Recent studies suggest that chemical reactions may be an important determinant of indoor air quality. This article describes the role that chemistry plays in degrading indoor air quality and provides guidance to homeowners and commercial building managers on how to prevent indoor chemistry from polluting the air they breathe.

It is becoming clear that for many airborne pollutants, indoor exposure outweighs outdoor exposure. Consider the fact that most people spend the majority of their time indoors; by some estimates, the “average” American spends 90–95% of his or her time indoors. Furthermore, indoor levels of many airborne pollutants are as great or greater than outdoor levels of the same pollutants. Most people now recognize that buildings are not always a refuge from polluted outdoor air. Indeed, the term “sick building syndrome” (SBS) is now a familiar part of our lexicon. Common symptoms associated with SBS include stinging, itchy eyes; throat and nasal membrane irritation; and the perception of odors. These sensory irritations may lead to headaches, lethargy, and fatigue. However, the causes of SBS still elude researchers, and there is growing evidence that there are some chemicals that may be responsible for SBS that are not routinely identified, or even considered, in sick building investigations.

Many people recoil at the memory of their high school chemistry class. Yet, homeowners and building managers inadvertently engage in indoor chemistry experiments by using reactive consumer products and allowing outdoor smog to come indoors. The extent and importance of indoor air chemistry is only beginning to be understood. This article demonstrates the role that chemistry plays in degrading indoor air quality and how it may contribute to symptoms of SBS. In addition, it provides some guidance to consumers on how to prevent indoor chemistry from impairing the air they breathe—that is, how to be more knowledgeable and environmentally friendly “chemists.”

INTRODUCTION
When you step into your home or office, you step into an atmosphere quite different from outdoor air. You are surrounded by a “chemical soup” composed of hundreds to thousands of compounds, many of which are rarely identified through routine sampling. You are probably familiar with the “primary” emissions of odors from furnishings (e.g., new carpet smell), air fresheners, cleaning solutions, and tobacco smoke. However, an emerging field of study has begun to unveil chemical transformations, or reactions, that are unique to indoor environments. The formation of these “secondary” pollutants may be as or more problematic than primary pollutants.

While the chemical reactions that take place indoors are not necessarily unique, the results of that chemistry are unique owing to the special characteristics of indoor spaces. First, indoor spaces are enclosed, temporarily trapping pollutants that might have been rapidly dispersed outdoors. Ventilation or infiltration of fresh air will dilute these pollutants, but this could take many hours. This phenomenon can intensify the concentration of an emitted compound and also of any products that form as a result of chemistry involving the originally emitted chemical. Also of significance is the fact that the degree of dilution by fresh air has been intentionally reduced over the past two decades, as homeowners and building managers have “weatherized” and “tightened” homes, office buildings, and schools for purposes of energy conservation. Second, the large surface area typically available in buildings can accelerate chemistry or even become a
source of volatile reaction products. The importance of the chemistry that occurs indoors increases as the degree of ventilation in buildings is reduced.

SMOG AND LEMONS
A criteria pollutant, ozone is a very reactive component of smog formed outside on summer days over urban areas. It can penetrate from outdoors into buildings through cracks around windows and doors, open windows and doors, or intentional intakes via mechanical ventilation systems. It is also released from indoor appliances, such as laser printers, photocopiers, and even ozone generators that are incongruously marketed as “air fresheners.” Terpenes are natural organic chemicals whose odors we are all familiar with: pinene has a pine odor and limonene has a citrus odor. Lemon-scented cleaners and pine air fresheners can release large amounts of terpenes into indoor air. Because of their chemical structures, terpenes are easily “attacked” and transformed by ozone.

When combined, ozone and terpenes react to form numerous byproducts that potentially degrade indoor air quality. A recent discovery of this unique chemistry created a great buzz of excitement among indoor air quality researchers. During experiments to study the possible reactions between ozone and terpenes in indoor air, researchers Charles Weschler and Helen Shields noticed that a white board in their laboratory became yellowed. The researchers soon realized that the board was becoming coated with particles that formed as a result of the chemical reactions between ozone and terpenes. Their observations have since been the catalyst for a number of related studies by researchers around the world.

Based on the pioneering work of Weschler and Shields, it was immediately clear that common airborne chemicals were combining to form potentially harmful particles. Why care about particles? Decades-long research on the adverse effects of outdoor pollutants has demonstrated that increased concentrations of small particles are directly related to increased mortality. For example, the Harvard Six Cities Study and similar epidemiological studies show that an increase of 25 µg/m³ in particles with aerodynamic diameters of less than 2.5 µm results in a 2–6% increase over baseline mortality. These results hold even when the adverse effects of all other measured pollutants have been carefully extracted from the data. Furthermore, recent studies by researchers at the Harvard School of Public Health suggest that indoor particles may be more bioactive (i.e., potentially unhealthy) than outdoor particles, the latter of which have received far greater attention over the past few decades.

Further studies of ozone–terpene reactions show that even typical uses of many common consumer products increase small particle concentrations enough to be of concern given the epidemiological research described above. As an example, Figure 1 shows the results of experiments completed in a large (11 m³) laboratory chamber, approximately the size of a walk-in closet or small bathroom, that was ventilated at a rate of approximately 0.6 air exchanges per hour. In this experiment, an ozone generator was used to increase ozone levels inside the chamber. A single, common solid air freshener was placed inside the chamber, which emitted several common terpenes that are used as scenting agents. The amount of particle mass in the chamber increased 12-fold within 30 minutes of placing the air freshener in the chamber, and continued to rise from a background level of 5 µg/m³ to nearly 120 µg/m³. More important, the entire new particle mass was composed of very small particles (i.e., less than 0.7 µm in diameter) that could easily penetrate deep into the human lungs. For perspective, the new National Ambient Air Quality Standards (NAAQS) for fine particulate matter (PM₂.₅; less than 2.5 µm in diameter) measured outdoors is only 15 µg/m³ (annual average) and 65 µg/m³ (24-hour average).
Direct evidence of physiological problems due to this chemistry has recently come out of Denmark. Peder Wolkoff and his colleagues at the Danish National Institute of Occupational Health exposed mice to a mixture of ozone and terpenes and observed a significant reduction in respiration (an indication of irritation). Their experiments demonstrated that neither ozone, nor the terpenes themselves, nor any identified products, caused irritation. They concluded that the mixture itself contained unidentified, short-lived irritants that are formed via unique indoor chemistry.

The chemistry of ozone reactions with terpenes is complex and not yet fully understood. However, Figure 2 demonstrates the pertinent features that help us understand why we observe particles and airway irritants. When ozone reacts with terpenes, a number of stable and unstable products may form. The key is that the terpenes become transformed through a process called “oxidation.” Many of the byproducts of this oxidation are of low volatility; in other words, they tend to condense (from a gas to liquid) onto surfaces or out of air to make particles. Hydroxyl radicals (OH) are important short-lived products that can attack and oxidize other compounds. They may also form low-volatility, particle-forming products. Recently, researchers identified short-lived products, such as hydroperoxides, that are likely candidates for irritation due to their highly reactive nature. These chemicals are very difficult to detect, and their “stealth” nature has kept them “below the radar” of those charged with investigating the causes of SBS. Odorous oxidized compounds such as stable aldehydes

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**Indoor Air Quality**

**Problems and Engineering Solutions**

**July 21-23, 2003**

Research Triangle Park, North Carolina

An international symposium cosponsored by the Air & Waste Management Association and EPA’s Office of Research and Development, will be held July 21–23, 2003, in Research Triangle Park, NC, at the Sheraton Imperial Hotel and Convention Center. Papers will be presented on topics including:

- Managing the risk of indoor air pollution
- Indoor air source characterization methods
- Protecting the indoor environment from terrorism
- Indoor air emissions—product certification
- Mold and other biocontaminants
- Indoor air cleaning methods
- Asthma and children’s health in the indoor environment
- And many more

The symposium will consist of one general session so that participants will be able to attend all sessions. A poster session, continuing education courses, and an exhibition of related products and services are planned. The conference site has convenient access to nearby restaurants, shopping, and entertainment. A reception is also planned for the first evening.

For more information, contact A&WMA at 1-800-270-3444 or 412-222-3444 or visit our Web site at www.awma.org/events
may also be formed through indoor chemistry, and may be a source of irritation or nuisance.

**SMOG AND CARPETS**
Moving beyond the chemistry of terpenes, which primarily occurs in the air within buildings, a second important feature of the indoor environment is the large amount of surface area in the form of painted walls, flooring, carpet, and furniture. To a chemist, surfaces are wild cards, whose properties and influence are difficult to understand and predict. However, studies have shown that indoor surfaces speed some chemical reactions10,11 and act as reservoirs for pollutants through a process known as “sorption.”12 Surfaces can remove some pollutants by chemical reaction, but, by the same token, produce new pollutants.

An important example of this chemistry focuses, once again, on ozone. For decades, researchers have recognized that indoor ozone concentrations are significantly lower than outdoor levels when no indoor sources of ozone are present. A series of recent studies shows that ozone reacts with, and is consumed by, indoor surfaces, thereby lowering human exposure to ozone.13 That’s good news, right? However, these reactions come at a cost. As with terpenes, byproducts are formed when ozone reacts with certain organic compounds that constitute indoor materials that are easily “attacked.” In this case, some of the products are more volatile and evaporate from surfaces into indoor air. Most of the products that have been identified are aldehydes, which can be toxic (e.g., formaldehyde), odorous, or just plain irritating. Painted surfaces, carpets, and duct-liners all release aldehydes when exposed to ozone (see Figure 2). In one study, carpet was observed to produce 2-nonenal, a compound with an odor threshold of less than 1 part per billion. Emissions rates for that carpet were predicted to degrade indoor air quality for years after installation.

**INDOOR CHEMISTRY, IRRITATION, AND ODOR**
To understand why products of ozone reactions may be problematic, we must consider the physiology of irritation. We focus first on eye irritation, a common complaint in sick buildings. A series of recent studies shows that ozone reacts with, and is consumed by, indoor surfaces, thereby lowering human exposure to ozone.13 That’s good news, right? However, these
form and composition to the film of a soap bubble. In the terminology of physiologists, an “unstable tear film” can cause problems mainly by drying. Imagine adding dirt and grease to a soap solution, thereby making bubble formation more difficult. Analogously, by modifying the chemical composition of the tear fluids, products of ozone reactions may destabilize the tear film and cause dry spots to form on the cornea.

Consider another sensitive spot: the human nose. Some of the resulting products of ozone chemistry turn out to be fairly odorous. However, just because something has an odor does not make it problematic. There are good odors and bad odors, right? Indeed, the quality of a fragrance is in the nose of the inhaler. How often have you encountered perfume or cologne and found it rather strong and offensive? Studies have shown that individual perception of odor (good or bad) may increase stress and reduce productivity.19

The overall irritancy of chemicals generated as byproducts of indoor chemical reactions is likely to be greater than that of the chemicals from which those products originate. Ten Brinke et al.20 showed that SBS is highly correlated with the presence of volatile organic compounds (VOCs) with high-irritancy potential, even when individual compound concentrations are 100–1000 times lower than that known to cause symptoms or irritation. Aldehydes and carboxylic acids, known products of ozone chemistry with terpenes and many indoor materials, are

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**A&WMA/EPA Host International IAQ Symposium**

by Michael McGinley, P.E.

A&WMA AB-7 Indoor Air Quality Committee Chair

This summer, the Air & Waste Management Association and the U.S. Environmental Protection Agency’s (EPA) Office of Research and Development will jointly host their fourth international symposium on indoor air quality (IAQ). Called Indoor Air Quality Problems and Engineering Solutions, the symposium will be held July 21–23, 2003, at the Sheraton Imperial Hotel and Convention Center in Research Triangle Park, NC.

Unlike previous meetings, which ran multiple session tracks simultaneously, this year’s symposium will consist of one general session track that will allow participants to attend and participate in all sessions. Proceedings will be published following the symposium. In addition to the general sessions, the symposium will include poster presentations, professional development courses, and an exhibition of IAQ-related products and services. A tour of EPA’s nearby research facilities is also planned. Presentations and discussions will include, but are not limited to, the following topics:

- managing the risk of indoor air pollution;
- indoor air source characterization methods;
- protecting the indoor environment from terrorism;
- indoor air emissions—product certification;
- mold and other biocontaminants;
- indoor air cleaning methods;
- asthma and children’s health in the indoor environment;
- particles and particle entry into the indoor environment;
- IAQ modeling; and
- exposures in the indoor environment.

Symposium participants will include IAQ policy-makers, health officials, researchers, consultants, service professionals, building managers, architects, engineers, and scientists. This meeting will also be of interest to representatives from industries such as IAQ testing services, remediation services, building services, legal services, training providers, building materials manufacturers, and equipment manufacturers.

As chair of A&WMA’s AB-7 Indoor Air Quality Committee, I invite you to take advantage of this opportunity to hear from key IAQ policy- and decision-makers, learn the latest information on important IAQ issues, and meet with technology developers and manufacturers of IAQ-related products and services by attending the 2003 symposium. For more information on the A&WMA/EPA IAQ symposium, visit A&WMA’s Web site at www.awma.org/events.

**Indoor Air Quality Committee—Opportunities within A&WMA**

A&WMA’s AB-7 Indoor Air Quality Committee’s mission is to “provide a platform for information exchange and foster research and development in indoor air quality.” The committee welcomes all A&WMA members interested in indoor air quality to participate in our activities. Current committee members are employed in industry, government, academia, consulting, and the IAQ product and service industry.

At the 96th Annual Conference & Exhibition, June 22–26, 2003, in San Diego, CA, the AB-7 Indoor Air Quality Committee is sponsoring two technical sessions with 11 paper presentations. The committee will also hold its annual meeting during the conference. A&WMA’s Technical Council and Technical Coordinating Committees, and their corresponding meetings, are open to everyone, so I encourage you to attend this year’s Annual Conference & Exhibition and participate in the technical sessions. For more information on A&WMA’s Indoor Air Quality Committee, please contact me, Michael McGinley, P.E., Committee Chair, at phone: (651) 439-0177, ext. 16; or e-mail: mike@fivesenses.com.
ranked high on the Ten Brinke irritancy scale, suggesting that they may also contribute to SBS. Although circumstantial at this time, the chemistry, physiological mechanisms, animal data, and SBS studies all support the hypothesis that this chemistry may be an important component of SBS symptoms.

**YOU AND YOUR INDOOR ENVIRONMENT**

What have we learned that will help consumers make choices that will improve air quality, or at least avoid some of the pitfalls of indoor chemistry? Unfortunately, there are few standards that target reducing indoor chemicals, and none that focus on chemistry. Without guidelines, consumers and building managers may find it difficult to make informed decisions on furnishings, fragrances, cleaning products, and air cleaners. However, common sense and a little knowledge can go a long way toward preventing indoor air quality problems.

First, avoid deliberately introducing “bad actors” into indoor environments. It should now be clear that ozone is to be avoided. Ozone is itself a criteria pollutant and very reactive. Interestingly, some manufacturers have promoted ozone generators as air cleaners. Their supposed ability to “destroy toxic chemicals,” “disinfect,” and “reduce allergens” has been thoroughly debunked, and the Federal Trade Commission has taken action against some manufacturers for making false claims. In fact, ozone is efficient at destroying certain chemicals, but, as mentioned above, the byproducts that are generated as a result of chemical reactions may be of greater concern than the original chemicals that are destroyed. Hence, we also recommend avoiding air cleaners that produce ozone, even as a byproduct. Effective air cleaners that operate without producing ozone are readily available through many commercial outlets. You may find that some ozone-producing appliances are difficult to live without; laser printers, for example, produce small amounts of ozone.

Ozone is a component of urban smog that seeps into buildings during the summer months. Many office buildings are reasonably well protected from ozone infiltration by sealed windows and doors. Recirculation of mechanically ventilated indoor air automatically reduces some of the outdoor ozone concentrations, but some outside “fresh” air must always be added to commercial building air to dilute gases emitted by building occupants. We do not recommend changing the ventilation characteristics of existing commercial buildings—the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has guidelines on these operations—but the installation of charcoal filters may help reduce indoor ozone levels. In homes, controlling ozone is difficult. Ozone enters by natural ventilation (e.g., open windows) and infiltration through cracks around doors and other openings. Reducing air exchange by closing windows can reduce indoor ozone concentrations but also trap other pollutants indoors. The complexities of indoor environments preclude specific recommendations regarding ventilation. However, we suggest that homeowners open windows in the evenings, when ozone levels are lower (unless occupants are especially sensitive to outdoor allergens such as pollen).

Terpene chemistry and particle formation can be avoided simply by reducing your use of products that contain these chemicals. Even though these chemicals are “natural,” there is now enough evidence to suggest that they may significantly degrade indoor air quality. Limonene is the most reactive of the terpenes and is the primary one to avoid. Most lemon-scented products contain this compound. It is unclear if reactions with other terpenes (such as pinene, which is found in pine scent) are hazardous, since the reaction rates are lower. However, studies conducted by Wolkoff et al. suggest that

**Why care about particles? Decades-long research on the adverse effects of outdoor pollutants has demonstrated that increased concentrations of small particles are directly related to increased mortality.**
other terpenes can also cause pulmonary irritation. We therefore recommend reducing the use of both lemon- and pine-scented household products during summer, when ozone levels are at their highest, or in rooms with internal ozone sources (e.g., photocopy rooms).

Surface chemistry is the most difficult (nigh impossible) phenomenon for consumers to avoid. After reducing ozone levels, the obvious move would be to reduce the use of products that form aldehydes upon oxidation. However, there is no information available to consumers that would help them make informed decisions regarding the “reactivity” of furnishings, building materials, and even architectural coatings. Not only are there no test data, there are no standards, or even guidelines, since there is no direct evidence that secondary emissions from surfaces are truly hazardous. Many carpets, paints, and furnishings are likely to be just fine. At this point, we can only recommend that some sort of organized product testing take place in the near future.

Nevertheless, consumers can make a difference by reducing the emissions of primary pollutants from furnishings. There are many labeling programs in place to help consumers choose products that are designed to reduce indoor emissions of organic compounds. For example, the Carpet and Rug Institute (www.carpet-rug.com) tests carpets for emissions of primary species (e.g., new carpet smell) and marks those carpets that are acceptably low-emitters with a “Green Label.” In addition, many paints are now water-based and conform to rules designed to improve urban air quality. These “low-VOC” paints also should reduce the emissions of organic compounds into indoor air. Levin presents a step-by-step guide to choosing furnishings and building materials for improved indoor air quality.

SUMMARY
Indoor air chemistry occurs in practically every type of indoor environment, and recent evidence suggests that this chemistry might be an important determinant of indoor air quality. The avoidance of indoor ozone is key to reducing the negative impacts of indoor chemistry. Also, during urban summertime conditions, or in rooms where ozone is generated internally (e.g., photocopy rooms), the use of terpene-based fragrances and cleaners should be avoided. The knowledge base related to indoor air chemistry has improved in the past four years to the extent that it is now generally known that it should be an area of concern to building occupants. However, the science of indoor air chemistry is still in its infancy and requires a great deal more research to better understand the exact nature of indoor chemical reactions in air and on the surfaces of indoor materials. We hope that this overview will make more people aware of this important issue, and motivate others to continue to research and expand the existing knowledge base related to indoor air chemistry.

REFERENCES
8. Schwartz, J.; Dockery, D.W.; Neas, L.M. Is Daily Mortality Associated Specified Primary Species (e.g., new carpet smell) and marks those carpets that are acceptably low-emitters with a “Green Label.” In addition, many paints are now water-based and conform to rules designed to improve urban air quality. These “low-VOC” paints also should reduce the emissions of organic compounds into indoor air. Levin presents a step-by-step guide to choosing furnishings and building materials for improved indoor air quality.

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Indoor air chemistry occurs in practically every type of indoor environment, and recent evidence suggests that this chemistry might be an important determinant of indoor air quality. The avoidance of indoor ozone is key to reducing the negative impacts of indoor chemistry. Also, during urban summertime conditions, or in rooms where ozone is generated internally (e.g., photocopy rooms), the use of terpene-based fragrances and cleaners should be avoided. The knowledge base related to indoor air chemistry has improved in the past four years to the extent that it is now generally known that it should be an area of concern to building occupants. However, the science of indoor air chemistry is still in its infancy and requires a great deal more research to better understand the exact nature of indoor chemical reactions in air and on the surfaces of indoor materials. We hope that this overview will make more people aware of this important issue, and motivate others to continue to research and expand the existing knowledge base related to indoor air chemistry.