Research Achievements (2008-2013): William W Nazaroff

Summary: Research Topics and Contributions

My research centers on air quality engineering, emphasizing two themes: pollutant dynamics in indoor air and exposure science. On the first, my primary interest is to better understand the physics and chemistry that control the concentrations, fates, and effects of pollutants in indoor environments. On the second topic, we apply basic knowledge about air pollutants to build a quantitative and mechanistic understanding of the relationship between emissions from sources and consequent human exposures. My group pursues research through a combination of laboratory and field experiments, modeling, and data analysis. In recent years, in addition to maintaining vigorous activities in the two primary areas, I have had a growing concern about and interest in the themes of sustainability, climate change, and energy-use efficiency. I have begun to pursue research opportunities in these newer thematic areas, especially when opportunities arise that intersect with the primary research themes.

During the five-year period, I authored or coauthored 30 research articles that were published in archival peer-reviewed journals. As summarized in Table 1, all of these articles were published in highly ranked journals. The following paragraphs highlight briefly the substantive achievements reflected in this body of research.

Pollutant Dynamics in Indoor Air

Most people spend most of their time indoors and consequently the composition of indoor air strongly influences air pollutant exposure. Because indoor air is exchanged with outdoor air, pollutants in outdoor air are routinely introduced into indoor environments. However, for many pollutants, the indoor levels caused by outdoor sources are not the same as the outdoor levels. Differences can arise owing to engineered removal processes, such as filtration, and to incidental processes, such as deposition or reaction on surfaces. Furthermore, there are important indoor emission sources that can substantially elevate the levels of some pollutants indoors relative to levels outdoors. Furthermore, energy use in buildings is enormous. Determining how to ensure good indoor air quality while not using excessive energy is a crucial challenge in environmental engineering, both with regards to environmental health concerns and for sustainability. Notwithstanding these conditions, for a host of reasons, indoor air quality is also a topic that tends to be understudied, relative to other environmental issues.

Table 1. Research publications during the period 2008-2013.

Journal	N [a]	IF [b]	Note
Atmospheric Environment	11	3.1	Ranked 37th of 209 in "Environmental Sciences"
Indoor Air	7	3.3	Ranked 2nd of 57 in "Construction & Building Tech."
Environ. Sci. Technology	3	5.3	Ranked 2nd of 42 in "Environmental Engineering"
Building & Environment	3	2.4	Ranked 6th of 57 in "Construction & Building Tech."
Environmental Res. Letters	3	3.6	Ranked 24th of 209 in "Environmental Sciences"
Environ. Health Perspect.	1	7.3	Ranked 4th of 209 in "Environmental Sciences"
ISME Journal	1	9.0	Ranked 8th of 116 in "Microbiology"
PLoS One	1	3.7	Ranked 7th of 56 in "Multidisciplinary Sciences"

[a] Number of publications

[b] Journal impact factor (2012), as reported in the Web of Science (rounded to 2 significant figures).

My research group seeks to develop an understanding of the factors that control the concentrations and fates of important pollutants indoor environments. We do so using diverse approaches that include laboratory experiments, field monitoring, mathematical modeling, and analysis, interpreting our own data or synthesizing and reinterpreting previously published data.

One important class of pollutants is airborne particulate matter or aerosols. Epidemiological evidence strongly links particulate matter in outdoor air with serious adverse health effects including increased risk of mortality from cardiopulmonary causes. During the past five years, we published an experimental study investigating the generation of indoor particulate matter from ozone reactions with terpene-rich household products such as air fresheners and cleaning agents (**Coleman et al., 2008**). We also published a series of detailed field investigations of ultrafine particles in households (**Mullen et al., 2011a**; **Bhangar et al., 2011**) and in schools (**Mullen et al., 2011b**). These studies brought fresh insight into the relative importance of indoor versus outdoor sources of this subclass of particulate matter of emerging concern.

Another important category of indoor air pollutants featuring rich scientific complexity and important health concerns is semivolatile organic compounds (SVOCs). Among many uses, this chemical class includes plasticizers, flame retardants, and pesticides. Many SVOCs have been shown to have endocrine disrupting properties. Along with a leading indoor air chemist, I coauthored two major review articles on the nature and significance of SVOCs in indoor environments (**Weschler and Nazaroff, 2008**) and on the phase partitioning of SVOCs between air and settled dust (**Weschler and Nazaroff, 2010**).

The advent of powerful and inexpensive methods for measuring DNA and RNA has opened new vistas for studying the microbiology of the indoor environment. I teamed up with Jordan Peccia's research group at Yale University to study indoor bioaerosols. This partnership combined my expertise in indoor pollutant dynamics and aerosol science with the Peccia group's experience in environmental applications of quantitative PCR and next-generation sequencing methods. During the current period, we published three jointly authored papers (**Hospodsky et al., 2012**; **Qian et al., 2012**; **Yamamoto et al., 2012**). Among these, the most important may be the paper by Qian et al., in which we describe the first ever size-resolved effective emission factors of airborne bacteria and fungi associated with human occupancy.

Another pertinent issue that is both important and challenging is ozone in aircraft cabins. Planes routinely fly into the lower stratosphere where they can encounter naturally elevated ozone levels. Some but not all planes are equipped with catalytic converters to destroy ozone from the ventilation supply air. When the converters are absent or ineffective, exposure to ozone inside the aircraft cabin can be high enough to raise health concerns for flight attendants and passengers. During the period 2008-2013, we published three articles on this topic. We reported on an assessment of outdoor ozone levels along the flight paths of about 850 flights between Europe and the US (**Bhangar et al., 2013a**). We published an experimental assessment of a passive sampler for inexpensively measuring ozone in aircraft cabins (**Bhangar et al., 2013b**). We published a study of the chemical interaction between ozone and surface bound permethrin, a commonly used pesticide in aircraft cabins (**Coleman et al., 2010**).

The effective operation of data centers that serve as the hardware backbone of the internet depends in part on managing indoor environmental quality in buildings that house the servers. The electricity requirements to operate this system are high and rapidly growing. In rough terms, for every kilowatt-hour supplied for computing, another kilowatt-hour must be provided for air conditioning. Exposure to particulate matter and to humidity are among the primary environmental concerns that necessitate server protection. We published the first ever field study measuring particulate matter in data centers (**Shehabi et al., 2008**) and used the understanding generated from that study to assess the potential to improve energy performance through the use of economizers while actively filtering air to protect equipment from increased particle exposure (**Shehabi et al., 2010**).

Buildings can be targets for terrorist releases of chemical or biological agents. Monitoring systems are being developed to protect high value buildings against such threats. Working in collaboration with researchers at Lawrence Berkeley National Laboratory, my group has contributed insight into the design of effective monitoring systems that aim to solve the inverse problem of identifying the source of a release event based on observations of concentrations dispersed throughout a multizone indoor environment (**Sreedharan et al., 2011**).

One of the basic challenges in understanding indoor pollutant dynamics is to more effectively predict the transport of pollutants between rooms through open doorways. My group teamed up with Lynn Hildemann's at Stanford to advance knowledge of this process based on experimental data they had collected (**Ferro et al., 2009**).

Publications on Pollutant Dynamics in Indoor Air (2008-2013)

Bhangar S, Mullen NA, Kreisberg NM, Hering SV, Nazaroff WW, Ultrafine particle concentrations and exposures in seven residences in northern California, *Indoor Air* **21**, 132-144, 2011.

Bhangar S, Nazaroff WW, Atmospheric ozone levels encountered by commercial aircraft on transatlantic routes, *Environmental Research Letters* **8**, 014006, 2013a.

Bhangar S, Singer BC, Nazaroff WW, Calibration of the Ogawa passive ozone sampler for aircraft cabins, *Atmospheric Environment* **65**, 21-24, 2013b.

Coleman BK, Lunden MM, Destaillats H, Nazaroff WW, Secondary organic aerosol from ozone-initiated reactions with terpene-rich household products, *Atmospheric Environment* **42**, 8234-8245, 2008.

Coleman BK, Wells JR, Nazaroff WW, Investigating ozone-induced decomposition of surface-bound permethrin for conditions in aircraft cabins, *Indoor Air* **20**, 61-71, 2010.

Ferro AR, Klepeis NE, Ott WR, Nazaroff WW, Hildemann LM, Switzer P, Effect of interior door position on room-to-room differences in residential pollutant concentrations after short-term releases, *Atmospheric Environment* **43**, 706-714, 2009.

Hospodsky D, Qian J, Nazaroff WW, Yamamoto Y, Bibby K, Rismani-Yazdi H, Peccia J, Human occupancy as a source of indoor airborne bacteria, *PLoS ONE* **7**, e34867, 2012.

Mullen NA, Liu C, Zhang Y, Wang S, Nazaroff WW, Ultrafine particle concentrations and exposures in four high-rise Beijing apartments, *Atmospheric Environment* **45**, 7574-7582, 2011a.

Mullen NA, Bhangar S, Hering SV, Kreisberg NM, Nazaroff WW, Ultrafine particle concentrations and exposures in six elementary school classrooms in northern California, *Indoor Air* **21**, 77-87, 2011b.

Qian J, Hospodsky D, Yamamoto N, Nazaroff WW, Peccia J, Size-resolved emission rates of airborne bacteria and fungi in an occupied classroom, *Indoor Air* **22**, 339-351, 2012.

Shehabi A, Horvath A, Tschudi W, Gadgil AJ, Nazaroff WW, Particle concentrations in data centers, *Atmospheric Environment* **42**, 5978-5990, 2008.

Shehabi A, Ganguly S, Gundel LA, Horvath A, Kirchstetter TW, Lunden MM, Tschudi W, Gadgil AJ, Nazaroff WW, Can combining economizers with improved filtration save energy and protect equipment in data centers? *Building and Environment* **45**, 718-726, 2010.

Sreedharan P, Sohn MD, Nazaroff WW, Gadgil AJ, Towards improved characterization of high-risk releases using heterogeneous indoor sensor systems, *Building and Environment* **46**, 438-446, 2011.

Weschler CJ, Nazaroff WW, Semivolatile organic compounds in indoor environments, *Atmospheric Environment* **42**, 9018-9040, 2008.

Weschler CJ, Nazaroff WW, SVOC partitioning between the gas phase and settled dust indoors, *Atmospheric Environment* **44**, 3609-3620, 2010.

Yamamoto N, Bibby K, Qian J, Hospodsky D, Rismani-Yazdi H, Nazaroff WW, Peccia J, Particle size distributions and seasonal diversity of allergenic and pathogenic fungi in outdoor air, *ISME Journal* **6**, 1801-1811, 2012.

Exposure Science

Much of environmental engineering practice is driven by regulations. Environmental regulations mainly seek to protect human health from the adverse effects of pollutant exposure. However, it is difficult to determine exposure directly. Consequently, many environmental regulations aim to limit contaminant concentrations in air and water, or to limit emissions into these environmental fluids. Over time, controls that have been focused on limiting contaminant concentrations and emissions have led to certain distortions. In air quality, for example, society has become more effective at controlling the sources that impact concentrations at monitoring stations than at controlling the sources that matter the most for human exposure. Specifically, less attention is devoted to the often small but numerous pollution sources that are in close proximity to people as compared to those emitted from small numbers of large facilities that are often remote from people. As control measures become effective in reducing emissions from large facilities, the distributed, proximate sources become increasingly important as sources of human exposure to air pollutants.

One constraint that hinders us from paying more attention to exposures is that the tools and techniques for determining exposure are limited in their scope and sophistication. Experimentally, sampling from the breathing zone of populations poses different challenges than devising instruments to collect and analyze pollutants at fixed monitoring stations. Modeling methods have not been nearly so broadly applied to exposure assessments as to the determination of contaminant concentrations in ambient air.

The general area of exposure science is of ongoing interest to me as I come to a deeper appreciation of the challenges and benefits of making progress in this area. My group develops tools for assessing exposure and applies both new and conventional methods to advance our understanding of important exposure problems.

During the past five years, I coauthored seven research articles pertaining to exposure science. One area of particular interest is exposure metrics. My group has been among the pioneering teams in the development and application of the intake fraction concept. The intake fraction is the dimensionless ratio of pollution inhaled to pollution emitted. We recently published the first evaluation of intake fractions for all global cities with populations above 100,000; altogether, this assessment informs air pollution exposure for more than 2 billion people (**Apte et al., 2012**). In cooperation with Yuguo Li's group, we published an empirical assessment of intake fraction for motor vehicle exhaust in Hong Kong (**Luo et al., 2010**). In collaboration with researchers from Lawrence Berkeley National Laboratory, we also developed the most detailed assessment to date on intake fractions of motor vehicle exhaust emissions for the United States (**Lobscheid et al., 2012**).

Two new articles explored the subject of human exposure to semivolatile organic compounds (SVOCs) in indoor environments. In **Little et al. (2012)**, we reported on a rapid method for estimating the emissions-to-intake relationship for SVOCs in indoor environments. **Weschler and Nazaroff (2012)** utilized insight gleaned from pharmaceutical research along with fundamental knowledge of physical chemistry to propose new methods of assessing transdermal permeation of SVOCs for people exposed in ordinary indoor environments.

Advancing the frontiers of exposure metrics, **Nazaroff et al. (2012)** report on an economy wide assessment approach for evaluating human intake of manufactured chemicals. The method utilizes biomonitoring data (e.g. analytes excreted in urine) from a representative sample of the US population in combination with manufacturing and importation data on xenobiotic chemicals. The results show a vast range in the "intake-to-production" ratio, illustrating the importance of exposure intimacy influencing human body burdens of manufactured chemicals.

In **Apte et al. (2011)**, we report on a field campaign to measure personal exposure to several attributes of particulate matter while traveling in an autorickshaw or an automobile in New Delhi. That research adds insight about the degree to which on-road exposures can exceed even the very high urban pollution levels for particulate matter emitted from on road vehicles.

Publications on Exposure Science (2008-2013)

Apte JS, Kirchstetter TW, Reich AH, Deshpande SJ, Kaushik G, Chel A, Marshall JD, Nazaroff WW, Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India, *Atmospheric Environment* **45**, 4470-4480, 2011.

Apte JS, Bombrun E, Marshall JD, Nazaroff WW, Global intraurban intake fractions for primary air pollutants emitted from vehicles and other distributed sources, *Environmental Science & Technology* **46**, 3415-3423, 2012.

Little JC, Weschler CJ, Nazaroff WW, Liu Z, Cohen Hubal EA, Rapid methods to estimate potential exposure to semivolatile organic compounds in the indoor environment, *Environmental Science & Technology* **46**, 11171-11178, 2012.

Lobscheid AB, Nazaroff WW, Spears M, Horvath A, McKone TE, Intake fractions of primary conserved air pollutants emitted from on-road vehicles in the United States, *Atmospheric Environment* **63**, 298-305, 2012.

Luo Z, Li Y, Nazaroff WW, Intake fraction of motor vehicle exhaust in Hong Kong, *Atmospheric Environment* **44**, 1913-1918, 2010.

Nazaroff WW, Weschler CJ, Little JC, Cohen Hubal EA, Intake to production ratio: A measure of exposure intimacy for manufactured chemicals, *Environmental Health Perspectives* **120**, 1678-1683, 2012.

Weschler CJ, Nazaroff WW, SVOC exposure indoors: Fresh look at dermal pathways, *Indoor Air* **22**, 356-377, 2012.

Energy, Climate, Air Quality, and the Built Environment

I have strong interests in the broader domains of energy, climate, air quality, and the built environment, and especially in the intersections among these topics. Over the past five years, I've participated in several efforts leading to seven research publications on these topics.

I worked with a team headed by Arpad Horvath and Tom McKone and funded by the Energy Biosciences Institute on lifecycle analysis of the environmental impacts of biofuels. A paper by **McKone et al. (2011)** described seven grand challenges that must be overcome to conduct compelling lifecycle assessments of biofuels. This paper was honored as one of thirteen "top papers" published in *Environmental Science & Technology* in 2011, from among almost 1400 papers published in the journal that year. A subsequent paper by **Scown et al. (2012)** addressed some of those grand challenges in assessing the implications for greenhouse gas emissions of a large-scale shift to cellulosic ethanol production as a substitute for either corn ethanol or gasoline.

Shehabi et al. (2011) considered how changes in the geographic location of data center buildings could influence the associated greenhouse gas emissions, taking into account both the differences in the energy supply mix and the consequences of different climatic conditions for air conditioning needs.

Two papers emerged from workshops in which I was an invited participant because of my strong reputation as a leading scholar on indoor environmental quality. **Sundell et al. (2011)** represents the culmination of a multidisciplinary systematic review of the scientific literature relating health consequences to the ventilation of buildings. It is listed as the "most cited" paper published in *Indoor Air* in 2011 (http://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291600-0668/homepage/MostCited.html). A one-day retreat in Denmark that involved ten leading scholars in the indoor air sciences was the basis for an article summarizing the current state of knowledge and future challenges in indoor environmental science (**Clausen et al., 2011**).

The two sole-authored papers published during the period were invited. **Nazaroff (2008)** is a brief perspective article in the "new directions" series published by *Atmospheric Environment*. Here, I argue that public health benefits could be realized if policy makers focused more explicit attention on human exposure in efforts to control air pollution. **Nazaroff (2013)** was published in a special issue of *Environmental Research Letters* dedicated to "environmental assessments in the built environment." This article assesses the state of knowledge concerning the nexus of climate change, indoor environmental quality, and public health. Its preparation was an outgrowth of my participation in an Institute of Medicine committee, as further described in the section on university and public service.

Publications on Energy, Climate, Air Quality and the Built Environment (2008-2013)

Clausen G, Bekö G, Corsi RL, Gunnarsen L, Nazaroff WW, Olesen BW, Sigsgaard T, Sundell J, Toftum J, Weschler CJ, Reflections on the state of research: Indoor environmental quality, *Indoor Air* **21**, 219-230, 2011.

McKone TE, Nazaroff WW, Berck P, Auffhammer M, Lipman T, Torn MS, Masanet E, Lobscheid A, Santero N, Mishra U, Barrett A, Bomberg M, Fingerman K, Scown C, Strogen B, Horvath A, Grand challenges for life-cycle assessment of biofuels, *Environmental Science & Technology* **45**, 1751-1756, 2011.

Nazaroff WW, New directions: It's time to put the human receptor into air pollution control policy, *Atmospheric Environment* **42**, 6565-6566, 2008.

Nazaroff WW, Exploring the consequences of climate change for indoor air quality, *Environmental Research Letters* **8**, 015022, 2013.

Scown CD, Nazaroff WW, Mishra U, Strogen B, Lobscheid AB, Masanet E, Santero NJ, Horvath A, McKone TE, Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production, *Environmental Research Letters* **7**, 014011, 2012.

Shehabi A, Masanet E, Price H, Horvath A, Nazaroff WW, Data center design and location: Consequences for electricity use and greenhouse-gas emissions, *Building and Environment* **46**, 990-998, 2011.

Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, Grimsrud DT, Gyntelberg F, Li Y, Persily AK, Pickering AC, Samet JM, Spengler JD, Taylor ST, Weschler CJ, Ventilation rates and health: Multidisciplinary review of the scientific literature, *Indoor Air* **21**, 191-204, 2011.