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Determination of Exposure-Response Relationships for Emissions from Building Products

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Abstract Building products have been shown to affect the perceived indoor air quality in buildings. Consequently, there is a need for characterizing the emissions from building products in sensory terms to evaluate their impact on the perceived air quality. Determining the exposure-response relationship between concentration of the emission from a building product and human response is recommended. A practical method is proposed based on an air-dilution system connected to the exhaust of a ventilated small-scale test chamber. The method was used to determine the exposure-response relationships for eight building products. For each building product, samples were placed in a test chamber. A typical room was used as a reference to calculate a building-realistic area-specific ventilation rate in the test chamber. A sensory panel assessed the immediate acceptability of polluted air at four different concentrations 3, 10 and 29 days after samples of the building products were placed in the test chambers. The exposure-response relationships show that the impact of dilution of polluted air on the perceived air quality varies between building products. For some building products it may only be possible in practice to improve the perceived air quality marginally by increasing dilution. The results of the present study suggest that for such building products, source control is recommended as the remedy for poor indoor air quality, rather than an increase of the ventilation rate.

Key words Building products; Emission testing; Exposure-response relationship; Indoor air quality; Sensory testing; Perceived air quality; Source characterization.

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Introduction

Emissions from building products have been shown to affect the perceived air quality in buildings (e.g., Fanger et al., 1988; Bluyssen et al., 1996). Therefore, a practical measuring method is needed to characterize the emissions from building products in sensory terms. The method should make it possible to rationally and economically evaluate the impact of building products on the perceived air quality. The method should be used within a system for classification or labeling of building products, e.g. the Danish Indoor Climate Labeling System (Larsen et al., 1997). Such a system will enable architects, engineers and builders to select less polluting building products and it will help manufacturers of building products to develop and produce low polluting building products. This will assist in providing a healthy and comfortable environment for building occupants.

At present, only sensory methods using human subjects are available for measurements of perceived air quality. Olfactory psychophysics, i.e. the study of the relationship between odor stimuli and odor sensation, show that for individual chemical compounds the relationship between perceived intensity and concentration varies between odorants (Cain, 1969; Berglund et al., 1971; Engen, 1982). As a consequence, the change in perceived odor intensity due to the same relative change of the concentration varies between odorants. Similarly, it has been shown for emissions from building products that exposure-response relationships between the concentration of air pollutants and perceived air quality differ between building products (Knudsen et al., 1997).

The most commonly used methods for expressing the level of odorants in the outdoor air are based on the number of dilutions necessary to arrive at absolute odor threshold, i.e. the concentration where 50% of a panel no longer detect odor (CEN, 1996; VDI, 1986; Lindvall, 1970). Some measurements have been made on indoor air (Berglund and Lindvall, 1979). Threshold values give valuable information on how difficult it is to eliminate an odor problem by dilution of the pol-

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luted air. The disadvantage of these methods is that no information is given on the perceived air quality above odor threshold. Such information is important for assessing the impact of emissions from building products on the perceived indoor air quality, since some odor from materials will probably have to be accepted in practice. To get information that enables an evaluation of both the effect of dilution and of the perceived air quality at a realistic material loading, determining the exposure-response relationship for building products is recommended (Knudsen et al., 1997). This requires assessments of perceived air quality at different concentrations. Different concentrations can be achieved by using several equally ventilated test chambers with different material loading. In practice, this will occupy too many test chambers and it will be difficult to rationally use a sensory panel if only a few test chambers are available at the same time. Therefore, it is suggested to place test samples in one constantly ventilated test chamber and obtain different concentrations by dilution of the polluted exhaust air from the chamber.

The objective of the present study was to develop an air-dilution system to be connected to a test chamber and apply it to determine the exposure-response relationships for the emissions from a series of building products.

Current practice when measuring the emission rate of volatile organic compounds (VOCs) from building products in small test chambers is to simulate in the laboratory the environmental conditions that the products are exposed to in a real room. Establishing a similar concentration of pollutants over the building product samples in the test chamber as in a typical room is recommended (Tichenor, 1989; ASTM, 1990; Nordtest, 1990; ECA, 1991). This is achieved by selecting an air exchange rate, N, and a loading (area of building product/volume of chamber), L, in the test chamber that match the values in the typical room that is simulated. The ratio N/L is used as the scaling parameter in designing test chamber experiments. The use of the scaling parameter N/L was validated experimentally, e.g., for chipboard (Myers, 1984; Nelms et al., 1986). However, the recommendation that both N and L shall match a real room is not feasible in practice when doing sensory testing in small-scale test chambers. For sensory testing an airflow rate of 0.9 L/s is recommended when a defined diffusor is used (Bluyssen, 1990; Clausen et al., 1995; Knudsen, 1994). This airflow is considerably higher than the airflow rate traditionally used for emission testing in small-scale test chambers. Therefore, if requiring that N is 1 h^{-1} and the airflow rate is 0.9 L/s at the same time it is not possible to perform experiments in test chambers with a volume less than 3.2 m^3. By requiring that both N and L shall be identical in the test chamber and in a real room, it is indirectly assumed that the volume of the chamber or room, where a building product is situated affects the emission rate of pollutants from the building product. It has been demonstrated that the size of test chambers does not affect the emission rate of pollutants (Hoetjer and Koerts, 1986; Sollinger et al., 1993; ECA, 1993). Therefore, it is reasonable to assume that, at a constant temperature and relative humidity, the primary factors that may affect the emission rate of pollutants from a building product are the concentration of pollutants in the air and the air velocity over the building product. Since the loading factor, L, is given by the ratio A/V, where A is the area of the building product and V is the volume of the test chamber or room where the building product is situated the scaling parameter N/L can be rewritten as follows:

$$\frac{N}{L} = \frac{N}{(A/V)} = \frac{N \times V}{A} = \frac{Q}{A} \tag{1}$$

where Q is the airflow rate. The ratio Q/A, i.e. the area-specific ventilation rate, describes more directly than N/L which parameters determine the concentration of pollutants in a room or in a test chamber. Therefore, it is recommended to design sensory test procedures in small-scale test chambers based on realistic values of the area-specific ventilation rate.

As described above, it is generally believed that the emission rate of VOCs is affected by the VOC concentration in the air. However, if the speed of diffusion inside the material is the limiting factor, the emission rate of VOCs will be independent of the concentration in the air. Recent studies support that it is reasonable for practical purposes, i.e., for relatively small variations of the concentration at a low level, to consider the emission rate of VOCs as being independent of variations of the concentration. This finding has been shown for a wide range of building products (Andersen et al., 1996; Wolkoff, 1998; Knudsen et al., 1998). Therefore, it seems feasible to obtain different concentrations by placing test samples in one constantly ventilated test chamber and dilute the polluted exhaust air from the chamber to different lower concentrations.

Method

An air-dilution system was designed to provide different concentrations of polluted air for sensory assessments. The system was connected to the outlet of a small-scale test chamber. Eight different building products were tested. Product samples were placed in test chambers each connected to a dilution system. The area of product samples placed in the test chambers was selected so that the area-specific ventilation rate in the test chamber corresponded to the area-specific ventilation rate in a typical room. A sensory panel assessed the immediate acceptability of polluted air at 4 concentrations for each building product. The procedure was repeated 3 , 10 and 29 days after placing the building products in the test chambers. Sample collection, test specimen preparation, specimen conditioning and handling of the sensory panel were performed in accordance with the "Protocol for testing of building materials" (Clausen et al., 1995) developed in the research program "European Data Base on Indoor Air Pollution Sources in Buildings" (Clausen et al., 1996).

Facilities for Exposure

The small-scale test chambers were of the chamber for laboratory investigations of materials, pollution and air quality (CLIMPAQ) type (Gunnarsen et al., 1994; Nordtest, 1998). This chamber is made mainly of glass with a volume of 50.9 L. The air inlets of the test chambers were connected to an external air supply system. Each test chamber was supplied with a constant airflow rate of conditioned and filtered outdoor air. The air temperature and relative humidity in the test chambers were kept constant at 23.0±0.2°C and 45±3% (mean±experimental standard deviation). The air was filtered first through a filter of class EU 5, then a coal filter of class F30/470 and finally a fine filter of class EU 7. The test chamber was operated with a slight positive pressure. The exhaust air from each test chamber was led through an air-dilution system connected to a diffusor specially designed for sensory assessments, see Figure 1.

The air-dilution system consisted of stainless steel (acid-proof, AISI 316) tubes with an inner diameter of 35 mm. Different degrees of dilution of the polluted exhaust air were achieved by mixing different flow rates of polluted exhaust air from the test chamber with different flow rates of unpolluted air. Unpolluted air in this context is conditioned and filtered outdoor air. The flow rates were regulated by varying the size of the opening in two orifice plates made of Teflon®. Two clamp rings with finger nuts for quick change of the orifice plates were mounted on the steel tubes, see Figure 1. Four sets of orifice plates were prepared. One set provided undiluted exhaust air to the diffusor. The other three sets were adjusted so that the polluted exhaust air from the test chamber was diluted in fixed steps to 1/2, 1/8 and 1/16 of the concentration in the test chamber. The diffusor was made of Teflon® covered brass. The opening had a diameter of 80 mm, the length was 430 mm and the angle was 8° (Bluyssen, 1990). To adjust and document the performance of the dilution system a tracer gas (SF_6) was dosed at a constant rate into the test chamber. The relative dilution of the exhaust air from the test chamber was determined by simultaneous measurements (Brüel and Kjær Multigas Monitor Type 1302) of the concentration of SF_6 in the diffusor and in the exhaust from the test chamber. Both the airflow rate through the diffusor and the airflow rate through the test chamber were kept constant at 0.9±0.02 L/s (mean±experimental standard deviation). A separate steel tube allowed the excess polluted exhaust air to escape to the outdoor when only a fraction of it was led to the diffusor. The air velocity over the building product samples was adjusted to be 0.1 m/s measured at a location equidistant from the product samples and equidistant from top and bottom of the test chamber. The air velocity was measured with a hot wire anemometer (DANTEC Flowmaster Type 54 N 60). The test chambers and the stainless steel tubes were cleaned before the test specimens were placed in the test chambers. They were cleaned by wiping with ethanol followed by scrubbing the inner surfaces with a solution of alkaline detergent diluted in hot tap water. They were rinsed with hot tap water, followed by a final rinse with de-ionized water. Then they were left to air dry in the main full-scale chamber, see below. During the study the test chambers were covered outside with aluminum plates to hide the building products from the view of the sensory panel.

The small-scale test chambers were situated in the air quality laboratory at the Danish Building Research Institute (Ekberg and Nielsen, 1995). The laboratory is specially designed for sensory and chemical characterization of emissions from building products. The laboratory facilities consist of two adjacent ventilated full-scale chambers. The main full-scale chamber has a volume of 96 m^3 and the antechamber has a volume of 32 m^3. The building products used for the construction of the laboratory were carefully selected to ensure a negligible emission of pollutants from the inner surfaces and a negligible sink effect. The walls and the ceilings of the laboratory consist of panes of glass mounted in aluminum frames and the floor consists of high-pressure laminated fiberboard. During this study the air quality laboratory was ventilated with conditioned and filtered outdoor air. The air exchange rate was 12 h^{-1}, the air temperature was 22.0±0.3°C and the relative humidity was 48±3% (mean±experimental standard deviation). The air quality laboratory is located in a 1800 m^3 hall, which was ventilated with an outdoor air exchange rate of 4 h^{-1}. The outdoor air

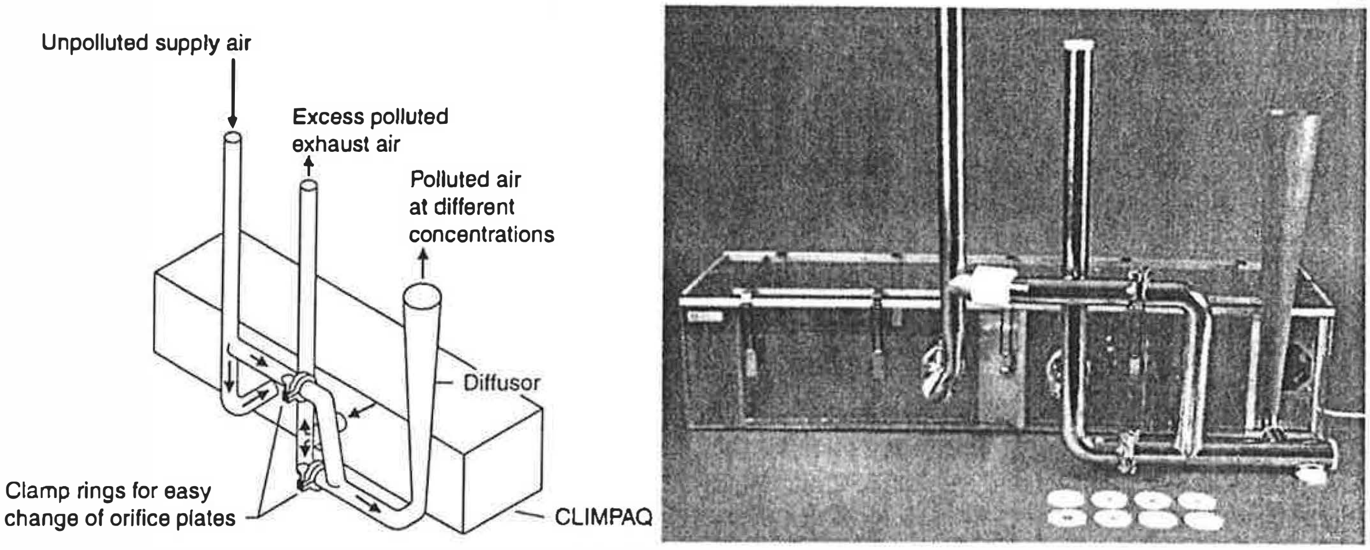

Fig. 1 The air-dilution system connected to the outlet of the CLIMPAQ. The set-up makes it possible to assess the quality of polluted air at different concentrations at the diffusor

supply to the air quality laboratory and to the small-scale test chambers was provided by a common ventilation system. This guarantees the same low background level of pollutants in all small-scale test chambers and in the air quality laboratory. This is essential for the quality of the sensory assessments of the sensory panel.

Building Products

The eight building products studied included 6 floor coverings: two types of tufted nylon carpet with latex foam backing (carpet 1 and carpet 2); two types of linoleum (linoleum 1 and linoleum 2); and two types of polyolefine (polyolefine 1 and polyolefine 2). Moreover, two types of water-borne acrylic sealant for indoor use (sealant 1 and sealant 2) were studied. The building products are typical for what is used in Denmark. When the building products were received from the manufacturer, samples were immediately prepared. Samples of each of the flooring materials were stapled together, back-to-back, and aluminum U-profiles were used to seal the edges of the samples. The sealant was injected into aluminum U-profile, 10 mm wide and 12 mm deep. In the test chambers the test specimens of the floor coverings were placed vertically, parallel with the long side of the test chamber and so that the surfaces were parallel to the direction of the airflow. The sealant in U-profiles was placed at the bottom of the test chamber, in parallel with the long side of the test chamber.

The area of the specimens placed in the test chamber was selected so that the area-specific ventilation rate was similar in the test chamber and in a typical room with an air exchange rate of 1 h^{-1}, see Table 1. The dimensions of the typical room correspond to the smallest room in dwellings in Europe (Gustafsson, 1988). Therefore, the highest concentrations of polluted air are expected in this room. The dimensions of the typical room, commonly designated a model room, were 3.2 m×2.2 m×2.4 m (length, width and height, respectively) giving a volume of 17 m^3 (Nordtest, 1990).

Sensory Panel

A sensory panel comprising 33 to 41 (average 36) subjects performed the sensory assessments. The subjects were recruited in the neighborhood of The Danish Building Research Institute. They had to pass a test to document a normal sense of smell. The test consisted of two parts to document their ability: 1) to discriminate between different odorous substances (matching test); and 2) to rank different odor intensities of the same odorous substance (ranking test). Moreover, the leader of the experiment assessed each subject's attitude and motivation concerning the experiment and the subject's personal hygiene. Those passing the tests satisfactorily became part of the sensory panel. There was an even distribution of men and women in the panel. The age ranged from 16 to 71 years with a mean of 40 years, and 15% of the subjects were smokers.

On each day of the experiment, the panel was divided into four groups of approximately 10 persons. Each group finished the assessments within a 2-h period. The subjects were placed in the hall outside the air quality laboratory, which was used as a waiting room between the assessments. Before doing the as-

Table 1 Area of specimens placed in the test chambers. The area was determined based on a model room with an air exchange rate of 1 h^{-1}

Building product	Model room		Test chamber	
	Surface area (m^2)	Area-specific ventilation rate ((m^3/h)/m^2)	Airflow rate (L/s)	Specimen area (m^2)
Carpet	7	2.4	0.9	1.45
Linoleum	7	2.4	0.9	1.45
Polyolefine	7	2.4	0.9	1.45
Sealant	0.2	85	0.9	0.038

sessments in the main chamber, the subjects waited for one minute in the antechamber. This procedure was followed to adapt the panel members to the general background air delivered to the small-scale test chambers and the full-scale chambers. Then the subjects entered the main chamber and assessed the immediate acceptability of air exhausted from one diffusor and marked their assessment on the acceptability scale shown in Figure 2. The scale was slightly modified from that used by Gunnarsen and Fanger (1992). Before doing the assessments the panel was instructed in how to use the scale. It was emphasized that they were not allowed to mark between *just acceptable* and *just unacceptable*. They were requested to decide on whether the air was acceptable or unacceptable and then rate the degree of acceptability. They were also instructed in how to use the exposure equipment. The assessments were done in random order. The time span between each assessment was at least 3 min to minimize adaptation to polluted air.

Procedure

The study was performed in one month. On days 3, 10 and 29 after the test specimens were placed in the test chambers, the emissions from the eight building products were assessed together with an assessment of the exhaust air from an empty test chamber. To measure the background level of all test chambers, the test specimens were removed from the test chambers immediately after measurements on day 10. On day 17 the exhaust air from all nine empty test chambers was assessed. From day 10 to day 17, the test specimens were conditioned in the main full-scale chamber of the air quality laboratory under similar temperature and relative humidity as in the test chambers. Just after measuring the background level of the empty test chambers on day 17, the test specimens were placed in the test chambers again until day 29 where the last assessments were performed. Moreover, the quality of the air in the main full-scale chamber was assessed on each of the 3 days.

Results

The mean acceptability vote as a function of the dilution factor is shown in Figure 3 for the eight building products and in Figure 4 for the empty test chamber. *Clearly unacceptable* corresponds to the value −1 and *clearly acceptable* corresponds to the value +1. *Just acceptable* and *just unacceptable* correspond to 0. The dilution factor is the ratio between the flow rate in the diffusor and the flow rate of polluted exhaust air from the test chamber through the diffusor. It was 1 at the highest concentration, i.e., undiluted, which was achieved at an area-specific ventilation rate corresponding to an air exchange rate of 1 h^{-1} in the model room. The concentration of polluted exhaust air was diluted approximately 2, 8 and 16 times.

The emissions from polyolefine 2 were nearly not perceivable, since the assessments only deviated slightly from the assessments of the air from the empty test chamber. Sealant 1 only affected the perceived air quality at the two lowest levels of dilution, i.e., at the two highest concentrations. For the other building products the mean acceptability vote at the highest concentration was approximately −0.5. When the dilution of the polluted air was increased, the perceived air quality gradually improved. The improvement was most pronounced for the two types of sealant. When the polluted air was diluted between 8 and 16 times, it

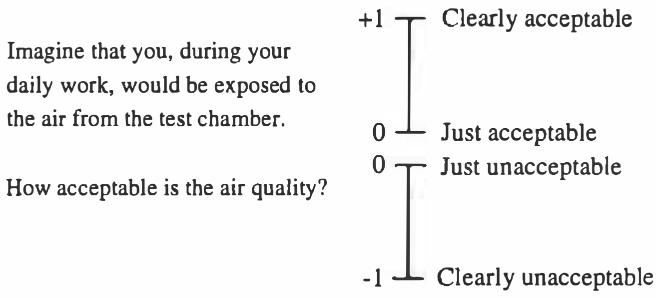

Fig. 2 Acceptability scale and the accompanying question. The scale was not numbered during the experiment, but the numbers were used for the data analysis

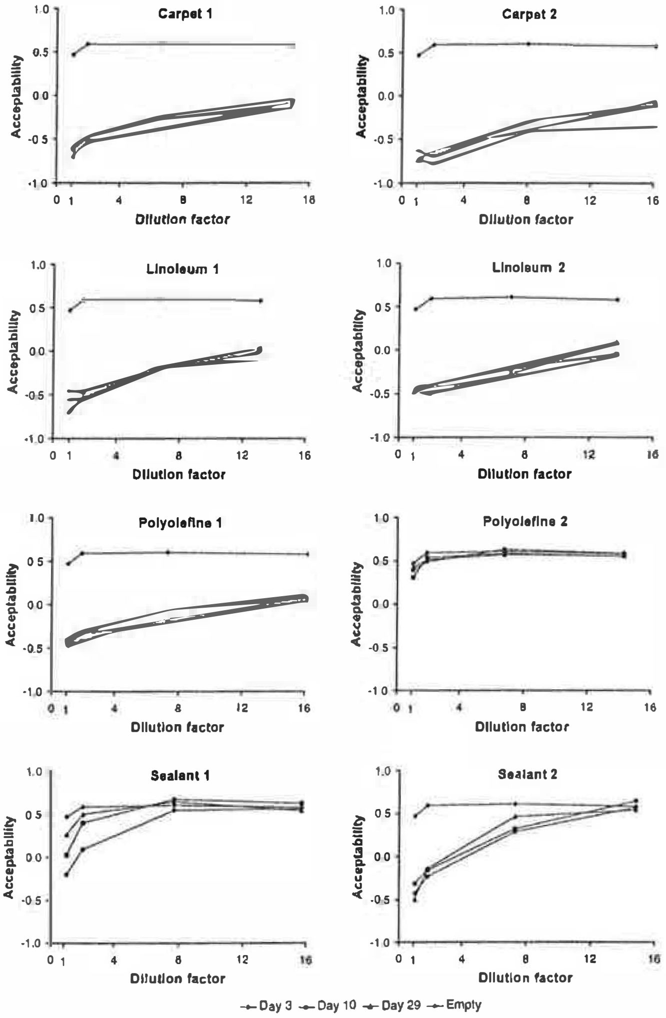

Fig. 3 Mean acceptability vote as a function of the dilution factor for the eight building products after 3, 10 and 29 days. The mean acceptability vote (mean of 3 days) for the empty test chamber as a function of the dilution factor is included for comparison

was not possible to distinguish between assessments of the chamber with material samples inside and the empty test chamber. This is in contrast to carpet, linoleum and polyolefine 1, where 16 times dilution only improved the perceived air quality to a mean acceptability vote of around 0. The mean acceptability vote of the background air in the main full-scale chamber was 0.47 after 3 days, 0.51 after 10 days and 0.49 after 29 days giving an average vote of 0.49. The mean acceptability vote for the 9 empty test chambers assessed on day 17 at an airflow rate of 0.9 L/s without dilution ranged from 0.29 to 0.52 with an average of 0.44. This relatively wide range of acceptability votes for the empty test chambers is believed to be due to desorption of previously adsorped pollutants to the inner surfaces of the test chambers. The period from removal of the material samples to the assessments of the empty test chambers was only 7 days. All the test chambers used for this study were flushed with clean conditioned and filtered air for 30 days before material samples were placed in the test chambers on day 0. This is, based on previous experience, sufficient to eliminate odor problems from previous adsorption. Therefore, the test chamber that was empty throughout the study is believed to be representative for the background in the other test chambers from day 0.

The experimental standard deviation of the acceptability vote as a function of the mean acceptability vote is shown in Figure 5. The average experimental standard deviation of the acceptability votes was 0.4. This corresponds to an approximate experimental standard deviation of the mean of 0.07.

Figure 6 shows the exposure-response relationship in a semi-log plot between the dilution factor and the mean acceptability vote for carpet 1, sealant 2, polyolefine 2 and empty test chamber at day 3. The dilution factor 1, i.e., no dilution, corresponds to the highest

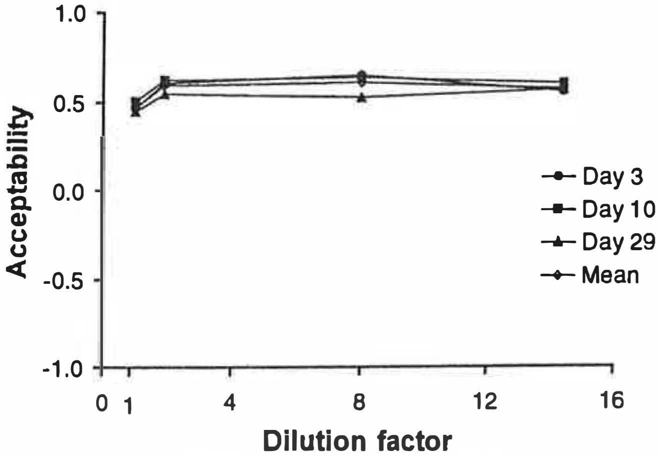

Fig. 4 Mean acceptability vote as a function of the dilution factor for the empty test chamber after 3, 10 and 29 days

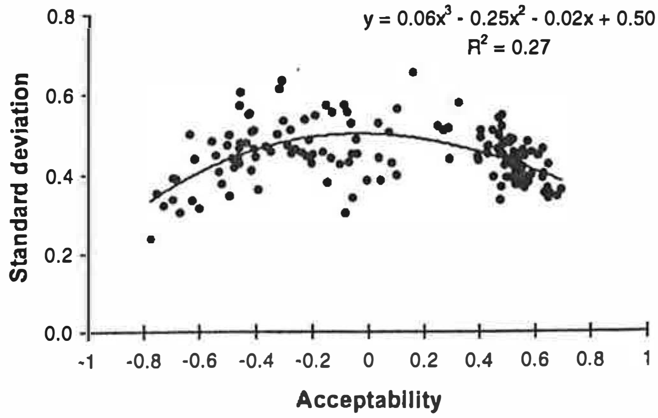

Fig. 5 The experimental standard deviation of acceptability votes as a function of the mean acceptability vote. Each point represents the mean vote of 36 persons

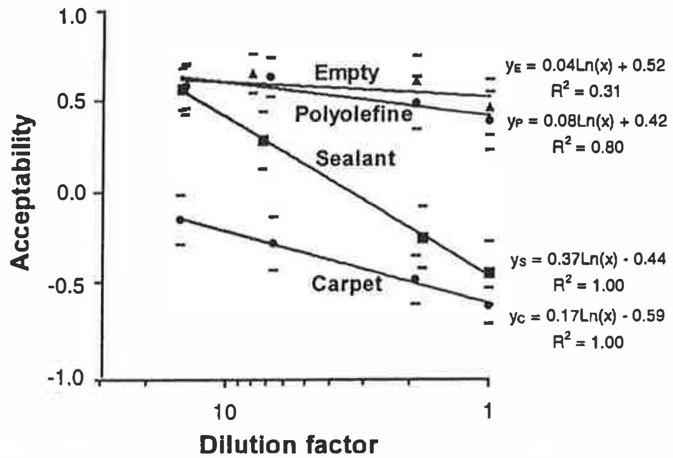

Fig. 6 Exposure-response relationship between the dilution factor and the mean acceptability vote for carpet 1, sealant 2, polyolefine 2 and empty test chamber in a semi-log plot. The 95% confidence intervals for the mean acceptability vote are shown

concentration, which is determined from the model room with an air exchange rate of 1 h^{-1}. The 95% confidence intervals for the mean acceptability votes are shown. The points for the various materials provide, with a good approximation, a linear relationship between the category rating for acceptability and the dilution factor. Therefore, it is suggested to characterize the emissions from a building product by this relationship. The relationship can be described by the formula (Cain and Moskowitz, 1974):

$$\text{ACC} = a \cdot \ln(\text{dilution factor}) + b \qquad (2)$$

Where

ACC = mean acceptability vote as assessed by the sensory panel using the scale in Figure 2

a = constant characterizing the slope of the line

b = constant characterizing the position of the line, i.e. the acceptability vote at the highest concentration

The mean acceptability votes were converted to percentage of dissatisfied (Gunnarsen and Fanger, 1992). Moreover, the dilution factor was converted to the ratio A/Q between the area of the building product, A, and the ventilation rate, Q. The ratio A/Q, the inverse area-specific ventilation rate, for the highest concentration of polluted air is calculated from the actual area of material samples in the test chamber and the ventilation rate of the test chamber. The ratio A/Q for the three lower concentrations is calculated as the ratio A/Q for the highest concentration divided by the dilution factor. The ratio A/Q is a practical measure of the concentration of pollutants in the air caused by a building product under the assumption that the emission rate is independent of the concentration. The exposure-response relationship between the ratio A/Q and the percentage of dissatisfied for the eight building products are shown in Figure 7. The perceived air quality is rather poor for the two types of carpet, the two types of linoleum and polyolefine 1. At the highest concentration, the percentage of dissatisfied is 90 or higher. At the lowest concentration, after 16 times of dilution, the percentage dissatisfied has decreased to a level around 50%. The corresponding relationship for the empty test chamber is shown in Figure 8. The relative concentration is defined as the ratio between the airflow rate from the test chamber in the diffusor and the total airflow rate in the diffusor. The mean percentage of dissatisfied for the 9 empty test chambers, at an airflow rate of 0.9 L/s, without dilution ranged from 5.0 to 15.4% with an average of 7.9%. The average percentage of dissatisfied in the main full-scale chamber was 5.6%.

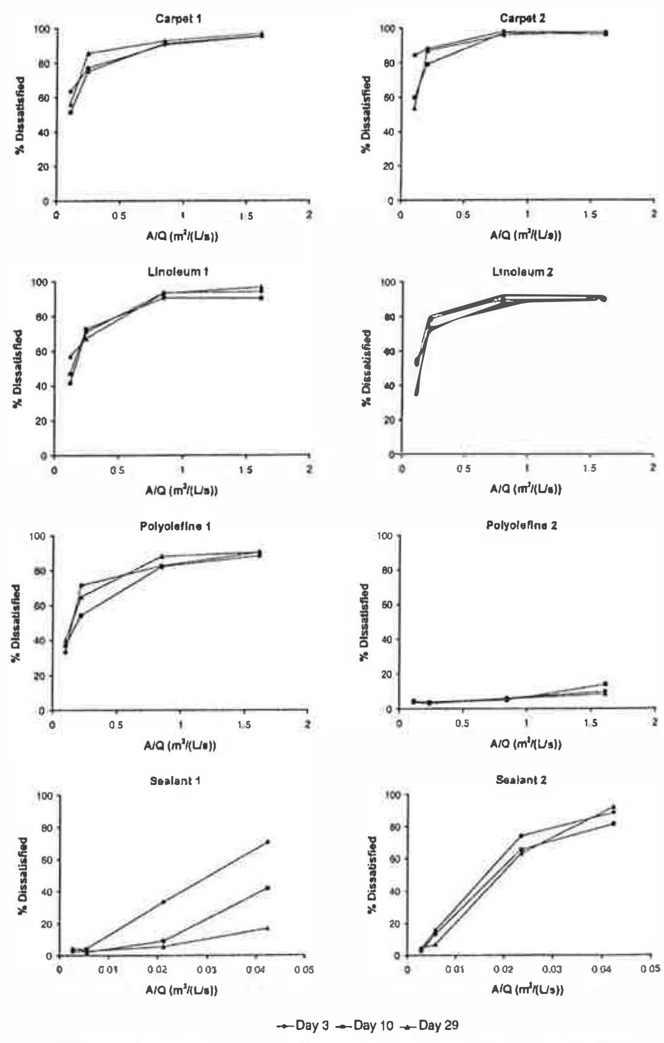

Fig. 7 Exposure-response relationship between the ratio A/Q and the percentage of dissatisfied for the eight building products after 3, 10 and 29 days

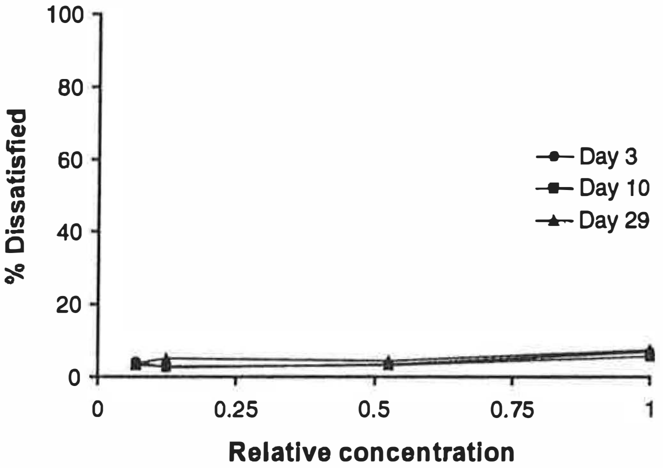

Fig. 8 Exposure-response relationship for the empty test chamber after 3, 10 and 29 days

Discussion

The principles and equipment for the suggested method are useful for determining exposure-response relationships for building products. Such relationships make it possible to quantify the impact of emissions from building products on the perceived air quality at different concentrations and to assess the impact of dilution of polluted air. Both aspects are important when the impact of different building products on the perceived air quality is evaluated.

It is an advantage to use a dilution system to determine exposure-response relationships because only one test chamber is required for each building product. This makes it possible to test more building products with less test chambers and space is saved in the laboratory. The specimen preparation is easier because less material is needed for each product type. In addition, when more materials are tested at the same time, it is possible to use a sensory panel more effectively and thereby reduce the expenses for subjects.

Impact of Dilution

The concentration of polluted air for the different building products was generated by having a realistic area-specific ventilation rate in the test chambers. The idea was to simulate a worst case situation, i.e., to test each material at the highest concentration that would be in a real room with that material alone. The lower concentrations were achieved by similar dilution factors for the different building products. The dilution steps were selected to study a realistic range of concentrations in relation to ventilation practice. The effect of dilution of the polluted air on the perceived air quality varied markedly between the building products, see Figures 3 and 6. In Figure 6, the exposure-response relationships for carpet 1, sealant 2, polyolefine 2 and empty test chamber are compared. A significant difference in the slopes for the different building products is seen. This is similar to previous findings for building products where another sensory method was used (Knudsen et al., 1997) and in agreement with studies of perceived intensity of individual chemical compounds (Cain, 1969; Berglund et al., 1971; Engen, 1982).

To assess the impact of dilution of polluted air on the perceived air quality, it is useful to know the relevant part of the exposure-response relationship. The investigated part of the exposure-response relationships for the different building products of the present study, represents different parts of a total S-shaped exposure-response relationship, when expressed in percentage dissatisfied. The relationship ranges from the percentage dissatisfied for the empty test chamber, i.e., the background level, to 100% dissatisfied for pollution concentrations at high intensities that are unacceptable to the whole panel. This is illustrated in Figure 9, where the exposure-response relationships for polyolefine 2, sealant 2 and carpet 2 are combined into one S-shaped curve in a semi-log plot. The highest "relative concentration", i.e., 1, corresponds to an area-specific ventilation rate determined from the model room with an air exchange rate of 1.

Polyolefine 2 represents the lower part of the total S-shaped exposure-response relationship. At all concentrations the percentage of dissatisfied do not differ from the percentage of dissatisfied for the empty test chamber. Sealant 2 represents the middle part of the S-

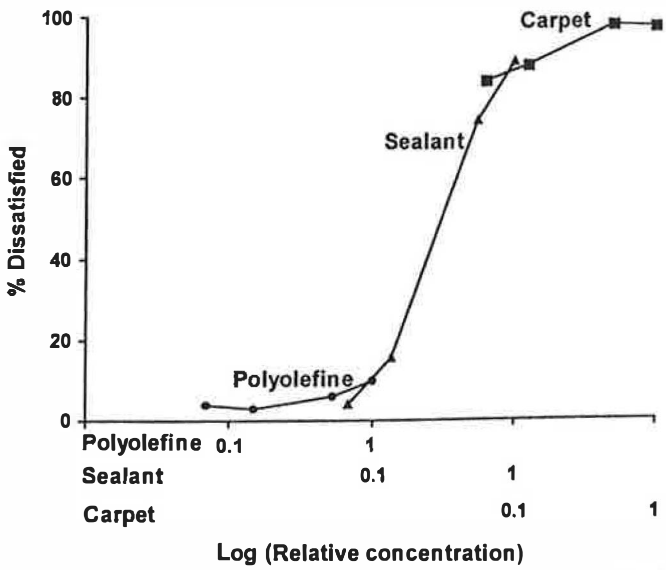

Fig. 9 Exposure-response relationships for carpet 2, sealant 2 and polyolefine 2 combined into one S-shaped curve in a semi-log plot

shaped exposure-response relationship. At the lowest concentrations the percentage of dissatisfied do not differ from the percentage of dissatisfied for the empty test chamber. At gradually higher concentrations the percentage of dissatisfied increases to approximately 90%. Carpet 2 represents the upper part of the S-shaped exposure-response relationship with a high percentage of dissatisfied at all concentrations.

It may be possible to determine an odor threshold for emissions from a building product from acceptability assessments. If the concentration is gradually decreased from above the threshold level the odor threshold may be reached when the mean acceptability vote from a test chamber with material inside equals the mean acceptability vote of an empty test chamber. This corresponds to the effective odor threshold (Berglund et al., 1991). The effective odor threshold is defined as the highest concentration where the probability of hits equals the probability of false alarms. This information determines how much dilution, or increased ventilation, is required to eliminate an odor problem that stems from a particular building product. From Figure 3 it is seen that for the two types of sealant a dilution of 8 to 16 times is sufficient to reach the odor threshold level. For carpet and linoleum 16 times of dilution is far from sufficient. From a unpublished study it has recently been shown that a dilution of approximately 250 to 300 times was required before emissions from a carpet identical to carpet 1 were indistinguishable from assessments of an empty test chamber. With such a material in a room a realistic increase of the ventilation rate of e.g. 5 times will probably only be waste of energy with only a marginal improvement of the perceived air quality. It means that it is difficult, and probably unrealistic in practice, to eliminate an odor problem that stems from the actual carpet by increased ventilation. An odor problem that originates from the sealant, however, may be reduced by increased ventilation. To be able to make such evaluations for building products it is recommended to determine the exposure-response relationships for the relevant range of pollution concentrations, i.e. at a relevant range of the area-specific ventilation rate. Assessments at only one concentration, i.e. at one area-specific ventilation rate, are not sufficient to be able to evaluate the impact of that material at other concentrations and to assess how difficult it is to dilute the pollutants to an acceptable low level.

Laboratory vs. Real Buildings

The ultimate goal of testing building products is to predict the perceived air quality in a room where the products are used from data obtained in the laboratory. The exposure-response relationships were determined for a realistic and relevant range of pollution concentration by using a model room as a reference to calculate a building-realistic area-specific ventilation rate in the test chamber. However, the percentage of dissatisfied for the individual building products, except polyolefine 2, of the present laboratory test was higher than the percentage of dissatisfied normally found in buildings where many building products and other pollution sources are present simultaneously. In field studies the percentage of dissatisfied for visitors is typically found in the range from 35 to 55%, e.g., in the investigation of 56 office buildings in the European IAQ-Audit project (Bluyssen et al., 1996). The percentage of dissatisfied for the two types of carpet and linoleum and for polyolefine 1 and sealant 2 corresponded to 70 to 95% dissatisfied for a realistic area-specific ventilation rate. Therefore, if these data were used directly to predict the perceived air quality in a room with the same building products and an air exchange rate of 1 h^{-1}, one would estimate more than 90% dissatisfied. This difference between laboratory data and field data needs to be understood before it is possible to predict from laboratory assessments, the impact of a building product or a combination of building products on the perceived air quality in real buildings. The fact that the building products were relatively new and that they may be of a high-polluting type at the moment of the tests can not alone explain the poor air quality. The building products were typical of what is used in Denmark. Therefore, it is not at present recommended to predict the perceived air quality in a building directly from data obtained in small-scale test chambers in the laboratory. A number of factors are likely to have an impact on the discrepancy between laboratory and field data. These factors may include: status of adaptation of the sensory panel members, the context in which the assessments are performed, psychological factors like the panel members' expectations and the panel members' familiarity and experience with the odors. Moreover, a better understanding of the impact of combining materials with respect to perception and secondary processes like sorption and oxidation is needed. To help assess the importance of data obtained in the laboratory in relation to a real room, it is suggested to determine the exposure-response relationship for identical building products in the laboratory and in the field.

Even though it is not recommended at present to predict the perceived air quality in a building directly from data obtained in small-scale test chambers in the laboratory, it is advised to test building products in the laboratory for the purpose of labeling or ranking building products. It has been demonstrated that a building product, which was found to have a low impact on the perceived air quality in the laboratory, also had a low impact in the field. In a study of an office building performed by Wargocki and Fanger (1997), a change of flooring material significantly improved the perceived air quality from nearly 30% dissatisfied in offices with felt carpet to approximately 15% dissatisfied in offices with tiles of low polluting polyolefine identical to polyolefine 2 of the present study.

Age of Material

Sensory assessments were performed 3, 10 and 29 days after the building products were placed in the test chambers in order to distinguish between slow and fast decaying emissions. The most pronounced improvement over time is seen for sealant 1 at the highest concentration. The impact of this building product will probably not constitute a problem after a one-month period. However, this is in contrast to the other building products, which only improve marginally during the one-month period. In practice, it may not be acceptable to wait several months before the perceived air quality reaches an acceptable level. As seen above, the impact of increased ventilation on the perceived air quality may be moderate for some building products. Therefore, source control is generally recommended as a remedy, i.e., to use products which have a low adverse impact on the perceived air quality from the moment they are taken into use. The continued impact on the perceived air quality may be explained by secondary emissions, i.e., originally chemically or physically bound VOCs that are formed by different mechanisms like decomposition, hydrolysis or oxidation and sorption processes (Knudsen et al., 1999).

Acceptance Criterion

When testing building products according to a labeling system, the acceptance criterion being used is important. One classic accept criterion for acceptable indoor air quality has been proposed in the ASHRAE Standard 62 (1989). The air quality is acceptable if 80% or more of people exposed do not express dissatisfaction. Based on the results of the present investigation, it is seen that this is not a reasonable criterion for assessments performed in the laboratory. Applying the method described in the present paper, most materials would probably be rejected. An acceptance criterion should be defined in order to let the better of the materials on today's market pass and the worse materials fail the test. The requirements can gradually be increased, if this is necessary to reach acceptable indoor conditions in real buildings. In the Danish Indoor Climate Labelling System (Larsen et al., 1997) the acceptance criterion has been based on a pragmatic choice of 0 for the mean acceptability vote on the scale for acceptability (Gunnarsen and Fanger, 1992). This corresponds to approximately 50% dissatisfied. It may not be reasonable to use the same acceptance criterion for all types of materials. Functional requirements (e.g., wear, fire and water resistance) can influence the ability of a material to meet a given acceptance criterion. It may be harder to comply with high requirements for floor materials than for wall materials.

Material Loading

It is important that the result of a test makes it possible to compare different materials. In a recent European Collaborative Action (ECA) report on "Evaluation of VOC emissions from building products – Solid flooring materials", no specific method is suggested for the sensory test of odor or perceived air quality. However, the area-specific ventilation rate is specified to be in the range from 0.625 to 2.5 $m^3/h \cdot m^2$ (ECA-IAQ, 1997). In the present study, the area-specific ventilation rate for the highest concentration for the flooring materials was 2.4 $m^3/h \cdot m^2$. At this loading, the percentage of dissatisfied was approximately 90% for the two types of carpet and the two types of linoleum. Similar results have been seen for other typical flooring materials tested in a similar way. At this high level of dissatisfaction an end-of-scale distortion may be reached for carpet and linoleum, where a considerable lowering of the pollution concentration is required to improve the perceived air quality. Assessments corresponding to this high percentage of dissatisfied indicate a problem, but because all assessments are made close to the end of the scale they do not contain useful information that make it possible to see any difference between the materials. The low area-specific ventilation rate of 0.625 $m^3/h \cdot m^2$ suggested in the ECA report will result in a concentration approximately four times higher than in the present study. Applying the sensory method of the present study at this lower area-specific ventilation rate will probably result in assessments that corresponds to more than 90% dissatisfied for many typical flooring materials. If all sensory assessments fall in a narrow range at this high level, it is not possible to compare or rank the tested flooring materials. For such materials it should therefore be considered to adjust the material loading in the test chamber to a level that assures that the range of the mean votes varies e.g. around 0 on the acceptability scale (corresponding to approximately 50% dissatisfied). That will make it possible to detect differences between the building products and to rank them. Another way of overcoming these end-of-scale distortions would be to use an open-ended scale, e.g., as suggested in the Master Scale procedure which is based on magnitude estimation (Berglund, 1991).

Conclusions

- To evaluate the impact of emissions from a building product on the perceived air quality, determining the exposure-response relationship between concentration of pollutants from the building product and the sensory response from humans is recommended. This relationship enables an evaluation of the impact of emissions from the building product on the perceived air quality at different concentrations and an assessment of the impact of dilution. Both aspects are important when building products are evaluated.
- A rational method has been developed for determination of the exposure-response relationship for a building product at a relevant range of pollution concentrations. The method is based on an air-dilution system connected to the exhaust of a ventilated small-scale test chamber.
- The impact of diluting the pollutants from different building products on the perceived air quality varied considerably. Information on the effect of dilution is important when deciding the most effective remedy to improve the perceived air quality, i.e., increased ventilation or replacing one or more building products.
- At present, it is not recommended to predict the perceived air quality in a building directly from data obtained in small-scale test chambers in the laboratory. Such data show a larger negative impact on the perceived air quality compared to data obtained in field investigations.

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References

Andersen, T.E., Knudsen, H.N., Tirkkonen, T., Orko, I., Saarela, K., Clausen, G. and Fanger, P.O. (1996) "Air pollutant concentration effects on VOC emission rates of building and furnishing materials". In: Yoshizawa, S., Kimura, K., Ikeda, K., Tanabe, S. and Iwata, T. (eds). *Proceedings of Indoor Air '96*, Nagoya, 7th International Conference on Indoor Air Quality and Climate, Vol. 1, pp. 559–564.

ASHRAE (1989) *Ventilation for Acceptable Indoor Air Quality*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers, (ASHRAE Standard 62-1989).

ASTM (1990) *Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products*, Philadelphia, PA, American Society for Testing and Materials, (ASTM D 5116–90).

Berglund, B. (1991) "Quality assurance in environmental psychophysics". In: Bolanowski, S.J. and Gescheider, G.A. (eds), *Ratio Scaling of Psychological Magnitudes – In Honor of the Memory of S.S. Stevens*. Hillsdale, NJ, Erlbaum, pp. 140–162.

Berglund, B., Berglund, U., Ekman, G. and Engen, T. (1971) "Individual psychophysical functions for 28 odorants", *Perception and Psychophysics*, 9(3B), 379–384.

Berglund, B. and Lindvall, T. (1979) "Olfactory evaluation of indoor air quality". In: Fanger, P.O. and Valbjørn, O. (eds), *Proceedings of First International Indoor Climate Symposium*, Copenhagen, Danish Building Research Institute, pp. 141–157.

Bluyssen, P.M. (1990) *Air Quality Evaluation by a Trained Panel*. Ph.D. thesis, Copenhagen, Laboratory of Heating and Air Conditioning, Technical University of Denmark.

Bluyssen, P.M., de Oliveira Fernandes, E., Groes, L., Clausen, G., Fanger, P.O., Valbjørn, O., Bernhard, C.A. and Roulet, C.A. (1996) "European indoor air quality audit project in 56 office buildings", *Indoor Air*, **6**, 221–238.

Cain, W.S. (1969) "Odor intensity: differences in the exponent of the psychophysical function", *Perception and Psychophysics*, **6**, 349–354.

Cain, W.S. and Moskowitz, H.R. (1974) "Psychophysical scaling of odor". In: Turk, A., Johnston, J.W., Jr. and Moulton, D.G. (eds), *Human Responses to Environmental Odors*, New York, Academic Press, pp. 1–32.

CEN TC 264/ WG2 Odours (1996) *Air Quality – Determination of odour concentration by dynamic olfactometry*. Document 222/e, 96–12–05, CEN.

Clausen, G., Fernandes, E. de O. and Fanger, P.O. (1996) "European data base on indoor air pollution sources in buildings". In: Yoshizowa, S., Kimura, K., Ikeda, K., Tanabe, S. and Iwata, T. (eds), *Proceedings of Indoor Air '96*, Nagoya, 7th International Conference on Indoor Air Quality and Climate, Vol. 2, pp. 639–644.

Clausen, G., Pejtersen, J., Saarela, K., Tirkkonen, T., Tähtinen, M. and Dickson, D. (1995) *European Data Base on Indoor Air Pollution Sources in Buildings, Protocol for testing of building materials*, Version 1.0., November 28.

ECA (European Collaborative Action "Indoor Air Quality and its Impact on Man") (1993) *Determination of VOCs Emitted from Indoor Materials and Products, Interlaboratory Comparison of Small Chamber Measurements*, Luxembourg, Office for Publications of the European Communities (Report No. 13 (EUR 15054 EN)).

ECA (European Concerted Action "Indoor Air Quality and its Impact on Man", COST Project 613) (1991) *Guideline for the Characterization of Volatile Organic Compounds Emitted from Indoor Materials and Products Using Small Test Chambers*, Luxembourg, Office for Publications of the European Communities (Report No. 8 (EUR 13593 EN)).

ECA-IAQ (European Collaborative Action "Indoor Air Quality and its Impact on Man") (1997) *Evaluation of VOC Emissions from Building Products – Solid Flooring Materials*, Luxembourg, Office for Publications of the European Communities (Report No. 18 (EUR 17334 EN)).

Ekberg, L.E. and Nielsen, J.B. (1995) "A laboratory for investigation of the air quality in simulated indoor environments", *The 16th AIVC Conference*, Palm Springs, CA USA, 19–22 September.

Engen, T. (1982) *The perception of odors*, New York, Academic Press.

Fanger, P.O., Lauridsen, J., Bluyssen, P. and Clausen, G. (1988) "Air pollution sources in offices and assembly halls quantified by the olf unit", *Energy and Buildings*, **12**, 1–6.

Gunnarsen, L. and Fanger, P.O. (1992) "Adaptation to indoor air pollution", *Environment International*, **18**, 43–54.

Gunnarsen, L., Nielsen, P.A. and Wolkoff, P. (1994) "Design and characterization of the CLIMPAQ, chamber for laboratory investigations of materials, pollution and air quality", *Indoor Air*, **4**, 56–62.

Gustafsson, H. (1988) "Proposal of an "European reference room" for testing formaldehyde and other indoor air pollutants", WKI-Bericht Nr.19, Braunschweig, Frauenhofer-Institut für Holzforschung, 23–32.

Hoetjer, J.J. and Koerts, F. (1986) "A Model for Formaldehyde Release from Particleboard", *ASC Symposium Series 316*, 125–144.

Knudsen, H.N. (1994) *"Modelling of Indoor air Quality"*, Ph.D. thesis, Copenhagen, Technical University of Denmark, Laboratory of Heating and Air Conditioning (In Danish).

Knudsen, H.N., Clausen, G. and Fanger, P.O. (1997) "Sensory characterization of emissions from materials", *Indoor Air*, **7**, 107–115.

Knudsen, H.N., Kjaer, U.D., Nielsen, P.A. and Wolkoff, P. (1999) "Sensory and chemical characterization of VOC emissions from building products: impact of concentration and air velocity", *Atmospheric Environment* (in press).

Larsen, A., Wolkoff, P. and Nielsen, P. (1997) "Introduction to the Principles behind the Danish Indoor Climate Labelling", Taastrup, Denmark, Danish Indoor Climate Labelling Association.

Lindvall, T. (1970) *On sensory evaluation of odorous air pollutant intensities*, Stockholm, Nordisk Hygienisk Tidskrift, Supplementum 2.

Myers, G.E. (1984) "Effect of Ventilation Rate and Board Loading on Formaldehyde Concentration: a Critical Review of the Literature", *Forest Products Journal*, **34**, 59–68.

Nelms, L.H., Mason, M.A. and Tichenor, B.A. (1986) "The Effects of Ventilation Rates and Product Loading on Organic Emission Rates from Particleboard". In: *Proceedings of IAQ '86*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers, pp. 469–485.

Nordtest Method 1216–95 (1998) *Building Materials: Emission Testing by CLIMPAQ chamber*, Nordtest, Esbo, Finland.

Nordtest, NT Build 358 (1990) *Building Materials: Emission of Volatile Compounds, Chamber Method*, Nordtest, Esbo, Finland.

Sollinger, S., Behnert, S. and Levsen, K. (1993) "Determination of Organic Emissions From Textile Floor Coverings". In: *Proceedings of Indoor Air '93*, Helsinki, International Conference on Indoor Air Quality and Climate, Vol. 2, pp. 471–476.

Tichenor, B.A. (1989) *Indoor Air Sources: Using Small Environmental Test Chambers to Characterize Organic Emissions from Indoor Materials and Products*, Research Triangle Park, NC, U.S. EPA, Air and Energy Engineering Research Laboratory (EPA-600/8-89-074 NTIS PB90-110131).

VDI (Verein Deutscher Ingenieure) (1986) *Olfactometry, odour threshold determination, fundamentals*, Düsseldorf, Germany, VDI-Richtlinien 3881, Blatt 1.

Wargocki, P. and Fanger, P.O. (1997) "Impact of changing the floor material on air quality in an office building". In: Woods, J.E., Grimsrud, D.T. and Boschi, N. (eds), *Proceedings of Healthy Buildings/IAQ '97*, Washington, Vol. 2, pp. 243–248.

Wolkoff, P. (1998) "Impact of air velocity, temperature, humidity, and air on long-term VOC emissions from building products", *Atmospheric Environment*, **32**, 1–10.