RESIDENTIAL INDOOR AIR QUALITY, VENTILATION, AND BUILDING-RELATED HEALTH EFFECTS: CRITICAL REVIEW OF SCIENTIFIC LITERATURE

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ABSTRACT
The scientific literature on residential indoor air quality (IAQ), ventilation, and building-related health effects was reviewed to define gaps where further research is needed. Representative ranges of pollutant concentrations were identified for benzene, carbon monoxide, formaldehyde, nitrogen dioxide, fine particles, and total volatile organic compounds. Building-related health effects, including asthma, were found for bioaerosols, pollutants associated with dampness, combustion-related pollutants, and volatile organic compounds. A limited number of studies on the effectiveness of prevention and remediation of IAQ problems in homes were identified. Major areas recommended for further attention were: exposure studies; research addressing carbon monoxide; damp buildings and respiratory disease; temperature and perceived air quality; mitigation investigations; and translation of research into guidelines and standards. Priorities from these recommendations were: a residential building assessment survey and evaluation (BASE) similar to the earlier commercial building BASE project; exposure studies; and ventilation rates and health effects investigations.

INDEX TERMS
Health effects, mitigation, pollutant concentrations, research recommendations, ventilation

INTRODUCTION
Indoor air quality research has been heavily weighted on questions involving commercial and institutional buildings including schools. Because people spend a majority of their time in their homes, it is important that we focus exposure research on residential indoor environments. Residential exposure to indoor air pollutants is especially important to some of the most vulnerable in the population including infants, elderly, and those with allergies, asthma, and suppressed immune systems. This paper summarizes a survey and critical review of recent published scientific literature examining indoor air quality (IAQ) in residences in the United States. The goal of this review is to identify adverse health effects caused by poor IAQ, identify causal associations between indoor pollutants and health effects, and describe techniques to reduce these pollutant concentrations. This review grows out of earlier cooperative strategic planning between the U.S. Environmental Protection Agency’s Radiation and Indoor Environments National Laboratory and the University of Minnesota to identify IAQ applied research priorities (Angell and Grimsrud 2002).

The purpose of this critical review is to describe the current scientific foundation for our knowledge of residential IAQ in the United States and the gaps in that understanding. Based on this new awareness, programs may be designed to better reflect current science and research priorities may be identified to fill important gaps in current knowledge.

METHODS
Publications in the scientific literature, especially those from 1998 through 2002, were identified and gathered from on-line and CD-ROM databases and proceedings of major international conferences. This search used 12 bibliographic databases and more than 50 online professional and scholarly publishing sources. Of the 2,880 papers identified in the search, only about 15 percent of these research studies were selected for intense review.

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based upon study design, methodology, and data collection. In addition to the electronic sources, a manual search of conference proceedings published between 2000 and 2003 was completed.

RESULTS

Health Effects Of Indoor Air Pollutants In Residences
The study of air pollution inside buildings is fundamentally an investigation of health and comfort effects. Clearly issues such as sources, concentrations, and control mechanisms are important but the raison d’être of the study is the concern that airborne contaminants will cause adverse health effects in those who occupy buildings with polluted indoor air. An important review was prepared by the working group of the European Community (EC) entitled “Effects of Indoor Air Pollution on Human Health” (Berglund et al. 1992). The authors of the EC study approached their review by describing broad categories of health effects that could be affected by indoor air pollution. Respiratory diseases lead the list of health effects since the respiratory system is the organ group most directly affected by air pollution. Principal agents identified in the EC review included combustion products, environmental tobacco smoke (ETS), and biological agents.

Allergies and other diseases of the immune system have become even more important since the EC study was published in 1992. Allergic asthma and extrinsic allergic alveolitis (hypersensitivity pneumonitis) are the two leading diseases caused by allergens in the indoor air. Principal agents include house dust mites, pets, insects, and molds. These are linked to allergic asthma and rhino conjunctivitis.

Lung cancer is the major form of cancer that has been linked to indoor air pollution. Principal agents include radon and ETS. Other known human carcinogens found in the indoor air are asbestos, polycyclic aromatic hydrocarbons, and benzene (US Department of Health and Human Services 2002).

Other health effects identified in the EC review included: skin and mucous membrane effects, especially from volatile organic compounds (VOC); sensory and central nervous system effects including sick building syndrome; and cardiovascular system effects, including those from ETS, carbon monoxide (CO), and particles.

Jones (1999) completed an extensive review of indoor air quality and health as one of the Millennial Reviews for Atmospheric Environment. Jones’ review provides a useful change of focus from the EC’s health categories to pollutant class. Jones concludes his review with a strong recommendation for the need for guidelines to govern indoor pollutants in buildings. He argues further that additional attention must be devoted to the design of new residences beginning with the choice of low-emitting materials in constructing and furnishing buildings.

The tension (real or imagined) that exists between limiting ventilation rates to reduce energy use in a building and providing sufficient ventilation for controlling indoor pollutant concentrations can be ameliorated by reducing emission rates of pollutant sources. This solution depends on the former recommendation, i.e. the existence of appropriate pollution concentration guidelines.

Causes Of Building-Related Health Effects
Causes of building-related health effects in residences cluster around overlapping pollutant classes: bioaerosols and pollutants associated with dampness; combustion pollutants; and VOCs.

Bioaerosols, including mold and fungal products (e.g., particles, microbial VOC), are linked to water intrusion. Shum (2002) and Harding et al. (2002) challenge the assertion mold causes respiratory problems since most studies are limited by small sample sizes and self-reported symptoms. Other dampness-related pollutants, such as mites and mycotoxins, have been linked with respiratory problems (Spengler et al. 1994; Bornehag et al. 2001; Engelhart et al. 2002). Asthma exacerbation, rather than cause, results from a complex exposure interaction involving house dust mites, cockroaches, dogs, and cats (Institute of Medicine 2000).

Cooking, space and water heating, and vehicles in attached garages are CO, NO₂, and particle sources. Bohac (2002) found 20% of water heaters and 10% of furnaces backdrafted under certain conditions. Dutton et al. (2001) observed 47 to 78 ppm of CO from unvented gas fireplaces. NO₂ from gas ranges has been widely studied. While there is a moderate risk of adverse health effects from gas cooking, the public health risk is significant due to common use of gas cooktops (Clauhan 1999). In addition to combustion, particles from foot traffic, cleaning, cooking, and ETS are principal environmental risk factors for cardiopulmonary and lung cancer mortality. The important and complex issue of co-pollutants is beginning to be addressed, e.g., Dennekamp’s (2001)
measurements of ultrafine particles and NO₂ from cooking.

VOC emissions from building materials, plastics, textiles, paints, solvents, unvented clothes dryers, auto exhaust, and mold have diverse health effects, ranging from cancer to mucosal irritation. VOC impact on children, including pulmonary infection, has been noted by Diez et al. (2000) and Jaakkola et al. (2002).

Pollutant Concentrations Observed In Residences
Several studies report CO concentrations, including Grimsrud et al. (1996) with 1100 ppm from furnace backdrafting and Dutton et al. (2001) with 128 ppm from unvented gas fireplaces. The World Health Organization (WHO) CO guidelines are 90 ppm (15 minutes) and 10 ppm (8 hours). Ten studies reported NO₂ concentrations, including Pilo et al. (1997) and Dutton et al. (2001) who found concentrations from unvented heaters and fireplaces in excess of the WHO one hour guideline (200 μg/m³). Fine particle concentrations were found in 12 studies including Wallace (1996) with a maximum value of 100 μg/m³ from smoking, kerosene heaters, and cooking. Formaldehyde concentrations in new homes were found at or above the 100 μg/m³ WHO guideline by Hodgson et al. (2000) and Brown (2002). Maximum benzene concentrations of 81 μg/m³ from attached garages, smokers, and unvented clothes dryers were also reported by Brown (2002).

Ventilation
Ventilation is the last line of defense in pollutant control. Øie et al. (1999) found bronchial obstructions in children were higher in homes with less than 0.5 air changes per hours (ACH). Many US houses have ventilation below 0.5 ACH (Pandian et al. 1998).

Prevention And Mitigation
An excellent meta-analysis of asthma control techniques reflects the broader problem of limited scientific evidence addressing the effectiveness of prevention and mitigation of IAQ problems in homes has been completed by Custovic et al. (2000). There are few peer reviewed prevention/mitigation studies, there are even fewer studies assessing epidemiological outcomes of remediation, and there are virtually no remediation studies with a randomized clinical base.

DISCUSSION
This review follows strategic planning reported in Angell and Grimsrud (2002) in which four major areas for residential IAQ research were identified: a residential baseline survey modeled after EPA’s earlier large buildings Building Assessment Survey and Evaluation (BASE); exposure studies focusing on biocontaminants, particles and other pollutants found in residences; Federal leadership in establishing IAQ guidelines; and methods development to support the residential baseline survey and the exposure studies.

Based upon this review, recommendations for further research were identified according to six major themes:

1. need for exposure studies including those addressing questions about co-pollutants involving asthma triggers, and respiratory effects caused by nitrogen dioxide, and particles;
2. call for research addressing carbon monoxide issues including long-term, low-level CO exposure (associated with developing countries, gas equipment maintenance, reliable alarms, and attached garages) and frequency of high-concentration events;
3. need for standards and guidelines including that resulting from Federal leadership and important endpoints (such as building guidance, codes, and standards);
4. the importance of research on damp buildings and respiratory disease health effects of mold and fungal products such as mycotoxins and metabolic volatile organic compounds;
5. importance of consideration of temperature and Perceived Air Quality; and
6. significance of mitigation and prevention studies including those with epidemiological and clinical components, investigation and diagnostic procedures, ventilation interactions, and mold remediation.

These themes vary, to a degree, and overlap with the four priority areas identified in earlier strategic planning (Angell and Grimsrud 2002).

CONCLUSION AND IMPLICATIONS
A critical research need is a national residential building assessment and survey evaluation (BASE), patterned after the US EPA’s commercial BASE study, characterizing residential IAQ across climatic regions. Second, exposure
studies are needed to better understand diverse health effects links with pollutant mixtures. Investigations of ventilation rates and health effects, carbon monoxide, dampness in buildings, and prevention and mitigation strategies are further research needs.

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REFERENCES