference materials and associated test methods. These prototypes and test methods will be first validated in NIST's stainless steel small-scale chambers and later by other test laboratories in a round robin test. Once validated materials and methods are available, NIST will work toward incorporating them into ASTM's D22.05 VOC emissions standards.

CURRENT STATE OF CHAMBER TESTING

VOCs are present in thousands of building materials and products used indoors. However, VOC content alone is not an accurate indicator of inhalation exposure. Many VOCs are contained in materials of varying porosity or diffusion properties, thereby limiting their release rate to indoor air. Other materials have dynamic VOC emissions profiles that depend on a room's environmental conditions. As a result, chambers are often used to measure the VOC emission rate of different materials. However, the emission rate is not directly measured, but rather determined empirically using a mass balance equation on the test chamber. As shown in Figure 1, the VOC concentration in the chamber (C) depends on the chamber volume (V), airflow rate through the chamber (Q), VOC concentration in ventilation air (C_{vent}) and the material emission rate (ER).

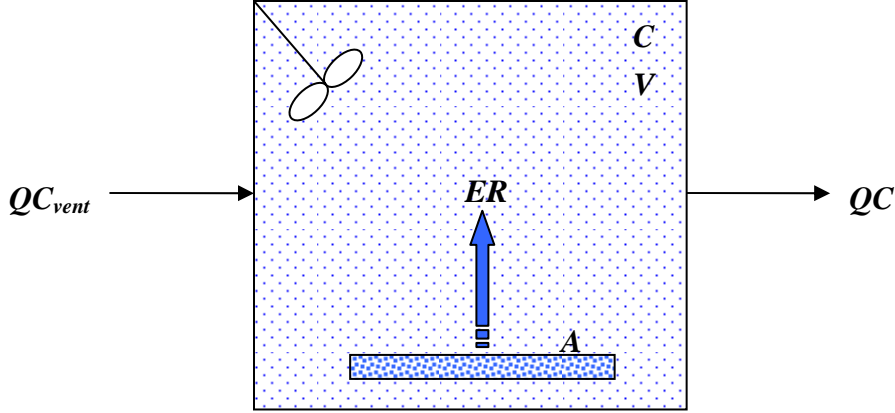


Figure 1. Emissions chamber mass balance parameters.

A contaminant mass balance on the chamber in Figure 1 for a single VOC, assuming a uniform contaminant concentration in the chamber and no sink losses is:

$$\frac{dCV}{dt} = QC_{vent} + ER - QC \quad (1)$$

where,

C = VOC concentration in chamber air (mg/m^3)

V = chamber volume (m^3)

t = time (h)

Q = airflow rate through chamber (m^3/s)

C_{vent} = contaminant concentration in ventilation air (mg/m^3)

ER = emission rate (mg/h).

Given that the chamber volume is constant and the ventilation air VOC concentration is usually negligible, Equation 1 simplifies to:

$$\frac{dC}{dt} = \frac{ER}{V} - NC \quad (2)$$

where

N = air change rate in chamber ($1/\text{h}$).

For materials with a measurable surface area, the emission rate is commonly reported as the product of an emission factor (EF) and surface area (A), changing Equation 2 to:

$$\frac{dC}{dt} = L * EF - NC \quad (3)$$

where

EF = emission factor ($\text{mg}/\text{m}^2 \cdot \text{h}$)

$L = \frac{A}{V}$ = loading factor (m^2/m^3).

It is possible to directly measure L , C , and N . Depending on the emission profile of the material and the number of concentration data points collected, different calculation techniques may be used to estimate the emission rate.¹³⁻¹⁵

A material's emission rate or emission factor is dependent on several mass transfer processes including diffusion within the material, desorption, and evaporative mass transfer. A diffusion-controlled source is limited by the movement of contaminants within the material boundaries. The rate of diffusion depends on the diffusivity of the VOC, temperature and structure of the material. An evaporation-controlled source is limited by a contaminant's ability to transfer from the material surface through a boundary layer to the surrounding air. The rate of mass transfer at the surface is dependent on VOC volatility, and air velocity and turbulence near the material surface. The dominating process depends on the age and type of material. For example, VOC emission rates from so-called "dry" materials (*e.g.*, carpet, tile, wallboard, *etc.*) are initially affected by mass transfer resistance,¹⁶ but are ultimately controlled by diffusion processes. The VOC emission rates from so-called "wet" materials tend to be more dynamic than dry materials with a high initial emission rate. The initial emission rate is primarily controlled by evaporation. Once the material has dried, the emission rate is controlled by diffusion processes as discussed above for dry materials.¹⁷

Knowledge regarding chemical and material properties does allow one to fundamentally predict emission rates using mass transfer models. For example, Cox *et al.*¹⁸ have successfully predicted the emission rate of contaminants from vinyl flooring using independently measured values of the initial material-phase concentration, the material phase diffusion coefficient, and the material/air partition coefficient. This approach, however, has only been applied to a limited number of materials, still making the empirical solution based on Equations 2 and 3 the most commonly used method to evaluate a material's VOC emission potential.

Emissions Test Method Issues

Although there are no standard test methods for measuring material emission rates in small-scale chambers that have been developed by a voluntary standards body using consensus approaches based on the elements of openness, balance of interest and due process,¹⁹ there are several emission testing guides.²⁰⁻²⁴ Chamber emissions testing involves several different protocols: sample preparation, setting chamber conditions, sample collection, and sample analysis. Differences in these protocols can have a significant effect on emission rate results.

Sample Preparation

Typically a portion of a material is used in small-scale chamber tests when measuring emission rates, with a loading ratio (L) similar to that in a real building. If a material is cut to meet this criterion, the resulting edges may have different material characteristics than the original material. As a result, cut edges are generally sealed with an inert material. Other potential issues for dry materials include product history, product age at time of testing, methods for pre-test

conditioning, and material contamination prior to testing. Wet materials are typically applied to a substrate prior to chamber testing. This process can result in uneven material application as well as significant pre-test losses from highly volatile compounds (Guo *et al.* 1996).¹³

Chamber Conditions

The mass transfer processes controlling material emission rates are affected by several indoor environmental conditions. To represent indoor conditions of a real building, test chambers are often operated at similar values.

For example, air temperature has been shown to have a significant effect on VOC emission rates, based on the dependence of a VOC's volatility and diffusivity on temperature.²⁵⁻²⁷ As temperature increases, so do the VOC mass transfer rates due to diffusion, desorption or evaporation. A commonly used temperature set point for chamber testing is 23 °C²⁸ with an associated precision and accuracy of ± 0.5 °C.²⁰

High levels of relative humidity can impact the emissions of water-soluble compounds, for example formaldehyde.^{25,27,29} A commonly used relative humidity set point for chamber testing is 50 %²⁸ with an associated precision of ± 5.0 % and accuracy of ± 10 %.²⁰

The air change rate of a test chamber is defined as “the flow rate of clean, conditioned air into the chamber divided by the chamber volume”²⁰ and characterizes the amount of air removing contaminant from a given space. VOC concentrations will therefore be lower for higher air change rates. The test chamber air concentration can in turn affect the rate of VOC evaporation from a given material as it provides resistance to that process. The greater the concentration difference between the material surface and the chamber air, the greater the evaporation rate.

Air velocity and turbulence are other factors that affect a material's evaporation rate by changing the resistance of the boundary layer between the material surface and the room air. At higher air velocities, and hence greater turbulence, the boundary layer resistance is reduced resulting in greater emissions. This effect, however, does have a threshold such that air velocities greater than a certain value will result in similar mass transfer rates.²⁰ Air velocities in residential indoor environments and many commercial buildings³⁰ tend to be lower than this threshold.²⁰ Air velocity also often varies substantially between chambers used in different laboratories.¹³

In general, chambers consist of non-adsorbent low-emitting smooth interior surfaces (*e.g.*, stainless steel and glass). However, a chamber's surfaces may still remove VOCs of lower volatility and VOCs with similar polarity to the surface material. These sink losses are not accounted for in the above mass balance (Equation 1). Several studies measuring the mass recovery in a chamber have explained poor results with such sink effects.³¹ Other chamber issues include mixing and leaks. Often chambers use mixing fans or multiport inlet and outlet diffusers to mix the air and contaminants. Short-circuiting or stagnant zones will reduce the effective chamber volume involved in the mass transfer processes, thereby affecting the emission rate calculation. Of course, use of mixing devices can also affect the air velocity and turbulence in the chamber.

Sample Collection

Contaminants emitted into a chamber during an emissions test are typically actively collected using a pump and solid sorbent. There is not a single sorbent available today that can effectively capture all possible VOCs emitted from building materials and products. As a result, different sorbents are required for different contaminants. The most commonly used method for collecting samples is 2,6-diphenyloxide sorbent material,³² which is best for non-polar VOCs. Other sorbents include activated carbon and molecular sieves.^{33,34}

Analytical method

Typically, the accuracy of a laboratory's analytical equipment is sufficiently high for the purpose of measuring concentrations for emission rate determinations. However, analytical instruments need frequent calibrations and can rarely be calibrated for all emission compounds. There are also inconsistencies in the analytical method that can cause variance between laboratories. Most emission test laboratories use a gas chromatograph with flame ionization detector (GC/FID) or gas chromatograph with mass spectrometer (GC/MS).³² As with the sample collection sorbents, a single detector cannot effectively measure all contaminants that may be present in an emissions test. For example, a GC/FID is effective for carbon based compounds and not as effective for chlorinated and oxidized compounds.³²

ROUND ROBIN TESTS

The primary issue facing manufacturers, commercial test laboratories and ultimately consumers is the lack of consistency for material emissions testing. Not all test chambers and analytical systems are alike, and there are no consensus test standards available for small scale chambers. As a result, different test laboratories often measure different emission rates for the same materials. These discrepancies have been highlighted in several round robin tests,^{10-12,35} results of which are summarized below and in Table 1 and Figure 2.

Two large round robin chamber studies have been led by the European Commission Joint Research Center.^{10,11} Table 1 provides a summary of each small-scale chamber round robin study. In the first study,¹⁰ the emission rate of three different materials was measured using 24 chambers in 20 different laboratories. The test materials included a diffusion vial with n-dodecane, PVC flooring tile, and a liquid, water-based floor wax. A limited number of prescribed test conditions were provided to participants for the study; however many procedures were still at the discretion of the participants. For the n-dodecane vial source, laboratories measured chamber concentrations at 24 h, 48 h, and 72 h, from which they calculated an emission rate at each sampling time. For this source, an emission rate was also determined based on an independent weight loss measurement. The percent coefficient of variation (% CV) between the different laboratory emission rates was 59 % at 24 h, 46 % at 48 h and 49 % at 72 h. The % CV for the emission rates measured independently by weight loss was 46 %. There was also large variation between emission rates measured by chamber and weight loss within several of the laboratories, indicating a mass recovery problem for those laboratories. Two tile samples were sent to each laboratory for analysis of the emission rate of phenol, 1,2,4-trimethylbenzene, n-decane, n-undecane, and total VOCs (TVOC). Again, there was wide variation in results with % CV ranging from 26 % to 42 % for the different contaminants and measurement times (see Figure 2). In addition to possible interlaboratory analytical and chamber differences, heterogeneity of the material was blamed for the variance. Finally, the floor wax emission rates

measured by the different laboratories showed the largest discrepancies. The emission factors predicted at 1 h using the source decay model for TVOC concentration data, ranged from $0.08 \mu\text{g}/\text{m}^2\cdot\text{h}$ to $25000 \mu\text{g}/\text{m}^2\cdot\text{h}$, with an average emission factor of $5100 \mu\text{g}/\text{m}^2\cdot\text{h}$ (% CV = 140 %). Possible reasons for these discrepancies include variations in wax application to the substrate and in chamber air velocities.

The Joint Research Centre – Environment Institute conducted a follow-up round robin study to address differences in the first round robin study and thus lower the variances between laboratories.¹¹ Initially, the sampling and analytical capability of the 18 laboratories participating in this round-robin were compared. One method compared analytical capabilities using liquid solutions of known concentration. Another method required each participating laboratory to collect and analyze an air sample from a Joint Research Centre chamber that was at a known concentration. Results showed several laboratories to exceed a ± 50 % difference from the known reference value, clearly indicating that analytical errors are a significant contributor to the overall variance between laboratories. This second study also included a quality check of mass recovery for each test chamber by emission of a specific contaminant whose weight loss was also measured. Results showed 5 of the 9 chambers tested to not meet the study criteria of > 80 % mass recovery. These discrepancies could be attributed to the sampling and analytical method or to sink losses in the chamber. In addition to quality checks, the round robin study included small chamber emission tests of the following three different materials: carpet, PVC flooring, and latex paint. Test method specifications were given for temperature, relative humidity, air velocity, and ventilation rate. For contaminant samples collected at 24 h, the mean % CV of the emission rate of the different compounds ranged from 21 % to 90 % for carpet, 24 % to 87 % for the PVC flooring, and 27 % to 77 % for the paint. Interestingly, the % CV of the wet material in this study improved dramatically from the % CV for the wet material in the first round robin study, verifying the importance of using a consistent air velocity for a wet source as has been indicated by other researchers (Zhang *et al.* 1996).³⁶ However, there was no significant improvement in the interlaboratory % CV for the dry materials. As shown in Figure 2, the % CV for phenol emission rates from PVC flooring doubled in the second study. There was also no noticeable trend in the % CV for emission rates measured at different time periods.

Discrepancies have also been noted in some smaller round robin studies. For example, researchers at the Institute of Maritime and Tropical Medicine in Poland conducted two round robin studies to compare the analytical capability of 9 laboratories and the emission rate measurements in small test chambers of 11 laboratories.¹² To test analytical capabilities, a known concentration of formaldehyde in water was analyzed by each laboratory with % CVs ranging from 4.4 % to 15.2 %. These relatively small interlaboratory differences indicated the analytical methods to be reasonably consistent across laboratories. The second study involved the measurement of formaldehyde emissions from a mineral wool board in a small test chamber with prescribed test conditions for temperature, relative humidity, air change rate and loading factor. Two runs were conducted with emission factors measured at 24 h and 28 h. Despite the apparent analytical consistency between laboratories, the associated interlaboratory % CVs ranged from 57 % to 67 %. The significant variation between laboratories was attributed to the deviation of chamber conditions and sample collection.

An earlier interlaboratory comparison study of formaldehyde emissions was conducted by Matthews *et al.*³⁵ This study produced much more consistent interlaboratory results, but only included two laboratories with small-scale chambers. In addition, prior to material testing, the two participating laboratories underwent several interlaboratory calibrations of methods and monitoring equipment. Two particleboard specimens were tested in each laboratory at specified chamber conditions. The average percent difference between the two laboratories was 9.0 % based on 8 tests (% CV = 2.0 %)

A summary of all the small-scale round-robin chamber % coefficient of variations is provided in Figure 2. Perhaps the most striking trend of Figure 2 is the number of % CV greater than 40 %. In fact, all but three of all contaminant/material emission rate % CV values are greater than 20 %. Confounding the problem of relatively high variation in emission rate results is the fact that there is no way to know which test laboratory is the most accurate. As a result, the accuracy and reliability of current emission rate measurements is limited. Most of the round robin studies blamed part of the emission rate variation on sampling or analytical methods, which in some cases were independently checked. The variation in these methods can also be detected by the range of % CVs for the different chemicals measured in an individual study. Another significant finding from the round robin studies is the importance of using a consistent chamber air velocity for wet material tests. When the air velocity was allowed to vary between laboratories, the % CV was as high as 284 %. However, a second wet material test with more consistent air velocities across the laboratories yielded variations similar to the variations in dry material tests. Not surprisingly, a more consistent air velocity did not appear to significantly affect dry material emission rate variation. The study with the lowest % CV of 2.0 % included a rigorous pre-test calibration protocol to ensure consistent chamber conditions and sampling/analytical techniques were being used. It was not uncommon for other round robin studies to report that not all participating laboratories were able to comply with the prescribed chamber conditions.

Table 1. Summary of round-robin small-scale chamber testing.

Study	# of Labs (Total # of chambers)	Chamber Sizes (m ³)	Prescribed Chamber Test Conditions					Test Materials	Requested Pre-Test QA Checks
			T (°C)	RH (%)	Vent. Rate	Air.Vel. (m/s)	L (m ² /m ³)		
ECA (1993) ¹⁰	20 (24)	3.5 x 10 ⁻⁵ to 1.5	23	45	1.0/h	n/a	0.4	Solvent in vial PVC flooring Floor wax	None
De Bortoli <i>et al.</i> (1999) ¹¹	18 (24)	3.5 x 10 ⁻⁵ to 1.0	23±1	50±5	1.0 m ³ /m ² *h, 2.5 m ³ /m ² *h	0.2	n/a	Carpet PVC flooring Latex paint	Analytical check by direct injection; Sampling/analytical check by collecting and analyzing air sample from single chamber; chamber mass recovery check
Wiglusz <i>et al.</i> (1999) ¹²	11 (11)	0.2 to 0.6	23	45	1/h	n/a	1	Mineral wool board	Analytical check by direct injection
Matthews <i>et al.</i> (1987) ³⁵	2 (2)	0.17 to 0.21	23	50	0.09 m ³ /h, 0.45 m ³ /h, 0.6 m ³ /h	n/a	n/a	Particleboard	Joint analytical instrument calibration

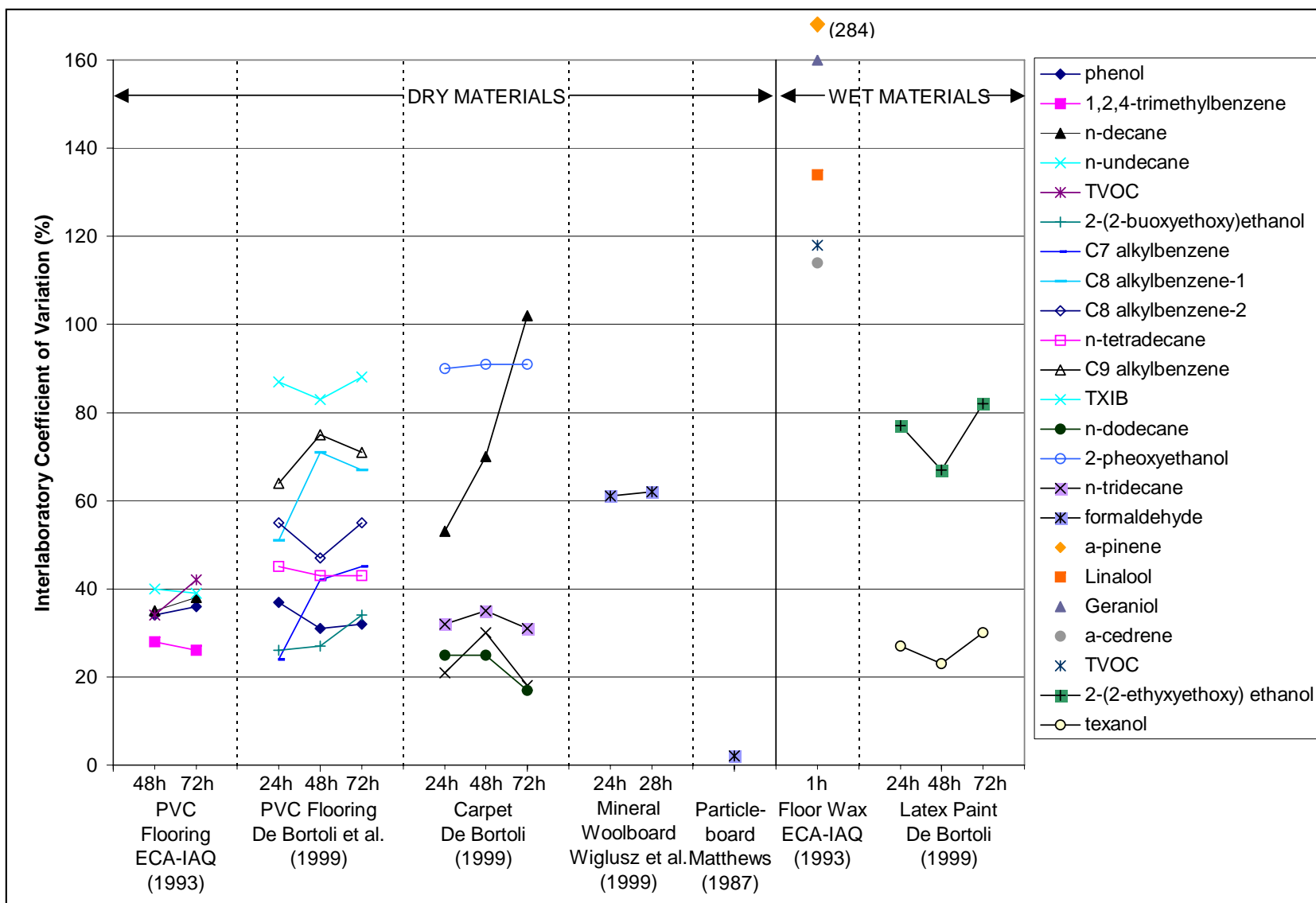


Figure 2. Interlaboratory percent coefficient of variations for four round robin studies and seven materials.

TEST CHAMBER CALIBRATIONS FOR EMISSIONS TESTS

A key finding from the round robin studies completed to date is the importance of chamber and test method calibrations. Pre-test quality assurance assessments that are used today include checking the analytical system, sample collection and mass recovery. To isolate issues with the analytical system and method, it is possible to directly inject compounds at a known concentration or to use sample sorbent tubes already spiked with contaminants. With an accurate analytical system, it is possible to check the sample collection technique by sampling from an atmosphere of known concentration. Chamber mass recovery tests may be used to assess the chamber mixing and inertness as well as sampling and analysis by comparing emission rates with known injections of contaminants²⁰ or independent weight measurements of an evaporating solvent.³⁷ In general, it is more difficult to use the solvent evaporation and weight loss method in a small scale chamber due to challenges in measuring very low values of evaporation or weight loss.

None of these checks, however, completely assess the accuracy of emissions tests in a particular test chamber and condition. For example, different laboratories can individually achieve adequate mass recovery, but still measure different emission rates due to variations in chamber conditions. In order to completely assess a test chamber/sampling/analytical system, it is necessary to use a reference source with a known emission rate for a given set of chamber conditions. To date, there are no reference sources available to conduct such an assessment.

REFERENCE MATERIAL CHARACTERISTICS

A reference material should have several characteristics to assess the accuracy of emissions test laboratories, including:

- First, the source should have an independently known emission rate for a given set of conditions over an adequate time period.
- The source should be easily reproducible with a consistent emission rate.
- The source contaminant emission rate should be affected by chamber conditions rather than be unaffected by them (*e.g.*, permeation device). The effect of chamber conditions on the reference material's emission rate should be well understood.
- The chamber conditions specified when using a reference material should at a minimum include chamber temperature, relative humidity, ventilation rate, and air velocity.
- The source should mimic the mass transfer processes of common indoor materials and products. In order to meet this criteria, a series of reference materials with different properties will be needed to represent both “wet” and “dry” materials.
- The source should be small enough to fit in most small scale chambers ($< 1 \text{ m}^3$) and still emit a measurable concentration of VOCs.
- The source should emit a range of VOCs to test both sampling and analytical capabilities.
- The source should be relatively stable and have a predictable shelf-life.

CONCLUSIONS

A significant problem facing the field of material emissions testing is the marked inconsistency between different test laboratories. The source of inconsistency stems from the range of test chambers and methods being used to measure material emission rates. Even when consistent test

methods are used, there is still a wide variation between laboratories (coefficient of variation often greater than 40 %). Adding to the problem is the fact that it is currently not possible to determine which test laboratories are the most accurate, thereby creating a frustrating situation for manufacturers, commercial test laboratories, and consumers. A reference material with a standard test protocol is one way to characterize emissions test chambers and introduce accuracy to the process. Results from this work have the potential to increase market competitiveness and improve quality of life for consumers. For example, more reliable emissions testing will potentially provide valuable information to manufacturers for product improvement and increase market competitiveness, especially internationally. More accurate and consistent testing will potentially normalize the capabilities of commercial test laboratories, thereby improving competitiveness and possibly providing the basis for an emissions testing laboratory accreditation program. Finally, improved emissions tests will strengthen green labeling programs and possibly broaden manufacturer participation, giving consumers more reliable information when deciding between products.

REFERENCES

1. Molhave L. *Indoor Air* **1991**, 4, 357 – 376.
2. Bako-Biro, Z., Wargocki, P., Weschler, C.J., Fanger, P.O. *Indoor Air* **2004**, 14, 178 – 187.
3. Fisk WJ, Rosenfeld AH. *Indoor Air* **1997**, 7, 158 - 172.
4. Brown, J.L., Sadie, S., Black, M.S. *Indoor Air Quality Specification for Washington State Natural Resources Building and Labor and Industries Building*, State of Washington Department of General Administration: Olympia, WA 1989.
5. Alevantis, L.E. *Reducing Occupant Exposure to Volatile Organic Compounds (VOCs) from Office Building Construction Materials: Non-Binding Guidelines*, Indoor Air Quality Section, Environmental Health Laboratory Branch, Division of Environmental and Occupational Disease Control, California Department of Health Services: Berkeley, CA 1996.
6. U.S. Environmental Protection Agency. *The Greening Curve – Lessons Learned in the Design of the New EPA Campus in North Carolina*; U.S. Environmental Protection Agency. 2001; EPA 220/K-02-001.
7. U.S. Environmental Protection Agency. *US EPA New Headquarters Project*; U.S. Environmental Protection Agency: Washington, D.C. 1995.
8. ECA. *European Collaborative Action Urban Air, Indoor Environment and Human Exposure, Harmonisation of Indoor Material Emissions Labelling Systems in the EU*, Report No. 24; Luxembourg. 2005.
9. U.S. Environmental Protection Agency. *Environmental Labeling Issues, Policies and Practices Worldwide*; U.S. Environmental Protection Agency, 1998; EPA 742-R-98-009.
10. ECA. *European Collaborative Action Indoor Air Quality and its Impact on Man, Determination of VOCs emitted from indoor materials and products – Interlaboratory comparison of small chamber measurements*, Report No. 13, Luxembourg. 1993.
11. De Bortoli, M., Kephanlopoulos, S., Kirchner, S., Schauenburg, H., Vissers, H. *Indoor Air*. **1999**, 9, 103 – 116.
12. Wiglusz, R., Jarnuszkiewicz, I., Sitko, E., Nikel, G. *Building and Environment*, **2000**, 35, 53 – 57.

13. Guo, Z., Tichenor, B.A., Krebs, K.A., Roache, N.F. In *Characterizing Sources of Indoor Air Pollution and Related Sink Effects*; Tichenor, B.A., Ed.; ASTM STP 1287, ASTM, 1996; 225 – 236.
14. Tichenor, B.A. (1996 In *Characterizing Sources of Indoor Air Pollution and Related Sink Effects*; Tichenor, B.A., Ed.; ASTM STP 1287, ASTM, 1996; 9 – 19.
15. Zhang, J.S., Zhu, J.P., Shaw, C.Y., Zeng, J., Plett, E.G., Bodalal, A., Chen, Q., Yang, X. *Models for Predicting Volatile Organic Compound (VOC) Emissions from Building Materials*; CMEIAQ Report 3.1, National Research Council Canada.1999.
16. Xu, Y., Zhang, Y. *Atmospheric Environment*, **2003**, 37, 2497 – 2505.
17. Zhang, J.S., Nong, G., Shaw, C.Y., Wang, J.M. *ASHRAE Transactions*, **1999**, 105, 279 - 288.
18. Cox, S.S., Little, J.C., Hodgson, A.T. *ES&T*, **2002**, 36, 709 – 714.
19. Office of Management and Budget, Circular No. A-119.
<http://www.whitehouse.gov/omb/circulars/a119/a119.html#3> (accessed June 2006).
20. ASTM. *Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products. D 5116-97*. ASTM. 1997.
21. ECA. *European Concerted Action Indoor Air Quality & Its Impact on Man (EUR 13593), Guideline for the Characterization of Volatile Organic Compounds Emitted from Indoor Materials and Products Using Small Test Chambers. Report No. 8*. COST Project 613. Luxembourg: Office for Publications of the European Communities, 1991.
22. U.S. Environmental Protection Agency. *Carpet Policy Dialogue, Compendium Report*, U.S. Environmental Protection Agency: Washington, DC. 1991; EPA/650/2-91-002
23. Tichenor, B.A. *Indoor Air Sources: Using Small Environmental Test Chambers to Characterize Organic Emissions from Indoor Materials and Products*, U.S. Environmental Protection Agency: RTP, NC. 1989; EPA-600/8-89-074.
24. Matthews, T.G. *Atmospheric Environment*, **1987**, 21, 321 – 329.
25. Haghighat, F., De Bellis, L. *Building and Environment*, **1998**, 33, 261 – 277.
26. Bluysen, P.M., Cornelissen, H.J.M., Hoogeveen, A.W., Wouda, P., van der Wal, J.F. In *Proceedings for Indoor Air '96*, 1996, vol. 3, 619.
27. Wolkoff, P., Kjar, U.D., Knudsen, H.N., Nielsen, P.A. In *Proceedings for Indoor Air '96*, 1996, vol. 4, 337.
28. Molhave, L. *Atmospheric Environment*, **1987**, 21, 313 – 314.
29. Roache, N., Howard, E., Guo, Z., Fortmann, R. In *Proceedings for Indoor Air '96*, 1996, vol. 2, 657.
30. ASHRAE. *ASHRAE Fundamentals Handbook*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA. 2005.
31. De Bortoli, M., Knoppel, H., Columbo, A., Kefalopoulos, S. In *Characterizing Sources of Indoor Air Pollution and Related Sink Effects*; Tichenor, B.A., Ed.; ASTM STP 1287, ASTM, 1996; 305 – 318.
32. Hodgson, A.T. *Indoor Air*, **1995**, 5, 247 – 257.
33. ASTM. *Standard Practice for Selection of Sorbents, Sampling, and Thermal Desorption Analysis Procedures for Volatile Organic Compounds in Air. D 6196-03*, ASTM. 2003.
34. ECA. *European Collaborative Action Indoor Air Quality and its Impact on Man, Sampling strategies for volatile organic compounds (VOCs) in indoor air, Report No. 14*, Luxembourg, 1994.

35. Matthews, T.G., Wilson, D.L., Thompson, A.J., Mason, M.A., Bailey, S.N., Nelms, L.H. *JAPCA*, **1987**, 37, 1320 – 1326.
36. Zhang, J.S., Shaw, C.Y., Kanabus-Kaminska, J.M., MacDonald, R.A., Magee, R.J., Luszyk, E., Weichert, H.J. In *Characterizing Sources of Indoor Air Pollution and Related Sink Effects*; Tichenor, B.A., Ed.; ASTM STP 1287, ASTM, 1996; 184 – 199.
37. ASTM. *Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products. D 6670-01*, ASTM. 2001.

KEY WORDS

Volatile organic compounds

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