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Research, Policies, and Program Options for Improving Indoor Environmental Quality

Office of Research and Development

RESEARCH, POLICIES AND PROGRAM OPTIONS FOR IMPROVING INDOOR ENVIRONMENTAL QUALITY

Synthesis Paper

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Synthesis Paper

This Synthesis paper is Part 2 of a two- part project. Part 1 was a State of Science Review of indoor environmental quality that forms the basis for this Synthesis paper. This Synthesis paper develops a context designed to assist EPA in establishing indoor environmental research goals, objectives and priorities and suggests an array of research options for improving indoor environmental quality over various time frames.

Both papers are intended to be internal EPA documents and not intended for publication or public consumption. As the reader will see from these reports, potential candidates for research are wide ranging and cover many topics, objectives and time frames for consideration. To do justice in the service to EPA, this necessitated the presentation of a substantial amount of information within the confines of limited resources for developing both reports. Because of this challenge, the format chosen for these reports included presenting information from broad based review articles in each subject area or area research options, supplemented by other key articles of narrower scope as needed. Such presentations involved selecting, integrating, and editing key portions of these articles that, were important information useful to EPA. The advantage of this format is that it allowed for a lot of information to be presented from a wide range of subjects and options for research that would not have been possible if such material were independently created. To do so would have required that the scope of coverage be severely limited thus providing EPA with a narrower set of potential research opportunities. The disadvantage of this format, however, is that the information provided necessarily includes some copyrighted material. **Therefore, both reports must be confined to EPA use only, and not for publication of public consumption. The decision about format was made early on under close coordination with the EPA Project Officer.**

Note: Full references for covered articles are embodied in the text and for those simply referenced are placed at the end of each major section. Readers of the Synthesis paper may choose to refer back to the State of Science Review for more detailed information and references. A full bibliography of all the articles covered or referenced in both reports is included in this Synthesis Report.

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INTRODUCTION

The purpose of this report is to synthesize what was learned in the Science Review, and, on that basis, provide guidance for the EPA and its partners in formulating research and policies for improving indoor environmental quality going forward. The term "indoor environmental quality" rather than just "indoor pollutants" is used to reflect the very significant interplay revealed in the science review between airborne, surface borne, and waterborne pollutants, and between indoor pollutants and indoor climate, and the influence of both on building occupants.

This report is broadly organized as follows:

> First, a contextual discussion to guide the reader in understanding and interpreting the material in this Synthesis Report.
>
> Second, themes from the science review are articulated in broad terms. Readers can refer to the Scientific Review for more detail.
>
> Third, the themes are "synthesized" to provide some direction for the assessment of issues relevant to developing future policies and research strategies, given budgetary constraints, designed to advance human health, comfort, and productivity associated with indoor environmental quality. In this discussion, research options are widely explored in the context of various policy and program options, including what exists, ideas for improvement, future possibilities, and potential research priorities to support such options, including research directions made available from technological advances.

While this report is an outgrowth of, and a companion document to the State of Science Review, it is designed to be readable as a partially stand-alone document where the reader can refer back to the State of Science Review for further detail and documentation of findings should they desire. . As in the Science Report, full references for covered articles are embodied in the text and those simply referenced are placed at the end of each major section. A full bibliography of all the articles covered or referenced in both this report and the State of Science Report is included at the end of this Synthesis Report.

The Context for Understanding and Interpreting this Synthesis Report

In addition to the discussion in the science review of studies identifying potential pollutants of interest because of high population risk, recent studies also suggest the need to be more attuned to issues such as the following:

- Combined and potential simultaneous exposure to multiple pollutants, some of which may not in themselves constitute substantial risks, and some of which may not have been evaluated for risk potency and for acute health risks and sick building syndrome, and may not necessarily be above the detection threshold.
- The high end (e.g. 95^{th} percentile or higher) of the concentration of exposure distribution where risks may be greatest but inadequately represented.
- Ability to protect against high risks of persons in individual buildings as well as high average population risks.
- The interrelatedness of surface-borne, airborne, and waterborne pollutants, and the relevance of including inhalation, dermal, and ingestion exposures when evaluating health impact.
- The role of indoor chemistry that is changing the character of the indoor pollutant mix and creating secondary organic aerosols which themselves may contain the highest risk and be the hardest to anticipate or quantify.
- The potential for green products and green buildings for significantly reducing VOC exposures in buildings, irrespective of the ventilation rate.
- The significant impact of CO_2 in human cognitive performance, irrespective of the ventilation rate or the concentration of other pollutants.
- The potential for advanced technologies for improving detection and monitoring activities, data collection, data organization and analytics that could revolutionize both research and policy control options.

These issues above highlight some questions that should be considered in development of research priorities. For example:

- Given technological advances, is it feasible to develop monitoring and other data collection programs that are large and extensive enough with sufficient update capabilities to adequately represent personal exposure of the population and support studies of its impact of individuals in specific environments and the U.S. population as a whole? If so, is it worth pursuing? Would this be the best vehicle for identifying a targeted set of pollutants that reflect individual and population exposures?
- Can such programs capture risk from exposures at the high end of the distribution, which may be episodic and short lived, but which may also represent very high individual and/or population risk?
- What areas of basic (vs applied) research are worth supporting, and for what purpose?
- What areas of applied research could most effectively and quickly help reduce adverse health and welfare impacts?
- Given that potential pollutants of interest based on population exposure are also likely have especially high risk to specific individuals with unduly high exposure, how can that

knowledge best be used to protect them even if regulatory controls to protect the population are not adopted?

- How should pollutants which are individually considered to be low risk, or which have no authoritatively established risk potency values, but which may, singly or combined, or in totality of exposure create significant adverse health impact on occupants be addressed by research and policy?
- How should research and policy most effectively address issues of acute health effects which prevail only when exposed, and which significantly impact overall health, comfort and productivity.
- What is the balance between basic research with no specific policy prescription and applied research to support a given policy prescription with or without a specific intent to implement such policy because of severe resource constraints?

The discussion in this Synthesis Report attempts to address these questions by considering various research and policy options, and, given the issues raised above, how they might be combined in ways that best meet both short term, medium term, and long-term needs.

Policy context

The ultimate purpose of indoor environmental research and policy is to reduce exposure to indoor pollutants and provide indoor environments that improve the health, comfort, and productivity of occupants. Strategies for doing so may be direct or indirect, targeted or generic, regulatory or non-regulatory or somewhere in between. For example, a targeted, direct approach may be to control the use of a specific chemical used indoors through either regulatory or voluntary programs. Somewhat less direct would be to limit the emissions of specific outdoor sources, understanding that most of the exposures to those emissions might be indoors. Generic approaches usually concern building specific controls that reduce indoor exposures to multiple pollutants simultaneously, through ventilation/exhaust or filtration/air cleaning or behavioral changes of occupants, singly or in some combination through "good building practices". Again, these might be accomplished through regulatory (e.g. building codes) or non-regulatory (e.g. educational guidance, incentive programs (e.g. green product or green building programs). The research that supports these different control options will differ, while the control option chosen may in part depend on what research has already been done, as well as the nature of the pollutant (e.g. chemical, biological, particulate) at issue.

Some attention also needs to be directed to the time frame. The type of exposure in the future may or may not be the same as the present, so current knowledge based on past research may be less relevant than research that anticipates future changes. In addition, current technology and technological trends may both impact the pollutant exposures in the future as well as the potential for more advanced control options or advanced research options. All of these and other considerations are relevant and are implicitly included in this synthesis report.

RELEVANT THEMES FROM THE INDOOR ENVIRONMENT SCIENCE REVIEW

Priority pollutants:

There is reason to be very cautious about adopting a targeted set of individual pollutants based on existing studies.

Estimates of risk lean heavily (but not exclusively) on epidemiologic studies of the relationship between estimated population exposure based on outdoor concentrations and data on health endpoints of those populations. However, there is considerable uncertainty of both the accuracy and relevance of that data in the pursuit of identifying specific indoor pollutants of concern.

- Outdoor concentrations for individual buildings are often based on ambient concentrations from central site monitoring stations which do not capture the spatial variations between buildings.
- Significant temporal and spatial variations between regions, and between buildings within a small area, combined with interpersonal differences in life activities and life styles of occupnts that affect personal exposures and that also vary by stages in life, shows how even large databases designed to represent larger portions the population are difficult to make truly representative and are likely biased in different ways.
- To partially overcome this problem, combining multiple small studies is a reasonable approach but is subject to the inherent difficulties of having multiple methodological approaches and inconsistent data parameters that require reasoned adjustments and assumptions that can create large areas of uncertainty.
- Risk thresholds and unit risks are generally designed to reflect values below which there is a low probabability that persons, including sensive individuals will suffer unacceptable risk, such that the value chosen will have a low probability of underestimating risks. Such estimates require the application of uncertainty factors of one or more orders of magnitude to insure that risks are not underestimated.
- Often there are significant differences in threshold or unit risk values among different authoritative sources.
- While the most severe risks may be concentrated in the high end of the concentration distribution (e.g. 95^{th} percentile), these high-end values also tend to be underrepresented. When modeled using the common assumption of a lognormal distribution, results tend to significantly underrepresent these extreme values.
- It is prohibitively expensive to conduct national level concentration studies. Thus, much of it is decades old and more representative of the past than the present (or potential future). For example, outdoor concentrations of many ambient and toxic air pollutants have been falling due to source reductions in both stationary and mobile sources, and indoor concentrations of

many pollutants are falling due to reduced smoking rates and lower volatile organic compoumd (VOC) emitting materials.

- The possibility that the highest risks may come from common mixtures of pollutants, rather than individual pollutants alone, has not been well studied, but stand to be potentially more important than individual pollutant consideration that could alter how we assign risks. For example, explorations into what combinations of VOCs are likely to appear simultaneously, including those with minimal health risks taken individually, but which may have unacceptable impact taken together have just begun to emerge.

SVOCs:

It would be a mistake to devalue one's interest in SVOCs relative to well-studied pollutants because information on their behavior, exposure, and risk has not been well developed but suggest that SVOCs can be of even greater significant concern.

SVOCs are a rapidly emerging concern and for good reason. SVOCs are endemic to a variety of plastic related building materials, consumer and commercial products, and food packaging, and are also used in or as pesticides, plasticizers and flame retardants. They are increasingly ubiquitous in today's indoor environments and their presence will likely increase in the future.

SVOCs are substantially different than other VOCs that could make them a more potent source of risk. For example:

- SVOCs are less volatile than their VOC counterparts but once released, can persist indoors for long periods of time, from hundreds of hours to years, depending on prevailing conditions.
- SVOCs have multiple transport mechanisms resulting in multimedia exposure. They can transport from surface to surface (including skin and food) through direct contact, or attach to particles and pass from surface to air and back to surfaces again (including food and skin).
- To adequately assess exposure, researchers need to take a more holistic view of indoor air pollution to include all media pathways resulting in exposure because the constant interplay between surfaces (including skin and food) and air means that inhalation, ingestion, and thermal exposure may all contribute significantly to total human exposure.

That specific numerical risks have not been established is a function of the lack of sufficient research rather than the potentially high risks they may entail. Given the pervasiveness of SVOCs in modern society, this lack of information and action is unsettling.

Several points revealed in the science review but await more study are worth considering:

- Air-to-skin transdermal uptake is estimated to be comparable to or larger than inhalation intake for many SVOCs of current or potential interest indoors (Weschler and Nazaroff (2012)). These include including:
    - butylated hydroxytoluene,
    - chlordane, chlorpyrifos,
    - diethyl phthalate,

- Galaxolide,
- geranyl acetone,
- nicotine (in free-base form),
- PCB28,
- PCB52,
- Phantolide,
- Texanol and
- Tonalide.

- Surface to air transport can be greatly affected by the surface characteristics. The sink effect for SVOCs on surfaces depends on the surface partition coefficient “k” which differs among surface materials. However, the development of grime (or organic film) on impervious surfaces may effectively mean that the SVOC reacts with the film rather than the surface and the “k” value of surfaces with such grime may tend to be virtually the same. One could argue that this is an advantage. However, biofilm is often purposefully removed with cleaning products and the degree of removal is often used as a metric of cleaning effectiveness.
- Ingestion of dust from hand-to-mouth behavior is an important pathway of total exposure to the SVOCs that adhere to or are adsorbed by particles.
- Fine particles have greater adherence to human hands than larger sizes, and particles in the size range for skin adherence is dominated by ultrafine particles that are thus greater candidates for ingestion from hand to mouth behaviors.
- Bioaccessibility is higher in the body as particle size decreases. However, desorption processes also significantly reduce the portion of SVOCs in the alveolar region of the respiratory tract.

Phthalates

Phthalates are a class of SVOCs that are used as plasticizers that make plastic products more flexible, soluble and stable. About 90% of phthalates are used in vinyl, and are widely used in vinyl building products, and many other consumer and commercial products. Phthalate plasticizers are not chemically bound to vinyl and can leach, migrate or evaporate into indoor air and concentrate in household dust. Building materials such as vinyl flooring and other consumer products containing phthalates can result in human exposure through direct contact and use, indirectly through leaching into other products, or general environmental contamination. Humans are exposed through ingestion, inhalation, and dermal exposure during their lifetimes.

Since plastics are so common, phthalate metabolites can be found in the urine of virtually everyone of all ages, including infants. In human studies of adults, some phthalates have been related to decreases in sex steroid and thyroid hormone levels, poor sperm quality, endometriosis, insulin resistance, obesity, breast cancer and are implicated in the pathogenesis of asthma.

Some studies have found that temperature and air change rates can affect the emissions and concentrations of phthalates, but the effects are not necessarily straightforward. For example, while higher temperatures may increase emissions, they also decrease adsorption on surfaces. Similarly, while higher air change rates increase emissions, they also reduce concentrations.

The scientific information is not well developed either in its breadth or depth. Given the pervasiveness of these exposures and the potential for persistence in the environment, many in the scientific community feel that the lack of information and governmental controls is unsettling and call for more substantial investigations.

Indoor Chemistry:

Resources devoted to atmospheric chemistry in determining outdoor pollutant activities and exposures represent a recognition of its importance, yet resources devoted to indoor chemistry research to date suggests that chemical reactions indoors are a far greater determinant on health than the level of effort devoted to this subject would indicate.

It is well known that the ultimate impact of chemical and particle emissions to the atmosphere on both public health and the environment depends in great part to the chemical reactions that take place in the atmosphere. Indeed, it is one of the most widely studied phenomenon and an important consideration in forming outdoor regulatory controls. Similarly, chemical reactions that take place in indoor air and on surfaces alter the mix of contaminants to which occupants are exposed that ultimately helps determine the impact on public health. Yet, the study of indoor chemistry and its impact on indoor pollution exposures remains a "boutique" subject, studied by a relatively small number of researchers with limited funds.

Selected cogent points of interest and research needs revealed in the Science Review suggest broad areas of needed research:

- The byproducts of indoor chemistry potentially may be more important than the original chemical or particle contaminant in determining both acute and chronic health impacts.
- Chemical reactions that occur on surfaces, including human skin are perhaps more important than those that occur in the air, but both ultimately impact health.
- Measuring emissions in an empty room will not capture either the primary or secondary aerosols from the presence of occupants.
- Products of ozone-initiated reactions may have high volatility such as formaldehyde, or low volatility such as such as dicarboxylic acids. Those with low volatility contribute to the formation of secondary organic aerosols (SOA) such as ozone-terpenoid reactions.
- In addition to condensation on preexisting particles, homogeneous nucleation can occur and these reaction can become a major source of ultrafine particles whose size distribution evolves toward larger particles over time.
- The building design and operational parameters such as new product materials and lower ventilation rates to save energy that tend to foster indoor chemical reactions are trending

upward suggesting that the impact of indoor chemistry on exposure and health is becoming more important over time.

Indoor Particle Pollution:

The multifaceted health-related characteristics of particles, their health impact, and multimedia presence suggest priority consideration for advancing their control.

A large body of data from epidemiological studies suggests that particle exposure results in the largest health impact of outdoor air pollutants**.** The health effects depend on size and shape, elemental composition, microbial character, chemicals adsorbed, and molecular/atomic configuration (e.g. engineered through nanoparticle technology). Paradoxically, while ultrafine/nanoparticles are known to penetrate deep into the respiratory system and beyond, and while it is expected that health impacts may be unduly high, no specific health threshold values have been developed, so the true impact of these particles has yet to be quantified. It is not clear why this is the case. It is possible that given the lack of target level of interest, governments have less incentive to monitor exposure which would create data needed to thoroughly and comprehensively evaluate potential health impacts and thus facilitate the creation of formal standards.

Particles can migrate from air to surfaces and vice versa, and thus affect dermal, inhalation, and ingestion exposures. Likewise, microbial particles have an independent impact on health, but also both alter and can be produced through indoor chemistry processes that themselves impact health. Like SVOCs, the multimedia aspects of exposure suggest the need for a broader and more holistic approach to protecting public health through total exposure reduction. Increased knowledge of the health impact of ultrafine and engineered nanoparticles, advancements in the control of particles indoors, and reduction in all routes of exposure all have the potential for significant improvement in public health.

Newly generated particles indoors may also be formed through chemical reactions involving both indoor and outdoor generated compounds. In addition, existing particles on surfaces may be re-suspended during human activity. Human activity induced particle production including re-suspension of settled particles usually results in human exposure concentrations that are higher than ambient indoor or outdoor concentrations.

Understanding the origin and pathways of airborne particles provides a framework for developing strategies to reduce exposure. Quantifying their importance and consistency across indoor environments and conditions could help establish priorities. However, this task is highly complex and there are wide variations among studies.

One major observation from studies of indoor particles is the potentially wide variability of indoor concentrations and personal exposures between homes both within the same general location, and between locations of indoor and outdoor generated fine, but especially ultrafine particles. These differences reflect differences in outdoor concentrations and indoor sources, but also differences in those factors that impact the transport of outdoor particles into indoor spaces such as air change rates, penetration coefficients (proportion of entering particles that fully penetrate to the indoors), and the deposition rate of particles on surfaces. It appears that particles of outdoor origin contribute from 30-70% of indoor particle exposures with large variations between households. Modeling studies suggest that controlling indoor particle exposure using HVAC related filtration is very cost effective, but significant work on filtration/air cleaning effectiveness on exposure and health remains to be done.

Sources of indoor particles that are continuous, or semi-continuous (e.g. migration of ambient particles from outdoors, pilot lights on gas appliances, heating appliances in winter) generally account for background indoor concentration, while human activities that occur periodically (e.g. elevated outdoor levels, cooking, cleaning, grooming, folding clothes, printing and copying) create peaks which can be substantially higher than background indoor levels. Both contribute to human exposure and associated health consequences

The largest difference appears to be locations related to outdoor traffic, different building characteristics, and differences of indoor activities of occupants. Personal activities generate peak concentrations when they occur that can significantly impact personal exposures of individuals engaged in that activity as well as those close by. Movement of any kind has the potential to disturb settled dust and contribute to what has been called a “personal cloud” of particles that contribute to personal particle exposure. Common activities that generate short term peak exposures include cooking (especially frying, or searing food); using toasters or grills; smoking, burning candles or incense; cleaning (e.g. dusting, sweeping, vacuuming); personal care (e.g. using blow dryers or curling irons); and folding clothes.

Cumulatively, the studies demonstrate that

- 80-89% of outdoor particle exposure occurs indoors
- Indoor exposure to $PM_{2.5}$ including both indoor and outdoor generated particle is among the largest contributors to total health impact of indoor pollution.
- Outdoor ambient particle concentrations do not necessarily correlate well with personal indoor exposures;
- Personal indoor exposures are generally greater and more variable than indoor concentration, which themselves are higher than outdoor concentration;
- Personal exposures are roughly twice as high as outdoor ambient concentrations, though there is significant variability;
- Composition differences between indoor and outdoor PM can impact health effects of identical exposures.

Microbial Issues and the Microbiome

The absence of advanced analytic tools has severely limited our knowledge of microbial activity indoors, limiting our focus and leaving many unanswered questions and mysteries

unsolved. Our past research represents a piecemeal approach to the larger reality we face. Recent advances in analytics are beginning to reveal multiple ways in which microbial activity influences interrelated dimensions of indoor environments, with both positive and negative impacts, an understanding of which could lead to more opportunities for improving public health.

The discussion of SVOCs, indoor chemistry, and particles suggest that there are relationships between chemical, biological, and particle pollutants, between indoor and outdoor air, between water air quality and air quality, between building climatic conditions and building air quality and the role played by HVAC system, building materials and furnishings, and occupant activities. Recognizing these broad interdependencies and relationships is opening our eyes to a broader reality of indoor environmental quality. And this appreciation has begun to extend toward recognizing the vast interrelationships between indoor microbial activity and virtually all aspects of our indoor environment.

To fully understand the microbial contamination indoors and its potential health effects, it is important to broaden one's view and go beyond the narrow issues of dampness and mold and pathogenic disease transmission into the larger microbial environment around us.

Distinct microbial populations inhabit our bodies and our external environment. We can't see them but their numbers and diversity are almost beyond human comprehension. Those that are in our bodies play key roles important to our biology. Similarly, microbial activity plays an essential role in the ecological systems of the world we inhabit. Microbial populations have their own biological and social structures, defenses, adaptation mechanisms, life cycles, propagation habits, biological needs and behavioral patterns. We are constantly interacting with the microbial universe but have extremely limited understanding of who they are, what they are doing, how they impact us, and how we may impact them. They can be our friend or our enemy but they vastly outnumber us. Thus, the overriding issue we face is to understand how we can live together in peaceful harmony and cooperation. And that requires new forms of research that is up to the task.

Building Ecology and the Exposome:

A more holistic view is needed to consider the interactions among pollutants, media, and the totality of exposure the health impact of such exposure.

Two relatively new concepts have been introduced that expand our view of research in indoor air. Building ecology refers to the totality of the interactions of all the elements of buildings that are continually creating and affecting the indoor environment. Similarly, the exposome refers to the totality of one's lifetime exposure from all sources and all media that effect human health. Both terms suggest that a holistic and dynamic view of the indoor environment may be necessary to understand and effectively deal with the issues of indoor environmental exposures in order to foster environments that promote human health, comfort, and functional efficiency. It suggests a host of interactive issues of import:

- The need to combine the interactions of all the factors that affect indoor air, indoor surfaces and indoor water and how they affect each other;
- The need to combine biological, chemical, and particle sources and pollutants, and how they affect each other;
- The need to combine dermal contact, inhalation and ingestion exposures and how they affect each other and to understand how the human body is affected by all of these exposures over time.

Research to date has been limited, mostly focusing on dampness and mold and the transmission of pathogens indoors. Gradually, however, some new insights have begun to evolve. From studies thus far, the indoor air community understand some key elements that influence building microbiomes. Here are a few.

- Outdoor microbes enter through air exchange, are circulated through ventilation ducts, and incubate in condensation on cooling coils or damp insulation close to the coils or in water reservoirs such as cooling towers and water heaters.
- Toilet flushing, especially when lids are opened, is a source of microbial exposure mitigated in part by the effectiveness of the exhaust fan.
- Condensation on cool surfaces such as outside walls, lack of drainage, lack of ventilation in closed spaces that may get damp, including within walls, can be important microbial sources.
- High occupant density increases both proliferation and transmission of microbes.
- Microbes on shower heads or faucets frequently breed microbial contaminants.
- Humans are sources and carriers, so microbes from humans are found in dust or on frequently touched surfaces.
- The presence or lack of nutrients affects microbial survival.
- Some microorganisms play a positive role in our bodies, particularly in our digestive system. There is some evidence that microbes in the built environment to which humans are exposed may adversely affect the microbiome on or in our bodies, thus creating a line of inquiry about interactions between these microbial populations.
- Some evidence suggests that childhood exposure to microbial populations, as, for example, on a farm or when children play in the dirt, helps train and strengthen the immune system and helps to reduce allergic reactions. However, little is known about this potentially important relationship.
- Microorganisms can directly and adversely impact human health. The dominant microbial components linked to adverse human health include pathogen-associated molecular patterns (PAMPs). These molecules are associated with groups of microbes (bacteria or fungi) that may influence human innate immune system responses, interact with airway epithelial cell or irritant receptors or have toxic effects.

Advancing research on the microbiome will require a number of new tools and lines of inquiry, some of which are products of modern technology. New approaches for analyzing genetic material have revolutionized microbiology, and the tools available for detecting microbial DNA and RNA that help with microbial identification have improved over the past decade. Simultaneously, databases containing reference microbial genomes have grown.

These culture-independent techniques will need to be combined with culture-dependent methods, computer modeling, building characterization tools, and epidemiology to increase knowledge about the environments in which people live and work and how building and microbial conditions are affecting them.

As described by the National Academy of Engineering report summarized in the Science Review, research that focuses only on one microbe, on a specific aspect of building design, or on a single human health outcome will not be sufficient to understand these multifactorial relationships. Integrating approaches from multiple disciplines and bodies of knowledge is essential to improve understanding of these relationships and develop effective strategies to improve occupant health and welfare.

The Impact of Cumulative Exposure and Implications for IAQ Control Strategies

In addition to the significant chronic health impacts of simultaneous exposure to mixtures of pollutants described earlier, the cumulative impact of a large number of pollutants, none of which may independently have noticeable affects at observed levels, may have dramatic impact on occupant health, comfort, and productivity, and lead to questions related to appropriate choice of indoor air quality control strategies.

Short lived acute health impacts have largely been explained in terms of odor and sensory irritation. Yet, studies of odor and sensory irritation thresholds of pollutants and their concentration distributions indoors does not adequately explain the very substantial literature on the pervasiveness of sick building syndrome and the consistent reductions achieved through ventilation. Ventilation is a generic control strategy that reduces all indoor generated pollutant concentrations. Though this literature was not specifically covered in the Science Review, it appears likely that the varied health symptoms of SBS result from the cumulative exposure to large numbers of pollutants, many of which are likely below any individual pollutant threshold value and may even be below the detection limit, that impact health, create discomfort, and lower productivity.

This raises the question of how to best combine various control strategies such as generic controls at the building level (e.g. ventilation, exhaust, air cleaning, material and product choices etc.), reducing emissions of indoor products and materials at manufacture (e.g. TSCA type options for limiting emissions, green product testing, etc.), and reducing outdoor contaminants through traditional EPA activity. There are regulatory and non-regulatory options associated with each physical intervention that need to be considered.

CO_2, Human Performance, Ventilation Rates and Pollutant Concentrations

There are compelling reasons related to health and productivity to revisit current practices associated with target levels of indoor CO_2, ventilation rates, and indoor pollutant emission controls

Because occupant respiration is the main source of CO_2 in buildings, especially offices and schools, and because outdoor air ventilation dilutes indoor concentrations from indoor generated sources, the level of CO_2 in buildings is often used as a proxy for level of outdoor air ventilation per occupant, but except at extraordinarily high concentrations not normally found in non-industrial settings, CO_2 itself has not been considered to be a pollutant. The American Society of Heating, Ventilation, and Air-Conditioning Engineers Inc. has established the most widely accepted standard for ventilation adequacy for indoor environments, (ASHRAE Standard 62). As such, assuming average outdoor CO_2 levels of 300 PPM as assumed in the 1989 version of ASHRAE Standard 62), steady state indoor values of CO_2 of 1,000 and 800 ppm have traditionally been used to approximate target acceptable levels of 15 and 20 cfm of outdoor air ventilation rate per person for schools and offices respectively.

A large body of research, some using indoor CO_2 levels as a surrogate for the outdoor ventilation rate, has established that low ventilation rates per person (i.e. high CO_2 levels) are associated with symptoms of sick building syndrome (SBS), including reduced productivity and increased sick absences, but as ventilation rates increase, adverse symptoms diminish, productivity improves, sick absences diminish and perceived indoor air quality improves. The rationale for this and the justification for ASHRAE standard practice has traditionally been the dilution of indoor generated pollutants associated with higher outdoor air ventilation rates.

Because incoming outdoor air must often be conditioned to meet thermal (heating, cooling, and humidity control) requirements for comfort of occupants, the energy costs of doing so can be a deterrent to providing adequate ventilation. This is particularly the case in schools and other high occupant density settings, where adequate ventilation per person can dramatically increase the operating energy burden. It is not surprising, therefore, that CO_2 levels in schools of 2,000 or 3,000 ppm corresponding to outdoor air ventilation levels around 5 cfm or less per occupant, are not unheard of. In addition, while outdoor ventilation levels in offices are generally in line with ASHRAE Standard 62, it is not uncommon for the building interior to fall well below the Standard, particularly with VAV type HVAC system designs or high occupant density spaces.

With the added emphasis on energy conservation in buildings due to climate change and other factors, the trade-off between energy savings and indoor air quality has become even more acute. However, recent studies [Satish et al. (2012), Allen et al (2016)] provide well documented evidence that CO_2 itself, independent of outdoor ventilation rates, reduces the brain's cognitive performance, particularly executive function (e.g. critical thinking) skills and suggests a new

CO_2 target level/standard for adequate human performance of only 600 ppm, irrespective of the ventilation rate, while preserving the ventilation rate requirement to reduce indoor generated contaminant concentrations, irrespective of the CO_2 level. The evidence is compelling because of the strong experimental study designs and direct measure of human performance. It has already been established that the economic cost of reduced productivity from poor indoor air quality is in the tens to hundreds of billion dollars annually.

Achieving CO_2 concentrations below those associated with the ASHRAE ventilation standards could be extremely burdensome and infeasible if done solely with higher ventilation rates, and many systems now in place are not be capable of doing so. Hardly explored options for achieving what has heretofore been considered contradictory goals—i.e. simultaneously reducing indoor CO2 exposures while relaxing outdoor ventilation requirements to save and reduce energy costs, while also reducing indoor pollution levels-- could create dramatic improvements in occupant welfare.

SYNTHESIS OF FINDINGS FROM THE SCIENCE REVIEW

IDENTIFYING A TARGETED LIST OF POLLUTANTS

Identifying Pollutants Based on Past Studies:

Some of the pollutants identified in the literature may be worth considering for further study. These include, for example:

- From Logue et al.(2010). Pollutants of concern suggested by combining data from multiple studies were acetaldehyde, acrolein, benzene, 1,3 –butadiene, 1,4-dichlorobenzene, formaldehyde, naphthalene, NO_2 and PM $_{2.5}$
- From Batterman et al., (2014). Used decades old RIOPA and NJANES data. Included extreme value analysis and select mixtures. Pollutants with highest risk were benzene, perchloroethylene, chloroform, and carbon tetrachloride. Selected mixtures all had high risk: Hematopoietic mixture (benzene, MTBE, 1-4-DCB, TCE and PERC), Liver kidney toxicant mixture (MBTE, 1-4 DCB, TCE, PERC. Chloroform, and CTC.); The TVOC Mixture was estimated to be the highest risk.
- From Loh et al (2007a): Used multiple information sources and a flexible modeling framework to create a database of total personal exposure. The highest estimated cancer risk (including ingestion) on the order of 10^{-4}–$10^{-5,}$ include 1,3-butadiene, formaldehyde, chloroform, benzene, and dioxin. Also identified was PM, particularly $PM_{2.5}$.

However, because nationally representative data on indoor concentrations and personal exposures has been expensive and budgets for indoor environmental research are extremely limited, data on which these major studies of priority pollutants are based is mostly relatively old, and/or dependent on extensive modeling uncertainties, and/or relies extensively on outdoor air research that only partially reflects indoor concentrations or personal exposure, and /or poorly reflects the diversity of indoor environments and exposures between regions and buildings, and/or does not capture changes in both sources and pollutants that have and will continue to take place as society advances.

Developing nationally representative data on indoor concentrations and personal exposures has been expensive and budgets for indoor environmental research are extremely limited. As a result, data on which these major studies of priority pollutants are based are (a) mostly relatively old, (b) and/or dependent on extensive modeling uncertainties, (c) and/or relies extensively on outdoor air research that only partially reflects indoor concentrations or personal exposure, (d) and /or poorly reflects the diversity of indoor environments and exposures between regions and buildings, and (e) and/or do not capture changes in both sources and pollutants that have and will continue to take place as society advances.

This raises questions of how to identify a targeted set of pollutants, whether to do so based on current knowledge or after further study, and once identified, how best to mitigate their attendant adverse health effects. There may be sufficient doubt that pollutants based on past data or that rely heavily on outdoor monitoring data adequately represents current and likely future indoor exposures and thus may not justify traditional regulatory options to limit the use of such pollutants in products or materials. If so, there may nevertheless be little doubt that individuals experiencing unduly high exposures will suffer from unacceptably high risk. Knowing exactly how many individuals are so exposed is not necessarily a precondition to taking action to lower their exposure. For example, EPA could:

- Require through regulation or encourage voluntary product labeling, (voluntary activities have lower information needs) and/or
- Develop a cooperative program assisting manufacturers to lower emissions, and/or
- Publish advisories that include known health effects, products likely containing the pollutant, how to limit exposure, optional products etc., and/or provide the above information in other guidance to targeted audiences such as other government agencies, model building codes, green product green building programs, various advocacy groups, the general public etc.
- As sensor technology continues to develop, and may be helped by EPA research (see later discussion), affordable monitoring devices capable of measuring the concentration of problem pollutants inside and around buildings to allow individuals to identify such pollutants and take building level actions to remove them or avoid undue exposure.

  There is no one-size –fits- all approach to all pollutants identified. However, it is always useful to use multiple avenues together for best results. For example, publishing advisories with appropriate press releases and online access and notifications of availability, along with notices to key advocacy groups, done in cooperation with other agencies, EPA offices, (especially IED and other offices with multiple working relationships with other agencies and advocacy groups) can provide significant leverage. Further, as the public becomes more concerned, manufacturers of sensing and air cleaning equipment will find it beneficial to market their equipment, further extending their use.

Practical considerations

Given the limitations of the current availability of current exposure data to adequately represent current and potential future personal exposures, EPA may want to consider whether further study of the exposure and health effects of any of the above pollutants, or others that may be identified from current literature, would be worthwhile unless EPA has specific intent to take action to reduce exposure—either actions similar to those described above, or stronger regulatory actions if deemed justified for any particular pollutant. Without such specific intent one would have to question what purpose it would serve. On the other hand, taking non-regulatory actions, justified by limiting policy to high exposure individuals could itself be a very positive step and any of those actions would involve a modest cost and resource commitment, compared with more substantial research that might be required to reduce population exposure through regulatory controls.

Ultrafine particles, plasticizers, BPA, and several other possible SVOCs

Many studies suggest that the health effects of ultrafine particles, including purposefully engineered nanoparticles, as well as SVOCs, especially plasticizers and BPA, potentially have exceedingly large adverse health impacts, are ubiquitous, long lasting, and transferable across media such that significant portions of total exposure include more than just inhalation, but digestion and thermal components as well. As of yet, no official or unofficial health threshold levels of exposure have been identified for ultrafine particles, though even an unofficial target level could spur more robust monitoring to develop necessary data to identify official threshold values. As for SVOCs, this field still remains relatively unexplored, though Nazaroff and Weschler (2012) have suggested some SVOCs of potential interest.

Plasticizers are contained in plastics that have become the building block of many products from building materials, furniture, food containers, electronics, and even clothing and are also contained in pesticides, some medicines, personal care skin products, flame retardants and other materials. Plastics also are apparently not biodegradable, but while they degrade into smaller micro particles and eventually nanoparticles, do not alter their chemical makeup. Plastics disposed of in the ocean have been found to be non-biodegradable, but rather degrades to microscopic and then nanoscopic particles taken up in sediment and biota with unknown consequences for ecological and human health. These problems of plastics are being studied elsewhere in ORD, so that more research into plasticizers in indoor environments might fit well within the overall EPA research program.

Having identified the lack of sufficient national level data on pollutant exposures as a major constraint, it is worthwhile to determine if there are long term options to address that issue. Such a program is discussed in a later section covering longer term research options, including ways to mitigate cost constraints.

APPLIED RESEARCH WITH POTENTIALLY SIGNIFICANT NEAR- AND MEDIUM-TERM PAYOFF THAT REDUCE EXPOSURES USING NEW BUILDING-LEVEL CONTROL OPTIONS

Integrating building level solutions to reduce exposures to CO_2, PM, ozone, ozone reactive byproducts, VOCs and other pollutants

Introduction and historical context

Given the multitude of indoor air exposures with the potential for significant public health impact but for which information is not sufficient to support controls to specific pollutants, plus advances in technology suggest opportunities for combined applied research and policy prescriptions to reduce such exposure in the near-term future. Historically with the banning of Urea Formaldehyde Foam Insulation (UFFI) by the Consumer Product Safety Commission in 1982, and even with the subsequent release of the ban in 1983, there was some expectation that "source control" regulations levied on manufacturers would be used to restrict emissions from products and materials and be the primary mechanism for reducing indoor air pollution. It was expected that outdoor air ventilation and air cleaning, which are generic controls not specific to individual pollutants, would be a secondary and tertiary forms of defense respectively. As it turned out, CPSC had no desire or resources to take such actions on other sources and the lack of definitive regulatory authority for indoor air quality in other agencies led to a historical reliance on ventilation (including exhaust) as the primary means of indoor air quality control at the building level, with building level source control and air cleaning as secondary methods.

As mentioned above, slowly, source control through "green product "emission testing (despite its weaknesses) and subsequent user demand for green products and green buildings has emerged as a potential significant source control mechanism, though its potential is far from being realized at this time. With the rising cost of energy, the drive toward energy conservations accelerated by demands for reducing CO_2 emissions, and constraints on energy use placed pressure to reduce outdoor air ventilation to only what was needed to satisfy ASHRAE standard, with target levels of indoor CO_2 of 1000 ppm for schools and 800 ppm for offices. However, recent studies have revealed that CO_2 itself is a pollutant that significantly reduces human performance, particularly affecting critical thinking and strategy development, and suggests that target levels of CO_2 ought to be much lower, perhaps around 600 ppm or lower. But such levels cannot feasibly be met using outdoor air ventilation, but would also require some form of air cleaning.

In addition, recent studies of indoor chemistry reveal that ozone reactive chemistry and resulting SOAs can be reduced using a modest air recirculation rate through an activated carbon filter. Presumably, the same might be true for other contaminants, either using charcoal or other impregnated media. Further, ASHRAE requires (though often not followed) that outdoor air that falls below EPA ambient standards be similarly cleaned before entering indoor occupied spaces. In addition, some research suggests that more advanced cleaning and filtering methods can be cost effective in removing many contaminants and thus make it possible to reduce required outdoor ventilation requirements, perhaps by 50%. Finally, materials produced through engineered nanoparticles (nanotechnology) stands to revolutionize filter technology as well as sensors and analytic capabilities.

All of these developments suggest a path forward which is slowly emerging for developing new and improved comprehensive strategies for building-level indoor air quality controls, as part of "smart homes" and "smart buildings". One can envision that in the future buildings might have multiple air quality sensors strategically located and automatic HVAC controls that strategically and cost effectively use changing combinations of gaseous air cleaning and filtration along with reduced ventilation and air recirculation, plus direct exhaust of pollutants from key sources in ways that optimally reduce energy use and operating costs while meeting target levels of critical contaminant and mixtures, including low levels of CO_2, while automatically adjusting that combination as building conditions and occupancies change. Interest in such a future has already started to emerge, but it will take a long time to develop on its own. EPA could consider accelerating that time frame with targeted research. There are three legs to such a potential venture

- air cleaning and filtration technology
- sensor technology, and
- **o**perational algorithms for optimizing their use.

The most critical needs at this time may be in the air cleaning and filtration field with the least critical in the need for research in operational algorithms. Substantially reducing ozone, particulate matter, CO_2, the most common and deleterious VOCs and microbiological contaminants by advancing air cleaning technologies could be achieved first, with significant improvements in indoor air quality, without necessarily advancing sensor technology or operational algorithms. These could be developed later as building operational technologies become more advanced. Sensor technologies are already rapidly developing and have broad fields of application, so once some operational air cleaning and filtration technologies are in place, complementary sensors might not be far behind. Optimization in their application using special algorithms could be considered last stage refinements.

Establishing a context to accelerate time frame for adoption

Should EPA choose to do this, it is important to emphasize that to accelerate the time frame of achieving adoption by the private sector, the context in which the research is undertaken is as important, perhaps more important, than the research itself. Research results that could contribute to such a goal could simply sit in the literature without being acted upon or without stimulating further developments. For example, over a decade ago, the Environmental Energy Technology Division of the Lawrence Berkeley National Laboratories (LBNL) published a series of reports showing the potential for advanced air cleaning/filtration technology to allow for the reduction of outdoor air ventilation rates by up to 50% while using less energy with no sacrifice of Indoor Air Quality. These reports are discussed in detail as part of the material below. However, while the results are extremely relevant toward achieving the future described above, the actual impact of that research in stimulating development toward commercialization and widespread adoption appears to have been minimal. However, were there a national recognized program, with a name and a logo, with participation by several other agencies and the private sector, at multiple conferences, that research alone could have had a much larger impact and stimulated more follow-up research by others. Perhaps EPA would want to consider conducting complementary research while working with others to establish a broader national effort with broad interest and participation.

The following discussion highlights selected existing research in the three fields mentioned above, with the overwhelming emphasis on air cleaning applications.

Advances in air cleaning/purification technologies

Practical air cleaning technologies for particles are widely available, typically consisting of fibrous filters in the supply airstream to remove particles from both the incoming outdoor air and the return air streams. Air cleaning technologies for VOCs are less advanced and surprisingly little has been published regarding their effectiveness and practicality when used in HVAC systems. Different air cleaning technologies may serve different purposes, from removing allergenic particles, killing bacteria and viruses, removing particles by particle size, removing ozone or CO_2, and removing or oxidizing VOCs. Given the cost limitations of outdoor air ventilation, the desire to save energy to reduce greenhouse gases, it is worthwhile to examine the potential for various air purification technologies to reduce air pollutants effectively at minimum cost.

A list of air purification technologies that could be investigated for appropriate applications are listed in Wikipedia (https://en.wikipedia.org/wiki/Air_purifier) and included below.

1. **Thermodynamic sterilization (TSS)** uses heat sterilization via a ceramic core with micro capillaries, which are heated to 200 °C (392 °F). It is claimed that 99.9% of microbiological particles - bacteria, viruses, dust mite allergens, mold and fungus spores - are incinerated. The air passes through the ceramic core by the natural process of air convection, and is then cooled using heat transfer plates and released. TSS is claimed not to emit harmful by-products (although the byproducts of partial thermal decomposition are not addressed) and also reduces the concentration of ozone in the atmosphere.
2. **Ultraviolet germicidal irradiation (UVGI**) can be used to sterilize air that passes UV lamps via forced air. Air purification UVGI systems can be freestanding units with shielded UV lamps that use a fan to force air past the UV light. Other systems are installed in forced air systems so that the circulation for the premises moves micro-organisms past the lamps. Key to this form of sterilization is placement of the UV lamps and a good filtration system to remove the dead micro-organisms. For example, forced air

systems by design impede line-of-sight, thus creating areas of the environment that will be shaded from the UV light. However, a UV lamp placed at the coils and drain pan of cooling system will keep micro-organisms from forming in these naturally damp places. The most effective method for treating the air rather than the coils is in-line duct systems, these systems are placed in the center of the duct and parallel to the air flow.

3. **Filter -** based purification traps airborne particles by size exclusion. Air is forced through a filter and particles are physically captured by the filter. High-efficiency particulate arrestance (HEPA) filters remove at least 99.97% of 0.3-micrometer particles and are usually more effective at removing both larger and smaller particles. HEPA purifiers, which filter all the air going into a clean room, must be arranged so that no air bypasses the HEPA filter. In dusty environments, a HEPA filter may follow an easily cleaned conventional filter (prefilter) which removes coarser impurities/larger particles so that the HEPA filter needs cleaning or replacing less frequently. HEPA filters do not generate ozone or harmful byproducts in course of operation.

- **Activated carbon** is a porous material that can adsorb volatile chemicals on a molecular basis, but does not remove particles. The adsorption process when using activated carbon must reach equilibrium and thus it may be difficult to completely remove contaminants. Activated carbon is merely a process of changing contaminants from a gaseous phase to a solid phase. Activated carbon can be used at room temperature and has a long history of commercial use. It is normally used in conjunction with another filter technology, especially with HEPA. Other materials can also absorb chemicals, but at higher cost.
- **Polarized-media electronic air cleaners** use active electronically enhanced media to combine elements of both electronic air cleaners and passive mechanical filters. Most polarized-media electronic air cleaners convert 24-volt current to safe DC voltage to establish the polarized electric field. Airborne particles become polarized as they pass through the electric field and adhere to a disposable fiber media pad. Ultra-fine particles (UFPs) that are not collected on their initial pass through the media pad are polarized and agglomerate to other particles, odor and VOC molecules and are collected on subsequent passes. The efficiency of polarized-media electronic air cleaners increases as they load, providing high-efficiency filtration, with air resistance typically equal to or less than passive filters. Polarized-media technology is non-ionizing, which means no ozone is produced.
- **Photocatalytic oxidation (PCO)** is an emerging technology in the HVAC industry. Photocatalytic oxidation systems are able to completely oxidize and degrade organic contaminants. For example, Volatile Organic Compounds found low concentrations within a few hundred ppm or less are the most likely to be completely oxidized. (PCO) uses short-wave ultraviolet light (UVC), commonly used for sterilization, to energize the catalyst (usually titanium dioxide ($TiO2$) and oxidize bacteria and viruses. PCO in-duct units can be mounted to an existing forced-air HVAC system. PCO is not a filtering technology, as it does not trap or remove particles. It is sometimes coupled with other filtering technologies for air purification. UV sterilization bulbs must be replaced about

once a year; manufacturers may require periodic replacement as a condition of warranty. Photocatalytic Oxidation systems often have high commercial costs.

- **Photoelectrochemical oxidation.** A related technology relevant to air purification is photoelectrochemical oxidation (PECO. While technically a type of PCO, PECO involves electrochemical interactions among the catalyst material and reactive species (e.g., through emplacement of cathodic materials) to improve quantum efficiency; in this way, it is possible to use lower energy UVA radiation as the light source and yet achieve improved effectiveness
- **Ionizer purifiers** use charged electrical surfaces or needles to generate electrically charged air or gas ions. These ions attach to airborne particles which are then electrostatically attracted to a charged collector plate. This mechanism produces trace amounts of ozone and other oxidants as by-products.[6] Most ionizers produce less than 0.05 ppm of ozone, an industrial safety standard. There are two major subdivisions: the fanless ionizer and fan-based ionizer. Fanless ionizers are noiseless and use little power, but are less efficient at air purification. Fan-based ionizers clean and distribute air much faster. Permanently mounted home and industrial ionizer purifiers are called electrostatic precipitators.
- **Immobilized cell technology** removes microfine particulate matter from the air by attracting charged particulates to a bio-reactive mass, or bioreactor, which enzymatically renders them inert.
- **Titanium dioxide (TiO_2) technology** - nanoparticles of TiO_2, together with calcium carbonate to neutralize any acidic gasses that may be adsorbed, is mixed into slightly porous paint. Photocatalysis initiates the decomposition of airborne contaminants at the surface.

All of these technologies have been studied to some extent and all have some degree of commercial availability. But with the exception of HEPA filters, movement toward effective adoption in common practice appears to be very slow. The following articles demonstrate what is possible and what remains to be done:

Summary of Informative Articles

Since the subject of cost effective advanced indoor air cleaning has only modestly developed, it is helpful to review some key articles that also suggest areas of research that may be useful to EPA.

Kabir Ehsanul and Kim Ki-hyun (2012). A Review of Some Representative Techniques for Controlling the Indoor Volatile Organic Compounds. Asian Journal of Atmospheric Environment. 6(3): 137-146.

The authors provided an extensive review of three indoor air treatment methods: Biological treatment using plants, activated carbon fiber, and photocatalytic oxidation. Of the three, the latter two appear to have the most promise for future use, though both require further research and refinement.

Activated Carbon Fiber: Adsorption process is one of the most efficient and safest processes to remove VOCs from indoor air. Activated carbon fiber (ACF) filter is a promising technology for removing VOCs from indoor air because of its larger surface area and higher adsorption rates and capacity than the more traditional activated carbon granules, both of which have good regenerative properties. ACF is generally made from rayon, polyacrylonitrile, or phenolic resin). The fibers are woven into a fabric and then activated in steam or CO_2 at high temperatures. The narrow pore size capacity and large surface area allow for significant adsorption while the fiber does not contain impurities that can catalyze oxidative reactions and lead to decomposition of the adsorbate within the adsorbent. The material requires a regeneration step in which the adsorbed VOCs must be periodically desorbed from the filter (and exhausted outdoors). Although activated carbon filters can remove a broad range of VOCs from indoor air, their capacity to adsorb formaldehyde is relatively low. However, using a double layer, adsorption efficiency of 40% can be for formaldehyde, while those of other VOCs can exceed 90%.

The media has a long adsorption life time and can be used effectively to remove indoor VOCs with periodic regeneration under reasonable COC concentrations. The isotherm data obtained for the ACF shows that it takes about 100 hours to fully saturate the media with realistic concentrations of indoor VOCs. Actual tine is site specific. There are various options for regeneration that have and should be tested to find the most cost effective.

Modeling indicates that the combination of ACF air cleaning and a 50 percent reduction in ventilation can decrease indoor concentrations of VOCs by 60 to 80 percent, while reducing formaldehyde by 12 to 40 percent. Thus, the system can suppress exposures to VOCs and formaldehyde, while simultaneously reducing the ventilation (up to half) to save energy. However, it is essential to optimize parameters such as duration and frequency of regeneration cycles, the air flow rate, and temperature. However, to allow a reduction in ventilation rates, an air cleaning system needs to be effective in removing a broad spectrum of VOCs that are present simultaneously in the indoor air at low ppb-level concentrations.

Photocatalytic Oxidation (PCO). Photocatalytic Oxidation (PCO) harnesses radiant energy from light source with heterogeneous catalyst to de-grade the organic pollutants into their inorganic components and is a comparatively cost-effective technology for VOC removal. Titanium dioxide (TiO) is the most widely used catalyst though other semiconductors are also commonly used. The PCO process creates hydroxyl radicals and superoxide ions, which are highly reactive electrons that aggressively combine with air pollutants creating a chemical reaction to effectively oxidize (or burn) air pollutants breaking down into carbon dioxide and water molecules. Raising the temperature above room levels generally increases performance. However, the performance is not uniform for all VOCs which creates challenges and tradeoffs to find acceptable solutions under varying indoor environmental conditions.

General Conclusion: There is yet no single fully satisfactory method for VOC removal from indoor air due to the difficulties linked to the very low concentration, diversity, and variability of VOCs in the indoor environment. The specific characteristics of indoor air pollutants and the indoor environment can yield numerous challenges. The methods for the treatment of indoor air must be able to purify a large amount of air in spatially confined environments with minimal nuisances. This requires technical innovations, the development of specific testing protocols, and a better understanding of the activities and mechanisms of VOC uptake by different substrates.

> ***Fisk WJ (2007). Can Sorbent-Based Gas Phase Air Cleaning For Vocs Substitute For Ventilation In Commercial Buildings? Published in Proceedings of IAQ 2007 "Healthy and Sustainable Buildings", October 1517, 2007, Baltimore, Maryland. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA*.**

This paper reviewed current knowledge about the suitability of sorbent-based air cleaning for removing volatile organic compounds (VOCs) from the air in commercial buildings in the context of partially substituting such air cleaning for outdoor air ventilation to save energy. The paper focuses on sorbent systems installed in HVAC supply airstreams.

Sorbent media used most commonly for indoor VOC control are activated carbons, aluminas, and synthetic zeolites in granular form. Various polymers can also be manufactured with pores in desired size ranges to serve as adsorbers. All of these materials have a very high surface area per unit mass because they have extensive microscopic pores. Gaseous contaminants physically adsorb to the surfaces of sorbent media because of van der Waals forces. In addition, contaminants can condense within the small pores. However, the physical adsorption process is reversible; i.e., sorbed VOCs can be released and emitted back into air upon heating. The maximum amount of VOC that can be retained on the sorbent, often called the equilibrium capacity, increases with an increase in the gas phase VOC concentration. For a given temperature, the generally non-linear curve of equilibrium-sorbed. The equilibrium capacity of a sorbent, and thus the adsorption isotherm, varies with temperature, relative humidity, and among VOCs, and tends to be larger for less volatile, higher molecular weight VOCs.

Sorbent media may be chemically treated with an agent designed to react chemically with VOCs that are less easily removed by physical adsorption. The resulting materials are often called "chemisorbents". Common examples are activated alumina or activated carbon impregnated with potassium or sodium permanganate which reacts with formaldehyde and several other compounds. The chemical reactions with the impregnates are irreversible; consequently, the reacted compound will not subsequently be released back into air. Gas phase adsorption systems sometime use a mixture of chemisorbent treated and untreated sorbent media.

Another sorbent deployment method, now quite common, is to integrate the sorbent media into a fibrous particle filter so that one product can be used for both particle and gas-phase filtration (Muller 1993). Some manufacturers of sorbent media offer a media with grains of sorbent bonded onto a three-dimensional non-woven fiber matrix not intended for particle filtration. With this method of sorbent deployment, the packing of sorbet grains is decoupled from sorbent grain size and smaller grains of sorbent may be used without encountering excessive airstream pressure drops.

The temporal variability in sorbent system performance will complicate the application of any of these criteria. VOC removal efficiency will diminish after the sorbent becomes substantially loaded with sorbed VOCs. The sorbent must be removed and replaced, or regenerated in-situ, when the efficiency falls or is predicted to fall below the minimum target value for the range of operating conditions. The lifetime of a sorbent system will, in general, increase in proportion to the amount of sorbent deployed. For physical adsorbents, increases in the humidity or temperature of air above standard conditions can diminish VOC removal efficiency. Also, an increase in the inlet concentration of a readily adsorbed VOC can decrease the efficiency of removal for a less readily adsorbed VOCs or even drive the less readily adsorbed VOC off the sorbent.

While hundreds of papers on the performance of sorbent systems have been published. This review identified only two studies that reported on long-term evaluations of sorbent systems installed in real buildings and that assessed performance for a range of VOCs. Also, only a few economic analyses of sorbents for commercial building IAQ applications were identified.

When the inlet air contains multiple VOCs, which is always the case in buildings, and a significant fraction of carbon is saturated with VOCs, a higher molecular weight VOC can drive a previously sorbed lower molecular weight VOC off a carbon sorbent bed. This potentially can cause the indoor VOC concentration to exceed that with no sorbent present.

Activated carbon, without any additives or impregnates, has a very low capacity for retention of some of the lower molecular weight polar compounds such as formaldehyde but chemisorbents can remove a few to several percent of their weight in formaldehyde. Consequently, a sorbent system that is effective in controlling indoor concentrations of the broad range of VOCs present indoors, as needed to enable reductions in outdoor air supply, will likely need to contain a physical sorbent and a chemisorbent

In commercial buildings, sorbent systems will be faced with mixtures of at least a dozen important VOCs. Inlet VOC concentrations, air temperatures, relative humidity, and air flow rates will often vary over time. Little is known about the performance of sorbent systems under these conditions. In fact, the review identified only two studies with significant data on the VOC removal performance of sorbent systems installed in commercial buildings.

The major conclusions from this review are:

• Considering the types of pollutants typically emitted inside commercial buildings, simultaneous air cleaning for particles and VOCs, using air cleaning systems with moderate pollutant removal efficiencies in the supply or return airstreams of HVAC systems, may enable reduced ventilation rates without a degradation of indoor air quality.

• Sorbent systems can remove a broad range of VOCs with moderate to high efficiency.

• Sorbent technologies perform effectively when challenged with the low VOC concentrations present indoors.

• There is a large uncertainty about the lifetimes of sorbent air cleaning for VOCs when used in commercial buildings.

• Based on the estimates of recurring costs, sorbent air cleaning appears economically attractive as a substitute for ventilation. However, such comparisons are tentative due to the uncertainties regarding the lifetime of sorbent media.

The following four highest priority areas of research suggested (in order of priority) given the near-term need for an air cleaning technology usable for energy efficiency applications in commercial buildings.

- First priority: Better define VOC removal efficiencies and the useful lifetime of sorbents for commercial building applications that characteristically have many VOCs present at low and time-varying concentrations. Evaluate advanced sorbent systems that contain both a physical adsorbent, such as activated carbon for removal of higher molecular weight non-polar compounds, and a chemisorbent for removal of lower molecular weight compounds like formaldehyde. The main concern is the lifetime of the physical adsorbent.
- Second priority: Research on in-situ regeneration of activated carbon using unheated outdoor air. If this process is effective, it would be much more practical and energy efficient than in-situ regeneration using heated air. Also, effective in-situ generation would reduce the expenditures needed on sorbent media replacement. Include carbon fiber systems in this research. The proposed study would evaluate sorbent performance for a broad range of VOCs encountered indoors.
- Third priority. An updated analysis of the cost of sorbent air cleaning, accounting for the new data on sorbent VOC removal performance and lifetimes.
- Fourth priority: use of the new data from sorbent performance testing in conjunction with existing information on odor thresholds, irritancy thresholds and potencies, and toxicity of

VOCs to determine if sorbents satisfy the criteria for systems that can counteract the VOC increases from decreased building ventilation.

Important Studies at the Lawrence Berkeley National Laboratory

As early as 2002, the Indoor Environments Department of the Environmental Energy Technologies Division of the Lawrence Berkeley National Laboratory (LBNL) began to realize that the growing tension developing between the need to save energy by limiting outdoor air ventilation and preserving good indoor air quality which largely depends on adequate outdoor ventilation would require some alternative indoor air quality strategies. They then embarked on a program to explore the use of air cleaning as an addition to ventilation that could allow for the reduction in ventilation without adversely impacting indoor air quality. Their studies largely focused on removing VOCs and ozone. The studies, summarized below, all show positive results in this emerging field but also recognize that more needs to be done to fully test, validate, and refine their results before these technologies can be fully commercialized and widely adopted. EPA may wish to interpret these studies as an invitation to further these technologies and introduce others. Such studies, if done cooperatively and as a national program as previously described, could have lasting impact in the near and medium term. The studies are summarized below.

LBNL on the Potential to Remove Ozone using Carbon Based Filtration Air Cleaning Technology

The ozone in outdoor air is the dominant source of indoor ozone within most buildings, although indoor ozone concentrations tend to be 20% to 70% of outdoor concentrations, where most human exposure occurs. In addition, while ozone itself directly affects health adversely, it also reacts with certain VOCs indoors, especially terpenoids, to create secondary byproducts which themselves have significant adverse impact. While increasing outdoor air ventilation will reduce the reaction time and thus the secondary reaction byproducts, indoor ozone levels would increase as would pollutants of outdoor origin and energy use. It is thus useful to find viable low cost methods to remove ozone from indoor air. The following LBNL report is useful in this regard

Gundel, L.A.; Sullivan, D.P.; Katsapov, G.Y.; Fisk, W.J. (2002). A pilot study of energy efficient air cleaning for ozone. Lawrence Berkeley National Laboratory (LBNL-51836), Berkeley, CA.

This report reviews prior studies and conducts a laboratory pilot study to explore and identify feasible (e.g. low cost, low pressure drop) carbon based filtration options for removing ozone from indoor air. From their review they found that the best performing air cleaner for this purpose was a commercially available pleated filter material having a thin layer of small activated carbon particles between two sheets of non-woven fibrous webbing and marketed commercially as a VOC removal from automobile passenger compartments. The filter was tested in a laboratory by passing air containing normal ambient VOC and ozone concentrations but with particles filtered out, and separately produced ozone at average concentration of 100 ppm through the filter for 3 months continuously at an air velocity typical for commercial building HVAC systems.

The ozone filter used resemble a 2.5 cm (1 inch) pleated particle filter that is used commonly in packaged air handling units. The efficiency was maintained at approximately 50% or higher during three months of continuous operation which is equivalent to approximately 6 months of commercial operation during daytime only. The inlet ozone concentration averaged 113 ppb, which is considerably higher than typical (e.g. 25 ppb) time-average ozone concentration in polluted urban areas. The pressure drop was only 25 Pa which at twice the velocity would be roughly 60 Pa, and those are roughly 10% of what is normal in commercial systems.

When 2.5 cm thick particle filters are used in air handlers, they are normally replaced every few months which is less that the anticipated life of the ozone filter. Higher ozone removal efficiencies and/or longer filter lifetime could be achieved without added pressure drop by increasing the thickness of the filter bed beyond 2.5 cm, which would not be unusual in commercial systems.

Thus, the authors conclude that such a system appears to be highly practical way to reduce ozone concentration indoors though further testing is suggested under varying operating conditions, such as lower inlet concentrations, alternative temperature and humidity conditions, and less efficient particle filtration upstream of the ozone filter.

LBNL on Exploring the Viability of Photocatalytic Oxidation (PCO)

Anticipating the need to reduce energy use in buildings, a large portion of which is associated with outdoor air ventilation, the Indoor Environments Department of the Environmental Energy Technologies Division of LBNL set out to identify air purification technologies that could be used to reduce levels of outdoor ventilation by 50% or more without sacrificing indoor air quality. They chose to evaluate Ultra-Violet Photocatalytic Oxidation (UVOCO) as a means of reducing indoor VOC concentrations at relatively low cost. In this exploration, they published three reports which are summarized below.

Alfred T. Hodgson, Douglas P. Sullivan, and William J. Fisk (2005). Evaluation of Ultra-Violet Photocatalytic Oxidation (UVPCO) for Indoor Air Applications: Conversion of Volatile Organic Compounds at Low Part-per-Billion Concentrations. LBNL Report 58936). Indoor Environment Department, Environmental Energy Technologies Division, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

In this study (LBNL Report-58936) the authors used controlled chamber experiments containing honeycomb monoliths coated with titanium dioxide and 3% by weight tungsten oxide which were radiated with 12 UVC lamps arranged in 4 banks.

Efficient removal of indoor generated airborne particles and volatile organic compounds (VOCs) in office buildings and other large buildings may allow for a reduction in outdoor air supply rates with concomitant energy savings while still maintaining acceptable indoor air quality in these buildings. Ultra-Violet Photocatalytic Oxidation (UVPCO) air cleaners have the potential to achieve the necessary reductions in indoor VOC concentrations at relatively low cost. In this study, laboratory experiments were conducted with a scaled prototype UVPCO device designed for use in a duct system to treat both outdoor and recirculated air. The experimental UVPCO contained two 30 by 30-cm honeycomb monoliths coated with titanium dioxide and 3% by weight tungsten oxide. The monoliths were irradiated with 12 UVC lamps arranged in four banks.

The UVPCO was challenged with four mixtures of VOCs typical of mixtures encountered in indoor air: A synthetic office mixture contained 27 VOCs; a cleaning product mixture contained three cleaning products with high market shares;, a building product mixture combining painted wallboard, composite wood products, carpet systems, vinyl flooring and others; plus a mixture contained formaldehyde and acetaldehyde. Steady-state concentrations were produced in a prototype classroom laboratory environmental chamber where flow rates were varied. Air was drawn through the UVPCO, and single pass conversion efficiencies were measured. Production of formaldehyde, acetaldehyde, acetone, formic acid, and acetic acid as reaction products was investigated.

Alcohols and glycol ethers were the most reactive chemical classes with conversion efficiencies often near or above 70% at the low flow rate and near 40% at the high flow rate. Ketones and terpene hydrocarbons were somewhat less reactive. The relative VOC conversion rates are generally favorable for treatment of indoor air since many contemporary products used in buildings employ oxygenated solvents. Assuming a recirculation rate comparable to three times the normal outdoor air supply rate, simple mass-balance modeling suggests that a device with similar characteristics to the study unit has sufficient conversion efficiencies for most VOCs to compensate for a 50% reduction in outdoor air supply without substantially impacting indoor VOC concentrations.

However, formaldehyde, acetaldehyde, acetone, formic acid, and acetic acid were produced in these experiments as reaction byproducts and suggests that evaluation of these contaminants is warranted. Other suggested studies include determining VOC conversion efficiencies in actual buildings and evaluating changes in VOC conversion efficiency as monoliths age with long-term operation.

Alfred T. Hodgson, Douglas P. Sullivan, and William J. Fisk (2005). Parametric Evaluation of an Innovative Ultra-Violet Photocatalytic Oxidation (UVPCO) Air Cleaning Technology for Indoor Applications. LBNL report 59074). Indoor

Environment Division, Environmental Energy Technologies Division, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

In this study (LBNL Report -59074), a parametric evaluation of the effects of monolith thickness, air flow rate through the device, UV power, and reactant concentrations in inlet air was conducted for the purpose of suggesting design improvements

The thickness of individual monolith panels was varied between 1.2 and 5 cm (5 to 20 cm total thickness) in experiments with the office mixture. VOC reaction efficiencies and rates increased with monolith thickness. However, the analysis of the relationship was confounded by high reaction efficiencies in all configurations for a number of compounds. These reaction efficiencies approached or exceeded 90% for alcohols, glycol ethers, and other individual compounds including d-limonene, 1,2,4-trimethylbenzene, and decamethylcyclopentasiloxane. This result implies a reaction efficiency of about 30% per irradiated monolith face. In these and other experiments, the performance of the system for highly reactive VOCs appeared to be limited by mass transport of reactants to the catalyst surface rather than by photocatalytic activity.

Increasing the air flow rate through the UVPCO device decreases the residence time of the air in the monoliths and improves mass transfer to the catalyst surface. Increased gas velocity caused a decrease in reaction efficiency for nearly all reactive VOCs. For all the more reactive VOCs, the decrease in performance was less, and often substantially less, than predicted based solely on residence time, again likely due to mass transfer limitations at the low flow rate. The results demonstrate that the UVPCO can achieve high conversion efficiencies for reactive VOCs at air flow rates above the base experimental rate of 175 m3/h.

The effect of UV power was examined in a series of in which the number of lamps was varied between nine and three. For the most reactive VOCs in the mixture, the effects of UV power were surprisingly small. Thus, even with only one lamp in each section, there appears to be sufficient photocatalytic activity to decompose most of the mass of reactive VOCs that reach the catalyst surface. For some less reactive VOCs, the trend of decreasing efficiency with decreasing UV intensity was in general agreement with simulation model predictions.

The UVPCO device easily decomposed formaldehyde. At an air flow rate near 300 m3/h, the reaction efficiency was about 60%. There was no apparent effect on conversion of formaldehyde concentration in the range of 24 to 88 ppb. However, the reaction efficiency was about 40 – 50% higher than predicted based on unreported experiments conducted at 1 ppm.

Formaldehyde, acetaldehyde, and acetone were produced as reaction products in these experiments. In experiments with the office VOC mixture there was substantial formation of acetaldehyde and low net formation of formaldehyde. The mixture contained ethanol, a likely reactant leading to acetaldehyde formation. In experiments with the building product mixture, both formaldehyde and acetaldehyde were formed. The design of a UVPCO device for use in occupied buildings needs to minimize the formation of these two unwanted byproducts as they are carcinogens and have relatively low exposure guidelines for noncancer effects.

Alfred T. Hodgson, Hugo Destaillats, Toshifumi Hotchi,and William J. Fisk (2007). Evaluation of a Combined Ultraviolet Photocatalytic Oxidation (UVPCO) / Chemisorbent Air Cleaner for Indoor Air Applications. (LBNL Report 62202). Indoor Environment Department, Environmental Energy Technologies Division, E.O. Lawrence Berkeley National Laboratory Berkeley, CA, USA.

A third study (LBNL-62202) sought to reduce the production of formaldehyde and acetaldehyde to acceptable levels by employing different chemisorbent scrubbers downstream of the UVPCO device. Additionally, the authors made preliminary measurements to estimate the capacity and expected lifetime of the chemisorbent media. The results also showed that formaldehyde was produced from many commonly encountered VOCs, while acetaldehyde was generated by specific VOCs, particularly ethanol. The implication is that formaldehyde concentrations are likely to increase when an effective UVPCO air cleaner is used in buildings containing typical VOC sources. A series of experiments were conducted to determine if the oxidizer, sodium permanganate ($NaMnO_4 \cdot H_2O$), has sufficient reaction rates and capacity to counteract formaldehyde and acetaldehyde production and enable a 50 % reduction in building ventilation rate without net increases in indoor aldehyde concentrations. A commercially produced filter element and two laboratory-fabricated media beds containing $NaMnO_4 \cdot H_2O$ chemisorbent media were evaluated. Six experiments were conducted with the commercial filter element installed downstream of the UVPCO reactor. Eleven experiments were conducted with a single panel media bed installed downstream of the UVPCO reactor. Two experiments were conducted with a four-panel, folded, media bed (approximately four times the size of the single panel bed) installed downstream of the reactor. Because the commercial unit contained activated carbon as an additional component, it was effective at removing lower volatility compounds that typically have low oxidation rates in the UVPCO reactor. The folded bed was considerably more effective; formaldehyde was removed with greater than 90 % efficiency, and acetaldehyde was removed at about 70 % efficiency. With the combined UVPCO/chemisorbent system, the net removal efficiencies for formaldehyde and acetaldehyde were 90 % and 40 %, respectively.

Two pairs of replicated experiments were conducted with the UVPCO system in a simulated HVAC mode with recirculation of chamber air. For one pair, the UVPCO air cleaner was operated alone, and for the other, the combined system of UVPCO air cleaner plus a downstream chemisorbent was used. The results showed that the chemisorbent media contributed substantially to the removal of VOCs in this mode. Concentrations were pulled down within the first hour. Net reductions for formaldehyde and acetaldehyde at near steady-state conditions were in the range of 50 to 70 %. From an analysis of $NaMnO_4 \cdot H_2O$ in new and used media and the conditions of the experiments with the single panel media bed, we estimated that, on average, about nine moles of NaMnO4·H2O were needed to mineralize one mole of VOCs, and about three moles of the reactant were needed to mineralize one mole of carbon. These values were used to make estimates of the media consumption rate for the experimental conditions and for a hypothetical building application. In summary, the use of a multi-panel, folded scrubber filled with NaMnO4·H2O chemisorbent media downstream of the prototype UVPCO air cleaner effectively counteracted the generation of formaldehyde and acetaldehyde due to incomplete oxidation of VOCs in the UVPCO reactor. Thus, this combined UVPCO air cleaner and chemisorbent system appears to have sufficient VOC removal efficiency to enable a 50 % reduction in ventilation rate without increasing indoor aldehyde concentrations.

Note1 to EPA: As previously mentioned, these studies were published in the 2005- 2000 period. But in the past decade, despite its potential relevance, they have received little follow-up toward commercialization. It is likely that more would have been done by the larger research community and by manufacturers to accelerate the development of this and similar technologies moving toward implementation if it had been conducted within the framework of a well-recognized national program with wide participation and some participation and marketing to advocacy groups as previously described.

Note 2 to EPA: The Combined Ultraviolet Photocatalytic Oxidation (UVPCO) / Chemisorbent Air Cleaner appears to be viable for indoor air applications, at least in office type buildings, but it could use field studies under varying conditions to confirm the current data or refine it to make it acceptable for commercial application.

Need to extend research to specifically address school environments in removal of VOCs, and to remove CO_2

All of the research described above was directed to removal of VOC or ozone in commercial environments, principally office environments. It should also be tested in school environments where population densities are much higher, where total outdoor ventilation rates are higher, and where typical VOC mixtures are likely to be different. It is thus important to test these air cleaning technologies in schools as well as offices.

In addition, the extent to which air cleaning can partially replace outdoor air ventilation, CO_2 levels will necessarily increase, and that runs counter to the need to reduce CO_2 concentrations even below the ASHRAE design levels because of its detrimental impact on cognitive function convincingly shown in recent research. This is especially relevant in schools, conference rooms, and auditoriums where CO_2 levels are often very high because of the high occupant density. It also doesn't help that CO_2 production is a byproduct of the UVPCO technology described above so well researched by LBNL.

Given these findings, elucidating air cleaning strategies to remove CO_2 becomes doubly important, and something that EPA research could potentially address.

Other related studies

Other related studies are worth noting. Hugo Destaillats at LBNL has studied the extent to which different common filter media designed to remove particles can also end up producing formaldehyde or other aldehydes under certain conditions. His research shows that both cotton/polyester filters and fiberglass filters, under various conditions are problematic in that regard.

See

> Hugo Destaillats (2009). Are Ventilation Filters Degrading Indoor Air Quality In California Classrooms? California Energy Commission, CEC-500-2009-054 at http://www.energy.ca.gov/2009publications/CEC-500-2009-054/CEC-500-2009-054.PDF and

> Hugo Destaillats (2018) Characterizing formaldehyde emissions from home central heating and air conditioning filters at https://www.arb.ca.gov/research/seminars/destaillats/destaillats2.htm?utm_medium=email&utm_source=govdelivery

In addition, Kyung JinLee et al.shows that elecrospun polyacrulonitrile nanofiber can effectively adsorb formaldeyde. See

> Kyung JinLee, Nanako Shiraton, Gang HoLee, Jin Miyawaki, Isao Mochida, Seong-Ho Yoon, Jyongsir Jang (2010). Activated carbon nanofiber produced from electrospun polyacrylonitrile nanofiber as a highly efficient formaldehyde adsorbent. Carbon 48(15): 4248-4255

Also, Ki Young Yoon (2008) shows that carbon based air cleaners have been shown to become contaminated with bacteria which can be readily corrected with the addition of silver nanoparticles to the medium. See

> Ki Young Yoon, Jeong Hoon Byeon, Chul Woo Park and Jungho Hwang. (2008). Antimicrobial Effect of Silver Particles on Bacterial Contamination of Activated Carbon Fibers Environ. Sci. Technol.42 (4): 1251–1255

Advanced Sensors using Nanotechnology

From Nanoparticles to Nanomaterials and Nano-Enhanced Sensors

The critical features of a nanoparticle is that a very large portion of its atoms exist on the surface relative to its core, and these atoms behave according to laws of quantum physics-such that the particle can have vastly different characteristics than its core substance. The availability of atoms at the surface means that they are available to interact with their surrounding environment and the varied physical and chemical interactions that take place provide a rich field for controlling and calibrating their physical and chemical properties. Properties such as electrical conductivity, magnetism, color and optical properties, boiling point and thermal conductivity, strength, chemical reactivity and many other properties are available for manipulation to form new and varied materials and products.

Note: Engineered nanomaterials have the potential to escape into the environment throughout their lifecycle; i.e., from their manufacture, distribution, and use /disposal. Information continues to emerge about their potential impact on human health or the environment, and it is likely that some will be found damaging enough to warrant EPA intervention and regulatory controls.

The demand is growing for highly selective, highly sensitive smart sensor systems capable of simultaneously detecting multiple species is growing. Nanotechnology holds the potential to enable a new generation of high-density, multianalyte sensors to fill this rising demand.

Nanotechnology coupled with the Internet of Things creates-the potential platform and opportunities to enhance environmental monitoring, data collection and analysis in dramatic ways with applications to outdoor, indoor, and personal environmental monitoring. Advanced nano-enabled sensors that are small, highly portable, and multifunctional, with highly robust performance capabilities are beginning to emerge.

With nanotechnology, sensors are being developed to detect lower concentrations of harmful pollutants, including nanoparticles themselves, but also including chemicals, explosives, and pathogens. Protection of human health, the environment and national security requires rapid, and sensitive detection of pollutants (chemical, physical, biological and radiological) with molecular precision.

Paradoxically, nano-enabled sensors can greatly improve EPA's ability to monitor, detect, identify, characterize, and control nanoparticles, as well as filter out, and/or neutralize harmful chemical or biological agents in the air and soil with much higher sensitivity than is possible today. This gives EPA a dual challenge—to deal effectively and timely with the potential risks of engineered nano-materials (ENMs) in the environment, while also taking advantage of the rapidly growing ability to avoid or remediate these risks.

Nano-enabled sensor technologies can be expected to produce sensors that are much smaller, more portable, more functional, more able to detect and assess multiple pollutants, and more easily networked with one another including the use of cell phone interfaces in large integrated networks. Eventually, they will be capable of providing real time or near real time data and analytic results on emissions, concentration distributions, individual exposures, and population exposures. The implications of these future capabilities for EPA challenge the imagination.

Measuring nanoscale particles

Nanoscale particles are more difficult to measure than their larger counterparts. Total particle mass has historically been the metric for measuring particle concentrations, but nanoscale particles have almost no mass; quantum particle forces and interactions can cause measurement error; and the equipment can be bulky, temperamental, and difficult to use. Further, while nanoscale particles account for very little of the total particle mass, they constitute a high fraction of the total number and the total surface area, and these dimensions along with chemical content and surface charge appear to be more determinant of health effects than particle mass. Current measurement methods may use a combination of two or three technologies to obtain accurate measures of these characteristics. Fortunately, as described in other sections of this report, emerging nano-enabled sensors show promise of overcoming many of these difficulties.

Some technologies are already available while others are still emerging. Like experience with computing and communications, initial high costs will reduce over time while performance will increase. Even as basic technologies become available, their application to products like sensors as well as the speed of cost reductions and improvement in performance depends greatly on industry's perception of the market. EPA and other agencies can help by working closely with industry and State and local governments to augment ongoing research, creating targeted research opportunities for monitoring pollutants of concern, providing leadership for high profile applications of sensors technologies, and becoming first users of new technologies.

Wearable personal sensors can be developed to monitor environmental concerns including ozone, carbon monoxide and nitrogen dioxide and specific or combined VOC levels at the same time that they are monitoring vital signs such as heart rate and hydration. The goal for these sensors will be to help people avoid exposure to the environmental conditions that exacerbate asthma and other health concerns.

Examples of Emerging Nano-Enabled Sensors

Detection and measurement of the smallest airborne nanoscale particles with commercially available technologies often presents difficulties due to the long sampling times and the bulky equipment needed (in the case of microscopy) or the small scattering cross sections of nanosized particles in optical detection techniques. Whispering gallery mode resonators (WGMs) can overcome these problems.

WGMs measure disruptions in resonator optical frequency from the deposition of ultrafine or nanoparticles on the resonator surface to detect particle composition and particle size. WGMs have high sensitivity to single nanosized particle binding events. The small size of the entire technology portends deployment of WGMs in environments where larger instruments would be seen as obtrusive, such as indoor residential settings, or multiple deployment in strategic locations to form networks of airborne biological monitors.

Nano-cantilevers

Detection of airborne pollutants including volatile organic compounds (VOCs) and nanoscale particles can be accomplished by measuring the change in resonant frequency of a nanoscale cantilever from deposition or absorption of pollutants. This change in oscillating frequency can be related to the deposited pollutant mass.

The significant advantage of nano-cantilevers is their ultra-high sensitivity towards binding events, and, when coated, the ability to detect specific gaseous pollutants shows great promise for many applications including ambient VOC detection, fence line monitoring, personal monitors and early warning systems for biological and chemical warfare agents.

Electrochemical sensors based on nanowires, nanofibers, and nanotubes

Electrochemical sensor technologies measure electrical changes due to binding of the gaseous pollutant with the nanomaterial and are able to detect gaseous pollutants at extremely low concentrations. The source of this sensitivity is based upon the high surface to volume ratio of the nanomaterials used in each sensor. This ratio allows for a high percentage of binding sites to be exposed to the gaseous pollutants, thereby increasing the chance of a binding event.

Nanofilms

Nanofilms are similar in function to the previously described electrochemical sensors except that the nanofilms incorporate nanoscale particles within the structure of a bulk material that make it capable of detecting airborne pollutants in a similar manner to the electrochemical sensors. However, demonstrated sensitivities are less than those of electrochemical sensors, because there is less exposure of the nanomaterial to the pollutant of interest.

One distinct advantage of nanofilm sensors could be attributed to their material strength capabilities as compared the electrochemical sensors that might make them more suitable for harsh environments such as emergency responders or some workplaces

Graphene

Researchers at the University of Manchester (Schedin, et al., 2007) reported the use of the graphene (world's thinnest material) to create micrometer-size sensors that can detect just a single molecule of a toxic gas when a gas molecule attaches to or detaches from graphene's surface. Graphene based sensors are emerging as very promising due to their exceptionally high sensitivity (1ppb) attributed to a unique low-noise material electronically which makes it a viable candidate not only for chemical detectors but also for other applications. For example, the development of graphene-based devices could eventually be used to detect deadly gases in homes or uncontrolled releases of dangerous situations (explosions, fires, gas leakage, etc.).

Research Discovering New Frontiers for Monitoring Air Pollution

Nanotechnology has motivated air pollution researchers around the world to develop novel monitoring systems that demonstrate potential uses of smaller and more functional sensors. These research projects provide a window into what the future in air pollution monitoring will be like. The following discussion presents some selective research projects that demonstrate multiple applications for both indoor and outdoor air monitoring

EC's Multi-SENsor System

European Commission, 2016. Nanotechnology based intelligent multi-SENsor System with selective pre-concentration for Indoor air quality control. Reports on completed projects are available at https://cordis.europa.eu/project/rcn/110553_en.html

This project used both physical and chemical nanotechnology applications to develop highly sensitive sensors that can selectively identify key target toxic compounds, that were then used in conjunction with HVAC controls to operate an effective demand controlled ventilation system. The SENSIndoor project developed of novel nanotechnology based intelligent sensor systems for selective monitoring of Volatile Organic Compounds (VOC) designed for application of demand controlled ventilation strategies for various indoor environments. The system can be optimized and adapted to specific application scenarios like offices, hospitals, schools, nurseries or private homes. The system is based on selective detection and reliable quantification of relevant at ppb or even sub-ppb levels in complex environments.

Within the SENSIndoor project novel sensor systems for extremely sensitive, highly selective and long-term stable operation were studied and developed. The project made use of both physical and chemical nanotechnologies for sensor components, MEMS technology for component realization and system integration as well as advanced signal processing and networking to integrate sensors into building control systems.

SENSIndoor has achieved this overall aim by realizing the following five specific objectives:
1. Identification of priority application scenarios for DCV based on comprehensive IAQ assessment.
2. Nanotechnology based Metal Oxide Semiconductor (MOS) and Gas-sensitive Field Effect Transistor (GasFET) sensors as complementary sensor technologies with unrivalled sensitivity for hazardous indoor air pollutants, especially VOCs.
3. Nanotechnology based selective pre-concentrators for boosting sensitivity and selectivity by at least two orders of magnitude.
4. Optimized dynamic operation of gas sensors and pre-concentrators combined with advanced data evaluation to further boost selectivity and improve long-term stability.
5. Integration of sensors and pre-concentrators in complex multi-sensor systems and demonstration of their performance in lab and field tests.

SENSIndoor was unique with its strong focus on selectivity. The key to successful development of sensor systems for control of IAQ lies in achieving supreme selectivity to distinguish target VOCs at very low concentrations against a large and varying background of non-toxic VOCs. This selectivity was previously only possible with laboratory equipment such as GC-MS, which is not suitable for control purposes due to high cost and long measurement intervals. While other projects have focused on sensitivity alone, the authors have demonstrated ppb-level sensitivity combined with unprecedented selectivity by combining pre-concentration of target gases and temperature cycled operation of the gas sensors. The project has achieved a novel integrated multi-sensor system with unrivalled performance tested in field evaluations for IAQ control.

EPA Air Sensors 2014: A New Frontier, which was an EPA Workshop held in Research Triangle Park, June 9 & 10.

The projects presented at this EPA workshop reveal trends toward use of small, high performance, low cost sensors in multiple sensor monitoring networks, some involving crowd sourcing with citizen involvement using smart phone interfaces. Such usage can provide unprecedented high spatial and temporal resolution for both gaseous and particle pollutants. They also open up opportunities for integrating personal exposure monitoring into current trends for personal health monitors.

In addition, projects reveal how the anticipated explosion of these small low-cost sensors also evokes a need for clear performance specifications with clarity and transparency of sensor performance and use to insure reliable interpretation of results. This is especially true for citizen-scientists uses and crowd-sourcing of data for community monitoring purposes.

Projects specific to indoor air and personal exposure

1. **Near-real-time personal exposure high resolution VOC monitor**: A program is described for developing a wearable personal exposure monitoring microsystem (PEMM) to measure near-real-time exposure to concentrations of over 15 VOCs chosen by the user at the ppb level (Jonathan Bryant-Genevier et al., University of Michigan).

2. **Consumer market challenges and opportunities for wearable sensors:** Personal monitors for health and fitness assessment have expanded from digital pedometers to biometric monitors and onward to health and fitness assessment platforms, and are now moving toward integration into earbuds, watches, smartphones and other frequently worn personal items. The author explores the opportunities and challenges to integrate personal environmental exposure monitoring into these systems (Steve LeBoeuf, Valencell Inc.)

Projects specific to outdoor monitoring, including the use of citizen participation (citizen scientists) to enhance data collection

1. **Novel highly spatially resolved air quality monitoring network:** Most air quality networks generally use a small handful of measurements to represent emissions from urban areas that do not capture the spatial-temporal heterogeneity of urban sources. A 25-sensor monitoring system was employed over a 2-km grid in Oakland, California for

higher data resolution. Evaluation of monitors is ongoing, and the potential for using correlations among observed gasses and particles to understand sources, trends in emissions, and human exposure is anticipated (Alexis Shusterman, University of Berkeley, Berkeley, CA)

2. **Crowd sourcing monitoring of atmospheric aerosols with citizens' iPhones in the Netherlands**: A low cost add-on to iPhone cameras along with an app enables smartphones to optically measure and characterize optical thickness, size distribution, and chemical composition. In 2013, several thousand citizens in the Netherlands participated in a large-scale crowdsourcing approach that successfully provided crucial aerosol measurements at locations and times that were previously under-sampled by professionals and allowed for the averaging out of intrinsic measurement errors (Frans Snik, Leiden University, The Netherlands).

3. **Low cost sensors and multi-sensor approaches for emission factors:** Data collected from multiple low-cost sensors has the potential to supply powerful information on specific source emissions, including source strengths and composition in addition to yielding key information on spatial and temporal pollutant distributions. But with the expected explosion of sensor technology, quality and performance of sensors needs to be carefully understood and controlled if data is to be meaningful. Field data of selected PM sensors was carried out in high and low concentration environments, and data using multiple low- cost sensors at a roadside site in Atlanta were evaluated (Mike Bergan, et al., EPA Office of Research and Development).

4. **Smart phone enabled radiation monitoring in Japan:** Smartphone connectivity and increased measurement range added to a battery-operated hand-held radiation monitor allows citizens to collect useful data taken from roadways, fields, streams, and structures in vicinities impacted by the Fukushima accident (Atsushi Yamamoto, Horiba Instruments, Inc.)

5. **Exploring whether the needs of scientific analysis can be compatible with extensive citizen involvement:** Pilot studies of urban and indoor air quality in nine European cities are described with a public engagement framework for sensor deployment. The study revealed both technical and citizen engagement issues that need to be addressed before these approaches for reliable air quality assessments can be fully realized (Alena Bartonova, NILU Norwegian Institute for Air Research, and the Citi-Sense consortium).

In addition to EPA, other agencies with activity in nanotechnology sensors include NIST, DOD, DOE (including LBNL), and NIOSH, and as such, provide an opportunity for interagency collaboration.

Algorithms for Control of Indoor Air Quality Using Modern Sensor and Computational Technologies

Automation of HVAC systems, of course, is not new. From the simple thermostat control, to more complex pneumatic controls to digitalization with optimization for energy efficiency and set points for thermal and humidity control, to the inclusion of CO_2 sensors and demand control ventilation, where CO_2 was considered both an indicator of outdoor air ventilation and as a useful indicator of acceptable IAQ. Now with the advent of sophisticated sensor, communication and computation technology combined with improved air cleaning technologies opens the door for including multiple contaminants with both distributed and central sensing, and this suggests opportunities for more sophisticated algorithms to simultaneously control indoor climate, and multiple indoor pollutants while minimizing energy use in ways that far exceed the more simplistic methods of the past. One might also envision future systems including SVOCs and microbiological contaminants in the air and water systems, conditions on indoor surfaces and conditions conducive to adverse effects of indoor chemistry (such as the presence of terpenoids. One might also anticipate that automatic controls would include lighting levels and window openings. This expanded field of building control automation is in its embryonic stage, but the door is opened wide. Should EPA choose to enter it could help to significantly improve public health from better indoor air quality.

In scanning popular commercial applications emerging in this area, there remains a tendency to over simplify the complexity of indoor contamination. For example, the objective to control indoor air quality is reduced to controlling particles (e.g. $PM_{2.5}$) or some form of TVOC (including all or some selected important VOCs) or perhaps both, along with indoor humidity and temperature. This tendency is likely driven by commercial interests to magnify claims of protection while minimizing costs, or by individuals heavily engaged in building controls with minimum knowledge of indoor air and related health sciences. But it is also admittedly difficult to imagine a system that would go to great expense to include 25 or 50 or more pollutants and to control them to levels below their individual health impact threshold. Whatever the case, the interest of public health would be well served by some knowledgeable assistance as these building control algorithms develop.

Over time, the cost of sensing and individually identifying many pollutants will decline. In the meantime, it would be useful for EPA and others to cooperatively suggest a limited number of pollutants to be included, along with a health-related index of those that are not included—an index that is more reflective of health than just TVOC. A discussion of the issue of an index was also suggested above as an improvement to current green product emissions certification programs. Beyond this issue, it is useful to consider what kind of objectives should building control algorithms be designed to achieve. For example:

- The algorithm could provide a real time summary readouts of contaminant levels in different areas of the building where sensors are located.

- As building controls are used to lower pollutant levels to below maximum health impact thresholds, the algorithm could allow for some exceedances to prevent costs of lowering such levels from exceeding a preset maximum cost constraint.
- The algorithm could include the capacity to estimate the location and type of source responsible for the exceedance (s) that would allow building management to remove or modify the source accordingly. This would be part of a "continual improvement" IAQ program.

Below are summaries of some of the current research in this area.

> *Xiang Liu and Zhigiang (John) Zhai (2009). Protecting a Whole Building from Critical Indoor Contamination with Optimal Sensor Network Design and Source Identification Methods. Building and Environment. 44 (11), 2276-2283.*

The authors apply the adjoint probability method (inverse modeling) to help design an IAQ sensor network and model the likely location of sources in buildings with multiple compartments but limited sensor locations. The example in the paper is for a residential dwelling. The case study presents the results of the proposed sensor network, verifies its feasibility, as well as its effectiveness and accuracy.

> *Jonghyuk Kim 1 and Hyunwoo Hwangbo (2018). Sensor-Based Optimization Model for Air Quality Improvement in Home IoT. Sensors ,18, 959*

The paper introduces the concept of an IAQ control solution for a home with the infrastructure of the Internet of Things (IoT), included in which is a pollution sensor, data processing and mathematic modeling.

> *Kolokotsa D., Stavrakakis GS, Kalaitzakis K, Agoris D (2002). Genetic algorithms optimized fuzzy controller for the indoor environmental management in buildings implemented using PLC and local operating networks. Engineering Applications of Artificial Intelligence. 15(5), 417-428.*

The authors present an optimized fuzzy controller for the control of the environmental parameters at the building zone level. A smart card unit monitors occupant preference while genetic algorithm optimization techniques are used to satisfy these preferences while also minimizing energy use by shifting the membership functions of the fuzzy controller. The system integrates a smart card unit, sensors actuators, interfaces, a programmable logic controller (PLC), local operating network (LON) modules and devices, and a central PC which monitors the performance of the system. This is a case study in which this system is demonstrated in a building.

Mingyang Li 2009. Application of computational intelligence in modeling optimization of HVAC systems. Theses and Dissertations, Iowa Research Online, University of Iowa.

The presentation is a dissertation at the University of Iowa in the fall of 2009. The thesis demonstrates and evaluates the advantages of applying the emerging area of computational intelligence to the problem of optimizing HVAC operations along multiple objectives and constraints. The author demonstrates how computational intelligent modeling provides powerful tools for modeling and analyzing complex systems which go beyond the limits of conventional methods. The method is enabled by modern systems which can collect and process large volumes of data, and patterns itself on biology-inspired paradigms like evolutionary computation and particle swarm intelligence in solving complex optimization problems. Such methods are useful for optimization of the HVAC operation where optimizing IAQ, including maximizing comfort and health under energy and other cost constraints.

References

Schedin et al. (2007). Detection of gas molecules adsorbed on graphene. Nature Materials 6: 652-655.

NEAR TERM OPPORTUNITIES FOR IMPROVING GREEN PRODUCT AND GREEN BUILDING PROGRAMS TO LIMIT INDOOR VOCS

One of the difficulties in using air cleaning technologies to reduce VOCs is the ability to accommodate varying mixtures of VOCs including a large array of VOCs at low concentrations. It is useful therefore to also consider advancing the development and adoption of source control at the building level to be used independently or in conjunction with these air cleaning technologies previously discussed. The one already institutionalized source control option is green product and green building programs.

As described in the Science Review, the simulated use of green products in a controlled study (Allen et al., 2016) reduced TVOC by 90%, so it is clear that there is substantial potential for the indoor air community to leverage this potential, though it is far from being achieved, and to work toward the continuing improvement of existing programs.

There are two main portions of green products programs that are worth examining: (1) the emissions testing protocol, and (2) the evaluation and reporting of results. In addition, the role played by manufacturers is important and will be briefly mentioned, but is less germane but not something that can be easily addressed.

Emission Testing Protocol

There are two general types of emission testing protocols. Both focus solely on VOCs and do not consider, for example on SVOCs or the fine particle emissions in the use of certain products. The first, and least useful, is simply to establish content limits for individual VOCs, based on limits established for different purposes. But content is not necessarily well correlated with emissions or related health impact from indoor air exposure. The second, and more relevant for indoor air quality are programs that test emissions in a controlled chamber, model the results to estimate indoor concentrations in a typical indoor space, and determine if the modeled concentrations are less than some fraction (usually 50%) of health-related threshold values. The threshold values are normally taken from or based on values established by authoritative organizations such as EPA or the California Office of Health Hazzard Assessment (OEHHA). The 50% adjustment is used to account for contributions to indoor air contaminants from sources other than the product being tested. Different organizations will have different testing protocols and different lists of contaminants tested. The original and most respected in the scientific community are those based on California Section 1350 Requirements for Green Buildings. Part of those requirements is the California Department of Public Health (CDPH) Standard Practice for VOC testing. The health threshold values are the California (OEHHA) (non-cancer) Chronic Reference Levels (CRELS).

While this is arguably the most advanced program, and recognizing the complexity inherent in such programs, there are areas for improvements that are worth considering and that EPA could possibly influence.

- Acute health impacts are not addressed, nor are emissions of wet products when applied or during the first few days after application.
- The pollutants are limited to VOCs but do not consider, for example, SVOCs or fine particle emissions in the use of some products.
- No consideration is given to the cumulative effect of multiple pollutant exposures.
- The testing chamber does not examine the potential for indoor chemistry reactions, particularly in the presence of reactive compounds such as ozone. Should ozone be added, as is common in indoor settings, the tested results might be different?

The evaluation and reporting of results

The results are reported only as 'Pass or Fail". This dichotomy is very limiting. If the modeled concentration of any VOC is above the established modified threshold, the product does not pass. For those that do pass, there is no way to compare the results of different brands of the same product type, or substitute products. The dichotomous reporting hurts users by limiting their ability to differentiate between those that pass with flying colors and those that may just squeak by. It also removes the incentive for manufacturers to improve their products beyond what is needed to just pass.

Consider the reporting of testing results for energy use in the Energy Star program. The reporting shows where the product stands in its typical energy cost when compared to competing products on the market. Thus, the comparison with other products is automatic and useful in buyer's decision-making. It also means that incentive to improve is continuous, even as the market overall becomes more efficient than before, the competitive pressure to constantly improve more than the competition does not diminish.

It is possible to index the results of the VOC testing into a single metric or a set of metrics that, while not perfect, would allow for such a comparison. The metric(s) could also be included in the green building point systems (see discussion below). But most importantly, since users would be comparing products from different manufacturers, that basic competition would induce manufacturers to improve their products to better their competitors and thus create an automatic continuous improvement incentive over time, without having to alter the pass-fail criteria, for which it is institutionally very difficult and sometimes tortuous to overcome resistance by those invested in the old system.

TVOC is a metric that is sometimes used as a general indicator though it is inherently flawed since it equally weights all VOCs despite their different toxicities. But subsets of TVOCs could be usefully developed by grouping VOCs with similar characteristics. Alternatively, the studies of extreme value analysis in the Science Review defined two metrics -- an immunotoxic mixture, a liver and kidney toxicant mixture of pollutants. This is a very useful, as would a respiratory and cardiovasular mixture metric. Another approach would be to do something similar to what EPA has done for outdoor pollution by establishing the Air Quality Index (AQI) that combines concentrations from multiple pollutants. Thus, EPA could play a useful role in exploring useful metrics that could be used to extend the “pass-fail” dichotomy into more useful reporting of one or more metrics to compare the health impacts of different products and brands of products and inculcate a continuous improvement incentive in the reporting of emission testing results. Should this approach be adopted, it could greatly advance the progress toward improved health and productivity from indoor air pollutant exposure. Since the State of California’s purpose in establishing its Standard Practice is to protect public health, it could well be interested in exploring this issue with EPA. And should CDPH make the change, it would reverberate throughout the green products market. Manufacturers would likely resist such an effort, but no more than their resistance to EPA or California regulations. CDPH, may wish to first apply this change only to State agency purchases as a demonstration before fully adopting the change. Research dollar expenditures for such an effort would be modest, in line with limited resources.

The role of manufacturers

Ideally, the testing facility or sponsor would randomly choose a product, or even multiple products, from the assembly line or purchase one or more on the market to be tested, in order to ensure that the product(s) is (are) representative. Also, ideally, the user, or representative of the public interest, would pay the testing facility to insure the results are not biased. In the case of product emission testing programs, however, the manufacturer both chooses the specific product or specimen to be tested and pays for the testing. This makes the manufacturer, rather than the users or public interest agency the paying customer who wants a positive certification from of the testing service provider. How much this perverse incentive to please the manufacturer affects results is hard to tell, but it is partially mitigated when the program is operated by a government agency, such as is the case in California, who also chooses the testing facility. But this is not always the case. How feasible it is to change this arrangement is not clear but it is worth noting since awareness is the first step toward improvement.

Green building programs

In the U.S. the most notable green building program is Leadership in Energy and Environmental Design (LEED) program of the United States Green Building Council (USGBC). The USGBC is an independent non-profit organization whose funding is provided by builders who choose to have their buildings certified, and who chooses the certifying agent who theoretically represents USGBC to determine if the building being certified meets the LEED requirements. However, since the builder pays the certifying agent, the builder is the paying customer, so that the potential biases mentioned above likely operate in this process as well.

That being said, the LEED program operates on a point system where points are earned from satisfying various environmental criteria. Some are minimum requirements, and some are optional. The level of certification (Silver, Gold or Platinum) that is granted is dependent on the number of total points that are achieved. The requirements and points are determined through a committee structure. Indoor air quality is one of the environmental areas and emissions testing of building materials using the CDPH Standard Practice or its equivalent is one of the criteria for IAQ. Given the potential importance of green products and green buildings to achieving healthy indoor environments, EPA’s involvement in the criteria development process is a highly leveraged use of EPA resources toward improving public health. It is also not resource intensive. EPA is might also be advised to participate in the other IAQ related committees beside product testing, and also be involved in higher level committees that decide on the distribution of points and requirements among all the environmental criteria.

OTHER POTENTIAL NEAR-TERM RESEARCH TO ADVANCE BUILDING-LEVEL POLLUTANT REMOVAL

Research to Reduce Exposure to Particles of Indoor and Outdoor Origin

Particles are a high priority pollutant-especially $PM_{2.5}$ and ultrafine particles. Below are some areas of research that EPA could undertake, which, added to existing research findings, could form the basis for developing policies and programs, in cooperation with manufacturers, builders, other governments and advocacy groups to reduce exposure to indoor particles with a manageable resource commitment.

Increasing current filtration efficiencies

Most studies of mitigation options focus on the efficacy of using higher efficiency filters. Studies include comparisons of filter efficiencies in removing selected filter size ranges (e.g. $PM_{2.5}$ or ultrafine particles) across the range of MERV rated filters. Such studies provide the potential effectiveness under controlled conditions of using higher rated filters. Other studies examine the effectiveness in reducing airborne particle concentrations in real life environments where effectiveness depends not only on the filter efficiency rating, but also on building and HVAC characteristics such as rates of deposition on HVAC ducts, airflow rates through the filter, on-off times of the fan, and volume of the indoor space. Finally, studies of high efficiency HVAC filters at MERV 14 or above are rated to remove airborne particles of 0.3 micrometers or larger. A high efficiency MERV 14 filter has a capture rate of at least 95% for particles between 0.3 to 1.0 micrometers. Although the capture rate of a MERV filter is lower than that of a HEPA filter, a central air system can move significantly more air in the same period of time. Using a high-grade MERV filter can be more effective than using a high-powered HEPA machine at a fraction of the initial capital expenditure. Unfortunately, many residential furnace filters are slid in place without an airtight seal, which allows air to pass around the filters. This problem is worse for the higher-efficiency MERV filters because of the increase in air resistance. Higher-efficiency MERV filters are usually denser and increase air resistance in the central system, requiring a greater air pressure drop and consequently increasing energy costs. However deeper bed filters (e.g. 4-5”) can greatly reduce that resistance. Their initial cost is higher, but they also last longer, and it is possible that all new furnace systems could be developed to accommodate such deep bed filters. In some existing residences, it is often possible to retrofit to a deeper bed filter by adding a commercially-available deeper filter bed housing.

Refining that existing research and providing data on relative costs, effectiveness and cost/effectiveness calculations, and doing so within the context of a national participatory program is one possibility.

Research to Reduce Exposure to Indoor Generated Particles

Particles generated indoors might be controlled by reducing their emissions through product modifications, exhausting them (e.g. kitchen exhaust) or by altering human behavior to reduce exposure. Kitchen emissions from cooking are a major indoor source. Research to improve kitchen exhaust systems might not be too difficult but if adopted, could be very effective in reducing exposure.

Improving kitchen exhaust design

Cooking is a dominant source of both fine and ultrafine particles. All forms of cooking produce some particles, but frying and searing food produce particularly high emissions. Particles are also produced by the gas flame on gas stoves, or the hot surface of electric stoves, ovens including toaster ovens, or toasters and grills.

For cooking, a good exhaust system can remove most particles. The most effective cooking exhausts are positioned to draw the particles from the cooking surface without the particles passing into the breathing zone of the cook or others. Studies have shown that in conventional above stove exhausts, have low capture efficiencies for front burners relative to back burners (Rim, 2012; Lunden, 2015). Thus, it is wise to advise people to use the back burner as much as possible to reduce exposure. But this is counter to what people are inclined to do naturally. Also, most people limit the use of the exhaust because it is noisy. A significant reduction in particle exposure from cooking could be achieved from more frequent use of the exhaust and from redesigning the exhaust system to improve capture from the front burner. A quiet exhaust that automatically comes on whenever the stove is turned on by a particle sensor would be helpful. All exhaust system should remove the exhaust stream to the outside rather than recirculate through a filter. Many exhaust fans are rated for noise, but even the quietest can be too noisy for comfort and inhibit their frequent use. If placed at the point of exit to the outside, the fan would be scarcely audible.

Research to improve kitchen exhaust systems is warranted, and should EPA choose to develop a more effective design, in conjunction with manufacturers, it could potentially be spread through green building standards in which credit is given to kitchen exhaust systems with preferential treatment for automatic use, high capture rate from all burners, and low noise level. Model building codes can follow with requirements for improved systems. Costs for such improvements appear to be very modest. If so, manufacturers would likely be more than willing to change current designs, especially in the context of public information and rising demand.

Promote the best surface cleaning strategies

Deposit on surfaces and are subject to re-suspension from human activity, including the act of cleaning itself (e.g. sweeping, vacuuming, and dusting with a low capture cloth). A combination of more frequent cleaning to minimize surface particles combined with high capture cleaning methods are viable options for minimizing exposure from re-suspension. High capture mopping rather than sweeping hard floor surfaces, high capture vacuuming with HEPA filtration of exiting air, and high capture dusting using microfiber dust cloths minimize particle emissions from cleaning. EPA could research these and other strategies to identify and measure their effectiveness, report results, and develop guides to help consumers, and cleaning professionals to maximize removal effectiveness. The cleaning industry is very interested in green cleaning practices and has already begun to develop such practices and establish standards, so they would likely welcome a cooperative program to both develop best practices and market the results.

Research to Determine Effective Methods to Control Agents of Indoor Chemistry that Reduces the Formation of their Toxic Byproducts.

As described in the Science Review, indoor chemistry is both critically influential in determining human exposure, and greatly understudied. There are many highly complex indoor chemical reactions and chain reactions in the air and on surfaces that potentially produce toxic byproducts or otherwise influence exposure that are currently hardly understood. To better understand critical elements of these processes would be a long-term research endeavor, and there are many subsets of issues to be investigated. These might include for example, chemical reactions related ozone, NO_2 and nitrate radicles; hydrolysis of certain products (e.g. plasticizers, flame retardants and pesticides) on damp surfaces; and the decomposition of chlorinated or brominated compounds in certain products (e.g. chlorinated or brominated flame retardants) possibly from microbial activity; the effect on these processes of natural light and artificial lighting choices, of indoor climatic conditions, and of HVAC types and settings indoors.

Ozone is the most widely studied indoor chemistry reactive agent. Reducing ozone through air cleaning was previously discussed. Removing sources of ozone is another potential action. Indoor sources of ozone include some laser printers, photocopiers, and electrostatic air cleaners. In these products, ozone is an unintended byproduct of their operation. Of more significance are ozone generators sold as air purifiers. These devices purposely produce ozone for its reactive properties to convert indoor chemical contaminants into hopefully less harmful chemicals. However, ozone itself is harmful, and the byproducts of reactions may also be more harmful than the targeted contaminant. Thus, limiting the use of ozone emitting products, and products containing terpenes is a useful low-cost strategy for limiting the indoor production of particles through indoor chemical reactions. Should EPA decide to accompany its research with guidance developed in conjunction with other agencies and organizations, this would be a useful addition.

While a comprehensive program in indoor chemistry research is warranted, it would also be a long-term endeavor requiring a substantial resource commitment. To make it more manageable, one might postulate and test the effect of reducing known critical agents, even without fully understanding the underlying processes. This could stimulate further interest by others in pursuing research to determine underlying processes and also provide preliminary material to advise consumers, builders and manufacturers. Research to examine the effect of ozone removal has already been discussed. Research on the impact of reducing other agents are also possible, and include for example removal of NO_2, excess humidity and dampness, or microbes on surfaces, which, singly or in combination with each other or with ozone, or in the presence of certain products (e.g. terpene containing products, products containing certain plasticizers, hard plastic products, and flame retardants) would impact results. This could be done in the short or medium term, with chamber experiments, to examine the impact on the concentration of certain air and surface contaminants (e.g. formaldehyde and other aldehydes, chlorinated organics, organic nitrates, BPA, ultrafine particles or $PM_{2.5}$, etc.).

It might be worthwhile considering whether actionable knowledge might be obtained from such research, that would include both the feasibility of such actions and the potential benefits and whether that could be accomplished without fully examining or fully understanding the chemical processes involved. The results could then be used to provide guidance and recommendations (if appropriate) for building- related indoor air quality controls, or that could stimulate further research that helps explain such impacts and ultimately lead to a fuller understanding and specific cost-effective methods of control.

Control possibilities revealed in previous discussions could be the impact of increased ventilation and/or recirculation (to reduce reactive agents like ozone with advanced filtration and/or air cleaning (to reduce particulate and critical gaseous contaminants), dehumidification (to reduce humidity and surface moisture), and surface sanitization to reduce surface microbes) using both chemically based and non-chemical sanitizing methods.

Relevant articles:

Fadeyi MO, Weschler CJ, and Tham KW (2009). The impact of recirculation, ventilation and filters on secondary aerosols generated by indoor chemistry. Atmospheric Environment 43((22-23):3538-47

This study extends the Zuraimi [(2007) (See Science Review)] study by also examining the impact of outdoor air exchange rates and filtration on the impact of ozone-limonene reaction byproduct particle distributions. Findings include:

- Increasing outdoor ventilation rate increased the entry of outdoor ozone into the indoor air, but not sufficiently to overcome the reduction of SOA from higher recirculation.
- In addition, the introduction of a filter with only a 35% single pass through removal rate of 100 nm size particles lowered particle concentrations due to substantial increased removal efficiency from higher recirculation, and further reduced the SOA particle concentration when a carbon filter was added to remove ozone.

The implication of the article is that feasible methods for reducing indoor ozone concentrations other than through ozone reactions with airborne or surface chemicals, such as the use of carbon filters while increasing recirculation with particle filtration can reduce ozone, particle, and secondary aerosols concentrations with the potential of improving occupant health.

MEDIUM TERM RESEARCH IN INDOOR CHEMISTRY

As with other research areas that are highly understudied, EPA could develop a strategy that "seeds" critical areas of inquiry, or that helps advance sensors or analytic tools that can serve to open doors that make it easier and more compelling for others to enter and conduct further research. Should EPA pursue such a strategy, it is critical, as described in other sections of this report, to develop a broad base of interest by others, including leaders in the field of study, funding sources, and various interest groups to encourage further interest.

The following subject areas (See Weschler, 2011) of potential research activity by EPA fall in that category, i.e. project development strategies cooperatively developed with other stakeholders with the potential to leverage the expenditure of limited resources.

Indoor Chemical Reactions May Help Explain Problems of Damp Buildings

There is considerable current interest in solving and mitigating the issue of dampness in buildings, and some answers may be attributable in indoor chemical surface reactions, even with modest levels of relative humidity allowing for aqueous surface reactions. But this has received little attention. It is possible that a modest amount of EPA sponsored research in this field could raise awareness of this potential effects and stimulate further inquiry from those interested in seeking answers.

While dampness has been frequently associated with respiratory illnesses, the specific causal factors remain a mystery though frequent reference is made to potential bacterial or fungal causes. Little attention has been focused on the byproducts of possible surface chemical reactions that could take place from sorbed water on surfaces and the presence of aqueous surface films. Sorbed water on surfaces, can affect hydrolysis reactions, corrosive reactions, and acid-based chemistry.

Phthalate esters (in plasticizers), phosphate esters (in flame retardants, pesticides, and plasticizers) and Texanol Isomes (in latex paint) are all subject to hydrolysis. To what extent does chemical decomposition by hydrolysis increase exposure to these decomposed products. It is also suggested that low volatility organic compounds may be formed by aqueous reactions. Further, microbes that are more prevalent in water sorbed surfaces can remove halogens from some halogenated chemicals, and they can also influence surface pH which can then influence hydrolysis and corrosive reactions (See State of Science Review, pp 52-53).

These are many possibilities that could be explored in the context of furthering knowledge of the role of moisture, dampness, and mold in buildings, a subject of great interest in many quarters.

Plastics, Flame Retardants and Pesticides: To What Extent are Indoor Chemical Reactions Responsible for Exposure to SVOCs of Concern in these Products?

As with issues of dampness, there is growing interest in reducing exposure to SVOCs, but understanding how that exposure occurs is critical to forming strategies to do so. Problems associated with SVOC pollutants in indoor air often refer to the ubiquitous nature of plastics and plasticizers, flame retardants, and pesticides, but little research has been done to investigate the contribution of indoor chemistry to indoor concentrations. In addition to dehalogenation, there is evidence to suggest that chlorinated organics derived from the degradation of chlorinated flame retardants, and brominated SVOCs resulting from the decomposition of brominated flame retardants, and the decomposition of polycarbonate through indoor chemical processes to form Bisphenol A (BPA), may be important contributors to indoor exposures. As with aqueous reactions mentioned above, some targeted research by EPA in this area with limited resources could be used to open lines of inquiry and stimulate further research by others which is desperately needed.

Create Better Analytic Methods to Allow Researchers to More Clearly See and Identify Short Lived but Highly Reactive Species

Much of what is known now about indoor chemical reactions that help determine the mix of chemicals into which people are exposed cannot be observed. Far greater understanding of these reactions would lead to more rapid advancements in knowledge and to better potential control methods that reduce exposure and advance health and welfare. Free radicals, thermally labile compounds, and compounds with multifunctional groups that require derivatization to accurately identify are among the subjects of concern. Organic nitrates are of concern because several of these compounds are known or suspected carcinogens.

In addition, such research would be integrated into the short- and medium-term research mentioned in the previous sections:

- Impact of ventilation, recirculation, particle and carbon filtration on ozone concentrations, chemical reactions, and particle concentrations and their size distributions.
- Ways to minimize harmful chemical activity by combinations of product choice, lighting (including sunlight) choice, minimizing ozone through ventilation and air cleaning /filtration choices, etc.

MEDIUM AND LONG TERM BASIC RESEARCH IN MICROBIOME

Help Coordinate and Facilitate the Development of Improved Microbiological Sensing and Analytic Technologies to Advance Studies of the Microbiome

Help refine molecular tools and methodologies for elucidating the identity, abundance, activity, and functions of the microbial communities present in built environments.

Traditional methods of culturing microorganisms are limited in what can be cultured and is generally has low-throughput that hinders detailed community-level analysis. New advanced approaches broadly referred to as "Omics" yield collective measurements of sets of biologic molecules. These approaches include genomics (analysis of DNA), transcriptomics (information on RNA, which reveals which genes are transcribed to be expressed by a cell), proteomics (data on the suites of proteins produced by cells), and metabolomics (focused on chemical metabolites). Such techniques in combination with culturing provide information on the presence of different taxonomic groups of microorganisms in a sample and characterize microbial functions and activities. DNA/RNA extraction practices are expected to continue to develop for the foreseeable future, particularly with respect to recovery from indoor aerosols.

- Research is needed to expand DNA sequencing so that one can distinguish between viable, dead, or just partial fragments or components of microbes.
- Research is needed to improve sensitivity and taxonomic resolution for more precise and detailed identification and characterization for microbial populations in low abundance, which is common in indoor environments.

Help Create and Sustain a Research Infrastructure (Data Commons) for Studying the Interrelationships Between the Indoor Microbiome and the Built Environment. Help Foster Standardization of Research Methodologies.

Data commons of this nature will help promote transparent and reproducible research using standardized protocols, increase access data and knowledge, expand current benchmarking efforts, and facilitate improved cross-study comparison. Include provisions for data storage, sharing, and knowledge retrieval. For example, the EPA Building Assessment Survey and Evaluation (BASE) study included protocols for collecting detailed information on both the building physical infrastructure, it equipment and settings, air contaminants, indoor climate, and occupant health and comfort. A similar approach could be used with detailed requirements for microbial monitoring and analysis to facilitate development of uniform data commons accessible to all researchers.

To help foster standardization of research methodologies, EPA could consider cooperatively developing guidance and actively working through standards organizations for such an effort.

Foster Cooperative Efforts of Disciplines and Organizations to Advance Studies of the Indoor Microbiome

Given the multidisciplinary aspects of microbiome research, the reality is that significant progress can only be made through cooperative research efforts and protocols established by representation from all relevant disciplines, including all those involved in indoor air quality (chemistry, microbiology, particle physics, building sciences and engineering, health sciences, statistical analysis), and expertise in sensor and monitor development . Sources for such cooperation can come from involved Federal Agencies (e.g. NIST, DOE, NIH etc.) and professional societies.

Involvement of the microbiology community is clearly most critical. EPA could actively promote greater involvement of microbiological professionals whose involvement in indoor air quality has heretofore been less active than needed. Outreach to the American Society for Microbiology could be productive in this regard.

Research to Determine if Indoor Pollution can Adversely Impact the Human Microbiome

The human microbiome is integral to human biology such that perturbations creating imbalances may have consequences for many disease outcomes. Scientists are beginning to suspect that exposure to the external microbiome or chemical pollutants can impact the human microbiome but little is currently known about these effects. In addition, it is possible that the human microbiome may mediate the impacts of external environmental chemical exposures. A recent report from the National Academy of Sciences, and sponsored by EPA and NIEHS, suggests a short term research strategy to determine whether and to what extent the nature and magnitude of adverse health effects from environmental chemicals is affected by the human microbiome interactions. Such research could as a prelude for determining if more robust long-term research into this subject is warranted. Highlights of this study and its recommendations are provided below.

NAS (2017). Environmental Chemicals, the Human Microbiome, and Health Risk: A Research Strategy. National Academy of Sciences, National Academies Press, Washington DC. December.

NAS Premise

- The human and animal microbiomes differ sufficiently to raise the question of whether animal studies alone are sufficiently informative for application to human health risk assessments.

- Research to date suggests that environmental chemicals can alter the composition of the human microbiome which also can modulate environmental chemical exposure.
- Microbiome-environmental chemical interactions effect human susceptibility to environmental chemicals in different ways suggesting that risk assessments, absent consideration of the microbiome, may either under-estimate or over-estimate risk.
- Research in this area may help explain differences currently found between animal and human studies and differences in exposure assessments on different human populations, and also reveal health consequences not previously recognized.

NAS Research Strategy

Given the current state of the science, the research strategy is comprised of three broad topical areas.

- Determine if anticipated human exposures can induce microbiome alterations that modulate adverse health effects:
    - Define toxicity endpoints for the microbiome
    - Identify environmental chemicals that perturb the microbiome
        - Discover whether such microbiome perturbations can cause or modulate a change in human health using animal and epidemiology studies.
- Determine the role of the human microbiome in modulating absorption, distribution, metabolism, and elimination (ADME) of environmental chemicals:
    - Generate ADME data from animal and in vitro experiments
    - Use new chemical probes and research technologies to identify specific microorganisms and their enzymes that mediate chemical transformation processes.
        - Characterize individual susceptibilities and interspecies extrapolation at a mechanistic level and the degree of functional redundancy within a microbiome.
- Determine the Importance of microbiome variation:
    - Determine if variation in human microbiomes helps explain individual health risks and susceptibility to environmental chemical exposure.
        - Use comparative studies to assess functional comparisons of factors that do or are suspected to microbiome diversity to suggest populations with potential vulnerabilities
    - Determine variation between species:
        - Examine whether variations are great enough to warrant reconsideration of using animal models to assess risks of environmental chemical exposures
        - Examine whether factors used to extrapolate from animal to humans sufficient to account for microbiome variations

  - Examine whether comparative studies reveal the functional capacity encoded by human microbiome to determine what species or study designs are most important for extrapolation.

The generalized research approach described above is a useful guide for short term research to answer the critical question of whether the human microbiome interactions with environmental chemical exposures is sufficient to warrant further refinement for consideration in risk assessments. But it could admittedly be resource intensive, in part, because of the current lack of foundational assets available to conduct such research. Helping to develop such assets with cooperative partners representing multiple relevant disciplines might also be considered as useful expenditures of EPA's limited resources. The authors point out several current needs. These include:

- In vitro model systems that accurately model the host environment, and that incorporate naturally occurring microbial communities.
- Microbial reference communities of the human microbiome that reflect individual variations that naturally occur based and that may be related to the health, age, living environment, diet, etc. of the host.
- Expansion of reference assets in genomic, transcriptomic, and metabolic databases and libraries that enable assessment of microbiome dynamics, to include annotation of relevant strains, genes, enzymes, metabolite identities and function, and associated characteristics of microbiome sources.
- Standardized experimental approaches.

The advantage of efforts to fill these needs is that the results would have broad application to all microbiome research while also being very relevant to the narrower issue of how the human microbiome affects the health consequences of environmental chemical exposure.

General Long Term Basic and Applied Research Agenda to study the Indoor Microbiome

In its report, the National Academy of Engineering (NAE, 2017) offered a broad long-term research agenda to guide cooperative efforts of the communities of indoor air quality and microbiology.

A. Characterize interrelationships among microbial communities and built environment systems of air, water, surfaces, and occupants. Such efforts would build on the existing foundation of knowledge, address gaps in current understanding, and enable future progress

  - Relationships among building site selection, design, construction, commissioning, operation, and maintenance; building occupants; and the microbial communities found in built environments.

- fuller characterization of interactions among indoor microbial communities and materials and chemicals in built environment air, water, and surfaces,
- further studies to elucidate microbial sources, reservoirs, and transport processes.
- Social and behavioral sciences to analyze the roles of the people who occupy and operate buildings, including their critical roles in building and system maintenance.

B. Assess the influences of the built environment and indoor microbial exposures on the composition and function of the human microbiome, on human functional responses, and on human health outcomes.

- Use complementary study designs—human epidemiologic observational studies (with an emphasis on collection of longitudinal data), animal model studies (for hypothesis generation and validation of human observational findings), and intervention studies—to test health-specific hypotheses.
- Clarify how timing (stage of life), dose, and differences in human sensitivity, including genetics, affect the relationships among microbial exposures and health. These relationships may be associated with protection or risk and are likely to have different strengths of effect, parameters that are important to understand further.
- Recognize that human exposures in built environments are complex and encompass microbial agents, chemicals, and physical materials. Develop exposure assessment approaches to address how combinations of exposures influence functional responses in different human compartments (e.g., the lungs, the brain, the peripheral nervous system, and the gut) and downstream health outcomes at different stages of life.

C. **Explore non-health impacts of interventions to manipulate microbial communities. The incorporation of data beyond health effects into the development of models would strengthen the assessment of potential interventions and inform future decision making.**

- Improve understanding of energy, environmental, and economic impacts of interventions that modify microbial exposures in built environments, and integrate the relevant data into existing built environment–microbial frameworks for assessing the effects of potential interventions.

D. Advance the tools and research infrastructure for addressing microbiome– built environment questions. The field relies on a diverse set of approaches aimed at understanding microbial communities, buildings, health, and other impacts.

Improvements to this toolkit and infrastructure would support accelerated progress.

- Refine molecular tools and methodologies for elucidating the identity, abundance, activity, and functions of the microbial communities present in built environments, with a focus on enabling more quantitative, sensitive, and reproducible experimental designs.
- Refine building and microbiome sensing and monitoring tools, including those that enable researchers to develop building-specific hypotheses related to microbiomes and that assist in conducting intervention studies.
- Develop guidance on sampling methods and exposure assessment approaches that are suitable for testing microbiome–built environment hypotheses.
- Develop a data common with data description standards and provisions for data storage, sharing, and knowledge retrieval. Creating and sustaining the microbiome–built environment research infrastructure would promote transparent and reproducible research in the field, increase access to experimental data and knowledge, support the development of new analytic and modeling tools, build on current benchmarking efforts, and facilitate improved cross-study comparison
- Develop new empirical, computational, and mechanistic modeling tools to improve understanding, prediction, and management of microbial dynamics and activities in built environments.

E. **Translate research into practice. As the interconnections among microbiomes, built environments, and health become more clearly understood, this knowledge should be translated into guidance applicable to varied public and professional audiences**.

- Support the development of effective communication and engagement materials to convey microbiome–built environment information to diverse audiences, including guidance for professional building design, operation, and maintenance communities; guidance for clinical practitioners; and information for building occupants and homeowners.

LONG TERM BASIC RESEARCH TO DEVELOP A "NEW AND IMPROVED" COMPREHENSIVE DATABASE OF INDIVIDUAL AND POPULATION EXPOSURES

Having identified the lack of sufficient national level data on pollutant exposures as a major constraint, it is worthwhile to determine if there are long term options to address that issue.

It's been 30 years since the EPA Total Exposure Assessment Methodology (TEAM) studies were established using personal monitors to measure personal exposures. Such monitoring was a breakthrough then since it made clear that personal exposures can differ significantly from outdoor concentrations, and result from both indoor and outdoor sources of pollutants, and from individual activities and individual locations as people passed through various microenvironments. Since then, the rapid development of nanotechnology has fostered the development of personal monitoring capabilities that are more robust, and less expensive, to which EPA is aware. In addition, rapidly expanding private sector marketing and positive consumer response to personal physiological data (the "fit bit" craze) now allows individuals to personally keep track of bodily functions (e.g. heartrate, metabolic rate, blood pressure etc.). There is little doubt that this technology will continue to expand and become more common as companies compete in this growing market.

Cell phone apps continue to expand in applications, and could likely include monitoring and transmission of personal exposures to pollutants. It would seem possible to also link such exposures to bodily functions also monitored. Body sensors are already employed in medicine to monitor bodily functions (e.g. heart health) with results being automatically transmitted to the prescribing doctor over the internet.

There is vast potential to collect monitoring data of both exposure and its effects by large numbers of people. This is not a pie in the sky idea and is already being used on smaller scales with plans for expansion (see discussion below). Thus, one can imagine the willing involvement of the citizenry in the collection and transmission of personal exposure data through cellphone applications with the possibility of combining such data to bodily function measurements (possibly in real time), and to location (down to specific building environments) using GPS and other data and transmitting such data to a central database. Obviously, protecting individual privacy would have to be accommodated.

In addition, computer advances in "big data" analytics opens enormous possibilities for data analysis. One can anticipate more comprehensive robust measurements enabling improved metrics and analytics to overcome the previously mentioned but significant deficiencies in past data. This includes, for example, assessing the probability of simultaneous exposures of different pollutant mixtures and their potential health impacts, improved capture of extreme value distribution, better characterizing TVOC to more accurately reflect health impact, identifying key parameters that explain the relationship between dampness/ mold and various health effects, identifying new pollutants of concern, measuring effectiveness of various programs and tracking progress, etc. Further, it would be possible to keep such a database current through continuous monitoring.

Relevant Research on use of Sensor-Network Applications with Cellphone Interface and Citizen Science Potential

The following are examples of recent research projects. They reflect the current state of affairs in this new and expanding field that act only as a starting point for further advances and refinements that are possible with continued research.

> *Min Mun et al. PEIR, the Personal Environmental Impact Report, as a Platform for Participatory Sensing Systems Research. MobiSys'09, June 22–25, 2009. Available at http://www.eecs.ucf.edu/~turgut/COURSES/EEL6788_AWN_Spr11/Papers/Mun-PersonalEnvironmentalImpactReport.pdf. As part of UCLA's , "Participatory Sensing / Urban SensingProjects"; http://research.cens.ucla.edu/*

The Personal Environmental Impact Report PEIR), is an example of an important class of emerging mobile systems that combine the distributed processing capacity of the web with the personal reach of mobile technology, along with established models to process data, and provide the user with a personalized estimate of the impact of their activity on the environment and of their personal exposure to environmental pollution The system, developed and tested in Los Angeles, where road travel is a primary source of air pollution and personal exposure, focuses primarily on transport between locations as its core activity to be evaluated.

The system includes mobile handset based GPS location data collection, and server-side processing stages such as a Hidden Markov Model-based activity classification (to determine transportation mode); automatic location data segmentation into "trips"; lookup of traffic, weather, and other context data needed by the models and provided by other data sources; and environmental impact and exposure calculation using available estimation models. The server-side calculations use map-matching techniques [(roadways (characterized by type), bus routes, and commercial activity location data], weather and traffic conditions, combined with GPS location data augmented by GMS data of phone tower location and signal strength, to classify mode of travel, location, activity and pollution impact on the environment as well as a personal exposure assessment which can be provided in near real time to the user.

Some key aspects of the program include:

- The program began in June 2008, starting with thirty trial users using the system intermittently, and is designed to continually improve and refine the program architecture and operation and expand its participation.

- After developing an initial end-to-end implementation, the improvements to the architecture focused on increasing calculation performance so that users can see their impact and exposure scores within minutes of uploading their location data.
- PEIR processing operates on the time-location traces consisting of GPS records sampled approximately every thirty seconds. Researchers experimentally selected the lowest sample rate that still resulted in good automatic classification of high speed travel by car.
- In many cases, the connected cell tower, radio signal strength, and battery information was accessed for debugging and testing of future features.
- PEIR accepts location records from mobile handsets as well as upload of bulk time-location data in most track log formats, and currently support three different phone clients.
- Plans include lowering power consumption to extend user interface, and use of WiFi and Bluetooth stumbling and accelerometer data to enhance location trace and activity classification accuracy.

Expansion regionally, nationally and globally will require integration capability with local models and data sets. This creates trade-offs between greater accuracy from local data with greater scalability from using more broadly applicable models as inputs. Similarly, activity classification will have to accommodate modalities common in other locations such as cycling, bus, train, and subway.

General issues in mobile phone/ sensor technology applications.

In addition to applications relevant to outdoor and indoor environmental collection and modeling, use of cell phone apps with or without separate sensing equipment is useful in many other fields of endeavor, but the basic technology developed is generally applicable. The following article does a reasonable job of describing the general issues that need to be addressed.

T. Das P. Mohan V. N. Padmanabhan R. Ramjee A. Sharma "PRISM: Platform for remote sensing using mobile smartphones" Proc. 8th Int. Conf. Mobile Syst. Appl. Services pp. 63-76 2010-Jun.

The popularity of the App Stores of all major smartphone vendors has made it possible for any entity with an App to quickly attract a very large number of users and distribute and run experiments with a large number of participants from all around the world rather than in laboratory controlled conditions using a small use study. The ability to gather large amounts of real world data so easily is a game changer for research.

Of course, many issues related to information sharing, privacy, data mining, and providing useful feedback to an individual, group, community, and population need to be addressed. For example:

- How to assess the accuracy of algorithms that interpret sensor data?
- How to validate experiments?
- How to select a good study group?
- How to deal with the potentially massive amount of data made available?
- How to protect the privacy of users?
- How to get approval for human subject studies from institutional review boards (IRBs)?
- How to construct cloud services to potentially deal with thousands of users and effectively process such data.

Operation in multiple scales: Future mobile phone sensing systems will operate at multiple scales, from personal to community (geographic or socioeconomic etc), to global.

User involvement options: Options relate to how much the person with the phone participates in the sensing-data collection process. For example, the person carrying the phone could actively participate (participatory sensing) by choosing when and where to collect the data or be passive (opportunistic sensing) and just carry the phone as they go about their daily activity. Each of these sensing paradigms presents important trade-offs.

Mobile phone sensing architecture: Decisions to be made include what architectural components from data collection to computation should run on the phone and what should run in the cloud. Likewise, the can be embedded in the phone or in a separate sensor that communicates data to the phone.

As resources of the phone rapidly expand, one of the main benefits of using the mobile computing cloud will be the ability to compute and mine big data from very large numbers of users. The availability of large-scale data benefits mobile phone sensing in a variety of ways; for example, more accurate interpretation algorithms that are updated based on sensor data sourced from an entire user community. This data enables personalizing of sensing systems based on the behavior of both the individual user and groups of people with selected similar characteristics (e.g. locational, behavioral, socioeconomic, occupational, etc.).

But make no mistake, while the infrastructure of an installed base of hundreds of millions to billions of mobile phones (and growing), when combined with supporting web services available in the cloud, make such adaptive, mobile, people involved sensing systems possible, new types of integrative platforms need to be developed to make them usable and scalable for individual applications. This type of work is rapidly developing in many fields of study, but still in its infancy. EPA has the opportunity, if it chooses, to take advantage of these developments, as well as make a meaningful contribution to its application for the development of an indoor air quality database, as well as a user-based assessment of personal exposure.

Further information and insights

Useful insights and information into this general field is available from the Institute of Electrical and Electronic Engineers: See ***Proceedings of the IEEE Volume 98 : Issue 11, November 2010***. This issue contains a Special Issue on Network Applications (pp 1804-1807) providing insights and trends, as well as a number or relevant articles on specific issues of interest (pp 1808-1973).

Is It Feasible for EPA to Develop A New And Improved Database of Population Exposures Using Advanced Sensor-Mobile-Network Applications?

There is little doubt about the value of having such a database available, not only to EPA, but to the whole of the indoor air scientific community and the more extended public health community. It could be the wellspring for further research in multiple fields to expand our knowledge, improve our understanding, support innovation and develop targeted solutions to specific problems through applied research. But that is only half the story. Whether it would be feasible given current budgets and other realities is an issue to be solved. Any large endeavor like this might not be feasible for EPA, but such a judgment would have to consider possibilities to reduce costs and complexities and allow for expansion over long time frames to improve its feasibility. Below are some considerations to consider.

Potential for a rational staged approach

One might think that establishing a program of this magnitude is out of reach given current budget constraints and potential uncertainties associated with the future of EPA's indoor air programs. It is true that to establish such a program will likely require significant resources extended over many years. However, several approaches could be used to mitigate such concerns. Consider the near term, medium term, and long-term stages of such a program, and consider the possibility of treating each stage as a separate and independently justified initiative. Maximizing the potential for cost sharing with collaborators, and the potential voluntary citizen participation in each stage could help make it feasible. And if each stage were considered a separate project justifiable, without depending on subsequent stages being funded to justify its implementation, obtaining necessary funding would be much easier. Further, various elements of the program could be tailored (expanded or cut back) or could be rolled out over a longer period of time to fit budget constraints. Could such a long-term venture be administratively structured with gradual roll out to keep costs manageable and with justifiable benefits for each stage? It obviously depends on many factors, but it's useful to consider some possibilities.

Planning Stage (near term): Examples of what the planning stage might involve include conceptual development with white paper (including a vision of the end result, basic goals, description of existing technologies, etc.); distribution to a select and manageable number of potential collaborators; development of an initial data collection protocol, plus subsequent meetings, presentations, and conference papers describing the initiative. Initial stage field study could be a small-scale proof of concept demonstration with subsequent refinement of a draft protocol for data collection to serve as the basis for gradual expansion (medium term stage). Industry participation for the demonstration to develop appropriate sensors and cell phone applications, plus some manageable citizen participation in collecting data would be part of such a demonstration project. The final portion of this stage would be a draft protocol for data collection and organization, a final report and conference papers describing results and future plans.

The benefits of this stage would persist even if EPA could no longer fund or control its expansion. After all, the TEAM studies mentioned above solidified the notion that "personal exposure" data as opposed to concentration data is what drove health impacts and personal exposure was more related to indoor rather than outdoor air. That is the lasting result of the TEAM studies long after the studies were completed. Thus, the draft protocol and conference papers of Stage 1 could be used by EPA to stimulate others to conduct similar experiments and suggest further refinements of the protocol. Valuable data would be collected and likely accessible by EPA and others even if not organized and collected by EPA. The costs to EPA would not be overly burdensome and could in part be shared by collaborators and include voluntary citizen involvement in data collection. Further, this initial stage would help establish a market for the equipment manufacturers, and stimulate further equipment refinements.

Expansion Stage (medium term): If funded, this stage would involve continuation of data collection and management of the original demonstration area, expanding its depth and/or geographic breadth of the demonstration, adding additional collaborators including international involvement who would conduct one of more independent studies, refining the protocol and working to have the protocol adopted as an national and international standard. Such an agreed upon standard for the conduct of such studies, would enable the sharing and combining of data from multiple studies without much loss of accuracy or representativeness. The standard would have to be flexible enough to allow for modifications to fit specific objectives of each study, but consistent enough to allow for smooth combining of datasets. This stage would involve further publications, journal articles and could involve the development of a separate conference devoted just to this subject.

Maintenance Stage (long term): This stage is to institutionalize the field data collection at least on a national scale, and possibly on an international scale, and to institutionalize ease of access to the data. At some point, whenever a person purchases sensing equipment or downloads a cell phone app that allows them to monitor their environment and/or body performance in a way comparable to the protocol, they would be invited to share their data and have it sent to a central depository, possibly in exchange for information on how their profile compares with national averages or percentiles or with some other incentive. EPA could operate the central data repository or just insure that one is set up by an independent nonprofit organization, funded partly by selling the data. Users should be able to access all or just certain desired subsets of the data, or search it online. EPA or the independent entity would insure the data was well maintained, kept up to date, was representative enough or could be so arranged to be a representative sample, or be able to satisfy statistical sampling requirements. States and jurisdictions might be interested in partly funding and monitoring data collection management for their own states. There are many possibilities that could be allowed to just evolve.

EPA could use the same program model to add data collection on different contaminants of interest. For example, SVOCs, biological agents, ultrafine and engineered nanoparticles are all important emerging pollutants. The development of such a data collection and data accessibility program would open the door for greatly expanding the research capacity into new and expanding areas of interest and promoting a much broader and comprehensive view of indoor environments. It would offer possibilities for a far more inclusive and integrated understanding of the current and future realities as described in the Science Review and open the door to more effective and efficient research and policy strategies.

FINAL OBSERVATIONS

Historical Perspective

When EPA was established in 1970, its name "Environmental Protection Agency" reflected the nature of its mandate—to "protect" the environment from polluters. Polluters were the bad guys, pollutants were the problem, and EPA's mandate was to protect the environment from pollutants, (both chemical and particulate), by establishing pollutant limits (emissions or concentrations) by regulations and enforcing those limits. That framework, generally referred to as "command and control" permeated every action the Agency took. The term "environment" referred solely to the outdoor environment so that "air quality" meant the outdoor air. Total exposure to air pollutants was interpreted as 24-hour exposure to pollutants of outdoor origin understanding that exposure occurred both outdoors and indoors.

As indoor generated pollutants became increasingly acknowledged, the Agency faced a dilemma, because it had no specific authority to regulate the air indoors. What people do indoors, especially in their homes was simply not considered subject to government interference. However, encouraged by the revelations of the TEAM studies, the Office of Research and Development began to study this new emerging issue to determine what indoor air pollutants people were exposed to through a national survey of homes. Meanwhile, European researchers were taking a broader approach, looking at "indoor air quality" to encompass both thermal comfort and indoor pollutants, where the HVAC system was seen as a critical influence on both. , and "source control" was seen as a voluntary effort by occupants. The Office of Air and Radiation adopted the European view and recommended a strategy to emphasizing the European view but reserving the need for regulation of very high risk individual pollutants using authority under TSCA. In that view, the "ventilation" part of HVAC was seen as a generic—not specific to pollutant or source—while control of sources was an act of choice of occupants or builders to minimize emissions by choice of products or methods of use. The term "policy" therefore was expanded from meaning "regulation" to also including inducements through education and guidance. As EPA matured, some shifts occurred toward more voluntary approaches to complement regulatory activity, but the core authorities, the funding, and the cultural orientation of the Agency has remained the same—identifying and controlling air pollutants.

The Current Reality

The Science Review demonstrated the reality of indoor air quality has changed, both because the world and technology has changed, but also because our understanding of indoor air pollutants and their impact on health, comfort, and productivity has changed. We can no longer be comfortable in just chemical and particle pollutants, that chemicals have changed and new contaminants such as SVOCs and nano-size (ultrafine) particles are important, that microbial populations outdoors, indoors and in our bodies are important, that the interplay and interactions of pollutant categories and exposure categories are important, and that new technologies have opened up vast opportunities for expanding our knowledge and our policy options.

The Synthesis Report tried to capture this new reality and offer new perspectives for choosing research directions. Making choices is not cut and dry in this reality because the possibilities are wide and the resources are constrained. Despite this, the foundational choice of the Agency is to choose between the past and the future and maybe a little bit of both, to choose to either go it alone or to join in cooperative and collaborative ventures with other agencies and organizations as described and to plant the seeds and cultivate a research environment that can sprout new growth and developments.

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