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Volatile Organic Compounds (VOC) Criteria for New Construction

White Paper

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1.0 Introduction

Low levels of volatile organic compounds (VOCs) are ubiquitous in indoor and outdoor air from both natural and man-made sources and have long been associated with health effects and nuisance odors. Today, sources of concern include building materials, and consequently, VOC concentrations have recently been included as criteria for classifying buildings as "green."

In this context, new construction is increasingly being tested prior to occupancy for airborne VOCs to verify that materials used for construction are "low-emitting." "Green buildings" in compliance with air quality criteria are often assumed to provide an environment which protects the health and comfort of building occupants.1 This white paper reviews the efficacy of preoccupancy VOC sampling and considers alternative approaches for evaluating indoor air quality (IAQ) in new construction.

VOC criteria for new and renovated buildings have been included in Leadership in Energy & Environmental Design (LEED) credits by the U.S. Green Building Council (USGBC),[1] the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) high-performance green building standard,[2] the International Green Construction Code (IgCC),[3] the WELL Building Standard[3a] and Green Globes.[3b] The most commonly used VOC criteria for indoor air are those specified by LEED. The most recent iteration of LEED VOC criteria are included in standard version 4 (v4), which sets concentration limits for 33 individual VOCs and for total VOCs (TVOCs).[1] ASHRAE 189.1 and IgCC also specify concentration limits for 33 VOCs, including 29 listed by LEED (Table 2).[2]

This white paper examines VOC concentration limits included in those three green building standards. It includes background information on VOCs in indoor air, describes IAQ concerns encountered during new construction, presents a critical review of VOC sampling and outlines alternative approaches for preoccupancy IAQ assessment. The information presented is based on a comprehensive review of the scientific literature. Where no studies were available documenting current conditions, this White Paper notes observations of members of the AIHA Project Team, who conduct field investigations of new construction.

Varying definitions are in use for VOCs and TVOCs. This white paper is based on a general definition of VOCs as "organic compounds that evaporate at ambient temperatures by off-gassing from solids or liquids." The term, "VOC criteria for new construction" references LEED v4, ASHRAE 189.12 and IgCC.[3] We are defining TVOCs in general terms as the cumulative concentration of measured VOCs in a sample."

2.0 Background

2.1 Historical Perspective

VOCs are ubiquitous in both outdoor and indoor air. Sampling typically identifies between 50 and 300 different VOCs in indoor air, with individual compounds in the 1 to 10 μg/m^3 range and TVOCs in the 200 to 5000 μg/m^3 range.[4-16] Indoor VOCs originate from construction materials in addition to outside sources, vegetation, bioeffluents, occupant activities, and building maintenance.[13-16]

Although the health effects of VOCs on building occupants have been recognized for over 100 years,[17] the first chemical characterization of VOCs in building air (in Rotterdam) was not published until the 1960s.[18] In the 1970s, the U.S. Environmental Protection Agency (EPA) measured the concentrations of air pollutants indoors and compared them to outdoor exposures, concluding that personal air exposures from chemicals indoors were greater than outdoor exposures.[5] At that time, the EPA recommended limiting VOC emissions from wet products used indoors (e.g., paint) because of their contribution to outdoor ozone levels (reactive organic gases).[9]

In 1973, ASHRAE addressed IAQ concerns by prescribing minimum ventilation rates and contaminant concentration limits based on standards for outdoor air and worker protection. In 1981, ASHRAE suggested criteria for over 40 indoor air pollutants, and in 1989 it added an IAQ limit of one-tenth the workplace standard to accommodate sensitive occupants.[19] During the 1980s, European guidelines recommended concentration limits for some VOCs in indoor air.[20] Compliance with these IAQ guidelines was determined by collecting air samples and analyzing them for the specified pollutants.

Strategies for controlling VOCs in buildings were discussed at the ASHRAE IAQ conference in 1987.[21] In 1991, VOC concentration limits to address off-gassing were first proposed for new buildings.[22] In 1999, the USGBC issued the LEED Green Building Rating System for New Construction. This was a voluntary program in which buildings were certified as LEED-compliant if specified procedures were followed promoting criteria for sustainability and environmental quality. Credits for awarding LEED status included concentration limits for formaldehyde, 4- phenylcyclohexene (4-PC), and TVOC based on sampling conducted prior to occupancy.[19] In 2013, LEED was updated to increase the number of VOCs to 33 compounds.[23] This expanded list was taken from State of California guidelines for chamber testing of product emissions.[24] The State of California derived that list based on industrial chemicals of general concern in drinking water, outside air, and the workplace,[21] but did not consider whether listed VOCs were present in indoor air.

In 2011, ASHRAE adopted Standard 189.1, Design of High-Performance Green Buildings,[2] which specified VOCs for preoccupancy sampling, providing a list of compounds similar to that for LEED. In 2012, similar IAQ provisions were added to the IgCC as an elective credit for new commercial buildings.[3] LEED, ASHRAE, and IgCC all allow a flush-out as an alternative to VOC sampling. Flush-out is based on the assumption that additional ventilation at the end of construction will reduce VOC concentrations to acceptable levels.[1-3]

In 2013, IgCC considered the addition of VOC criteria to its National Green Building Standard (NGBS) for residential structures. However, it elected not to add them because of concerns that VOC sampling was not predictive of overall IAQ, would unnecessarily increase costs, could delay occupancy, and would not detect construction-related IAQ problems.[68]

2.2 Effects of VOCs at IAQ Concentrations

Over 100 VOCs are typically measured in the air in buildings without occupant complaints.4-16 Little toxicological information is available for these compounds at the relatively low levels found in buildings. A review of studies comparing the health of green building occupants to those in conventional buildings identified no assessment that included VOC measurements.[26] Some highly sensitive individuals may experience symptoms when exposed to VOCs at very low concentrations, including background levels

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typically present in buildings. Irritation of the eyes, nose, and throat has been the most widely investigated health effect at IAQ concentrations. These studies have found that sensory irritation thresholds generally exceed VOC concentrations found indoors.[27,28] Another review of IAQ data from across Europe found that conservative exposure limits for noncancer effects of VOCs were not exceeded, with the exception of formaldehyde (discussed below).[29]

Some studies of sick building syndrome (SBS) have suggested that nonspecific symptoms reported by occupants may be related to VOC exposure, but such an association has not been established.[30] SBS studies typically have been limited in scope and based solely on occupant questionnaires rather than on medical findings; do not consider other potentially important environmental factors (e.g., dampness, noise); and do not differentiate among reactions to environmental conditions, psychosocial factors, and unrelated illness. Factors unrelated to VOCs can contribute to reported SBS symptoms, as seen in a recent study where SBS symptoms were associated with job stress, interpersonal conflicts, and overcrowding.[31] VOC off- gassing from building materials has also been suggested as a cause of asthma,[29] but results of epidemiological studies have been inconclusive.[30,31] Studies comparing VOCs in building areas with and without occupant reports of building-related symptoms (e.g., irritation of the eyes, nose and throat) show no consistent pattern.[30]

A recent study of the effects of VOC mixtures on occupants was based on improved methodology, where all variables were closely controlled. A panel of office workers was evaluated in a controlled experimental environment at TVOC concentrations of 50 μg/m^3 versus 500 μg/m^3. Lower cognitive function was measured at the higher TVOC level. In the study, VOCs contributing to TVOC concentrations were compounds typically off-gassed by building materials.[26]

Formaldehyde is one of the few indoor air pollutants for which there is a demonstrated association between IAQ concentrations and human health effects. Occupant formaldehyde complaints were first reported in the 1980s when high concentrations emitted by pressed wood and urea-formaldehyde foam insulation were prevalent and ambient concentrations exceeded 100 μg/m^3.[32] A study of symptoms reported by 2,000 occupants at this time (1987) found a dose-response relationship with airborne formaldehyde as follows:[33]

Table 1: Dose-Response Relationship of Symptoms and Formaldehyde Concentrations in Ambient Air

Formaldehyde (μg/m3)	Eye Irritation	Nose/Throat Irritation	Headache	Rash
>300	90%	~85%	71%	~25%
300	32%	36%	36%	17%
100	12%	12%	-	None
<100	~2%	~5%	7%	None

Improvements in urea-formaldehyde resin formulations used in pressed wood products have substantially reduced indoor concentrations, which are now typically below 50 μg/m^3.[34,35]

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Chronic effects such as cancer are also a concern with VOC exposure. Theoretical cancer risks exceeding an incremental risk of one additional cancer case per million people, which is considered to be an acceptable risk, have been calculated for some compounds,[36] suggesting that air concentrations typically measured for some VOCs indoors may be of concern. For example, benzene, which is classified as a human carcinogen, is typically present at 1 ppb (3.19 µg/m^3) in both indoor and outdoor air.[4-16] According to WHO, this concentration has an associated excess lifetime risk of cancer of approximately 1 in 100,000.37

Cancer risk estimates have much uncertainty, and associations between VOC concentrations in a building and cancer incidence in occupants have not been evaluated in epidemiological studies, due in large part to the difficulty of doing so when exposures are relatively low and the populations exposed are transient. Although theoretical risks have been suggested at typical IAQ concentrations for some compounds, chronic effects specifically associated with IAQ concentrations have not been consistently demonstrated. Thus clinical (observable) health effects from exposure to VOCs related to building occupancy are uncertain.

In general, assertions that VOCs present a hazard to building occupants are based on health effects documented at higher concentrations than those typically measured indoors,[38] although studies of individual VOCs in animals and humans have shown the potential for long-term effects (other than cancer), such as neurological, endocrine, and reproductive effects.[39] At higher levels of exposure than experienced in indoor environments (e.g., occupational), no conclusive evidence indicates that these effects occur in building occupants.

2.3 Development of VOC Concentration Criteria

VOC criteria for new construction were derived from California's Chronic Reference Exposure Levels (CRELs) for noncancer chronic effects developed by California's Office of Environmental Health Hazard Assessment (OEHHA). CRELs are based on "points of departure" (POD), defined as either a no observed adverse effect level (NOAEL), a lowest observed adverse effect level (LOAEL) if a NOAEL was not identified, or a benchmark concentration (BMC) (which is calculated using a model and the dose-response data from a single, key study). PODs are identified by first choosing the best study and identifying the most sensitive endpoint. Next, the dose- response data are reviewed to identify the lowest dose at which an adverse effect occurs (LOAEL) and then the next lowest dose, by definition, is the NOAEL (which must be a non-zero dose). The true threshold for an effect would likely be between the LOAEL and NOAEL. In some studies, effects are seen at the lowest dose evaluated, so the LOAEL can be identified but the NOAEL cannot, given the available data. CRELs are based on a NOAEL, LOAEL, or BMC, divided by uncertainty factors to account for incomplete information (e.g., using a LOAEL instead of a NOAEL, using subchronic data to evaluate chronic exposure), interspecies differences, and intraspecies differences (e.g., to protect sensitive subpopulations). The resulting CREL is considered protective of sensitive individuals.[40]

The methodology used to develop CRELs is illustrated by the supporting documentation for formaldehyde:

> In the study chosen as the basis for the CREL (Wilhelmsson and Holmstrom, 1992), nasal obstruction and discharge and frequent cough, wheezing, and symptoms of bronchitis were reported in 66 workers exposed for 1 to 36 years (mean, 10 years) to a mean formaldehyde concentration of 0.21 ppm (260 µg/

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m³) (range, 50-600 µg/m³) in a formaldehyde production plant. The referent group (office workers) were exposed to a mean concentration of 90 µg/m³. Symptom data were collected using a questionnaire, and exposed industrial workers had significantly more symptoms than the office workers. The State of California identified the critical effects as nasal obstruction and discomfort, lower airway discomfort, and eye irritation. Sampling and symptom reports were collected at a single point in time. OEHHA considered the cited formaldehyde study to be relatively free of confounding exposures (it should be noted that this study was conducted in a petrochemical plant, a setting where workers are typically exposed to multiple irritants). OEHHA applied an uncertainty factor of 10 because of concern for potential asthma exacerbation in children related to the depletion by formaldehyde of S-nitrosoglutathione (GSNO), an endogenous bronchodilator, resulting in a CREL of 0.009 mg/m³ or 9 µg/m³.[41]

New construction VOC concentration limits were set at the CREL value. Formaldehyde and benzene are exceptions, with new construction VOC concentration limits set higher than the CREL in recognition of the fact that background levels exceed the CREL.1 There is no CREL for TVOCs 42 and no toxicological basis for the TVOC limit of 500 µg/m³.

2.4 IAQ and New Construction

VOC concentrations at construction sites typically evolve as follows:

- Before the structure is enclosed, VOC concentrations reflect outdoor air concentrations and off-gassing from initial construction materials (e.g., framing, concrete).
- As interior finishing materials are applied (e.g., adhesives), VOCs from off- gassing are initially elevated but decrease rapidly.
- At substantial completion of the building, IAQ is often affected by products used for final touch-up work (punch-out).
- After move-in, off-gassing from the completed building assembly declines while furniture, occupants, and building operation continue to emit VOCs.

Owner acceptance of new construction has traditionally been based on an inspection to verify completion, structural integrity, systems operation, and aesthetics. Preoccupancy VOC testing has only recently been included in this process. IAQ became widely recognized as a concern in the 1980s, when off-gassing from pressed wood, insulation, 4-phenyl cyclohexane (4-PC) from carpets, and solvents from various construction products became health concerns.[43] Many complaints (e.g., eye and respiratory irritation) were associated with emissions from construction materials, and off-gassing odors were often highly noticeable, persisting for many months.[32]

Since that time, many product manufacturers have reduced these emissions considerably through product modifications and substitutions.9 With increasing use of lower-emitting products in building assemblies, there has been a downward trend in ambient VOC levels. A comparison of indoor VOC levels from 1981-1984 as compared to 1999-2000 found a significant reduction in the concentrations of many compounds listed for pre-occupancy sampling.10 A review of IAQ in homes across Canada, similarly found that the concentration of most VOCs declined by factors of 2 to 5 times between 1992 and 2010.[44]

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The use of construction materials and furnishings with lower emissions has become increasingly common since 1990 (pre-dating green building standards),[33] leading to a substantial reduction in the intensity and duration of off-gassing odors after construction.[44,45] This reduction in a significant source of indoor contaminants was achieved in part from using pressed wood containing less free formaldehyde in the urea-formaldehyde resins, products with little or no solvent content, and carpets made without 4-PC.[45]

While there are no recent studies documenting the prevalence of occupant IAQ complaints, the experience of AIHA Project Team members conducting field investigations indicates that occupant complaints associated with off-gassing are no longer common, but occasionally occur when products are installed that either do not comply with industry standards or are misapplied. These practitioners also report that IAQ complaints in new buildings are now primarily related to thermal discomfort, excess moisture, poor control of pollutant sources other than those related to construction, migration of odors from ongoing construction adjacent to newly occupied areas or noise.

3.0 Critical Review of New Construction IAQ Assessment Based on VOC Sampling

3.1 Relevance of Listed VOCs to IAQ

VOC criteria for new construction were developed from listings of industrial chemicals of concern in the workplace, drinking water, and outdoor air[41]; many of these chemicals are not relevant to IAQ assessment. The AIHA Project Team reviewed data from published studies with respect to the prevalence of VOCs specified for pre-occupancy sampling and found that approximately half are not typically found in buildings. Furthermore, approximately half of the specified VOCs that are present in indoor air are detected only at very low concentrations (<5 μg/m^3). In contrast, the majority of compounds typically present in indoor air do not have new-construction VOC criteria and thus are not considered in preoccupancy sampling. For example, acetic acid and hexanal are not measured even though they are often among the highest VOC concentrations reported in indoor air. [4-16,46-48]

3.2 Use of Health-Based Target Levels as VOC Criteria

Although new-construction VOC criteria are not considered health standards, they were derived from target levels (CRELs) calculated by the State of California using a health risk assessment approach.[24] Objectives and assumptions underlying CREL calculations should be considered in relation to IAQ assessment. CREL target levels are intended to *prevent* health effects in sensitive populations without considering feasibility.[41] An alternative approach would be to *minimize* health effects to the extent feasible. This latter approach protects most sensitive individuals while recognizing that a few may still be affected by extremely low concentrations.

Risk assessments are complex. To conduct a risk assessment, numerous choices must be made (e.g., key study, key endpoint, exposure variables, uncertainty or safety factors). Acceptable concentrations may differ when risk assessors select different values for these elements. Consequently, different organizations may develop different acceptable concentrations using approaches based on risk assessment principles.

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For example, the CREL for formaldehyde (9 ppb)49 is an order of magnitude lower than the formaldehyde concentration calculated by the World Health Organization to be acceptable for indoor air (100 ppb)[37] because of different objectives and approaches underlying these risk assessments. Also, WHO's formaldehyde risk assessment considered the availability of control technology,[37] which the State of California did not consider in its CREL calculation.[49] The resulting CREL is lower than background levels typically present in the absence of significant emission sources (~40 ppb).[35]

The most significant limitation of depending on CRELs to assess overall IAQ is that there are CRELs for only a small fraction of VOCs found in buildings. CRELs have been developed for only 99 compounds and have not been established for the majority of compounds present in indoor air. Although the listed VOCs may all be in compliance with the specified concentration limits, other VOCs can still be present at levels impacting occupants.

3.3 Use of the TVOC Parameter

Mixtures of chemicals in indoor air are an additional concern. They are rarely evaluated, either in general or in terms of indoor air, because their composition is so variable that testing one mixture may not provide results that can be used to assess possible effects from exposure to another mixture.

Some agencies have tackled the toxicity of mixtures. For example, EPA has developed Provisional Peer-Reviewed Toxicity Values for Complex Mixtures of Aliphatic and Aromatic Hydrocarbons.[50] The Agency for Toxic Substances and Disease Registry (ATSDR) has developed Toxicological Profiles, and in some cases Minimal Risk Levels (MRLs) for a number of mixtures including jet fuels, fuel oils, gasoline, and total petroleum hydrocarbons.[51] ATSDR also specifically targeted the toxicity of mixtures in their "Interaction Profiles."[52] In 2007, for example, ATSDR evaluated a mixture of carbon monoxide, formaldehyde, methylene chloride, nitrogen dioxide, and tetrachloroethylene based primarily on concerns regarding coexposure to these chemicals in residential indoor air (post occupancy). ATSDR found no data to suggest that joint toxic action was anything but additive (i.e., the joint toxic action was not synergistic or antagonistic), however they did note that the data available were incomplete.[54]

ATSDR's findings are consistent with an evaluation of mixture toxicity conducted by the Interdepartmental Group on Health Risks from Chemicals (IGHRC), which succinctly stated: if dose levels are below thresholds of effect for each component, "no toxicodynamic interactions will arise."[55] Three independent scientific committees of the European Commission recently analyzed the available scientific literature regarding chemical mixtures and concluded that interactions (including antagonism, potentiation, and synergism) usually occur at medium or high doses (relative to the lowest effect levels of the individual constituents in a mixture) and, at low exposure levels, interactions are either unlikely to occur or are toxicologically insignificant.[56-58] Therefore, from a toxicological standpoint, most mixtures of chemicals exert toxicity related to the threshold of effect for each chemical (lowest concentration associated with health effects).

In 1986, guideline values of TVOC were proposed as a measure of acceptable IAQ.[59] However, in 1997, the European Commission reviewed the scientific literature and found that a variety of noncomparable TVOC analytical methods were in use and that, in addition, TVOC concentrations could not be associated with adverse health effects, concluding, "Available data does not allow establishing thresholds for TVOC health

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effects."[54] Since toxicity criteria do not exist for specific mixtures, effects are best evaluated by comparing the concentrations of individual chemicals to their respective toxicity criteria. Measuring the concentrations of TVOC mixtures (with varying compositions) using methodology that produces inconsistent results, and comparing those results to a toxicity criterion with no scientific basis, does not provide useful information.

Subsequent evaluations have reached the same conclusion and do not recommend using TVOC as an IAQ standard.[29] For example, AIHA stated in 2015:

> "Currently, there is no accepted definition for TVOCs by IAQ practitioners and those conducting post-construction IAQ sampling. This lack of a commonly accepted definition has resulted in significant differences in the reported TVOC measurements collected by practitioners, which in turn results in the inability to compare sampling and analytical data from one set of samples to another set."

AIHA Project Team members conducting field investigations report that the TVOC limit is the criterion most frequently exceeded in preoccupancy sampling.

3.4 Use of VOC Criteria as a Screening Tool for Materials Emissions

Although an important objective of VOC sampling for new construction is to assess off-gassing from building materials, many VOCs in indoor air prior to occupancy may originate from nonconstruction sources such as industries, transportation, outdoor vegetation and building maintenance.[13-16] One study investigated the origin of VOCs identified in office air and found that only a few compounds could be primarily attributed to materials off-gassing, while most VOCs detected were from outside air or multiple sources.[46] Another study found that proximity to road traffic was a significant contributor to VOCs listed as new construction criteria.[14]

In a 2014 study, VOCs associated solely with building materials (no furniture or occupants; outside concentrations subtracted) were tracked in a test home constructed with commercially available, low-emitting materials. This study identified 32 VOCs as consistent indicators of structural emissions.[60,61] Eighty percent of the construction-related VOCs identified in this study are not included for pre-occupancy sampling. Conversely, 80% of listed VOCs were not considered to be construction-related in the test home study.

3.5 Sampling Strategy

VOCs vary both spatially (between sites) and temporally (when collected at different times). Factors influencing concentrations include temperature, humidity, ventilation, surface scavenging, and indoor chemistry (i.e., reactions with ozone).12- 16,62 A study tracking VOC levels in a newly constructed test home without furniture or occupants found VOC concentrations to be seasonal, with significant changes associated with outdoor temperature.[63] New construction VOC criteria do not consider variability and prescribe only a minimum number of samples to be collected.[1] Sampling for a few hours under "as is" conditions does not reliably document average or worst-case exposures.

Most materials emissions are diminishing at the time of preoccupancy sampling. Where this occurs, actual occupant exposure to construction-related VOCs would be lower after move-in. A study of 11 renovations found VOC concentrations decreased by 70% after 1 week and 90% after one month.[64]

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VOC concentrations measured during pre-occupancy sampling may also exceed the long-term average when samples are collected soon after application of wet products. Although green building standards specify that VOC measurements are to be made after construction is completed, AIHA Project Team members conducting field investigations, note that punch-out work sometimes continues during pre-occupancy sampling. Conversely, VOC concentrations may be underpredicted when samples are collected under building conditions that temporarily reduce emissions (e.g., cool temperatures).

Pre-occupancy VOC samples can be collected by either sorbent tubes or Summa canisters, methods which have different collection efficiencies. Analysis of sorbent tubes is typically by thermal desorption, followed by gas chromatography and mass spectrometry. Such analyses do not detect some VOCs in indoor air and are associated with considerable uncertainty.[9] Comparison of side-by-side samples collected by different sampling and analytical methods found that variability could result in different compliance levels with green building criteria.[65]

3.6 Resolution of IAQ Problems

Noncompliance with new construction VOC criteria is resolved by either resampling until a complying value is obtained or by flushing out the building with outside air.1 The AIHA project team is not aware of any cases where preoccupancy sampling actually linked specific materials to exceedance of preoccupancy VOC criteria. Pre- occupancy VOC sampling has not been shown to provide additional benefit in terms of improved IAQ. It does increase project cost and can delay occupancy without producing useful data.

AIHA Project Team members have noted that the relative prevalence of IAQ complaints in new buildings related to non-VOC factors such as excess moisture has increased as emissions from construction materials have declined. Pre-occupancy IAQ assessment based on VOC sampling does not address many construction-related conditions that may adversely affect occupants, as illustrated by the following scenarios:

- **A problematic compound is detected by prescribed analytical methods but is not listed for new construction VOC sampling.** For example, acetic acid, which is a ubiquitous contaminant emitted by natural wood, has been associated with the corrosion of museum exhibits70 and building HVAC coils.61
- **A problematic compound is not measured by prescribed sampling method.** Amines can cause ongoing odors from misapplied insulation,62 but they are often not detected by the VOC sampling methods specified for preoccupancy sampling.
- **Samples are not collected under critical conditions.** Peak concentrations associated with occupant irritation are not measured.
- **Problematic conditions (e.g., moisture) cannot be measured by air sampling.** A moisture investigation is needed to identify building dampness associated with allergy symptoms.
- **Post construction VOC concentrations overstate conditions after occupancy.** Emissions from building materials diminish rapidly after installation.

The following case studies from investigations conducted by AIHA Project Team members illustrate the failure of VOC sampling to identify IAQ problems:

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A LEED Gold building with all materials certified as low-emitting had an ongoing fishlike odor after occupancy. Air samples analyzed by standard methods for VOCs failed to identify the source. A general assessment determined that the source was an insulating material that had been misapplied in the return air plenum. The odorant was identified as tri-methyl amine; a compound not included in new-construction VOC criteria and not detected by standard VOC analysis.

Mold growth occurred during the summer following construction of a LEED Gold building because of excessive infiltration of hot and humid outdoor air. Although the HVAC systems had received the LEED commissioning credit, they were never balanced, and the building operated under strong negative pressure. Indoor environmental quality evaluation under LEED does not consider moisture issues.

4.0 Alternative Approaches for Preoccupancy IAQ Assessment

Other protocols have been proposed for assessing IAQ in new construction. Of the approaches discussed below, two continue to rely on VOC sampling, while the third conducts a general evaluation without sampling.

4.1 LEED Pilot Credit

USGBC has proposed an alternative path to LEED compliance based on ASHRAE Standard 62.1, Indoor Air Quality Procedure: Currently listed VOCs are retained, the TVOC standard is dropped, and unlisted compounds detected in significant quantities in air samples are considered concentration limits based on health guidelines from a "cognizant authority." This alternative also allows a reduction in ventilation if VOC concentration limits are met and if 80% of a test panel of occupants or other individuals finds the air "acceptable".[66] While this approach does consider additional VOCs, it is subject to the other deficiencies noted in section 3.0.

4.2 Proposed IgCC Revision

Comments to IgCC on VOC criteria have noted that several listed compounds exceed 500 µg/m^3, the cumulative concentration allowed for TVOC. A proposed revision to the IgCC would modify VOC criteria by deleting 11 compounds with concentration limits exceeding 500 µg/m3. It would also subtract concentrations measured in outdoor air.[67] This approach is subject to the other deficiencies noted in section 3.0.

4.3 IAQ Performance Standards

In lieu of VOC sampling, a general preoccupancy assessment can be conducted to determine if building conditions are consistent with specified performance standards. Two performance standards related to VOC control are already included by LEED, ASHRAE, and IgCC as options for green building credit. These specify that HVAC systems must provide a minimum ventilation rate and that compliance with emission limitations must be documented for construction materials. VOC concentrations are reduced when ventilation rates and materials emission standards are met.[34] Performance standards could also be set for control of excess moisture and other contaminant sources. For example, the IgCC National Green Building Standard (NGBS) includes a preoccupancy assessment to determine whether moisture control objectives have been met.[25]

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A performance standard-based approach to preoccupancy assessment could be more comprehensive and more conclusive than currently achieved by VOC sampling. An assessment of building performance could include an inspection to determine if:

- All surfaces are dry and free of mold growth;
- Construction-related moisture sources have been eliminated; and
- Structural and mechanical surfaces are clean.

If unusual odors are detected, the assessment could include identification of the source and consideration of control measures. Construction records can also be reviewed to confirm that:

- All materials used comply with emission specifications;
- HVAC commissioning establishes that ventilation and comfort specifications will be met; and
- Special use areas are designed and constructed to minimize occupant exposure.

5.0 Conclusions

5.1 VOC sampling does not evaluate overall IAQ.

5.1.1 Building construction and renovation are major determinants of IAQ and may create conditions adversely impacting the health and comfort of occupants.

5.1.2 Sampling a complex, variable mixture of compounds, cannot be relied on to draw conclusions on overall building IAQ.

5.1.3 Low-emitting products are now in common use and substitution of low- emitting construction materials has significantly improved IAQ. Green building specifications minimize VOC concentrations in new construction. As a result, overall VOC concentrations are lower, and complaints related to off-gassing are less prevalent. IAQ complaints reported in new buildings now primarily involve thermal discomfort, HVAC deficiencies, dampness, accumulated dust contaminant migration into occupied areas from ongoing construction or noise. These problems are not identified by VOC sampling.

5.2 VOC sampling is not an effective screening tool for materials emissions.

5.2.1 A critical review of current protocols in use to assess potential IAQ impacts of new construction and renovation finds that they are inconclusive with respect to screening materials emissions.

5.2.2. The majority of VOCs in indoor air originate from nonconstruction sources and new-construction VOC criteria do not target compounds related to IAQ. Identified VOCs for new-construction VOC criteria were selected from lists of industrial chemicals without considering IAQ. As a result, the majority of compounds with new-construction VOC criteria are not significant with respect to IAQ.

5.2.3 Green building specifications are generally effective in controlling VOCs through limits on product emission and ventilation requirements. VOC sampling has not been shown to provide additional benefit in terms of improved IAQ. It adds to project cost and can delay occupancy without producing useful data.

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5.3 VOC sampling is not predictive of occupant health effects.

5.3.1 VOCs are ubiquitous in indoor air and may affect occupant health when present in elevated concentrations. Formaldehyde is unique among VOCs in that studies are available demonstrating clinically observable symptoms at typical IAQ concentrations.

5.3.2 Contaminant concentration limits have been effective in protecting workers from process activities in their workplace, and these criteria are established based on extensive documentation. Such information is not available to support VOC criteria for new construction.

5.3.3 New-construction VOC criteria were derived from the state of California's Chronic Reference Exposure Levels (CRELs), which may not be relevant to assessment of IAQ. CREL target values are intended to *prevent* health effects in sensitive populations without considering feasibility. A more realistic IAQ objective may be to *minimize* health effects to the extent feasible, especially for chemicals with relatively high background concentrations.

Risk assessments are complex, requiring that numerous choices be made (e.g., key study, key endpoint, exposure variables, uncertainty or safety factors). Consequently, different organizations can develop acceptable concentrations that are quite different. For example, different results produced by risk assessments considering essentially the same health effects literature are illustrated by comparing the CREL for formaldehyde (9 ppb) to the WHO IAQ standard of 100 ppb.

5.3.4 VOC criteria for new construction only include a small fraction of compounds present in indoor air. Therefore, when listed VOCs are in compliance with specified concentration limits, other VOCs may be present at levels impacting occupants.

5.3.5 A TVOC concentration limit is no longer supported by IAQ researchers as a standard for indoor air because it cannot be associated with health effects. The proportion of one constituent that is prevalent, but with low toxicity, can far outweigh one that is a smaller fraction but has a larger impact on human health. Even though the TVOC concentration is sometimes assumed to account for the cumulative toxicity of the mixture of VOCs, interactions (e.g., synergism, antagonism) have generally not been found from exposure to chemical mixtures at low concentrations. TVOC's utility as a parameter for evaluating new construction is further limited because nonconstruction sources are significant contributors and noncomparable methods are used for measurement.

5.4 VOC sampling strategies for new constructive are not representative of long- term occupant exposure.

5.4.1 Results of air sampling at the end of construction may not reflect long-term occupant exposure and cannot be relied on to predict building performance. Since VOC types and amounts vary both temporally and spatially, a small number of randomly collected samples do not document average or worst-case concentrations.

5.4.2 Measurements made at the end of construction measure off-gassing at a time when it is continuing to diminish rapidly. False positive conclusions regarding overall IAQ can also be made when VOC measurements exceed specified limits in buildings without adversely impacting occupants. On the other

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hand, false negative conclusions regarding overall IAQ can occur where VOC measurements comply with concentration limits, but unlisted compounds or conditions unrelated to VOCs adversely affect occupants (e.g., excess moisture).

5.4.3 Considerable uncertainty is associated with the various sampling and analytical methods used to determine compliance with new-construction VOC criteria.

5.5 Alternative IAQ assessment strategies for new construction should be considered.

5.5.1 Proposed modifications of IAQ criteria that retain VOC sampling but modify concentration limits may still produce false positive and false negative conclusions.

5.5.2 A general IAQ assessment can be more informative than measurement of VOCs. Such an evaluation could be structured to determine if new construction meets specified building performance standards related to IAQ, resulting in a more comprehensive evaluation of overall IAQ. Green building standards specify performance standards for ventilation and product emission limits to control VOCs and similar performance standards could be set for moisture, source control, odor and cleanliness.

5.6 VOC sampling can be useful in resolving IAQ issues following a general assessment.

5.6.1 Although VOC sampling has not been demonstrated as an effective tool for screening new construction, it can be useful in investigating some IAQ complaints where site conditions have first been characterized by a general assessment and a hypothesis is advanced that can be tested by a site-specific sampling strategy.

6.0 Recommendations

6.1. VOC sampling to assess new construction is inconclusive and should not be relied on as the sole means for evaluating the effectiveness of source controls or identifying construction-related conditions that may impact occupants.

6.2 In addition to evaluating VOCs, IAQ screening of new construction and renovation should also assess other determinants of IAQ such as thermal comfort, moisture, ventilation effectiveness, source control, and cleanliness.

6.4 A study should be conducted comparing construction-related IAQ concerns in new buildings screened by VOC sampling to those shown to meet performance standards by a general pre-occupancy assessment.

6.5. Research and development is needed to identify better protocols for evaluating VOCs and other contaminants' in new construction. Sampling strategies should be representative of typical conditions.

6.6 Continued research is needed to better characterize health risks associated with VOCs at IAQ concentrations.

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Table 2: LEED and ASHRAE VOC Criteria

Substance (CAS Number)	LEED Criteria (µg/m³)	ASHRAE 189.1 Criteria (µg/m³)
Acetaldehyde (75-07-0)	140	140
Benzene (71-43-2)	3	60
Carbon disulfide (75-15-0)	800	800
Carbon tetrachloride (56-23-5)	40	40
Chlorobenzene (108-90-7)	1000	1000
Chloroform (67-66-3)	300	300
Dichlorobenzene (1,4-) (106-46-7)	800	800
Dichloroethylene (1,1) (75-35-4)	70	70
Dimethylformamide (N,N-) (68-12-2)	80	80
Dioxane (1,4-) (123-91-1)	3,000	3,000
Epichlorohydrin (106-89-8)	3	3
Ethylbenzene(100-41-4)	2,000	2,000
Ethylene glycol (107-21-1)	400	400
Ethylene glycol monoethyl ether (110-80-5)	70	—
Ethylene glycol monoethyl ether acetate (111-15-9)	300	—
Ethylene glycol monomethyl ether (109-86-4)	60	—
Ethylene glycol monomethyl ether acetate (110-49-6)	90	—
Formaldehyde (50-00-0)	27	33
Hexane (n-)(110-54-3)	7,000	7,000
Isophorone (78-59-1)	2,000	2,000
Isopropanol (67-63-0)	7,000	7,000

Substance (CAS Number)	LEED Criteria (µg/m³)	ASHRAE 189.1 Criteria (µg/m³)
Methyl chloroform (71-55-6)	1,000	1,000
Methylene chloride (75-09-2)	400	400
Methyl t-butyl ether (1634-04-4)	8,000	8,000
Naphthalene (91-20-3)	9	9
Phenol (108-95-2)	200	200
Propylene glycol monomethyl ether (107-98-2)	7,000	7,000
Styrene (100-42-5)	900	900
Tetrachloroethylene (127-18-4)	35	35
Toluene (108-88-3)	300	300
Trichloroethylene (79-01-6)	600	600
Vinyl acetate (108-05-4)	200	200
Xylenes (1330-20-7)	700	700
TVOC	500	—
Acrylonitrile	—	5
1,3- Butadiene	—	20
t-Butyl methyl ether	—	8000
Isopropanol	—	7000
ASHRAE 189.1 also specifies testing for these VOCs if rubber-backed carpets are used:		
Caprolactam	—	100
2-Ethylhexanoic acid	—	25
1-Methyl-2-pyrrolidinone	—	160
Nonanal	—	13
Octanal	—	72
4-Phenylcyclohexene	—	2.5

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