Vinyl Meeting Today's and Tomorrow's Indoor Air Quality Requirements

Frank E. Borrelli
The Vinyl Institute, Inc., 1300 Wilson Boulevard, Arlington, Virginia 22209

The growth of the "green" building market has raised new questions about the indoor air performance of building products. Indoor air pollution can consist of chemical, biological, and particulate irritants. Vinyl products have been shown to be well suited with respect to indoor air criteria as defined in current standards and "green" building guidelines. People spend more that 80% of their time indoors. Measurements have shown that levels of some indoor air contaminants can be many times higher than those outdoors. Known sources and factors for poor indoor air quality include tobacco smoke, radon, microbial contamination, dust, pet dander, fibers, and particulates. But they seem to be secondary to public concern for chemical emissions from products. Concerns of health effects from certain chemical air pollutants at even very low concentrations (parts per billion) in the workplace and the home have driven suppliers to test their products for emissions in order to assess the impact of those products on indoor air quality. Technology and methods to evaluate the indoor air performance of products have advanced over the past decade. State, federal, and green building rating guidelines with health-based exposure limits have evolved both domestically and globally. At the same time, the use of vinyl as a replacement for traditional materials and products in the building and construction sector continues to grow. New uses such as vinyl decking and rail, vinyl moldings and trims, along with new flooring and wall covering designs, have increased the use of vinyl in both exteriors and interiors of buildings. Product manufacturers' attention to impacts of products on indoor air quality has resulted in the development of new innovative vinyl compounds and new installation methods. Taken together, these improvements allow vinyl products to meet and exceed even the evolving target for product performance from an indoor air quality perspective. Many of these products require less maintenance and cleaning, thus resulting in lowering of indoor pollutants. Although technical successes have evolved, commercial success will depend on a conscientious consumer. **J. VINYL ADDIT. TECHNOL., 13:138–142, 2007.**

INTRODUCTION

The outbreak of "Legionnaires Disease" in Philadelphia in 1976, high profile court cases involving lead, asbestos, and mold over the past decades, unanswered questions about childhood asthma and other respiratory illnesses, and now, recent movements in "green" and "healthy" building markets, all have brought public attention to the quality of air we breathe while in buildings. Most people do spend most of their time indoors. Most experts agree that air quality inside a building depends on a number of factors, including how a building is designed, built and maintained; the construction materials, furnishings, and cleaning materials used in the building; the heating/ventilating/air conditioning (HVAC) system and moisture control; and the behavior of occupants.

Measurements have shown that levels of some indoor air contaminants can be many times higher than those outdoors. Although chemicals have been targeted as indoor air contaminants, relatively few have been found or suspected to be associated with public health issues. A 2000 report from a committee of the Institute of Medicine (IOM) of the National Academy of Sciences found strong causal evidence linking common indoor substances to the development or worsening of asthma symptoms in susceptible populations [1]. The report found "sufficient" evidence to show that cat dander, cockroaches, and dust mites make asthma worse, and that second-hand tobacco smoke worsens symptoms in small children. Evidence of an association was found for exposure to dogs, mold, fungi, and cold viruses, as well as to nitrogen dioxide from poorly functioning gas appliances. Limited or suggestive evidence also existed that indicated chemical contaminants such as formaldehyde fumes from furniture and building materials, as well as fragrances in personal care and household products, could worsen asthma symptoms.

Chemicals, particularly volatile organic compounds (VOCs), continue to receive high interest as indoor air

This paper was presented at *Vinyltec 2006*, Society of Plastics Engineers (SPE), Atlanta, GA, October 17–18 (2006).
Correspondence to: Frank E. Borrelli; e-mail: frank_borrelli@americanchemistry.com
DOI 10.1002/vnl.20116
Published online in Wiley InterScience (www.interscience.wiley.com).

contaminants. The VOCs for indoor air consideration include all volatile organics with sufficient vapor pressure to form a vapor at ambient temperatures and pressures. Most indoor air quality measurements include total VOC (TVOC), which refers to volatile organics evolving in the total area of a gas chromatogram between C_6 and C_{16}. Many—especially ketones and aldehydes—have noticeable odors at low concentrations.

Vinyl is one of the most versatile plastics in modern society and is used extensively in the building and construction market. Because the surfaces of some vinyl products are nonporous and easy to clean, uses such as resilient flooring, wall covering, and upholstery aid in minimizing the opportunity for buildup and proliferation of common indoor biological and dust-related pollutants. Vinyl is so effective in this regard that it plays an important role in health care facilities.

For example, researchers at Northwestern Memorial Hospital, Chicago, found that upholstery, such as vinyl, which can be easily disinfected, provides less opportunity than fabrics for the proliferation of antibiotic-resistant microbes [2]. And a recent survey of interior designers who specialize in health care design found that many of them prefer sheet vinyl flooring where infection control is an issue, because its seams can be heat-welded and it is self-coving [3].

Early on, manufacturers of vinyl wall coverings had taken steps to address moisture buildup behind their products with innovations such as mildew-resistant or "micro-vented" products that allow moisture trapped behind a decorative surface to escape into the room. Mildew-resistant adhesives help as well [4].

Vinyl's other uses include pipes, window frames, interior and exterior house trim, siding, decking and rail, roof membranes, wire and cable, carpet backing, and numerous consumer products, such as shower curtains, bed liners, coated fabrics, medical products, packaging materials, and toys. The unique versatility of vinyl is expanded by the ability to incorporate physical properties through the use of adjuvants to the polymer matrix. Some of these adjuvants may contain materials that are VOCs or other air contaminants. Also, solvents used for decorative printing or coatings can contribute VOCs that may release from the product. In most cases, VOCs would be released from the product during the fabrication step, when the materials are subjected to elevated temperatures (>300F), such as during thermoforming and calendering, or from weathering at the time of initial installation, before building occupancy.

Regardless, early concerns for the toxicological properties of vinyl chloride monomer, the use of additives, and the multitude of applications in building and construction make vinyl products of particular interest for understanding their potential contribution to indoor contamination.

RESIDUAL MONOMERS

With the 1970s discovery of the health risk of occupational exposure to vinyl chloride, the monomer used in the production of poly(vinyl chloride) (PVC) resins, and ensuing changes in the manufacture of resin to reduce workplace exposures, today's vinyl products are virtually devoid of residual vinyl chloride monomer. Typical resins produced today have residual vinyl chloride monomer levels of 1 part per million (ppm) or less [5]. Fabricated products subjected to thermal processing conditions above 300F have been found to have residual levels that meet low part-per-billion specifications for critical applications such as food contact [5]. Diffusion models and actual testing of products, even with higher residual levels, indicate that any residual vinyl chloride monomer would not release from the product to warrant concerns of exposure in an indoor environment.

STABILIZERS AND OTHER ADDITIVES

In 1996 the Vinyl Institute initiated research on the potential emissions evolving during the processing of a rigid vinyl product [6]. Much of the previous process emission research focused on industrial hygiene studies in the workplace around extruders and calendering equipment, and it was not aimed at quantification of volatile compounds. The research [6] was intended to identify and quantify the potential air pollutants evolving from vinyl compounds during processing at elevated temperatures (<300F). The research showed that emissions during the processing of rigid PVC compounds were relatively low and were mostly aliphatic hydrocarbons, such as mineral spirits. No hazardous air pollutants were found.

During this work, several additives used in rigid vinyl products were screened by using headspace gas chromatography – mass spectrometry (GC/MS) analysis to identify sources for these volatile emissions. Stabilizer packages were shown to have contributed to these low levels of volatile hydrocarbon. Although this work cannot be directly correlated to emissions from vinyl products at normal room temperature conditions, it provided insight into the source of volatile components in vinyl formulations.

Since that time, reports of research by stabilizer suppliers on low-VOC mixed-metal stabilizer packages for flexible vinyl have evolved [7]. Light hydrocarbons used as compatibilizing reagents, mixed with the stabilizers, and phenols have been targeted for reduction with the introduction of low-VOC stabilizer packages.

Similar results have come from investigation of the "new car" smell. Samples of commercial shower curtains, including samples of clear and printed shower curtains and a similar pigmented flexible vinyl film, were evaluated. Five-gram samples of each film were placed into 30-mL septum-sealed glass vials and maintained at room temperature for 16 h prior to GC/MS headspace sampling. The headspace sampling was performed by solid phase micro-extraction (SPME) for an exposure period of 1 h. Volatiles analysis was performed by desorption of the SPME material directly into the GC/MS instrument. The

DOI 10.1002/vnl

results found aliphatic hydrocarbons and phenol as volatile components of the clear shower curtain and film. The printed curtain volatile components included printing solvents, such as toluene and cyclohexanone, in addition to the aliphatic hydrocarbons and phenol.

PHTHALATES

Phthalates are used primarily as plasticizers in flexible PVC products, such as blood bags, children's toys, wire and cable coatings, and flexible vinyl wall and floor coverings. Nonpolymeric uses of phthalates, such as fixatives, detergents, lubricating oils, and solvents, lead to their inclusion in numerous and diverse products, such as cosmetics and wood finishes. The widespread use of phthalates results in multiple human exposure routes (oral, dermal, inhalation, and intravenous).

The potential for human exposure by inhalation to phthalates normally used in vinyl consumer products, especially diethylhexyl phthalate (DEHP) and diisononyl phthalate (DINP), is mitigated by high molecular weight, permanency in the vinyl polymer matrix, and low vapor pressure of these materials. Phthalates have vapor pressures several orders of magnitude lower than the VOCs usually associated with indoor air quality concerns (Fig. 1).

Headspace analysis by GC of samples of typical flooring and wall covering formulations indicates that phthalates are not present in the off gases 30 min after initial fabrication [8]. Some formulations contained the more volatile phthalate, diisobutyl phthalate (DBP). Measurements of air in an emission chamber containing 1 m^2 of PVC flooring material for 96 h showed no detectable levels of plasticizers at a detection limit of 4 ppb [9]. Recent research in Japan found that the air in a controlled experimental room containing new vinyl wall and floor coverings with a composition of ~15% of DEHP, tested over a one-year period from the time of installation, contained DEHP concentrations that were consistently several orders of magnitude below government guidelines of 120 micrograms per cubic meter ($\mu g/m^3$) [10].

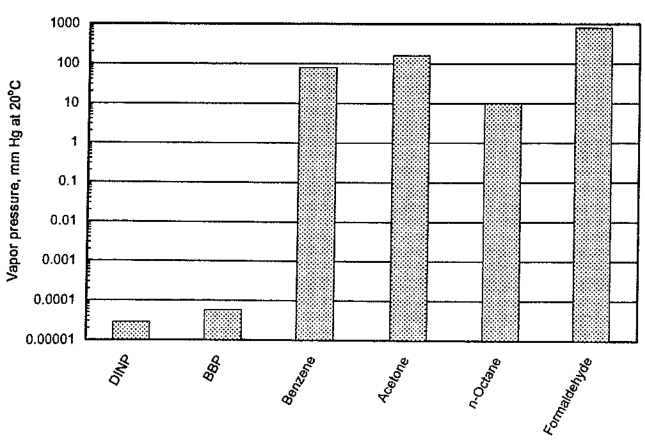

FIG. 1. Vapor pressure of various organic compounds.

Other studies involving the analysis of house dust have shown that some dusts contain low levels of phthalates. Indoor air concentrations of ~0.1 $\mu g/m^3$ have been reported and are associated with suspended particulate matter containing phthalates [11]. The bioavailability of DEHP associated with particulate matter is likely to be much lower than for vaporized DEHP [11]. It was estimated that human exposure to DEHP in indoor air is 0.13–1.18 $\mu g/L$ (mean 0.76 $\mu g/day$), or a maximum of 0.017 $\mu g/kg/day$ for a 70-kg person.

A more recent assessment showed that the potential human exposure levels from phthalates in dust are between 100,000 and 1,000,000 times lower than levels in rodents that produced minimal effects indicative of respiratory inflammation [12].

Since 1999, advanced methods have been used by the Centers for Disease Control and Prevention (CDC) to test blood and urine samples from thousands of Americans for the presence of more than 100 chemicals, from components of soybeans to phthalates. The CDC reports, in all, found only trace levels of phthalates at levels well within EPA safety levels that, therefore, should not pose a concern for human health (http://www.cdc.gov/exposurereport/).

STANDARDS AND GUIDELINES

Early standards, such as those developed by the state of Washington [13] and the United States Environmental Protection Agency (EPA) [14] to address the suite of symptoms commonly known as Sick Building Syndrome (SBS), set limits for relatively few specific chemicals, i.e., aldehyde, formaldehyde, PCH, and total volatile organic compounds (TVOC) (0.5 mg/m^3) for building products, based on environmental chamber tests. In addition, individual VOCs were not to be greater than 1/10 the threshold limit value (TLV) of occupational levels, and all emission levels had to meet applicable National Ambient Air Quality Standards (NAAQS). The SBS events are characterized by a significant number of building occupants with specific health complaints.

The science of measuring and assessing the impact of VOCs and other chemical pollutants on indoor air quality has improved greatly over the past decade. The concept of using TVOC as a screening method with further investigation into the specific VOC is now in more common practice. Key elements of the product review now include product/material assessment by using dynamic chamber test methods, estimated exposure assessment, and health risk assessment.

One particular assessment tool, California's Special Environmental Specification Section 01350 (http://www.ciwmb.ca.gov/greenbuilding/Specs/Section01350), screens products for a list of chemicals of concern and develops exposure models based on chamber emission rate test results. The standard uses California Non Cancer Chronic Reference Exposure Levels (CREL) values (http://www.oehha.org/air/chronic_rels/allChrels.html), California

DOI 10.1002/vnl

TABLE 1. Indoor concentration guidelines for 13 substances formulated by MHLW (as of Dec. 2004).

Substance	Indoor concentration guidelines[a]	Primary sources
Formaldehyde	100 $\mu g/m^3$ (0.08 ppm)	Adhesive for plywood, wallpaper, etc.
Toluene	260 $\mu g/m^3$ (0.07 ppm)	Adhesive, paint for interior finishing materials, furniture, etc.
Xylene	870 $\mu g/m^3$ (0.20 ppm)	
p-Dichlorobenzene	240 $\mu g/m^3$ (0.04 ppm)	Mothballs and toilet air fresheners
Ethylbenzene	3,800 $\mu g/m^3$ (0.88 ppm)	Adhesive, paint for plywood, furniture, etc.
Styrene	220 $\mu g/m^3$ (0.05 ppm)	Insulating material, bathroom unit
Chlorpyrifos	1 $\mu g/m^3$ (0.07 ppb) 0.1 $\mu g/m^3$ (0.007 ppb) for children	Ant repellant
Di-*n*-butyl phthalate	220 $\mu g/m^3$ (0.02 ppm)	Paint, pigment, adhesive
Tetradecane	330 $\mu g/m^3$ (0.04 ppm)	Kerosene, paint
Diethylhexyl phthalate	120 $\mu g/m^3$ (7.6 ppb)	Wallpaper, flooring material, electrical wire cover
Diazinon	0.29 $\mu g/m^3$ (0.02 ppb)	Insecticide
Acetaldehyde	48 $\mu g/m^3$ (0.03 ppm)	Adhesive for building materials, wallpaper
BPMC (carbamate-type insecticide)	33 $\mu g/m^3$ (3.8 ppb)	Termite eradicator

[a] Converted to values at 25°C; 1 ppb = 1/1000 ppm.

Proposition 65 lists [15], and listed chemicals with olfactory properties. The standard also covers chemicals that meet certain rate emission factors and make up more than 10% of the TVOCs. A number of product certification programs have incorporated California 01350 criteria into their programs.

The Carpet and Rug Institute (CRI) (http://www.carpet-rug.com/) first established an indoor air quality (IAQ) labeling program in 1992 to encourage manufacturers to decrease chemical emissions from carpet to very low ranges. Air Quality Sciences (AQS) worked with the carpet industry and the EPA to develop the emissions testing protocol by using environmental chamber technology, or ECT™. The AQS, as a third party testing organization, conducts IAQ testing for the industry. The program was later expanded to include carpet cushions and adhesives. More recently, CRI introduced Green Label Plus™, an enhancement to the CRI Green Label, which incorporates additional requirements to meet California's Collaborative for High Performance Schools (CHPS) low-emitting materials criteria. Products listed as CHPS-compliant materials have been chamber-tested to meet indoor air quality guidelines outlined in California's specification Section 01350.

In 2002 OMNOVA Solutions became one of the first companies in the interiors industry to achieve GREENGUARD INDOOR AIR QUALITY CERTIFICATION™ for its water-based vinyl wall coverings. Many wall covering products are offered as having low or no VOCs, as many of the formulations have been converted from solvent into water-based.

In 2005, the Resilient Floor Covering Institute (RFCI) introduced a certification program for resilient flooring, including vinyl floor covering, based on the California Section 01350 emission limits (www.rfci.com). The RFCI Floor Score® third-party certifier, Scientific Certification Systems, Inc. (SCS), not only reviews the results of the product VOC emissions report, but also reviews raw material inputs and manufacturing processes to ensure that a product is consistently manufactured to the standard.

Also in 2005, Greenguard introduced GREENGUARD Emission Criteria For Children and Schools™. This guideline suggests that children are more susceptible to toxins and sets limits for total phthalates at $<10\ \mu g/m^3$, TVOC at 0.215 mg/m^3, and individual VOC at 1/100 TLV, or ½ the CA chronic REL. This standard is unique in including phthalates. Phthalates measured include dibutyl (DBP), diethylhexyl (DEHP), diethyl (DEP), butylbenzyl (BBP), dioctyl (DOP), and dimethyl (DMP) phthalates.

GREEN BUILDING GUIDELINES

Each of the major green building guidelines for residential and commercial buildings contains specifications for managing indoor air quality.

The National Association of Home Builders (NAHB) Model Green Home Building Guidelines (www.toolbase.org) provide IAQ credits for homes designed with proper ventilation, particularly local ventilations for kitchens, water heaters and space heaters, and ventilation as a moisture management technique. Also, the guidelines specify credits for separation of house and garage, a major source of indoor air contaminants. Use of low-emitting versions of adhesives, carpets, particle board, composite wood, and wall coverings is also encouraged by the guidelines.

The USGBC LEED® www.usgbc.org/ rating systems provide credits covering tobacco smoke, carbon dioxide, ventilation, low VOC requirements for adhesives and sealants, paints and coatings, carpet systems, and elimination of urea-formaldehyde in composite wood.

The Green Globes rating system for commercial buildings, marketed by Green Building Initiative (GBI) www.thegbi.org, includes indoor environment credits, constituting ~20% of the building credits. Green Globes focuses on proper ventilation, indoor pollution control, and mois-

DOI 10.1002/vnl

ture control, as well as other design features for thermal, lighting, and acoustic comfort. Credits also cover the use of interior materials that are low-VOC emitting, nontoxic, and chemically inert.

National Institute of Standards and Technology (NIST) has developed BEES (Building for Environmental and Economic Sustainability) software for selecting cost-effective, environmentally preferable building products (www.bfrl.nist.gov/oae/software/bees.html) that includes criteria for comparing the indoor air quality performance of alternative products.

WORLDWIDE INDOOR AIR GUIDELINES

A number of countries have indoor air guidelines for products. In Europe, Germany has traditionally led these efforts, but recently a mandate has been given to the European Committee for Standardization (CEN) to harmonize guidance for the "Assessment of Release of Dangerous Substances from Construction Products." A technical committee (TC 351) has been put in place, and the work is progressing.

The Japanese Ministry of Health, Labor, and Welfare has published guidelines for 13 substances, including di-*n*-butyl phthalate (DBP) and di-*n*-ethylhexyl phthalate (DEHP) (Table 1). This list is also being referenced in a Japanese Automobile Manufacturers Association (JAMA) voluntary program to reduce VOC in automobiles.

CONCLUSIONS

Indoor air pollution can consist of chemical, biological, and particulate irritants. Vinyl products have been shown to be well suited with respect to indoor air criteria as defined in current standards and "green" building guidelines.

Progress has been made to identify and reduce VOCs as a potential indoor air contaminant in vinyl compounds and products used in the building environment. Certification programs have evolved for chemical emissions from products used in interior applications.

Common indoor air pollutants include chemicals emitted from such household items as cleaning products, insulation, adhesives, paint strippers, pressed wood products, tobacco smoke, and pesticides. Mold, pollen, pet dander, dust and dust mites, and microscopic insects can also cause problems, especially for the millions of people who are prone to allergies, asthma, and other indoor sensitivities.

The importance of adequate air exchange and moisture control in buildings and homes cannot be overstressed as a tool for minimizing indoor air problems.

ACKNOWLEDGMENTS

The author thanks the Vinyl Institute and its members for permission to publish this paper and Dr. William F. Carroll, Jr., and Mr. Robert A. Paradis for providing comments on a draft of the paper.

REFERENCES

1. "Clearing the Air: Asthma and Indoor Air Exposures," National Academy of Sciences, January (2000).
2. G.A. Noskin, P. Bednarz, T. Suriano, S. Reiner, and L.R. Peterson, *Am. J. Infect. Control*, **28**, 311 (2000).
3. "Materials Selection in Healthcare Design," a survey of the members of the International Interior Design Association Healthcare Forum, conducted by JSR Associates, Inc. on behalf of the Vinyl Institute, April, 2002.
4. www.wallcoverings.org.
5. F.E. Borrelli, P.L. de la Cruz, and R.A. Paradis, *J. Vinyl Additives Technol.*, **11**, 65 (2005).
6. D. Ernes and J. Griffin, *J. Vinyl Additives Technol.*, **12**, 180 (1996).
7. M. Jakupca, D. Stevenson, M. Harr, and T. Jennings, "Examination and Reduction of VOC's from Flexible PVC Formulations", in *SPE Vinyltec* (2002).
8. C. Howick and S. McCarthy, *J. Vinyl Additives Technol.*, **2**, 134 (1996).
9. D.F. Cadogan, *J. Vinyl Technol.*, **13**, 104 (1991).
10. Y. Kondou, H. Takahashi, H. Tanaka, and T. Yamamoto, "Long-Term Monitoring of Phthalates in Indoor Air After New Installment of PVC Products," in *Architectural Institute of Japan Annual Meeting* (2005).
11. L. Øie, L.-G. Hersoug, and J.Ø. Madsen, *Environ. Health Perspect.*, **105**, 972 (1997).
12. R. McKee, R. David, J. Butala, R. Parod, and L. Navarro, "Assessment of Hazard Potential and Risk for Asthmatic Responses Following Residential Exposure to Phthalates," in *The Society of Toxicology Annual Meeting* (2005). Abstract No. 264. http://www.phthalates.org/.
13. State of Washington Department of Environmental Health and Safety.
14. Indoor Environment Division under the Office of Air and Radiation. http://www.epa.gov/iaq/.
15. California Safe Drinking Water and Toxic Enforcement Act of 1986. http://www.oehha.org/prop65.html.

DOI 10.1002/vnl