Emissions Testing Data and Indoor Air Quality

Hal Levin
Hal Levin & Associates
Santa Cruz, California 95060

ABSTRACT
This paper examines the relationships between concentrations, emissions test data, and ventilation rate data in order to identify the critical factors that control concentrations in indoor air. It discusses volatile organic compounds (VOCs) measurement results and ventilation rate measurements from several multi-building surveys. It examines the relationship between the key variables and describes the issues facing investigators, researchers, building design professionals, and policy makers. It concludes that while the health effects knowledge base is lacking, "prudent avoidance" of exposure to VOCs by source control and ventilation are warranted given the current state of knowledge.

INTRODUCTION
Activity in recent years by researchers and investigators of problems related to indoor air quality has increased substantially the use of and reliance on emissions tests from sources of indoor air pollutants. Emitted pollutants of greatest concern are volatile organic chemicals (VOCs) and formaldehdye (HCHO). Many methods for conducting the tests are now in use, and some of them have been or are now being considered for standardization. Reliance on these tests stems from recognition of the importance of controlling indoor air quality by control of pollution sources. Ventilation can also reduce airborne concentrations of pollutants. Policy debates have often centered around indoor pollution control by ventilation versus source control. However, there is very little discussion or understanding of the optimum combination of source control and ventilation to achieve good indoor air quality (IAQ) (1).

Uses of the emissions test data include product development and quality control for manufacturing, selection of products for design or purchasing, and estimation of concentrations in buildings where the products are to be or have been used. Users include a wide range including product manufacturers, building design professionals, indoor air investigators, and researchers. Carpet manufacturers use the data for rough quality control for manufacturing or for labeling to provide consumer information or protection (1). Examples of manufacturer testing include the Carpet and Rug Institute's labeling program in the United States where manufacturers that are members of the Institute must test the products to demonstrate compliance with industry standards. Also in the U.S., pressed wood products (plywood and particleboard) intended for use in federally insured manufactured housing and mobile homes must meet regulations of the U.S. Department of Housing and Urban Development limiting formaldehyde concentrations in a large test chamber . Similar programs exist in some European countries for both carpets and pressed wood products.

In a small but growing number of cases, consumer or purchaser information obtained from manufacturers is being used by architects, engineers, interior designers, and facility planners to inform product selection and specification decisions. Numerous labeling programs exist although still in their infancy in Europe and America. IAQ investigators use emissions test data to understand the potential sources of contaminants in buildings they study. Researchers have attempted to model exposure based on test data and information on products used in buildings and people's time patterns. Regulatory bodies have begun to rely on test data while considering the need for action.

Limitations on the Use of Emissions Test Data

There are many sources of uncertainty in all of these applications of emissions test data. Among them are some involving the test methods and conditions themselves, some of them involving the products being tested, and some involving the environments for which the test data are being applied. Some of the important variables include the age and condition of the materials being tested, the representativeness of the test specimen, the temperature and ventilation rate of the test apparatus, and the ventilation rates in the actual building.

A major factor is the method for measuring the emitted substances, identifying them, and determining their quantities. Various methods produce different results, and even the same methods in different hands produces considerable variation. Additionally the variations between the products tested and those actually installed in buildings may be quite large. Products vary from one manufacturing run to another and, for some products, even within manufacturing runs. Manufacturers change formulations or the sources of the raw materials incorporated into their products based on market considerations, cost, and other factors. Testing is most often conducted with materials obtained directly from manufacturers at the end of the production process. Yet products installed in buildings have often been stored for some time and may have released some of their embodied chemicals to the environment or have substances from the environment deposited on their surfaces (1).

Need for Ventilation Rate Data

Without ventilation rate data for the buildings where products are used, interpretation of test data is limited for many of the purposes discussed above. This is because ventilation rates affect significantly the concentrations in air and indirectly affect the emission rates themselves (1). As the air concentration is lowered by the dilution and removal from increasing ventilation, the emission rate increases. The more the emission rate is determined by evaporation from the surface, such as with coatings applied wet to surfaces, the more changes in the air concentration will affect emissions. The more emission rate is determined by diffusion through the material, the more temperature and not air concentration will determine emission rates.

What Do We Need To Know?

Human exposure to contaminants is the focus of control efforts. Exposure is the product of concentration times time of exposure. This paper examines the relationships between concentrations, emissions test data, and ventilation rate data in order to identify the critical factors that control concentrations in indoor air. These relationships determine the importance of emissions and the usefulness of emissions test data in controlling exposure to indoor air pollutants emitted from indoor sources.

Because ventilation rates impact energy consumption, it is important to determine the value of ventilation in determining concentrations. The use of energy is important due to its economic and resource costs as well as the associated environmental impacts (e.g., atmospheric pollution, global warming, ozone depletion, water consumption, waste production, etc.). There is a need to evaluate alternatives to ventilation involving non-energy intensive technologies that can be used to reduce concentrations. The most important of these is source control, most often, the selection of low-emitting building products and materials. While outside the scope of this paper, evaluation of alternative source control methods should include consideration of the embodied energy in the materials and products and the impacts of the alternative materials on building operational energy and maintenance energy requirements associated with each alternative. Finally, the evaluation of alternatives should also include the relative impacts on resource depletion, habitat destruction, biodiversity, and other global environmental considerations.

VENTILATION RATES IN BUILDINGS

Ventilation rates vary by a factor of 10 from around 0.4 to 10.0 air changes per hour with typical mechanical system operations in offices, schools, and public assembly buildings. Most minimum ventilation rates for non-residential occupancies recommended in standards and guidelines and required by codes are tied to occupant density, not to building area or volume. In typical offices, minimum ventilation requirements of 7.5 to 10 litres per second per person (l/s/p) translate to about 0.9 air changes per hour (ach). In the denser occupancy categories such as classrooms, conference rooms, dining areas, and public assembly spaces, air exchange rates tend to be higher than in offices, retail establishments, or recreation areas. Laboratory spaces and certain other functions that generate moisture, odors, toxins, or noxious air contaminants usually have high air exchange rates, often above 6 per hour (h^{-1}). School classrooms typically have minimum required air exchange rates of 3 to 6 h^{-1}.

In practice, buildings with variable air volume (VAV) supply of outdoor air may operate with considerably more than the minimums for much of the year. Typically, while outdoor air temperatures are lower than those indoors, air exchange rates increase. In offices, for example, with "economizer" systems capable of supplying 100% outdoor air, air exchange rates may be as high as 5 or 6 h^{-1}. These same mechanical ventilation systems reduce air exchange when outside weather conditions are extreme resulting in low air exchange rates of 0.2 to 0.4 h^{-1} .

VOC CONCENTRATIONS AND EMISSIONS DATA

The focus of most emissions testing is on VOCs and formaldehyde (HCHO). The concentrations found in occupied non-industrial buildings are often reported as total VOC (TVOC). Virtually every method, when used correctly, likely underestimates the actual TVOC concentration due to method-specific limits on the compounds that can be collected and analyzed. Compounds with very low or very high volatility are not measured by most of the methods in common use. The values obtained by different measurement methods cannot be meaningfully compared, although more research may improve our understanding of the results obtained by different methods (2). Values reported using the various common methods tend to fall in a range from less than 0.1 milligrams per cubic meter (mg/m^3) to 1.0 mg/m^3. A few buildings have been reported to have concentrations above 1.0 mg/m^3, and even fewer above 2.0 or 3.0 mg/m^3. Occasionally a building is reported with 10.0 to 20.0 mg/m^3, and even more rarely, with concentrations of 20 to 100 mg/m^3.

Source strengths can be determined from measurements of concentrations and ventilation rates. For most buildings where these measurements have been made together, building-wide average source strengths tend to range from about 0.5 milligrams per square meter per hour ($mg\ m^{-2}\ h^{-1}$) to around 1.5 $mg\ m^{-2}\ h^{-1}$. In very "clean" buildings, source strengths have been reported well below 0.5 $mg\ m^{-2}\ h^{-1}$, and in many less clean buildings, source strengths of 2.0 to 10.0 $mg\ m^{-2}\ h^{-1}$ have been found.

Telephone Company Administrative Offices Study

Figure 1 shows concentrations reported from long-term (~30-day) samples collected passively on charcoal reported by Helen Shields of Bell Research Corporation (3). The samples were collected at ten telephone company administrative offices throughout the United States. None of these offices was new at the time of the study, although minor construction activity was reported in some. By observation we note that most buildings measured had VOC concentrations ranging from about 0.15 to 0.30 mg/m^3. None of the ten buildings had VOC concentrations that exceeded 1.0 mg/m^3. However, the reported limitations of the measurement method included loss of certain compounds and an inability to identify certain others. (Shields, 1993)

EPA "Public Buildings Study"

Figure 2 shows concentrations reported by Sheldon *et al* from the EPA Public Buildings Study, actually two separate studies conducted over a period of several years (4). The data shown in Figure 2 are plotted against building age in weeks. The buildings included offices, nursing homes, elderly homes, and schools. In most of the buildings, the age of the building was reported. In some buildings, measurements were made on separate occasions several weeks or even months apart, thus allowing observation of the trend toward decaying emissions as building materials and furnishings age. Note that both the values reported above 1.0 mg/m^3 were collected in buildings reported as being measured 1 week after completion of construction. Also note that the three data points shown in the lower right hand corner of the graph at 900 weeks were from buildings of unreported age identified as "old" by the investigators.

The concentrations generally seem low compared to data reported by others. However, the TVOC values reported here are merely the sum of the concentrations of the measured individual VOC. In a later study, Wallace *et al* attempted to estimate total VOC systematically and derived concentration values considerably higher than the totals of the compounds reported in the original study.

There is a clear overall trend in the data suggesting that the older a building may be, the lower the VOC concentrations are likely to be. However, in one building, a hospital, the concentrations rose dramatically from the early to the later measurements. The specific compounds responsible for this increase were ingredients of common cleaning and maintenance materials that were most likely responsible for the increase over time.

Figure 3 shows the decay in concentrations in three of the buildings from the EPA Public Buildings Study where concentrations were measured on multiple occasions beginning close to the time initial construction was completed. Note that there is a consistent pattern of decay in all three building. This suggests that the initial concentrations were elevated due to emissions from construction materials. While there is no direct proof that this is the case, data on the decay of emissions from new materials provides important indirect evidence.

European Audit Project Preliminary Data

Figures 4 to 8 show preliminary data on VOCs in 27 buildings from five of the nine countries participating in the European Audit Project (5-9). These countries are France (FR), United Kingdom (UK), Denmark (DK), Greece (GR), and Switzerland (SC). Figure 7 shows TVOC concentrations by country for each building measured. The measurements were made by researchers in each of the participating countries using standardized sampling and analytical methods based on sample collection on Tenax, and analysis by GC/MS. (Note that these are preliminary data visually interpolated by the present author from graphs on poster presentations at Healthy Buildings '94 in Budapest. Final data may differ and are expected to be reported in Fall 1995.)

The buildings were of various ages and were served by a variety of ventilation types. Many of the buildings were ventilated with mechanical systems. Smoking was permitted in some and not in others. There was a degree of variety in the buildings in each country but no strict mix formula appears to have been applied for building selection.

The data plotted in Figure 4 indicate that with only one exception, TVOC concentrations in buildings were <1 mg/m^3, and, in most cases, they were <0.5 mg/m^3. There were significant variations among buildings in most of the countries reported here.

Figure 5 shows plot of TVOC concentrations plotted against ventilation rates. Ventilation rates ranged from 0.4 air changes per hour (ach) to 10.5 ach. Country averages for air exchange rates were from a low of 0.9 ach in the UK to a high of 3.6 ach in Greece. Ventilation rates were 1.1, 1.2, 2.5 ach respectively in Switzerland, France, and Denmark.

The scatter of the data for VOC concentration as well as for ventilation rates in Figure 5 is large, but there is a discernible trend of increasing concentration as ventilation rates increase. This is hard to explain in terms of widely held concepts that increasing ventilation decreases contaminant concentrations. One plausible explanation is that in buildings where source strengths are greatest and concentrations are highest, ventilation is increased in response to sensory or other occupant responses. If source strengths are large, then concentrations may remain high in spite of extra ventilation. Another explanation is that where ventilation is expensive due to extreme climate conditions, people are more careful not to bring strong sources into buildings. More research is necessary to explain these results None of the buildings in the study was reported to be new or newly renovated.

Ventilation Not Dominant Factor

Whatever the explanation may be, it is clear that ventilation alone does not determine concentrations. It is a combination of ventilation and source strength, along with other less important factors, that ultimately determine concentrations, and, consequently, human exposure.

Figure 6 shows average TVOC source strengths by country calculated from reported TVOC concentrations and ventilation rates. Note that the source strengths in Figure 6 are not consistent with those reported by the investigators on the posters from each country. The final report may explain reasons for the discrepancies. Note also that we have removed one building with extremely high source strength from the Swiss building set. Figure 7 shows source strengths for each building in each of the five countries.

Figure 8 shows VOC concentrations and source strengths for each building in each of the five countries. Note the consistent relationship between source strength and concentration only in the UK. In each of the other four countries, there was a seemingly random pattern of relationships. This relationship is not expected and remains to be explained. There is, however, a general overall correspondence between the magnitude of the source strengths and the VOC concentrations discernible among these five sets of plots. Denmark, for example, clearly has both the lowest concentrations and the lowest source strengths. Greece generally appears to have the highest overall concentrations and source strengths, especially if we disregard the single very high value from the Switzerland.

MATERIALS AGE AND THEIR EMISSIONS DECAY

Figures 9, 10, and 11 show results from emissions tests of various types of carpets. Figure 9 shows test on four types of carpet from a study conducted for the U.S. Consumer Product Safety Commission by Al Hodgson of Lawrence Berkeley

Laboratory (10). Emissions were reported at 24 and 168 hours. While the emissions rates varied by a factor of more than six at 24 hours, all decayed significantly over the six days between the initial and final measurement. However, the large range of differences persisted at least until 168 hours. The fractional reductions over that time period were from 0.61 to 0.76, a fairly small range considering the significant differences in the types of carpet studied. The fundamental question is whether the concentrations observed at 168 hours suggest any concerns for human health effects.

Figures 10 and 11 show results from carpet studies by Tappler *et* al of Austria (11). All three carpets shown in Figure 10 were vinyl backed. The results show clear trends of decreasing emissions in the time frames reported. Figure 11 shows tests of five carpets with textile secondary backing. Again, the results are consistent in showing significant decays in emission during the early days of exposure to the environment.

These and many other tests of new and slightly aged building materials of various types consistently show the decreases in emissions that most likely account for a significant part of the general decline in VOC concentrations as new buildings age (1, 12, 13).

EMISSIONS AND VENTILATION

Using a crude model that oversimplifies the complex, interdependent relationships that determine contaminant concentrations, ignores sink effects, and ignores contaminant sources in outdoor air supplied to the interior, concentrations can vary by a factor of 10 or more, inversely with ventilation, from the same source strength. Figure 12 shows the relationship of concentration ventilation for four source strengths. The source strengths and ventilation rates plotted in Figure 12 span those typically encountered in buildings.

It is important to note that mechanically ventilated office buildings in the United States have ventilation rates typically ranging from 0.4 to 1.8 ach. Within this range, there are significant differences in the concentrations resulting from the different source strengths. Examining the difference just between the lowest two source strengths, 0.5 and 1.5 mg m^{-2} h^{-1} , we note that at the lower end of the ventilation rate range, there are significant differences in the concentrations plotted.

In fact, the model used to plot the curves in Figure 12 neglects the effect of increasing concentrations at low ventilation on emission rates. As concentrations rise, emissions decrease so that the increase in concentrations is not linear. On the other hand, as we go from higher to lower concentrations by increasing ventilation, concentrations rise more rapidly than a straight line project from concentration decreases measured at higher ventilation rates.

Use and Limitations of Emission Test Data

There is a possibility that entirely too much faith is placed in emission test results due to variety of factors. Several factors related to the test specimens, the test conditions and the building conditions to which the test data are applied affect the interpretation and use of indoor source emissions test data. These factors include the following:

- Product/material age and history of environmental exposure
- Air exchange rate
- Temperature
- Air flow at surface
- Material thickness
- Material density
- Material surface characteristics
- Material influence on sink effects, adsorption and desorption.

DOES IT MATTER?

How important are concentrations of pollutants found indoors? In fact, for most chemicals, the answer is not known. Not only is it not known for most individual compounds, far less is known about the complex mixtures of hundreds of chemicals typically found indoors. Some investigators have found positive correlations between VOC concentrations and sick building syndrome (SBS) symptoms, others have found no correlations while others still have found negative correlations (14) .

Mølhave has found correlations between concentrations of a defined mixture of 22 compounds and certain responses of his study subjects (15-17).. But most of the responses are generally at concentrations far above those typically found in indoor air in occupied buildings. Furthermore, his work has focused on this particular combination of chemicals, and it is not known how applicable the results are to other mixtures or even to different ratios of the same chemicals studied by Mølhave (18).

Why The Differences?

Perhaps, as many have argued, TVOC concentrations alone are poor predictors of health effects and human responses. Preliminary data from the European Audit Project appears to show very little to no correlation between VOC concentrations and SBS symptoms. Furthermore, the sensory evaluations reported in those studies did not correlate with reported SBS symptom prevalence. Results from a review of the major epidemiologic studies show little evidence of a correlation between VOC exposure and SBS (14). Most field studies have not measured VOCs in the same temporal context and microenvironment as that occupied by the study subjects. M. Hodgson *et al* reported a positive association between VOCs measured in the study subjects" microenvironment and the prevalence of SBS symptom reports in nonproblem buildings they studied(19). At this point, too little is known to predict occupant reactions to non-specific mixtures of VOCs and more work is needed, possibly with contemporaneous administration of questionnaires or interviews and microenvironmental measurements of air quality parameters.

CONCLUSION

What is an appropriate level of confidence and use of emissions test data? The range of values from one product to another is very large, and even with a similar product type, it is very large. Alternative product choices for the same building function can vary by two orders of magnitude. Thus, the choice of products may be quite significant if source strength Is an important determinant of IAQ. These variations can result from differences in product formulation, design, manufacture, treatment, storage, installation, curing, and other factors. Because these differences may produce such large variations in emissions, it is important to select low emitting products in order to keep concentrations low. On the other hand, it is important not to place too much confidence in a specific test result or to impute more precision or accuracy than is either appropriate or truly useful.

It is clear that measurements of contaminants cannot be meaningfully interpreted without concomitant measurements of ventilation. Estimates of concentrations cannot be made from emission test data without knowledge of the ventilation rates used for the test and expected in the actual building. Ventilation rates in buildings cannot be established to achieve a given concentration absent knowledge of the source strengths that will be present. There is very little information and almost no data that allows us to distinguish the contributions of people, their activities, building materials, and other sources in indoor air. Until such detailed data are available we must use both ventilation and source control to achieve good indoor air quality. Absent convincing evidence to the contrary, it is prudent to avoid exposing people unnecessarily to high concentrations of contaminants from indoor sources.

REFERENCES

1. H. Levin, Controlling sources of indoor air pollution" in H. Knöppel and P. Wolkoff (Eds.) *Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality -- State of the Art in SBS*. Dordecht, The Netherlands: Kluwer Academic Publishers. pp. 321-342. 1992,

2. L. Wallace, E. Pellizzari, and C. Wendel, Total volatiles organic concentrations in 2 700 person, indoor, and outdoor air samples collected in the US EPA Team studies, *Indoor Air*, Vol. 1, 465-477. 1991.

3. H. Shields, D. M. Fleischer, VOC survey: sixty-eight telecommunication facilities, Proceedings of the 6th International Conference on Indoor Air Quality an Climate, Vol. 2, 93-98, 1993.

4. L. Sheldon, R. W. Handy, T. D. Hartwell, R. W. Whitmore, H. S. Zelon, and E .D Pellizzari, and L. Wallace, Indoor air quality in public buildings. Volumes II and II. EPA Report EPA/600/6-88/009a and EPA/600/6-88/009b. 1988.

5. C. Aizlewood and R. Walker, and D. Dickson, The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: UK. Poster presentation at Healthy Buildings '94, Budapest. 1994.

6. C. Cochet, S. Kirchener, and J. Ribéron, The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: France. Poster presentation at Healthy Buildings '94, Budapest. 1994.

7. C.-A. Roulet, F. Foradiri, C.-A. Bernhard, L.Carlucci, The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: Switzerland. Poster presentation at Healthy Buildings '94, Budapest. 1994.

8. L. Groes, G. Clausen, J. Peitersen, and P. O. Fanger, The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: Denmark. Poster presentation at Healthy Buildings '94, Budapest. 1994.

9. A. Lazoudi, D. Asimakopoulos, M. Santamouris, The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: Greece. Poster presentation at Healthy Buildings '94, Budapest. 1994.

10. A. T. Hodgson, J. D. Wooley, and J. M Daisey, Volatile organic chemical emissions from carpets, final report. Prepared for Directorate of Health Sciences, U. S. Consumer Products Safety Commission. April 1992. (LBL-31916, UC 600).

11. F. Tappler, R. Boos, and F. Fiala, Emissions of volatile organic compounds from textile floor coverings, Healthy Buildings '94, Proceedings of the 3rd International Conference, Vol. 1, 237-242.

12. M.S. Black, W.J. Pearson, L.M. Work. A methodology for determining VOC emissions from new SBR latex-backed carpet, adhesives, cushions, and installed systems and predicting their impact on indoor air quality. in *IAQ '91 - Healthy Buildings*, Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., pp. 267-272. 1991.

13. W. G. Tucker, Emissions of air pollutants from indoor materials: an emerging design consideration. Presented at the 5th Canadian Building and Construction Congress, Montreal, Canada, November 27-29, 1988.

14. M. Mendell, Non-specific symptoms in office workers: a review and summary of the epidemiologic literature. *Indoor Air*, Vol. 3, 227-236, 1993.

15. L. Mølhave. Volatile organic compounds, indoor air quality and health. *Indoor Air*, 4:357-76. 1991.

16. L. Mølhave,. "The sick buildings -- a subpopulation among the problem buildings?" Indoor Air '87; Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Vol. 2. West Berlin, 17-21 August. Berlin: Institute for Water, Soil and Air Hygiene, pp. 469-473. 1987.

17. L. Mølhave, G. D. Nielsen, Interpretation of the concept "total volatile organic compounds" (TVOC) as an indicator or human responses to exposures of volatile organic compounds in indoor air. *indoor Air*, Vol. 2, 65-77. 1992.

18. S. Brown, M. Sim, M. J. Abrahamson, C. N. Gray, Progress towards national indoor air quality goals for volatile organic compounds, report to the Air Quality Panel of the National Health and Medical Research Council (Australia), 1992.

19. M. J. Hodgson, J. Frohliger, and E. Permar, Symptoms and microenvironmental measures in nonproblem buildings, *Journal of Occupational and Environmental Hygiene*, Vol. 31, 527-533.

Figure 1. Average VOC concentration by building: telephone company administratve buildings.

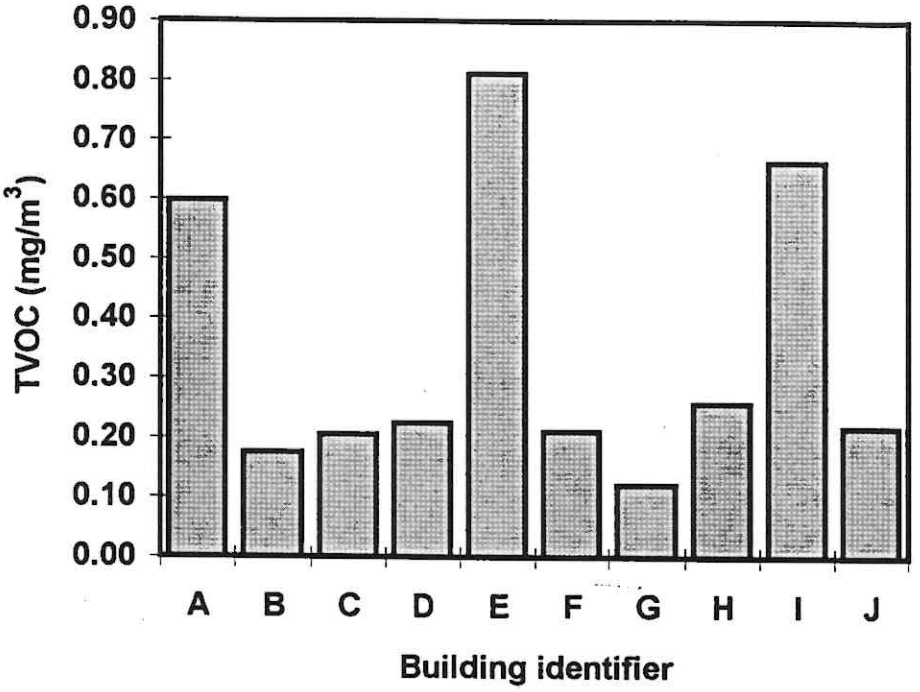

Figure 2. VOC concentrations in 10 buildings from the EPA Public Buildings Study (Ref. 2)

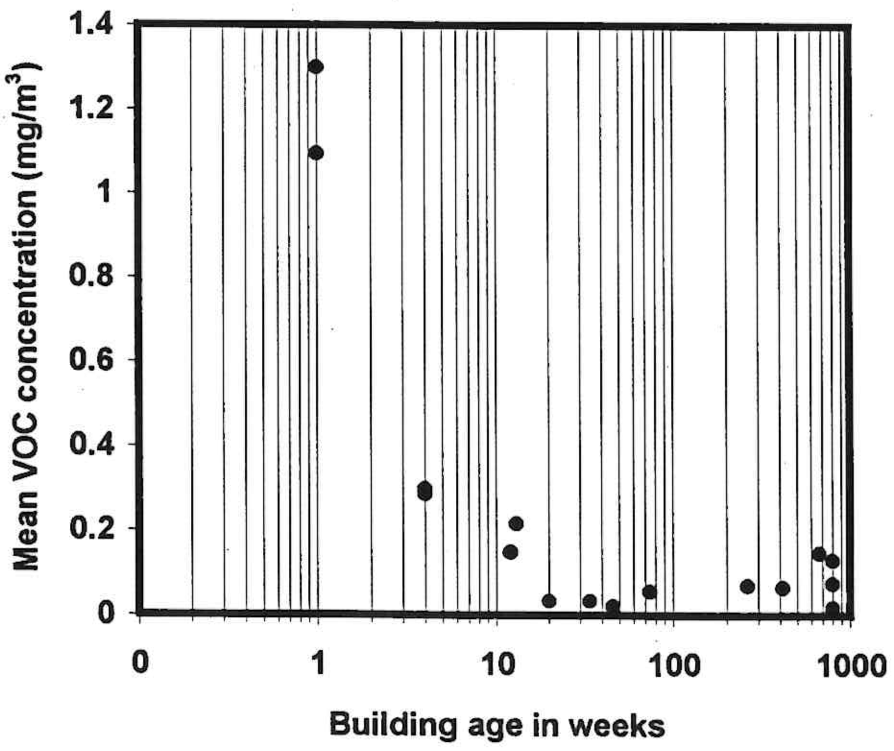

Figure 3. VOC concentrations in 3 buildings from the EPA Public Buildings Study.

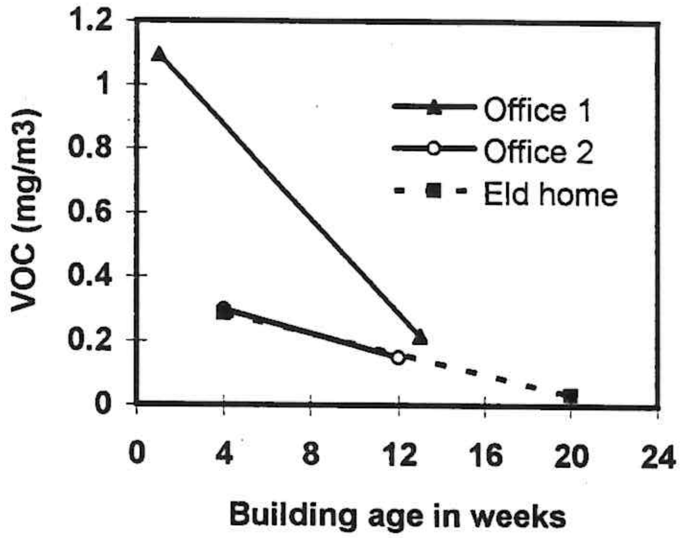

Figure 4. VOC concentrations by building in five countries: European Audit Project preliminary data

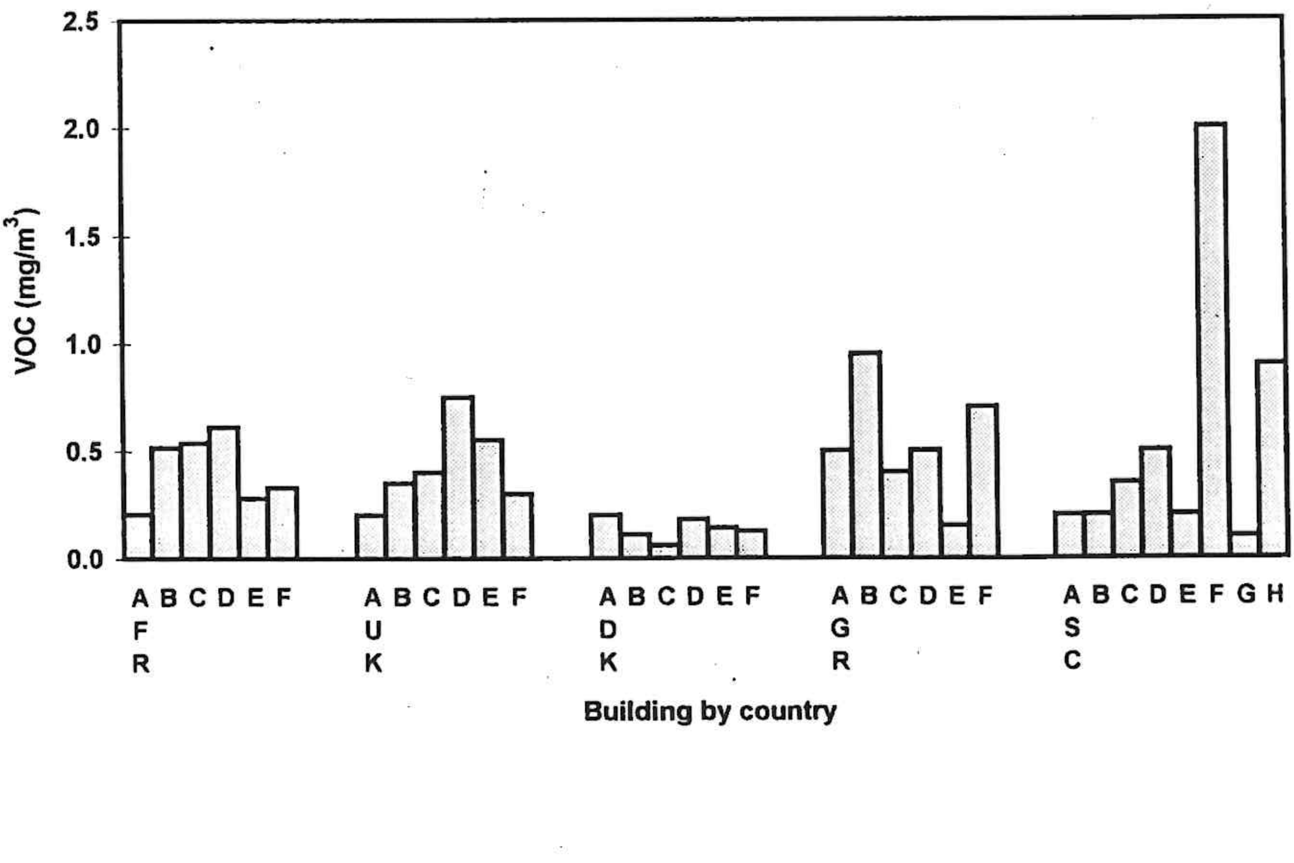

Figure 5. TVOC Concentration versus ventilation rate: European Audit Project preliminary data.

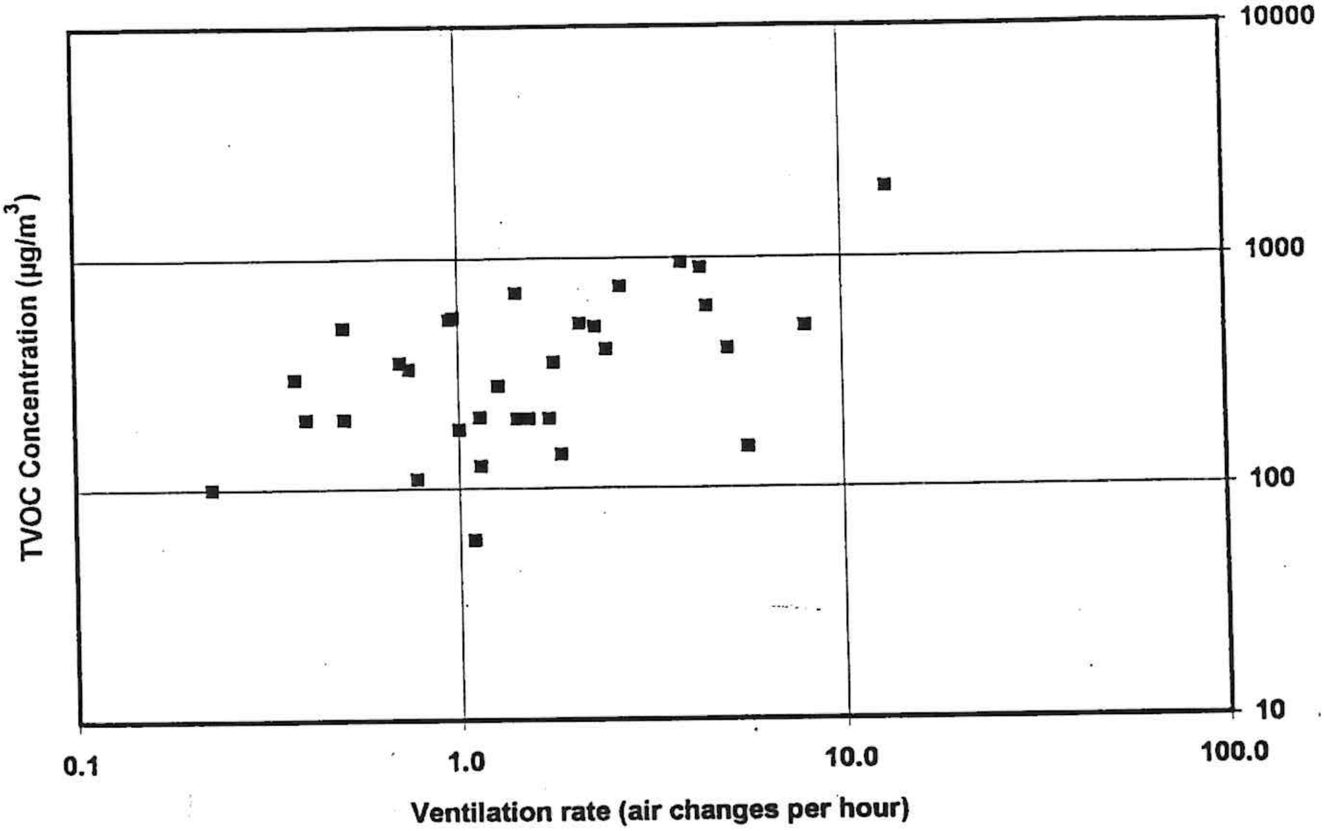

Figure 6. Average TVOC source strengths by country from European Audit Project preliminary data.

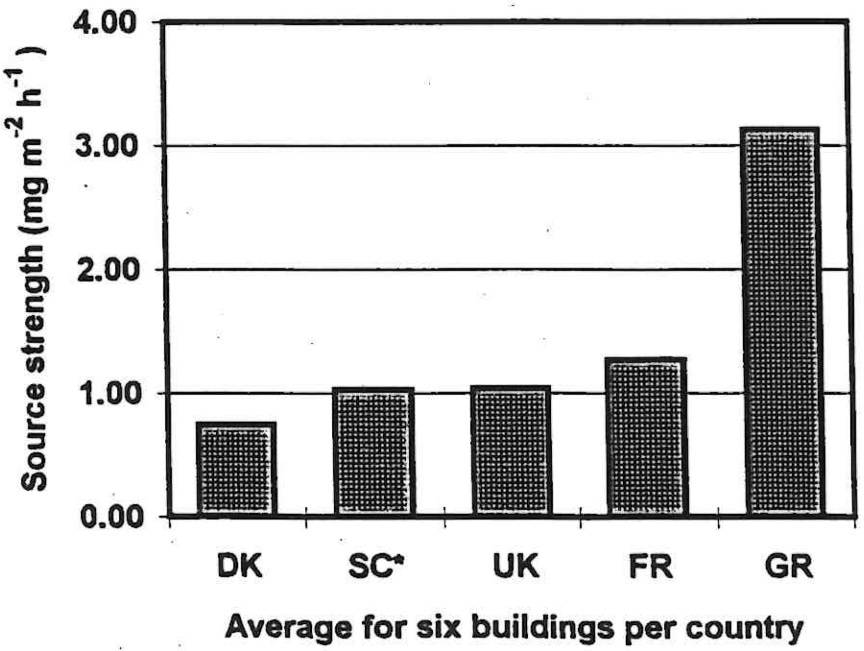

Figure 7. TVOC source strengths for five countries: European Audit Project preliminary data.

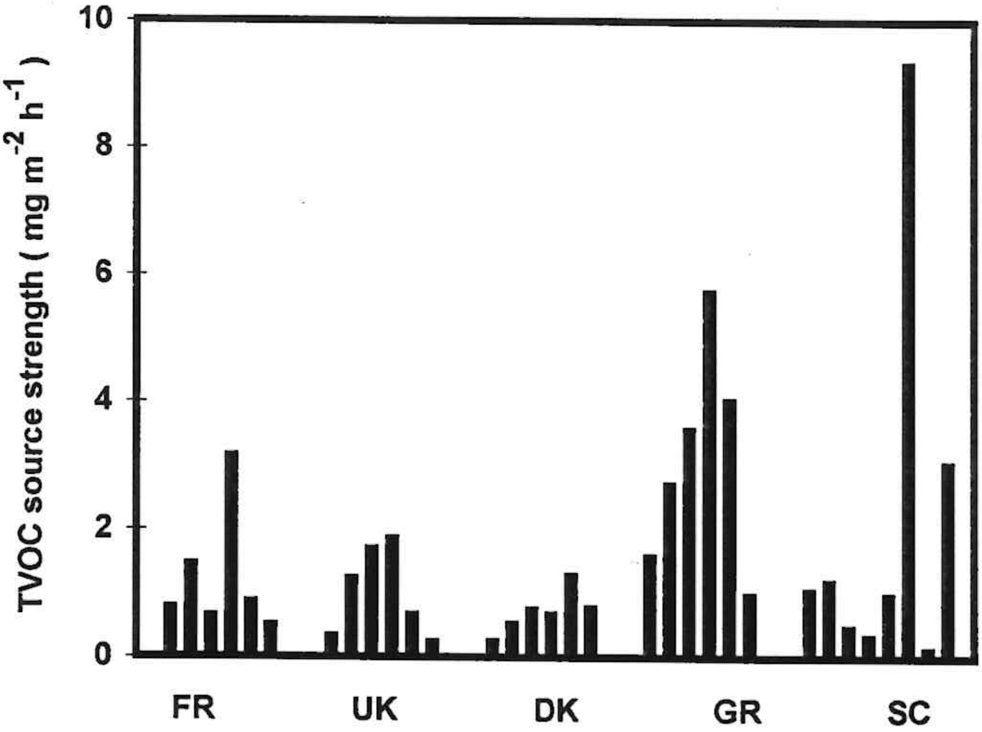

Figure 8. VOC source strengths and concentrations: European Audit Project preliminary data.

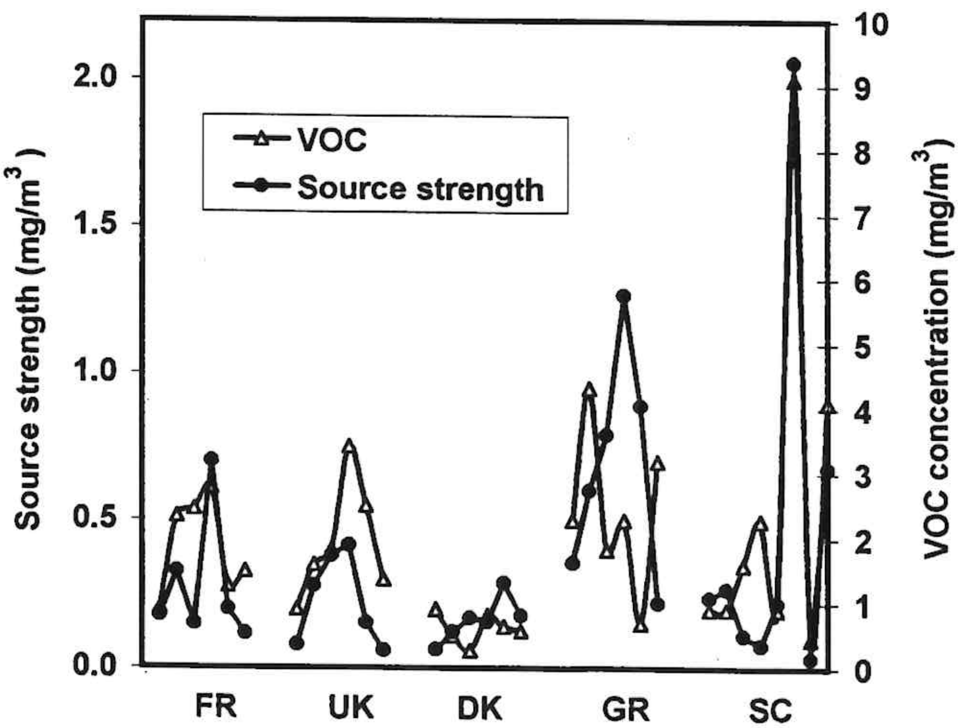

Figure 9. TVOC emission rate decays from various carpet assemblies (Ref. 10).

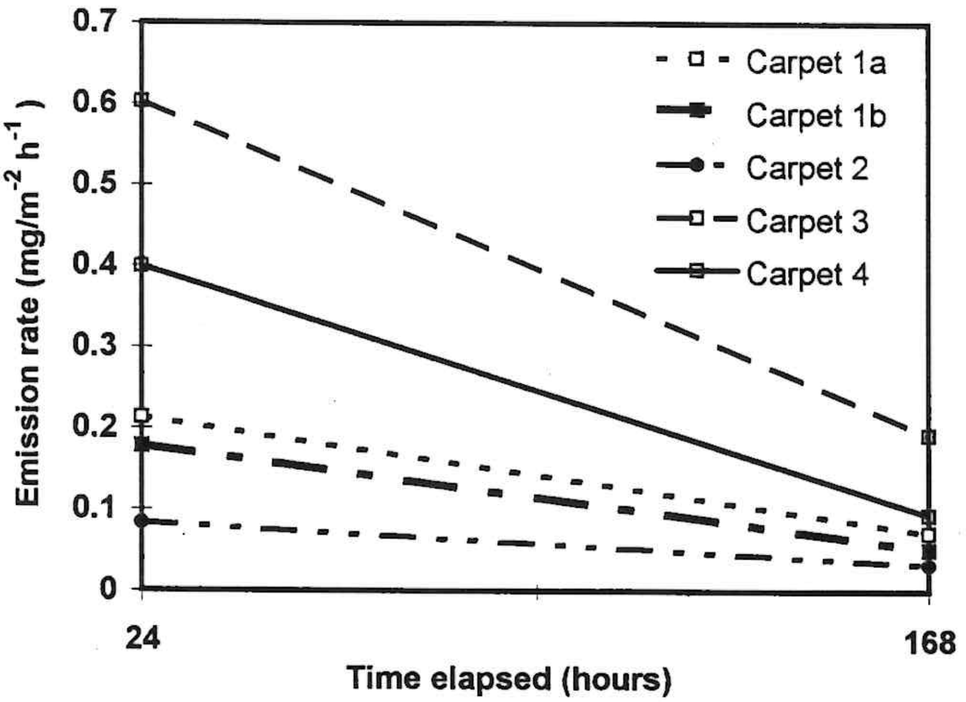

Figure 10. TVOC emission rate decays from vinyl backed carpet (Ref. 11).

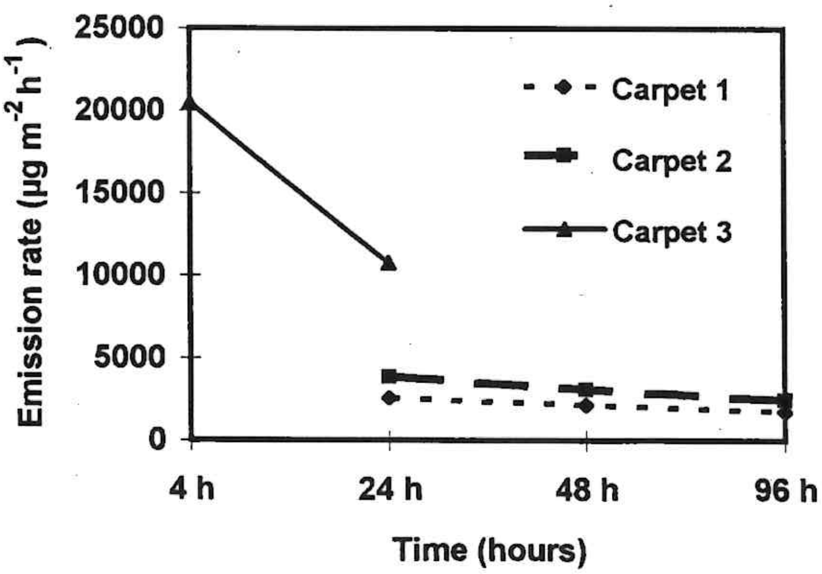

Figure 11. TVOC emission rate decay from carpet with textile secondary backing (Ref. 11).

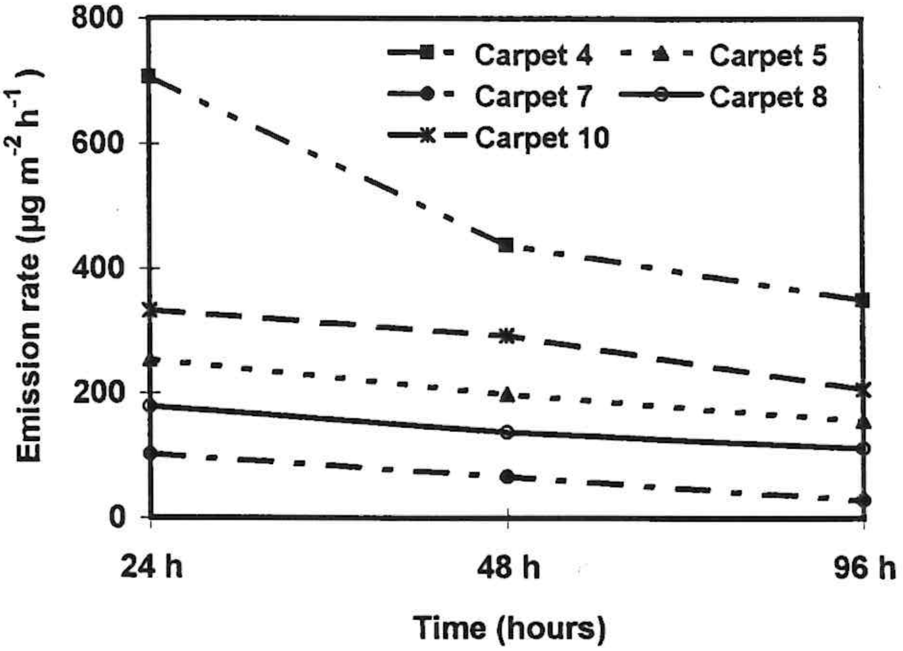

Figure 12. VOC concentration as a function of source strength and ventilation rate.