Examination Study/Review Packet

Council-certified Environmental Allergen Consultant (CEAC)
Council-certified Environmental Allergen Investigator (CEAI)
Council-certified Environmental Allergen Technician (CEAT)

Exam Topics:

The effective practice of environmental allergen investigation requires detailed knowledge of a variety of subjects ranging from microbiology to the various disciplines of the building sciences. Candidates for the CEAC, CEAI, or CEAT designations must demonstrate familiarity with the basic principles of the discipline as represented by the following domains of knowledge:

The allergic response in humans

- Potential health effects associated with environmental allergens
- Methods for preventing and reducing exposure
- Role of physicians in addressing allergen issues

Types of allergens and their presence in the built environment

- Scientific data on the full range of environmental allergens
- Common sources of allergens in the built environment

Principles of the Built Environment

- Pathways and driving forces for environmental allergens
- Role of HVAC systems in controlling environmental allergen contaminants
- Psychromterics and moisture control

Investigation principles, procedures, and equipment

- General investigation procedures
- Principles of sampling and monitoring
- Equipment selection, calibration, and operation
- Personal protective equipment

Allergen evaulation and remediation strategies

- Principles of data analysis and interpretation
- Principles of containment engineering and construction
- Common remediation techniques
- Post remediation verification

Guidelines, reguations, and standards

- Federal, state, and local guidelines touching environmental allergens
- Industry guidelines touching environmental allergens
- The ACAC code of conduct

These domains of knowledge are addressed in a variety of publicly available industry publications, but items on the CEAC, CEAI, and CEAT examinations are drawn from the following texts, which are included in this packet:

(Click a title to go to a specific document in the packet.)

- APHL, Environmental Laboratories and Indoor Air Testing: A Primer (2015)
- CDC, *Healthy Housing Reference Manual*, chapter 5 (2006)
- EPA, Exposure Factors Handbook, chapter 19 (updated 2018)
- Estelle Levetin, PhD, "Methods for Aeroallergen Sampling" in Springer Nature, *Current Allergy and Asthma Reports* (2004), 4:376–383. Reprinted by permission of the publisher. All rights reserved.
- HHS, Airborne Allergens: Something in the Air (2003)
- HUD, *Healthy Homes Issues: Asthma* (2012)
- HUD, *Vacuum Dust Sample Collection Protocol for Allergens* (2008)

Recommended Study Procedures:

To prepare for the CEAC, CEAI, or CEAT exams, first read each reference texts included in this packet in its entirety. Then review the following sections from each text in more detail.

WARNING: Limiting your study to only the following pages will put you in danger of failing the exam. The exam assumes a comprehensive knowledge of each reference text.

- **APHL, Environmental Laboratories and Indoor Air Testing: A Primer (2015)** -- Pages 6, 18, 19, 20, and 25
- **CDC, *Healthy Housing Reference Manual*, chapter 5 (2006)** -- Pages 5-2 through 5-5
- **EPA, Exposure Factors Handbook, chapter 19 (updated 2018)** -- Pages 1, 2, 3, 11, 12, 13, 14, 15, 21, 22, 23, and 27
- **Estelle Levetin, PhD, "Methods for Aeroallergen Sampling," Current Allergy and Asthma Reports 2004, 4:376–383** -- Pages 376, 377, 378, 380, 381, and 382
- **HHS, Airborne Allergens: Something in the Air (2003)** -- Pages 2, 3, 6, 7, 9, 10, 12, 13, 14, 15, 16, 17, 19, 21, 22, 24, 26, and 27
- **HUD, *Healthy Homes Issues: Asthma* (2012)** -- Pages 1, 3, 4, 8, 10, 11, 12, 14, 15, 18, 22, 23, 35, and 42
- **HUD, *Vacuum Dust Sample Collection Protocol for Allergens* (2008)** -- Pages 2, 4, 5, 7, 8, 9, 10, 11, 12, and 13

Environmental Laboratories and Indoor Air Testing: A Primer

MARCH 2015

APHL ASSOCIATION OF PUBLIC HEALTH LABORATORIES™

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National Center for Zoonotic, Vector-borne, and Enteric Diseases (CK)
National Center for Environmental Health (NCEH)
Coordinating Office for Terrorism Preparedness and Emergency Response (CTPER)

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About APHL

The Association of Public Health Laboratories (APHL) works to safeguard the public's health by strengthening public health laboratories in the United States and across the world. In collaboration with its members, APHL advances laboratory systems and practices, and promotes policies that support healthy communities. Its membership includes state and local public health laboratories, environmental laboratories and others that conduct testing of public health significance. Individuals and international representatives also participate in the association.

APHL is a non-profit, 501(c)(3) organization with a history of over 50 years. APHL is located in Silver Spring, MD. More information is available at www.aphl.org.

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Executive Summary

People are paying more attention to “local” environmental conditions, such as residential indoor air conditions. However, in many instances, environmental laboratories do not have an indoor air-testing program. In other examples, laboratories may have a basic program, but are considering expansion to better serve their community.

This Primer provides basic information on the most significant residential indoor air pollutants. While the list of contaminants is not comprehensive, laboratories interested in launching a testing program will likely consider these ten areas first. In the context of the specific contaminants, the Primer addresses a number of basic issues for laboratories to consider, including screening methods, cost, and resources that may be necessary to start or expand an indoor air-testing program. Finally, the Appendices provide additional information on study design and referral sources for technical assistance and local housing partnership opportunities.

Introduction

Indoor air contamination comes in many forms. Allergens, smoke, mold, radon and other pollutants all negatively impact the health of building occupants. In the residential setting, particularly susceptible populations, including children, the elderly and those with compromised immune systems, may be exposed to a variety of health risks. These pollutants are the result of gases or particles coming from sources located throughout the house.[1]

The US EPA,[2] CDC[3] and World Health Organization[4] provide information and conduct research into indoor air quality issues. In addition, most states conduct some level of work regarding indoor air quality investigation or assistance.[5]

Environmental Health Laboratories can play a critical role in determining the dangers posed to residents by instituting a testing program for indoor air pollutants. An indoor air-testing program may take specialized equipment or new methods in order to address its unique issues.

This primer provides the basic information needed to implement a new or expanded indoor air-testing program. The contaminants covered below are not a complete list of the various indoor air pollutants that a residential setting may encounter. Instead, the 10 pollutants or class of pollutants are the areas where Environmental Health Laboratories may receive the bulk of the testing requests. Specifically, this primer covers:

- Allergens
- Abestos
- Formaldehyde and Acrolein
- Isocyanates
- Lead
- Mercury
- Mold and Mildew
- Particular Matter
- Radon

[1] US Environmental Protection Agency. An Introduction to Indoor Air Quality (IAQ). Retrieved from http://www.epa.gov/iaq/ia-intro.html, August 7, 2014.
[2] US Environmental Protection Agency. An Introduction to Indoor Air Quality (IAQ). Retrieved from http://www.epa.gov/iaq/ia-intro.html, August 7, 2014.
[3] US Centers for Disease Control and Prevention. Indoor Air Quality. Retrieved from http://www.cdc.gov/healthyhomes/bytopic/airquality.html, August 7, 2014.
[4] World Health Organization. Indoor air pollution and household energy. Retrieved August 20, 2014 from http://www.who.int/heli/risks/indoorair/indoorair/en/. For specific WHO guidelines on testing for common chemicals in indoor air, see: World Health Organization. WHO guidelines for indoor air quality: selected pollutants. 2010. Retrieved August 20, 2014 from http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf?ua=1.
[5] US Centers for Disease Control and Prevention. Indoor Air Quality Information. Retrieved from http://www.cdc.gov/nceh/airpollution/indoor_air.htm, August 7, 2014.

Each section addresses the types of equipment, screening and analytical methods, costs, and other basic issues that laboratories should deliberate when considering a new or expanded indoor air testing program. Additionally, laboratories should be aware that they may not always receive pure air samples in every case. For example, with air contaminants such as mold, lead and allergens, the tested media may consist of vacuumed dust samples, tape samples, or wipe samples to analyze the particles causing a degradation of indoor air quality.

It should also be noted that emerging sensor technology may provide opportunities for air monitoring across many of the pollutants discussed below.[6] The US EPA's Air Sensor Guidebook provides detailed information on sensor technology and applications.[7] Government laboratories may consider assisting community efforts with regards to sensor technologies through citizen science efforts. Local public health systems may appreciate laboratory input when implementing air sensor programs, through programs like the Air Sensor Toolbox for Citizen Scientists.[8]

This primer addresses residential indoor air specifically. For information concerning occupational indoor air issues, the National Institute of Occupational Safety and Health (NIOSH)[9] and the Occupational Safety and Health Administration (OSHA)[10] both comprehensively address indoor air quality in workplace settings.

Finally, the Appendices provide additional information concerning indoor air testing study design as well as technical and community points of contact. Environmental Health Laboratories are encouraged to reach out to community organizations to determine local needs and areas of focus when considering the type of indoor air testing program to launch.

[6] US Environmental Protection Agency. Next Generation Air Measuring. Retrieved August 19, 2014 from http://www.epa.gov/research/airscience/next-generation-air-measuring.htm.
[7] US Environmental Protection Agency. Air Sensor Guidebook. Retrieved August 19, 2014 from http://www.epa.gov/research/airscience/docs/air-sensor-guidebook.pdf.
[8] US Environmental Protection Agency. EPA's Air Sensor Toolbox for Citizen Scientists. Retrieved August 19, 2014 from http://www.epa.gov/heasd/airsensortoolbox/index.html.
[9] US Centers for Disease Control and Prevention. Workplace Safety & Health Tips: Indoor Environmental Quality. Retrieved from http://www.cdc.gov/niosh/topics/indoorenv/, August 7, 2014.
[10] US Occupational Safety & Health Administration. Indoor Air Quality. Retrieved from https://www.osha.gov/SLTC/indoorairquality/, August 7, 2014.

Allergens

Allergens come in many forms and manifest in many different ways. Insects, plants, pets and other sources may cause irritation in both children and adults. Recent studies and Institute of Medicine recommendations indicated that in-house cleaning,[11] education for household, nurse case management and housing Interventions can significantly reduce allergen exposures, thus reduce the asthma in home environments.[12]

Screening methods and equipment vary by type of allergen.[13] Two methods provide a wide range of analysis options:

1. Enzyme-linked immuno-sorbent assay (ELISA)
2. Multiple Array for Indoor Allergens (MARIA®)[14]

ELISA can detect allergens (antigen-antibody reactions using monoclonal or polyclonal antibodies) from:

- animal allergens
  - — Fel d 1 (cat, Felis domesticus)
  - — Can f 1 (dog, Canis familiaris)
  - — Mus m1 (mouse, Mus musculus)
  - — Rat r1 (rat, Rattus norwegicus)
- common German cockroach (Blattella germanica- Bla g1, Bla g2)
- dust mites (Dermatophagoides farina- Der p1, Der f1)[15]
- foods
- molds
- pollen

However, only individual (single) target testing is available via ELISA, suggesting the need for specific targeting and confirmation testing. Additionally, ELISA is limited to select World Health Organization (WHO)-recommended allergens.[16] While ELISA is cost-effective, it is more time-consuming and requires more “hands-on time” from laboratory personnel.

[11] Institute of Medicine, Division of Health Promotion and Disease Prevention, Committee on the Assessment of Asthma and Indoor Air. Clearing the air: asthma and indoor air exposures. Washington: National Academy Press; 2000.
[12] Breysse, J., Wendt, J., Dixon, S., Murphy, A., Wilson, J., Meurer, J., Cohn, J., Jacobs,D.E. Nurse Case Management and Housing Interventions Reduce Allergen Exposures: The Milwaukee Randomized Controlled Trial. Public Health Reports, 2011; Supplement 1, Volume 126, p89-99.
[13] Specific allergen concentration of WHO and FDA reference preparations measured using a multiple allergen standard. J Allergy Clin Immunol 2012; 129:1408-1410.
[14] King, E.M., Filep, S., Smith, B., Platts-Mills, T., Hamilton, R.G., Schmechel, D., Sordillo, J.E., Milton, D., van Ree, R., Krop, E.J., Heederik, D.J., Metwali, N., Thorne, P.S., Zeldin, D.C., Sever, M.L., Calatroni, A., Arbes Jr., S.J., Mitchell, H.E., Chapman, M.D. A multi-center ring trial of allergen analysis using fluorescent multiplex array technology. J Immunol Methods 2013; 387(1-2):89-95.
[15] Chapman, M.D., Heymann, P.W., Wilkins, S.R., Brown, M.J., Platts-Mills, T.A. Monoclonal immunoassays for major dust mite (Dermatophagoides) allergens, Der p I and Der f I, and quantitative analysis of the allergen content of mite and house dust extracts. J Allergy Clin Immunol 1987; 80:184-94.
[16] Specific allergen concentration of WHO and FDA reference preparations measured using a multiple allergen standard. J Allergy Clin Immunol 2012; 129:1408-1410.

Alternatively, MARIA can simultaneously detect multiple allergens in a single test. The test provides improved assay performance (primarily uses monoclonal antibodies, thus increased sensitivity and accuracy while achieving high throughput of samples by testing up to 11 targets that can consist of the following in combination:

- animal allergens
  — Fel d 1 (cat, Felis domesticus)
  — Can f 1 (dog, Canis familiaris)
  — Mus m 1 (mouse, Mus musculus)
  — Rat n 1 (rat, Rattus norwegicus)
- common German cockroach, Bla g 2 (Blattella germanica)
- dust mite
  — Der p1, Der f1 (Dermatophagoides farina)
  — Mite Group 2
- mold allergen Alt a 1 (Alternaria alternata)
- pollens
  —Bet v 1 (Birch, Betula verrucosa)
  —Phl p 5 (Timothy grass, Phleum pratense)

MARIA could provide substantial time savings, including overall improved turn-around-time, high throughput analysis, and cost-effective allergen testing (due to less use of disposable plastics, reagents, and man-hours). Additionally, MARIA can be automated via Luminex multiplex technology, but will still require extensive sample processing.

Both ELISA and MARIA have accepted analytical methods. As noted above ELISA relies on WHO standards as well as standards from the CDC. MARIA uses a Universal Allergen Standard to quantify the allergens. Both ELISA and MARIA are acceptable; however, ELISA is more widely used due to the low cost of analysis, and MARIA is considered a “relatively new” technique, thus, requiring extensive training and skilled staff with understanding and interpretation of test results.

Equipment options vary depending on the test platform chosen. ELISA requires plate readers, washers, and unique calibration standards, chemicals and reagents. MARIA utilizes either Luminex (200 or comparable software, plate-filtration manifold and related equipment) or Bio-RAD (Bio-Plex 200 system) technology. Commercial reagents are available and both require staff training and participation in proficiency testing.

Asbestos

Asbestos is a naturally occurring mineral fiber used in insulation and other building materials.[17] During renovation or maintenance operations in homes, asbestos may be dislodged and become airborne. Asbestos is normally not a source of acute health effects; however, long-term exposure to asbestos can result in a variety of lung diseases.[18]

In order to conduct asbestos monitoring and measurements, laboratories need: air samplers, filters, phase contrast microscopy (PCM) with polarized light microscopic (PLM) filtering capabilities, and access to transmission electronic microscopy (TEM) services to confirm the identity of fibers using TEM methods.[19]

Phase contrast microscopy (PCM) is the analytical method for measuring airborne asbestos, and should be done in accordance with the proper OSHA Standards. Air is drawn through a filter to capture airborne asbestos fibers. A portion of the filter is removed and a measured area is viewed by PCM. All the fibers meeting defined criteria for asbestos are counted and considered a measure of the airborne asbestos concentration.[20] There are two specific methods for PCM (currently, there are no sensor technology for asbestos):

- ASTM 7201[21]
- NIOSH 7400[22]

There are four main advantages of PCM:[23]

1. Phase contrast is a fiber counting technique and excludes non-fibrous particles from the analysis.
2. The technique is inexpensive and does not require specialized knowledge to carryout the analysis for total fiber counts.
3. The analysis is quick and can be performed on-site for rapid determination of asbestos fiber concentration in the air.
4. The technique has continuity with historical epidemiological studies so that estimates of expected disease can be inferred from long-term determinations of asbestos exposures.

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[17] US Environmental Protection Agency. An Introduction to Indoor Air (IAQ): Asbestos. Retrieved August 7, 2014 from http://www.epa.gov/iaq/asbestos.html.
[18] US Environmental Protection Agency. Learn About Asbestos. Retrieved October 21, 2014 from http://www2.epa.gov/asbestos/learn-about-asbestos#effects.
[19] https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10005 OSHA. Polarized Light Microscopy of Asbestos
[20] Occupational Safety and Health Administrations. Detailed procedure for asbestos sampling and analysis - Non-Mandatory. Retrieved August 28, 2014, from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9997.
[21] ASTM International. ASTM D7201: Standard Practice for Sampling and Counting Airborne Fibers, Including Asbestos Fibers, in the Workplace, by Phase Contrast Microscopy (with an option of Transmission Electron Microscopy). Retrieved August 25, 2014 from http://www.astm.org/Standards/D7201.htm.
[22] National Institute of Occupational Safety and Health. Asbestos and Other Fibers by PCM (7400). Retrieved August 25, 2014 from http://www.cdc.gov/niosh/docs/2003-154/pdfs/7400.pdf.
[23] Occupational Safety and Health Administrations. Detailed procedure for asbestos sampling and analysis - Non-Mandatory. Retrieved August 28, 2014, from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9997.

There are, however, disadvantages:[24]

1. PCM does not positively identify asbestos fibers. Other fibers which are not asbestos may be included in the count unless differential counting is performed. This requires a great deal of experience to adequately differentiate asbestos from non-asbestos fibers.
2. The smallest visible fibers are about 0.2 µm in diameter while the finest asbestos fibers may be as small as 0.02 µm in diameter. For some exposures, substantially more fibers may be present than are actually counted.

To positively identify asbestos, or differentiate among different types of asbestos, analyses must be performed by polarized light microscopy (PLM) or transmission electron microscopy (TEM).

PLM can be used to distinguish between asbestos and non-asbestos fibers.[25] PLM equipment and procedures are far less expensive than TEM, which identifies specific asbestos fiber type.

The advantages of PLM are:

- Basic identification of the materials was first performed by light microscopy and gross analysis. This provides a large base of published information against which to check analysis and analytical technique.
- The analysis is specific to fibers. The minerals present can exist in asbestiform, fibrous, prismatic, or massive varieties all at the same time. Therefore, bulk methods of analysis such as X-ray diffraction, IR analysis, DTA, etc. are inappropriate where the material is not known to be fibrous.
- The analysis is quick, requires little preparation time and can be performed on-site if a suitably equipped microscope is available.

The disadvantages of PLM are:

- Even using phase-polar illumination, not all the fibers present may be seen. This is a problem for very low asbestos concentrations where agglomerations or large bundles of fibers may not be present to allow identification by inference.
- The method requires a great degree of sophistication on the part of the microscopist. The mineralogical training of the analyst is very important. It is the basis on which subjective decisions are made.
- The method uses only a tiny amount of material for analysis. This may lead to sampling bias and false results (high or low). This is especially true if the sample is severely inhomogeneous.
- Fibers may be bound in a matrix and not distinguishable as fibers so identification cannot be made.

When asbestos fibers are present but not identifiable by light microscopy, TEM is used to determine the fiber identity.

[24] Occupational Safety and Health Administrations. Detailed procedure for asbestos sampling and analysis - Non-Mandatory. Retrieved August 28, 2014, from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9997.
[25] Occupational Safety and Health Administration. Polarized Light Microscopy of Asbestos -- Non-Mandatory. Retrieved August 28, 2014, from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10005.

Compared to PLM, the TEM equipment, maintenance and procedure are very expensive. If considering TEM, the following methods are available:

- ASTM D-6281[26]
- EPA Level II (Yamate)[27]
- ISO 10312[28]
- ISO 13794[29]
- NIOSH 7402[30]

Both PLM and TEM require expertise and proficiency to describe, measure, identify and count asbestos fibers.

[26] ASTM International. ASTM D6281-09: Standard Test Method for Airborne Asbestos Concentration in Ambient and Indoor Atmospheres as Determined by Transmission Electron Microscopy Direct Transfer (TEM). Retrieved August 25, 2014 from http://www.astm.org/Standards/D6281.htm.
[27] Yamate, G.; Agarwal, S.C.; Gibbons, R.D. Methodology for the Measurement of Airborne Asbestos by Electron Microscopy, EPA's Report No. 68-02-3266. 1984. Retrieved August 28, 2014, from http://www.epa.gov/region9/toxic/noa/eldorado/pdf/EPA-ERT-Asbestos-Sampling-SOP-2015.pdf.
[28] ISO. ISO 10312:1995: Ambient air—Determination of asbestos fibers—Direct transfer transmission electron microscopy method. Retrieved August 25, 2014 from http://www.iso.org/iso/catalogue_detail.htm?csnumber=18358.
[29] ISO. ISO 13794:1999: Ambient air — Determination of asbestos fibers—Indirect-transfer transmission electron microscopy method. Retrieved August 25, 2014, from http://www.iso.org/iso/catalogue_detail.htm?csnumber=22933.
[30] National Institute of Occupational Safety and Health. Asbestos by TEM (7402). Retrieved August 25, 2014, from http://www.cdc.gov/niosh/docs/2003-154/pdfs/7402.pdf.

Formaldehyde and Acrolein

Formaldehyde is a chemical widely found in building materials, household products, and which can be produced via a variety of combustion processes.[31] Acrolein may be formed from the breakdown of certain pollutants found in air, from the burning of organic matter including tobacco, or from the burning of fuels such as gasoline or oil. Airborne exposure to acrolein may occur by breathing contaminated air, by smoking tobacco or by being in the proximity of someone who is smoking, by being near vehicle exhaust, or by being near oil- or coal-fired power plants.[32]

To screen for formaldehyde or acrolein, contaminants can be collected using passive samplers or low-level (0.04-1 ppm) detector tubes to evaluate complaints of eye, nose, and throat irritation which may be due to off-gassing from insulation, building materials, carpets, drapes, or glues and adhesives.

Sensors are an option for formaldehyde with the Interscan Corporation 400 Series Portable Analyzer.[33] This sensor is a stand-alone monitor that is relatively simple to use; however, it is not a NIOSH or EPA approved method, and therefore requires further evaluation.

Both NIOSH and OSHA created analytical methods for measuring both formaldehyde and acrolein:

- NIOSH Method 2016[34]
- OSHA Method 52[35]

Both the sampling and analytical procedures permit the simultaneous determination of acrolein and formaldehyde. Additionally, samples can be collected using passive samplers or sampling pump and commercially available sorbent tube. One disadvantage is that organic solvent extraction is required. Extracts must be analyzed using a gas chromatograph coupled with a nitrogen selective detector.

EPA also created an accepted analytical method for both formaldehyde and acrolein:

- TO-11A[36]

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[31] US Environmental Protection Agency. An Introduction to Indoor Air (IAQ): Formaldehyde. Retrieved from http://www.epa.gov/iaq/formaldehyde.html, August 7, 2014.
[32] Agency for Toxic Substances and Disease Registry. 2007. ToxGuide™ for Acrolein, CH2=CH-CHO, CAS # 107-02-8. Retrieved August 25, 2014, from http://www.atsdr.cdc.gov/toxguides/toxguide-124.pdf. See also, US Environmental Protection Agency. 2003. Toxicological Review of Acrolein: In Support of Summary Information on the Integrated Risk Information System (IRIS). Retrieved August 25, 2014 from http://www.epa.gov/iris/toxreviews/0364tr.pdf.
[33] Interscan Corporation. Formaldehyde Monitoring Instruments and Systems. Retrieved August 25, 2014 from http://www.gasdetection.com/wp-content/uploads/hcho_monitoring_instruments_and_systems.pdf.
[34] National Institute of Occupational Safety and Health. Formaldehyde (2016). Retrieved August 25, 2014 from http://www.cdc.gov/niosh/docs/2003-154/pdfs/2016.pdf.
[35] US Occupational Safety and Health Administration. Acrolein and/or Formaldehyde. Retrieved August 25, 2014 from https://www.osha.gov/dts/sltc/methods/organic/org052/org052.html.
[36] US Environmental Protection Agency. Compendium Method TO-11A: Determination of Formaldehyde in Ambient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC) [Active Sampling Methodology]. Retrieved August 25, 2014 from http://www.epa.gov/ttnamti1/files/ambient/airtox/to-11ar.pdf.

For TO-11A, the sampling and analytical procedures permit the simultaneous determination of acrolein and formaldehyde. Additionally, samples can be collected using a sampling pump and commercially-available DNPH absorbent cartridge. However, this method requires organic extraction using acetonitrile and analysis of extracts by high performance liquid chromatography.

Finally, NIOSH has a method for detecting formaldehyde only:

- NIOSH 3500[37]

This spectrophotometric method is less expensive than chromatographic methods, but it may be difficult to set up the air sampler with impingers. Only those with proper chemical handling training should consider this method.

For laboratories considering any of these methods, they may need the following equipment:

- NIOSH 2016 and EPA Method TO-11A:
  - — Air sampling pump
  - — DNPH cartridges
  - — HPLC
  - — UV detector
- OSHA Method 52
  - — XAD-2 adsorbent tubes
  - — Air sampler
  - — GC with a nitrogen selective detector
- NIOSH 3500:
  - — Air sampler
  - — Impingers
  - — Spectrophotometer

[37] National Institute of Occupational Safety and Health. Formaldehyde by VIS (3500). Retrieved August 25, 2014, from http://www.cdc.gov/niosh/docs/2003-154/pdfs/3500.pdf.

Isocyanates

Isocyanates are chemicals that can cause occupational asthma, irritation of the skin, eyes, nose and throat, and cancer. Deaths have occurred due to both asthma and hypersensitivity pneumonitis from isocyanate exposure. Respiratory illnesses also can be caused by exposure to the skin.

Isocyanates react with compounds containing alcohol (hydroxyl) groups to produce polyurethane polymers, which are components of polyurethane foams, thermoplastic elastomers, spandex fibers, and polyurethane paints.[38] Isocyanates are the raw materials that make up all polyurethane products. Isocyanates are found in a number of commercial products, including paint, polyurethane foam, insulation materials, surface coatings, car seats, furniture, foam mattresses, under-carpet padding, packaging materials, shoes, laminated fabrics, polyurethane rubber, and adhesives. Do-it-yourself products containing isocyanates are available to homeowners to seal cracks themselves. Without proper ventilation indoor air exposure is likely.

While there are no screening methods available, there are two NIOSH methods that laboratories may select:

- Method 5525 Isocyanates Total[39]
- Method 5521 Monomeric Isocyanates[40]

The value of Method 5525[41] is the lower reporting limits that can be achieved, 50 ng for both the monomer and oligomer species, due to the strong fluorescence response of the 1-(9-anthracenylmethyl)piperazine (MAP) derivatives. Another benefit is the ability to calculate total isocyanate for the collected atmosphere even when all the possible isocyanate species are not known. This is due to the MAP isocyanate derivatives all exhibiting the same equivalent response in the ultraviolet analysis making it possible for the laboratory to calculate all confirmed isocyanate species. This is accomplished by comparing both the fluorescence and ultraviolet chromatograms and calculating the total using the response of one isocyanate species.

Conversely, the disadvantages associated with Method 5525 are having to use impingers for sample collection and the lack of commercial availability of the MAP derivatizing agent. Only those who are properly trained at chemical handling should attempt to use this procedure.

[38] US Occupational Safety and Health Administration. Isocyanates. Retrieved August 25, 2014, from https://www.osha.gov/SLTC/isocyanates/index.html.
[39] National Institute of Occupational Safety and Health. Isocyanates, Total (MAP) (5525). Retrieved August 25, 2014, from http://www.cdc.gov/niosh/docs/2003-154/pdfs/5525.pdf.
[40] National Institute of Occupational Safety and Health. Isocyanates, Monomeric (5521). Retrieved August 25, 2014, from http://www.cdc.gov/niosh/docs/2003-154/pdfs/5521.pdf.
[41] Bureau Veritas. Isocyanates-A Sampling Primer. Retrieved August 25, 2014, from http://www.us.bureauveritas.com/wps/wcm/connect/b181b395-3358-42ec-833c-14b1e497ac12/Isocyanates+-+A+Sampling+Primer.pdf?MOD=AJPERES.

Advantages to Method 5521 include the ability to collect for the vapor and aerosol in one sampler without the need for field desorption.[42] However, disadvantages include the method determines the air concentration of specific diisocyanates. It uses impingers and has a short holding time (7 days) for the impinger reagent. Only those who are properly trained at chemical handling should attempt to use this procedure.

Laboratories considering either of these methods may need the following equipment:

- NIOSH 5525
  - — Air sampler
  - — 1-(9-anthracenylmethyl)piperazine (MAP) [5,6] impregnated filters
  - — HPLC with gradient capabilities, coupled with UV and Fluorescence Detectors
- NIOSH 5521
  - — Air sampler
  - — Impingers
  - — HPLC with gradient, coupled with electrochemical detector

Note that OSHA announced a new National Emphasis Program for occupational exposure to isocyanates.[43] "Workers exposed to isocyanates can suffer debilitating health problems for months or even years after exposure," said Assistant Secretary of Labor for Occupational Safety and Health Dr. David Michaels. "Through this program, OSHA will strengthen protections for workers exposed to isocyanates."

[42] Bureau Veritas. Isocyanates-A Sampling Primer. Retrieved August 25, 2014, from http://www.us.bureauveritas.com/wps/wcm/connect/b181b395-3358-42ec-833c-14b1e497ac12/Isocyanates+-+A+Sampling+Primer.pdf?MOD=AJPERES.
[43] Occupational Safety and Health Administration. 2013. OSHA Announces new National Emphasis Program for occupational exposure to isocyanates. Retrieved August 25, 2014, from https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=NEWS_RELEASES&p_id=24273.

Lead

Lead has a long history of negative health impacts in residential settings. While lead-based paint remains a significant source of indoor air contamination, other sources include combustion and being tracked in from outside sources.[44]

Currently, there are no available screening methods for lead in air. Instead, the air must be collected and analyzed using reference methods, including indirect methods using wipe samples and similar collection methods.

There is one primary accepted analytical method, NIOSH Method 7303.[45] It involves digesting a filter (either MCE or PVC) with nitric and hydrochloric acids in a hot block at 95°C. To collect the sample one would need a pump and filter cassette. The total volume collected will determine the reported concentration (mg/m3 is a common unit used by OSHA). Analysis is then conducted by Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), with a 1.8 µg/sample reporting limit.

There are other acceptable methods for lead analysis, which may be used by commercial laboratories.[46]

[44] US Environmental Protection Agency. An Introduction to Indoor Air (IAQ): Lead. Retrieved from http://www.epa.gov/iaq/lead.html, August 7, 2014.
[45] National Institute of Occupational Safety and Health. Elements by ICP (7303). Retrieved August 25, 2014 from http://www.cdc.gov/niosh/docs/2003-154/pdfs/7303.pdf.
[46] See e.g.: ASTM International. ASTM E1613-12: Standard Test Method for Determination of Lead by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES), Flame Atomic Absorption Spectrometry (FAAS), or Graphite Furnace Atomic Absorption Spectrometry (GFAAS) Techniques. Retrieved August 25, 2014 from http://www.astm.org/Standards/E1613.htm.

Mercury

Mercury is a chemical found in many household products and in some medicines or medical procedures. Household products can include family heirlooms, antiques, fluorescent light bulbs (including compact fluorescent light bulbs—CFLs), paint, thermometers, thermostats, batteries, switches and relays.[47] Mercury may also be found in dental fillings, skin creams, necklaces and other jewelry. It can be used in alternative medicine and cultural practices. When mercury is exposed to the air, it can evaporate into an invisible, odorless and potentially-toxic vapor, especially in warm or poorly ventilated areas.[48]

The main method used to perform analyses of mercury vapor is cold vapor-atomic absorption spectrophotometer (CVAA). Two primary tests use CVAA for mercury vapor testing, although both are for workplace environments.

- OSHA ID-140[49]
- NIOSH 6009[50]

These methods use a solid sorbent device to collect the samples, which are then digested and analyzed using the CVAA method. There are both passive and active sorbent collection devices that can be used in a variety of settings. The tests listed above are very similar to the Standard Methods for the Examination of Water and Wastewater by 3112B[51] or EPA Methods 245.1[52] and 245.2.[53]

The collected samples are stable for at least 28 days (30 days per the OSHA method), which allows adequate time for collection and testing. In addition the sampling and analytical techniques provide acceptable sensitivity to the various exposure limits.[54] For those laboratories considering this analyte for testing, the technique is well known and is not considered difficult to perform.

However, there are some concerns with the sampling devices. The passive dosimeter cannot collect particulate compounds with the device, and a separate sampling process should be used for particulate collection. In addition, passive dosimeters do not provide appropriate sampling where the air velocity is greater than 229 m/min (750 ft/min). When collecting samples using an active sampler, there is dependence on a calibrated pump to take the sample.[55]

[47] Mercury Consumer and Commercial Products. US EPA. Retrieved September 12, 2014, from http://www.epa.gov/mercury/consumer.htm.
[48] How People are Exposed to Mercury, Exposures to Elemental Mercury. US EPA. Retrieved September 12, 2014 from http://www.epa.gov/mercury/exposure.htm.
[49] OSHA Method ID-140: Mercury Vapor in Workplace Atmospheres. June 1991. OSHA. Retrieved September 15, 2014 https://www.osha.gov/dts/sltc/methods/inorganic/id140/id140.pdf.
[50] NIOSH Method 6009: Mercury. August 15, 1994. NIOSH. Retrieved September 15, 2014 http://www.cdc.gov/niosh/docs/2003-154/pdfs/6009.pdf.
[51] National Environmental Methods Index. Standard Methods: 3112B: Metals in Water by CV-AAS. Retrieved September 16, 2014, from https://www.nemi.gov/methods/method_summary/9737/.
[52] National Environmental Methods Index. ERPA-NERL: 245.1: Mercury by CVAA. Retrieved September 16, 2014 from https://www.nemi.gov/methods/method_summary/4821/.
[53] National Environmental Methods Index. ERPA-NERL: 245.2: Mercury by CVAA (Automated). Retrieved September 16, 2014 from https://www.nemi.gov/methods/method_summary/4822/.
[54] NIOSH Pocket Guide to Chemical Hazards: Mercury Compounds [except (organo) alkyls]. NIOSH. Retrieved September 15, 2014 http://www.cdc.gov/niosh/npg/npgd0383.html.
[55] OSHA Method ID-140: Mercury Vapor in Workplace Atmospheres. June 1991. OSHA. Retrieved September 15, 2014

Note that there are a number of EPA-approved methods for outdoor air testing and if interested, laboratories can investigate further at the following sites under EPA Technology Transfer Network:

- Emission Measurement Center: CFR Promulgated Test Methods[56]
- Emission Measurement Center: Other Methods[57]
- Ambient Monitoring Technology Information Center: Air Monitoring Methods – Inorganic (IO) Compendium Methods; IO-5[58]

There are also a number of sensors on the market listing their ability to test for chemicals, including household chemicals. However, the highlighted items for these sensors were volatile organic compounds, lead, and formaldehyde. This does not rule out mercury as a chemical that could be detected by these particular sensors, but further research is required. Portable mercury analyzers are available from some companies that provide the ability to detect mercury vapor in the field. These portable devices are primarily based on atomic absorption technology.

Laboratories considering the above OSHA and NIOSH methods would need the following equipment:

- Instrumentation
  — CVAA analyzer (mercury analyzer) **or**
  — Atomic Absorption Spectrophotometer
- Sampling
  — Calibrated air sampling pumps
  — Dosimeters

https://www.osha.gov/dts/sltc/methods/inorganic/id140/id140.pdf.

[56] EPA CFR Promulgated Test Methods. EPA Technology Transfer Network: Emission Measurement Center. Retrieved September 15, 2014 http://www.epa.gov/ttn/emc/promgate.html.

[57] EPA Other Methods. EPA Technology Transfer Network: Emission Measurement Center. Retrieved September 15, 2014 http://www.epa.gov/ttn/emc/prelim.html.

[58] EPA Air Monitoring Methods – Inorganic (IO) Compendium Methods. EPA Technology Transfer Network: Ambient Monitoring Technology Information Center. Retrieved September 15, 2014 http://www.epa.gov/ttnamti1/inorg.html.

Mold and Mildew

In many instances, laboratory testing for mold and mildew will be unnecessary. Although there are over 200 species of mold that can cause illness from a number of sources,[59] mold visibility correlates to mold exposure. As the US Department of Housing and Urban Development describes it, "visual observation of active or past microbial growth, or measurement of mold in dust or a sample of source material, can be used to establish potential for mold exposure."[60] Consequently, there is generally little need to test for mold in a residential setting — if the mold is visible, then abatement is generally recommended. However, should testing be requested or required, there are a number of options available, both in terms of the type of environmental sample (see Table 1) or the analytical method (see Table 2). Note that the relative costs associated with mold testing may be high or that it may require new pieces of equipment or validated methods.

Moreover, interpreting data results associated with mold testing may pose its own difficulties.[61] Baseline levels are difficult to establish and communicating results to the lay public may cause added confusion or uncertainty. Should mold testing be requested or preferred, refer to Guide for interpreting reports from inspections/investigations of indoor mold for examples of the forms and reports that may be needed.[62]

Table 1: Selected Mold Sampling Strategies[63]

Type of Environmental Sample	Sampling Technique	Advantages/Disadvantages	Relative Cost	Possible/Example Results
Bulk	Remove section of building material (e.g., wallboard)	Destructive technique	Moderate	Detection of past mold colonization or active growth
Surface	Press collection material (contract plate of adhesive tape) Wipe small area with a wetted swag, cloth, or filter Vaccum sample of settled dust	Non-Destructive Spatially and temporally variable Settled dust samples expected to be less temporally variable and be a better indicator of exposure over time	Low	Detection of past mold colonization or active growth Identification of surfaces/ areas where airborne mold spores and fragments have settled and accumulated

[59] US Environmental Protection Agency. An Introduction to Indoor Air (IAQ): Biological Pollutants. Retrieved from http://www.epa.gov/iaq/biologic.html, August 7, 2014.
[60] US Department of Housing and Urban Development. 2011. Healthy Homes Issue: Mold. Retrieved August 6, 2014 from: http://www.healthyhousingsolutions.com/Portals/0/HUD_Mold_Paper_Final_11-20-12.pdf.
[61] Horner, W.E., Barnes, C., Codina, R., Levetin, E. J. Guide for interpreting reports from inspections/investigations of indoor mold. Allergy Clin. Immunol. 2008. 121(3): 592-597.
[62] Horner, W.E., Barnes, C., Codina, R., Levetin, E. J. Guide for interpreting reports from inspections/investigations of indoor mold. Allergy Clin. Immunol. 2008. 121(3): 592-597.
[63] Reproduced from: US Department of Housing and Urban Development. 2011. Healthy Homes Issue: Mold. Retrieved August 6, 2014 from: http://www.healthyhousingsolutions.com/Portals/0/HUD_Mold_Paper_Final_11-20-12.pdf.

Type of Environmental Sample	Sampling Technique	Advantages/Disadvantages	Relative Cost	Possible/Example Results
Air	Static sampler Personal sampler With HVAC off and on	Useful if it is suspected that the ventilation systems are contaminated Air levels are variable, especially with disturbance Short-term air samples limit sensitivity Requires calibration and careful handling	Most expensive	Detection of mold contamination where the presence of mold is suspected but cannot be identified by a visual inspection or bulk sampling
Sedimentary	Gravity Slide Settled Plate Electrostatic dust collector Dust fall collector	Simple Deposition can be affected by air turbulence; may underesitmate small cells	Moderate	Determination of cumulative assessment over a given period of time
Aerosolization	Fungal Spore Source Strength Test (FSSST)	Destructive technique Testing requires specialized equipment and a chamber	Moderate	Evaluation of potential for fungal spores to aerolize from building materials Calculation of maximum fungal load Source identification

Table 2: Selected Methods for Analyzing Home Environmental Samples for Mold[64]

ANALYSIS		Test Applicability	
Method (units)	**Advantages/Limitations**	**Important Species**	**Data Obtained[65]**
Allergen immunoassay, ELIZA[66] (µg/g or pg/m^3)	Not currently reliable for fungi (e.g. *Alternaria* counts must be very high or germinating, cross reactivity occurs between *Penicillium* and *Aspergillus* and between *Alternaria* and non-related fungi)	*Aspergillus, Alternaria, Caldosporium*	Allergen levels (Asp f 1 and Alt a 1)
Direct microscopy—Spore identification, (spore count)	Intact spores may not account for total allergen load	All (*Aspergillus*, *Penicillium*, *Trichoderma*, and yeasts difficult to identify)	Concentration of spores; spore identification

[64] Reproduced from: US Department of Housing and Urban Development. 2011. Healthy Homes Issue: Mold. Retrieved August 6, 2014 from: http://www.healthyhousingsolutions.com/Portals/0/HUD_Mold_Paper_Final_11-20-12.pdf.
[65] Allergens listed in this column are those for which monoclonal antibodies are typically commercially available for immunoassay purposes (see INDOOR Biotechnologies website, http://www.inbio.com/index.html).
[66] Quantitative differences between allergen standards are currently an important source of assay (ELISA) variability.

Culture (CFUs)	Viable fungi may not account for total allergen load	All	Species identification Estimates of fungal concentrations as colony forming units (CFUs)
Chemical biomarkers (ergosterol, extracellular polysaccharides [EPS], β-glucan, VOCs, mycotoxins)	Ergosterol and EPS are good indicators of total biomass (components in all fungal hyphae and spores, cannot identify species)	Not species specific Non-fungal sources can affect β-glucan and VOC results Methods not well developed for fungal VOCs or mycotoxins in indoor environments	Concentration of chemical biomarker Estimates of fungal biomass
Polymerase chain reaction (PCR) base technologies (i.e., genetic probes)	Accurate: Based on targeting species-specific sequences of DNA Identifies both viable and nonviable fungal elements, but is prone to amplifying sample contaminants Genetic probes available for about 36 mold species Particulate materials in the air may inhibit the PCR reaction	Species specific, including but not limited to *Alternaria*, *Aspergillus*, *Cladosporium*, and *Penicillium*	Mold identification to the species level

Particulate Matter

Particulate matter (PM) can be a complex mixture of extremely small particles and liquid droplets. PM or particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects. The US EPA groups particle pollution into two categories:[67]

1) Inhalable coarse particles, such as those found near roadways, transportation sources, coal-burning power plants, steel mills, mining operations, and dusty industries which are larger than 2.5 microns and smaller than 10 microns in diameter (PM10).
2) Fine particles such as those found in smoke and haze and are 2.5 microns in diameter (PM2.5) and smaller. These particles can be directly emitted from sources such as forest fires or form when gases from power plants, industries and automobiles react in the air.

One commonly used method for particulate matter analysis is the use of filter collection and gravimetric analysis. Size selective impactors are used to collect PM onto a filter, which is then analyzed gravimetrically.[68]

The use of relatively low-cost air sensors compared to stationary outdoor monitors is now available as an emerging technology to assist citizen scientists and others in making appropriate choices for monitoring equipment. Basic information is required to calibrate sensors and determine precision of the device's response as well as other bias. EPA's Air Sensor Guidebook can assist those interested in using lower-cost air quality sensor technology for air quality measurements.[69] One disadvantage of the air sensor methodology is that it is in early-stage development and many sensors have yet to be evaluated to determine accuracy of measurements.

EPA offers technology developers the opportunity to send in air sensors for evaluation in a controlled laboratory setting, http://www.epa.gov/airscience/air-sensor.htm. The sensors listed below are from the US EPA Air Sensor Guidebook that have been evaluated to date.

[67] US Environmental Protection Agency. Particulate Matter. Retrieved September 11, 2014, from http://www.epa.gov/airquality/particlepollution/index.html.
[68] State of Alaska Department of Environmental Conservation. Standard Operating Procedure for Laboratory Gravimetric Analysis of Fine Particulate Matter (PM2.5) Air Quality Filter Samples. Retrieved October 23, 2014 from https://dec.alaska.gov/air/doc/Lab SOP- Grametric Analysis - Morgan Rev.pdf
[69] US Environmental Protection Agency. Air Sensor Guidebook. Retrieved August 25, 2014 from http://www.epa.gov/research/airscience/docs/air-sensor-guidebook.pdf.

Table 3: Performance characteristics of commercially available and emerging sensors for continuous measurements of PM mass and physical properties.[70]

Reference Sampler / Sensor	Measurement Principle	Manufacturer	Accuracy	Precision	Limit of Detection ($\mu g/m^3$) or Lower Particle Size Detected (µm)	More Information** Weight (kg) and ~Cost ($, when available) as of May 2014
831 Aerosol Mass Monitor	Light scattering; Mass concentration	MetOne Instruments	±10% to calibration aerosol	-[b]	0.5 µm	Range: 0-1,000 $\mu g/m^3$; 0.8 kg; <$2,000
Personal DataRAM, Model pDR-1500	Light Scattering; Mass concentration	Thermo Scientific	±5% of reading ± precision	±0.2% of reading or ±0.5 $\mu g/m^3$ 60-s avg	0.1 µm	Size Range: 0.1–10 µm; Conc Range: 1 to $4x10^5$ $\mu g/m^3$ Precision (2σ); 10-s avg; 1.2 kg; $5500 with PM2.5 and PM10 cyclones
DC1100 Air Quality Monitor	Light scattering; Laser particle counter	Dylos Corp.	-[b]	±15%, collocated**	0.5 µm	Size ranges: Pro: >0.5 µm, >2.5 µm or Household: >1 µm, >5 µm, difference between size ranges equals reported counts; Linear up to ~10^8 pt/mL with <10% coincidence**; ~0.4 kg;< $300
microAeth® Model AE51	Light absorption, 880 nm	AethLabs; Black Carbon	no standard for comparison	±0.1 µg BC/m^3 60-s avg**	<0.16 $\mu g/m^3$, 2.5 mL/s, 60-s avg	Precision at 2.5 mL/s flow rate; Range: 1-1000 µg BC/m^3 Resolution 1 ng BC/m^3; 0.3 kg; $6,000

[a]Conversion from light scattering, particle number or size distribution, requires estimates of particle density and shape factors; [b]No data. Performance capabilities are from manufacturers' datasheets except where noted with a **. Text in bold type represents a typical fixed-site higher-cost monitor for comparison purposes only to the sensors that follow in that category. Adapted from Snyder et al[29].

It is important that purchased sensors have informative user manuals for general operation, storing data, conditions of operation including sensitivity, sensor expiration, directions for calibrations, precision and bias, maintenance requirements and demonstrations from scientific articles about performance.

One type of sensor, a light scattering laser particle counter is a tool that provides information crucial to determine indoor air quality. The laser particle counters can be purchased for approximately $200 and are capable of detecting the number and size of particles in homes from mold, smoke, bacteria, pollen, plant spore and dust mites. Once pollution levels have been determined air purifiers or air sterilizers can be used to rectify indoor quality issues. As airborne particles pass through the laser light source, the unit measures the amount of light the particles scatter when passing through the detection area. Monitors are able to detect particulate matter in two concentration thresholds; small particles (approximately 1 micron) and large particles (5 microns).[71]

[70] US Environmental Protection Agency. Air Sensor Guidebook. Retrieved August 25, 2014 from http://www.epa.gov/research/airscience/docs/air-sensor-guidebook.pdf.
[71] A.M.I. Services. Dylos DC1100 Air Quality Monitor/particle counter. Retrieved September 10, 2014 from http://www.amiservices.us/dc1100.html.

Radon

Radon is a radioactive gas that appears in residences via underground infiltration.[72] According to EPA, radon is estimated to cause 21,000 deaths from lung cancer per year, more than drunk driving and other causes. The level of concern for radon is 4 pCi/L of air and the point at which remediation is recommended, but levels below that are still of concern.[73]

Testing falls into two categories. First, short term (typically 1 -3 days), is often used for real estate transactions and represents a point in time and is used as a screening technique. Second, long-term testing (in some instances up to a year but more often weeks to a month) provides an integrated exposure that is more representative of an average exposure and considered to be definitive testing.

Additionally, the types of radon air testing can be broken down into two broad categories: field[74] and laboratory. One common type of field sampler is a continuous radon monitor. The monitor uses a flow-through cell or detection chamber after passing through a filter that removes radon decay products and dust. The radon decays are then detected by a scintillation cell, an ionization chamber or a solid-state silicon detector. A second type of field detector is the Electret Ion Chamber radon detector. This system is composed of an electrostatically charged disk of Teflon®. They measure the average concentration of radon during the period that they are exposed. The ions generated by the radon decay are drawn to the surface of the filter and cause the voltage to decrease compared to the start of the exposure period. This measurement can take place in either the field or the laboratory. There are also grab sampling techniques that can be used to determine radon concentration in air, with detection techniques that can be either in the field or in the laboratory.[75]

The two most common types of laboratory analysis for radon uses activated charcoal to trap the radon. Activated charcoal devices do not require power to function, and rely on adsorption of radon by the activated charcoal. They are typically exposed for two-to-seven days, and during that time period the adsorbed radon decays. Consequently, this technique does not integrate the radon concentrations over the exposure period. Activated charcoal systems can also incorporate diffusion barriers to improve the uniformity of response to temporal variations in radon concentration. The average radon concentration is decay corrected to the midpoint of the exposure time, which can introduce error if the ambient radon concentration varies greatly during that time period. Quality Assurance elements include calibration of the activated charcoal system Including cartridges and detector), known exposure cartridges (i.e. spiked samples), duplicate cartridges, laboratory and field blanks and daily instrument performance checks.[76]

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[72] US Environmental Protection Agency. Radon. Retrieved from, http://www.epa.gov/radon/index.html, August 7, 2014.
[73] US Environmental Protection Agency. Consumer's Guide to Radon Reduction. Retrieved August 19, 2014 from http://www.epa.gov/radon/pubs/consguid.html.
[74] Although field testing is beyond the scope of this document, it will be discussed at a high level for informational purposes.
[75] Office of Air and Radiation. US Environmental Protection Agency. Indoor Radon and Radon Decay: Product Measurement Device Protocols. Retrieved August 19, 2014 from http://infohouse.p2ric.org/ref/17/radon/pubs/devprot1.html.
[76] Office of Air and Radiation. US Environmental Protection Agency. Indoor Radon and Radon Decay: Product Measurement Device Protocols. Retrieved August 19, 2014 from http://infohouse.p2ric.org/ref/17/radon/pubs/devprot1.html.

One type of activated charcoal procedure uses gamma spectroscopy for analysis. There are a variety of implementations of this procedure, and a common one is a circular container (approx. 10 cm in diameter and 2.5 cm deep) filled with 25 to 100 grams of charcoal. One side of the container has a screen (to keep the charcoal in) and some devices have a diffusion barrier over the opening. Some also include a desiccant to reduce interferences from moisture adsorption. The canister is returned to the laboratory and placed on the gamma detector and analyzed for the radon decay products. The result should be corrected for any adsorbed water, as water reduces the sensitivity. Accounting for the water is done by weighing the device before and after deployment, and assuming any weight gain is due to the water. The gamma detector system must be calibrated before use, and the detector response verified before any sample analysis is performed.[77,78]

Another activated charcoal procedure uses liquid scintillation counting. A typical device is a 20 mm liquid scintillation vial (approx. 25 mm in diameter and 60 mm deep) containing one-to-three grams of activated charcoal. Some cartridge designs also include a diffusion barrier and desiccant. After the vial is returned to the laboratory, liquid scintillation cocktail is added and the vial is counted on a liquid scintillation counter. As with the method discussed above, cartridge results must be corrected for adsorbed moisture. Further corrections must be made for radon transfer from the activated charcoal to the scintillation fluid as well as for the counting efficiency of the system. Finally, the entire detection system should be calibrated as for the charcoal canisters.[79]

A final laboratory procedure for radon in air is the Alpha Track Detector. These were commonly used in the United States in the 1980's (and are still more common in Europe), but less so today because of the need for a quick turn-around time driven by the real estate market. The device is a piece of plastic or film encased in a holder with a filter covered opening. As the radon diffuses into the device, the alpha particles hit the film and create tracks in it. When the device is returned to the laboratory, the filters are chemically etched in caustic to make the tracks more visible. The tracks are then counted either with a microscope or an automated counting device. This technique provides a true integrated reading of the radon concentration because every alpha particle causes a track on the film.[80]

[77] Office of Radiation Programs. US Environmental Protection Agency. EERF Standard Operating Procedures for Rn-222 Measurements Using Charcoal Canisters. Retrieved August 19, 2014 from http://1.usa.gov/1AuFAAv.
[78] For information of measurement uncertainty, see: Panteli, G., Savkovic, M.E., Zivanovic, M., Nikolic, J., Rajacic, M., Todorovic, D. Uncertainty evaluation in radon concentration measurement using charcoal canister. Applied Radiation and Isotopes, 87 (2014) 452–455. Retrieved August 19, 2014 from http://www.academia.edu/7319700/Uncertainty_evaluation_in_radon_concentration_measurement_using_charcoal_canister.
[79] George, A.C., Esposito, J.Z., Bredhoff, N. Determination of Environmental 222Rn by Adsorption in a Diffusion Barrier Activated Carbon Collector Using Liquid Scintillation Counting. Radon Testing Corporation of America. Retrieved August 19, 2014 from http://bit.ly/1p9Hi6M.
[80] Office of Air and Radiation. US Environmental Protection Agency. Indoor Radon and Radon Decay: Product Measurement Device Protocols. Retrieved August 19, 2014 from http://infohouse.p2ric.org/ref/17/radon/pubs/devprot1.html.

Volatile Organic Compounds

Volatile Organic Compounds (VOCs) and semi-volatile organic compounds (sVOCs) are emitted from materials such as paints, cleaning supplies, building materials and adhesives.[81] In addition, petroleum combustion, from powered garden tools or other outside sources that can enter the house may also be a source of VOCs. Soil vapor intrusion occurs when the organic compounds from a contaminated water and/or soil site enters the interstitial air space in soil. Some organic compounds may not be toxic but may be irritants.

There are several well-established EPA methods to test indoor and outdoor air for VOCs. EPA methods TO-15[82] and TO-17[83] are widely used for fence line, soil gas, stack, outdoor and indoor air monitoring. These are quantitative and qualitative methods using mass spectrometry (MS) detection. The system is calibrated using a standard of known concentration. When the unknown sample is investigated, it is referenced to this known standard which determines the concentration of the sample. The sample volume collected is applied to the calculation. The greater the sample volume the better the detection limits will be.

EPA TO-15 uses a summa canister to collect the sample. After sampling, the canister is sent to a laboratory that has the analytical capability to perform the analysis. A canister introductory system is connected to a gas chromatograph/mass spectrometer (GC/MS). The canister is attached to this sample introductory system. The laboratory analyzes a known volume from the canister and the compounds are focused on a trap. Then the effluent passes to the GC analytical column for separation and then detection by the MS detector. TO-15 has a fixed sample volume and can measure only VOCs in the boiling point range from C2 to C12.

EPA TO-17 uses sorbent tube sampling which can sample larger volumes; therefore, the detection limits are lower with TO-17 making it a more sensitive technique than TO-15. There are two sampling techniques: active (pumped) and passive (long-term). During active sampling, a known volume of air is pumped through the tube via time and flow. The tubes are shipped to a laboratory for analysis by inserting them into an automated thermal desorber (sample introductory system) that desorbs the sample onto a concentrator trap. The trap is then heated to releases the compounds bringing the effluent into the GC column for separation and then analysis by GC/MS. Thermal desorption has more flexibility in that it can be used for a broader sampling range of components both VOCs and SVOCs.[84] Depending on the sorbent tube, the boiling point range of compounds is from C2 to C40. TO-17 is more cost effective because tubes are smaller and lighter than other sampling media; therefore, shipping costs are less.

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[81] US Environmental Protection Agency. An Introduction to Indoor Air (IAQ): Volatile Organic Compounds (VOCs). Retrieved August 7, 2014, from http://www.epa.gov/iaq/voc.html.
[82] US Environmental Protection Agency. Compendium Method TO-15: Determination Of Volatile Organic Compounds (VOCs) In Air Collected In Specially-Prepared Canisters And Analyzed By Gas Chromatography/Mass Spectrometry (GC/MS).
[83] US Environmental Protection Agency. Compendium Method TO-17: Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling Onto Sorbent Tubes Center for Environmental Research Information.
[84] Provost, R., Marotta, L., Thomas, R. A Single-Method Approach for the Analysis of Volatile and Semivolatile Organic Compounds in Air Using Thermal Desorption Coupled with GC–MS. 2014. Chromatography Online. Retrieved October 24, 2014, from http://www.chromatographyonline.com/lcgc/article/articleDetail.jsp?id=856296.

Passive sampling is used for long-term average sampling. The uptake rate for passive sampling is significantly slower than what can be achieved in pumped sampling. Consequently, to attain the needed sensitivity, passive samples are usually taken for weeks to a month in addition to gathering long-term sampling information. The media for passive sampling are either sorbent tubes or badges used in industrial hygiene for instance Radielle tubes.

The EPA recently released a Method 325.[85] This method uses sorbent tube and thermal desorption (method TO-17) and focuses on petroleum sources of contamination. While primarily a method for outdoor use, these passive tubes can be used for indoor air and the uptake rates will be the same.

Air samples may also be collected in tedlar bags called grab samples. The sample volume is limited. After collection and shipment, TO-15 or TO-17 methodologies may be employed.

Finally, VOCs may also be analyzed by sensor technology. These technologies positively identify only a few compounds but provide a total organic compound analysis and can be used for screening purposes (Table 4).

Table 4: Comparison of Sensor Technology

	Product			
	PerkinElmer ELM	Aeroqual Series 930	Aeroqual SM70	Libelium waspmote
Target				
VOC	Yes	Yes	Yes	Yes
Specification on VOC in ppm (humidity)	50 - 2,000	1 - 500	1 - 500	40 - 400
Ozone	Yes	Yes	Yes	Yes
PM	Yes (PM10)*	Yes	Yes	Yes
Noise	Yes	No	No	Yes
Humidity	Yes	No	No	Yes
Temperature	Yes	No	No	Yes
NO2	Yes	Yes	No	Yes
Other gases	Yes	Yes	Yes	Yes
Support	Yes	Unknown	Unknown	Unknown
Price	$	$$$	Unknown	Unknown
Network	Standard	Optional	No	Standard

*Will have PM2.5 in next version of product

[85] See 79 FR 36880, 37046, retrieved October 21, 2014 from http://www.gpo.gov/fdsys/pkg/FR-2014-06-30/pdf/2014-12167.pdf.

Appendix I: Summary of Sampling and Analysis Procedures Used in Recent Studies of Affordable Housing Renovation Conducted by the National Center for Healthy Housing[86]

STUDY 1

The study will compare resident health parameters and environmental quality within affordable multifamily properties before and after substantial rehabilitations that meet the Enterprise Green Communities criteria. Our overall goal is to gather concrete evidence that integrating healthy building practices in the development and rehabilitation of affordable housing improves respiratory and other health outcomes for low-income people and also reduces health care costs.

The primary hypothesis is that green housing renovations complying with the Enterprise Green Communities criteria will reduce asthma-related health care utilization of resident children with asthma from baseline to one year after intervention, and this reduction will be greater for study group children than for control group children. Health care utilization will be measured principally by caregiver reports of the number of emergency department visits and unscheduled clinical care visits for asthma in the prior 12 months. The change in the number of hospitalizations for asthma in the prior 12 months will also be analyzed. The secondary hypothesis is that green housing renovations will improve the self-reported general physical (including asthma control, quality of life, and other metrics) and mental health of adult and child residents one year after intervention, and study group improvement will be greater than control group improvement.

Samples are collected for a 4-day period at pre-renovation, immediate post-renovation, and 1-year post-renovation.

1.2.1 Air Sampling Methods

1.2.1.1 Passive Sampling for Formaldehyde (UMEX 100)

The UMEX 100 Passive Samplers for formaldehyde contain a tape treated with 2,4-dinitrophenylhydrazine (DNPH) for reliable collection of formaldehyde. Samplers are provided in individual aluminized pouches that can be used to transport the sampler to a laboratory after sampling. The shelf-life date is printed on a label on the outside of each pouch. Samplers outside the shelf life shall not be used (nominal 12-month period). The UMEX 100 Sampler includes a clip for attachment to an appropriate location or ring stand for area sampling.

Remove the sampler from the pouch, record sampling information using the environmental sampling form (see Appendix), including sampler serial number, Study ID, and start and stop dates and times to the nearest second, and slide the cover to the “on” position. Place the sampler using the clip so that the screen is open to the air (do not lay it flat on a shelf).

[86] For specific questions on this Sampling and Analysis Procedure, or for more information on the National Center for Health Housing, see www.nchh.org or call (410) 992-0712.

When sampling is complete, slide the cover to the "off" position, place the sampler back in the pouch immediately, and seal. Analysis is completed with high-performance liquid chromatography. The UMEX 100 sampler is designed for single use only and cannot be reused. See Table 4 for refrigeration and sample shipping requirements.

Laboratory analysis is completed in accordance with International Standard for Determination of Formaldehyde—Diffusive Sampling Method (ISO/FDIS 16000-2004) or equivalent. With this method, formaldehyde vapor diffuses into the sampler and is collected on silica gel filter paper that has been treated with 2,4-Dinitrophenylhydrazine (DNPH) with a phosphoric acid stabilizer. A stable hydrazone is formed, which is desorbed with acetonitrile and analyzed by HPLC with ultraviolet (UV) detector. Refrigeration requirements for all sampling devices are provided below in the Quality Assurance section. Accuracy is 5 ppb to 5 ppm ± 25 percent, which exceeds OSHA requirements.

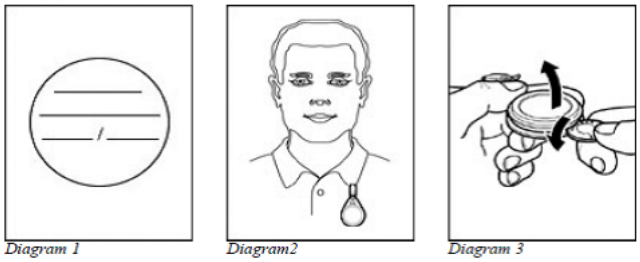


Diagram 1

Diagram2

Diagram 3


Diagram 4


Diagram 5

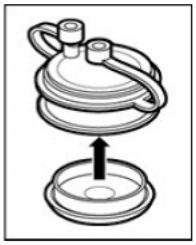


Diagram 6

1.2.1.2 Passive Sampling for Total VOCs (3M 3520 Badge)

1. Remove the badge from the sealed can (Diagram 1).
2. Record the following information on the environmental sampling form (see Appendix): badge serial number, study sampler number, sampling start and stop times should be recorded on both the badge label and field form. DO NOT REMOVE WHITE FILM AND PLASTIC RING.
3. Hang badge away from walls, corners, tabletops, or other regions where the air movement in the room may be limited. (Note: Diagram 2 is not used for this study.)
4. After sampling period is ended, remove plastic ring and white film from the badge (Diagram 3).
5. Separate the primary body and secondary body sections. Snap the bottom cup (no plugs) into the bottom of the primary section (diagrams 4, 5, and 6). Snap elution cap on the secondary body. Monitor is now ready for shipment. (Note: Check to make sure the primary and secondary sections have the same identification numbers.)
6. Return badge to can and close with plastic lid provided.

View this video to understand how to use the VOC sampler: http://www.youtube.com/watch?v=MrmPiCVZPBQ

Laboratory analysis is completed using EPA Method TO-15, with total VOCs reported as hexane equivalents. Refrigeration and shipping requirements are provided in the Quality Assurance Section.

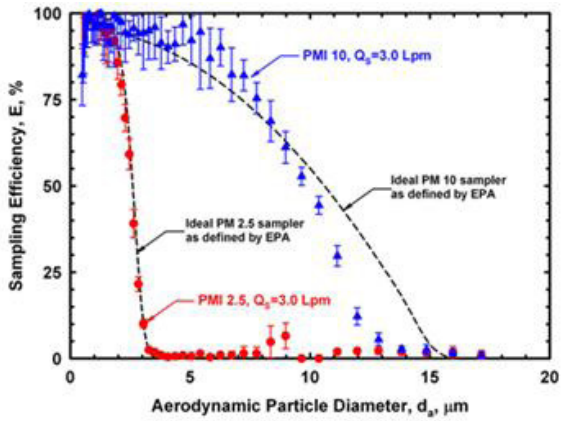
Passive Sampling for NO2 (UMEX 200)

The single-use SKC UMEX 200 Passive Sampler collects NO2 using a sample medium with a tape treated with triethanolamine (TEA). Samplers are provided in individual aluminized pouches that can be used to transport the sampler to a laboratory. The label on the outside of each pouch contains the shelf-life date and has an 18-month shelf life and shall not be used if outside the shelf life. Refrigeration requirements are provided in the QC section below.

Remove the sampler from the pouch, record sampling information (including sampler serial number) on the environmental sampling form (see Appendix), Study ID, and start and stop dates and times to the nearest minute, and slide the cover to the "on" or sampling position. When sampling is complete, slide the cover to the "off" position, place the sampler back in the pouch immediately, and seal. Send the sampler and the completed chain of custody to the laboratory for analysis by solvent extraction ion chromatography (IC) with conductivity detection.

1.2.1.3 Active Sampling for PM2.5 (Personal Modular Impactor (PMI))

The patented (U.S. Patent No. 7,334,453) SKC Single-stage Personal Modular Impactors (PMIs) are designed for the highly efficient collection of PM10, PM2.5, or PM Coarse (10-2.5). For this study, only PM2.5 will be measured. The samplers have a removable filter cassette and pre-oiled impaction disc. The PMI media changes are done by removing the filter cassette and replacing it with one already loaded with a 37-mm final filter; for this study, filter loading will be done in the laboratory. The 25-mm pre-oiled impaction disc mounts directly on top of the filter cassette and reduces particle bounce for high collection efficiency.



Collection Efficiency of PMI 2.5 and PMI 10 Samplers

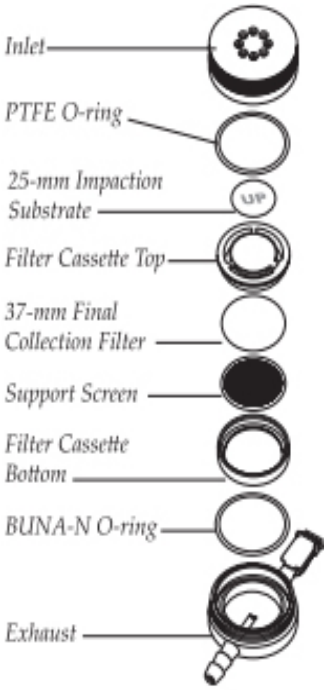


Figure 1. PMI 2.5 exploded

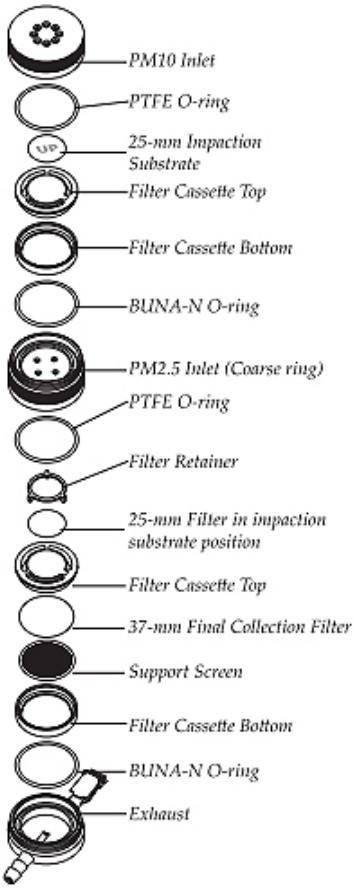


Figure 2. PMI Coarse exploded

Performance Profile

Flow Rate	3 L/min for all models
50% Cut-point	10 µm or 2.5 µm (model dependant)
Material	**Inlet:** Precision-tooled aluminum
	Exhaust: PVC
	Filter Cassette: Delrin® with stainless steel support screen
	O-ring: Inlet — PTFE **O-ring:** Exhaust — BUNA-N
Final Collection Filter	37-mm filter, select filter material based on application
Impaction Subsrtate	25-mm pre-oiled, disposable porous plastic disc to reduce particle bounce or 25-mm filter for optional chemical analysis
Analyses	Gravimetric and chemical
Dimensions (without clip)	**Diameter:** 2 in (5.1 cm)
	Height: 1 in (2.6 cm)
	Weight: 2.5 oz (70.9 gm)
Tubing	1/4-inch ID

For this study, all PMIs will be prepared and pre-weighed in the laboratory, not the field. Field personnel will attach the PMI to an air-sampling pump supplied by the lab using Tygon tubing. Pumps will be operated at a nominal flow rate of 3.0 liters/minute. Pump flow rate will be measured prior to sampling using a laboratory-supplied rotameter (which has been calibrated against a primary standard) recorded to the nearest 0.1 liters/minute. At the end of the sampling period but before turning off the pump, record the flow rate using the rotameter on the pump. Use the top of the ball to read the flowrate. The laboratory will calculate the average flow rate in reporting its analytical results. Sampling personnel shall enter the start and stop times to the nearest minute and designate AM or PM. Place the PMI sampler into a ziplock plastic baggie and label with the study ID as specified above. Record the pump number, PMI serial number and other data specified on the electronic environmental sampling form.

1.2.2 Allergens in Settled Dust

Five allergens will be measured in settled dust using 5-Plex Multiplex Array for Indoor Allergens (MARIA®) methodology: dust mite allergens Der p 1 and Der f1; cat allergen Fel d 1; cockroach allergen Bla g 2; mouse allergen Mus m 1. Two separate allergen samples will be collected from the floors of each of two rooms: one from the youngest index child's bedroom and the second from the living room floor (n=2 total samples).

The Eureka Mighty Mite (EMM) (model 3670, Electrolux Home Care Products, Inc., Peoria, IL) or equivalent catches dust in a Whatman cellulose extraction thimble (Whatman International Ltd., Maidstone, UK), part of the DUSTREAM™ Collector (Indoor Biotechnologies, Inc., Charlottesville, VA). After collection, the extraction thimble is immediately placed in a 76x20 mm tube with cap (Sarstedt Aktiengeselischaft and Co.). Record the Study ID and sample number on the shipment tube and on the field sampling form. The allergen sampling protocol is based on HUD's Office of Healthy Homes and Lead Hazard Control "Vacuum Dust Sample Collection Protocol for Allergens," Version 2.0 (May 2008), available at this link: http://portal.hud.gov/hudportal/documents/huddoc?id=DOC_12539.pdf.

Laboratory sample preparation and analysis details are at these links, respectively:
http://inbio.com/US/images/pdfs/Sample_Extraction_Procedure.pdf
http://inbio.com/US/images/pdfs/MRA-P8_CoA.pdf

STUDY 2

The study will determine the resident health and environmental impacts of two randomly assigned residential ventilation protocols, the more typically used standard, ASHRAE 62-1989, and the more recent standard, ASHRAE 62.2. Under ASHRAE 62-1989, a Building Tightness Limit (BTL) is determined from characteristics of the house and occupancy, and air-tightening efforts are directed towards not tightening below the BTL. Under ASHRAE 62.2, air-tightening efforts are directed to continue as far as technically feasible, and mechanical ventilation is provided to meet the requirements of the standard. The ventilation modifications will be included as part of weatherization work performed in low-income housing. The air exchange standards of ASHRAE 62-1989 are more typically used in

standard weatherization assistance interventions and will be performed in Control Group dwellings, while dwellings randomly assigned to the ASHRAE 62.2 group (Study Group) will have alternative ventilation interventions performed in accordance with the newer standard.

1.1.1 IAQ Sampling

Air sampling for formaldehyde and Volatile Organic Compounds (VOCs) as well as placement of radon charcoal canisters will be done for one-week periods both before and after installation of weatherization measures. The sampling instruments and analytical methods are described in Table 5, below:

Table 5. Sampling and Analytical Methods

	Output	Number	Instrument	Source
VOC	Average value	180	VOC Passive Ultra I	http://www.skcinc.com/passive.asp
HCHO	Average value	180	UMEX-100	http://gasdetectors.conceptcontrols.com/
CO	Time series	12	LASCAR-EL-USB-CO	http://www.lascarelectronics.com/temperaturedatalogger.php?datalogger=104
CO2	Time series	12	Telaire 7001 + U12	http://www.onsetcomp.com/products/sensors/tel-7001
T/RH	Time series	48	LASCAR-EL-USB-2	http://www.lascarelectronics.com/temperaturedatalogger.php?datalogger=102
Rn-charcoal	Average Value	180	EPA charcoal canister	US EPA lab, Las Vegas NV
Rn-cont	Time series	12	Radstar RS300	http://www.4radon.com/rarscoragasm.html

Sampling for VOCs and formaldehyde (HCHO) is done using badges (passive air samplers). Following exposure, the badges are sent to an AIHA accredited laboratory for analysis using method EPA TO-17. Radon canisters will be analyzed by the EPA lab in Las Vegas.

Sample Locations

- Continuous radon monitors and charcoal canisters will be located on the lowest living level. In any zone that may be occupied (including basements) the instruments will be located at breathing zone height and away from exterior walls and doors, and away from vents. Test kits will be placed to minimize the risk of occupant interference, and will be identified to residents with instructions to avoid disruption.
- Formaldehyde and VOC Badges will be exposed in the living room.

IAQ Sampling Materials and Supplies

- Sampling Equipment listed in Table 5
- Lab chain-of-custody form
- IAQ Sampling Form
- Non-sterilized non-powdered disposable gloves (vinyl or latex)
- Permanent ink pen
- Trash bags
- Ziploc bags

1.1 ANALYTICAL METHODS

1.1.1 Single-Use IAQ Samplers

Single-use IAQ VOC and formaldehyde samplers will be analyzed by laboratories accredited by the American Industrial Hygiene Association.

The per-house results of single-use IAQ (VOC and HCHO) samplers will be analyzed as simple differences between pre- and post-weatherization with adjustments for indoor-outdoor temperature difference as appropriate. Because an individual house may have changes in sources that cannot be controlled, such as new furnishings that contain formaldehyde, the distribution of these results will be compared between control and treatment group homes using standard statistical methods.

For charcoal canister radon measurements, additional adjustments will be made to reflect temporal and seasonal variations as measured with the continuous radon monitors, and the difference between pre- and post-weatherization results will be analyzed for statistical significance relative to these differences.

These differences will all be analyzed for correlation to weatherization measures, including ventilation, overall air sealing, and air sealing at certain building boundaries such as between the house and a crawl space.

STUDY 3

The general study hypothesis is that green healthy housing rehabilitation of public housing occupied by elders improves their health status. The goal of this study is to characterize those occupant health factors that can be related to housing undergoing green rehabilitation over a one-year time period in multifamily housing.

Hypothesis: Pre-renovation levels of CO, CO2, allergens, TVOC, and formaldehyde in a subset of enrolled units are significantly higher than post-renovation levels.

2.1.1 Environmental Sample Collection

In a convenience sample of 21 non-smoking units from the first set of units enrolled in the study, CSBR will collect environmental samples for the following analytes using the methods listed below:

- Temperature, Humidity, CO2 (a marker of fresh air) and CO (a marker of inadequate venting of combustion appliances): HOBO dataloggers. The purpose of this monitoring is to determine if adequate ventilation is occurring within the units. CSBR will begin tracking temperature, relative humidity, CO2, and CO by placing dataloggers in 21 enrolled, nonsmoking units for an approximate one month period before renovation begins in their part of the building. CSBR will remove the dataloggers prior to renovation and reinstall them immediately after renovation is complete. The re-installed dataloggers will remain in place for approximately one year, with data downloaded electronically on a quarterly basis.

- Total Volatile Organic Chemicals (TVOCs): 3M 3500 Organic Vapor Monitors (passive diffusion monitors). CSBR will collect a 3-day sample from each of the 21 units once at pre-renovation, once immediately post-renovation, and once at one-year post-renovation.
- Formaldehyde: 3M 3720 Formaldehyde passive monitoring badge with accuracy ± 10% and detection limit of 0.000242 ppm. CSBR will collect a 3-day sample from each of the 21 units once at pre-renovation, once immediately post-renovation, and once at one-year post-renovation.
- Allergens: Settled dust vacuum sampling on floors using guidance provided in HUD's Office of Healthy Homes and Lead Hazard Control "Vacuum Dust Sample Collection Protocol for Allergens," Version 1.0 (April 2004). CSBR will collect one dust vacuum sample from each of the 21 units, once at pre-renovation and once at one-year post-renovation.

2.1.2 TVOCs

CSBR will collect total volatile organic compound (TVOC) data using 3M 3500 Organic Vapor Monitors (a passive diffusion monitor) with an exposure time of three days or approximately 72 hours, with data collection done at pre-renovation, immediate post-intervention and one-year post-intervention to evaluate changes in these gases over time. CSBR will place one TVOC monitor in the kitchen in a location open to the room but out of the way of cooking and other resident disturbances. When the three-day sample period is complete, CSBR will remove the badge from the sampling location and place it in Ziploc bag labeled with the Unit ID and Sample ID.

2.1.3 Formaldehyde

CSBR will collect formaldehyde data using a passive diffusion monitor with an exposure time of three days or approximately 72 hours, with data collection done at pre-renovation, immediate post-intervention and one-year post-intervention to evaluate changes in these gases over time. CSBR will place one formaldehyde monitor in the kitchen in a location open to the room but out of the way of cooking and other resident disturbances. When the three-day sample period is complete, CSBR will remove the badge from the sampling location and place it in Ziploc bag labeled with the Unit ID and Sample ID.

2.1.4 Allergens

This protocol provides for measurement of settled allergens on floor surfaces where children may play. It is not intended to determine compliance with any existing regulations or to determine if allergen cleanup is needed. These methods were developed in accordance with the guidance provided in HUD's Office of Healthy Homes and Lead Hazard Control "Vacuum Dust Sample Collection Protocol for Allergens," Version 1.0 (April, 2004).

Allergen Sample Collection Materials

- Powderless vinyl gloves (appropriate size for technician)
- Wet wipes to be used for decontaminating equipment and wiping hands when necessary
- Tape measure showing units in inches
- Trash bags

- Masking tape-must be painter's tape
- Pen/clipboard
- Permanent marker
- Timing device/watch
- Extension cord (25 feet) with 2-prong adapter and plug strip
- Temperature/relative humidity gauge
- Allergen Dust Sampling Form
- Sketch
- Chain of custody form
- Cooler containing blue ice or equivalent to keep samples cold while in field (no ice cubes)
- Clean DustreamTM collectors (nozzles) stored in resealable Ziploc bag (three per dwelling). Filter collection device (DustreamTM filters), each packaged in screw top centrifuge tubes with pre-marked sample label. Write the sample ID on the dust filter and on outside of the centrifuge tube. Label each sample with an "A" (for "allergen") followed by the sample number. Label the kitchen floor sample "A1," and the bedroom as "A2."
- Vacuum and vacuum supplies:
  — Plug-in, portable vacuum cleaner (2) fitted with new clean vacuum bag.
  — Vacuum bags

General Rules

- Do not begin to collect allergen samples until potential participant has signed an informed consent.
- Do not sample under large furniture or refrigerators.
- Move small throw rugs if needed.
- Sample only one surface type (i.e., bare floor or carpet) in each room, preferably carpet.
- Avoid vacuuming wet or damp areas or collecting moist materials.
- Attempt to remove all dust in the sampling area.
- Hold the collector pointing upwards before turning off the vacuum to avoid dust dropping out of filter. Do not shake the hose or sample may be lost.
- Bulky debris in the sampling area will quickly fill the dust filters; therefore, in locations having a large quantity of visible debris (e.g., paint chips, trash, etc.), remove debris by gloved hand before vacuuming. Do not remove bulky debris by vacuuming.

Identification of Rooms and Floor Areas to be Sampled

Room Identification. One sample will be collected from the kitchen (K) and one from the bedroom (BR). Record these rooms on the Sketch. During the baseline and one-year post-renovation visits, collect one vacuum sample each from the floor of the kitchen and bedroom, sampling non-carpeted rooms prior to carpeted rooms.

Floor Surface Type and Condition. Identify the predominant surface type in each room and record it on the Allergen Dust Sampling Form. "Predominant" is defined as follows: if more of the floor is bare, then consider the surface type to be "bare" and sample the non-carpeted area. If more than 50% of the floor is carpeted or covered with an area rug, then consider the surface type to be carpeted and sample the carpeted area. For each room, record on

Allergen Dust Sampling Form the surface type and the condition of the floor surface to be sampled. For carpets, "not cleanable" is defined as very matted, soiled, old, worn carpet, while "cleanable" is defined as unsoiled, new carpet, with few if any worn or matted spots.

Outline of Floor Area to be Sampled in Each Room. At the baseline visit, choose the following floor area to be sampled in each room:

- **Kitchen:** You will not need to mark a taped outline of the kitchen sampling area because you will vacuum the entire perimeter of the kitchen (i.e., along the base of walls, appliances cabinets, etc.).
- **Bedroom:**
  — *Carpeted Floor*: On the carpeted floor below the bed, use painter's tape to outline a roughly rectangular section, approximately 12 inches by 36 inches (1 foot by 3 feet, or a total of 3 ft2) along the long side of the bed, making sure that about one quarter of the outline is underneath the bed.
  — *Bare Floor*: Because bare floors are expected to have less dust, sample a larger area to ensure you collect enough dust to be analyzed. On the bare floor below the bed, outline a roughly rectangular section, approximately 2 by 5, with the longest length following the length of the bed, and with about one quarter of the outline is underneath the bed. If needed to get enough dust, mark another sample location along a second length of the same bed, and collect dust into the same Dustream collector used for the first side of the bed.

Place masking tape to mark each rectangular area to be sampled. Avoid walking inside the area while marking it off and once you finished marking it.

On the one-year post-renovation visit, to the extent possible, collect the sample from the same floor location sampled at the baseline visit, collecting dust from approximately the same surface area (i.e., same length and width).

Vacuum Sampling Procedures

Collect single surface allergen dust vacuum samples systematically to allow results from different visits to be compared. At the one-year post-renovation visit, collect the sample from the same rooms that were sampled at the baseline visit and from the same general floor location, collecting the sample from approximately the same surface area that was sampled at baseline.

Initial Set-Up of the Vacuum Sampler. Plug in vacuum and make sure the cord will reach the vacuum area. Use an extension cord if necessary. If you must unplug an existing electrical cord in order to plug in the vacuum, avoid unplugging clocks, computers, etc., and plug items back in once you finish sampling. Obtain the resident's permission.
Insert the nylon filter into the Dustream collector and attach the collector to the vacuum cleaner tube. If the collector does not fit the vacuum cleaner tube, attach the adaptor piece to the collector. Use the side of the adaptor that best fits the vacuum cleaner. Use blue painter's tape if needed to ensure that the nozzle will not come off during sampling.

Vacuum Procedure for Floor

1. With the hose in a vertical position pointing up and the Dustream collector pointed upwards, turn the vacuum on and check that the filter is tightly fitted.
2. Placing the Dustream collector in the upper corner of the marked area, press down firmly, but not excessively, holding the long tip of the collector in firm contact with the surface to be vacuumed. On bare floors, do not place the whole face of the collector onto the floor surface because you will not be able to collect dust into the filter.

Bedroom:

- *Carpeted Floors:* Proceed to vacuum the marked area using a side-to-side motion along the width (short side) of the outline area. Collect the sample for approximately 2 minutes for 3 ft2. If the carpeted floor is dusty, you may need to periodically turn off the vacuum and let the vacuum cool off before collecting more sample into the same filter. If the filter becomes full before you are done sampling the entire outlined area, remove and cap the used filter and place it into a centrifuge tube that has been labeled with the Unit ID, Room ID, and the Sample ID. Place another clean filter into the collector and finish sampling the outlined area. Place the second filter into the SAME centrifuge tube with the first filter. If the centrifuge tube is too small to hold two filters place the second filter in another centrifuge tube with the same labeling as the first. Place all centrifuge tubes with dust samples from the same location in a marked Ziploc bag. Make sure that the lab knows to extract both filters as a SINGLE SAMPLE.
- *Bare Floors:* Dust from this marked area will be collected into a single dust filter. Collect the sample for approximately 6 minutes for 9 ft2. If the floor is dusty, you may need to periodically turn off the vacuum and let the vacuum cool off before collecting more sample into the same filter. Do not make a special effort to sample the crevices between floorboards.

Kitchen: In the kitchen, sample the entire perimeter of the kitchen (i.e., along the base of walls, appliances, and cabinets) where pests are more likely to walk. Do not move appliances to vacuum behind or between them. Press one edge of the nozzle against the wall/appliance. Do not sample inside cabinets or underneath refrigerators and other appliances. Perform sampling for a minimum of 5 minutes. You will need to measure the perimeter of the floor area sampled (including all turns) to the nearest inch. This measurement will constitute the length sampled. The width of the nozzle constitutes the width of the area sampled-this should always be recorded as ***7/8 inch (0.875 inch)***.

3. Once the sample collection is complete, hold the collector in an upright position and turn off the vacuum. Remove the filter containing the dust sample, put a cap on it, and place it in a centrifuge tube that has been labeled with the Unit ID, Room ID, and Sample ID. Place the used Dustream collector into a plastic bag labeled “dirty” (not with the clean collectors) until you can clean it. Estimate the approximate length and width sampled in feet to the nearest inch and record these measurements on the Allergen Dust Sampling Form.
4. Repeat steps 1 through 3 in the next room to be sampled, using a new, clean Dustream collector and new filter.
5. Once both rooms have been sampled in a dwelling, place the two sample collections with all, labeled centrifuge tubes into one large Ziploc bag and label the large bag with the Participant ID. Place large bag into cooler until you return to the office.

2.2 ANALYTICAL METHODS

2.2.1 TVOCs and Formaldehyde

For TVOCs, Braun Intertec will analyze the samples by gas chromatography according to 3M methods. Results will be reported as total hydrocarbons as hexane with an accuracy of +/- 15% and a detection limit of 0.029 ppm.

For formaldehyde, Braun Intertec will analyze the samples by gas chromatography according to 3M methods. Accuracy is +/- 10% with a detection limit of 0.00242 ppm.
Braun Intertec is an AIHA Industrial Hygiene accredited laboratory (AIHA #101103).

2.2.2 Allergens

Indoor Biotechnologies will conduct analysis of the dust vacuum samples by Multiplex Array for Indoor Allergens (MARIA) for five allergens: der f1, der p1, bla g2, mus m1, and rat n1.

No federal or state laboratory accreditation is required for the measurement of indoor allergens since it is an environmental measurement that is not regulated by CDC. Turnaround time for laboratory analysis will depend on the number of specimens received in a given batch but will generally be 2 weeks from the date of receipt if the sample does not need to be analyzed repeatedly because its concentration exceeds the working range of the assay. The MARIA analytical method combines allergen-specific monoclonal antibodies with Luminex xMAPR technology.

STUDY 4

This study will determine if low-cost, simple retrofit activities reduce radon exposures in different types of housing in two different climate zones in areas with high radon levels, as well as quantify any benefit regarding moisture.

Radon measurement methods and protocols will comply with Illinois regulation as defined in 32 Illinois Administrative Code. Measurements made in New Hampshire, where radon is not regulated, will follow the same methods and protocols as in Illinois. Radon samples are collected at 3 phases: pre-weatherization, immediate post-weatherization, and 1-year post-weatherization.

The instruments to be used in this study for measurement of average radon concentration are Electret ion chamber instruments from Radelec, Inc. (radelec.com). These consist of a Teflon plate initially charged to approximately 750V. The plate is placed in a chamber which is closed except during the time of exposure. Ionization due to radon decay leads to a reduction in the electret charge. The instrumentation units selected for this research are short-term (ST) electrets in small (L-00, 53 ml) chambers.

UIUC will purchase electrets and chambers from Radelec, to be sent directly to UIUC. Illinois Licensed Measurement Professionals at UIUC will conduct voltage readings using a SPER-1E electret voltage reader, to be purchased from Radelec, Inc. Voltage readings from the voltage

reader will be converted to average radon concentrations using the software provided by Radelec, or the appropriate functions.

In each home at each sampling phase, one instrument set will be placed in the primary living space and another in the basements of homes with basements, in compliance with instrumentation placement protocols from IAC Section 422.130. The instruments will be left in place from 14 to 21 days.

The instruments will be deployed and retrieved either by the researchers or by agency personnel trained in placement and retrieval. The time and date of exposure and closure will be recorded. Samplers will be shipped to UIUC within one week of retrieval. The Chain of Custody form (Appendix C) will be used in all sample shipments; paper forms will be maintained at NCHH and electronic scans of those forms will be posted to the secure UIUC Box.com site. A shipping account will be established with an appropriate carrier. Pre-addressed labels will be used for all shipments.

Appendix II: Selected Contacts for Technical Assistance

1) **American Industrial Hygiene Association (AIHA)**
3141 Fairview Park Dr.
Suite 777
Falls Church, VA 22042
703-849-8888
https://www.aiha.org/
Directory of Certified Indoor Air Testing Laboratories: https://www.aiha.org/publications-and-resources/buyers-guide/Pages/Indoor-Air-Quality.aspx

2) **Underwriters Laboratories, Air Quality Sciences (UL AQS)**
847-664-2040
http://newscience.ul.com/indoorairquality

Marilyn S. Black, Ph.D., and LEED AP
President and Founder, UL AQS
Marilyn.Black@ul.com

Elliott Horner, Ph.D., LEED AP and FAAAAI
Principal Scientist
Elliott.Horner@ul.com

3) **The American Academy of Allergy, Asthma & Immunology**
555 East Wells Street
Suite 1100
Milwaukee, WI 53202-3823
414-272-6071
http://www.aaaai.org/conditions-and-treatments/library/at-a-glance/indoor-allergens.aspx
http://www.aaaai.org/conditions-and-treatments/allergies/mold-allergy.aspx

Appendix III: Selected Contacts for Local Governments and Community Organizations

1) **National Center for Healthy Housing**
10320 Little Patuxent Parkway
Suite 500
Columbia, MD 21044
410-992-0712 or 877-312-3046
http://nchh.org/Home.aspx

2) **National Association of Clean Air Agencies**
444 N. Capitol Street, NW
Suite 307
Washington, DC 20001
202-624-7864
4cleanair@4cleanair.org
http://www.4cleanair.org/
Listing of State and Local Air Agencies: http://www.4cleanair.org/agencies

3) **Alameda County Health Homes** (Alameda County, CA)
2000 Embarcadero
Suite 300
Oakland, CA 94606
510-567-8280
http://www.achhd.org/

4) **Ashland-Boyd County Health Department** (Kentucky)
P.O. Box 4069
Ashland, KY 41105
606-329-9444

5) **Building Performance Center** (Washington, Alaska, Oregon, Idaho)
3406 Redwood Ave.
Bellingham, WA 98225
360-734-5121 ext. 114
http://www.buildingperformancecenter.org/services-2/environmental-investigation/

6) **Children's Mercy Hospitals and Clinics** (Missouri)
2401 Gillham Road
Kansas City, MO 64108
816-960-8919
http://www.childrensmercy.org/Patients_and_Families/Support_and_Services/Environmental_Health/Healthy_Home_Program/

7) **City of Houston Department of Health and Human Services** (Texas)
8000 North Stadium Drive
2nd Floor
Houston, TX 77054
832-393-5141
http://www.houstontx.gov/health/Environmental/healthy_homes.html

8) **City of San Diego Environmental Services Dept/Energy, Sustainability & Environmental Protection Division**
9601 Ridgehaven Court
Suite 310
San Diego, CA 92123
858-694-7000
http://www.sandiego.gov/environmental-services/ep/leadsafety/sdhhc.shtml

9) **Florida Department of Health**
4052 Bald Cypress Way, Bin #A08
Tallahassee, FL 32399
850-245-4444 ext. 2204
http://www.floridahealth.gov/environmental-health/lead-poisoning/

10) **Michigan Department of Community Health**
Healthy Homes Section
P.O. Box 30195
Lansing, MI 48909
517-335-9390
Toll-free (866) 691-LEAD (5323)
http://www.michigan.gov/mdch/0,1607,7-132-2940_2955_2983-19366--,00.html#HHS

11) **Georgia Department of Public Health**
2 Peachtree St. N.W., Ste. 13-464
Atlanta, GA 30303
404-463-2619
http://dph.georgia.gov/lead-and-healthy-homes

12) **Kansas City, MO Health Department**
2400 Troost Ave.
Suite 3300
Kansas City, MO 64108
816-513-6008
http://kcmo.gov/health/childhood-lead-poisoning-prevention-and-healthy-homes-program/

13) **Kansas Department of Health and the Environment, Healthy Homes & Lead Hazard Prevention Program**
1000 SW Jackson Street
Suite 330
Topeka, KS 66612
866-865-3233
http://www.kshealthyhomes.org/

14) **Kenosha County Division of Health** (Wisconsin)
8600 Sheridan Road
Suite 600
Kenosha, WI 53143
262-605-6741
http://www.healthyhomespartnership.com/

15) **Los Angeles County Department of Public Health**
5555 Ferguson Drive
Ste 210-02
Commerce, CA 90022
800-LA-4-LEAD (5323)
http://www.publichealth.lacounty.gov/eh/TEA/Lead_Programs/lead_main.htm

16) **Marion County Health Department - Lead Safe and Healthy Homes Department** (Indiana)
3838 N. Rural St.
Indianapolis, IN 46205
317-221-2266
http://www.mchd.com/ia.htm

17) **New Jersey Department of Health and Senior Services**
PO Box 360
369 South Warren Street
Trenton, NJ 08608
609-826-4950
http://www.state.nj.us/health/iep/index.shtml

Association of Public Health Laboratories

The Association of Public Health Laboratories (APHL) is a national nonprofit dedicated to working with members to strengthen laboratories with a public health mandate. By promoting effective programs and public policy, APHL strives to provide public health laboratories with the resources and infrastructure needed to protect the health of US residents and to prevent and control disease globally.

8515 Georgia Avenue, Suite 700
Silver Spring, MD 20910
Phone: 240.485.2745
Fax: 240.485.2700
Web: www.aphl.org

U.S. Department of Health and Human Services

U.S. Department of Housing and Urban Development

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Additional copies of this manual can be downloaded from www.cdc.gov/healthyhomes/publications.html

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Chapter 5: Indoor Air Pollutants and Toxic Materials

"Walking into a modern building can sometimes be compared to placing your head inside a plastic bag that is filled with toxic fumes."

John Bower
Founder, *Healthy House Institute*

Introduction

We all face a variety of risks to our health as we go about our day-to-day lives. Driving in cars, flying in airplanes, engaging in recreational activities, and being exposed to environmental pollutants all pose varying degrees of risk. Some risks are simply unavoidable. Some we choose to accept because to do otherwise would restrict our ability to lead our lives the way we want. Some are risks we might decide to avoid if we had the opportunity to make informed choices. Indoor air pollution and exposure to hazardous substances in the home are risks we can do something about.

In the last several years, a growing body of scientific evidence has indicated that the air within homes and other buildings can be more seriously polluted than the outdoor air in even the largest and most industrialized cities. Other research indicates that people spend approximately 90% of their time indoors. Thus, for many people, the risks to health from exposure to indoor air pollution may be greater than risks from outdoor pollution.

In addition, people exposed to indoor air pollutants for the longest periods are often those most susceptible to their effects. Such groups include the young, the elderly, and the chronically ill, especially those suffering from respiratory or cardiovascular disease [1].

Indoor Air Pollution

Numerous forms of indoor air pollution are possible in the modern home. Air pollutant levels in the home increase if not enough outdoor air is brought in to dilute emissions from indoor sources and to carry indoor air pollutants out of the home. In addition, high temperature and humidity levels can increase the concentration of some pollutants. Indoor pollutants can be placed into two groups, biologic and chemical.

Biologic Pollutants

Biologic pollutants include bacteria, molds, viruses, animal dander, cat saliva, dust mites, cockroaches, and pollen. These biologic pollutants can be related to some serious health effects. Some biologic pollutants, such as measles, chickenpox, and influenza are transmitted through the air. However, the first two are now preventable with vaccines. Influenza virus transmission, although vaccines have been developed, still remains of concern in crowded indoor conditions and can be affected by ventilation levels in the home.

Common pollutants, such as pollen, originate from plants and can elicit symptoms such as sneezing, watery eyes, coughing, shortness of breath, dizziness, lethargy, fever, and digestive problems. Allergic reactions are the result of repeated exposure and immunologic sensitization to particular biologic allergens.

Although pollen allergies can be bothersome, asthmatic responses to pollutants can be life threatening. Asthma is a chronic disease of the airways that causes recurrent and distressing episodes of wheezing, breathlessness, chest tightness, and coughing [2]. Asthma can be broken down into two groups based on the causes of an attack: extrinsic (allergic) and intrinsic (nonallergic). Most people with asthma do not fall neatly into either type, but somewhere in between, displaying characteristics of both classifications. Extrinsic asthma has a known cause, such as allergies to dust mites, various pollens, grass or weeds, or pet danders. Individuals with extrinsic asthma produce an excess amount of antibodies when exposed to triggers. Intrinsic asthma has a known cause, but the connection between the cause and the symptoms is not clearly understood. There is no antibody hypersensitivity in intrinsic asthma. Intrinsic asthma usually starts in adulthood without a strong family history of asthma. Some of the known triggers of intrinsic asthma are infections, such as cold and flu viruses, exercise and cold air, industrial and occupational pollutants, food additives and preservatives, drugs such as aspirin, and emotional stress. Asthma is more common in children than in adults, with nearly 1 of every 13 school-age children having asthma [3]. Low-income African-Americans and certain Hispanic populations suffer disproportionately, with urban inner cities having particularly severe problems. The impact on neighborhoods, school systems, and health care facilities from asthma is severe because one-third of all pediatric emergency room visits are due to asthma, and it is the fourth most prominent cause of physician office visits. Additionally, it is the leading cause of school absenteeism—14 million school days lost each year—from chronic illness [4]. The U.S. population, on the average,

spends as much as 90% of its time indoors. Consquently, allergens and irritants from the indoor environment may play a significant role in triggering asthma episodes. A number of indoor environmental asthma triggers are biologic pollutants. These can include rodents (discussed in Chapter 4), cockroaches, mites, and mold.

Cockroaches

The droppings, body parts, and saliva of cockroaches can be asthma triggers. Cockroaches are commonly found in crowded cities and in the southern United States. Allergens contained in the feces and saliva of cockroaches can cause allergic reactions or trigger asthma symptoms. A national study by Crain et al. [5] of 994 inner-city allergic children from seven U.S. cities revealed that cockroaches were reported in 58% of the homes. The Community Environmental Health Resource Center reports that cockroach debris, such as body parts and old shells, trigger asthma attacks in individuals who are sensitized to cockroach allergen [6]. Special attention to cleaning must be a priority after eliminating the presence of cockroaches to get rid of the presence of any allergens left that can be asthma triggers.

House Dust Mites

Another group of arthropods linked to asthma is house dust mites. In 1921, a link was suggested between asthmatic symptoms and house dust, but it was not until 1964 that investigators suggested that a mite could be responsible. Further investigation linked a number of mite species to the allergen response and revealed that humid homes have more mites and, subsequently, more allergens. In addition, researchers established that fecal pellets deposited by the mites accumulated in home fabrics and could become airborne via domestic activities such as vacuuming and dusting, resulting in inhalation by the inhabitants of the home. House dust mites are distributed worldwide, with a minimum of 13 species identified from house dust. The two most common in the United States are the North American house dust mite (*Dermatophagoides farinae*) and the European house dust mite (*D. pteronyssinus*). According to Lyon [7], house dust mites thrive in homes that provide a source of food and shelter and adequate humidity. Mites prefer relative humidity levels of 70% to 80% and temperatures of 75°F to 80°F (24°C to 27°C). Most mites are found in bedrooms in bedding, where they spend up to a third of their lives. A typical used mattress may have from 100,000 to 10 million mites in it. In addition, carpeted floors, especially long, loose pile carpet, provide a microhabitat for the accumulation of food and moisture for the mite, and also provide protection from removal by vacuuming. The house dust mite's favorite food is human dander (skin flakes), which are shed at a rate of approximately 0.20 ounces per week.

A good microscope and a trained observer are imperative in detecting mites. House dust mites also can be detected using diagnostic tests that measure the presence and infestation level of mites by combining dust samples collected from various places inside the home with indicator reagents [7]. Assuming the presence of mites, the precautions listed below should be taken if people with asthma are present in the home:

- Use synthetic rather than feather and down pillows.
- Use an approved allergen barrier cover to enclose the top and sides of mattresses and pillows and the base of the bed.
- Use a damp cloth to dust the plastic mattress cover daily.
- Change bedding and vacuum the bed base and mattress weekly.
- Use nylon or cotton cellulose blankets rather than wool blankets.
- Use hot (120°F–130°F [49°C–54°C]) water to wash all bedding, as well as room curtains.
- Eliminate or reduce fabric wall hangings, curtains, and drapes.
- Use wood, tile, linoleum, or vinyl floor covering rather than carpet. If carpet is present, vacuum regularly with a high-efficiency particulate air (HEPA) vacuum or a household vacuum with a microfiltration bag.
- Purchase stuffed toys that are machine washable.
- Use fitted sheets to help reduce the accumulation of human skin on the mattress surface.

HEPA vacuums are now widely available and have also been shown to be effective [8]. A conventional vacuum tends to be inefficient as a control measure and results in a significant increase in airborne dust concentrations, but can be used with multilayer microfiltration collection bags. Another approach to mite control is reducing indoor humidity to below 50% and installing central air conditioning.

Two products are available to treat house dust mites and their allergens. These products contain the active ingredients benzyl benzoate and tannic acid.

Pets

According to the U.S. Environmental Protection Agency (EPA) [9], pets can be significant asthma triggers because of dead skin flakes, urine, feces, saliva, and hair. Proteins in the dander, urine, or saliva of warm-blooded animals can sensitize individuals and lead to allergic reactions or trigger asthmatic episodes. Warm-blooded animals include dogs, cats, birds, and rodents (hamsters, guinea pigs, gerbils, rats, and mice). Numerous strategies, such as the following, can diminish or eliminate animal allergens in the home:

- Eliminate animals from the home.
- Thoroughly clean the home (including floors and walls) after animal removal.
- If pets must remain in the home, reduce pet exposure in sleeping areas. Keep pets away from upholstered furniture, carpeted areas, and stuffed toys, and keep the pets outdoors as much as possible.

However, there is some evidence that pets introduced early into the home may prevent asthma. Several studies have shown that exposure to dogs and cats in the first year of life decreases a child's chances of developing allergies [10] and that exposure to cats significantly decreases sensitivity to cats in adulthood [11]. Many other studies have shown a decrease in allergies and asthma among children who grew up on a farm and were around many animals [12].

Mold

People are routinely exposed to more than 200 species of fungi indoors and outdoors [13]. These include moldlike fungi, as well as other fungi such as yeasts and mushrooms. The terms "mold" and "mildew" are nontechnical names commonly used to refer to any fungus that is growing in the indoor environment. Mold colonies may appear cottony, velvety, granular, or leathery, and may be white, gray, black, brown, yellow, greenish, or other colors. Many reproduce via the production and dispersion of spores. They usually feed on dead organic matter and, provided with sufficient moisture, can live off of many materials found in homes, such as wood, cellulose in the paper backing on drywall, insulation, wallpaper, glues used to bond carpet to its backing, and everyday dust and dirt.

Certain molds can cause a variety of adverse human health effects, including allergic reactions and immune responses (e.g., asthma), infectious disease (e.g., histoplasmosis), and toxic effects (e.g., aflatoxin-induced liver cancer from exposure to this mold-produced toxin in food) [14]. A recent Institute of Medicine (IOM) review of the scientific literature found sufficient evidence for an association between exposure to mold or other agents in damp indoor environments and the following conditions: upper respiratory tract symptoms, cough, wheeze, hypersensitivity pneumonitis in susceptible persons, and asthma symptoms in sensitized persons [15]. A previous scientific review was more specific in concluding that sufficient evidence exists to support associations between fungal allergen exposure and asthma exacerbation and upper respiratory disease [13]. Finally, mold toxins can cause direct lung damage leading to pulmonary diseases other than asthma [13].

The topic of residential mold has received increasing public and media attention over the past decade. Many news stories have focused on problems associated with "toxic mold" or "black mold," which is often a reference to the toxin-producing mold, *Stachybotrys chartarum*. This might give the impression that mold problems in homes are more frequent now than in past years; however, no good evidence supports this. Reasons for the increasing attention to this issue include high-visibility lawsuits brought by property owners against builders and developers, scientific controversies regarding the degree to which specific illness outbreaks are mold-induced, and an increase in the cost of homeowner insurance policies due to the increasing number of mold-related claims. Modern construction might be more vulnerable to mold problems because tighter construction makes it more difficult for internally generated water vapor to escape, as well as the widespread use of paper-backed drywall in construction (paper is an excellent medium for mold growth when wet), and the widespread use of carpeting.

Allergic Health Effects. Many molds produce numerous protein or glycoprotein allergens capable of causing allergic reactions in people. These allergens have been measured in spores as well as in other fungal fragments. An estimated 6%–10% of the general population and 15%–50% of those who are genetically susceptible are sensitized to mold allergens [13]. Fifty percent of the 937 children tested in a large multicity asthma study sponsored by the National Institutes of Health showed sensitivity to mold, indicating the importance of mold as an asthma trigger among these children [16]. Molds are thought to play a role in asthma in several ways. Molds produce many potentially allergenic compounds, and molds may play a role in asthma via release of irritants that increase potential for sensitization or release of toxins (mycotoxins) that affect immune response [13].

Toxics and Irritants. Many molds also produce mycotoxins that can be a health hazard on ingestion, dermal contact, or inhalation [14]. Although common outdoor

molds present in ambient air, such as *Cladosporium cladosporioides* and *Alternaria alternata*, do not usually produce toxins, many other different mold species do [17]. Genera-producing fungi associated with wet buildings, such as *Aspergillus versicolor, Fusarium verticillioides, Penicillium aiurantiorisen,* and *S. chartarum*, can produce potent toxins [17]. A single mold species may produce several different toxins, and a given mycotoxin may be produced by more than one species of fungi. Furthermore, toxin-producing fungi do not necessarily produce mycotoxins under all growth conditions, with production being dependent on the substrate it is metabolizing, temperature, water content, and humidity [17]. Because species of toxin-producing molds generally have a higher water requirement than do common household molds, they tend to thrive only under conditions of chronic and severe water damage [18]. For example, *Stachybotrys* typically only grows under continuously wet conditions [19]. It has been suggested that very young children may be especially vulnerable to certain mycotoxins [19,20]. For example, associations have been reported for pulmonary hemorrhage (bleeding lung) deaths in infants and the presence of *S. chartarum* [21–24].

Causes of Mold. Mold growth can be caused by any condition resulting in excess moisture. Common moisture sources include rain leaks (e.g., on roofs and wall joints); surface and groundwater leaks (e.g., poorly designed or clogged rain gutters and footing drains, basement leaks); plumbing leaks; and stagnant water in appliances (e.g., dehumidifiers, dishwashers, refrigerator drip pans, and condensing coils and drip pans in HVAC systems). Moisture problems can also be due to water vapor migration and condensation problems, including uneven indoor temperatures, poor air circulation, soil air entry into basements, contact of humid unconditioned air with cooled interior surfaces, and poor insulation on indoor chilled surfaces (e.g., chilled water lines). Problems can also be caused by the production of excess moisture within homes from humidifiers, unvented clothes dryers, overcrowding, etc. Finished basements are particularly susceptible to mold problems caused by the combination of poorly controlled moisture and mold-supporting materials (e.g., carpet, paper-backed sheetrock) [15]. There is also some evidence that mold spores from damp or wet crawl spaces can be transported through air currents into the upper living quarters. Older, substandard housing low income families can be particularly prone to mold problems because of inadequate maintenance (e.g., inoperable gutters, basement and roof leaks), overcrowding, inadequate insulation, lack of air conditioning, and poor heating. Low interior temperatures (e.g., when one or two rooms are left unheated) result in an increase in the relative humidity, increasing the potential for water to condense on cold surfaces.

Mold Assessment Methods. Mold growth or the potential for mold growth can be detected by visual inspection for active or past microbial growth, detection of musty odors, and inspection for water staining or damage. If it is not possible or practical to inspect a residence, this information can be obtained using occupant questionnaires. Visual observation of mold growth, however, is limited by the fact that fungal elements such as spores are microscopic, and that their presence is often not apparent until growth is extensive and the fact that growth can occur in hidden spaces (e.g., wall cavities, air ducts).

Portable, hand-held moisture meters, for the direct measurement of moisture levels in materials, may also be useful in qualitative home assessments to aid in pinpointing areas of potential biologic growth that may not otherwise be obvious during a visual inspection [14].

For routine assessments in which the goal is to identify possible mold contamination problems before remediation, it is usually unnecessary to collect and analyze air or settled dust samples for mold analysis because decisions about appropriate intervention strategies can typically be made on the basis of a visual inspection [25]. Also, sampling and analysis costs can be relatively high and the interpretation of results is not straightforward. Air and dust monitoring may, however, be necessary in certain situations, including 1) if an individual has been diagnosed with a disease associated with fungal exposure through inhalation, 2) if it is suspected that the ventilation systems are contaminated, or 3) if the presence of mold is suspected but cannot be identified by a visual inspection or bulk sampling [26]. Generally, indoor environments contain large reservoirs of mold spores in settled dust and contaminated building materials, of which only a relatively small amount is airborne at a given time.

Common methods for sampling for mold growth include bulk sampling techniques, air sampling, and collection of settled dust samples. In bulk sampling, portions of materials with visual or suspected mold growth (e.g., sections of wallboard, pieces of duct lining, carpet segments, or return air filters) are collected and directly examined to determine if mold is growing and to identify the mold species or groups that are present. Surface sampling in mold contamination investigations may also be used when a less destructive technique than bulk sampling is desired. For example, nondestructive samples of mold may be collected using a simple swab or adhesive tape [14].

Air can also be sampled for mold using pumps that pull air across a filter medium, which traps airborne mold spores and fragments. It is generally recommended that outdoor air samples are collected concurrent with indoor samples for comparison purposes for measurement of baseline ambient air conditions. Indoor contamination can be indicated by indoor mold distributions (both species and concentrations) that differ significantly from the distributions in outdoor samples [14]. Captured mold spores can be examined under a microscope to identify the mold species/groups and determine concentrations or they can be cultured on growth media and the resulting colonies counted and identified. Both techniques require considerable expertise.

Dust sampling involves the collection of settled dust samples (e.g., floor dust) using a vacuum method in which the dust is collected onto a porous filter medium or into a container. The dust is then processed in the laboratory and the mold identified by culturing viable spores.

Mold Standards. No standard numeric guidelines exist for assessing whether mold contamination exists in an area. In the United States, no EPA regulations or standards exist for airborne mold contaminants [26]. Various governmental and private organizations have, however, proposed guidance on the interpretation of fungal measures of environmental media in indoor environments (quantitative limits for fungal concentrations).

Given evidence that young children may be especially vulnerable to certain mycotoxins [18] and in view of the potential severity or diseases associated with mycotoxin exposure, some organizations support a precautionary approach to limiting mold exposure [19]. For example, the American Academy of Pediatrics recommends that infants under 1 year of age are not exposed at all to chronically moldy, water-damaged environments [18].

Mold Mitigation. Common intervention methods for addressing mold problems include the following:

- maintaining heating, ventilating, and air conditioning (HVAC) systems;
- changing HVAC filters frequently, as recommended by manufacturer;
- keeping gutters and downspouts in working order and ensuring that they drain water away from the foundation;
- routinely checking, cleaning, and drying drip pans in air conditioners, refrigerators, and dehumidifiers;
- increasing ventilation (e.g., using exhaust fans or open windows to remove humidity when cooking, showering, or using the dishwasher);
- venting clothes dryers to the outside; and
- maintaining an ideal relative humidity level in the home of 40% to 60%.
- locating and removing sources of moisture (controlling dampness and humidity and repairing water leakage problems);
- cleaning or removing mold-contaminated materials;
- removing materials with severe mold growth; and
- using high-efficiency air filters.

Moisture Control. Because one of the most important factors affecting mold growth in homes is moisture level, controlling this factor is crucial in mold abatement strategies. Many simple measures can significantly control moisture, for example maintaining indoor relative humidity at no greater than 40%–60% through the use of dehumidifiers, fixing water leakage problems, increasing ventilation in kitchens and bathrooms by using exhaust fans, venting clothes dryers to the outside, reducing the number of indoor plants, using air conditioning at times of high outdoor humidity, heating all rooms in the winter and adding heating to outside wall closets, sloping surrounding soil away from building foundations, fixing gutters and downspouts, and using a sump pump in basements prone to flooding [27]. Vapor barriers, sump pumps, and aboveground vents can also be installed in crawlspaces to prevent moisture problems [28].

Removal and Cleaning of Mold-contaminated Materials. Nonporous (e.g., metals, glass, and hard plastics) and semiporous (e.g., wood and concrete) materials contaminated with mold and that are still structurally sound can often be cleaned with bleach-and-water solutions. However, in some cases, the material may not be easily cleaned or may be so severely contaminated that it may have to be removed. It is recommended that porous materials (e.g., ceiling tiles, wallboards, and fabrics) that cannot be cleaned be removed and discarded [29]. In severe cases, clean-up and repair of mold-contaminated buildings may be conducted using methods similar to those used for abatement of other hazardous substances such as asbestos [30]. For example, in situations of extensive colonization (large surface areas greater than 100 square feet or where the material is severely degraded), extreme precautions may be required, including full containment (complete isolation of work area) with critical barriers (airlock and decontami-

nation room) and negative pressurization, personnel trained to handle hazardous wastes, and the use of full-face respirators with HEPA filters, eye protection, and disposable full-body covering [26].

Worker Protection When Conducting Mold Assessment and Mitigation Projects. Activities such as cleaning or removal of mold-contaminated materials in homes, as well as investigations of mold contamination extent, have the potential to disturb areas of mold growth and release fungal spores and fragments into the air. Recommended measures to protect workers during mold remediation efforts depend on the severity and nature of the mold contamination being addressed, but include the use of well fitted particulate masks or respirators that retain particles as small as 1 micrometer or less, disposable gloves and coveralls, and protective eyewear [31].

Following are examples of guidance documents for remediation of mold contamination:

- New York City Department of Health and Mental Hygiene. Guidelines on Assessment and Remediation of Fungi in Indoor Environments (available from URL: http://www.nyc.gov/html/doh/html/epi/moldrpt1.shtml).
- American Conference of Governmental Industrial Hygienists (ACGIH) 1999 document, Biosaerosols: Assessment and Control (can be ordered at URL http://www.acgih.org/home.htm).
- American Industrial Hygiene Association (AIHA) 2004 document, Assessment, Remediation, and Post-Remediation Verification of Mold in Buildings (can be ordered at URL http://www.aiha.org)
- Environmental Protection Agency guidance, Mold Remediation in Schools and Commercial Buildings (includes many general principles also applicable to residential mold mitigation efforts; available at URL: http://www.epa.gov/iaq/molds/mold_remediation.html)
- Environmental Protection Agency guidance, A Brief Guide to Mold, Moisture, and Your Home (for homeowners and renters on how to clean up residential mold problems and how to prevent mold growth; available at URL: http://www.epa.gov/iaq/molds/images/moldguide.pdf)
- Canada Mortgage and Housing Corporation, Clean-up Procedures for Mold in Houses, (provides qualitative guidance for mold mitigation; can be ordered at URL: https://www.cmhc-schl.gc.ca:50104/b2c/b2c/init.do?language=en).

Figure 5.1 shows mold growth in the home.

Figure 5.1. Mold Growth in the Home

Chemical Pollutants

Carbon Monoxide

Carbon monoxide (CO) is a significant combustion pollutant in the United States. CO is a leading cause of poisoning deaths [32]. According to the National Fire Protection Association (NFPA), CO-related nonfire deaths are often attributed to heating and cooking equipment. The leading specific types of equipment blamed for CO-related deaths include gas-fueled space heaters, gas-fueled furnaces, charcoal grills, gas-fueled ranges, portable kerosene heaters, and wood stoves.

As with fire deaths, the risk for unintentional CO death is highest for the very young (ages 4 years and younger) and the very old (ages 75 years and older). CO is an odorless, colorless gas that can cause sudden illness and death. It is a result of the incomplete combustion of carbon. Headache, dizziness, weakness, nausea, vomiting, chest pain, and confusion are the most frequent symptoms of CO poisoning. According to the American Lung Association (ALA) [33], breathing low levels of CO can cause fatigue and increase chest pain in people with chronic heart disease. Higher levels of CO can cause flulike symptoms in healthy people. In addition, extremely high levels of CO cause loss of consciousness and death. In the home, any fuel-burning appliance that is not adequately vented and maintained can be a potential source of CO. The following steps should be followed to reduce CO (as well as sulfur dioxide and oxides of nitrogen) levels:

- Never use gas-powered equipment, charcoal grills, hibachis, lanterns, or portable camping stoves in enclosed areas or indoors.

- Install a CO monitor (Figure 5.2) in appropriate areas of the home. These monitors are designed to provide a warning before potentially life-threatening levels of CO are reached.
- Choose vented appliances when possible and keep gas appliances properly adjusted to decrease the combustion to CO. (Note: Vented appliances are always preferable for several reasons: oxygen levels, carbon dioxide buildup, and humidity management).
- Only buy certified and tested combustion appliances that meet current safety standards, as certified by Underwriter's Laboratories (UL), American Gas Association (AGA) Laboratories, or equivalent.
- Assure that all gas heaters possess safety devices that shut off an improperly vented gas heater. Heaters made after 1982 use a pilot light safety system known as an oxygen depletion sensor. When inadequate fresh air exists, this system shuts off the heater before large amounts of CO can be produced.
- Use appliances that have electronic ignitions instead of pilot lights. These appliances are typically more energy efficient and eliminate the continuous low-level pollutants from pilot lights.
- Use the proper fuel in kerosene appliances.
- Install and use an exhaust fan vented to the outdoors over gas stoves.
- Have a trained professional annually inspect, clean, and tune up central heating systems (furnaces, flues, and chimneys) and repair them as needed.
- Do not idle a car inside a garage.

The U.S. Consumer Product Safety Commission (CPSC) recommends installing at least one CO alarm per household near the sleeping area. For an extra measure of safety, another alarm should be placed near the home's heating source. ALA recommends weighing the benefits of using models powered by electrical outlets versus models powered by batteries that run out of power and need replacing. Battery-powered CO detectors provide continuous protection and do not require recalibration in the event of a power outage. Electric-powered systems do not provide protection during a loss of power and can take up to 2 days to recalibrate. A device that can be easily self-tested and reset to ensure proper functioning should be chosen. The product should meet Underwriters Laboratories Standard UL 2034.

Ozone

Figure 5.2. Home Carbon Monoxide Monitor
Source: U.S. Navy

Inhaling ozone can damage the lungs. Inhaling small amounts of ozone can result in chest pain, coughing, shortness of breath, and throat irritation. Ozone can also exacerbate chronic respiratory diseases such as asthma. Susceptibility to the effects of ozone varies from person to person, but even healthy people can experience respiratory difficulties from exposure.

According to the North Carolina Department of Health and Human Services [34], the major source of indoor ozone is outdoor ozone. Indoor levels can vary from 10% of the outdoor air to levels as high as 80% of the outdoor air. The Food and Drug Administration has set a limit of 0.05 ppm of ozone in indoor air. In recent years, there have been numerous advertisements for ion generators that destroy harmful indoor air pollutants. These devices create ozone or elemental oxygen that reacts with pollutants. EPA has reviewed the evidence on ozone generators and states: "available scientific evidence shows that at concentrations that do not exceed public health standards, ozone has little potential to remove indoor air contaminants," and "there is evidence to show that at concentrations that do not exceed public health standards, ozone is not effective at removing many odor causing chemicals" [35].

Ozone is also created by the exposure of polluted air to sunlight or ultraviolet light emitters. This ozone produced outside of the home can infiltrate the house and react with indoor surfaces, creating additional pollutants.

Environmental Tobacco Smoke or Secondhand Smoke

Like CO, environmental tobacco smoke (ETS; also known as secondhand smoke), is a product of combustion. The National Cancer Institute (NCI) [36], states that ETS is the combination of two forms of smoke from burning tobacco products:

- Sidestream smoke, or smoke that is emitted between the puffs of a burning cigarette, pipe, or cigar; and
- Mainstream smoke, or the smoke that is exhaled by the smoker.

The physiologic effects of ETS are numerous. ETS can trigger asthma; irritate the eyes, nose, and throat; and cause ear infections in children, respiratory illnesses, and lung cancer. ETS is believed to cause asthma by irritating chronically inflamed bronchial passages. According to the EPA [37], ETS is a Group A carcinogen; thus, it is a known cause of cancer in humans. Laboratory analysis has revealed that ETS contains in excess of 4,000 substances, more than 60 of which cause cancer in humans or animals. The EPA also estimates that approximately 3,000 lung cancer deaths occur each year in nonsmokers due to ETS. Additionally, passive smoking can lead to coughing, excess phlegm, and chest discomfort. NCI also notes that spontaneous abortion (miscarriage), cervical cancer, sudden infant death syndrome, low birth weight, nasal sinus cancer, decreased lung function, exacerbation of cystic fibrosis, and negative cognitive and behavioral effects in children have been linked to ETS [36].

The EPA [37] states that, because of their relative body size and respiratory rates, children are affected by ETS more than adults are. It is estimated that an additional 7,500 to 15,000 hospitalizations resulting from increased respiratory infections occur in children younger than 18 months of age due to ETS exposure. Figure 5.3 shows the ETS exposure levels in homes with children under age 7 years. The following actions are recommended in the home to protect children from ETS:

- if individuals insist on smoking, increase ventilation in the smoking area by opening windows or using exhaust fans; and
- refrain from smoking in the presence of children and do not allow babysitters or others who work in the home to smoke in the home or near children.

Volatile Organic Compounds

In the modern home, many organic chemicals are used as ingredients in household products. Organic chemicals that vaporize and become gases at normal room temperature are collectively known as VOCs.

Examples of common items that can release VOCs include paints, varnishes, and wax, as well as in many cleaning, disinfecting, cosmetic, degreasing, and hobby products. Levels of approximately a dozen common VOCs can be two to five times higher inside the home, as opposed to outside, whether in highly industrialized areas or rural areas. VOCs that frequently pollute indoor air include toluene, styrene, xylenes, and trichloroethylene. Some of these chemicals may be emitted from aerosol products, dry-cleaned clothing, paints, varnishes, glues, art supplies, cleaners, spot removers, floor waxes, polishes, and air fresheners. The health effects of these chemicals are varied. Trichlorethylene has been linked to childhood leukemia. Exposure to toluene can put pregnant women at risk for having babies with neurologic problems, retarded growth, and developmental problems. Xylenes have been linked to birth defects. Styrene is a suspected endocrine disruptor, a chemical that can block or mimic hormones in humans or animals. EPA data reveal that methylene chloride, a common component of some paint strippers, adhesive removers, and specialized aerosol spray paints, causes cancer in animals [38]. Methylene chloride is also converted to CO in the body and can cause symptoms associated with CO exposure. Benzene, a known human carcinogen, is contained in tobacco smoke, stored fuels, and paint supplies. Perchloroethylene, a product uncommonly found in homes, but common to dry cleaners, can be a pollution source by off-gassing from newly cleaned clothing. Environmental Media Services [39] also notes that xylene, ketones, and aldehydes are used in aerosol products and air fresheners.

To lower levels of VOCs in the home, follow these steps:

- use all household products according to directions;
- provide good ventilation when using these products;
- properly dispose of partially full containers of old or unneeded chemicals;
- purchase limited quantities of products; and
- minimize exposure to emissions from products containing methylene chloride, benzene, and perchlorethylene.

A prominent VOC found in household products and construction products is formaldehyde. According to CPSC [40], these products include the glue or adhesive used in pressed wood products; preservatives in paints, coating, and cosmetics; coatings used for permanent-press quality in fabrics and draperies; and the finish on paper products and certain insulation materials. Formaldehyde

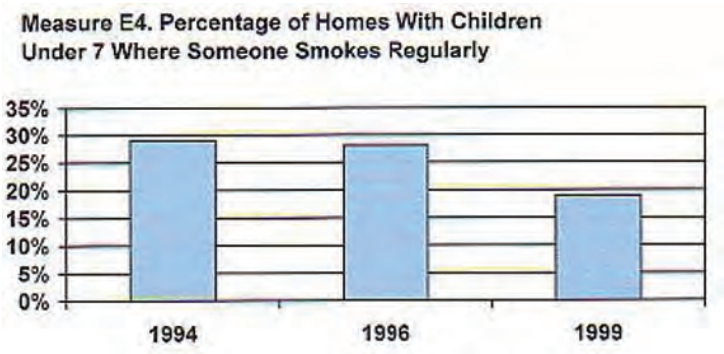

Figure 5.3. Environmental Tobacco Smoke and Children's Exposure [37]

is contained in urea-formaldehyde (UF) foam insulation installed in the wall cavities of homes as an energy conservation measure. Levels of formaldehyde increase soon after installation of this product, but these levels decline with time. In 1982, CPSC voted to ban UF foam insulation. The courts overturned the ban; however, the publicity has decreased the use of this product.

More recently, the most significant source of formaldehyde in homes has been pressed wood products made using adhesives that contain UF resins [41]. The most significant of these is medium-density fiberboard, which contains a higher resin-to-wood ratio than any other UF pressed wood product. This product is generally recognized as being the highest formaldehyde-emitting pressed wood product. Additional pressed wood products are produced using phenol-formaldehyde resin. The latter type of resin generally emits formaldehyde at a considerably slower rate than those containing UF resin. The emission rate for both resins will change over time and will be influenced by high indoor temperatures and humidity. Since 1985, U.S. Department of Housing and Urban Development (HUD) regulations (24 CFR 3280.308, 3280.309, and 3280.406) have permitted only the use of plywood and particleboard that conform to specified formaldehyde emission limits in the construction of prefabricated and manufactured homes [42]. This limit was to ensure that indoor formaldehyde levels are below 0.4 ppm.

CPSC [40] notes that formaldehyde is a colorless, strong-smelling gas. At an air level above 0.1 ppm, it can cause watery eyes; burning sensations in the eyes, nose, and throat; nausea; coughing; chest tightness; wheezing; skin rashes; and allergic reactions. Laboratory animal studies have revealed that formaldehyde can cause cancer in animals and may cause cancer in humans. Formaldehyde is usually present at levels less than 0.03 ppm indoors and outdoors, with rural areas generally experiencing lower concentrations than urban areas. Indoor areas that contain products that release formaldehyde can have levels greater than 0.03 ppm. CPSC also recommends the following actions to avoid high levels of exposure to formaldehyde:

- Purchase pressed wood products that are labeled or stamped to be in conformance with American National Standards Institute criteria ANSI A208.1-1993. Use particleboard flooring marked with ANSI grades PBU, D2, or D3. Medium-density fiberboard should be in conformance with ANSI A208.2-1994 and hardwood plywood with ANSI/HPVA HP-1-1994 (Figure 5.4).

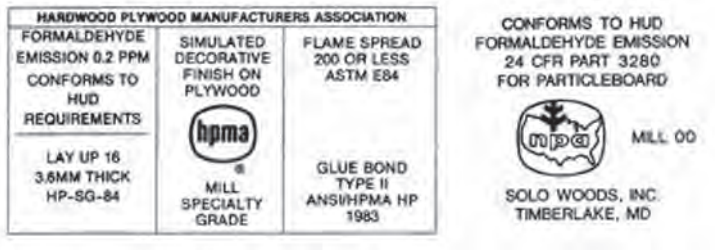

Figure 5.4. Wood Products Label [42]

- Purchase furniture or cabinets that contain a high percentage of panel surface and edges that are laminated or coated. Unlaminated or uncoated (raw) panels of pressed wood panel products will generally emit more formaldehyde than those that are laminated or coated.
- Use alternative products, such as wood panel products not made with UF glues, lumber, or metal.
- Avoid the use of foamed-in-place insulation containing formaldehyde, especially UF foam insulation.
- Wash durable-press fabrics before use.

CPSC also recommends the following actions to reduce existing levels of indoor formaldehyde:

- Ventilate the home well by opening doors and windows and installing an exhaust fan(s).
- Seal the surfaces of formaldehyde-containing products that are not laminated or coated with paint, varnish, or a layer of vinyl or polyurethane-like materials.
- Remove products that release formaldehyde in the indoor air from the home.

Radon

According to the EPA [43], radon is a colorless, odorless gas that occurs naturally in soil and rock and is a decay product of uranium. The U.S. Geological Survey (USGS) [44] notes that the typical uranium content of rock and the surrounding soil is between 1 and 3 ppm. Higher levels of uranium are often contained in rock such as light-colored volcanic rock, granite, dark shale, and sedimentary rock containing phosphate. Uranium levels as high as 100 ppm may be present in various areas of the United States because of these rocks. The main source of high-level radon pollution in buildings is surrounding uranium-containing soil. Thus, the greater the level of uranium nearby, the greater the chances are that buildings in the area will have high levels of indoor radon. Figure 5.5 demonstrates the geographic variation in radon levels in the United States. Maps of the individual states and areas that have proven high for radon are available at

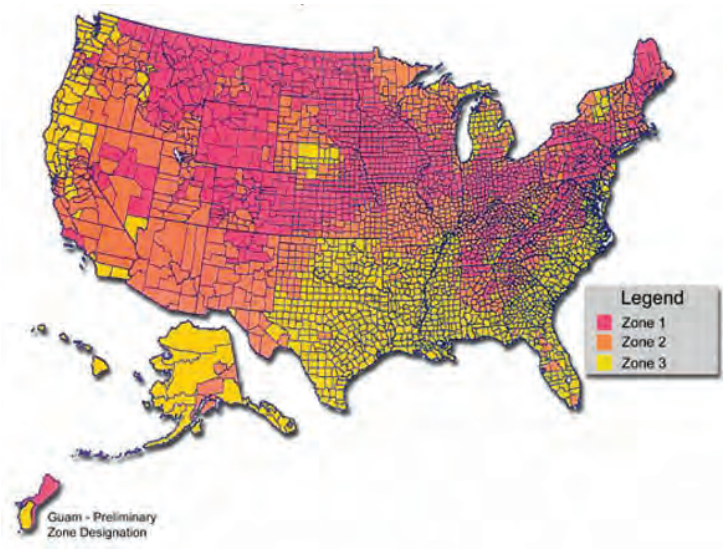

Figure 5.5. EPA Map of Radon Zones [43]
Zone 1: predicted average indoor radon screening level greater than 4 pCi/L [picocuries per liter]
Zone 2: predicted average indoor radon screening level between 2 and 4 pCi/L
Zone 3: predicted average indoor radon screening level less than 2 pCi/L
Important: Consult the EPA Map of Radon Zones document [EPA-402-R-93-071] before using this map. This document contains information on radon potential variations within counties.
EPA also recommends that this map be supplemented with any available local data to further understand and predict the radon potential of a specific area.

http://www.epa.gov/iaq/radon/ zonemap.html. A free video is available from the U.S. EPA: call 1-800-438-4318 and ask for EPA 402-V-02-003 (TRT 13.10).

Radon, according to the California Geological Survey [45], is one of the intermediate radioactive elements formed during the radioactive decay of uranium-238, uranium-235, or thorium-232. Radon-222 is the radon isotope of most concern to public health because of its longer half-life (3.8 days). The mobility of radon gas is much greater than are uranium and radium, which are solids at room temperature. Thus, radon can leave rocks and soil, move through fractures and pore spaces, and ultimately enter a building to collect in high concentrations. When in water, radon moves less than 1 inch before it decays, compared to 6 feet or more in dry rocks or soil. USGS [44] notes that radon near the surface of soil typically escapes into the atmosphere. However, where a house is present, soil air often flows toward the house foundation because of

- differences in air pressure between the soil and the house, with soil pressure often being higher;
- presence of openings in the house's foundation; and
- increases in permeability around the basement (if present).

Houses are often constructed with loose fill under a basement slab and between the walls and exterior ground. This fill is more permeable than the original ground. Houses typically draw less than 1% of their indoor air from the soil. However, houses with low indoor air pressures, poorly sealed foundations, and several entry points for soil air may draw up to 20% of their indoor air from the soil.

USGS [44] states that radon may also enter the home through the water systems. Surface water sources typically contain little radon because it escapes into the air. In larger cities, radon is released to the air by municipal processing systems that aerate the water. However, in areas where groundwater is the main water supply for communities, small public systems and private wells are typically closed systems that do not allow radon to escape. Radon then enters the indoor air from showers, clothes washing, dishwashing, and other uses of water. Figure 5.6 shows typical entry points of radon.

Health risks of radon stem from its breakdown into "radon daughters," which emit high-energy alpha particles. These progeny enter the lungs, attach themselves, and may eventually lead to lung cancer. This exposure to radon is believed to contribute to between 15,000 and 21,000 excess lung cancer deaths in the United States each year. The EPA has identified levels greater than 4 picocuries per liter as levels at which remedial action should be taken. Approximately 1 in 15 homes nationwide have radon above this level, according to the U.S. Surgeon General's recent advisory [46]. Smokers are at significantly higher risk for radon-related lung cancer.

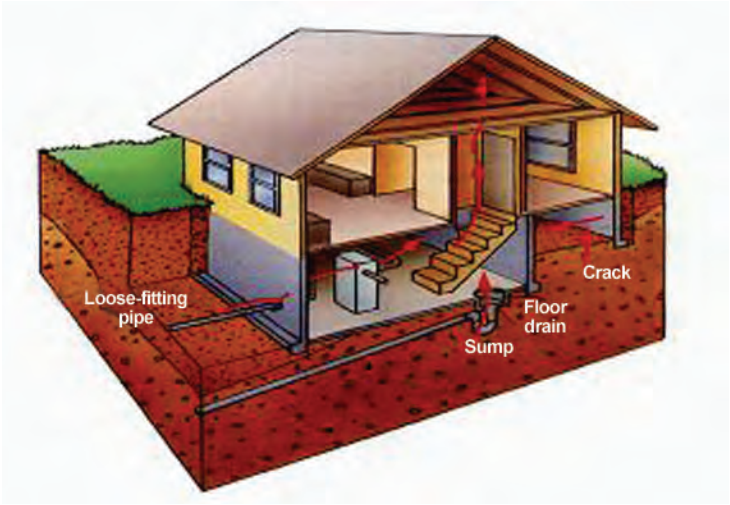

Figure 5.6. Radon Entry [30]

Radon in the home can be measured either by the occupant or by a professional. Because radon has no odor or color, special devices are used to measure its presence. Radon levels vary from day to day and season to season. Short-term tests (2 to 90 days) are best if quick results are needed, but long-term tests (more than 3 months) yield better information on average year-round exposure. Measurement devices are routinely placed in the lowest occupied level of the home. The devices either measure the radon gas directly or the daughter products. The simplest devices are passive, require no electricity, and include a charcoal canister, charcoal liquid scintillation device, alpha tract detector, and electret ion detectors [47].

All of these devices, with the exception of the ion detector, can be purchased in hardware stores or by mail. The ion detector generally is only available through laboratories. These devices are inexpensive, primarily used for short-term testing, and require little to no training. Active devices, however, need electrical power and include continuous monitoring devices. They are customarily more expensive and require professionally trained testers for their operation. Figure 5.7 shows examples of the charcoal tester (a; left) and the alpha tract detector (b; right).

After testing and evaluation by a professional, it may be necessary to lower the radon levels in the structure. The Pennsylvania Department of Environmental Protection [48] states that in most cases, a system with pipes and a fan is used to reduce radon. This system, known as a subslab depressurization system, requires no major changes to the home. The cost typically ranges from $500 to $2,500 and averages approximately $1,000, varying with geographic region. The typical mitigation system usually has only one pipe penetrating through the basement floor; the pipe also may be installed outside the house. The Connecticut Department of Public Health [49] notes that it is more cost effective to include radon-resistant techniques while constructing a building than to install a

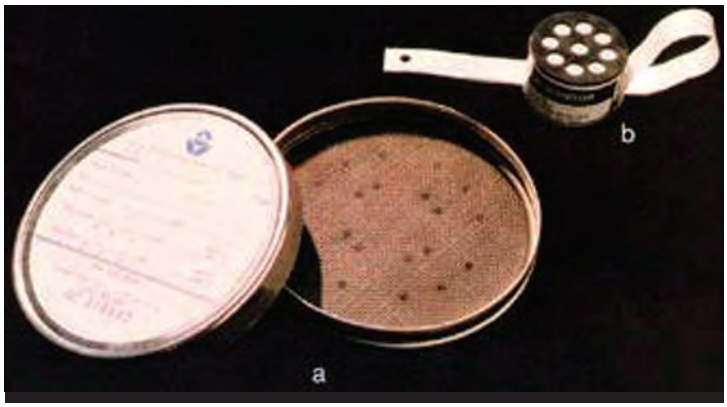

Figure 5.7. Home Radon Detectors [31]

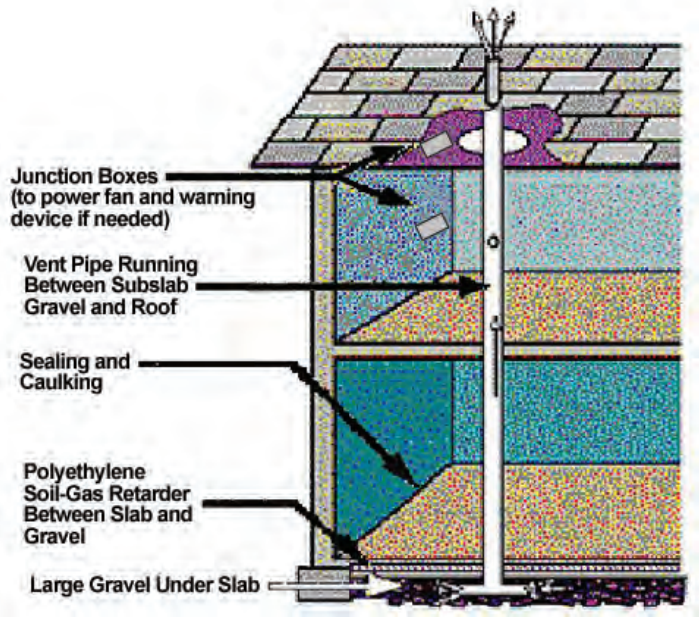

Figure 5.8. Radon-resistant Construction [50]

reduction system in an existing home. Inclusion of radon-resistant techniques in initial construction costs approximately $350 to $500 [50]. Figure 5.8 shows examples of radon-resistant construction techniques.

A passive radon-resistant system has five major parts:

1. A layer of gas-permeable material under the foundation.
2. The foundation (usually 4 inches of gravel).
3. Plastic sheeting over the foundation, with all openings in the concrete foundation floor sealed and caulked.
4. A gas-tight, 3- or 4-inch vent pipe running from under the foundation through the house to the roof.
5. A roughed-in electrical junction box for the future installation of a fan, if needed.

These features create a physical barrier to radon entry. The vent pipe redirects the flow of air under the foundation, preventing radon from seeping into the house.

Pesticides

Much pesticide use could be reduced if integrated pest management (IPM) practices were used in the home. IPM is a coordinated approach to managing roaches, rodents, mosquitoes, and other pests that integrates inspection, monitoring, treatment, and evaluation, with special emphasis on the decreased use of toxic agents. However, all pest management options, including natural, biologic, cultural, and chemical methods, should be considered. Those that have the least impact on health and the environment should be selected. Most household

pests can be controlled by eliminating the habitat for the pest both inside and outside, building or screening them out, eliminating food and harborage areas, and safely using appropriate pesticides if necessary.

EPA [51] states that 75% of U.S. households used at least one pesticide indoors during the past year and that 80% of most people's exposure to pesticides occurs indoors. Measurable levels of up to a dozen pesticides have been found in the air inside homes. Pesticides used in and around the home include products to control insects (insecticides), termites (termiticides), rodents (rodenticides), fungi (fungicides), and microbes (disinfectants). These products are found in sprays, sticks, powders, crystals, balls, and foggers.

Delaplane [52] notes that the ancient Romans killed insect pests by burning sulfur and controlled weeds with salt. In the 1600s, ants were controlled with mixtures of honey and arsenic. U.S. farmers in the late 19th century used copper actoarsenite (Paris green), calcium arsenate, nicotine sulfate, and sulfur to control insect pests in field crops. By World War II and afterward, numerous pesticides had been introduced, including DDT, BHC, aldrin, dieldrin, endrin, and 2,4-D. A significant factor with regard to these pesticides used in and around the home is their impact on children. According to a 2003 EPA survey, 47% of all households with children under the age of 5 years had at least one pesticide stored in an unlocked cabinet less than 4 feet off the ground. This is within easy reach of children. Similarly, 74% of households without children under the age of 5 also stored pesticides in an unlocked cabinet less than 4 feet off the ground. This issue is significant because 13% of all pesticide poisoning incidents occur in homes other than the child's home. The EPA [53] notes a report by the American Association of Poison Control Centers indicating that approximately 79,000 children were involved in common household pesticide poisonings or exposures.

The health effects of pesticides vary with the product. However, local effects from most of the products will be on eyes, noses, and throats; more severe consequences, such as on the central nervous system and kidneys and on cancer risks, are possible. The active and inert ingredients of pesticides can be organic compounds, which can contribute to the level of organic compounds in indoor air. More significantly, products containing cyclodiene pesticides have been commonly associated with misapplication. Individuals inadvertently exposed during this misapplication had numerous symptoms, including headaches, dizziness, muscle twitching, weakness, tingling sensations, and nausea. In addition, there is concern that these pesticides may cause long-term damage to the liver and the central nervous system, as well as an increased cancer risk. Cyclodiene pesticides were developed for use as insecticides in the 1940s and 1950s. The four main cyclodiene pesticides—aldrin, dieldrin, chlordane, and heptachlor—were used to guard soil and seed against insect infestation and to control insect pests in crops. Outside of agriculture they were used for ant control; farm, industrial, and domestic control of fleas, flies, lice, and mites; locust control; termite control in buildings, fences, and power poles; and pest control in home gardens. No other commercial use is permitted for cyclodiene or related products. The only exception is the use of heptachlor by utility companies to control fire ants in underground cable boxes.

An EPA survey [53] revealed that bathrooms and kitchens are areas in the home most likely to have improperly stored pesticides. In the United States, EPA regulates pesticides under the pesticide law known as the Federal Insecticide, Fungicide, and Rodenticide Act. Since 1981, this law has required most residential-use pesticides to bear a signal word such as "danger" or "warning" and to be contained in child-resistant packaging. This type of packaging is designed to prevent or delay access by most children under the age of 5 years. EPA offers the following recommendations for preventing accidental poisoning:

- store pesticides away from the reach of children in a locked cabinet, garden shed, or similar location;
- read the product label and follow all directions exactly, especially precautions and restrictions;
- remove children, pets, and toys from areas before applying pesticides;
- if interrupted while applying a pesticide, properly close the package and assure that the container is not within reach of children;
- do not transfer pesticides to other containers that children may associate with food or drink;
- do not place rodent or insect baits where small children have access to them;
- use child-resistant packaging properly by closing the container tightly after use;
- assure that other caregivers for children are aware of the potential hazards of pesticides;

- teach children that pesticides are poisons and should not be handled; and
- keep the local Poison Control Center telephone number available.

Toxic Materials

Asbestos

Asbestos, from the Greek word meaning "inextinguishable," refers to a group of six naturally occurring mineral fibers. Asbestos is a mineral fiber of which there are several types: amosite, crocidiolite, tremolite, actinolite, anthrophyllite, and chrysotile. Chrysotile asbestos, also known as white asbestos, is the predominant commercial form of asbestos. Asbestos is strong, flexible, resistant to heat and chemical corrosion, and insulates well. These features led to the use of asbestos in up to 3,000 consumer products before government agencies began to phase it out in the 1970s because of its health hazards. Asbestos has been used in insulation, roofing, siding, vinyl floor tiles, fireproofing materials, texturized paint and soundproofing materials, heating appliances (such as clothes dryers and ovens), fireproof gloves, and ironing boards. Asbestos continues to be used in some products, such as brake pads. Other mineral products, such as talc and vermiculite, can be contaminated with asbestos.

The health effects of asbestos exposure are numerous and varied. Industrial studies of workers exposed to asbestos in factories and shipyards have revealed three primary health risk concerns from breathing high levels of asbestos fibers: lung cancer, mesothelioma (a cancer of the lining of the chest and the abdominal cavity), and asbestosis (a condition in which the lungs become scarred with fibrous tissue).

The risk for all of these conditions is amplified as the number of fibers inhaled increases. Smoking also enhances the risk for lung cancer from inhaling asbestos fibers by acting synergistically. The incubation period (from time of exposure to appearance of symptoms) of these diseases is usually about 20 to 30 years. Individuals who develop asbestosis have typically been exposed to high levels of asbestos for a long time. Exposure levels to asbestos are measured in fibers per cubic centimeter of air. Most individuals are exposed to small amounts of asbestos in daily living activities; however, a preponderance of them do not develop health problems. According to the Agency for Toxic Substances and Disease Registry (ATSDR), if an individual is exposed, several factors determine whether the individual will be harmed [54]. These factors include the dose (how much), the duration (how long), and the fiber type (mineral form and distribution). ATSDR also states that children may be more adversely affected than adults [54]. Children breathe differently and have different lung structures than adults; however, it has not been determined whether these differences cause a greater amount of asbestos fibers to stay in the lungs of a child than in the lungs of an adult. In addition, children drink more fluids per kilogram of body weight than do adults and they can be exposed through asbestos-contaminated drinking water. Eating asbestos-contaminated soil and dust is another source of exposure for children. Certain children intentionally eat soil and children's hand-to-mouth activities mean that all young children eat more soil than do adults. Family members also have been exposed to asbestos that was carried home on the clothing of other family members who worked in asbestos mines or mills. Breathing asbestos fibers may result in difficulty in breathing. Diseases usually appear many years after the first exposure to asbestos and are therefore not likely to be seen in children. But people who have been exposed to asbestos at a young age may be more likely to contract diseases than those who are first exposed later in life. In the small number of studies that have specifically looked at asbestos exposure in children, there is no indication that younger people might develop asbestos-related diseases more quickly than older people. Developing fetuses and infants are not likely to be exposed to asbestos through the placenta or breast milk of the mother. Results of animal studies do not indicate that exposure to asbestos is likely to result in birth defects.

A joint document issued by CPSC, EPA, and ALA, notes that most products in today's homes do not contain asbestos. However, asbestos can still be found in products and areas of the home. These products contain asbestos that could be inhaled and are required to be labeled as such. Until the 1970s, many types of building products and insulation materials used in homes routinely contained asbestos. A potential asbestos problem both inside and outside the home is that of vermiculite. According to the USGS [55], vermiculite is a claylike material that expands when heated to form wormlike particles. It is used in concrete aggregate, fertilizer carriers, insulation, potting soil, and soil conditioners. This product ceased being mined in 1992, but old stocks may still be available. Common products that contained asbestos in the past and conditions that may release fibers include the following:

- Steam pipes, boilers, and furnace ducts insulated with an asbestos blanket or asbestos paper tape. These materials may release asbestos fibers if damaged, repaired, or removed improperly.

- Resilient floor tiles (vinyl asbestos, asphalt, and rubber), the backing on vinyl sheet flooring, and adhesives used for installing floor tile. Sanding tiles can release fibers, as may scraping or sanding the backing of sheet flooring during removal.
- Cement sheet, millboard, and paper used as insulation around furnaces and wood-burning stoves. Repairing or removing appliances may release asbestos fibers, as may cutting, tearing, sanding, drilling, or sawing insulation.
- Door gaskets in furnaces, wood stoves, and coal stoves. Worn seals can release asbestos fibers during use.
- Soundproofing or decorative material sprayed on walls and ceilings. Loose, crumbly, or water-damaged material may release fibers, as will sanding, drilling, or scraping the material.
- Patching and joint compounds for walls, ceilings, and textured paints. Sanding, scraping, or drilling these surfaces may release asbestos.
- Asbestos cement roofing, shingles, and siding. These products are not likely to release asbestos fibers unless sawed, drilled, or cut.
- Artificial ashes and embers sold for use in gas-fired fireplaces in addition to other older household products such as fireproof gloves, stove-top pads, ironing board covers, and certain hair dryers.
- Automobile brake pads and linings, clutch facings, and gaskets.

Homeowners who believe material in their home may be asbestos should not disturb the material. Generally, material in good condition will not release asbestos fibers, and there is little danger unless the fibers are released and inhaled into the lungs. However, if disturbed, asbestos material may release asbestos fibers, which can be inhaled into the lungs. The fibers can remain in the lungs for a long time, increasing the risk for disease. Suspected asbestos-containing material should be checked regularly for damage from abrasions, tears, or water. If possible, access to the area should be limited. Asbestos-containing products such as asbestos gloves, stove-top pads, and ironing board covers should be discarded if damaged or worn. Permission and proper disposal methods should be obtainable from local health, environmental, or other appropriate officials. If asbestos material is more than slightly damaged, or if planned changes in the home might disturb it, repair or removal by a professional is needed. Before remodeling, determine whether asbestos materials are present.

Only a trained professional can confirm suspected asbestos materials that are part of a home's construction. This individual will take samples for analysis and submit them to an EPA-approved laboratory.

If the asbestos material is in good shape and will not be disturbed, the best approach is to take no action and continue to monitor the material. If the material needs action to address potential exposure problems, there are two approaches to correcting the problem: repair and removal.

Repair involves sealing or covering the asbestos material. Sealing or encapsulation involves treating the material with a sealant that either binds the asbestos fibers together or coats the material so fibers are not released. This is an approach often used for pipe, furnace, and boiler insulation; however, this work should be done only by a professional who is trained to handle asbestos safely. Covering (enclosing) involves placing something over or around the material that contains asbestos to prevent release of fibers. Exposed insulated piping may be covered with a protective wrap or jacket. In the repair process, the approach is for the material to remain in position undisturbed. Repair is a less expensive process than is removal.

With any type of repair, the asbestos remains in place. Repair may make later removal of asbestos, if necessary, more difficult and costly. Repairs can be major or minor. Both major and minor repairs must be done only by a professional trained in methods for safely handling asbestos.

Removal is usually the most expensive and, unless required by state or local regulations, should be the last option considered in most situations. This is because removal poses the greatest risk for fiber release. However, removal may be required when remodeling or making major changes to the home that will disturb asbestos material. In addition, removal may be called for if asbestos material is damaged extensively and cannot be otherwise repaired. Removal is complex and must be done only by a contractor with special training. Improper removal of asbestos material may create more of a problem than simply leaving it alone.

Lead

Many individuals recognize lead in the form often seen in tire weights and fishing equipment, but few recognize its various forms in and around the home. The Merriam-Webster Dictionary [56] defines lead as "a heavy soft malleable ductile plastic but inelastic bluish white metallic element found mostly in combination and used especially in pipes, cable sheaths, batteries, solder, and shields

against radioactivity." Lead is a metal with many uses. It melts easily and quickly. It can be molded or shaped into thin sheets and can be drawn out into wire or threads. Lead also is very resistant to weather conditions. Lead and lead compounds are toxic and can present a severe hazard to those who are overexposed to them. Whether ingested or inhaled, lead is readily absorbed and distributed throughout the body.

Until 1978, lead compounds were an important component of many paints. Lead was added to paint to promote adhesion, corrosion control, drying, and covering. White lead (lead carbonate), linseed oil, and inorganic pigments were the basic components for paint in the 18th and 19th centuries, and continued until the middle of the 20th century. Lead was banned by CPSC in 1978. Lead-based paint was used extensively on exteriors and interior trim-work, window sills, sashes, window frames, baseboards, wainscoting, doors, frames, and high-gloss wall surfaces, such as those found in kitchens and bathrooms. The only way to determine which building components are coated with lead paint is through an inspection for lead-based paint. Almost all painted metals were primed with red lead or painted with lead-based paints. Even milk (casein) and water-based paints (distemper and calcimines) could contain some lead, usually in the form of hiding agents or pigments. Varnishes sometimes contained lead. Lead compounds also were used as driers in paint and window-glazing putty.

Lead is widespread in the environment. People absorb lead from a variety of sources every day. Although lead has been used in numerous consumer products, the most important sources of lead exposure to children and others today are the following:

- contaminated house dust that has settled on horizontal surfaces,
- deteriorated lead-based paint,
- contaminated bare soil,
- food (which can be contaminated by lead in the air or in food containers, particularly lead-soldered food containers),
- drinking water (from corrosion of plumbing systems), and
- occupational exposure or hobbies.

Federal controls on lead in gasoline, new paint, food canning, and drinking water, as well as lead from industrial air emissions, have significantly reduced total human exposure to lead. The number of children with blood lead levels above 10 micrograms per deciliter (µg/dL), a level designated as showing no physiologic toxicity, has declined from 1.7 million in the late 1980s to 310,000 in 1999–2002. This demonstrates that the controls have been effective, but that many children are still at risk. CDC data show that deteriorated lead-based paint and the contaminated dust and soil it generates are the most common sources of exposure to children today. HUD data show that the number of houses with lead paint declined from 64 million in 1990 to 38 million in 2000 [57].

Children are more vulnerable to lead poisoning than are adults. Infants can be exposed to lead in the womb if their mothers have lead in their bodies. Infants and children can swallow and breathe lead in dirt, dust, or sand through normal hand-to-mouth contact while they play on the floor or ground. These activities make it easier for children to be exposed to lead. Other sources of exposure have included imported vinyl miniblinds, crayons, children's jewelry, and candy. In 2004, increases in lead in water service pipes were observed in Washington, D.C., accompanied by increases in blood lead levels in children under the age of 6 years who were served by the water system [58].

In some cases, children swallow nonfood items such as paint chips. These may contain very large amounts of lead, particularly in and around older houses that were painted with lead-based paint. Many studies have verified the effect of lead exposure on IQ scores in the United States. The effects of lead exposure have been reviewed by the National Academy of Sciences [59].

Generally, the tests for blood lead levels are from drawn blood, not from a finger-stick test, which can be unreliable if performed improperly. Units are measured in micrograms per deciliter and reflect the 1991 guidance from the Centers of Disease Control [60]:

- Children: 10 µg/dL (level of concern)—find source of lead;
- Children: 15 µg/dL and above—environmental intervention, counseling, medical monitoring;
- Children: 20 µg/dL and above—medical treatment;
- Adults: 25 µg/dL (level of concern)—find source of lead; and
- Adults: 50 µg/dL—Occupational Safety and Health Administration (OSHA) standard for medical removal from the worksite.

Adults are usually exposed to lead from occupational sources (e.g., battery construction, paint removal) or at home (e.g., paint removal, home renovations).

In 1978, CPSC banned the use of lead-based paint in residential housing. Because houses are periodically repainted, the most recent layer of paint will most likely not contain lead, but the older layers underneath probably will. Therefore, the only way to accurately determine the amount of lead present in older paint is to have it analyzed.

It is important that owners of homes built before 1978 be aware that layers of older paint can contain a great deal of lead. Guidelines on identifying and controlling lead-based paint hazards in housing have been published by HUD [61].

Controlling Lead Hazards

The purpose of a home risk assessment is to determine, through testing and evaluation, where hazards from lead warrant remedial action. A certified inspector or risk assessor can test paint, soil, or lead dust either on-site or in a laboratory using methods such as x-ray fluorescence (XRF) analyzers, chemicals, dust wipe tests, and atomic absorption spectroscopy. Lists of service providers are available by calling 1-800-424-LEAD. Do-it-yourself test kits are commercially available; however, these kits do not tell you how much lead is present, and their reliability at detecting low levels of lead has not been determined. Professional testing for lead in paint is recommended. The recommended sampling method for dust is the surface wet wipe. Dust samples are collected from different surfaces, such as bare floors, window sills, and window wells. Each sample is collected from a measured surface area using a wet wipe, which is sent to a laboratory for testing. Risk assessments can be fairly low-cost investigations of the location, condition, and severity of lead hazards found in house dust, soil, water, and deteriorating paint. Risk assessments also will address other sources of lead from hobbies, crockery, water, and work environments. These services are critical when owners are seeking to implement measures to reduce suspected lead hazards in housing and day-care centers or when extensive rehabilitation is planned.

HUD has published detailed protocols for risk assessments and inspections [61].

It is important from a health standpoint that future tenants, painters, and construction workers know that lead-based paint is present, even under treated surfaces, so they can take precautions when working in areas that will generate lead dust. Whenever mitigation work is completed, it is important to have a clearance test using the dust wipe method to ensure that lead-laden dust generated during the work does not remain at levels above those established by the EPA and HUD. Such testing is required for owners of most housing that is receiving federal financial assistance, such as Section 8 rental housing. A building or housing file should be maintained and updated whenever any additional lead hazard control work is completed. Owners are required by law to disclose information about lead-based paint or lead-based paint hazards to buyers or tenants before completing a sales or lease contract [62].

All hazards should be controlled as identified in a risk assessment.

Whenever extensive amounts of lead must be removed

Action Levels for Lead

Lead in paint. Differing methods report results in differing units. Lead is considered a potential hazard if above the following levels, but can be a hazard at lower levels if improperly handled. Below are the current action levels identified by HUD [62] and EPA (40 CFR Part 745):

Lab analysis of samples:
5,000 milligram per kilogram (mg/kg) or 5,000 parts per million (ppm) 0.5% lead by weight.

X-ray fluorescence:
1 milligram per square centimeter (mg/cm^2)

Lead in dust:
Floors, 40 micrograms per square foot ($\mu g/ft^2$)

Window sills, 250 $\mu g/ft^2$ Window troughs, 400 $\mu g/ft^2$ (clearance only)

Lead in soil:
High-contact bare play areas: 400 ppm

Other yard areas: 1,200 ppm

from a property, or when methods of removing toxic substances will affect the environment, it is extremely important that the owner be aware of the issues surrounding worker safety, environmental controls, and proper disposal. Appropriate architectural, engineering, and environmental professionals should be consulted when lead hazard projects are complex.

Following are brief explanations of the two approaches for controlling lead hazard risks. These controls are recommended by HUD in HUD *Guidelines for the Evaluation and Control of Lead-Based Paint Hazards in Housing* [61], and are summarized here to focus on special considerations for historic housing:

Interim Controls. Short-term solutions include thorough dust removal and thorough washdown and cleanup, paint film stabilization and repainting, covering of lead-contaminated soil, and informing tenants about lead hazards. Interim controls require ongoing maintenance and evaluation.

Hazard Abatement. Long-term solutions are defined as having an expected life of 20 years or more and involve permanent removal of hazardous paint through chemicals, heat guns, or controlled sanding or abrasive methods; permanent removal of deteriorated painted features through replacement; removal or permanent covering of contaminated soil; and the use of enclosures (such as drywall) to isolate painted surfaces. The use of specialized encapsulant products can be considered as permanent abatement of lead.

Reducing and controlling lead hazards can be successfully accomplished without destroying the character-defining features and finishes of historic buildings. Federal and state laws generally support the reasonable control of lead-based paint hazards through a variety of treatments, ranging from modified maintenance to selective substrate removal. The key to protecting children, workers, and the environment is to be informed about the hazards of lead, to control exposure to lead dust and lead in soil and lead paint chips, and to follow existing regulations.

The following summarizes several important regulations that affect lead-hazard reduction projects. Owners should be aware that regulations change, and they have a responsibility to check state and local ordinances as well. Care must be taken to ensure that any procedures used to release lead from the home protect both the residents and workers from lead dust exposure.

Residential Lead-Based Paint Hazard Reduction Act of 1992, Title X [62]. Part of the Housing and Community Development Act of 1992 (Public Law 102-550) [63]. It established that HUD issue *Guidelines for the Evaluation and Control of Lead-Based Paint Hazards in Housing* [61] to outline risk assessments, interim controls, and abatement of lead-based paint hazards in housing. Title X calls for the reduction of lead in federally supported housing. It outlines the federal responsibility toward its own residential units and the need for disclosure of lead in residences, even private residences, before a sale. Title X also required HUD to establish regulations for federally assisted housing (24 CFR Part 35) and EPA to establish

Definitions Related to Lead

Deteriorated lead-based paint: Paint known to contain lead above the regulated level that shows signs of peeling, chipping, chalking, blistering, alligatoring, or otherwise separating from its substrate.

Dust removal: The process of removing dust to avoid creating a greater problem of spreading lead particles; usually through wet or damp collection and use of HEPA vacuums.

Hazard abatement: Long-term measures to remove the hazards of lead-based paint through replacement of building components, enclosure, encapsulation, or paint removal.

Interim control: Short-term methods to remove lead dust, stabilize deteriorating painted surfaces, treat friction and impact surfaces that generate lead dust, and repaint surfaces. Maintenance can ensure that housing remains lead-safe.

Lead-based paint: Any existing paint, varnish, shellac, or other coating that is equal to or greater than 1.0 milligrams per square centimeter (mg/cm^2) or greater than 0.5% by weight (5,000 ppm, 5,000 micrograms per gram [µg/g], or 5,000 milligrams per kilogram [mg/kg]). For new paint, CPSC has established 0.06% as the maximum amount of lead allowed in new paint. Lead in paint can be measured by x-ray fluorescence analyzers or laboratory analysis by certified personnel and approved laboratories.

Risk assessment: An on-site investigation to determine the presence and condition of lead-based paint, including limited test samples and an evaluation of the age, condition, housekeeping practices, and uses of a residence.

standards for lead in paint, dust, and soil, as well as standards for laboratory accreditation (40 CFR Part 745). EPA's residential lead hazard standards are available at http://www.epa.gov/lead/leadhaz.htm.

Interim Final Rule on Lead in Construction (29 Code of Federal Regulations [CFR] 1926.62) [64]. Issued by OSHA, these regulations address worker safety, training, and protective measures. The regulations are based in part on personal-air sampling to determine the amount of lead dust exposure to workers.

State Laws. States generally have the authority to regulate the removal and transportation of lead-based paint and the generated waste through the appropriate state environmental and public health agencies. Most requirements are for mitigation in the case of a lead-poisoned child, for protection of children, or for oversight to ensure the safe handling and disposal of lead waste. When undertaking a lead-based paint reduction program, it is important to determine which laws are in place that may affect the project.

Local Ordinances. Check with local health departments, poison control centers, and offices of housing and community development to determine whether any laws require compliance by building owners. Determine whether projects are considered abatements and will require special contractors and permits.

Owner's Responsibility. Owners are ultimately responsible for ensuring that hazardous waste is properly disposed of when it is generated on their own sites. Owners should check with their state government to determine whether an abatement project requires a certified contractor. Owners should establish that the contractor is responsible for the safety of the crew, to ensure that all applicable laws are followed, and that transporters and disposers of hazardous waste have liability insurance as a protection for the owner. The owner should notify the contractor that lead-based paint may be present and that it is the contractor's responsibility to follow appropriate work practices to protect workers and to complete a thorough cleanup to ensure that lead-laden dust is not present after the work is completed. Renovation contractors are required by EPA to distribute an informative educational pamphlet (Protect Your Family from Lead in Your Home) to occupants before starting work that could disturb lead-based paint (http://www.epa.gov/lead/ leadinfo.htm#remodeling).

Arsenic

Lead arsenate was used legally up to 1988 in most of the orchards in the United States. Often 50 applications or more of this pesticide were applied each year. This toxic heavy metal compound has accumulated in the soil around houses and under the numerous orchards in the country, contaminating both wells and land. These orchards are often turned into subdivisions as cities expand and sprawl occurs. Residues from the pesticide lead arsenate, once used heavily on apple, pear, and other orchards, contaminate an estimated 70,000 to 120,000 acres in the state of Washington alone, some of it in areas where agriculture has been replaced with housing, according to state ecology department officials and others.

Lead arsenate, which was not banned for use on food crops until 1988, nevertheless was mostly replaced by the pesticide dichlorodiphenyltrichloroethane (DDT) and its derivatives in the late 1940s. DDT was banned in the United States in 1972, but is used elsewhere in the world.

For more than 20 years, the wood industry has infused green wood with heavy doses of arsenic to kill bugs and prevent rot. Numerous studies show that arsenic sticks to children's hands when they play on treated wood, and it is absorbed through the skin and ingested when they put their hands in their mouths. Although most uses of arsenic wood treatments were phased out by 2004, an estimated 90% of existing outdoor structures are made of arsenic-treated wood [65].

In a study conducted by the University of North Carolina Environmental Quality Institute in Asheville, wood samples were analyzed and showed that

- Older decks and play sets (7 to 15 years old) that were preserved with chromated copper arsenic expose people to just as much arsenic on the wood surface as do newer structures (less than 1 year old). The amount of arsenic that testers wiped off a small area of wood about the size of a 4-year-old's handprint typically far exceeds what EPA allows in a glass of water under the Safe Drinking Water Act standard. Figure 5.9 shows a safety warning label placed on wood products.
- Arsenic in the soil from two of every five backyards or parks tested exceeded EPA's Superfund cleanup level of 20 ppm.

Arsenic is not just poisonous in the short term, it causes cancer in the long term. Arsenic is on EPA's short list of chemicals known to cause cancer in humans. According to the National Academy of Sciences, exposure to arsenic

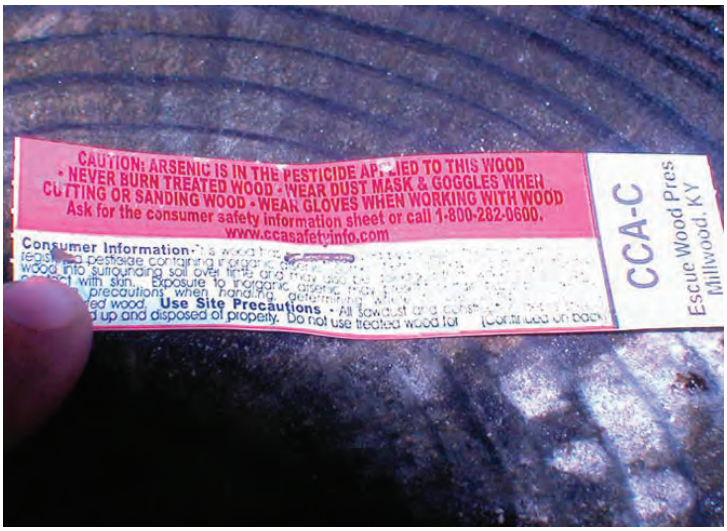

Figure 5.9. Arsenic Label

causes lung, bladder, and skin cancer in humans, and is suspected as a cause of kidney, prostate, and nasal passage cancer.

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Building Characteristics

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19. BUILDING CHARACTERISTICS

19.1. INTRODUCTION

This document is an update to Chapter 19 (Building Characteristics) of the *Exposure Factors Handbook; 2011 Edition*. New information that has become available since 2011 has been added, and the recommended values have been revised, as needed to reflect the additional information. The chapter includes a comprehensive review of the scientific literature through 2017. The new literature was identified via formal literature searches conducted by EPA library services as well as targeted internet searches conducted by the authors of this chapter. Appendix A provides a list of the key terms that were used in the literature searches. Revisions to this chapter have been made in accordance with the approved quality assurance plan for the *Exposure Factors Handbook*.

As described in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011), key studies represent the most up-to-date and scientifically sound for deriving recommendations for exposure factors, whereas other studies are designated "relevant," meaning applicable or pertinent, but not necessarily the most important. For example, studies that provide supporting data or information related to the factor of interest (e.g., building materials, building foundation types), or have study designs or approaches that make the data less applicable to the population of interest (e.g., studies not conducted in the United States) have been designated as relevant rather than key. Key studies were selected based on the general assessment factors described in Chapter 1 of the Handbook.

Unlike previous chapters in this handbook, which focus on human behavior or characteristics that affect exposure, this chapter focuses on building characteristics. Assessment of exposure in indoor settings requires information on the availability of the chemical(s) of concern at the point of exposure, characteristics of the structure and microenvironment that affect exposure, and human presence within the building. The purpose of this chapter is to provide data that are available on building characteristics that affect exposure in an indoor environment. This chapter addresses residential and nonresidential building characteristics (volumes, surface areas, mechanical systems, and types of foundations), transport phenomena that affect chemical transport within a building (airflow, chemical-specific deposition and filtration, and soil tracking), information on indoor water uses, and on various types of indoor building-related sources associated with airborne exposure and soil/house dust sources. Source-receptor relationships in indoor exposure scenarios can be complex due to interactions among sources, and transport/transformation processes that result from chemical-specific and building-specific factors.

There are many factors that affect indoor air exposures. Indoor air models generally require data on several parameters. This chapter provides recommendations on two parameters, volume and air exchange rates. Other factors that affect indoor air quality are furnishings, siting, weather, ventilation and infiltration, environmental control systems, material durability, operation and maintenance, occupants and their activities, and building structure. Available relevant information on some of these other factors is provided in this chapter, but specific recommendations are not provided, as site-specific parameters are preferred.

Figure 19-1 illustrates the complex factors that must be considered when conducting exposure assessments in an indoor setting. The primary cause of indoor pollution is the release of gases or particles into the air from indoor and outdoor sources. In addition to sources within the building, chemicals of concern may enter the indoor environment from outdoor air, soil, gas, water supply, tracked-in soil, and industrial work clothes worn by the residents. Indoor concentrations are affected by loss mechanisms, also illustrated in Figure 19-1, involving chemical reactions, deposition to and re-emission from surfaces, and transport out of the building. Particle-bound chemicals can enter indoor air through resuspension. Indoor air concentrations of gas-phase organic chemicals are affected by the presence of reversible sinks formed by a wide range of indoor materials. In addition, the activity of human receptors greatly affects their exposure as they move from room to room, entering and leaving areas with different levels and types of chemicals. Data on human activities, such as time spent at various rooms in the house, can be found in Chapter 16 of this handbook.

Inhalation of airborne chemicals in indoor settings are typically modeled by considering the building as an assemblage of one or more well-mixed zones. A zone is defined as one room, a group of interconnected rooms, or an entire building. At this macroscopic level, well-mixed assumptions form the basis for interpretation of measurement data as well as simulation of hypothetical scenarios. Exposure assessment models on a macroscopic level incorporate important physical factors and processes. These well-mixed, macroscopic models have been used to perform indoor air quality simulations (Axley, 1989), as well as indoor air exposure assessments (McKone, 1989; Ryan, 1991). Nazaroff and Cass (1986) and Wilkes et al. (1992) have used computer programs

featuring finite difference or finite element numerical techniques to model mass balance. A simplified approach using desktop spreadsheet programs has been used by Jennings et al. (1987a). U.S. Environmental Protection Agency (EPA) has created two useful indoor air quality models: the (I-BEAM) (https://www.epa.gov/indoor-air-quality-iaq/indoor-air-quality-building-education-and-assessment-model), which estimates indoor air quality in commercial buildings and the *Multi-Chamber Concentration and Exposure Model* (MCCEM) (https://www.epa.gov/tsca-screening-tools/multi-chamber-concentration-and-exposure-model-mccem-version-12), which estimates average and peak indoor air concentrations of chemicals released from residences.

Major air transport pathways for airborne substances in buildings include the following:

- Air exchange across the building envelope—Air leakage through windows, doorways, intakes and exhausts, and "adventitious openings" (i.e., cracks and seams) that combine to form the leakage configuration of the building envelope plus natural and mechanical ventilation;
- Interzonal airflows—Transport through doorways, ductwork, and service chaseways that interconnect rooms or zones within a building; and
- Local circulation—Convective and advective air circulation and mixing within a room or within a zone.

The air exchange rate is generally expressed in terms of air changes per hour (ACH), with units of ($hour^{-1}$). It is defined as the ratio of the airflow ($m^3\ hour^{-1}$) to the volume (m^3). The distribution of airflows across the building envelope that contributes to air exchange and the interzonal airflows along interior flowpaths is determined by the interior pressure distribution. The forces causing the airflows are temperature differences, the actions of wind, and natural and mechanical ventilation systems. Basic concepts on distributions and airflows have been reviewed by the American Society of Heating Refrigerating & Air Conditioning Engineers (ASHRAE, 2013). Indoor-outdoor and room-to-room temperature differences create density differences that help determine basic patterns of air motion. During the heating season, warmer indoor air tends to rise to exit the building at upper levels by stack action. Exiting air is replaced at lower levels by an influx of colder outdoor air. During the cooling season, this pattern is reversed: stack forces during the cooling season are generally not as strong as in the heating season because the indoor-outdoor temperature differences are not as pronounced.

The position of the neutral pressure level (i.e., the point where indoor-outdoor pressures are equal) depends on the leakage configuration of the building envelope. The stack effect arising from indoor-outdoor temperature differences is also influenced by the partitioning of the building interior. When there is free communication between floors or stories, the building behaves as a single volume affected by a generally rising current during the heating season and a generally falling current during the cooling season. When vertical communication is restricted, each level essentially becomes an independent zone. As the wind flows past a building, regions of positive and negative pressure (relative to indoors) are created within the building; positive pressures induce an influx of air, whereas negative pressures induce an outflow. Wind effects and stack effects combine to determine a net inflow or outflow.

The final element of indoor transport involves the actions of natural and mechanical ventilation systems. Natural ventilation uses pressure differences indoors and outdoors that arise from natural forces through openings such as windows, while mechanical systems circulate indoor air through the use of fans. There are generally three air distribution methods used for room ventilation: mixed ventilation, displacement ventilation, and stratum ventilation (Cheng and Lin, 2015). A mixed ventilation results in a uniform environment since air is supplied by jets. Displacement ventilation uses gravity to form a stratified environment. In stratum ventilation, the air is directly delivered to occupants' head level.

Mechanical ventilation systems may be connected to heating/cooling systems that, depending on the type of building, recirculate thermally treated indoor air or a mixture of fresh air and recirculated air. Mechanical systems also may be solely dedicated to exhausting air from a designated area, as with some kitchen range hoods and bath exhausts, or to recirculating air in designated areas as with a room fan. Local air circulation also is influenced by the movement of people and the operation of local heat sources.

19.2. RECOMMENDATIONS

Table 19-1 presents the recommendations for residential building volumes and air exchange rates. Table 19-2 presents the confidence ratings for the recommended residential building volumes. The 2009 Residential Energy Consumption Survey (RECS) data

indicates a 446 m^3 average living space (approximately 2000 ft^2 area, assuming an 8 ft ceiling height) (U.S. DOE, 2013). However, these values vary depending on the type of housing (see Section 19.3.1.1). The recommended lower end of housing volume is 154 m^3 (approximately 675 ft^2 area assuming ceiling height of 8 ft). The 10th percentile is based on EPA's analysis of the data from the 2005 RECS survey. Other percentiles are available in Section 19.3.1.1.

Residential air exchange rates vary by region of the country and seasonally. The recommended median air exchange rate for all regions combined is 0.45 ACH. The arithmetic mean is not preferred because it is influenced fairly heavily by extreme values at the upper tail of the distribution. This value was derived by Koontz and Rector (1995) using the perflourocarbon tracer (PFT) database and is supported by Persily et al. (2010). Although Persily et al. (2010) provides more recent information on air exchange rates, the data were based on modeling data from two databases including the RECS database and the U.S. Census Bureau American Housing Survey (AHS) database. Koontz and Rector (1995) also has an advantage over Persily et al. (2010) in that it provides data for the various regions of the country. Section 19.5.1.1.1 presents distributions for the various regions of the country. For a conservative value, the 10th percentile for the PFT database (0.18 ACH) is recommended (see Section 19.5.1.1.1).

Table 19-3 presents the recommended values for nonresidential building volumes and air exchange rates. Volumes of nonresidential buildings vary with type of building (e.g., office space, malls). They range from 1,889 m^3 for food services to 287,978 m^3 for enclosed malls. The mean for all buildings combined is 5,575 m^3. These data come from the Commercial Buildings Energy Consumption Survey (CBECS) (U.S. DOE, 2008b). The last CBECS for which data are publicly available was conducted in 2012. However, microdata from this survey year have not been analyzed by EPA. Instead, analyses of the 2003 data were conducted by EPA to derive recommendations for nonresidential building volume and air exchange rates. Table 19-4 presents the confidence ratings for the nonresidential building volume recommendations. The mean air exchange rate for all nonresidential buildings combined is 1.5 ACH. The 10th percentile air exchange rate for all buildings combined is 0.60 ACH. These data come from Turk et al. (1987).

Table 19-5 presents the confidence ratings for the air exchange rate recommendations for both residential and nonresidential buildings. Air exchange rate data presented in the studies are extremely limited. Therefore, the recommended values have been assigned a "low" overall confidence rating, and these values should be used with caution.

Volume and air exchange rates can be used by exposure assessors in modeling indoor-air concentrations as one of the inputs to exposure estimation. Other inputs to the modeling effort include rates of indoor pollutant generation and losses to (and, in some cases, re-emissions from) indoor sinks. Other things being equal (i.e., holding constant the pollutant generation rate and effect of indoor sinks), lower values for either the indoor volume or the air exchange rate will result in higher indoor-air concentrations. Thus, values near the lower end of the distribution (e.g., 10th percentile) for either parameter are appropriate in developing conservative estimates of exposure.

There are some uncertainties in, or limitations on, the distribution for volumes and air exchange rates that are presented in this chapter. In addition, there are no systematic survey studies of air exchange rate. For example, the RECS contains information on floor area rather than total volume. The PFT database did not base its measurements on a sample that was statistically representative of the national housing stock or balanced by time of the year. PFT has been found to underpredict seasonal average air exchange by 15 to 35% Sherman (1989). Using PFT to determine air exchange can produce significant errors when conditions during the measurements greatly deviate from idealizations calling for constant, well-mixed conditions. Principal concerns focus on the effects of naturally varying air exchange and the effects of temperature in the permeation source. Some researchers have found that failing to use a time-weighted average temperature can greatly affect air exchange rate estimates (Leaderer et al., 1985). A final difficulty in estimating air exchange rates for any particular zone results from interconnectedness of multizone models and the effect of neighboring zones as demonstrated by Sinden (1978) and Sandberg (1984).

Table 19-1. Summary of Recommended Values for Residential Building Parameters

	Mean	10th Percentile	Source
Volume of residence[a]	446 m^3 (central estimate)[b]	154 m^3 (lower percentile)[c]	EPA analysis of U.S. DOE, (2013, 2008a)
Air exchange rate	0.45 ACH (central estimate)[d]	0.18 ACH (lower percentile)[e]	Koontz and Rector (1995); Persily et al. (2010)

[a] Volumes vary with type of housing. For specific housing type volumes, see Tables 19-6 and 19-7.
[b] Mean value presented in Table 19-6 recommended for use as a central estimate for all single family homes, including mobile homes and multifamily units.
[c] 10th percentile value from Table 19-9 recommended to be used as a lower percentile estimate.
[d] Median value recommended to be used as a central estimate based across all U.S. census regions and various housing types (see Tables 19-25 and 19-26).
[e] 10th percentile value across all U.S. census regions recommended to be used as a lower percentile value (see Table 19-25).
ACH = Air changes per hour.

Table 19-2. Confidence in Residential Volume Recommendations[a]

General Assessment Factors	Rationale	Rating
Soundness		Medium
Adequacy of Approach	The study was based on primary data. Volumes were estimated assuming an 8-foot ceiling height. The effect of this assumption has been tested by Murray (1997) and found to be insignificant.	
Minimal (or defined) bias	Selection of residences was random.	
Applicability and utility		Medium
Exposure factor of interest	The focus of the studies was on estimating house volume as well as other factors.	
Representativeness	Residences in the United States were the focus of the study. The sample size was fairly large and representative of the entire United States. Samples were selected at random.	
Currency	The most recent RECS surveys for which volume data are available were conducted in 2005 and 2009.	
Data collection period	Data were collected in 2005 and 2009.	
Clarity and completeness		High
Accessibility	The RECS database is publicly available.	
Reproducibility	Direct measurements were made.	
Quality assurance	Not applicable.	
Variability and uncertainty		Medium
Variability in population	Distributions are presented by housing type and regions, but some subcategory sample sizes were small.	
Uncertainty	Although residence volumes were estimated using the assumption of 8-foot ceiling height, Murray (1997) found this assumption to have minimal impact.	
Evaluation and review		Medium
Peer review	The RECS database is publicly available. Some data analysis was conducted by EPA.	
Number and agreement of studies	Only one study was used to derive recommendations. Other relevant studies provide supporting evidence.	
Overall Rating		**Medium**

[a] See Section 1.5.2 in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011) for a detailed description of the evaluation criteria used in this table.

Table 19-3. Summary of Recommended Values for Nonresidential Building Parameters

	Mean[a]	10th Percentile[b]	Source
Volume of building (m^3)[c]			
Vacant	4,789	408	EPA analysis of U.S. DOE (2008b)
Office	5,036	510	
Laboratory	24,681	2,039	
Nonrefrigerated warehouse	9,298	1,019	
Food sales	1,889	476	
Public order and safety	5,253	816	
Outpatient healthcare	3,537	680	
Refrigerated warehouse	19,716	1,133	
Religious worship	3,443	612	
Public assembly	4,839	595	
Education	8,694	527	
Food service	1,889	442	
Inpatient healthcare	82,034	17,330	
Nursing	15,522	1,546	
Lodging	11,559	527	
Strip shopping mall	7,891	1,359	
Enclosed mall	287,978	35,679	
Retail other than mall	3,310	510	
Service	2,213	459	
Other	5,236	425	
All buildings[d]	5,575	527	
Air Exchange Rate[e]	Mean (SD)1.5 (0.87) ACH Range 0.3−4.1 ACH	0.60 ACH	Turk et al. (1987)

[a] Mean values are recommended as central estimates for nonresidential buildings (see Table 19-21).
[b] 10th percentile values are recommended as lower estimates for nonresidential buildings (see Table 19-21).
[c] Volumes were calculated assuming a ceiling height of 20 feet for warehouses and enclosed malls and 12 feet for other structures (see Table 19-21).
[d] Weighted average assuming a ceiling height of 20 feet for warehouses and enclosed malls and 12 feet for other structures (see Table 19-21).
[e] Air exchange rates for commercial buildings (see Table 19-30).
SD = Standard deviation.
ACH = Air changes per hour.

Table 19-4. Confidence in Nonresidential Volume Recommendations[a]

General Assessment Factors	Rationale	Rating
Soundness		Medium
Adequacy of approach	All nonresidential data were based on one study: CBECS (U.S. DOE, 2008b). Volumes were estimated assuming a 20-foot ceiling height assumption for warehouses and a 12-foot height assumption for all other nonresidential buildings based on scant anecdotal information. Although Murray (1997) found that the impact of an 8-foot ceiling assumption was insignificant for residential structures, the impact of these ceiling height assumptions for nonresidential buildings is unknown.	
Minimal (or defined) bias	Selection of residences was random for CBECS.	
Applicability and utility		High
Exposure factor of interest	CBECS (U.S. DOE, 2008b) contained ample building size data, which were used as the basis provided for volume estimates.	
Representativeness	CBECS (U.S. DOE, 2008b) was a nationwide study that generated weighted nationwide data based upon a large random sample.	
Currency, data collection period	The data were collected in 2003.	
Clarity and completeness		High
Accessibility	The data are available online in both summary tables and raw data. http://www.eia.doe.gov/emeu/cbecs/contents.html.	
Reproducibility	Direct measurements were made.	
Quality assurance	Not applicable.	
Variability and uncertainty		Medium
Variability in population	Distributions are presented by building type, heating and cooling system type, and employment, but a few subcategory sample sizes were small.	
Uncertainty	Volumes were calculated using speculative assumptions for building height. The impact of such assumptions may or may not be significant.	
Evaluation and review		Low
Peer review	There are no studies from the peer-reviewed literature.	
Number and agreement of studies	All data are based upon one study: CBECS (U.S. DOE, 2008b).	
Overall Rating		**Medium**

[a] See Section 1.5.2 in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011) for a detailed description of the evaluation criteria used in this table.

Table 19-5. Confidence in Air Exchange Rate Recommendations for Residential and Nonresidential Buildings[a]

General Assessment Factors	Rationale	Rating
Soundness		Low
Adequacy of approach	The studies were based on primary data; however, most approaches contained major limitations, such as assuming uniform mixing, and residences were typically not selected at random.	
Minimal (or defined) bias	Bias may result because the selection of residences and buildings was not random or balanced by time of the year. The commercial building study (Turk et al., 1987) was conducted only on buildings in the northwest United States.	
Applicability and utility		Low
Exposure factor of interest	The focus of the studies was on estimating air exchange rates as well as other factors.	
Representativeness	Study residences were typically in the United States, but only RECS (U.S. DOE, 2008a and 2013) and the AHS selected residences randomly. PFT residences were not representative of the United States. Distributions are presented by housing type and regions; although some of the sample sizes for the subcategories were small. The commercial building study (Turk et al., 1987) was conducted only on buildings in the northwest United States.	
Currency	Measurements in the PFT database were taken between 1982−1987. The Turk et al. (1987) study was conducted in the mid-1980s.	
Data Collection Period	Only short-term data were collected; some residences were measured during different seasons; however, long-term air exchange rates are not well characterized. Individual commercial buildings were measured during one season.	
Clarity and completeness		Medium
Accessibility	Papers are widely available from government reports and peer-reviewed journals.	
Reproducibility	Precision across repeat analyses has been documented to be acceptable.	
Quality assurance	Not applicable.	

Table 19-5. Confidence in Air Exchange Rate Recommendations for Residential and Nonresidential Buildings[a] (Continued)

General Assessment Factors	Rationale	Rating
Variability and uncertainty		Medium
Variability in population	For the residential estimates, distributions are presented by U.S. regions, seasons, and climatic regions, but some of the sample sizes for the subcategories were small. The commercial estimate comes from buildings in the northwest United States representing two climate zones, and measurements were taken in three seasons (spring, summer, and winter).	
Uncertainty	Some measurement error may exist. Additionally, PFT has been found to underpredict seasonal average air exchange by 15−35% (Sherman, 1989). Turk et al. (1987) estimates a 10−20% measurement error for the technique used to measure ventilation in commercial buildings.	
Evaluation and review		Low
Peer review	The studies appear in peer-reviewed literature.	
Number and agreement of studies	Three residential studies are based on the same PFT database. The database contains results of 20 projects of varying scope. The commercial building rate is based on one study.	
Overall rating		**Low**

[a] See Section 1.5.2 in Chapter 1 of the *Exposure Factors Handbook: 2011 Edition* (U.S. EPA, 2011) for a detailed description of the evaluation criteria used in this table.

19.3. RESIDENTIAL BUILDING CHARACTERISTICS STUDIES

19.3.1. Key Study of Volumes of Residences

19.3.1.1. *U.S. DOE (2017, 2013, 2008a)—Residential Energy Consumption Survey (RECS)*

Measurement surveys have not been conducted to directly characterize the range and distribution of volumes for a random sample of U.S. residences. Related data, however, are regularly collected through the U.S. Department of Energy's (DOE) RECS. In addition to collecting information on energy use, this survey collects data on housing characteristics including direct measurements of total and heated floor space for buildings visited by survey specialists. The last three surveys were conducted in 2005, 2009, and 2015. Data from these survey years were made available in 2008, 2013, and 2017, respectively. For the most recent survey conducted in 2015, a multistage probability sample of more than 5,600 residences was surveyed, representing 118.2 million housing units nationwide (www.eia.gov/consumption/residential/about.php). However, not all of the data from the 2015 survey were available in time for the revisions to this chapter. For example, the floor space area from the residences surveyed in 2015 is not available yet. In 2009, the survey consisted of a multistage probability sample of 12,083 residences, representing 113.6 million housing units nationwide. The 2009 survey response rate was 79% (U.S. DOE, 2013). Housing volumes were estimated using the RECS 2009 data since the data from the 2015 were not available. These were estimated by multiplying the heated floor space area by an assumed ceiling height of 8 feet. The data and data tables were released to the public in 2013 and are available from https://www.eia.gov/consumption/residential/data/2009/index.php?view=characteristics.

Table 19-6 presents results for average residential volume by type of residence, census region, and urbanicity (i.e., urban vs. rural). The predominant housing type—single-family detached homes—also had the largest average volume. Multifamily units and mobile homes had volumes averaging about half that of single-family detached homes, with single-family attached homes about halfway between these extremes. The average house volume for all types of units for all years was estimated to be 446 m^3. Table 19-7 presents the average residential volume for single family homes, multifamily homes, and mobile homes by housing unit type, census region, and urbanicity. Data on the relationship of residential volume to year of construction are provided in Table 19-8 and indicate a slight decrease in residential volumes between 1950 and 1979, followed by an increasing trend. A ceiling height of 8 feet was assumed in estimating the average volumes, whereas there may have been some time-related trends in ceiling height. It is important to note that the available data used to derived volumes included all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

In 2010, the EPA conducted an analysis of the RECS 2005 survey microdata files. The RECS 2005 survey consisted of a sample of 4,382 residences representing 111 million housing units nationwide. The response rate in the 2005 RECS survey was 71% (U.S. DOE 2008a). Table 19-9 presents distributions of residential volumes for all house types and all units estimated by the EPA using the 2005 microdata. Similar analysis has not been conducted with the more recent data sets from 2009 and 2015.

The advantages of this study were that the sample size was large, and it was representative of houses in the United States. Also, it included various housing types. A limitation of this analysis is that volumes were estimated assuming a ceiling height of 8 feet. Volumes of individual rooms in the house cannot be estimated. In addition, not all the data from the most recent survey years have been released.

19.3.2. Relevant Studies of Volumes of Residences

19.3.2.1. *Versar (1990)—Database on Perfluorocarbon Tracer (PFT) Ventilation Measurements*

Versar (1990) compiled a database of time-averaged air exchange and interzonal airflow measurements in more than 4,000 residences. These data were collected between 1982 and 1987. The residences that appear in this database are not a random sample of U.S. homes. However, they represent a compilation of homes visited in about 100 different field studies, some of which involved random sampling. In each study, the house volumes were directly measured or estimated. The collective homes visited in these field projects are not geographically balanced. A large fraction of these homes are located in southern California. Statistical weighting techniques were applied in developing estimates of nationwide distributions to compensate for the geographic imbalance. The Versar (1990) PFT database found a mean value of 369 m^3 (see Table 19-10).

The advantage of this study is that it provides a distribution of house volumes. However, more up-to-date data are available from RECS 2009 (U.S. DOE, 2013).

19.3.2.2. *Murray (1997)—Analysis of RECS and PFT Databases*

Using a database from the 1993 RECS and an assumed ceiling height of 8 feet, Murray (1997) estimated a mean residential volume of 382 m^3 using RECS estimates of heated floor space. This estimate is slightly different from the mean of 369 m^3 given in Table 19-10. Murray's (1997) sensitivity analysis indicated that when a fixed ceiling height of 8 feet was replaced with a randomly varying height with a mean of 8 feet, there was little effect on the standard deviation of the estimated distribution. From a separate analysis of the PFT database, based on 1,751 individual household measurements, Murray (1997) estimated an average volume of 369 m^3, the same as previously given in Table 19-10. In performing this analysis, the author carefully reviewed the PFT database in an effort to use each residence only once, for those residences thought to have multiple PFT measurements.

Murray (1997) analyzed the distribution of selected residential zones (i.e., a series of connected rooms) using the PFT database. The author analyzed the "kitchen zone" and the "bedroom zone" for houses in the Los Angeles area that were labeled in this manner by field researchers, and "basement," "first floor," and "second floor" zones for houses outside of Los Angeles for which the researchers labeled individual floors as zones. The kitchen zone contained the kitchen in addition to any of the following associated spaces: utility room, dining room, living room, and family room. The bedroom zone contained all the bedrooms plus any bathrooms and hallways associated with the bedrooms. The following summary statistics (mean ± standard deviation) were reported by Murray (1997) for the volumes of the zones described above: 199 ± 115 m^3 for the kitchen zone, 128 ± 67 m^3 for the bedroom zone, 205 ± 64 m^3 for the basement, 233 ± 72 m^3 for the first floor, and 233 ± 111 m^3 for the second floor.

The advantage of this study is that the data are representative of homes in the United States. However, more up-to-date data are available from the RECS 2009 (U.S. DOE, 2013).

19.3.2.3. *U.S. Census Bureau (2017)—American Housing Survey for the United States: 2015*

The American Housing Survey (AHS) is conducted by the Census Bureau for the Department of Housing and Urban Development. It collects data on the Nation's housing, including apartments, single-family homes, mobile homes, vacant housing units, household characteristics, housing quality, foundation type, drinking water source, equipment and fuels, and housing unit size. National data are collected biennially between May and September in odd-numbered years. The 2015 survey was comprised of a national sample of 5,686 housing units representing 118.2 million occupied primary households in the United States. The U.S. Census Bureau (2017) lists the number of residential single detached and manufactured/mobile homes in the United States within the owner or renter categories, based on the AHS (see Table 19-11). Assuming an 8-foot ceiling, these units have a median size of 340 m^3; however, these values do not include multifamily units, but include single detached and manufactured/mobile homes. It should be mentioned that 8 feet is the most common assumed ceiling height, and Murray (1997) has shown that the effect of the 8-foot ceiling height assumption is not significant.

The advantage of this study is that it was a large national sample and, therefore, representative of the United States. The limitations of these data are that distributions were not provided by the authors, and the analysis did not include multifamily units.

19.3.3. Other Factors

19.3.3.1. *Surface Area and Room Volumes*

The surface areas of floors are commonly considered in relation to the room or house volume, and their relative loadings are expressed as a surface area-to-volume, or loading ratio. Table 19-12 provides the basis for calculating loading ratios for typical-sized rooms. Constant features in the examples are a room width of 12 feet and a ceiling height of 8 feet (typical for residential buildings), or a ceiling height of 12 feet (typical for some types of commercial buildings).

Volumes of individual rooms are dependent on the building size and configuration, but summary data are not readily available. The exposure assessor is advised to define specific rooms, or assemblies of rooms, that best fit the scenario of interest. Most models for predicting indoor air concentrations specify airflows in m^3 per hour and, correspondingly, express volumes in m^3. A measurement in ft^3 can be converted to m^3 by multiplying the value in ft^3 by

0.0283 m^3/ft^3. For example, a bedroom that is 9 feet wide by 12 feet long by 8 feet high has a volume of 864 ft^3 or 24.5 m^3. Similarly, a living room with dimensions of 12 feet wide by 20 feet long by 8 feet high has a volume of 1,920 ft^3 or 54.3 m^3, and a bathroom with dimensions of 5 feet by 12 feet by 8 feet has a volume of 480 ft^3 or 13.6 m^3.

19.3.3.2. *Products and Materials*

Table 19-13 presents examples of assumed amounts of selected products and materials used in constructing or finishing residential surfaces (Tucker, 1991). Products used for floor surfaces include adhesive, varnish, and wood stain; and materials used for walls include paneling, painted gypsum board, and wallpaper. Particleboard and chipboard are commonly used for interior furnishings such as shelves or cabinets but could also be used for decking or underlayment. It should be noted that numbers presented in the table for surface area are based on typical values for residences, and they are presented as examples. In contrast to the concept of loading ratios presented above (as a surface area), the numbers in the table also are not scaled to any particular residential volume. In some cases, it may be preferable for the exposure assessor to use professional judgment in combination with the loading ratios given above. For example, if the exposure scenario involves residential wall to wall carpeting in a room of 3 × 4 m with a ceiling height of 2.5 m (approximately 8 feet), it will have a loading ratio of 0.4 m^2m^{-3} (Tichenor, 2006). This can be multiplied by an assumed residential volume and assumed fractional coverage of carpeting to derive an estimate of the surface area. More specifically, a residence with a volume of 300 m^3, a loading ratio of 0.4 m^2m^{-3}, and coverage of 80%, would have 96 m^2 of carpeting. The estimates discussed here relate to macroscopic surfaces; the true surface area for carpeting, for example, would be considerably larger because of the nature of its fibrous material.

19.3.3.3. *Mechanical System Configurations*

Mechanical systems for air movement in residences can affect the migration and mixing of pollutants released indoors and the rate of pollutant removal. Three types of mechanical systems are (1) systems associated with heating, ventilating, and air conditioning (HVAC); (2) systems whose primary function is providing localized exhaust; and (3) systems intended to increase the overall air exchange rate of the residence.

Portable space heaters intended to serve a single room, or a series of adjacent rooms, may or may not be equipped with blowers that promote air movement and mixing. Without a blower, these heaters still have the ability to induce mixing through convective heat transfer. If the heater is a source of combustion pollutants, as with unvented gas or kerosene space heaters, then the combination of convective heat transfer and thermal buoyancy of combustion products will result in fairly rapid dispersal of such pollutants. The pollutants will disperse throughout the floor where the heater is located and to floors above the heater, but may not disperse to floors below.

Central forced-air HVAC systems are common in many residences. Such systems, through a network of supply/return ducts and registers, can achieve fairly complete mixing within 20 to 30 minutes (Koontz et al., 1988). The air handler for such systems is commonly equipped with a filter (see Figure 19-2) that can remove particle-phase contaminants. Further removal of particles, via deposition on various room surfaces (see Section 19.5.5), is accomplished through increased air movement when the air handler is operating.

Figure 19-2 also distinguishes forced-air HVAC systems by the return layout in relation to supply registers. The return layout shown in the upper portion of the figure is the type most commonly found in residential settings. On any floor of the residence, it is typical to find one or more supply registers to individual rooms, with one or two centralized return registers. With this layout, supply/return imbalances can often occur in individual rooms, particularly if the interior doors to rooms are closed. In comparison, the supply/return layout shown in the lower portion of the figure by design tends to achieve a balance in individual rooms or zones. Airflow imbalances can also be caused by inadvertent duct leakage to unconditioned spaces such as attics, basements, and crawl spaces. Such imbalances usually depressurize the house, thereby increasing the likelihood of contaminant entry via soil-gas transport or through spillage of combustion products from vented fossil-fuel appliances such as fireplaces and gas/oil furnaces.

Mechanical devices such as kitchen fans, bathroom fans, and clothes dryers are intended primarily to provide localized removal of unwanted heat, moisture, or odors. Operation of these devices tends to increase the air exchange rate between the indoors and outdoors. Because local exhaust devices are designed to be near certain indoor sources, their effective removal rate for locally generated pollutants is greater than would be expected from the dilution effect of increased air exchange. Operation of these devices also tends to depressurize the house, because

replacement air usually is not provided to balance the exhausted air.

An alternative approach to pollutant removal is one which relies on an increase in air exchange to dilute pollutants generated indoors. This approach can be accomplished using heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs). Both types of ventilators are designed to provide balanced supply and exhaust airflows and are intended to recover most of the energy that normally is lost when additional outdoor air is introduced. Although ventilators can provide for more rapid dilution of internally generated pollutants, they also increase the rate at which outdoor pollutants are brought into the house. A distinguishing feature of the two types is that ERVs provide for recovery of latent heat (moisture) in addition to sensible heat. Moreover, ERVs typically recover latent heat using a moisture-transfer device such as a desiccant wheel. It has been observed in some studies that the transfer of moisture between outbound and inbound air streams can result in some re-entrainment of indoor pollutants that otherwise would have been exhausted from the house (Andersson et al., 1993). Inadvertent air communication between the supply and exhaust air streams can have a similar effect.

Studies quantifying the effect of mechanical devices on air exchange using tracer-gas measurements are uncommon and typically provide only anecdotal data. The common approach is for the expected increment in the air exchange rate to be estimated from the rated airflow capacity of the device(s). For example, if a device with a rated capacity of 100 ft^3 per minute, or 170 m^3 per hour, is operated continuously in a house with a volume of 400 m^3, then the expected increment in the air exchange rate of the house would be 170 m^3 $hour^{-1}$/400 m^3, or approximately 0.4 ACH.

U.S. DOE RECS contains data on residential heating characteristics. The data show that most homes in the United States have some kind of heating and air conditioning system (U.S. DOE, 2017). The types of system vary regionally within the United States. Table 19-14 shows the type of primary and secondary heating systems found in U.S. residences. The predominant primary heating system in the Midwest is natural gas (used by 67.0% of homes there) while most homes in the South (60.1%) primarily heat with electricity. Nationwide, 36.6% of residences have a secondary heating source, typically an electric source.

Table 19-15 shows the type of heating systems found in the United States by climate region. It is noteworthy that 51.4% of residences in very cold/cold climate use central heating compared to 19.7% in hot humid climate.

Table 19-16 shows that 87.2% of U.S. residences have some type of cooling system: 65.2% have central air while 26.7% use individual air conditioning units. Like heating systems, cooling system type varies regionally as well. In the South, 95.3% of residences have either central or room air conditioning units whereas only 54.9% of residences in the Western United States have air conditioning.

19.3.3.4. *Type of Foundation*

The type of foundation of a residence is of interest in residential exposure assessment. It provides some indication of the number of stories and house configuration, as well as an indication of the relative potential for soil−gas transport. For example, such transport can occur readily in homes with enclosed crawl spaces. Homes with basements provide some resistance, but still have numerous pathways for soil−gas entry. By comparison, homes with crawl spaces open to the outside have significant opportunities for dilution of soil gases prior to transport into the house. Using data from the 2015 AHS, of total housing units in the United States, 31% have a basement under the entire building, 11% have a basement under part of the building, 22% have a crawl space, and 36% are on a concrete slab (U.S. Census Bureau, 2017).

19.3.3.4.1. Lucas et al. (1992)—National Residential Radon Survey

The estimated percentage of homes with a full or partial basement according to the National Residential Radon Survey of 5,700 households nationwide was 44% (see Table 19-17) (Lucas et al., 1992). The National Residential Radon Survey provides data for more refined geographical areas, with a breakdown by the 10 EPA Regions. The New England region (i.e., EPA Region 1), which includes Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont, had the highest prevalence of basements (93%). The lowest prevalence (4%) was for the South Central region (i.e., EPA Region 6), which includes Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Section 19.3.3.4.2 presents the states associated with each census region and EPA region.

19.3.3.4.2. U.S. DOE (2008a, 2013, 2017)—Residential Energy Consumption Survey (RECS)

The three most recent RECS (described in Section 19.3.1.1) were administered in 2005, 2009,

and 2015 (U.S. DOE, 2008a, 2013, 2017). The type of information requested by the survey questionnaire included the type of foundation for the residence (i.e., basement, enclosed crawl space, crawl space open to outside, or concrete slab). This information was not obtained for multifamily structures with five or more dwelling units or for mobile homes. EPA analyzed the RECS 2015 data (U.S. DOE, 2017) to estimate the percentage of residences with basements by census region. Table 19-18 indicates that 43.5% of residences have basements nationwide. Table 19-19 shows the states associated with each EPA region and census region. Table 19-20 presents the percentage of residences with each foundation type, by census region, and for the entire United States. The foundation type data (other than basements) were not included in the RECS 2015 survey. Therefore, the values presented in Table 19-20 are based on data from the RECS 2009 survey (U.S. DOE, 2013). The percentages can add up to more than 100% because some residences have more than one type of foundation; for example, many split-level structures have a partial basement combined with some crawlspace that typically is enclosed. The data in Table 19-20 indicate that 39.9% of residences nationwide have a basement. It also shows that a large fraction of homes have concrete slabs (46.5%). There are also variations by census region. For example, around 74.7 and 72.5% of the residences in the Northeast and Midwest regions, respectively, have basements. In the South and West regions, the predominant foundation type is concrete slab.

The advantage of this study is that it had a large sample size, and it was representative of houses in the United States. Also, it included various housing types. A limitation of this analysis is that homes have multiple foundation types, and the analysis does not provide estimates of square footage for each type of foundation. Also, the information collected varied slightly across survey years and the data from the most recent survey were not available to be analyzed.

19.4. NONRESIDENTIAL BUILDING CHARACTERISTICS STUDIES

19.4.1. U.S. DOE (2008b, 2016)—Nonresidential Building Characteristics—Commercial Buildings Energy Consumption Survey (CBECS)

The U.S. Department of Energy conducts the CBECS to collect data on the characteristics and energy use of commercial buildings. CBECS is a national survey of U.S. buildings that DOE first conducted in 1979. The survey is conducted every 4 years. In 2010, EPA conducted an analysis of the U.S. DOE CBECS 2003 data, released in 2008. CBECS defines "Commercial" buildings as all buildings in which at least half of the floorspace is used for a purpose that is not residential, industrial, or agricultural, so they include building types that might not traditionally be considered commercial, such as schools, correctional institutions, and buildings used for religious worship.

The 2003 CBECS provided nationwide estimates for the United States based upon a weighted statistical sample of 5,215 buildings. DOE releases a data set about the sample buildings for public use. The 2003 CBECS Public Use Microdata set includes data for 4,820 nonmall commercial buildings (U.S. DOE, 2008b). A second data set is available that includes information on malls, lacks building characteristics data. Building characteristics data provided by CBECS includes floor area, number of floors, census division, heating and cooling design, principal building activity, number of employees, and weighting factors. Although DOE released the Microdata from the 2012 survey in 2016, EPA did not analyze these data to estimate volumes of commercial buildings, the number of hours per week they are open, and the number of employees during the main shift because of the amount of effort involved and the likelihood that values have not changed considerably.

Table 19-21 shows that nonresidential buildings vary greatly in volumes. The table shows average volume for a numbers of structures including offices (5,036 m^3), restaurants (food services) (1,889 m^3), schools (education) (8,694 m^3), hotels (lodging) (11,559 m^3), and enclosed shopping malls (287,978 m^3). Each of these structures varies considerably in size as well. The large shopping malls are over 500,000 m^3 (90^{th} percentile). The most numerous of the nonresidential buildings are office buildings (17%), nonfood service buildings (13%), and warehouses (12%).

Table 19-22 presents data on the number of hours various types of nonresidential buildings are open for business and the number of employees that work in such buildings. In general, places of worship have the most limited hours. The average place of worship is open 32 hours per week. On the other extreme are healthcare facilities, which are open 168 hours a week (24 hours per day, 7 days per week). The average restaurant is open 86 hours per week. Hours vary considerably by building type. Some offices, labs, warehouses, restaurants, police stations, and hotels are also open 24 hours per day, 7 days per week, as reflected by the 90^{th} percentiles. Table 19-22 also presents the number of employees typically employed in such buildings during the main shift. Overall, the average building houses 16 workers during its primary

shift, but some facilities employ many more. The average hospital employs 471 workers during its main shift, although those in the 10th percentile employ only 175, and those in the 90th employ 2,250.

EPA used the 2012 CBECS, however, to update the information on the heating and cooling sources using the summary tables tabulated by the U.S. Energy Information Administration of the U.S. DOE and released to the public in 2016 (U.S. DOE, 2016). Tables 19-23 and 19-24 present these data. Table 19-23 indicates that electricity and natural gas are the heating sources used by a majority of nonresidential buildings. Of those buildings heated by fuel oil, most are older buildings.

Table 19-24 describes nonresidential building cooling characteristics. About 80% (i.e., 4,461/5,557 × 100) of nonresidential buildings have air conditioning, but this varies regionally from 14% in the Northeast to 40% in the South. Nationwide, 79% (i.e., 4,413/5,557 × 100) of nonresidential buildings use electricity for air conditioning. The remaining fraction use natural gas or chilled water.

It should be noted, however, that there are many critical exposure assessment elements not addressed by CBECS. These include a number of elements discussed in more detail in the Residential Building Characteristics Studies section (i.e., Section 19.3). Data to characterize the room volume, products and materials, and foundation type for nonresidential buildings were not available in CBECS.

Another characteristic of nonresidential buildings needed in ventilation and air exchange calculations is ceiling height. Unseen spaces (e.g. above ceiling tiles) complicate the volume and mixing assumptions by creating rather large separate compartments. In the residential section of this chapter, ceiling height was assumed to be 8 feet, a figure often assumed for residential buildings. For nonresidential buildings, EPA has assumed a 20-foot ceiling height for warehouses and enclosed shopping malls and a 12-foot average ceiling height for other structures. These assumptions are based on EPA's professional judgment. Murray (1997) found that the impact of assuming an 8-foot ceiling height for residences was insignificant, but nonresidential ceiling height varies more greatly and may or may not have a significant impact on calculations.

19.5. TRANSPORT RATE STUDIES

19.5.1. Air Exchange Rates

Air exchange is the balanced flow into and out of a building and is composed of three processes: (1) infiltration—air leakage through random cracks, interstices, and other unintentional openings in the building envelope; (2) natural ventilation—airflows through open windows, doors, and other designed openings in the building envelope; and (3) forced or mechanical ventilation—controlled air movement driven by fans (Breen et al., 2014).

For nearly all indoor exposure scenarios, air exchange is treated as the principal means of diluting indoor concentrations. The air exchange rate is generally expressed in terms of ACH (with units of $hours^{-1}$). It is defined as the ratio of the airflow ($m^3\ hours^{-1}$) to the volume (m^3). Thus, ACH and building size and volume are negatively correlated. Air exchange rates can affect the dynamic and the steady state behavior of indoor air pollutants (Breen et al., 2014).

Air exchange rates are influenced by many factors including building characteristics, type of ventilation system affecting air flow patterns (includes natural and mechanical), temperature differentials between rooms and floors and between indoors and outdoors, seasonality, occupant behavior (e.g., walking from room to room, opening of windows) and measurement techniques (Lee et al., 2016; Wu and Lin, 2015; Breen et al., 2014). Higher air exchange rates have been observed in the summer and during occupied daytime periods (Bekö et al., 2016; Lee et al., 2016; Wu and Lin, 2015; Breen et al., 2014; Kearney et al 2014; Zhao and Zeng, 2009).

The primary method for measuring air exchange rates in a building consist of releasing a nonreactive gas tracer into the building and allowing it to mix with the indoor air. The tracer gas can be injected into the building using an emitter device (e.g., SF_6) or released from the exhaled breath of building occupants in the form of CO_2. These tracer concentrations are monitored to estimate the air exchange rates. The gas tracer methods are based on a mass balance approach assuming that the gas tracer is well mixed, the tracer concentration outdoor is zero, and accounting for air leakage (Breen et al., 2014).

No measurement surveys have been conducted to directly evaluate the range and distribution of building air exchange rates. In addition, there is almost no information on the use of natural ventilation (e.g., how much or often windows are kept open). Although a significant number of air exchange measurements have been carried out over the years, there has been a diversity of protocols and study objectives. Since the early 1980s, however, an inexpensive PFT technique has been used to measure time-averaged air exchange and interzonal airflows in thousands of occupied residences using essentially similar protocols (Dietz et al., 1986). The PFT technique utilizes miniature permeation tubes as tracer emitters and passive samplers to collect the tracers. Sampling periods

(e.g., days, weeks, months) vary depending on the study design. The passive samplers are returned to the laboratory for analysis by gas chromatography. These measurement results have been compiled to allow various researchers to access the data (Versar, 1989).

19.5.1.1. *Key Study of Residential Air Exchange Rates*

19.5.1.1.1. Koontz and Rector (1995)—Estimation of distributions for residential air exchange rates

In analyzing the composite data from various projects (2,971 measurements), Koontz and Rector (1995) assigned weights to the results from each state to compensate for the geographic imbalance in locations where PFT measurements were taken. The results were weighted in such a way that the resultant number of cases would represent each state in proportion to its share of occupied housing units, as determined from the 1990 U.S. Census of Population and Housing.

Table 19-25 shows summary statistics from the Koontz and Rector (1995) analysis, for the country as a whole and by census regions. Based on the statistics for all regions combined, the authors suggested that a 10^{th} percentile value of 0.18 ACH would be appropriate as a conservative estimator for air exchange in residential settings, and that the 50^{th} percentile value of 0.45 ACH would be appropriate as a typical air exchange rate. In applying conservative or typical values of air exchange rates, it is important to realize the limitations of the underlying database. Although the estimates are based on thousands of measurements, the residences represented in the database are not a random sample of the U.S. housing stock. Also, the sample population is not balanced in terms of geography or time of year, although statistical techniques were applied to compensate for some of these imbalances. In addition, PFT measurements of air exchange rates assume uniform mixing of the tracer within the building. This is not always so easily achieved. Furthermore, the degree of mixing can vary from day to day and house to house because of the nature of the factors controlling mixing (e.g., convective air monitoring driven by weather, and type and operation of the heating system). The relative placement of the PFT source and the sampler can also cause variability and uncertainty. It should be noted that sampling is typically done in a single location in a house that may not represent the average from that house. In addition, very high and very low values of air exchange rates based on PFT measurements have greater uncertainties than those in the middle of the distribution. Despite such limitations, the estimates in Table 19-25 are believed to represent the best available information on the distribution of air exchange rates across U.S. residences throughout the year.

19.5.1.1.2. Persily et al. (2010)—Modeled infiltration rate distributions for U.S. housing

Persily et al. (2010) generated frequency distributions of residential infiltration rates using CONTAM, a multizone airflow model. A collection of 209 residences was selected to be representative of 80% of the U.S. housing stock. The residences were taken from a database resulting from two residential housing surveys: the U.S. Department of Energy Residential Energy Consumptions Survey (RECS) and the U.S. Census Bureau American Housing Survey (AHS). Together, these data sets included over 60,000 U.S. residences. The RECS 1997 was conducted between mid-April to the middle of June 1997 (U.S. DOE, 1997). The residences were grouped into four categories: detached, attached, manufactured homes, and apartments, and include key characteristics such as age, floor area, number of floors, foundation type, and garage. Representations of these residences were created in the airflow model CONTAM, and were used in this study to provide distributions for infiltration rates. The simulations were conducted for 19 cities representing U.S. climates and accounted for the impacts of ventilation system operation on infiltration rates.

Distributions of air change rates for various house categories are presented in Table 19-26. The 10^{th} and 50^{th} percentiles national average air change rate for single family homes were 0.16 and 0.44 ACH, respectively. For all house categories, the 50^{th} percentile air change rate ranged from 0.09 to 0.58 ACH. In general, houses built after 1970 are tighter and show lower air exchange rates than those built before 1970.

The advantages of this study are that it is based on a relatively large number of homes and that the residences are representative of homes across the United States. However, the results of the study are based on modeling and the data used to generate the simulations were collected in 1997.

19.5.1.2. *Relevant Studies of Residential Air Exchange Rates*

19.5.1.2.1. Nazaroff et al. (1988)—Radon entry via potable water

Nazaroff et al. (1988) aggregated the data from two studies conducted earlier using tracer-gas decay.

At the time these studies were conducted, they were the largest U.S. studies to include air exchange measurements. The first (Grot and Clark, 1981) was conducted in 266 dwellings occupied by low-income families in 14 different cities. The geometric mean ± standard deviation for the air exchange measurements in these homes, with a median house age of 45 years, was 0.90 ± 2.13 ACH. The second study (Grimsrud et al., 1983) involved 312 newer residences, with a median age of less than 10 years. Most of the houses were located in Washington, California, Colorado, New York and Ontario, Canada. Based on measurements taken during the heating season, the geometric mean ± standard deviation for these homes was 0.53 ± 1.71 ACH. Based on an aggregation of the two distributions with proportional weighting by the respective number of houses studied, Nazaroff et al. (1988) developed an overall distribution with a geometric mean of 0.68 ACH and a geometric standard deviation of 2.01.

The limitation of this study is that houses did not represent all climatic regions of the United States and the number of houses included in the studies was small.

19.5.1.2.2. Versar (1989)—Database of PFT ventilation measurements

The residences included in the PFT database do not constitute a random sample across the United States. They represent a compilation of homes visited in the course of about 100 separate field-research projects by various organizations, some of which involved random sampling, and some of which involved judgmental or fortuitous sampling. Table 19-27 summarizes the larger projects in the PFT database, in terms of the number of measurements (samples), states where samples were taken, months when samples were taken, and summary statistics for their respective distributions of measured air exchange rates. For selected projects (Lawrence Berkeley Laboratory, Research Triangle Institute, Southern California—SOCAL), multiple measurements were taken for the same house, usually during different seasons. A large majority of the measurements are from the SOCAL project that was conducted in Southern California. The means of the respective studies generally range from 0.2 to 1.0 ACH, with the exception of two California projects—RTI2 and SOCAL2. Both projects involved measurements in Southern California during a time of year (July) when windows would likely be opened by many occupants.

The limitation of this study is that the PFT database did not base its measurements on a sample that was statistically representative of the national housing stock. PFT has been found to underpredict seasonal average air exchange by 15 to 35% (Sherman, 1989). Using PFT to determine air exchange can produce significant errors when conditions in the measurement scene greatly deviate from idealizations calling for constant, well-mixed conditions.

19.5.1.2.3. Murray and Burmaster (1995)—Residential air exchange rates in the United States: empirical and estimated parametric distributions by season and climatic region

Murray and Burmaster (1995) analyzed the PFT database using 2,844 measurements (essentially the same cases as analyzed by Koontz and Rector (1995), but without the compensating weights). These authors summarized distributions for subsets of the data defined by climate region and season. The months of December, January, and February were defined as winter; March, April, and May were defined as spring; and so on. Table 19-28 summarizes the results of Murray and Burmaster (1995) Neglecting the summer results in the colder regions, which have only a few observations, the results indicate that the highest air exchange rates occur in the warmest climate region during the summer. As noted earlier, many of the measurements in the warmer climate region were from field studies conducted in Southern California during a time of year (July) when windows would tend to be open in that area. Data for warmer climate region in particular should be used with caution because other areas within this region tend to have very hot summers, and residences use air conditioners, resulting in lower air exchange rates. The lowest rates generally occur in the colder regions during the fall.

19.5.1.2.4. Diamond et al. (1996)—Ventilation and infiltration in high-rise apartment buildings

Diamond et al. (1996) studied air flow in a 13-story apartment building and concluded that "the ventilation to the individual units varies considerably." With the ventilation system disabled, units at the lower level of the building had adequate ventilation only on days with high temperature differences, while units on higher floors had no ventilation at all. At times, units facing the windward side were over-ventilated. With the mechanical ventilation system operating, they found wide variation in the air flows to individual apartments. Diamond et al. (1996) also conducted a literature review and concluded there were little published data on air exchange in multifamily buildings, and that there was a general problem measuring, modeling, and designing ventilation systems for high-rise multifamily buildings. Air flow

was dependent upon building type, occupants' behavior, unit location, and meteorological conditions.

19.5.1.2.5. Graham et al. (2004)—Contribution of vehicle emissions from an attached garage to residential indoor air pollution levels

There have been several studies of vehicle emission seepage into homes from attached garages, which examined a single home. Graham et al. (2004) conducted a study of vehicle emission seepage of 16 homes with attached garages. On average, 11% of total house leakage was attributed to the house/garage interface (equivalent to an opening of 124 cm^2), but this varied from 0.6 to 29.6%. The amount of in-house chemical concentrations attributed to vehicle emissions from the garage varied widely between homes from 9 to 85%. Greater leakage tended to occur in houses where the garage attached to the house on more than one side. The home's age was not an important factor. Whether the engine was warm or cold when it was started was important because cold-start emissions are dominated by the by-products of incomplete combustion. Cold-start tail pipe emissions were 32 times greater for carbon monoxide (CO), 10 times greater for nitrogen oxide (NO_x), and 18 times greater for total hydrocarbon emissions than hot-start tailpipe emissions.

19.5.1.2.6. Price et al. (2006)—Indoor-outdoor air leakage of apartments and commercial buildings

Price et al. (2006) compiled air exchange rate data from 14 different studies on apartment buildings in the United States and Canada. The authors found that indoor-outdoor air exchange rates seem to be twice as high for apartments as for single-family houses. The observed apartment air exchange rates ranged from 0.5 to 2 ACH.

19.5.1.2.7. Breen et al. (2010)—Residential air exchange rates from questionnaires and meteorology: model evaluation in central North Carolina

Breen et al. (2010) conducted a study comparing air exchange rate predictions from two mechanistic models with measurements from 31 detached homes in central North Carolina. Air monitoring was performed for 7 consecutive days in each of four consecutive seasons from summer 2000 to spring 2001. The study included two cohorts. The Raleigh cohort consisted of low to moderate socioeconomic status neighborhoods and the Chapel Hill cohort include moderate socioeconomic status neighborhoods (Breen et al., 2010). Daily 24-hour air exchange rates were measured using the PFT method. Distributions of air exchange rate for each season and number of days that windows were opened are presented in Table 19-29. It is important to note that information about amount of time that windows were open during the day is lacking.

19.5.1.2.8. Yamamoto et al. (2010)—Residential air exchange rates in three U.S. metropolitan areas: results from the relationship among indoor, outdoor, and personal air study 1999—2001

Between 1999 and 2001, Yamamoto et al. (2010) conducted approximately 500 indoor-outdoor air exchange rate calculations based on residences in metropolitan Elizabeth, NJ; Houston, TX; and Los Angeles, CA. The median air exchange rate across these urban areas was 0.71 ACH; 0.87 in California, 0.88 in New Jersey, and 0.47 in Texas. In Texas, the measured air exchange rates were lower in the summer cooling season (median = 0.37 ACH) than in the winter heating season (median = 0.63 ACH), likely because of the reported use of room air conditioners. The measured air exchange rates in California were higher in summer (median = 1.13 ACH) than in winter (median = 0.61 ACH) because summers in Los Angeles County are less humid than New Jersey or Texas, and residents are more likely to utilize natural ventilation through open windows and screened doors. In New Jersey, air exchange rates in the heating and cooling seasons were similar.

19.5.1.3. *Key Study of Nonresidential Air Exchange Rates*

19.5.1.3.1. Turk et al. (1987)—Commercial building ventilation rates and particle concentrations

Few air exchange rates for commercial buildings are provided in the literature. Turk et al. (1987) conducted indoor air quality measurements, including air exchange rates, in 38 commercial buildings. The buildings ranged in age from 0.5 to 90 years old. One test was conducted in 36 buildings, and two tests were conducted in 2 buildings. Each building was monitored for 10 working days over a 2-week period yielding a minimum sampling time of 75 hours per building. Researchers found an average ventilation measurement of 1.5 ACH, which ranged from 0.3 to 4.1 ACH with a standard deviation of 0.87. Table 19-30 presents the results by building type.

19.5.1.3.2. Bennett et al. (2012)—Ventilation, temperature, and HVAC characteristics in small and medium commercial buildings in California

HVAC system characteristics and ventilation rates of commercial buildings in California were evaluated by Bennett et al. (2012). A total of 37 small and medium commercial buildings (SMCBs) were selected for study and were classified into small (24 buildings, 90–1,100 m^2), medium (7 buildings, 1,100–2,300 m^2), and medium/large (6 buildings, 2,300–4,600 m^2). The majority of the SMCBs were selected to be representative of retail establishments, offices and restaurants, the most frequent building types in California. Other building types, selected for their potential for indoor pollutant sources, included beauty salons, dental offices, gas stations and gyms. For each building, the heating, ventilating, and air conditioning (HVAC) systems were inspected and measurements of air exchange and indoor environmental quality parameters, such as CO_2 levels, temperature and relative humidity were taken. In addition, whole building ventilation rates were determined using a tracer decay method.

Ventilation measurements for the buildings are presented in Table 19-31. The mean air exchange rate was 1.6 ± 1.7 exchanges per hour, and was similar between buildings with or without outdoor air provided.

This study provides useful information on the HVAC system characteristics and ventilation rates of SMCBs. However, the sample size was relatively small and all of the SMCBs were located in California which may not be representative of SMCBs located in other areas of the United States.

19.5.2. Indoor Air Models

Achieving adequate indoor air quality in a nonresidential building can be challenging. There are many factors that affect indoor air quality in buildings (e.g., building materials, building configuration, outdoor environment, ventilation systems, operation and maintenance, occupants and their activities). Indoor air models are typically used to study, identify, and solve problems involving indoor air quality in buildings, as well as to assess efficiency of energy use. The emphasis of most models is on the physical processes, but for some chemical reactions indoor which may be an important, but variable sink. Models generally assume a known and constant rate of reaction.

Indoor air quality models generally are not software products that can be purchased as "off-the-shelf" items. Most existing software models are research tools that have been developed for specific purposes and are being continuously refined by researchers. Leading examples of indoor air models implemented as software products are as follows:

- CONTAM 3.2—CONTAM was developed at the National Institute of Standards and Technology (NIST) with support from EPA and the U.S. DOE. (Dols and Polidoro, 2016; Wang et al., 2010; Axley, 1988). CONTAM has been used by others to study the effects of model parameters (e.g., wind speed, presence of natural and mechanical ventilation) and the presence of an attached garage on the infiltration of contaminants indoors (Nirvan et al., 2012).
- IAQX—The Indoor Air Quality and Inhalation Exposure model is a Windows-based simulation software package developed by EPA (Guo, 2000).
- CPIEM 2.0—The California Population Indoor Exposure Model was developed for the California Air Resources Board (Rosenbaum et al., 2002).
- TEM—The Total Exposure Model was developed with support from EPA and the U.S. Air Force (Wilkes, 1998; Wilkes and Nuckols, 2000).
- RISK—RISK was developed by the Indoor Environment Management Branch of the EPA National Risk Management Research Laboratory (Sparks, 1997).
- TRIM—The Total Risk Integrated Methodology is an ongoing modeling project of EPA's Office of Air Quality Planning and Standards (Efroymson and Murphy, 2001; Palma et al., 1999).
- TOXLT/TOXST—The Toxic Modeling System Long-Term was developed along with the release of the new version of the EPA's Industrial Source Complex Dispersion Models (U.S. EPA, 1995).
- MIAQ—The Multi-Chamber Indoor Air Quality Model was developed for the California Institute of Technology and Lawrence Berkeley National Laboratory. Documentation last updated in 2002. (Nazaroff and Cass, 1986; Nazzaroff and Cass, 1989a).
- MCCEM 1.2—the Multi-Chamber Consumer Exposure Model was developed for EPA Office of Pollution Prevention and Toxics (EPA/OPPT) (GEOMET, 1989; Koontz and Nagda, 1991).
- ART—Advanced Regulation, Evaluation, Authorization and restriction of Chemicals

(REACH) Tool was designed to model inhalation exposures in the occupational setting for a defined group of workers sharing specific operational conditions (Tielemans et al., 2011, 2008; Cherrie et al., 2011)

Price (2001) evaluated the use of many of the above products (TOXLT/TOXST, MCCEM, IAQX, CONTAM, CPIEM, TEM, TRIM, and RISK) in a tiered approach to assessing exposures and risks to children. The information provided is also applicable to adults.

19.5.3. Air Infiltration Models

A variety of mathematical models exist for prediction of air infiltration rates in individual buildings. A number of these models have been reviewed, for example, by Breen et al., (2014), Liddament and Allen (1983), and by Persily and Linteris (1984). Basic principles are concisely summarized in the ASHRAE Handbook of Fundamentals (ASHRAE, 2013). These models have a similar theoretical basis; all address indoor-outdoor pressure differences that are maintained by the actions of wind and stack (temperature difference) effects. The models generally incorporate a network of airflows where nodes representing regions of different pressure are interconnected by leakage paths. Individual models differ in details such as the number of nodes they can treat or the specifics of leakage paths (e.g., individual components such as cracks around doors or windows versus a combination of components such as an entire section of a building). Such models are not easily applied by exposure assessors, however, because the required inputs (e.g., inferred leakage areas, crack lengths) for the model are not easy to gather.

Another approach for estimating air infiltration rates is developing empirical models. Such models generally rely on the collection of infiltration measurements in a specific building under a variety of weather conditions. The relationship between the infiltration rate and weather conditions can then be estimated through regression analysis and is usually stated in the following form:

$$A = a + b\left|T_i - T_0\right| + cU^n \qquad \text{(Eqn. 19-1)}$$

where:

A = air exchange rate (hours^{-1}),
T_i = indoor temperature (°C),
T_o = outdoor temperature (°C),
U = windspeed (m/second),
n is an exponent with a value typically between 1 and 2, and
a, b and c are parameters to be estimated.

Relatively good predictive accuracy usually can be obtained for individual buildings through this approach. However, exposure assessors often do not have the information resources required to develop parameter estimates for making such predictions.

A reasonable compromise between the theoretical and empirical approaches has been developed in the model specified by Dietz et al. (1986). The model, drawn from correlation analysis of environmental measurements and air infiltration data, is formulated as follows:

$$A = L\left(0.006\Delta T\frac{0.03}{C}U^{1.5}\right) \qquad \text{(Eqn. 19-2)}$$

where:

A = average ACH or infiltration rate, hours^{-1},
L = generalized house leakiness factor ($1 < L < 5$),
C = terrain sheltering factor ($1 < C < 10$),
ΔT = indoor-outdoor temperature difference (°C), and
U = windspeed (m/second).

The value of L is greater as house leakiness increases, and the value of C is greater as terrain sheltering (reflects shielding of nearby wind barrier) increases. Although the above model has not been extensively validated, it has intuitive appeal, and it is possible for the user to develop reasonable estimates for L and C with limited guidance. Historical data from various U.S. airports are available for estimation of the temperature and windspeed parameters. As an example application, consider a house that has central values of 3 and 5 for L and C, respectively. Under conditions where the indoor temperature is 20°C (68°F), the outdoor temperature is 0°C (32°F), and the windspeed is 5 m/second, the predicted infiltration rate for that house would be

3 (0.006 × 20 + 0.03/5 × 51.5), or 0.56 ACH. This prediction applies under the condition that exterior doors and windows are closed and does not include the contributions, if any, from mechanical systems (see Section 19.3.3.3). Occupant behavior, such as opening windows, can, of course, overwhelm the idealized effects of temperature and wind speed.

Chan et al. (2005) analyzed the U.S. Residential Air Leakage database at Lawrence Berkley National Laboratory (LBNL) containing approximately 70,000 air leakage measurements from 30 states (predominantly Ohio, Alaska, and Wisconsin). They present the following equation for estimating ACH:

$$ACH = 48\left(\frac{2.5}{H}\right)^{0.3}\frac{NL}{HF}\left[h^{-1}\right] \qquad \text{(Eqn. 19-3)}$$

where:

ACH = air changes per hour,
H = building height (meters),
NL = normalized leakage (unitless),
F = scaling factor (unitless), and
h = hours.

Chan et al. (2005) found that "older and smaller homes are more likely to have higher normalized leakage areas than newer and larger ones." Table 19-32 summarizes the normalized leakage distributions in the United States.

It should be noted that newer homes were generally built tighter until about 1997 when the construction trend leveled off. Sherman and Matson (2002) also examined LBNL's U.S. Residential Air Leakage database and found that average normalized leakage for 22,000 houses already in the database was 1.18 *NL* (total leakage cm^2 normalized for dwelling size m^2), but leakage among the 8,300 newer homes averaged 0.30 *NL*.

19.5.4. Vapor Intrusion

Vapor intrusion is the process by which contaminants present in the subsurface (both soil and groundwater) migrate through the soil via diffusion and advection and can enter building structures through the foundation cracks (U.S. EPA 2015, 2012; Murphy and Chan, 2011; Yao et al., 2011). In 1998, concerns about subsurface contamination of soil or ground water impacting indoor air quality led the EPA to develop a series of models for estimating health risks from subsurface vapor intrusion into buildings based on the analytical solutions of Johnson and Ettinger (1991). Models describing the vapor entry into buildings generally consist of two main parts. One part describes the vapor transport in the soil and the other its entry into the building (Yao and Suuberg, 2013). Models can vary from simple 1-dimentional screening tools to more complex 3-dimentional models requiring numerical solutions (Yao and Suuberg, 2013). Since 1991, the models have been revised, and new models have been added. The 3-phase soil contamination models theoretically partition the contamination into three discrete phases: (1) in solution with water, (2) sorbed to the soil organic carbon, and (3) in vapor phase within the air-filled pores of the soil. Two new models have been added, allowing the user to estimate vapor intrusion into buildings from measured soil gas data (U.S. EPA 2000a). When Non-Aqueous Phase Liquid (NAPL) is present in soils, the contamination includes a fourth or residual phase. In such cases, the new NAPL models can be used to estimate the rate of vapor intrusion into buildings and the associated health risks. The new NAPL models use a numerical approach for simultaneously solving the time-averaged soil and building vapor concentration for each of up to 10 soil contaminants (U.S. EPA 2000a). This involves a series of iterative calculations for each contaminant. A spreadsheet with these models is available online from EPA at https://www.epa.gov/vaporintrusion/epa-spreadsheet-modeling-subsurface-vapor-intrusion. Technical information and resources pertaining to vapor intrusion can be found in https://www.epa.gov/vaporintrusion/vapor-intrusion-resources.

Although mathematical models such as the Johnson and Ettinger (1991) have been widely used, vapor intrusion modeling has been the focus of more recent studies (Yao and Suuberg, 2013). Other analytical approximations have been applied to estimate contaminant subslab concentrations and study the effects of foundation features and source location on vapor intrusion (Yao et al., 2012, Yao et al., 2011). Other researchers have developed a systematic approach to model steady state advective and diffusive fluxes between multimedia compartments including ground water, soil, and air with applications to vapor intrusion calculations (Murphy and Chan, 2011). They determined that the presence of a basement significantly reduces first floor exposures. In addition, they concluded that the resistance associated with diffusion in ground water and water table fluctuations cannot be neglected (Murphy and Chan, 2011.) In addition to foundation characteristics, Yao and Suuberg (2013) observed that biodegradation plays a significant role in subslab

concentration attenuation. However, other processes, like reaction mechanisms and kinetics, are not well understood. The lack of formal vapor intrusion model validation continues to be a challenge (Yao and Suuberg, 2013).

19.5.5. Deposition and Filtration

Deposition refers to the removal of airborne substances to available surfaces that occurs as a result of gravitational settling and diffusion, as well as electrophoresis and thermophoresis. Filtration is driven by similar processes, but is confined to material through which air passes. Filtration is usually a matter of design, whereas deposition is a matter of fact.

Outdoor particles can penetrate (infiltrate) building structures and become a source of indoor particle exposure (Gao and Zhang et al., 2009). Infiltration factors are affected by numerous elements including: air exchange rates, forced air heating, exhaust fan operation, air conditioning use, the use of filtration devices, meteorological parameters such as wind speed, indoor-outdoor temperature differentials, particle size, and composition of particulate matter (e.g., volatile chemicals) (Kearney et al., 2014). Air exchange rates can have a significant effect on particle number concentrations indoor under stable outdoor particle number concentrations. Generally, a higher ACH results in lower particulate number concentrations indoors (Guo et al., 2008). Models have been developed that help predict indoor concentrations of outdoor particles in residences (El Orch et al., 2014).

Semivolatile organic compounds (SVOC) are also present in indoor air environments. Sources of these compounds include for example: indoor materials, consumer products (e.g., personal care products, household cleaning products), combustion products, environmental tobacco smoke, and intrusion from outdoor air (Singer et al., 2003; Weschler and Nazaroff 2008). The formation of organic films on indoor surfaces have been confirmed by both direct and indirect measurements (Weschler and Nazaroff, 2017). Weschler and Nazaroff (2017) developed a simple model of organic film growth to improve estimates of human exposure to SVOCs.

Gases can also penetrate the building envelope from attached garages. In addition to automobile exhaust, people often store gasoline, oil, paints, lacquers, and yard and garden supplies in garages. Appliances such as furnaces, heaters, hot water heaters, dryers, gasoline-powered appliances, and wood stoves may also impact indoor air quality. Garages can be a source of volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, *m*,*p*-xylene, and *o*-xylene. Emmerich et al. (2003) conducted a literature review on indoor air quality and the transport of pollutants from attached garages to residential living spaces. The authors found the body of literature on the subject was limited and contained little data with regard to airtightness and geometry of the house-garage interface, and the impact of heating and cooling equipment. They concluded, however, that there is substantial evidence that the transport of contaminants from garages has the potential to negatively impact residences.

19.5.5.1. *Deposition*

The deposition of particulate matter and reactive gas-phase pollutants to indoor surfaces is often stated in terms of a characteristic deposition velocity ($m\ hour^{-1}$) allied to the surface-to-volume ratio ($m^2\ m^{-3}$) of the building or room interior, forming a first order loss rate ($hour^{-1}$). Theoretical considerations specific to indoor environments have been summarized in comprehensive reviews by Nazaroff and Cass (1989b) and Nazaroff et al. (1993).

For airborne particles, deposition rates depend on aerosol properties (size, shape, density) as well as room factors (thermal gradients, turbulence, surface geometry). The motions of larger particles are dominated by gravitational settling; the motions of smaller particles are subject to convection and diffusion. Consequently, larger particles tend to accumulate more rapidly on floors and up-facing surfaces while smaller particles may accumulate on surfaces facing in any direction. Figure 19-3 illustrates the general trend for particle deposition across the size range of general concern for inhalation exposure (<10 μm). Nano-particles have been demonstrated to have higher deposition rates and lower penetration efficiencies (Guo et al., 2008). Penetration refers to the infiltration of particles in the air that passes through the building shell (Chen and Zhao, 2011) (See also Section 19.5.7). The current thought is that theoretical calculations of deposition rates are likely to provide unsatisfactory results due to knowledge gaps relating to near-surface air motions and other sources of inhomogeneity (Nazaroff et al., 1993).

19.5.5.1.1. Thatcher and Layton (1995)—Deposition, resuspension, and penetration of particles within a residence

Thatcher and Layton (1995) evaluated removal rates for indoor particles in four size ranges (1−5, 5—10, 10−25, and >25 μm) in a study of one house occupied by a family of four. Table 19-33 lists these values. In a subsequent evaluation of data collected in

100 Dutch residences, Layton and Thatcher (1995) estimated settling velocities of 2.7 m hour^{-1} for lead-bearing particles captured in total suspended particulate matter samples.

19.5.5.1.2. Wallace (1996)—Indoor particles: a review

In a major review of indoor particles, Wallace (1996) cited overall particle deposition per hour (hour^{-1}) for respirable ($PM_{2.5}$), inhalable (PM_{10}), and coarse (difference between PM_{10} and $PM_{2.5}$) size fractions determined from EPA's Particle Total Exposure Assessment Methodological Study (PTEAM) study. These values, listed in Table 19-34, were derived from measurements conducted in nearly 200 residences.

19.5.5.1.3. Thatcher et al. (2002)—Effects of room furnishings and air speed on particle deposition rates indoors

Thatcher et al. (2002) measured deposition loss rate coefficients for particles of different median diameters (0.55 to 8.66 mm) with fans off and on at various airspeeds in three types of experimental rooms: (1) bare (unfurnished with metal floor), (2) carpeted and unfurnished, and (3) fully furnished. Table 19-35 summarizes the results.

19.5.5.1.4. He et al. (2005)—Particle deposition rates in residential houses

He et al. (2005) investigated particle deposition rates for particles ranging in size from 0.015 to 6 μm. The lowest deposition rates were found for particles between 0.2 and 0.3 μm for both minimum (air exchange rate: 0.61 ± 0.45 hour^{-1}) and normal (air exchange rate: 3.00 ± 1.23 hour^{-1}) conditions. Thus, air exchange rate was an important factor affecting deposition rates for particles between 0.08 and 1.0 μm, but not for particles smaller than 0.08 μm or larger than 1.0 μm.

19.5.5.2. *Filtration*

A variety of air cleaning techniques have been applied to residential settings. EPA (2009) summarizes available information on residential air cleaners. Basic principles related to residential-scale air cleaning technologies have also been summarized in conjunction with reporting early test results (Offerman et al., 1984). General engineering principles are summarized in ASHRAE (2016). In addition to fibrous filters integrated into central heating and air conditioning systems, extended surface filters and High Efficiency Particle Arrest filters, as well as electrostatic systems, are available to increase removal efficiency. Free-standing air cleaners (portable and/or console) are also being used. Shaughnessy and Sextro (2007) discuss the testing process to evaluate the efficacy of portable air cleaners. Product-by-product test results reported by Hanley et al. (1994); Shaughnessy et al. (1994); and Offerman et al. (1984) exhibit considerable variability across systems, ranging from ineffectual (<1% efficiency) to nearly complete removal.

19.5.6. Interzonal Airflows

Exposure assessments for indoor air pollutants generally assume a well-mixed environment. However, pollutant concentrations vary with distance from the source, ventilation rate, and relative height of the source (Acevedo-Bolton et al., 2012).

Residential structures consist of a number of rooms that may be connected horizontally, vertically, or both horizontally and vertically. Before considering residential structures as a detailed network of rooms, it is convenient to divide them into one or more zones. At a minimum, each floor is typically defined as a separate zone. For indoor air exposure assessments, further divisions are sometimes made within a floor, depending on (1) locations of specific contaminant sources and (2) the presumed degree of air communication among areas with and without sources.

Defining the airflow balance for a multiple-zone exposure scenario rapidly increases the information requirements as rooms or zones are added. As shown in Figure 19-4, a single-zone system (considering the entire building as a single well-mixed volume) requires only two airflows to define air exchange. Further, because air exchange is balanced flow (air does not "pile up" in the building, nor is a vacuum formed), only one number (the air exchange rate) is needed. With two zones, 6 airflows are needed to accommodate interzonal airflows plus air exchange; with three zones, 12 airflows are required. In some cases, the complexity can be reduced using judicious (if not convenient) assumptions. Interzonal airflows connecting nonadjacent rooms can be set to zero, for example, if flow pathways do not exist. Symmetry also can be applied to the system by assuming that each flow pair is balanced.

Axley (2007) discusses the history and theory of multizonal airflow models. Examples of interzonal airflow models include CONTAM (developed by NIST) and COMIS (Haas et al., 2002; Feustel, 1999; Feustel and Raynor-Hoosen, 1990).

19.5.7. House Dust and Soil Loadings

House dust is a complex mixture of biologically derived material (animal dander, fungal spores, etc.), particulate matter deposited from the indoor aerosol, and soil particles brought in by foot traffic. House dust may contain VOCs (Wolkoff and Wilkins, 1994; Hirvonen et al., 1995), pesticides from imported soil particles as well as from direct applications indoors (Roberts et al., 1991), and trace metals derived from outdoor sources (Layton and Thatcher, 1995). The indoor abundance of house dust depends on the interplay of deposition from the airborne state, resuspension due to various activities, direct accumulation, and infiltration.

In the absence of indoor sources, indoor concentrations of particulate matter are significantly lower than outdoor levels. For some time, this observation supported the idea that a significant fraction of the outdoor aerosol is filtered out by the building envelope. The ratios of indoor to outdoor particle concentrations vary depending on factors such as: the difference in size-dependent indoor particle emission rates, the geometry of the cracks in building envelopes, and the air exchange rates (Chen and Zhao, 2011).

It should be noted that carpet dust loadings may be higher than previously believed. This is important because embedded dust is a reservoir for organic compounds. Fortune et al. (2000) compared the mass of dust in carpets removed using conventional vacuuming to that removed by vacuuming with a beater-bar to remove deeply embedded dust. The amount removed was 10 times that removed by conventional vacuuming.

19.5.7.1. *Roberts et al. (1991)—Development and Field Testing of a High-Volume Sampler for Pesticides and Toxics in Dust*

Dust loadings, reported by Roberts et al. (1991), were measured in conjunction with the Nonoccupational Pesticide Exposure Study (NOPES). In this study, house dust was sampled from a representative grid using a specially constructed high-volume surface sampler. The surface sampler collection efficiency was verified in conformance with ASTM F608 (ASTM, 1989). Table 19-36 summarizes data collected from carpeted areas in volunteer households in Florida encountered during the course of NOPES. Seven of the nine sites were single-family detached homes, and two were mobile homes. The authors noted that the two houses exhibiting the highest dust loadings were only those homes where a vacuum cleaner was not used for housekeeping.

19.5.7.2. *Thatcher and Layton (1995)—Deposition, Resuspension, and Penetration of Particles within a Residence*

Relatively few studies have been conducted at the level of detail needed to clarify the dynamics of indoor aerosols. One intensive study of a California residence (Thatcher and Layton, 1995), however, provides instructive results. Using a model-based analysis for data collected under controlled circumstances, the investigators verified penetration of the outdoor aerosol and estimated rates for particle deposition and resuspension (see Table 19-37). The investigators stressed that normal household activities are a significant source of airborne particles larger than 5 μm. During the study, they observed that just walking into and out of a room could momentarily double the concentration. The airborne abundance of submicrometer particles, on the other hand, was unaffected by either cleaning or walking. They also concluded that large particles (over 25 μm) settle eight times faster than small particles (1−5 μm).

Mass loading of floor surfaces (see Table 19-38) was measured in the study of Thatcher and Layton (1995) by thoroughly cleaning the house and sampling accumulated dust, after 1 week of normal habitation and no vacuuming. The methodology, validated under ASTM F608 (ASTM, 1989), showed fine dust recovery efficiencies of 50% with new carpet and 72% for linoleum. Tracked areas showed consistently higher accumulations than untracked areas, confirming the importance of tracked-in material. Differences between tracked areas upstairs and downstairs show that tracked-in material is not readily transported upstairs. The consistency of untracked carpeted areas throughout the house, suggests that, in the absence of tracking, particle transport processes are similar on both floors.

19.6. CHARACTERIZING INDOOR SOURCES

Product- and chemical-specific mechanisms for indoor sources can be described using simple emission factors to represent instantaneous releases, as well as constant releases over defined time periods; more complex formulations may be required for time-varying sources. Guidance documents for characterizing indoor sources within the context of the exposure assessment process are limited (see, for example, Jennings et al., 1987b; Wolkoff, 1995). Fairly extensive guidance exists in the technical literature, however, provided that the exposure assessor has the means to define (or estimate) key mechanisms and chemical-specific parameters. Basic

concepts are summarized below for the broad source categories that relate to airborne contaminants, waterborne contaminants, and for soil/house dust indoor sources.

19.6.1. Source Descriptions for Airborne Contaminants

Table 19-39 summarizes simplified indoor source descriptions for airborne chemicals for direct emission sources (e.g., combustion, pressurized propellant products), as well as emanation sources (e.g., evaporation from "wet" films, diffusion from porous media), and transport-related sources (e.g., infiltration of outdoor air contaminants, soil gas entry).

Direct-emission sources can be approximated using simple formulas that relate pollutant mass released to characteristic process rates. Combustion sources, for example, may be stated in terms of an emission factor, fuel content (or heating value), and fuel consumption (or carrier delivery) rate. Emission factors for combustion products of general concern (e.g., CO, NO_x) have been measured for a number of combustion appliances using room-sized chambers (see, for example, Relwani et al., 1986). Other direct-emission sources would include volatiles released from water use and from pressurized consumer products. Resuspension of house dust (see Section 19.5.5.1) would take on a similar form by combining an activity-specific rate constant with an applicable dust mass.

Diffusion-limited sources (e.g., carpet backing, furniture, flooring, dried paint) represent probably the greatest challenge in source characterization for indoor air quality. Vapor-phase organics dominate this group, offering great complexity because (1) there is a fairly long list of chemicals that could be of concern, (2) ubiquitous consumer products, building materials, coatings, and furnishings contain varying amounts of different chemicals, (3) source dynamics may include nonlinear mechanisms, and (4) for many of the chemicals, emitting as well as nonemitting materials evident in realistic settings may promote reversible and irreversible sink effects. Very detailed descriptions for diffusion-limited sources can be constructed to link specific properties of the chemical, the source material, and the receiving environment to calculate expected behavior (see, for example, Schwope et al., 1992; Cussler, 1984). Validation to actual circumstances, however, suffers practical shortfalls because many parameters simply cannot be measured directly.

The exponential formulation listed in Table 19-39 was derived based on a series of papers generated during the development of chamber testing methodology by EPA (Dunn, 1987; Dunn and Tichenor, 1988; Dunn and Chen, 1993). This framework represents an empirical alternative that works best when the results of chamber tests are available. Estimates for the initial emission rate (E_o) and decay factor (k_s) can be developed for hypothetical sources from information on pollutant mass available for release (M) and supporting assumptions.

Assuming that a critical time period (t_c) coincides with reduction of the emission rate to a critical level (E_c) or with the release of a critical fraction of the total mass (M_c), the decay factor can be estimated by solving either of these relationships:

$$\frac{E_c}{E_0} = e^{-k_s t_c} \qquad \text{(Eqn. 19-4)}$$

where:

E_c = emission rate to a critical level (µg hour^{-1}),
E_0 = initial emission rate (µg hour^{-1}),
k_s = decay factor (µg hour^{-1}), and
t_c = critical time period (hours),

or

$$\frac{M_c}{M} = 1 - e^{-k_s t_c} \qquad \text{(Eqn. 19-5)}$$

where:

M_c = critical mass (µg), and
M = total mass (µg).

The critical time period can be derived from product-specific considerations (e.g., equating drying time for paint to 90% emissions reduction). Given such an estimate for k_s, the initial emission rate can be estimated by integrating the emission formula to infinite time under the assumption that all chemical mass is released:

$$M = \int_0^\infty E_0 \, e - k_s t \, dt = \frac{E_0}{k_s} \qquad \text{(Eqn. 19-6)}$$

The basis for the exponential source algorithm has also been extended to the description of more complex diffusion-limited sources. With these sources, diffusive or evaporative transport at the interface may be much more rapid than diffusive transport from within the source material, so that the abundance at the source/air interface becomes depleted, limiting the transfer rate to the air. Such effects can prevail with skin formation in "wet" sources like stains and paints (see, for example, Chang and Guo, 1992). Similar emission profiles have been observed with the emanation of formaldehyde from particleboard with "rapid" decline as formaldehyde evaporates from surface sites of the particleboard over the first few weeks. It is then followed by a much slower decline over ensuing years as formaldehyde diffuses from within the matrix to reach the surface (see, for example, Zinn et al., 1990).

Transport-based sources bring contaminated air from other areas into the airspace of concern. Examples include infiltration of outdoor contaminants, and soil gas entry. Soil gas entry is a particularly complex phenomenon and is frequently treated as a separate modeling issue (Provoost et al., 2010; Little et al., 1992; Sextro, 1994). Room-to-room migration of indoor contaminants would also fall under this category, but this concept is best considered using multizone models.

19.6.2. Source Descriptions for Waterborne Contaminants

Residential water supplies may be a route for exposure to chemicals through ingestion, dermal contact, or inhalation. These chemicals may appear in the form of contaminants (e.g., trichloroethylene) as well as naturally occurring by-products of water system history (e.g., chloroform, radon). Among indoor water uses, showering, bathing, and hand-washing of dishes or clothes provide the primary opportunities for dermal exposure. The escape of volatile chemicals to the gas phase associates water use with inhalation exposure. The exposure potential for a given chemical will depend on the source of water, the types and extents of water uses, and the extent of volatilization of specific chemicals. Primary types of residential water use include showering/bathing, toilet use, clothes washing, dishwashing, and faucet use (e.g., for drinking, cooking, general cleaning, or washing hands). Information about household water use has been investigated by the Water Research Foundation and published in the Residential End Use of Water (REU) (DeOreo et al., 2016). The survey collected data from 2010 through 2013 from randomly selected single-family houses in the United States and Canada. The average per capita indoor water use was 58.6 gal/day. Figure 19-5 shows the relative percentage of indoor per capita water use across all uses. Toilet flushing was the largest indoor water use in gallons per capita per day (14.2 gpcd, 24%). Other relevant information on activity patterns (e.g., time showering, time indoors, etc.) can be bound in Chapter 16 of the *Exposure Factors Handbook* (U.S. EPA 2011).

Upper-bounding estimates of chemical release rates from water use can be formulated as simple emission factors by combining the concentration in the feed water (g m^{-3}) with the flow rate for the water use (m^3 $hour^{-1}$), and assuming that the chemical escapes to the gas phase. For some chemicals, however, not all of the chemical escapes in realistic situations due to diffusion-limited transport and solubility factors. For inhalation exposure estimates, this may not pose a problem because the bounding estimate would overestimate emissions by no more than approximately a factor of two. For multiple exposure pathways, the chemical mass remaining in the water may be of importance. Refined estimates of volatile emissions are usually considered under two-resistance theory to accommodate mass transport aspects of the water-air system (see, for example, U.S. EPA, 2000b; Howard-Reed et al., 1999; Moya et al., 1999; Little, 1992; Andelman, 1990; McKone, 1987). More detailed descriptions of models used to estimate emissions from indoor water sources including showers, bathtubs, dishwashers, and washing machines are included in EPA, (2000b). Release rates (S) are formulated as

$$S = K_m F_w \left[C_w - \frac{C_a}{H} \right] \qquad \text{(Eqn. 19-7)}$$

where:

S = chemical release rate (g $hour^{-1}$),
K_m = dimensionless mass-transfer coefficient,
F_w = water flow rate (m^3 $hour^{-1}$),
C_w = concentration in feed water (g m^{-3}),
C_a = concentration in air (g m^{-3}), and
H = dimensionless Henry's Law constant.

Because the emission rate is dependent on the air concentration, recursive techniques are required. The mass-transfer coefficient is a function of water use

characteristics (e.g., water droplet size spectrum, fall distance, water film) and chemical properties (diffusion in gas and liquid phases). Estimates of practical value are based on empirical tests to incorporate system characteristics into a single parameter (see, for example, Giardino et al., 1990). Once characteristics of one chemical-water use system are known (reference chemical, subscript *r*), the mass-transfer coefficient for another chemical (index chemical, subscript *i*) delivered by the same system can be estimated using formulations identified in the review by Little (1992):

$$\frac{1}{K}\left(\frac{D_{Li}}{D_{Lr}}\right)^{1/2} = \frac{1}{K_{Lr}} = \frac{1}{K_{Gr}} - \frac{1}{H}\left(\frac{D_{Gr}}{D_{Gi}}\right)^{2/3}\left(\frac{D_{Li}}{D_{Lr}}\right)^{1/2} \quad \text{(Eqn. 19-8)}$$

where:

D_L = liquid diffusivity (m^2 $second^{-1}$),
DG = gas diffusivity (m^2 $second^{-1}$),
KL = liquid-phase mass-transfer coefficient,
KG = gas-phase mass transfer coefficient, and
H = dimensionless Henry's Law constant.

19.6.3. Soil and House Dust Sources

The rate process descriptions compiled for soil and house dust provide inputs for estimating indoor emission rates:

$$S_d = M_d R_d A_f \quad \text{(Eqn. 19-9)}$$

where:

S_d = dust emission (g $hour^{-1}$),
M_d = dust mass loading (g m^{-2}),
R_d = resuspension rates ($hour^{-1}$), and
A_f = floor area (m^2).

Because house dust is a complex mixture, transfer of particle-bound constituents to the gas phase may be of concern for some exposure assessments. For emission estimates, one would then need to consider particle mass residing in each reservoir (dust deposit, airborne).

19.7. ADVANCED CONCEPTS

19.7.1. Uniform Mixing Assumption

Many exposure measurements are predicated on the assumption of uniform mixing within a room or zone of a house. Mage and Ott (1994) offer an extensive review of the history of use and misuse of the concept. Experimental work by Baughman et al. (1994) and Drescher et al. (1995) indicates that, for an instantaneous release from a point source in a room, fairly complete mixing is achieved within 10 minutes when convective flow is induced by solar radiation. Another study by Gadgil et al. (2003) showed that mixing time depended on the room airflow the source location. However, up to 100 minutes may be required for complete mixing under quiescent (nearly isothermal) conditions. While these experiments were conducted at extremely low air exchange rates (<0.1 ACH), based on the results, attention is focused on mixing within a room.

The situation changes if a human invokes a point source for a longer period and remains in the immediate vicinity of that source. Personal exposure in the near vicinity of a source can be much higher than the well-mixed assumption would suggest. A series of experiments conducted by GEOMET (1989) for the EPA involved controlled point-source releases of carbon monoxide tracer (CO), each for 30 minutes. Breathing-zone measurements located within 0.4 m of the release point were 10 times higher than for other locations in the room during early stages of mixing and transport.

Similar investigations by Acevedo-Bolton et al. (2012) studied the proximity of source effects in two naturally ventilated homes in Northern California. They found high variability of CO concentrations measured within 1 m from the source with 5 minute averages varying more than 100 fold. Other research conducted by Furtaw et al. (1996) involved a series of experiments in a controlled-environment, room-sized chamber. Furtaw et al. (1996) studied spatial concentration gradients around a continuous point source simulated by sulfur hexafluoride (SF_6) tracer with a human moving about the room. Average breathing-zone concentrations when the subject was near the source exceeded those several meters away by a factor that varied inversely with the ventilation intensity in the room. At typical room ventilation rates, the ratio of source-proximate to slightly-removed concentration was on the order of 2:1.

19.7.2. Reversible Sinks

The sorption of SVOCs onto indoor surfaces are referred to as the "sink effect." Different building materials sorb different compounds based on polarity, indoor humidity, and temperature (Won et al., 2001). Surface roughness also plays a role in the absorption of chemicals onto surfaces (Wu et al., 2017). The subsequent re-emission of these compounds into indoor air is referred to as a "reversible sink." The reversible sink effect can significantly affect the fate and transport of indoor SVOCs (Wu et al., 2017). For some chemicals, the actions of reversible sinks are of concern. For an initially "clean" condition in the sink material, sorption effects can greatly deplete indoor concentrations. However, once enough of the chemical has been adsorbed, the diffusion gradient will reverse, allowing the chemical to escape. For persistent indoor sources, such effects can serve to reduce indoor levels initially, but once the system equilibrates, the net effect on the average concentration of the reversible sink is negligible. Over suitably short time frames, this can also affect integrated exposure. For indoor sources whose emission profile declines with time (or ends abruptly), reversible sinks can serve to extend the emissions period as the chemical desorbs long after direct emissions are finished. Reversible sink effects have been observed for a number of chemicals in the presence of carpeting, wall coverings, and other materials commonly found in residential environments. As an example, in the case of environmental tobacco smoke, clothing and human skin have been found to serve as a reversible sink. The lingering residues of tobacco products are referred to as third-hand smoke (Sleiman et al., 2010).

Interactive sinks (and models of the processes) are of special importance; while sink effects can greatly reduce indoor air concentrations, re-emission at lower rates over longer time periods could greatly extend the exposure period of concern. For completely reversible sinks, the extended time could bring the cumulative exposure to levels approaching the sink-free case. Publications (Axley and Lorenzetti, 1993; Tichenor et al., 1991) show that first principles provide useful guidance in postulating models and setting assumptions for reversible-irreversible sink models. Sorption/desorption can be described in terms of Langmuir (monolayer) as well as Brunauer-Emmet-Teller (BET, multilayer) adsorption.

19.8. REFERENCES FOR CHAPTER 19

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Table 19-6. Average Estimated Volumes of U.S. Residences, by Housing Type, Census Region, and Urbanicity

	Volume (m^3)[a]	% of Total
Housing Type		
Single-family detached	562	63.3
Single-family attached	401	5.9
Apartments in 2−4 unit buildings	249	7.9
Apartments in 5 or more unit buildings	192	16.8
Mobile homes	246	6.1
Census Region		
Northeast	480	18.3
Midwest	515	22.8
South	423	37.1
West	387	21.8
Urban and Rural[b]		
Urban	421	77.6
Rural	536	22.4
All housing types	446	NA

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet. Includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

[b] Housing units are classified as urban or rural using definitions created by the U.S. census bureau.

Source: U.S. DOE (2013).

Table 19-7. Average Volume of Single Family, Multifamily and Mobile Homes by Type[a]

Number of Stories or Levels in Housing Unit	Single Family		Multifamily		Mobile Homes	
	Volume (m^3)	% of Total	Volume (m^3)	% of Total	Volume (m^3)	% of Total
1 story	438	58.8	199	90.8	NA	NA
2 stories	705	37.7	321	8.5	NA	NA
3 or more stories	777	2.0	494	0.7	NA	NA
Split level	635	1.5	NA	NA	NA	NA
Census region						
Northeast	644	16.2	224	27.0	233	7.2
Midwest	616	24.5	217	19.9	247	15.9
South	506	37.8	209	29.9	256	56.5
West	476	21.5	191	23.1	225	20.3
Urbanicity[b]						
Urban	531	73.4	210	95.7	227	50
Rural	598	26.6	225	4.3	266	50

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet. Includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

[b] Housing units are classified as urban or rural using definitions created by the U.S. Census Bureau.

Source: U.S. DOE (2013).

Table 19-8. Residential Volumes in Relation to Year of Construction

Year of Construction	Volume[a] (m^3)	% of Total
Before 1940	483	12.7
1940−1949	421	4.6
1950−1959	419	11.9
1960−1969	397	11.7
1970−1979	382	16.1
1980−1989	401	15.0
1990−1999	498	14.4
2000−2009	558	13.7
All years	447	100

[a] Volumes calculated from floor areas assuming a ceiling height of 8 feet. Includes all basements, finished or conditioned (heated or cooled) areas of attics, and conditioned garage space that is attached to the home. Unconditioned and unfinished areas in attics and attached garages are excluded.

Source: U.S. DOE (2013).

Table 19-9. Summary of Residential Volume Distributions Based on U.S. DOE (2008a)[a] (m^3)

Parameter	Volume
Arithmetic mean	492
Standard deviation	349
10th percentile	154
25th percentile	231
50th percentile	395
75th percentile	648
90th percentile	971

[a] All housing types, all units.

Source: EPA's Analysis of U.S. DOE (2008a).

Table 19-10. Summary of Residential Volume Distributions Based on Versar (1989) (m^3)

Parameter	Volume
Arithmetic mean	369
Standard deviation	209
10th percentile	167
25th percentile	225
50th percentile	321
75th percentile	473
90th percentile	575

Source: Versar (1989); based on PFT database.

Table 19-11. Number of Residential Single Detached and Mobile Homes by Volume[a] (m^3) and Median Volumes by Housing Type

Volume (m^3)[a]	Total Housing Units	Occupied	Seasonal	Vacant
Less than 113.3	2,738	2,218	133	388
113.3−169.7	7,940	6,368	339	1,233
169.9−226.3	13,805	11,409	383	2,012
226.5−339.6	27,098	23,563	664	2,871
339.8−452.8	21,635	19,657	356	1,621
453.1−566.1	14,007	13,028	167	813
566.3−679.4	7,290	6,817	83	390
679.6−905.9	7,075	6,593	93	389
906 or more	3,313	3,024	66	223
Not reported/don't know	29,889	25,614	638	3,637
Median volume (m^3)[b]	340	340	261	NA

[a] Includes single detached and manufactured/mobile homes.
[b] Converted from ft^2. Assumes 8-foot ceiling.

Source: U.S. Census Bureau (2015).

Table 19-12. Dimensional Quantities for Residential Rooms

Nominal Dimensions	Length (meters)	Width (meters)	Height (meters)	Volume (m^3)	Wall Area (m^2)	Floor Area (m^2)	Total Area (m^2)
8-foot ceiling							
12’ × 15’	4.6	3.7	2.4	41	40	17	74
12’ × 12’	3.7	3.7	2.4	33	36	13	62
10’ × 12’	3.0	3.7	2.4	27	33	11	55
9’ × 12’	2.7	3.7	2.4	24	31	10	51
6’ × 12’	1.8	3.7	2.4	16	27	7	40
4’ × 12’	1.2	3.7	2.4	11	24	4	32
12-foot ceiling							
12’ × 15’	4.6	3.7	3.7	61	60	17	94
12’ × 12’	3.7	3.7	3.7	49	54	13	80
10’ × 12’	3.0	3.7	3.7	41	49	11	71
9’ × 12’	2.7	3.7	3.7	37	47	10	67
6’ × 12’	1.8	3.7	3.7	24	40	7	54
4’ × 12’	1.2	3.7	3.7	16	36	4	44

Table 19-13. Examples of Products and Materials Associated with Floor and Wall Surfaces in Residences

Material Sources	Assumed Amount of Surface Covered[a] (m^2)
Silicone caulk	0.2
Floor adhesive	10.0
Floor wax	50.0
Wood stain	10.0
Polyurethane wood finish	10.0
Floor varnish or lacquer	50.0
Plywood paneling	100.0
Chipboard	100.0
Gypsum board	100.0
Wallpaper	100.0

[a] Based on typical values for a residence.

Source: Adapted from Tucker (1991).

Table 19-14. Residential Heating Characteristics by U.S. Census (%)

Space Heating Characteristics	Housing Units %[a]	U.S. Census Region			
		Northeast	Midwest	South	West
Total homes	100.0	100.0	100.0	100.0	100.0
Space heating equipment					
Use space heating equipment	96.0	100.0	100.0	95.9	89.4
Have space heating equipment but do not use it	2.8	Q	N	3.6	6.4
Do not have space heating equipment	1.2	N	N	0.7	4.2
Main heating fuel and equipment[b]					
Natural gas	47.3	53.8	67.0	28.8	53.4
Central warm-air furnace	38.1	31.9	59.8	24.1	44.7
Steam or hot water system	5.5	19.0	5.7	1.1	1.9
Built-in room heater	1.8	1.9	Q	1.6	3.4
Other equipment	1.9	Q	0.8	2.0	3.4
Electricity	36.3	14.8	20.8	60.1	29.2
Central warm-air furnace	15.1	3.3	9.1	26.6	11.4
Heat pump	10.2	3.3	2.7	20.0	6.8
Built-in electric units	7.6	6.2	7.2	8.3	8.0
Portable electric heater	2.5	Q	Q	4.5	2.3
Other equipment	0.8	N	Q	0.7	0.8
Fuel oil/kerosene	5.0	22.4	Q	2.0	Q
Central warm-air furnace	3.1	13.3	Q	1.4	Q
Steam or hot water system	1.4	7.1	Q	Q	Q
Other equipment	0.6	1.9	Q	Q	Q
Propane	4.7	3.3	8.7	3.8	3.4
Central warm-air furnace	3.6	2.4	7.6	2.3	2.3
Other equipment	1.2	Q	1.1	1.4	0.8
Wood	1.9	2.9	2.3	1.1	2.7
Heating stove	1.5	1.9	1.5	0.9	1.9
Other equipment	0.4	0.5	Q	Q	0.8
Some other fuel[c]	Q	Q	Q	N	Q
Do not have or use heating equipment	4.0	Q	N	4.3	10.6
Main heating equipment (including all fuels)					
Central warm-air furnace	60.1	51.4	77.3	54.5	59.1
Heat pump	11.6	3.8	3.4	22.1	8.3
Steam or hot water system	7.9	28.1	7.6	1.4	3.0
Built-in electric units	7.6	6.2	7.2	8.3	8.0
Built-in oil or gas room heater	2.6	3.3	1.1	2.5	3.8

Table 19-14. Residential Heating Characteristics by U.S. Census (%) (Continued)

Space Heating Characteristics	Housing Units %[a]	U.S. Census Region			
		Northeast	Midwest	South	West
Portable electric heater	2.5	Q	Q	4.5	2.3
Heating stove burning wood	1.5	1.9	1.5	0.9	1.9
Built-in pipeless furnace	1.0	Q	Q	0.7	1.9
Fireplace	0.6	Q	Q	0.5	1.1
Some other equipment	0.8	Q	Q	0.7	Q
Do not use heating equipment	4.0	Q	N	4.3	10.6
Secondary heating fuel and equipment					
Secondary heating equipment used	36.6	41.0	39.8	35.4	32.2
Natural gas	6.3	6.7	7.6	5.6	6.4
Fireplace	5.5	5.7	6.4	4.7	6.1
Some other equipment	0.8	Q	1.1	0.9	0.4
Electricity	19.4	21.9	22.0	18.0	16.7
Portable electric heaters	17.0	18.6	19.7	16.4	14.0
Some other equipment	2.4	3.3	2.3	1.6	2.7
Wood	7.9	7.6	7.6	8.1	7.6
Heating stove	3.1	4.8	3.0	2.5	3.0
Fireplace	4.7	2.9	4.2	5.6	4.5
Some other equipment	Q	N	Q	N	N
Some other fuel	3.0	4.3	2.3	3.6	1.5
Do not use secondary heating equipment	59.4	59.0	60.2	60.6	57.2

[a] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded. Housing characteristics data were collected between August 2015 and April 2016.

[b] Use of heating equipment for another housing unit also includes the use of the heating equipment for a business or farm building as well as another housing unit.

[c] Some other fuel includes coal and district steam.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled

N = No cases in reporting sample.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2015).

Table 19-15. Residential Heating Characteristics by Climate Region (%)

Space Heating	Housing Units %[a]	Climate Region[b]				
		Very Cold/ Cold	Mixed-Humid	Mixed-Dry/ Hot-Dry	Hot-Humid	Marine
Total homes	100.0	100.0	100.0	100.0	100.0	100.0
Space heating equipment						
Use space heating equipment	96.0	99.8	100.0	84.5	89.9	93.9
Have space heating equipment but do not use it	2.8	Q	Q	10.9	7.0	4.5
Do not have space heating equipment	1.2	Q	Q	4.7	3.1	Q
Main heating fuel and equipment[c]						
Natural gas	47.3	61.6	42.9	54.3	22.8	48.5
Central warm-air furnace	38.1	51.4	31.0	44.2	19.7	40.9
Steam or hot water system	5.5	7.8	8.3	2.3	Q	Q
Built-in room heater	1.8	1.2	1.2	4.7	2.2	3.0
Other equipment	1.9	1.2	2.7	3.9	0.9	3.0
Electricity	36.3	19.3	41.7	27.9	64.5	36.4
Central warm-air furnace	15.1	7.1	16.1	13.2	31.6	9.1
Heat pump	10.2	3.1	15.2	7.0	18.4	10.6
Built-in electric units	7.6	7.3	7.1	5.4	8.3	13.6
Portable electric heater	2.5	0.9	3.0	2.3	5.3	3.0
Other equipment	0.8	1.2	Q	Q	Q	Q
Fuel oil	5.0	8.3	6.8	N	Q	Q
Central warm-air furnace	3.1	5.7	3.6	N	Q	Q
Steam or hot water system	1.4	2.1	2.1	N	N	N
Other equipment	0.6	0.7	1.2	N	N	N
Propane	4.7	6.4	6.3	1.6	1.8	3.0
Central warm-air furnace	3.6	5.2	4.5	Q	0.9	Q
Other equipment	1.2	1.2	1.5	Q	0.9	Q
Wood	1.9	2.8	1.8	Q	0.4	4.5
Heating stove	1.5	2.1	1.5	Q	Q	3.0
Other equipment	0.4	0.7	Q	Q	Q	Q
Some other fuel[d]	Q	Q	Q	N	N	N
Do not have or use heating equipment	4.0	Q	Q	15.5	10.1	6.1
Main heating equipment (including all fuels)						
Central warm-air furnace	60.1	69.6	55.1	58.1	52.6	51.5
Heat pump	11.6	3.3	17.9	8.5	18.9	10.6
Steam or hot water system	7.9	11.6	11.6	2.3	Q	Q

Table 19-15. Residential Heating Characteristics by Climate Region (%) (Continued)

Space Heating	Housing Units %[a]	Climate Region[b]				
		Very Cold/ Cold	Mixed-Humid	Mixed-Dry/ Hot-Dry	Hot-Humid	Marine
Built-in electric units	7.6	7.3	7.1	5.4	8.3	13.6
Built-in oil or gas room heater	2.6	2.1	2.1	4.7	2.6	4.5
Portable electric heater	2.5	0.9	3.0	2.3	5.3	3.0
Heating stove burning wood	1.5	2.1	1.5	Q	Q	3.0
Built-in pipeless furnace	1.0	0.7	0.9	2.3	Q	Q
Fireplace	0.6	0.5	Q	Q	Q	Q
Some other equipment	0.8	1.7	Q	N	Q	Q
Do not have or use heating equipment	4.0	Q	Q	15.5	10.1	6.1
Secondary heating fuel and equipment						
Secondary heating equipment used	36.6	41.5	41.1	23.3	25.4	45.5
Natural gas	6.3	7.8	6.8	6.2	3.5	4.5
Fireplace	5.5	6.6	6.0	6.2	2.6	4.5
Some other equipment	0.8	1.2	0.9	Q	Q	Q
Electricity	19.4	21.9	21.4	10.9	14.5	25.8
Portable electric heaters	17.0	18.6	19.6	10.9	13.2	19.7
Some other equipment	2.4	3.3	1.8	Q	1.3	6.1
Wood	7.9	8.0	8.6	5.4	6.6	12.1
Heating stove	3.1	4.5	3.9	Q	Q	6.1
Fireplace	4.7	3.5	4.8	4.7	6.1	6.1
Some other equipment	Q	Q	Q	N	N	N
Some other fuel	3.0	4.0	4.2	Q	1.3	3.0
Do not use secondary heating equipment	59.4	58.3	58.9	61.2	64.5	48.5
Do not use any heating equipment	4.0	Q	Q	15.5	10.1	6.1

[a] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded. Housing characteristics data were collected between August 2015 and April 2016.

[b] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy and Efficiency and Renewable Energy (EERE).

[c] Use of heating equipment for another housing unit also includes the use of the heating equipment for a business or farm building as well as another housing unit.

[d] Some other fuel includes coal and district steam.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled.

N = No cases in reporting sample.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2015).

Table 19-16. Residential Air Conditioning Characteristics by U.S. Census Region (%)

	Housing Units %[a]	Northeast	Midwest	South	West
All homes	100.0	100.0	100.0	100.0	100.0
Air-conditioning equipment					
Use air-conditioning equipment	87.2	85.7	92.0	95.3	70.1
Do not use air-conditioning equipment	12.8	14.3	7.6	5.0	29.9
Type of air-conditioning equipment used (more than one may apply)					
Use central air-conditioning equipment	65.2	36.2	70.8	81.5	54.9
Do not use central air-conditioning equipment	34.8	63.8	29.2	18.5	45.1
Use individual air-conditioning units	26.7	53.3	26.1	19.6	18.2
With 1 unit	13.3	21.9	15.2	9.0	11.7
With 2 units	8.0	17.6	8.0	5.4	4.5
With 3 or more units	5.5	13.8	2.7	5.2	1.9
Do not use individual air-conditioning units	73.3	46.7	73.9	80.6	81.8
Air-conditioned basement					
Yes	11.9	10.0	30.3	6.1	4.9
No	15.0	34.3	24.2	6.1	4.9
Not asked (air-conditioned homes with no basement)	33.8	8.6	14.4	54.7	38.3
Not asked (unair-conditioned homes, apartments, and mobile homes)	39.3	47.1	30.7	33.3	51.9
Air-conditioned attic					
Yes	1.4	2.9	1.9	0.9	0.8
No	33.8	29.0	36.4	41.4	22.3
Not asked (air-conditioned homes with no attic)	25.5	21.4	31.1	24.3	25.0
Not asked (unair-conditioned homes, apartments, and mobile homes)	39.3	47.1	30.7	33.3	51.9
Air-conditioned, attached garage					
Yes	0.8	Q	0.8	1.1	0.8
No	35.0	27.1	41.3	34.9	35.2
Not asked (air-conditioned homes with no attached garage)	24.8	25.2	26.9	30.6	12.5
Not asked (unair-conditioned homes, apartments, and mobile homes)	39.3	47.1	30.7	33.3	51.9
Dehumidifier usage					
Use a dehumidifier	14.0	25.2	26.5	7.7	3.4
Less than 4 months	4.9	10.0	9.1	2.0	1.5
4 to 6 months	5.5	8.1	12.1	3.2	0.8

Table 19-16. Residential Air Conditioning Characteristics by U.S. Census Region (%) (Continued)

	Housing Units %[a]	Northeast	Midwest	South	West
7 to 9 months	1.7	3.3	2.7	1.1	Q
10 to 11 months	Q	Q	Q	Q	N
Turned on all 12 months	1.8	3.3	2.7	1.4	Q
Do not use a dehumidifier	86.0	74.8	73.5	92.3	96.6
Use an evaporative or swamp cooler (asked only in arid areas)					
Yes	2.4	N	N	1.1	8.7
No	46.4	N	N	71.8	86.7
Not asked	51.3	100.0	100.0	27.0	4.5
Fan types used (more than one may apply)					
Ceiling fans	72.3	58.6	75.4	81.5	64.4
Floor, window, or table fans	45.9	51.9	52.7	38.7	46.6
Whole house fans	5.2	4.3	5.7	4.3	6.8
Attic fans	7.4	8.6	8.0	7.7	5.3
Number of ceiling fans used					
0	27.7	41.4	24.6	18.7	35.6
1	17.9	18.1	20.5	13.5	23.1
2	16.0	14.8	17.4	17.1	13.6
3	12.8	11.4	13.6	14.6	9.5
4 or more	25.5	14.8	23.5	36.3	18.2

[a] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded. Housing characteristics data were collected between August 2015 and April 2016.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled.

N = No cases in reporting sample.

Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2015).

Table 19-17. Percentage of Residences with Basement, by Census Region and EPA Region

Census Region	EPA Regions	% of Residences With Basements
Northeast	1	93.4
Northeast	2	55.9
Midwest	3	67.9
Midwest	4	19.3
South	5	73.5
South	6	4.1
South	7	75.3
West	8	68.5
West	9	10.3
West	10	11.5
	All Regions	45.2

Source: Lucas et al. (1992).

Table 19-18. Percentage of Residences with Basement, by Census Region[a]

Census Region[b]	Census Divisions	% of Residences with Basements[c]
Northeast	New England	82.9
Northeast	Mid Atlantic	84.8
Midwest	East North Central	75.8
Midwest	West North Central	84.1
South	South Atlantic	26.5
South	East South Central	23.1
South	West South Central	Q
West	Mountain	31.7
West	Mountain North	65.5
West	Mountain South	Q
West	Pacific	14.5
	All Divisions	43.5

[a] Housing characteristics data were collected between August 2015 and April 2016.

[b] Housing units are classified using criteria created by the U.S. Census Bureau based on 2010 Census data. Urbanized areas are densely settled groupings of blocks or tracts with 50,000 or more people, while urban clusters have at least 2,500 but less than 50,000 people. All other areas are rural.

[c] Total United States includes all primary occupied housing units in the 50 states and the District of Columbia. Vacant housing units, seasonal units, second homes, military houses, and group quarters are excluded. Includes single family detached and attached homes.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 10 households were sampled.

Source: EPA Analysis of U.S. DOE (2017).

Table 19-19. States Associated with EPA Regions and Census Regions

EPA Regions

Region 1	Region 4	Region 6	Region 8
Connecticut	Alabama	Arkansas	Colorado
Maine	Florida	Louisiana	Montana
Massachusetts	Georgia	New Mexico	North Dakota
New Hampshire	Kentucky	Oklahoma	South Dakota
Rhode Island	Mississippi	Texas	Utah
Vermont	North Carolina		Wyoming
	South Carolina	Region 7	
Region 2	Tennessee	Iowa	Region 9
New Jersey		Kansas	Arizona
New York	Region 5	Missouri	California
	Illinois	Nebraska	Hawaii
Region 3	Indiana		Nevada
Delaware	Michigan		
District of Columbia	Minnesota		Region 10
Maryland	Ohio		Alaska
Pennsylvania	Wisconsin		Idaho
Virginia			Oregon
West Virginia			Washington

U.S. Census Bureau Regions

Northeast region	Midwest region	South region	West region
Connecticut	Illinois	Alabama	Alaska
Maine	Indiana	Arkansas	Arizona
Massachusetts	Iowa	Delaware	California
New Hampshire	Kansas	District of Columbia	Colorado
New Jersey	Michigan	Florida	Hawaii
New York	Minnesota	Georgia	Idaho
Pennsylvania	Missouri	Kentucky	Montana
Rhode Island	Nebraska	Louisiana	Nevada
Vermont	North Dakota	Maryland	New Mexico
	Ohio	Mississippi	Oregon
	South Dakota	North Carolina	Utah
	Wisconsin	Oklahoma	Washington
		South Carolina	Wyoming
		Tennessee	
		Texas	
		Virginia	
		West Virginia	

Source: RECS Terminology available on line at: https://www.eia.gov/consumption/residential/terminology.php#c

Table 19-20. Percentage of Residences with Certain Foundation Types by Census Region

Census Region	% of Residences[a, b] With Basement	With Crawlspace	With Concrete Slab
Northeast	74.7	18.4	27.8
Midwest	72.5	26.1	28.9
South	14.7	32.6	59.6
West	16.7	39.2	60.2
All Regions	39.9	29.8	46.5

[a] Percentage may add to more than 100 because more than one foundation type may apply to a given residence.

[b] Included single family attached and detached homes and apartments in buildings of 2−4 units.

Source: EPA Analysis of U.S. DOE, 2013.

Table 19-21. Average Estimated Volumes[a] of U.S. Commercial Buildings, by Primary Activity

Primary Building Activity	*N*	Mean	SE of Mean	Percentiles					% of Total
				10th	25th	50th	75th	90th	
Vacant	134	4,789	581	408	612	1,257	3,823	11,213	3.7
Office	976	5,036	397	510	714	1,359	3,398	8,155	17.0
Laboratory	43	24,681	1,114	2,039	5,437	10,534	40,776	61,164	0.2
Nonrefrigerated warehouse	473	9,298	992	1,019	1,812	2,945	7,504	16,990	12.0
Food sales	125	1,889	106	476	680	951	2,039	3,398	4.6
Public order and safety	85	5,253	482	816	1,019	1,699	3,398	8,495	1.5
Outpatient healthcare	144	3,537	251	680	1,019	2,039	3,398	6,966	2.5
Refrigerated warehouse	20	19,716	3,377	1,133	1,699	3,398	8,212	38,511	0.3
Religious worship	311	3,443	186	612	917	2,039	4,163	8,325	7.6
Public assembly	279	4,839	394	595	1,019	2,277	4,417	7,136	5.7
Education	649	8,694	513	527	867	2,379	10,194	23,786	7.9
Food service	242	1,889	112	442	680	1,189	2,039	3,568	6.1
Inpatient healthcare	217	82,034	5,541	17,330	25,485	36,019	95,145	203,881	0.2
Nursing	73	15,522	559	1,546	5,097	10,534	17,330	38,737	0.4
Lodging	260	11,559	1,257	527	1,376	4,078	10,194	27,184	2.5
Strip shopping mall	349	7,891	610	1,359	2,277	4,078	6,966	19,709	4.3
Enclosed mall	46	287,978	14,780	35,679	35,679	113,268	453,070	849,505	0.1
Retail other than mall	355	3,310	218	510	680	1,631	3,398	6,116	9.1
Service	370	2,213	182	459	629	934	2,039	4,587	12.8
Other	64	5,236	984	425	544	1,427	3,398	9,175	1.4
All buildings[b]	5,215	5,575	256	527	816	1,699	4,248	10,194	100

[a] Volumes calculated from floor areas assuming a ceiling height of 12 feet for other structures and 20 feet for warehouses.

[b] Weighted average calculated from floor areas assuming a ceiling height of 12 feet for all buildings except warehouses and enclosed malls, which assumed 20-foot ceilings.

N = Number of observations.

SE = Standard error.

Source: EPA Analysis of U.S. DOE (2008b).

Table 19-22. Nonresidential Buildings: Hours per Week Open and Number of Employees

Primary Building Activity	*N*	%	Number of Hours/Week Open							Number of Employees During Main Shift						
			Mean	SE of Mean	Percentiles					Mean	SE of Mean	Percentiles				
					10th	25th	50th	75th	90th			10th	25th	50th	75th	90th
Vacant	134	2.8	6.7	1.2	0	0	0	0	40	0.35	0.08	0	0	0	0	0
Office	976	20.2	54.7	1.6	40	45	54	65	168	34.2	2.8	4	11	57	300	886
Laboratory	43	0.9	103.5	0.8	50	58	98	168	168	105.6	4.5	20	55	156	300	435
Nonrefrigerated warehouse	473	9.8	66.2	4.8	20	40	55	80	168	7.0	0.9	0	1	8	25	64
Food sales	125	2.6	107.3	2.5	60	80	109	127	168	6.3	0.5	1	2	4	15	50
Public order and safety	85	1.8	103.0	7.6	10	40	168	168	168	19.1	2.2	1	4	15	60	200
Outpatient healthcare	144	3.0	52.0	2.8	40	45	54	70	168	21.5	1.9	5	8	40	125	200
Refrigerated warehouse	20	0.4	61.3	0.7	44	53	102	126	168	18.2	2.4	4	8	38	61	165
Religious worship	311	6.5	32.0	2.4	5	13	40	60	79	4.6	0.5	1	1	3	10	19
Public assembly	279	5.8	50.3	3.8	12	40	63	96	125	8.7	1.5	0	2	5	22	80
Education	649	13.5	49.6	1.0	38	42	54	70	85	32.4	8.8	3	14	38	75	133
Food service	242	5.0	85.8	2.6	40	66	84	105	130	10.5	0.9	2	4	8	15	33
Inpatient healthcare	217	4.5	168.0	*	168	168	168	168	168	471.0	40.4	175	315	785	1,300	2,250
Nursing	73	1.5	168.0	*	168	168	168	168	168	44.8	2.5	15	25	50	80	170
Lodging	260	5.4	166.6	0.8	168	168	168	168	168	12.3	2.0	1	3	10	25	80
Retail other than mall	355	7.4	59.1	1.5	42	50	62	80	105	7.8	0.7	2	3	6	22	72
Service	370	7.7	55.0	2.1	40	40	50	68	105	5.9	0.6	1	2	4	10	35
Other	64	1.3	57.8	7.1	12	40	51	90	168	12.3	1.7	1	2	10	44	150
All Activities	4,820	100.0	61.2	1.2	30	45	60	98	168	15.7	1.2	1	3	14	66	300

* All sampled inpatient healthcare and nursing buildings reported being open 24 hours a day, 7 days a week.
N = Number of observations.
SE = Standard error.

Source: EPA Analysis of U.S. DOE (2008b).

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
All buildings	5,557	4,722	1,819	2,322	205	47
Building floorspace (square feet)						
1,001 to 5,000	50	48	51	44	58	Q
5,001 to 10,000	22	22	22	22	18	Q
10,001 to 25,000	16	17	15	19	16	Q
25,001 to 50,000	6	6	6	7	Q	13
50,001 to 100,000	4	4	4	4	3	21
100,001 to 200,000	2	2	1	2	1	19
200,001 to 500,000	1	1	0	1	Q	11
Over 500,000	0	0	0	0	Q	4
Principal building activity						
Education	7	8	8	8	8	26
Food sales	3	3	5	2	Q	N
Food service	7	8	8	8	Q	Q
Health care	3	3	3	4	2	4
Inpatient	0	0	Q	0	Q	2
Outpatient	3	3	3	3	Q	Q
Lodging	3	3	5	2	Q	9
Mercantile	11	12	13	12	Q	Q
Retail (other than mall)	8	9	9	8	Q	Q
Enclosed and strip malls	3	3	4	4	Q	Q
Office	18	21	23	21	16	26
Public assembly	6	7	5	7	Q	15
Public order and safety	2	2	Q	2	Q	Q
Religious worship	7	9	7	9	Q	N
Service	11	11	7	12	23	Q
Warehouse and storage	14	9	10	9	Q	Q
Other	2	2	2	2	Q	Q
Vacant	5	2	2	2	Q	Q

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings (Continued)

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
Year constructed						
Before 1920	7	7	4	8	20	11
1920 to 1945	9	9	6	11	12	15
1946 to 1959	11	11	10	11	14	11
1960 to 1969	11	12	9	14	18	19
1970 to 1979	12	13	12	13	Q	21
1980 to 1989	16	16	20	14	Q	4
1990 to 1999	15	14	15	14	10	4
2000 to 2003	7	7	8	6	Q	9
2004 to 2007	6	6	9	5	Q	4
2008 to 2012	5	6	7	4	Q	Q
Census region and division						
Northeast	14	15	8	16	69	32
New England	5	6	2	3	45	Q
Middle Atlantic	9	10	5	12	23	19
Midwest	22	23	11	33	Q	13
East North Central	13	14	5	23	Q	6
West North Central	9	9	6	10	Q	9
South	40	39	57	28	16	38
South Atlantic	20	18	31	10	10	17
East South Central	7	7	8	6	Q	Q
West South Central	14	13	18	12	Q	11
West	23	22	24	24	Q	15
Mountain	6	6	4	8	Q	Q
Pacific	17	16	20	16	Q	11
Climate region[b]						
Very cold/cold	37	38	19	47	76	36
Mixed-humid	31	33	36	31	25	43
Mixed-dry/hot-dry	15	14	18	14	N	9
Hot-humid	14	13	26	5	N	Q
Marine	3	2	Q	4	N	Q
Ownership and occupancy						
Nongovernment owned	86	85	88	84	86	45
Owner occupied	44	47	46	44	53	28

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings (Continued)

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
Leased to tenant(s)	31	31	34	32	25	Q
Owner occupied and leased	6	7	7	7	Q	4
Unoccupied	4	1	Q	1	Q	Q
Government owned	14	15	12	16	14	55
Federal	1	1	Q	1	Q	2
State	3	4	3	3	Q	38
Local	10	10	8	12	13	15
Energy sources (more than one may apply)						
Electricity	94	100	100	100	100	100
Natural gas	53	61	28	100	7	36
Fuel oil	8	10	5	5	100	21
District heat	1	1	Q	Q	Q	100
District chilled water	1	1	1	0	N	55
Propane	9	10	7	2	23	Q
Other	3	4	2	2	Q	2
Energy end uses (more than one may apply)						
Buildings with space heating	85	100	100	100	100	100
Buildings with cooling	80	90	95	92	66	91
Buildings with water heating	80	90	88	93	82	94
Buildings with cooking	29	32	31	33	28	28
Buildings with manufacturing	5	5	5	5	Q	Q
Buildings with electricity generation	7	8	7	9	12	32
Percentage of floorspace heated						
Not heated	15	N	N	N	N	N
1 to 50	13	15	20	11	15	Q
51 to 99	13	15	15	16	14	15
100	59	70	65	74	71	85

Table 19-23. Nonresidential Heating Energy Sources for Commercial Buildings (Continued)

			Primary Space-Heating Energy Source Used[a]			
	All Buildings	Buildings with Space Heating	Electricity	Natural Gas	Fuel Oil	District Heat
Heating equipment (more than one may apply)						
Heat pumps	11	13	27	5	Q	4
Furnaces	14	16	11	21	Q	Q
Individual space heaters	22	26	22	27	40	17
District heat	1	1	Q	Q	Q	100
Boilers	10	12	5	15	35	Q
Packaged heating units	50	59	58	65	41	6
Other	1	1	1	1	Q	Q

[a] Additionally, 261,000 buildings used propane and 67,000 buildings used wood, coal, or some other energy source for primary space heating.
[b] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).
Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 20 buildings were sampled.
N = No cases in reporting sample.

Source: EPA Analysis of U.S. DOE (2016).

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
All buildings (N)	5,557	4,461	4,413	12	54	87,093	79,294	76,034	732	4,608
Building floorspace (ft^2)										
1,001 to 5,000	50	46	47	Q	Q	8,041	6,124	6,107	Q	Q
5,001 to 10,000	22	23	23	Q	Q	8,900	7,304	7,252	Q	Q
10,001 to 25,000	16	17	17	Q	17	14,105	12,357	12,211	Q	145
25,001 to 50,000	6	7	7	Q	Q	11,917	10,813	10,615	Q	Q
50,001 to 100,000	4	4	4	Q	19	13,918	13,069	12,618	Q	567
100,001 to 200,000	2	2	2	Q	17	12,415	12,152	11,034	Q	1,273
200,001 to 500,000	1	1	1	Q	7	10,724	10,518	9,887	Q	1,064
Over 500,000	0	0	0	(*)	2	7,074	6,958	6,310	167	1,306
Principal building activity										
Education	7	8	8	Q	46	12,239	11,811	10,673	Q	1,292
Food sales	3	4	4	N	N	1,252	1,190	1,190	N	N
Food service	7	8	8	N	Q	1,819	1,712	1,668	N	Q
Health care	3	3	3	(*)	Q	4,155	4,148	3,966	200	523
Inpatient	0	0	0	(*)	2	2,374	2,374	2,227	176	477
Outpatient	3	3	3	Q	Q	1,781	1,774	1,739	Q	Q
Lodging	3	3	3	Q	Q	5,826	5,700	5,308	Q	Q
Mercantile	11	13	13	Q	N	11,330	11,121	11,121	Q	N
Retail (other than mall)	8	9	9	N	N	5,439	5,230	5,230	N	N
Enclosed and strip malls	3	4	4	Q	N	5,890	5,890	5,890	Q	N

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%) (Continued)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
Office	18	22	22	Q	19	15,952	15,882	15,179	Q	1,096
Public assembly	6	7	7	N	9	5,559	5,235	4,629	N	880
Public order and safety	2	2	2	Q	Q	1,440	1,384	1,358	Q	Q
Religious worship	7	8	8	N	Q	4,557	4,271	4,271	N	Q
Service	11	10	10	N	N	4,630	3,773	3,758	N	N
Warehouse and storage	14	9	9	Q	N	13,077	10,120	10,059	Q	N
Other	2	2	2	Q	Q	2,002	1,820	1,806	Q	Q
Vacant	5	1	1	N	Q	3,256	1,125	1,048	N	Q
Year constructed										
Before 1920	7	6	6	N	Q	3,983	3,087	2,908	N	Q
1920 to 1945	9	8	8	Q	Q	6,025	5,215	5,081	Q	Q
1946 to 1959	11	11	11	Q	Q	7,381	6,679	6,569	Q	203
1960 to 1969	11	12	12	Q	20	10,362	9,634	8,962	Q	923
1970 to 1979	12	13	13	Q	17	10,846	10,031	9,440	Q	811
1980 to 1989	16	16	16	Q	6	15,230	14,011	13,830	Q	310
1990 to 1999	15	15	15	Q	19	13,803	12,402	11,924	Q	664
2000 to 2003	7	7	7	Q	9	7,215	6,939	6,463	Q	Q
2004 to 2007	6	7	7	Q	11	6,524	6,071	5,722	Q	418
2008 to 2012	5	5	5	Q	Q	5,723	5,225	5,135	Q	Q
Census region and division										
Northeast	14	13	13	50	13	15,534	13,949	13,303	305	794
New England	5	4	4	Q	Q	4,302	3,482	3,317	Q	Q

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%) (Continued)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
Middle Atlantic	9	9	9	25	Q	11,232	10,467	9,986	216	656
Midwest	22	22	22	Q	4	18,919	17,144	16,826	Q	585
East North Central	13	13	14	Q	4	12,742	11,675	11,474	Q	420
West North Central	9	8	8	Q	Q	6,178	5,469	5,352	Q	Q
South	40	42	42	Q	65	34,279	31,734	29,950	Q	2,479
South Atlantic	20	21	21	Q	41	17,981	17,094	16,368	Q	1,202
East South Central	7	8	7	Q	Q	4,904	4,710	4,307	Q	Q
West South Central	14	14	14	Q	11	11,394	9,931	9,275	Q	773
West	23	23	23	Q	17	18,360	16,467	15,955	Q	749
Mountain	6	6	6	Q	2	4,981	4,489	4,205	Q	Q
Pacific	17	17	17	Q	15	13,379	11,978	11,749	Q	329
Climate region[a]										
Very cold/cold	37	34	34	67	13	31,898	28,228	27,377	403	1,227
Mixed-humid	31	33	33	25	33	27,873	26,365	24,968	272	2,027
Mixed-dry/hot-dry	15	15	15	Q	13	12,037	10,887	10,490	Q	Q
Hot-humid	14	16	15	Q	39	12,831	11,624	11,043	Q	752
Marine	3	2	2	Q	Q	2,454	2,190	2,157	Q	Q
Ownership and occupancy										
Nongovernment owned	86	86	86	92	31	67,550	60,960	59,329	542	2,104
Owner occupied	44	46	46	Q	26	30,637	28,174	26,984	147	1,478
Leased to tenant(s)	31	32	32	Q	4	26,115	23,907	23,688	Q	297
Owner occupied and leased	6	7	7	Q	2	8,873	8,602	8,379	Q	329

Table 19-24. Air Conditioning Energy Sources for Nonresidential (%) (Continued)

	Cooling Energy Sources Used (More Than One May Apply)					Floor Space by Cooling Energy Sources Used (More Than One May Apply) (million ft^2)				
	All Buildings	Buildings with Cooling	Elect-ricity	Natural Gas	District Chilled Water	All Buildings	Buildings with Cooling	Electricity	Natural Gas	District Chilled Water
Unoccupied	4	1	1	N	N	1,925	278	278	N	N
Government owned	14	14	14	Q	69	19,543	18,334	16,705	Q	2,504
Federal	1	1	1	Q	Q	1,573	1,573	1,403	Q	Q
State	3	4	3	Q	37	5,539	5,252	4,086	Q	1,448
Local	10	10	10	Q	30	12,431	11,508	11,217	Q	612

[a] These climate regions were created by the Building America program, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).
Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50% or fewer than 20 buildings were sampled.
N = No cases in reporting sample.
(*) = Value rounds to zero in the units displayed.
Notes: Because of rounding, data may not sum to totals.

Source: EPA Analysis of U.S. DOE (2016).

Table 19-25. Summary Statistics for Residential Air Exchange Rates (in ACH),[a] by Region

	West Region	North Central Region	Northeast Region	South Region	All Regions
Arithmetic mean	0.66	0.57	0.71	0.61	0.63
Arithmetic standard deviation	0.87	0.63	0.60	0.51	0.65
Geometric mean	0.47	0.39	0.54	0.46	0.46
Geometric standard deviation	2.11	2.36	2.14	2.28	2.25
10^{th} percentile	0.20	0.16	0.23	0.16	0.18
50^{th} percentile	0.43	0.35	0.49	0.49	0.45
90^{th} percentile	1.25	1.49	1.33	1.21	1.26
Maximum	23.32	4.52	5.49	3.44	23.32

[a] ACH = Air changes per hour.

Source: Koontz and Rector (1995).

Table 19-26. Distribution of Air Exchange Rates in (ACH)[a] by House Category

House Category	5%	10%	25%	50%	75%	90%	95%
Single family—national average	0.10	0.16	0.27	0.44	0.70	1.00	1.21
Single family—built before 1940	0.17	0.25	0.39	0.58	0.92	1.33	1.57
Single family—built 1941-1969	0.14	0.21	0.34	0.54	0.81	1.10	1.28
Single family—built 1970-1989	0.09	0.14	0.22	0.36	0.55	0.76	0.89
Single family—built 1990 or newer	0.05	0.09	0.15	0.26	0.43	0.60	0.70
Detached—East North Central	0.11	0.17	0.28	0.42	0.75	1.10	1.31
Detached—East South Central	0.08	0.13	0.24	0.48	0.67	0.95	1.12
Detached—Middle Atlantic	0.14	0.20	0.30	0.41	0.76	1.09	1.29
Detached—Mountain	0.09	0.14	0.24	0.50	0.63	0.84	0.98
Detached—New England	0.15	0.22	0.32	0.44	0.82	1.18	1.39
Detached—Pacific	0.15	0.20	0.29	0.40	0.61	0.83	0.97
Detached—South Atlantic	0.07	0.12	0.22	0.48	0.63	0.88	1.04
Detached—West North Central	0.11	0.18	0.29	0.45	0.79	1.16	1.39
Detached—West South Central	0.09	0.15	0.28	0.42	0.67	0.90	1.06
Apartments built before 1940	0.11	0.16	0.21	0.31	0.46	0.61	0.72
Apartments built 1941−1969	0.09	0.13	0.18	0.29	0.42	0.56	0.65
Apartments built 1970−1989	0.06	0.10	0.15	0.23	0.39	0.49	0.55
Apartments built 1990 or newer	0.05	0.07	0.08	0.14	0.18	0.31	0.39

[a] ACH = Air changes per hour.

Source: Persily et al. (2010).

Table 19-27. Summary of Major Projects Providing Air Exchange Measurements in the PFT Database

Project Code	State	Month(s)[a]	Number of Measurements	Mean Air Exchange Rate (ACH)	SD[b]	Percentiles				
						10th	25th	50th	75th	90th
ADM	CA	5−7	29	0.70	0.52	0.29	0.36	0.48	0.81	1.75
BSG	CA	1, 8−12	40	0.53	0.30	0.21	0.30	0.40	0.70	0.90
GSS	AZ	1–3, 8–9	25	0.39	0.21	0.16	0.23	0.33	0.49	0.77
FLEMING	NY	1–6, 8−12	56	0.24	0.28	0.05	0.12	0.22	0.29	0.37
GEOMET1	FL	1,6−8, 10−12	18	0.31	0.16	0.15	0.18	0.25	0.48	0.60
GEOMET2	MD	1−6	23	0.59	0.34	0.12	0.29	0.65	0.83	0.92
GEOMET3	TX	1−3	42	0.87	0.59	0.33	0.51	0.71	1.09	1.58
LAMBERT1	ID	2−3, 10−11	36	0.25	0.13	0.10	0.17	0.23	0.33	0.49
LAMBERT2	MT	1−3, 11	51	0.23	0.15	0.10	0.14	0.19	0.26	0.38
LAMBERT3	OR	1−3, 10−12	83	0.46	0.40	0.19	0.26	0.38	0.56	0.80
LAMBERT4	WA	1−3, 10−12	114	0.30	0.15	0.14	0.20	0.30	0.39	0.50
LBL1	OR	1−4, 10−12	126	0.56	0.37	0.28	0.35	0.45	0.60	1.02
LBL2	WA	1−4, 10−12	71	0.36	0.19	0.18	0.25	0.32	0.42	0.52
LBL3	ID	1−5, 11−12	23	1.03	0.47	0.37	0.73	0.99	1.34	1.76
LBL4	WA	1−4, 11−12	29	0.39	0.27	0.14	0.18	0.36	0.47	0.63
LBL5	WA	2−4	21	0.36	0.21	0.13	0.19	0.30	0.47	0.62
LBL6	ID	3−4	19	0.28	0.14	0.11	0.17	0.26	0.38	0.55
NAHB	MN	1−5, 9−12	28	0.22	0.11	0.11	0.16	0.20	0.24	0.38
NYSDH	NY	1−2, 4, 12	74	0.59	0.37	0.28	0.37	0.50	0.68	1.07
PEI	MD	3−4	140	0.59	0.45	0.15	0.26	0.49	0.83	1.20
PIERCE	CT	1−3	25	0.80	1.14	0.20	0.22	0.38	0.77	2.35
RTI1	CA	2	45	0.90	0.73	0.38	0.48	0.78	1.08	1.52
RTI2	CA	7	41	2.77	2.12	0.79	1.18	2.31	3.59	5.89
RTI3	NY	1–4	397	0.55	0.37	0.26	0.33	0.44	0.63	0.94
SOCAL1	CA	3	551	0.81	0.66	0.29	0.44	0.66	0.94	1.43
SOCAL2	CA	7	408	1.51	1.48	0.35	0.59	1.08	1.90	3.11
SOCAL3	CA	1	330	0.76	1.76	0.26	0.37	0.48	0.75	1.11
UMINN	MN	1–4	35	0.36	0.32	0.17	0.20	0.28	0.40	0.56
UWISC	WI	2–5	57	0.82	0.76	0.22	0.33	0.55	1.04	1.87

[a] 1 = January, 2 = February, etc.
[b] SD = Standard deviation.

Source: Adapted from Versar (1990).

Table 19-28. Distributions of Residential Air Exchange Rates (in ACH)[a] by Climate Region and Season

Climate Region[b]	Season	Sample Size	Arithmetic Mean	Standard Deviation	Percentiles				
					10th	25th	50th	75th	90th
Coldest	Winter	161	0.36	0.28	0.11	0.18	0.27	0.48	0.71
	Spring	254	0.44	0.31	0.18	0.24	0.36	0.53	0.80
	Summer	5	0.82	0.69	0.27	0.41	0.57	1.08	2.01
	Fall	47	0.25	0.12	0.10	0.15	0.22	0.34	0.42
Colder	Winter	428	0.57	0.43	0.21	0.30	0.42	0.69	1.18
	Spring	43	0.52	0.91	0.13	0.21	0.24	0.39	0.83
	Summer	2	1.31	—	—	—	—	—	—
	Fall	23	0.35	0.18	0.15	0.22	0.33	0.41	0.59
Warmer	Winter	96	0.47	0.40	0.19	0.26	0.39	0.58	0.78
	Spring	165	0.59	0.43	0.18	0.28	0.48	0.82	1.11
	Summer	34	0.68	0.50	0.27	0.36	0.51	0.83	1.30
	Fall	37	0.51	0.25	0.30	0.30	0.44	0.60	0.82
Warmest	Winter	454	0.63	0.52	0.24	0.34	0.48	0.78	1.13
	Spring	589	0.77	0.62	0.28	0.42	0.63	0.92	1.42
	Summer	488	1.57	1.56	0.33	0.58	1.10	1.98	3.28
	Fall	18	0.72	1.43	0.22	0.25	0.42	0.46	0.74

[a] ACH = air changes per hour.

[b] The coldest region was defined as having 7,000 or more heating degree days, the colder region as 5,500−6,999 degree days, the warmer region as 2,500−5,499 degree days, and the warmest region as fewer than 2,500 degree days.

— Few observations for summer results in colder regions. Data not available.

Source: Murray and Burmaster (1995).

Table 19-29. Distribution of Measured 24-hour Average Air Exchange Rates in 31 Detached Homes in North Carolina

Season: Year[a] or Cohort	Number of Detached Homes	Number of days Windows Opened[b]	Air Exchange Rates (h^{-1})											
			Sample Size	Mean	SD	Min	P5	P10	P25	P50	P75	P90	P95	Max
Summer: 2000	29	90(44%)	203	0.50	0.58	0.05	0.16	0.21	0.26	0.36	0.50	0.70	1.53	4.83
Fall: 2000	27	63(38%)	167	0.60	0.37	0.09	0.21	0.24	0.35	0.51	0.77	1.03	1.29	2.24
Winter: 2000−01	23	29(22%)	129	1.11	0.88	0.23	0.34	0.40	0.56	0.81	1.25	2.53	3.34	4.87
Spring: 2001	23	71(50%)	143	0.64	0.48	0.15	0.20	0.22	0.34	0.53	0.72	1.16	1.76	3.17
Raleigh cohort[c]	27	215(39%)	555	0.70	0.66	0.05	0.21	0.24	0.32	0.51	0.77	1.29	2.00	4.87
Chapell Hill cohort[d]	4	38(44%)	87	0.56	0.44	0.06	0.12	0.16	0.26	0.45	0.70	1.25	1.43	2.58
All	31	253(39%)	642	0.68	0.63	0.05	0.20	0.23	0.32	0.50	0.76	1.27	1.85	4.87

[a] Summer: June, July, and August; fall: September, October, and November; winter: December, January, and February; spring: March, April, and May.
[b] Percentage of days windows are opened in parenthesis relative to corresponding sample size.
[c] Low to moderate socioeconomic status neighborhoods.
[d] Moderate socioeconomic status neighborhoods.
SD = Standard deviation.

Source: Breen et al. (2010).

Table 19-30. Air Exchange Rates in Commercial Buildings by Building Type

Building Type	*N*	Mean (ACH[a])	SD	10th Percentile	Range (ACH)
Educational	7	1.9			0.8 to 3.0
Office (<100,000 ft^2)	8	1.5			0.3 to 4.1
Office (>100,000 ft^2)	14	1.8			0.7 to 3.6
Libraries	3	0.6			0.3 to 1.0
Multiuse	5	1.4			0.6 to 1.9
Naturally ventilated	3	0.8			0.6 to 0.9
Total (all commercial)	40	1.5	0.87	0.60[b]	0.3 to 4.1

[a] ACH = air changes per hour.
[b] Calculated from data presented in Turk et al. (1987), Table IV.C.1.
N = Number of observations.
SD = Standard deviation.

Source: Turk et al. (1987).

Table 19-31. Summary Statistics of Ventilation Rates

Measurement	*n*	Mean	SD	Min	25th %	Median	75th %	95th %	Max
Whole building ventilation rate									
Ventilation rate per area (L/s per m^2)	40	1.4	1.4	0.1	0.6	1.0	1.5	3.9	7.7
Ventilation rate per person (L/s per person)	40	61	71	7	17	36	72	261	321
Air exchange rate (per hour)	40	1.6	1.7	0.3	0.7	1.0	1.9	4.7	9.1
Air exchange rate, doors open (per hour)	7	3.1	2.9	0.6	1.0	2.3	4.0	9.1	9.1
Air exchange rate, doors shut (per hour)	33	1.3	1.1	0.3	0.7	1.0	1.5	4.3	5.1
HVAC ventilation[a]									
Outdoor air delivery rate by HVAC units per Unit floor area (L/s per m^2)	23	1.2	1.4	0.1	0.3	0.6	1.3	3.4	5.4
Outdoor air delivery rate by HVAC units per person (L/s per person)	23	35	30	2	10	26	69	83	95
Percentage of total ventilation supplied through HVAC units[b] (%)	14	39	25	8	14	35	63	78	78
Additional ventilation rate (per hour) [c]									
In buildings with doors kept open	7	2.9	3.0	0.4	1.2	1.8	4.0	9.1	9.1
In buildings with doors shut	29	0.5	0.6	0.0	0.0	0.4	0.7	1.9	1.9

[a] Fourteen buildings had HVAC units that did not provide outdoor air. Complete measurements could not be made on three buildings.

[b] Fourteen buildings had 0% of outdoor air provided through the HVAC units, and nine buildings were estimated to have 100% of outdoor air provided through HVAC units.

[c] One of the 14 buildings that did not provide HVAC ventilation had leakage into the system, and thus, is not included in the calculation for additional ventilation.

Source: Bennett et al. (2012).

Table 19-32. Statistics of Estimated Normalized Leakage Distribution Weighted for all Dwellings in the United States

House Code	Estimated Normalized Leakage Percentiles							Estimated	
	5th	10th	25th	50th	75th	90th	95th	GM	GSD
Low income	0.30	0.39	0.62	0.98	1.5	2.2	2.7	0.92	1.9
Conventional	0.17	0.21	0.31	0.48	0.75	1.1	1.4	0.49	1.9
Whole United States	0.17	0.22	0.33	0.52	0.84	1.3	1.7	0.54	2.0

GM = Geometric mean.
GSD = Geometric standard deviation.

Source: Chan et al. (2005).

Table 19-33. Particle Deposition During Normal Activities

Particle Size Range	Particle Removal Rate ($hour^{-1}$)
1−5	0.5
5−10	1.4
10−25	2.4
>25	4.1

Source: Adapted from Thatcher and Layton (1995).

Table 19-34. Deposition Rates for Indoor Particles

Size Fraction	Deposition Rate ($hour^{-1}$)
$PM_{2.5}$	0.39
PM_{10}	0.65
Coarse	1.01

Source: Adapted from Wallace (1996).

Table 19-35. Measured Deposition Loss Rate Coefficients (hour^{-1})

Median particle diameter (μm)	Fans Off			Room Core Airspeed 5.4 cm/second			Room Core Airspeed 14.2 cm/second 14.2 cm/s			Room Core Airspeed 19.1 cm/second		
	Bare room surfaces	Carpeted room	Fully furnished	Bare room surfaces	Carpeted room	Fully furnished	Bare room surfaces	Carpeted room	Fully furnished	Bare room surfaces	Carpeted room	Fully furnished
0.55	1.10	0.12	0.20	0.10	0.13	0.23	0.09	0.18	0.23	0.14	0.16	0.27
0.65	0.10	0.12	0.20	0.10	0.13	0.23	0.10	0.19	0.24	0.14	0.17	0.28
0.81	0.10	0.11	0.19	0.10	0.15	0.24	0.11	0.19	0.27	0.15	0.19	0.30
1.00	0.13	0.12	0.21	0.12	0.20	0.28	0.15	0.23	0.33	0.20	0.25	0.38
1.24	0.20	0.18	0.29	0.18	0.28	0.38	0.25	0.34	0.47	0.33	0.38	0.53
1.54	0.32	0.28	0.42	0.27	0.39	0.54	0.39	0.51	0.67	0.51	0.59	0.77
1.91	0.49	0.44	0.61	0.42	0.58	0.75	0.61	0.78	0.93	0.80	0.89	1.11
2.37	0.78	0.70	0.93	0.64	0.84	1.07	0.92	1.17	1.32	1.27	1.45	1.60
2.94	1.24	1.02	1.30	0.92	1.17	1.46	1.45	1.78	1.93	2.12	2.27	2.89
3.65	1.81	1.37	1.93	1.28	1.58	1.93	2.54	2.64	3.39	3.28	3.13	3.88
4.53	2.83	2.13	2.64	1.95	2.41	2.95	3.79	4.11	4.71	4.55	4.60	5.46
5.62	4.41	2.92	3.43	3.01	3.17	3.51	4.88	5.19	5.73	6.65	5.79	6.59
6.98	5.33	3.97	4.12	4.29	4.06	4.47	6.48	6.73	7.78	10.6	8.33	8.89
8.66	6.79	4.92	5.45	6.72	5.55	5.77	8.84	8.83	10.5	12.6	11.6	11.6

Source: Thatcher et al. (2002).

Table 19-36. Total Dust Loading for Carpeted Areas

Household	Total Dust Load (g/m^2)	Fine Dust (<150 μm) Load (g/m^2)
1	10.8	6.6
2	4.2	3.0
3	0.3	0.1
4	2.2; 0.8	1.2; 0.3
5	1.4; 4.3	1.0; 1.1
6	0.8	0.3
7	6.6	4.7
8	33.7	23.3
9	812.7	168.9

Source: Adapted from Roberts et al. (1991).

Table 19-37. Particle Deposition and Resuspension During Normal Activities

Particle Size Range (μm)	Particle Deposition Rate ($hour^{-1}$)	Particle Resuspension Rate ($hour^{-1}$)
0.3−0.5	(Not measured)	9.9×10^{-7}
0.6−1	(Not measured)	4.4×10^{-7}
1−5	0.5	1.8×10^{-5}
5−10	1.4	8.3×10^{-5}
10−25	2.4	3.8×10^{-4}
>25	4.1	3.4×10^{-5}

Source: Adapted from Thatcher and Layton (1995).

Table 19-38. Dust Mass Loading after 1 Week without Vacuum Cleaning

Location in Test House	Dust Loading (g/m^2)
Tracked area of downstairs carpet	2.20
Untracked area of downstairs carpet	0.58
Tracked area of linoleum	0.08
Untracked area of linoleum	0.06
Tracked area of upstairs carpet	1.08
Untracked area of upstairs carpet	0.60
Front doormat	43.4

Source: Adapted from Thatcher and Layton (1995).

Table 19-39. Simplified Source Descriptions for Airborne Contaminants

Description	Components	Dimensions
Direct emission rate		
Combustion emission rate	$E_f H_f M_f$	g hour^{-1}
	E_f = emission factor	g J^{-1}
	H_f = fuel content	J mol^{-1}
	M_f = fuel consumption rate	mol hour^{-1}
Volume emission rate	$Q_p C_{p\_} \varepsilon$	g hour^{-1}
	Q_p = volume delivery rate	m^3 hour^{-1}
	C_p = concentration in carrier	g m^{-3}
	ε = transfer efficiency	g g^{-1}
Mass emission rate	$M_p w_e \varepsilon$	g hour^{-1}
	M_p = mass delivery rate	g hour^{-1}
	w_e = weight fraction	g g^{-1}
	ε = transfer efficiency	g g^{-1}
Diffusion limited emission rate	$(D_f \delta^{-1})(C_s - C_i) A_i$	g hour^{-1}
	D_f = diffusivity	m^2 hour^{-1}
	δ^{-1} = boundary layer thickness	meters
	C_s = vapor pressure of surface	g m^{-3}
	C_i = room concentration	g m^{-3}
	A_i = area	m^2
Exponential emission rate	$A_i E_o e^{-k t}$	g hour^{-1}
	A_i = area	m^2
	E_o = initial unit emission rate	g hour^{-1} m^{-2}
	k = emission decay factor	hour^{-1}
	t = time	hours
Transport		
Infiltration	$Q_{ji} C_j$	g hour^{-1}
Interzonal	Q_{ji} = air flow from zone j	m^3 hour^{-1}
Soil gas	C_j = air concentration in zone j	g m^{-3}

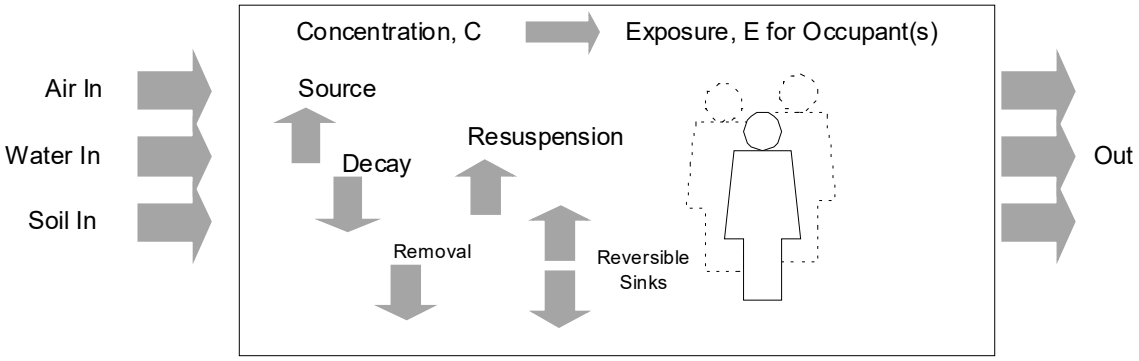

Figure 19-1. Elements of residential exposure.

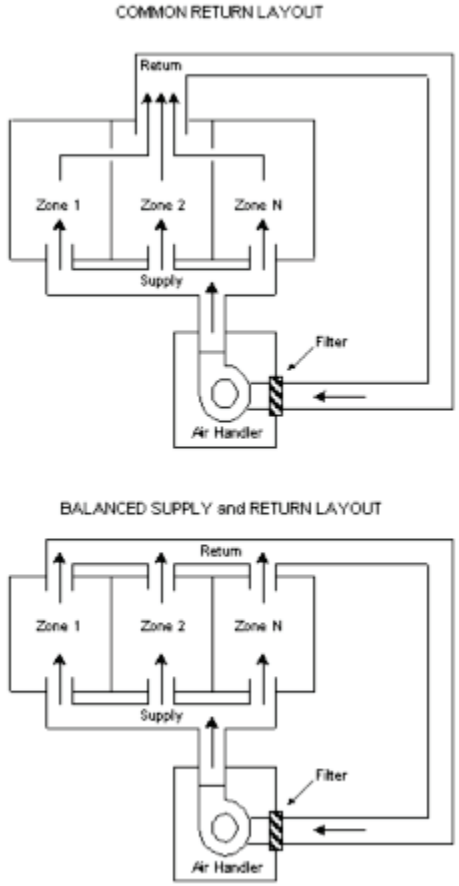

Figure 19-2. Configuration for residential forced-air systems.

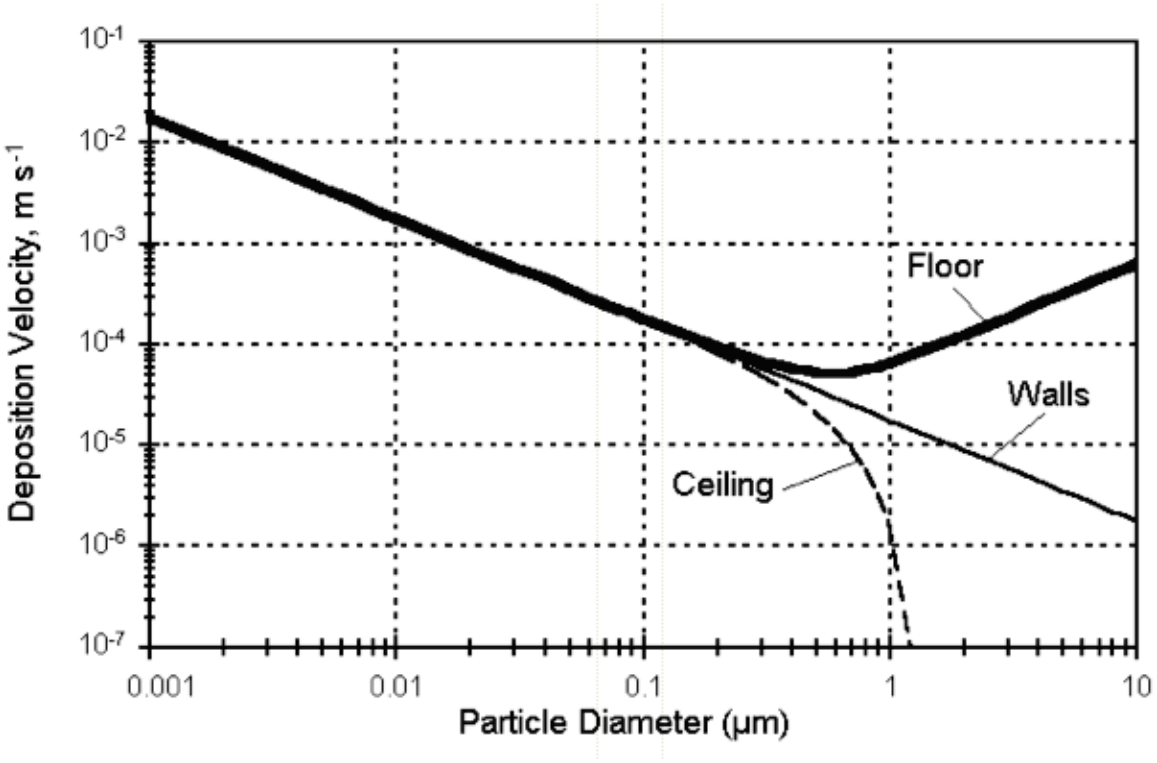

Figure 19-3. Idealized patterns of particle deposition indoors.

Source: Adapted from Nazaroff and Cass (1989a).

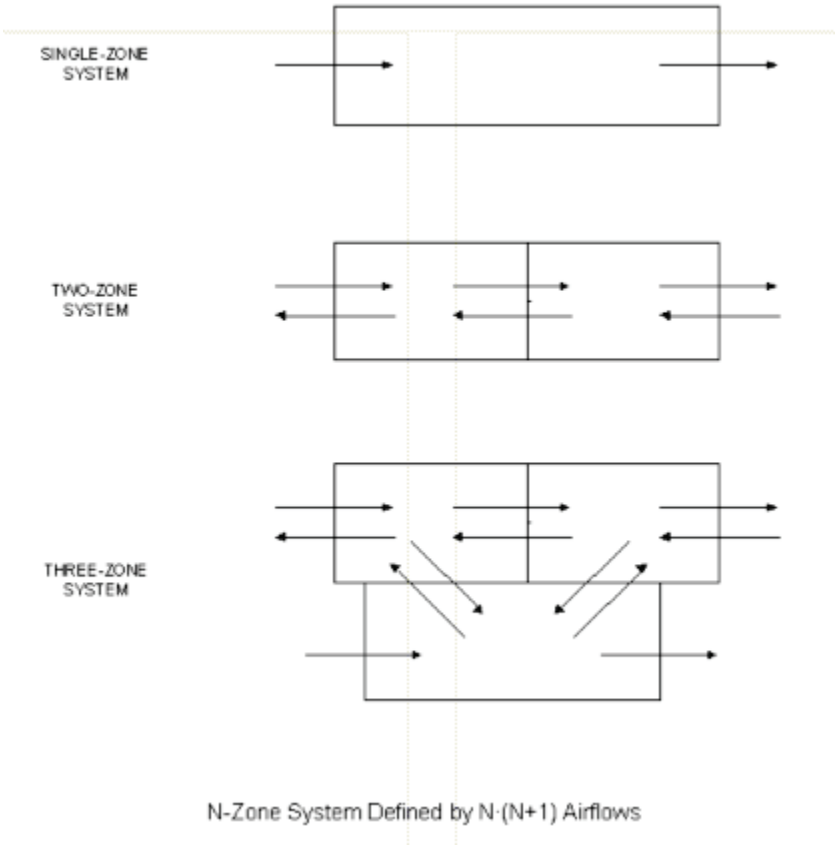

Figure 19-4. Air flows for multiple-zone systems.

Source: Koontz and Rector (1995).

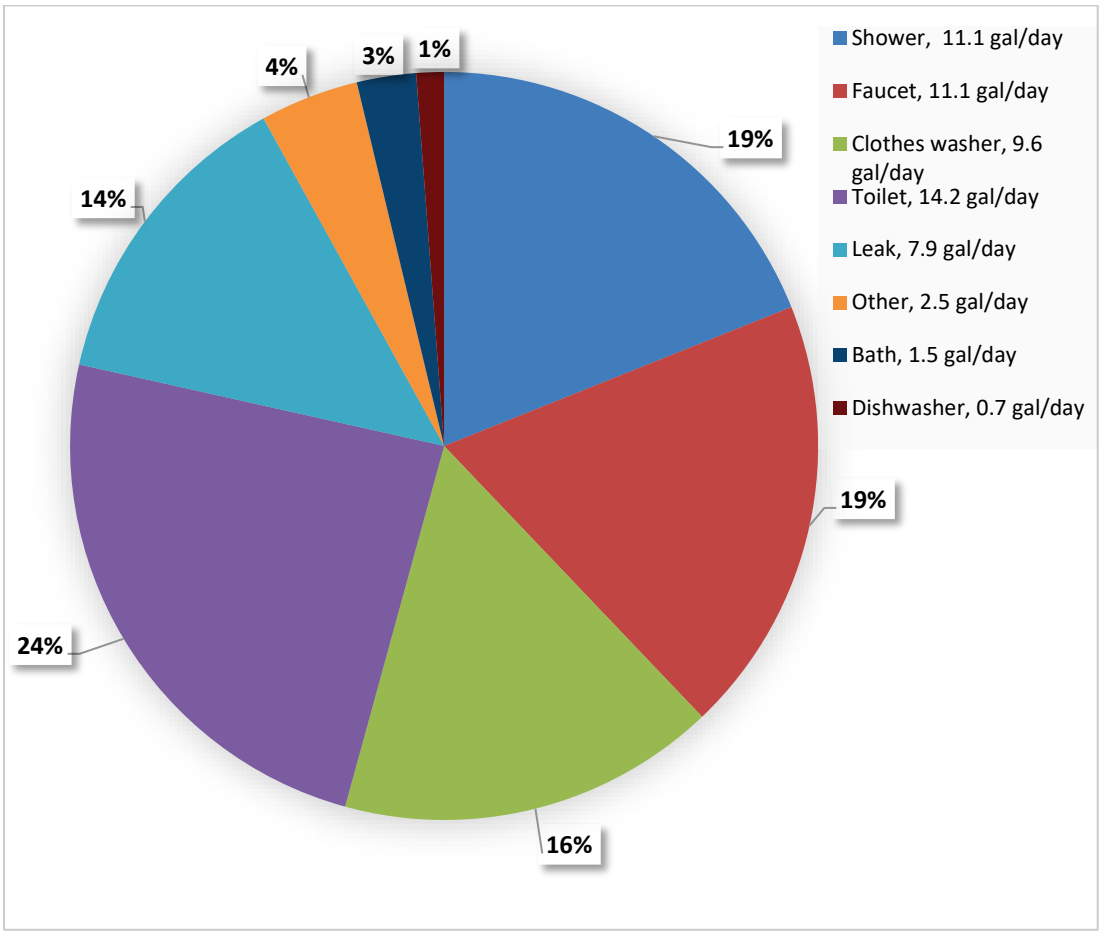

Figure 19-5. Average percentage per capita indoor water use across all uses.

Source: DeOreo et al. (2016). Reprinted with permission. © Water Research Foundation.

APPENDIX A

Table A-1. Terms Used in Literature Searches
Indoor air and pollutant
Indoor air and mixing
Indoor air and exposure
Indoor air and quality
Indoor air and sinks
Indoor air and exchange
Infiltration rates
Vapor intrusion
House volume
Room volumes
Dunn JE
Axley JW
Koontz MD
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Methods for Aeroallergen Sampling

Estelle Levetin, PhD

Address
Faculty of Biological Science, The University of Tulsa,
600 S. College, Tulsa, OK 74104, USA.
E-mail: Estelle-levetin@utulsa.edu

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Air sampling provides information about the bioaerosol composition of the atmosphere. Principal methods of volumetric sample collection include impaction, impingement, and filtration. Many instruments have been developed based on these collection methods. The most widely used devices are slit impactors, rotating arm impactors, and sieve impactors. Samples can be analyzed by various methods, with microscopy and culturing the most important approaches; however, immunoassays, molecular methods such as polymerase chain reaction, and other new techniques are becoming more widely used to analyze samples.

Introduction

Air sampling has been used since the 19th century to examine the bioaerosol composition of the atmosphere. The early history of aerobiology and the development of air samplers have been thoroughly reviewed in several publications [1–5]. Aerobiological data have been used by physicians as well as scientists in many disciplines. Allergists have used aeroallergen information to aid in the diagnosis and treatment of patients and to determine pollen calendars for their geographic areas. The air sampling data have also been used in the medical community to determine the effects of allergen exposure on patient symptoms and to evaluate clinical trials. Plant pathologists utilize air sampling to study the dispersal of agriculturally important pathogens, and epidemiologists study human or animal pathogens. Air sampling is used to monitor the spread of genetically engineered microbes and pollen from genetically engineered crops in the natural environment. Paleoecologists, geologists, and archeologists use air sampling to understand the relationship between modern pollen deposition and modern plant communities as a guide to interpreting former plant communities using fossil pollen records. Recently, mycologists, industrial hygienists, and other indoor investigators have used air sampling data to evaluate exposure where indoor fungal amplification is evident or suspect.

A wide variety of sampling devices are in use today, and new methods and instruments are continually being developed. No single method is appropriate for all bioaerosols or for all applications. In addition, no standard protocols are available for many investigations. In this review, we describe several widely used samplers along with some new instruments and the analytical techniques used to study aeroallergens in both outdoor and indoor environments.

Principal Collection Methods

Airborne particles can be collected passively by gravity as well as with specific instruments that actively sample the atmosphere through impaction, impingement, filtration, or other methods that provide volumetric samples [2,6,7•,8–11]. The simplest, least expensive, but least accurate method of collecting airborne biological samples is through the use of gravity. This method often consists of exposing a coated microscope slide or open Petri dish containing agar (often called a settle plate) to the outdoor atmosphere or indoor air for a set period of time. Gravity sampling is nonquantitative for atmospheric concentrations of aeroallergens and is affected by particle size and shape and also by air movement. Gravity samples are biased toward larger and, therefore, heavier pollen and spore types. Consequently, small pollen, such as *Morus* and *Urtica*, and small spores, such as *Penicillium* and *Aspergillus*, will be underrepresented in the sample, although these four taxa are important allergens. This bias is well recognized, and gravity sampling is not recommended. Nevertheless, a mold test kit using a settle plate is sold commercially at home-improvement stores around the country. In addition, similar services are offered on the Internet by dozens of vendors.

The most widely used instruments for air sampling are impaction samplers. These samplers separate particles from the air stream by using the inertia of the particles; this causes deposition of the particles onto a solid or agar surface as the air stream bends to bypass the surface. The deflection of the air stream is achieved in both suction impactors and rotating arm impactors. A wide variety of impaction samplers are available for both outdoor and indoor sampling, including slit samplers for total spores and pollen, rotating arm impactors for total spores and pollen, and sieve samplers for culturable fungi (Table 1). Several of these are discussed in detail later. Analysis of the samples is generally done by microscopy or culturing.

Like impactors, impingement samplers separate particles from the air stream using inertia; however, the particles are deposited into a liquid collecting medium. Air is drawn in by a vacuum pump and bubbles through water or a dilute buffer. Particles from the air stream are dispersed into the

Table 1. Characteristics of commonly used impaction samplers

Collection method	Sampler	d_{50} (μm)	Comments
Slit impaction	Burkard spore traps (Burkard Manufacturing, Ltd, Rickmansworth, UK)	3.7	One-day and 7-day sampling heads available. Collects pollen and total spores.
	Lanzoni VPPS 2000 (Lanzoni, S.r.L., Bologna, Italy)		Wind oriented and allows time-discriminate sampling.
	Kraemer-Collins sampler (G R Electric, Manhattan , KS)		
	Burkard continuous recording sampler (Burkard Manufacturing, Ltd, Rickmansworth, UK)	5	Allows for time discrimination. Not wind oriented, so more suitable for indoor use.
	Allergenco MK-3 (Environmental Monitoring Systems, Charleston, SC)	2	Not wind oriented, so more suitable for indoor use. Programmable sampling and small particle efficiency.
	Burkard personal sampler (Burkard Manufacturing, Ltd, Rickmansworth, UK)	2.5	Single-grab sample for total spores and pollen. Battery operated.
	Air-O-Cell cassette (Zefon, St. Petersburg, FL)	2.6	Single-grab sample for total spores and pollen. Easy to sample and analyze.
	Cyclex-d (Environmental Monitoring Systems, Charleston, SC)	2	Single-grab sample for total spores and pollen.
Rotating-arm impaction	Rotorod sampler (Sampling Technologies/ Multidata, St. Louis Park, MN)	10	Independent of wind speed and direction. Easy to use and efficient for pollen sampling.
Culture plate impaction	Andersen 6 stage (Thermo Andersen, Franklin, MA)	7.0 for stage 1 to 0.65 for stage 6	Sieve impactor. Only for culturable fungi able to grow on medium used. Biocassette sampler is disposable N-6 sampler.
	Andersen 2 stage (Thermo Andersen, Franklin, MA)		
	Andersen 1 stage (N-6) (Thermo Andersen, Franklin, MA)		
	Aerotech 6 (Aerotech Laboratories, Phoenix, AZ)		
	Biocassette (Environmental Microbiology Labs, San Bruno, CA)		
	Burkard sampler for agar plates (Burkard Manufacturing, Rickmansworth, UK)	4	Sieve impactor. Only for culturable fungi able to grow on the medium used. Battery operated.
	SAS (Biotest Diagnostic Corp, Denville, NJ)	1.5 to 2.0	Sieve impactor. Only for culturable fungi able to grow on medium used.
	Biotest RCS (Bioscience International, Rockville, MD)	7.5	Centrifugal sampler with collection onto agar strips. Only for culturable fungi able to grow on medium used.

collecting fluid. Because the liquid will evaporate during prolonged sampling, and thus reduce sampling efficiency, most impingement samplers, such as the AGI-30, are only useful for short sampling periods of 1 hour or less [12]. However, the BioSampler (SKC, Eighty Four, PA) permits sampling for longer periods into nonevaporating fluids. Samples collected by impingers can be analyzed by a variety of methods, including microscopy, culture, biochemistry, immunochemistry, and molecular biology.

Filtration separates particles from the air stream by trapping them in a fibrous or porous substrate. Filtration samplers range from small, personal-cassette samplers worn by individuals to determine personal exposure to large, high-volume samplers that can process thousands of liters of air per hour [9]. Most applications use disposable plastic cassettes that hold filters from 25 to 47 mm in diameter. A wide range of filter material is available for use, depending on the type of bioaerosol to be trapped and the type of analysis desired. Collection efficiency is generally high but depends on filter pore size and flow rate. Also, loss of viability may occur during sampling due to dehydration [7•]. Like impingement samples, several analytical methods can be used for samples collected by filtration.

Other collection methods include electrostatic precipitation, thermal precipitation, and cyclone sampling [10], although these are not widely used compared with the methods previously described. In electrostatic precipitators or ionizers, particles are first charged and then attracted to an opposite charge on a collector plate in the sampler. This device is best suited for small particles. In a recent study, an ionizer was used for monitoring Fel d 1 cat allergen in homes and daycare centers [13]. The drawback pointed out by the authors of this study was the inability to quantify the amount of allergen per volume of air; results were expressed as allergen collected per 24 hours.

Sampler Performance

Sampler efficiency is based on the ability to capture the particles onto a collection surface or into a collection medium. Both physical and biological aspects are involved in the efficiency. Physical aspects include the size and shape of sampler inlet and the airflow rate, which are used to determine the d_{50}, often referred to as the cut size. This is the particle diameter at which 50% of the particles are collected. Because of a sharp cut-off, it is generally accepted that all larger particles are collected [7•]. For example, a d_{50} of 5 μm means that sampler efficiency drops significantly for particles smaller than 5 μm. The d_{50} values for several samplers are listed in Table 1. Wind velocity and direction also effect sampler performance. Biological aspects of efficiency relate to loss of viability due to sampling stress and are only important for samples analyzed by culture.

Widely Used Sampling Instruments

No single sampler is appropriate for all applications, and investigators must select the sampler type and method of analysis carefully, based on the type of data to be collected. Various samplers and methods have been reviewed and compared in previous publications [2,5,6,7•,8,10,11,14,15•], and these should be consulted in conjunction with the information herein. The major emphasis here is on impaction samplers.

Spore trap slit impactors

The Burkard spore trap (Burkard, Hertfordshire, England) is a suction slit impactor used for pollen and spore sampling. The first sampler of this type was designed by Hirst in 1952 [16]. In addition to the Burkard spore trap, other samplers based on the Hirst trap design include the Lanzoni (S.r.l., Bologna, Italy) sampler and the Kramer-Collins (G R Electric, Manhattan, KS) sampler (Table 1). Also, the slit orifice based on the Hirst sampler is the basis for the orifice design in the Burkard personal sampler, the Allergenco MK-3 (Environmental Monitoring Systems, Charleston, SC), Air-O-Cell sampling cassettes (Zefon, St. Petersburg, FL), and others.

In the Burkard spore trap, air is drawn into the 14 mm × 2 mm orifice at 10 L/min, and airborne particles with sufficient inertia are impacted on either tape or a microscope slide beneath the orifice. The impaction surface moves past the orifice at 2 mm/hr, permitting time-discriminate sampling. A wind vane is attached to the sampler head, which is able to rotate. This ensures that the orifice is always oriented into the wind. The standard orifice on the Burkard sampler is efficient for particles down to 3.7 μm; this means that all but the smallest spores will be efficiently trapped. An interchangeable orifice is available from the manufacturer for increasing trapping efficiencies for spores as small as 1 μm. The alternative orifice is 14 mm × 2 mm at the intake but tapers down to 14 mm × 0.5 mm.

Two sampling lids are available for the Burkard spore trap—the standard 7-day lid and an alternate 24-hour lid. In the 7-day lid, a metal drum is mounted on a clock attached to the lid. The clock causes the drum to make a complete revolution in 7 days (at 2 mm/hr). A strip of clear cellophane tape is fixed on the drum and held in place with a small piece of double-stick tape. The cellophane tape is lightly coated with an adhesive such as Lubriseal (Thomas, Swedesboro, NJ), silicone grease, petroleum jelly, or high-vacuum grease. The drum is changed weekly, and the tape is removed and cut into seven 48-mm pieces, representing the previous 7 days. The daily tape segments are affixed to microscope slides; a mounting medium, such as glycerin jelly containing basic fuchsin, and a cover slip are added.

In the alternate lid assembly, a slide-holding carriage is attached to the clock. A standard 25 mm × 75 mm microscope slide is coated with an adhesive and placed in the carriage that moves past the orifice. The slide is changed daily and carriage re-oriented at start position. The exposed slide is stained as described earlier for the daily tape segments. This lid assembly is widely used by allergists and other scientists who need bioaerosol data on a daily basis. Slides from either lid are examined with a compound microscope for spore identification and enumeration as described later.

Portable spore traps

Various types of portable spore traps are used for indoor sampling as well as for some outdoor applications. These include the Allergenco (Samplair) MK-3 and the Burkard continuous recording air sampler, which allow for time-discriminate sampling. The Allergenco was initially designed for outdoor use; however, the lack of wind orientation makes this instrument more suitable for indoor sampling. A programmable step mechanism allows the sampler to be programmed to take up to 24 discrete samples on a single microscope slide. The Burkard continuous air sampler is similar in operation, although the programming is not as versatile.

Several spore trap impactors collect a single air sample over a 1- to 15-minute period; these are often called grab samplers. They are commonly used for indoor air sampling because of their portability and ease of use. The Burkard personal sampler impacts airborne particles onto a standard coated microscope slide. The sampler flow rate is 10 L/min, and the orifice is 14 mm × 1 mm. This sampler is efficient for spores down to 2.52 μm in diameter [7•]. The Air-O-Cell cassette is a disposable spore trap manufactured by Zefon International. The intake orifice is similar in design to the Burkard sampler, tapering to a 14.4 mm × 1.1 mm slit. The cassette can be attached to any pump capable of drawing 15 L/min and has an efficiency down to 2.3 μm [7•]. Particles impact on a small adhesive-coated piece of glass within the cassette. Although the cassettes are individually expensive, they are convenient to use and easy to analyze. Cyclex-d (WSLH, Madison, WI) sampling cassettes are similar; however, instead of a slit orifice, there is a single, round-jet orifice 4 mm in diameter. The cassettes are attached to a pump drawing 20 L/min. All of the portable spore traps are analyzed by microscopy.

Rotating arm impactors

Rotorod samplers (Sampling Technologies, Minnetonka, MN) have been widely used by investigators in the allergy community. The first rotating impactor of this type was developed in the 1950s, and within the next decade various modifications of this instrument were developed [17]. These samplers contained a small battery-driven motor that rotated the sampling head at 2400 rpm; airborne particles are collected by adhesive-coated rods, bars, slides, or tape attached to the rotating component. On current and previous models, sampling rate is approximately 120 L of air per minute. As a result, these samplers are volumetric, and the average atmospheric concentration of the pollen and spores can be determined. The samplers can be run continuously for short periods of time or intermittently for longer periods. The Rotorod samplers that are currently available are intermittent samplers usually run for 30 to 60 seconds out of every 10 minutes (5% to 10% sampling time). Airborne particulates are collected onto two small plastic retractable "I" rods; the exposed area of each rod is 1.52 mm by 23 mm. When the instrument cycles on, the rods drop down as the arm begins rotating. The leading edge of the rods is coated with an adhesive, usually silicon grease. The rods are changed each day, placed in a specially designed plastic microscope slide with grooves to hold the rods, and stained with Calberla's stain. The rods are then examined with a compound microscope for pollen and spore identification and enumeration. This sampler is easy to use and is relatively efficient for pollen and large fungal spores. Unfortunately, sampler efficiency drops for particles below 10 μm [18]. This means that many small spores, especially basidiospores and small ascospores, will be significantly underrepresented in the total catch. Also, sampler efficiency decreases over time, with increasing numbers of particles, causing overloading of the exposed side of the rods. For areas where high concentrations of pollen and spores are common, 5% sampling times, or even less, should be used to avoid overload.

Sieve impactors

Culture-plate samplers impact airborne particles directly onto the surface of culture medium in a Petri dish. These samplers are used for airborne fungi and bacteria in both outdoor and indoor environments. These are often sieve impactors, with multiple holes that deposit the catch over the surface of the plate. The original sampler of this type is the Andersen six-stage cascade impactor (Thermo Andersen, Franklin, MA). Each stage has a perforated plate composed of 400 holes with decreasing diameter. The holes in the first stage have a diameter of 1.18 mm, whereas the holes in the bottom plate are 0.25 mm in diameter [10]. Size discrimination is possible as the air velocity increases through the smaller holes. One-stage and two-stage models of the Andersen sampler are widely used. In the two-stage sampler, only the second and fifth stages are used, and each stage has 200 holes. In the single-stage model, only the sixth stage (N-6) is used with 400 holes in the plate. The single-stage sampler is extensively used in indoor air investigations. Other manufacturers offer very similar samplers. Recently, a disposable sieve impactor, the Biocassette (Environmental Microbiology Labs, San Bruno, CA), has been developed. Studies showed no statistical difference between the mean of samples collected with the Biocassette and with the single-stage Andersen sampler [19]. The Burkard culture plate sampler is a portable sieve impactor with 100 holes.

Sampling times for sieve impactors are normally for 1 to 5 minutes at a flow rate of 28.3 L/min, although the Burkard model uses a lower flow rate. Following sampling, the Petri dishes are incubated, and the resulting colonies are counted and identified. Concentrations are expressed as colony forming units (CFU)/m^3 of air. With any sieve impactor, there is a possibility of multiple impactions on the agar beneath a single hole; however, these would appear and be counted as a single colony. The possibility of multiple impactions increases with increasing concentration of culturable organisms.

Personal samplers

Personal samplers are used to determine more precise levels of exposure to aeroallergens or other airborne particles. These samplers are also widely used in the workplace for testing compliance with permissible exposure limits. Although some personal samplers are passive samplers, they often consist of a small, disposable filter cassette worn in the breathing zone (usually on a lapel) attached to a lightweight, battery-powered pump worn at the waist. The flow rate is usually approximately 2 L/min, and it is worn for many hours. Several types of filter membranes can be used along with various methods of analysis [20]. The Button aerosol sampler is a reusable filter sampler with a porous, curved inlet that improves particle collection over the surface of the filter [21]. Because of the spherical inlet, this sampler has been shown to be wind insensitive. As a result, it is suitable for both indoor and outdoor environments for a variety of applications [22].

The nasal air sampler was recently developed to obtain a more precise personal exposure than current filters [23–25]. This novel personal sampler is an impaction sampler worn just inside the nose and requires no outside power source because it uses normal human respiration to impact airborne particles onto a pressure-sensitive adhesive tape. Particles that are 5 μm and larger are collected with minimal discomfort to subjects. This sampler has been used to measure inhaled pollen and spores, dust mite allergen, and other allergens with analysis by microscopy or immunochemistry [23–25].

Methods of Analysis

Air samples collected by the instruments described here can be analyzed by various methods, based on the type of sample and the information desired. The main methods of analysis for air samples include culture, direct microscopy, biochem-

Table 2. Methods of analysis for air samples

Method	Sampler types used with	Comments
Microscopy	Slit impactors, liquid impingers, filter samples	Pollen and total spores identification. Does not permit species identification for similar spore or pollen types.
Culturing	Sieve impactors, liquid impingers, filter samples	Allows for species identification. Only for viable organisms able to grow on culture medium used.
Biochemistry	Slit impactors, liquid impingers, filter samples	Estimate of total fungal biomass or identification of specific mycotoxins.
Immunochemistry	Slit impactors, liquid impingers, filter samples	Specific assays for allergens. Limited number of allergen assays commercially available.
Molecular biology (PCR)	Slit impactors, liquid impingers, filter samples	Detects specific DNA sequences. Eliminates the need for culturing or microscopy. Thus far, limited use in aeroallergen sampling.
Flow cytometry	Liquid impingers	Rapid analysis for quantifying total spores or pollen. Limited use in aerobiology.
Image analysis	Slit impactors, liquid impingers	Rapid analysis of spore and pollen identification. Eliminates the need for microscopy. Early stage of development for this methodology.

istry, immunochemistry, and molecular biology (Table 2). Flow cytometry and image analysis are also finding applications in air sample analysis. Culturing and microscopy are the most commonly used methods.

Culturing

Culturing is, of course, required for samples from Andersen samplers, other sieve impactors, and slit samplers used to collect fungal spores directly onto a culture plate. Samples collected by impingers and filter samplers can also be analyzed by culturing. Regardless of the type of sample, culturing is only useful for fungal spores that can germinate and grow on the culture medium utilized. A broad-based culture medium, such as malt-extract agar, is often suggested for mesophilic fungi. DG-18 agar, which contains dichloran and 18% glycerol, is recommended for xerophilic fungi. Both media are considered acceptable for environmental sampling [11,26]. Incubation is normally at room temperature for 5 to 10 days, although the incubation temperature and time, as well as the type of culture medium, may vary for different applications. Identification of fungal colonies usually depends on microscopic characteristics of reproductive structures and methods of spore development. As indicated earlier, multiple impactions at one spot can occur when using sieve impactors, and corrections to the count should be made to account for this possibility. Correction tables are usually available from the manufacturer and can be found in other publications [14]. The advantage of culture analysis is that fungi can be accurately identified to the species level, provided personnel are trained in fungal taxonomy. The disadvantage is that only a fraction of the airborne fungal spores will grow on the culture medium used. An air sample will normally contain a heterogeneous mixture of viable spores, spores that have lost viability, spores that cannot be grown in culture, and fastidious spores that have specific nutrient requirements. Although many of these spores are not culturable, they may still have allergenic properties.

Microscopy

Samples collected by spore-trap samplers or Rotorod samplers are usually analyzed by direct microscopy. Microscopy can also be used for the analysis of impingement and filter samples. This is the most important method of analysis for outdoor samples that contain a mixture of pollen and fungal spores. Outdoor samples are typically stained with basic fuchsin or phenosafranin to aid in pollen identification. Samples can be examined almost immediately without lengthy incubation periods. Another advantage is that microscopy permits the enumeration of all spores, culturable as well as nonculturable. However, there are several disadvantages. Some spores cannot be identified, especially small, spherical spores that lack distinctive morphologic features. Also, species identification is not possible, and, therefore, spores are usually identified to the generic level. Other spores can only be identified to a general group. For example, species of *Penicillium* and *Aspergillus* cannot be distinguished from each other and are usually categorized as *Penicillium*/*Aspergillus*–type spores. This is especially a disadvantage for indoor samples because *Penicillium* and *Aspergillus* are common indoor contaminants. Analysis by microscopy takes considerable time and requires trained personnel to identify the many types of spores and pollen common in air samples.

A magnification of 400× is normally used for pollen identification and enumeration. Fungal spores are generally analyzed with an oil immersion objective at a total magnification of 1000×. As a result, each sample is analyzed twice. For Rotorod samples, the entire sample on each rod is usually

analyzed. The exposed portion of each slide from a Burkard spore-trap sample is 14 mm × 48 mm, and the most accurate analysis would involve counting the entire sample. However, this is usually not possible because of the time required. As a result, a subset of the sample is analyzed. There are several methods in use for the microscopic analysis of slides from a Burkard spore trap. The most common methods involve one to four longitudinal traverses (down the 48 mm long axis of the sample) or 12 transverse traverses (across the 14 mm short axis of the sample). Because the slide carriage or sampler-drum with attached tape moves at 2 mm/hr by the intake orifice, analysis of the slide at 4-mm intervals (12 transverse traverses) can provide information on the concentrations every 2 hours during the day. The resulting data show the diurnal rhythm of airborne pollen and spores. The longitudinal traverses provide information on the average daily concentration. The accuracy of these counting methods has been reviewed in several studies [27–29]. None of the methods was equivalent to counting the entire slide, but the 12 transverse traverses gave slightly better approximations. These studies indicate that the usual methods of analysis for Burkard slides provide good indicators of the aeroallergen concentrations, but these should not be considered as absolute values.

Biochemistry

Biochemical analyses have been used as indicators of microbial presence as well as for the identification of specific compounds, usually from samples collected by an impingement sampler or by filtration. General compounds, such as ergosterol, β-glucans, or endotoxin, are detected by biochemistry. Ergosterol is sterol occurring in fungal cell membranes, and β-glucan is a carbohydrate that occurs in fungal wall. Both assays provide an estimate of total fungal biomass but are not specific for any genus or species. Ergosterol assays have been recently used to measure exposure to indoor mold in several studies [30,31]. β-glucan assays are less specific because other sources of β-glucan may be present [31,32]. Endotoxins are lipopolysaccharides found in the cell walls of gram-negative bacteria. Specific mycotoxins have also been identified by biochemical analyses from air samples. Mycotoxins from *Stachybotrys chartarum* have been detected on filter samples in both experimental conditions and in contaminated environments [33,34]. Also, ochratoxin A was detected from airborne conidia of *Penicillium verrucosum* isolated from a cowshed [35]. Different methods have been used from filter washings for identifying these compounds. Ergosterol and mycotoxins have been identified through HPLC, whereas *Limulus* amoebocyte lysate assay is usually used for endotoxin and β-glucan analysis. However, β-glucans can also be identified through an enzyme-linked immunoassay.

Immunochemistry

Air samples can also be analyzed by immunoassays for specific allergen molecules. As a result, these assays are not useful for routine analysis of air samples. These techniques are usually applied to filter or impingement samples; however, they can also be used with spore-trap samples. Immunoassays involve the binding of antibodies to the allergen of interest; therefore, they require the prior development of antibodies. Because of their greater specificity, monoclonal antibodies are usually preferred. Antibody binding is usually detected by linking a fluorescent dye, an enzyme, or radioactive label to the antibody.

A number of commercial immunoassays are available for several dust mite allergens, two cockroach allergens, and single allergens for cat, dog, mouse, rat, and horse. Although applicable for air samples, many of these have greater application for dust samples. For fungal analyses, immunoassays are currently available for *Alternaria alternata* (Alt a 1 allergen) and *Aspergillus fumigatus* (Asp f 1 allergen). Although several investigators have developed Alt a 1 assays, these have largely been used to quantify the amount of Alt a 1 allergen in commercial allergy extracts and in dust samples [36]. The advantages of immunoassays are their reported specificity, sensitivity, and ease of use, once the antibodies are available. The disadvantages involve the expense and time for the initial research effort required in developing the assay and equipment costs. In addition, recent studies showed the limitations of this technique. Low levels of Asp f 1 allergen were detected in only two out of 120 air samples from office environments, including areas where culturable *A. fumigatus* colonies were isolated from dust. Also, no Asp f 1 allergen was isolated from dust samples in these locations [37]. It is possible that Asp f 1 is not expressed in dormant spores collected in air or dust samples; spore germination may be necessary before this allergen can be detected. In another study, monoclonal antibodies were produced to detect *P. brevicompactum* spores from air samples in an experimental setting. Five monoclonal antibodies were produced, but all of them cross-reacted with several species of *Aspergillus*, *Penicillium*, and *Eurotium*. This would indicate that positive results obtained from an air sample with a cross-reacting monoclonal antibody could be due to various combinations of fungi in the sample [38]. Similar problems were found in attempting to develop air sample immunoassays for plant pathogenic fungi [39]. Clearly, for these immunoassays to work, greater focus must be placed on developing species-specific antibodies.

Molecular biology

Air samples from spore traps, rotating arm impactors, impingers, and filtration have also been analyzed by polymerase chain reaction (PCR). PCR is a method used to rapidly produce multiple copies of specific DNA sequences; this technique has been applied to many areas of research to improve detection of various organisms, including airborne fungal spores. Wakefield [40] identified *Pneumocystis carinii* from air samples collected in an orchard by three different types of air samplers, including a Burkard spore trap, a liquid impinger, and a cascade impactor. PCR was also used to identify plant pathogenic fungal spores from two

different species collected by a spore trap [41•]. *Penicillium roqueforti* spores were identified using samples from a spore trap, a rotating arm impactor, and a cyclone sampler [39,42]. Haugland *et al.* [43] described the detection of *Stachybotrys* spores with PCR from samples collected by a liquid impinger. Also, a system using fungus-specific primers and PCR has been developed to estimate total fungal biomass in an environment [44]. The expanding use of this technique suggests that PCR may one day become a standard method for routine monitoring of aeroallergens. The advantage of this method is the ability to detect organisms that cannot be easily grown in culture and lack distinctive spores for microscopic identification. The speed of identification with this method is also an advantage, even for organisms that can be grown in culture. However, it is known that allergens can also be carried on small particles released from pollen grains or on fungal fragments from the break-up of fungal hyphae [45]. These allergens may occur in the atmosphere in the absence of DNA and would not be detected by this technique.

Flow cytometry

Flow cytometry involves the analysis of a suspension of cells that are autofluorescent or that have been treated with fluorescent probes. A large number of cells can be rapidly detected and enumerated with a flow cytometer. This technique has been widely used in research and has been applied to environmental detection of organisms from aquatic samples. However, there has been limited use of flow cytometry for bioaerosols. In one study, it was shown that flow cytometry could differentiate *Phytophthora infestans* sporangia from most other airborne spores or pollen [46]. This study was conducted to develop methods for late blight detection and forecasting, and limited air sampling data were presented. Prigione *et al.* [47] recently developed a method to improve fluorescent staining of fungal spores prior to flow cytometry. This permitted the detection of accurate counts for total fungal spores in air samples collected with a liquid impinger. However, the fluorescent stain used, propidium iodide, is not specific for fungi, and small pollen might not be differentiated from spores. These studies suggest that flow cytometry may have practical applications in aeroallergen analysis, but some difficulties still need to be overcome. In addition, instrument expense suggests it will never replace current methods.

Image analysis

Direct microscopy of air samples is time consuming and requires highly skilled technicians. A fully automated system able to sample, identify, and quantify airborne pollen and spores is still far in the future. Image analysis, an important component of a fully automated system, is making some progress in recognizing specific pollen and spores. Boucher *et al.* [48] described the methods being used in the development of an automated system for the Advanced System of Teledetection for Healthcare Management of Asthma (ASTHMA). The project is focused on pollen in the families Cupressaceae, Poaceae, Urticaeae, and *Olea* pollen. Although still in early stages of development, the results show the recognition of 77% of pollen grains on reference images of 30 pollen types. Ronneberger *et al.* [49] describe a system based on the use of 3D fluorescent images of pollen taken with a confocal laser scanning microscope. This method achieved a 92% recognition rate for reference specimens of the 26 most important pollen taxa in Germany. Benyon *et al.* [50] described the detection of fungal spores by image analysis. Using seven spore parameters, this program was able to discriminate seven out of 11 genera of spores with an accuracy of 82%. Like the pollen analysis projects, the recognition was based on reference specimens, not on air samples.

Conclusions

Air sampling is widely used to identify aeroallergens in the environment. This can be a valuable tool to estimate exposure, but it is essential that a volumetric sampler be used. Currently, spore traps, rotating-arm impactors, and sieve impactors are the most widely used type of sampling equipment for routine monitoring of the outdoor atmosphere and the indoor environment. Direct microscopy and culture are the most important analytical methods for these sampling instruments. New instruments are constantly being developed, and analysis methods are constantly improved. Techniques on the horizon include expanded use of PCR and immunoassays for specific allergens and image analysis for real-time identification of bioaerosols in the atmosphere.

References and Recommended Reading

Papers of particular interest, published recently,
have been highlighted as:

- • Of importance
- •• Of major importance

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NIAID HEALTH INFO

Airborne Allergens

SOMETHING IN THE AIR

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
National Institutes of Health
National Institute of Allergy and Infectious Diseases

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Introduction

Sneezing is not always the symptom of a cold. Sometimes, it is an allergic reaction to something in the air. Health experts estimate that 35 million Americans suffer from **upper respiratory tract** symptoms that are allergic reactions to airborne **allergens**. Pollen allergy, commonly called hay fever, is one of the most common chronic diseases in the United States. Worldwide, airborne allergens cause the most problems for people with allergies. The respiratory symptoms of asthma, which affect approximately 11 million Americans, are often provoked by airborne allergens.

Overall, allergic diseases are among the major causes of illness and disability in the United States, affecting as many as 40 to 50 million Americans.

The National Institute of Allergy and Infectious Diseases (NIAID) of the National Institutes of Health (an agency of the U.S. Department of Health and Human Services) supports and conducts research on allergic diseases. The goals of this research are to provide a better understanding of the causes of allergy, to improve methods for diagnosing and treating allergic reactions, and eventually to prevent allergies.

This booklet summarizes what health experts know about the causes and symptoms of allergic reactions to airborne allergens, how health care providers diagnose and treat these reactions, and what medical researchers are doing to help people who suffer from these allergies.

Note: Words in bold are defined in the glossary at the end of this booklet.

What is an allergy?

An allergy is a specific reaction of the body's **immune system** to a normally harmless substance, one that does not bother most people. People who have allergies often are sensitive to more than one substance. Types of allergens that cause allergic reactions include

- Pollens
- House dust mites
- Mold spores
- Food
- Latex rubber
- Insect venom
- Medicines

Why are some people allergic?

Scientists think that some people inherit a tendency to be allergic from one or both parents. This means they are more likely to have allergies. They probably, however, do not inherit a tendency to be allergic to any specific allergen. Children are more likely to develop allergies if one or both parents have allergies. In addition, exposure to allergens at times when the body's defenses are lowered or weakened, such as after a viral infection or during pregnancy, seems to contribute to developing allergies.

What is an allergic reaction?

Normally, the immune system functions as the body's defense against invading germs such as bacteria and viruses. In most allergic reactions, however, the immune system is responding to a false alarm. When an allergic person first comes into contact with an allergen, the immune system treats the allergen as an invader and gets ready to attack.

The immune system does this by generating large amounts of a type of **antibody** called immunoglobulin E, or IgE. Each IgE antibody is specific for one particular substance. In the case of pollen allergy, each antibody is specific for one type of pollen. For example, the immune system may produce one type of antibody to react against oak pollen and another against ragweed pollen.

The IgE **molecules** are special because IgE is the only type of antibody that attaches tightly to the body's **mast cells**, which are **tissue** cells, and to **basophils**, which are blood cells. When the allergen next encounters its specific IgE, it attaches to the antibody like a key fitting into a lock. This action signals the cell to which the IgE is attached to release (and, in some cases, to produce) powerful chemicals like histamine, which cause **inflammation**. These chemicals act on tissues in various parts of the body, such as the respiratory system, and cause the symptoms of allergy.

Symptoms

The signs and symptoms of airborne allergies are familiar to many.

- Sneezing, often with a runny or clogged nose
- Coughing and postnasal drip
- Itching eyes, nose, and throat
- Watering eyes
- **Conjunctivitis**
- "Allergic shiners" (dark circles under the eyes caused by increased blood flow near the **sinuses**)
- "Allergic salute" (in a child, persistent upward rubbing of the nose that causes a crease mark on the nose)

In people who are not allergic, the mucus in the nasal passages simply moves foreign particles to the throat, where they are swallowed or coughed out. But something different happens in a person who is sensitive to airborne allergens.

In sensitive people, as soon as the allergen lands on the lining inside the nose, a chain reaction occurs that leads the mast cells in these tissues to release histamine and other chemicals. The powerful chemicals contract certain cells that line some small blood vessels in the nose. This allows fluids to escape, which causes the nasal passages to swell—resulting in nasal congestion. Histamine also can cause sneezing, itching, irritation, and excess mucus production, which can result in allergic **rhinitis**.

Other chemicals released by mast cells, including cytokines and leukotrienes, also contribute to allergic symptoms.

Some people with allergy develop asthma, which can be a very serious condition. The symptoms of asthma include

- Coughing
- Wheezing
- Shortness of breath

The shortness of breath is due to a narrowing of the airways in the lungs and to excess mucus production and inflammation. Asthma can be disabling and sometimes fatal. If wheezing and shortness of breath accompany allergy symptoms, it is a signal that the airways also have become involved.

Is it an allergy or a cold?

There is no good way to tell the difference between allergy symptoms of runny nose, coughing, and sneezing and cold symptoms. Allergy symptoms, however, may last longer than cold symptoms. Anyone who has any respiratory illness that lasts longer than a week or two should consult a health care provider.

Pollen Allergy

Each spring, summer, and fall, tiny pollen grains are released from trees, weeds, and grasses. These grains hitch rides on currents of air. Although the mission of pollen is to fertilize parts of other plants, many never reach their targets. Instead, pollen enters human noses and throats, triggering a type of seasonal allergic rhinitis called pollen allergy. Many people know this as hay fever.

Of all the things that can cause an allergy, pollen is one of the most common. Many of the foods, medicines, or animals that cause allergies can be avoided to a great extent. Even insects and household dust are escapable. But short of staying indoors, with the windows closed, when the pollen count is high—and even that may not help—there is no easy way to avoid airborne pollen.

What is pollen?

Plants produce tiny—too tiny to see with the naked eye—round or oval pollen grains to reproduce. In some species, the plant uses the pollen from its own flowers to fertilize itself. Other types must be cross-pollinated. Cross-pollination means that for fertilization to take place and seeds to form, pollen must be transferred from the flower of one plant to that of another of the same species. Insects do this job for certain flowering plants, while other plants rely on wind for transport.

The types of pollen that most commonly cause allergic reactions are produced by the plain-looking plants (trees, grasses, and weeds) that do not have showy flowers. These plants make small, light, dry pollen grains that are custom-made for wind transport.

Amazingly, scientists have collected samples of ragweed pollen 400 miles out at sea and 2 miles high in the air. Because airborne pollen can drift for many miles, it does little good to rid an area of an offending plant. In addition, most allergenic pollen comes from plants that produce it in huge quantities. For example, a single ragweed plant can generate a million grains of pollen a day.

The type of allergens in the pollen is the main factor that determines whether the pollen is likely to cause hay fever. For example, pine tree pollen is produced in large amounts by a common tree, which would make it a good candidate for causing allergy. It is, however, a relatively rare cause of allergy because the type of allergens in pine pollen appear to make it less **allergenic**.

Among North American plants, weeds are the most prolific producers of allergenic pollen. Ragweed is the major culprit, but other important sources are sagebrush, redroot pigweed, lamb's quarters, Russian thistle (tumbleweed), and English plantain.

Grasses and trees, too, are important sources of allergenic pollens. Although more than 1,000 species of grass grow in North America, only a few produce highly allergenic pollen.

It is common to hear people say they are allergic to colorful or scented flowers like roses. In fact, only florists, gardeners, and others who have prolonged, close contact with flowers are likely to be sensitive to pollen from these plants. Most people have little contact with the large, heavy, waxy pollen grains of such flowering plants because this type of pollen is not carried by wind but by insects such as butterflies and bees.

Some grasses that produce pollen

- Timothy grass
- Kentucky bluegrass
- Johnson grass
- Bermuda grass
- Redtop grass
- Orchard grass
- Sweet vernal grass

Some trees that produce pollen

- Oak
- Ash
- Elm
- Hickory
- Pecan
- Box elder
- Mountain cedar

When do plants make pollen?

One of the most obvious features of pollen allergy is its seasonal nature—people have symptoms only when the pollen grains to which they are allergic are in the air. Each plant has a pollinating period that is more or less the same from year to year. Exactly when a plant starts to pollinate seems to depend on the relative length of night and day—and therefore on geographical location—rather than on the weather. On the other hand, weather conditions during pollination can affect the amount of pollen produced and distributed in a specific year. Thus, in the Northern Hemisphere, the farther north you go, the later the start of the pollinating period and the later the start of the allergy season.

A pollen count, familiar to many people from local weather reports, is a measure of how much pollen is in the air. This count represents the concentration of all the pollen (or of one particular type, like ragweed) in the air in a certain area at a specific time. It is shown in grains of pollen per square meter of air collected over 24 hours. Pollen counts tend to be the highest early in the morning on warm, dry, breezy days and lowest during chilly, wet periods. Although the pollen count is an approximate measure that changes, it is useful as a general guide for when it may be wise to stay indoors and avoid contact with the pollen.

Mold Allergy

What is mold?

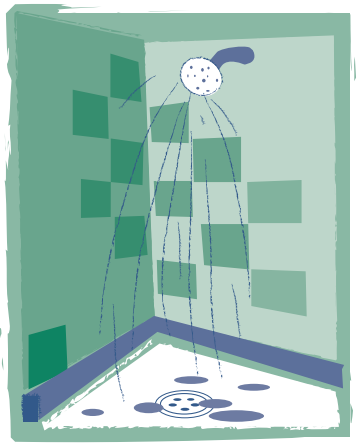
There are thousands of types of molds and yeasts in the fungus family. Yeasts are single cells that divide to form clusters. Molds are made of many cells that grow as branching threads called hyphae. Although both can probably cause allergic reactions, only a small number of molds are widely recognized offenders.

The seeds or reproductive pieces of fungi are called spores. Spores differ in size, shape, and color among types of mold. Each spore that germinates can give rise to new mold growth, which in turn can produce millions of spores.

What is mold allergy?

When inhaled, tiny fungal spores, or sometimes pieces of fungi, may cause allergic rhinitis. Because they are so small, mold spores also can reach the lungs.

In a small number of people, symptoms of mold allergy may be brought on or worsened by eating certain foods such as cheeses processed with fungi. Occasionally, mushrooms, dried fruits, and foods containing yeast, soy sauce, or vinegar will produce allergy symptoms.



Where do molds grow?

Molds can be found wherever there is moisture, oxygen, and a source of the few other chemicals they need. In the fall, they grow on rotting logs and fallen leaves, especially in moist, shady areas. In gardens they can be found in compost piles and on certain grasses and weeds. Some molds attach to grains such as wheat, oats, barley, and corn, which makes farms, grain bins, and silos likely places to find mold.

Hot spots of mold growth in the home include damp basements and closets, bathrooms (especially shower stalls), places where fresh food is stored, refrigerator drip trays, house plants, air conditioners, humidifiers, garbage pails, mattresses, upholstered furniture, and old foam rubber pillows.

Molds also like bakeries, breweries, barns, dairies, and greenhouses. Loggers, mill workers, carpenters, furniture repairers, and upholsterers often work in moldy environments.

What molds are allergenic?

Like pollens, mold spores are important airborne allergens only if they are abundant, easily carried by air currents, and allergenic in their chemical makeup. Found almost everywhere, mold spores in some areas are so numerous they often outnumber the pollens in the air. Fortunately, however, only a few dozen different types are significant allergens.

In general, *Alternaria* and *Cladosporium* (Hormodendrum) are the molds most commonly found both indoors and outdoors in the United States. *Aspergillus*, *Penicillium*, *Helminthosporium*, *Epicoccum*, *Fusarium*, *Mucor*, *Rhizopus*, and *Aureobasidium (Pullularia)* are common as well.

There is no relationship, however, between a respiratory allergy to the mold *Penicillium* and an allergy to the drug penicillin, which is made from mold.

Are mold counts helpful?

Similar to pollen counts, mold counts may suggest the types and number of fungi present at a certain time and place. For several reasons, however, these counts probably cannot be used as a constant guide for daily activities.

One reason is that the number and types of spores actually present in the mold count may have changed considerably in 24 hours because weather and spore distribution are directly related. Many common allergenic molds are of the dry spore type—they release their spores during dry, windy weather. Other fungi need high humidity, fog, or dew to release their spores. Although rain washes many larger spores out of the air, it also causes some smaller spores to be propelled into the air.

In addition to the effect of weather changes during 24-hour periods on mold counts, spore populations may also differ between day and night. Dry spore types are usually released during daytime, and wet spore types are usually released at night.

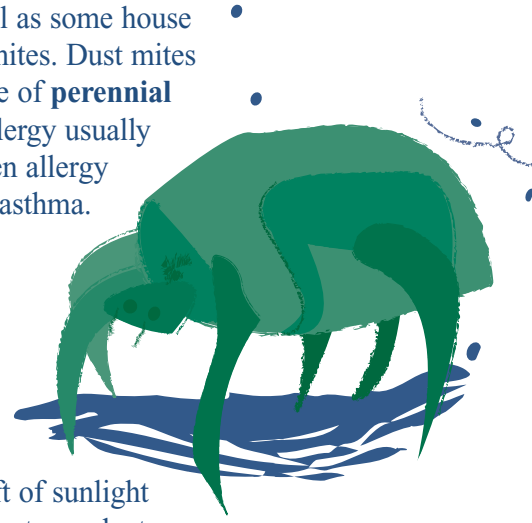
Are there other mold-related disorders?

Fungi or **organisms** related to them may cause other health problems similar to allergic diseases. Some kinds of *Aspergillus* may cause several different illnesses, including both infections and allergies. These fungi may lodge in the airways or a distant part of the lung and grow until they form a compact sphere known as a "fungus ball." In people with lung damage or serious underlying illnesses, *Aspergillus* may grasp the opportunity to invade the lungs or the whole body.

In some people, exposure to these fungi also can lead to asthma or to a lung disease resembling severe inflammatory asthma called allergic bronchopulmonary aspergillosis. This latter condition, which occurs only in a small number of people with asthma, causes wheezing, low-grade fever, and coughing up of brown-flecked masses or mucus plugs. Skin testing, blood tests, X Rays, and examination of the **sputum** for fungi can help establish the diagnosis. Corticosteroid drugs usually treat this reaction effectively. Immunotherapy (allergy shots) is not helpful.

Dust Mite Allergy

Dust mite allergy is an allergy to a microscopic organism that lives in the dust found in all dwellings and workplaces. House dust, as well as some house furnishings, contains microscopic mites. Dust mites are perhaps the most common cause of **perennial** allergic rhinitis. House dust mite allergy usually produces symptoms similar to pollen allergy and also can produce symptoms of asthma.



House dust mites, which live in bedding, upholstered furniture, and carpets, thrive in summer and die in winter. In a warm, humid house, however, they continue to thrive even in the coldest months. The particles seen floating in a shaft of sunlight include dead dust mites and their waste products. These waste products, which are proteins, actually provoke the allergic reaction.

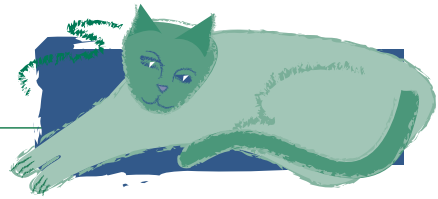
What is house dust?

Rather than a single substance, so-called house dust is a varied mixture of potentially allergenic materials. It may contain fibers from different types of fabrics and materials such as

- Cotton lint, feathers, and other stuffing materials
- Dander from cats, dogs, and other animals
- Bacteria
- Mold and fungus spores (especially in damp areas)
- Food particles
- Bits of plants and insects
- Other allergens peculiar to an individual house or building

Cockroaches are commonly found in crowded cities and in the southern United States. Certain proteins in cockroach feces and saliva also can be found in house dust. These proteins can cause allergic reactions or trigger asthma symptoms in some people, especially children. Cockroach allergens likely play a significant role in causing asthma in many inner-city populations.

Animal Allergy



Household pets are the most common source of allergic reactions to animals.

Many people think that pet allergy is provoked by the fur of cats and dogs. Researchers have found, however, that the major allergens are proteins in the saliva. These proteins stick to the fur when the animal licks itself.

Urine is also a source of allergy-causing proteins, as is the skin. When the substance carrying the proteins dries, the proteins can then float into the air. Cats may be more likely than dogs to cause allergic reactions because they lick themselves more, may be held more, and spend more time in the house, close to humans.

Some rodents, such as guinea pigs and gerbils, have become increasingly popular as household pets. They, too, can cause allergic reactions in some people, as can mice and rats. Urine is the major source of allergens from these animals.

Allergies to animals can take 2 years or more to develop and may not decrease until 6 months or more after ending contact with the animal. Carpet and furniture are a reservoir for pet allergens, and the allergens can remain in them for 4 to 6 weeks. In addition, these allergens can stay in household air for months after the animal has been removed. Therefore, it is wise for people with an animal allergy to check with the landlord or previous owner to find out if furry pets lived on the premises.

Chemical Sensitivity

Some people report that they react to chemicals in their environments and that these allergy-like reactions seem to result from exposure to a wide variety of synthetic and natural substances. Such substances can include those found in

- Paints
- Carpeting
- Plastics
- Perfumes
- Cigarette smoke
- Plants

Although the symptoms may resemble those of allergies, sensitivity to chemicals does not represent a true allergic reaction involving IgE and the release of histamine or other chemicals. Rather than a reaction to an allergen, it is a reaction to a chemical irritant, which may affect people with allergies more than others.

Diagnosis

People with allergy symptoms—such as the runny nose of allergic rhinitis—may at first suspect they have a cold, but the "cold" lingers on. Testing for allergies is the best way to find out if a person is allergic.

Skin tests

Allergists (doctors who specialize in allergic diseases) use skin tests to determine whether a person has IgE antibodies in the skin that react to a specific allergen. The allergist will use weakened extracts from allergens such as dust mites, pollens, or molds commonly found in the local area. The extract of each kind of allergen is injected under a person's skin or is applied to a tiny scratch or puncture made on the arm or back.

Skin tests are one way of measuring the level of IgE antibody in a person. With a positive reaction, a small, raised, reddened area, called a wheal (hive), with a surrounding flush, called a flare, will appear at the test site. The size of the wheal can give the doctor an important diagnostic clue, but a positive reaction does not prove that a particular allergen is the cause of symptoms. Although such a reaction indicates that IgE antibody to a specific allergen is present, respiratory symptoms do not necessarily result.

Blood tests

Skin testing is the most sensitive and least costly way to identify allergies. People with widespread skin conditions like eczema, however, should not be tested using this method.

There are other diagnostic tests that use a blood sample to detect levels of IgE antibody to a particular allergen. One such blood test is called the radioallergosorbent test (RAST), which can be performed when eczema is present or if a person has taken medicines that interfere with skin testing.

Some ways to handle airborne allergies

- Avoid the allergen
- Take medicine
- Get allergy shots

Prevention

Avoidance

Pollen and Molds

Complete avoidance of allergenic pollen or mold means moving to a place where the offending substance does not grow and where it is not present in the air. Even this extreme solution may offer only temporary relief because a person sensitive to a specific pollen or mold may develop allergies to new allergens after repeated exposure to them. For example, people allergic to ragweed may leave their ragweed-ridden communities and relocate to areas where ragweed does not grow, only to develop allergies to other weeds or even to grasses or trees in their new surroundings. Because relocating is not a reliable solution, allergy specialists do not encourage this approach.

There are other ways to reduce exposure to offending pollens.

- Remain indoors with the windows closed in the morning, for example, when the outdoor pollen levels are highest. Sunny, windy days can be especially troublesome.
- Wear a face mask designed to filter pollen out of the air and keep it from reaching nasal passages, if you must work outdoors.
- Take your vacation at the height of the expected pollinating period and choose a location where such exposure would be minimal.

Vacationing at the seashore or on a cruise, for example, may be effective retreats for avoiding pollen allergies.

House Dust

If you have dust mite allergy, pay careful attention to dust-proofing your bedroom. The worst things to have in the bedroom are

- Wall-to-wall carpet
- Blinds
- Down-filled blankets
- Feather pillows
- Stuffed animals
- Heating vents with forced hot air
- Dogs and cats
- Closets full of clothing

Carpets trap dust and make dust control impossible.

- Shag carpets are the worst type of carpet for people who are sensitive to dust mites.
- Vacuuming doesn't get rid of dust mite proteins in furniture and carpeting, but redistributes them back into the room, unless the vacuum has a special HEPA (high-efficiency particulate air) filter.
- Rugs on concrete floors encourage dust mite growth.

If possible, replace wall-to-wall carpets with washable throw rugs over hardwood, tile, or linoleum floors, and wash the rugs frequently.

Reducing the amount of dust mites in your home may mean new cleaning techniques as well as some changes in furnishings to eliminate dust collectors. Water is often the secret to effective dust removal.

- Clean washable items, including throw rugs, often, using water hotter than 130 degrees Fahrenheit. Lower temperatures will not kill dust mites.
- Clean washable items at a commercial establishment that uses high water temperature, if you cannot or do not want to set water temperature in your home at 130 degrees. (There is a danger of getting scalded if the water is more than 120 degrees.)
- Dust frequently with a damp cloth or oiled mop.

If cockroaches are a problem in your home, the U.S. Environmental Protection Agency suggests some ways to get rid of them.

- Do not leave food or garbage out.
- Store food in airtight containers.
- Clean all food crumbs or spilled liquids right away.
- Try using poison baits, boric acid (for cockroaches), or traps first, before using pesticide sprays.

If you use sprays:

- Do not spray in food preparation or storage areas.
- Do not spray in areas where children play or sleep.
- Limit the spray to the infested area.
- Follow instructions on the label carefully.
- Make sure there is plenty of fresh air when you spray.
- Keep the person with allergies or asthma out of the room while spraying.

Pets

If you or your child is allergic to furry pets, especially cats, the best way to avoid allergic reactions is to find them another home. If you are like most people who are attached to their pets, that is usually not a desirable option. There are ways, however, to help lower the levels of animal allergens in the air, which may reduce allergic reactions.

- Bathe your cat weekly and brush it more frequently (ideally, a non-allergic person should do this).
- Keep cats out of your bedroom.
- Remove carpets and soft furnishings, which collect animal allergens.
- Use a vacuum cleaner and room air cleaners with HEPA filters.
- Wear a face mask while house and cat cleaning.

Chemicals

Irritants such as chemicals can worsen airborne allergy symptoms, and you should avoid them as much as possible. For example, if you have pollen allergy, avoid unnecessary exposure to irritants such as insect sprays, tobacco smoke, air pollution, and fresh tar or paint during periods of high pollen levels.

Air Conditioners and Filters

When possible, use air conditioners inside your home or car to help prevent pollen and mold allergens from entering. Various types of air-filtering devices made with fiberglass or electrically charged plates may help reduce allergens produced in the home. You can add these to your present heating and cooling system. In addition, portable devices that can be used in individual rooms are especially helpful in reducing animal allergens.

An allergist can suggest which kind of filter is best for your home. Before buying a filtering device, rent one and use it in a closed room (the bedroom, for instance) for a month or two to see whether your allergy symptoms diminish. The airflow should be sufficient to exchange the air in the room five or six times per hour. Therefore, the size and efficiency of the filtering device should be determined in part by the size of the room.

You should be wary of exaggerated claims for appliances that cannot really clean the air. Very small air cleaners cannot remove dust and pollen. No air purifier can prevent viral or bacterial diseases such as the flu, pneumonia, or tuberculosis.

Before buying an electrostatic precipitator, you should compare the machine's ozone output with Federal standards. Ozone can irritate the noses and airways of people with allergies, especially those with asthma, and can increase their allergy symptoms. Other kinds of air filters, such as HEPA filters, do not release ozone into the air. HEPA filters, however, require adequate air flow to force air through them.

Treatment

Medicines

If you cannot adequately avoid airborne allergens, your symptoms often can be controlled by medicines. You can buy medicines without a prescription that can relieve allergy symptoms. If, however, they don't give you relief or they cause unwanted side effects such as sleepiness, your health care provider can prescribe antihistamines and topical nasal steroids. You can use either medicine alone or together.

Antihistamines

As the name indicates, an antihistamine counters the effects of histamine, which is released by the mast cells in your body's tissues and contributes to your allergy symptoms. For many years, antihistamines have proven useful in relieving itching in the nose and eyes; sneezing; and in reducing nasal swelling and drainage.

Many people who take antihistamines have some distressing side effects such as drowsiness and loss of alertness and coordination. Adults may interpret such reactions in children as behavior problems.

Antihistamines that cause fewer of these side effects are available over-the-counter or by prescription. These non-sedating antihistamines are as effective as other antihistamines in preventing histamine-induced symptoms, but most do so without causing sleepiness.

Topical Nasal Steroids

You should not confuse topical nasal steroids with anabolic steroids, which athletes sometimes use to enlarge muscle mass and which can have serious side effects. The chemicals in nasal steroids are different from those in anabolic steroids.

Topical nasal steroids are anti-inflammatory medicines that stop the allergic reaction. In addition to other helpful actions, they decrease the number of mast cells in the nose and reduce mucus secretion and nasal swelling. The combination of antihistamines and nasal steroids is a very effective way to treat allergic rhinitis, especially if you have moderate or severe allergic rhinitis.

Although topical nasal steroids can have side effects, they are safe when used at recommended doses.

Cromolyn Sodium

Cromolyn sodium is a nasal spray that in some people helps prevent allergic rhinitis from starting. When used as a nasal spray, it can safely stop the release of chemicals like histamine from mast cells. It has few side effects when used as directed and significantly helps some people manage their allergies.

Decongestants

Sometimes helping the nasal passages to drain away mucus will help relieve symptoms such as congestion, swelling, excess secretions, and discomfort in the sinus areas that can be caused by nasal allergies. Your doctor may recommend using oral or nasal decongestants to reduce congestion along with an antihistamine to control allergic symptoms.

You should not, however, use over-the-counter or prescription decongestant nose drops and sprays for more than a few days. When used for longer periods, these medicines can lead to even more congestion and swelling of the nasal passages. Because of recent concern about the bad effects of decongestant sprays and drops, some have been removed from store shelves.

Immunotherapy

Immunotherapy, or a series of allergy shots, is the only available treatment that has a chance of reducing your allergy symptoms over a longer period of time. You would receive subcutaneous (under the skin) injections of increasing concentrations of the allergen(s) to which you are sensitive. These injections reduce the level of IgE antibodies in the blood and cause the body to make a protective antibody called IgG.

About 85 percent of people with allergic rhinitis will see their hay fever symptoms and need for medicines drop significantly within 12 months of starting immunotherapy. Those who benefit from allergy shots may continue it for 3 years and then consider stopping. While many are able to stop the injections with good results lasting for several years, others do get worse after the shots are stopped.

One research study shows that children treated for allergic rhinitis with immunotherapy were less likely to develop asthma. Researchers need to study this further, however.

As researchers produce better allergens for immunotherapy, this technique will be become an even more effective treatment.

Allergy Research

Research on allergies is focused on understanding what happens to the human body during the allergic process—the sequence of events leading to the allergic response and the factors responsible for allergic diseases.

Scientists supported by NIAID found that, during the first years of their lives, children raised in a house with two or more dogs or cats may be less likely to develop allergic diseases as compared with children raised without pets. The striking finding here is that high pet exposure early in life appears to protect some children from not only pet allergy but also other types of common allergies, such as allergy to house dust mites, ragweed, and grass. This new finding is changing the way scientists think about pet exposure. Scientists must now figure out how pet exposure causes a general shift of the immune system away from an allergic response.

The results of this and a number of other studies suggest that bacteria carried by pets may be responsible for holding back the immune system's allergic response. These bacteria release molecules called endotoxin. Some researchers think endotoxin is the molecule responsible for shifting the developing immune system away from responding to allergens through a class of **lymphocytes** called Th-2 cells. (These cells are associated with allergic reactions.) Instead, endotoxin may stimulate the immune system to block allergic reactions.

If scientists can find out exactly what it is about pets or the bacteria they carry that prevents the allergic response, they might be able to develop a new allergy treatment.

Some studies are seeking better ways to diagnose as well as treat people with allergic diseases and to better understand the factors that regulate IgE production to reduce the allergic response. Several research institutions are focusing on ways to influence the cells that participate in the allergic response.

NIAID supports a network of Asthma, Allergic and Immunologic Diseases Cooperative Research Centers throughout the United States. The centers encourage close coordination among scientists studying basic and clinical immunology, genetics, biochemistry, pharmacology, and environmental science. This interdisciplinary approach helps move research knowledge as quickly as possible from the lab into the hands of doctors and their allergy patients.

Educating patients and health care providers is an important tool in controlling allergic diseases. All of these research centers conduct and evaluate education programs focused on methods to control allergic diseases.

Since 1991, researchers participating in NIAID's Inner-City Asthma Study have been examining ways to treat asthma in minority children living in inner-city environments. Asthma, a major cause of illness and hospitalizations among these children, is provoked by a number of possible factors, including allergies to airborne substances.

The success of NIAID's model asthma program led the U.S. Centers for Disease Control and Prevention to award grants to help community-based health organizations throughout the United States implement the program.

Based on the success of the first National Cooperative Inner-City Asthma Study, NIAID and the National Institute of Environmental Health Sciences, also part of NIH, started a second cooperative multicenter study in 1996. This study recruited children with asthma, aged 4 to 11, to test the effectiveness of two interventions. One intervention uses a novel communication and doctor education system. Information about the children's asthma severity is provided to their primary care physicians, with the intent that this information will help the doctors give the children the best care possible.

The other intervention involves educating families about reducing exposure to passive cigarette smoke and to indoor allergens, including cockroach, house dust mite, and mold. Researchers are assessing the effectiveness of both interventions by evaluating their capacity to reduce the severity of asthma in these children.

Early data show that by reducing allergen levels in children's beds by one-third, investigators reduced by nearly one-quarter (22 percent) both the number of days the children wheezed and the number of days the children missed school.

Although several factors provoke allergic responses, scientists know that heredity plays a major role in determining who will develop an allergy. Therefore, scientists are trying to identify and describe the **genes** that make a person susceptible to allergic diseases.

Because researchers are becoming increasingly aware of the role of environmental factors in allergies, they are evaluating ways to control environmental exposures to allergens and pollutants to prevent allergic disease.

These studies offer the promise of improving the treatment and control of allergic diseases and the hope that one day allergic diseases will be preventable.

Glossary

allergen—substance that causes an allergic reaction

allergenic—describes a substance which produces an allergic reaction

antibody—molecule tailor-made by the immune system to lock onto and destroy specific germs

basophils—white blood cells that contribute to inflammatory reactions

conjunctivitis—inflammation of the lining of the eyelid, causing red-rimmed, swollen eyes, and crusting of the eyelids

genes—units of genetic material that carry the directions a cell uses to perform a specific function

granules—small particles; in cells the particles typically include enzymes and other chemicals

immune system—a complex network of specialized cells, tissues, and organs that defends the body against attacks by disease-causing organisms

inflammation—an immune system process that stops the progression of disease-causing organisms

lymphocytes—small white blood cells which are important parts of the immune system

mast cells—granule-containing cells found in tissue

molecules—the building blocks of a cell. Some examples are proteins, fats, and carbohydrates

organism—an individual living thing

perennial—describes something that occurs throughout the year

rhinitis—inflammation of the nasal passages, which can cause a runny nose

sinuses—hollow air spaces located within the bones of the skull surrounding the nose

sputum—matter ejected from the lungs and windpipe through the mouth

tissues—groups of similar cells joined to perform the same function

upper respiratory tract—area of the body which includes the nasal passages, mouth, and throat

More Information

National Institute of Allergy and Infectious Diseases
National Institutes of Health
31 Center Drive, MSC 2520
Bethesda, Maryland 20892-2520
301-496-5717
www.niaid.nih.gov

National Institute of Environmental Health Sciences
National Institutes of Health
P.O. Box 12233
Research Triangle Park, North Carolina 27709
919-541-3345
www.niehs.nih.gov

National Library of Medicine
MedlinePlus
8600 Rockville Pike
Bethesda, Maryland 20894
1-888-FIND-NLM (1-888-346-3656) or 301-594-5983
www.medlineplus.gov

U.S. Environmental Protection Agency
Indoor Air Quality Information Clearinghouse
P.O. Box 37133
Washington, D.C. 20013-7133
1-800-438-4318 or 703-356-4020
www.epa.gov

Allergy and Asthma Network/Mothers of Asthmatics, Inc.
2751 Prosperity Avenue, Suite 150
Fairfax, Virginia 22031
1-800-878-4403
www.aanma.org

American Academy of Allergy, Asthma & Immunology
611 East Wells Street
Milwaukee, Wisconsin 53202
1-800-822-ASMA (1-800-822-2762)
www.aaaai.org

American College of Allergy, Asthma & Immunology
85 W. Algonquin Road, Suite 550
Arlington Heights, Illinois 60005
1-800-842-7777
www.acaai.org

Asthma and Allergy Foundation of America
1233 20th Street, NW, Suite 402
Washington, D.C. 20036
1-800-7-ASTHMA (1-800-727-8462) or 202-466-7643
www.aafa.org

National Allergy Bureau (pollen information)
1-800-9-POLLEN (1-800-976-5536)
www.aaaai.org/nab

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Healthy Homes Issues:

Asthma

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U.S. Department of Housing and Urban Development
Office of Healthy Homes and Lead Hazard Control

HEALTHYHOMES
Healthy Families | Healthy Children

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Asthma

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This and previous versions of the document were prepared by:
Peter Ashley, DrPH, HUD OHHLHC
J. Kofi Berko, PhD, HUD OHHLHC
Carolyn Kawecki, MA, BSN, RN, Healthy Housing Solutions, Inc.
Jackson Anderson, Jr., Healthy Housing Solutions, Inc.
David Jacobs, PhD, National Center for Healthy Housing
Stevenson Weitz, MS, Healthy Housing Solutions, Inc.
Jill Breysse, MS, CIH, National Center for Healthy Housing
John Menkedick, Battelle
Maureen Wooton, Battelle
Jennifer Zewatsky, Battelle

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Elizabeth Herman, M.D, M.P.H
Department of Health and Human Services
Centers for Disease Control and Prevention,
National Center for Environmental Health

Felicia A. Rabito, Ph.D.
Department of Epidemiology, Tulane University
School of Public Health and Tropical Medicine

Terrence M. Allan, M.P.H.
Cuyahoga County Board of Health

Gary Adamkiewicz, Ph.D., M.P.H
Harvard School of Public Health

Martin D. Chapman, Ph.D.
INDOOR Biotechnologies, Inc.

Dorr G. Dearborn, Ph.D., M.D.
Director, Swetland Center for Environmental Health
Case Western University

Peter Gergen, M.D.
Department of Health and Human Services
Agency for Healthcare Research and Quality

Stuart Greenberg, Executive Director
Environmental Health Watch

J. David Miller, Ph.D.
Department of Chemistry, Carleton University

Megan Sandel, M.D., M.P.H.
Boston University School of Medicine

Tim K. Takaro, M.D., M.P.H.
Faculty of Health Sciences, Simon Fraser University

Preface

In 1998, Congress appropriated funds and directed the U.S. Department of Housing and Urban Development (HUD) to "develop and implement a program of research and demonstration projects that would address multiple housing-related problems affecting the health of children." In response, HUD solicited the advice of experts in several disciplines and developed a preliminary plan for the Healthy Homes Initiative (HHI). The primary goal of the HHI is to protect children from housing conditions that are responsible for multiple diseases and injuries. As part of this initiative, HUD has prepared a series of papers to provide background information to their current HHI grantees, as well as other programs considering adopting a healthy homes approach. This background paper focuses on asthma and provides a brief overview of the current status of knowledge on:

- The extent and nature of asthma triggers in the home;
- Assessing the home environment;
- Interventions to reduce exposure to residential asthma triggers in the home; and
- Research needs with respect to housing and asthma.

Please send all comments to:
hhpgmfeedback@hud.gov

HUD, OHHLHC
Fax: 202–755–1000

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Summary and Relevance to Healthy Homes Programs

- Asthma affects over 24 million people in the U.S., with the costs of lost school days and wages in the tens of millions of dollars annually. Children and the elderly are at greater risk for severe symptoms, including more frequent emergency room visits, hospitalization, and deaths.
- Asthma is a complex disease that involves genetic predispositions and a dose/response relationship to exposure to environmental triggers—that is, the greater the exposure, the more likely those symptoms will worsen in predisposed individuals.
- Exposure to environmental triggers (dust mites, mold, pets, pests, particulates, indoor environmental pollutants in the home), is associated both sensitization to those triggers and asthma exacerbation. Psychosocial stressors, such as domestic or chronic community violence, and unsafe or overcrowded housing also increase asthma severity. Some triggers produce allergic reactions that lead to symptoms; others are irritants that produce irritation and inflammation. The mechanism by which this occurs for each trigger in genetically-predisposed individuals is still the subject of research, and is presented in detail throughout this paper.
- There are disparities in asthma rates and in exposure to environmental triggers by race and ethnicity, income, region, trigger, and housing type. Neighborhood-level factors, such as exposure to traffic and stress associated with neighborhood violence are also associated with asthma severity.
- Dust mite exposure is the single most common trigger in the home environment associated with asthma exacerbation. Exposures to environmental tobacco smoke and cockroaches also play critical roles in asthma severity in children.
- Statistically significant associations have been found between the development of asthma and measures of home dampness, visible mold, and mold odor.
- Asthma management requires a combination of medical management (medication and identification of the specific allergic predispositions) and reduced exposure to environmental triggers.
- The research indicates that a tailored multifaceted environmental intervention is the key to long term reduction in symptoms. No single intervention has been associated with sustained improvement. Education is a critical component of asthma management and must be built into any intervention project.
- There are a variety of methods used to assess environmental exposure. Most healthy homes programs use a combination of visual assessments and resident interviews to identify common triggers. Other allergen and irritant sampling techniques are also available and reviewed in this paper.
- Because of limited resources, healthy homes programs should consider focusing home asthma intervention efforts in the homes of children with poorly controlled asthma.
- Healthy Homes programs need to select a package of the most cost-effective interventions tailored to the population, allergens, regional conditions, and housing stock with which they work. The interventions included in this package that have shown the most consistent benefits include:
- Use of Community Health Workers (individuals from the target communities) to deliver education and coach residents in implementing low-level interventions and improving asthma self management.
- Dust mite control through cleaning, humidity control, allergen-proof mattress and pillow covers, and use of High Efficiency Particulate Air (HEPA) filtration for vacuums and forced air systems.

- Pest control through use of Integrated Pest Management (i.e. sealing of all cracks/holes in the unit, removing access to food, water, and habitation, effective use of pesticides when needed, ongoing monitoring of pest populations, and prompt intervention if pests return).
- Smoking cessation in the home and no-smoking policies in multifamily units.
- Prohibiting pet access to sleeping areas and, if necessary, removal of pets;
- Moisture control and reduction through improved ventilation (e.g., whole-house and/or individual kitchen and bath fans vented to the exterior) and addressing sources of moisture such as leaks, condensation, and water infiltration from the exterior.
- Remediation of any significant mold growth and underlying moisture issues.
- Control of indoor air pollutants such as Nitrous Oxide and other combustion products through improved ventilation of combustion appliances, and reduction in exposure to particulates and Volatile Organic Compounds through use of less toxic materials and improved ventilation.
- HUD grantees and other programs working to address indoor asthma triggers may wish to consult the *Healthy Homes Program Guidance Manual* for additional strategies to strengthen their programs.

Asthma

1.0 Overview of Asthma and the Home Environment

More than 24 million people in the United States (8.2% of the population) are estimated to have asthma (Akinbami et al. 2011; CDC 2003). In 2008, persons with asthma had an estimated 10.5 million missed school days and 14.2 million lost work days (Akinbami et al. 2011). Among children, it is the one of the most common chronic illnesses and a primary factor in school absences (CDC 2011a; American Lung Association 2011; NAS 2000). A substantial body of research, including population-based studies of school-aged children and young adults, indicates that the prevalence and severity of asthma have increased dramatically over the last several decades in the United States and many other parts of the world (Patel et al. 2008; Braman 2006); Pearce et al. 2007; CDC 1998b; Carter and Platts-Mills, 1998; Platts-Mills, 1998). The gap in prevalence rates found between English-speaking and other Western European countries and those of African, Latin American and parts of Asia appears to have narrowed as awareness and diagnosis of asthma increased globally (Pearce et al. 2007).

Asthma is a complex condition that involves the interaction of many environmental agents on different cells in the airway, which alters the function and expression of genes associated with immune responses. It is characterized by episodic airway obstruction caused by extensive narrowing of the bronchi and bronchioles. The narrowing is caused by spasm of smooth muscle, edema (swelling from fluid accumulation) of the mucosa, and the presence of mucus in the airway resulting from an immunologic reaction induced by allergies, irritants, infection, stress, and other factors in a genetically predisposed individual. Because individuals differ in genetic predisposition and have unique exposures to environmental agents at different times and places, the identification and control of a particular person's asthma is challenging (Reed 2010).

In the U.S., rates of increase of asthma are disproportionately high among children, African Americans, Puerto Ricans, persons with incomes below the poverty level, and those residing in the Northeast and Midwest (CDC 2011b; Eggleston 2000).

Research has suggested that a large portion of the observed racial/ethnic differences in asthma prevalence is explained by factors related to income and level of education (Litonjua et al. 1999). Residence in an urban area has also been implicated as an important risk factor for children (Aligne et al. 2000), but more recent research suggests that behavioral, demographic, and other features specific to the place of residence for adults may be a more powerful explanation than the distinction between rural and urban setting alone (Frazier et al. 2012; Morrison et al. 2009). Researchers have found marked differences in the types of asthma triggers found in homes in inner-city areas compared to suburban or rural areas (Simons et al. 2007; Kitch 2000; Kattan et al. 1997). However, substantial differences in the overall burden of agents that exacerbate asthma have not necessarily been established (Diette et al. 2007; Kitch 2000). Diette et al. (2007) for example, found that exposures to common indoor air pollutants and allergens were similar in Baltimore inner-city children with and without asthma, suggesting that exposures may exacerbate, but not necessarily cause, the development of symptoms.

Increases in asthma prevalence and severity have occurred despite general reductions in levels of most ambient air pollutants; therefore, many researchers point to coinciding changes in the home environment as potentially influential, and possibly more important, factors in determining asthma risk (Custovic et al. 1998). In particular, housing designs intended to increase energy efficiency, resulting in a decrease in passive ventilation, and the presence of upholstered furnishings and carpeting have all

The strongest established risk factors for development of asthma in children and young adults are family history of allergic disease and sensitization to one or more indoor allergens (Gaffin and Phipatanukul 2009; Liu et al. 2009).

been cited as conditions in the home that have the potential to affect indoor air quality and the prevalence and severity of asthma (Sundell et al. 2011; Platts-Mills, 1998; Carter and Platts-Mills, 1998; Custovic et al. 1998, Platts-Mills et al. 1997). Potentially increasing the significance of indoor air exposures as risk factors for asthma, data show children in the U.S. currently spend the overwhelming majority of their time indoors (USEPA 2009; 1997a). Exposures in schools may also contribute to asthma symptoms for children whose homes do not contain high levels of allergens to which they have sensitivity (Sheehan et al. 2009).

Allergens are proteins with the ability to trigger immune responses and cause allergic reactions (atopy) in susceptible individuals (e.g., those with a family history of allergic disease). They are typically found adhered to very small particles, which can be airborne as well as present in household dust reservoirs (e.g., in carpets and on surfaces). In indoor environments, allergen exposure primarily occurs through inhalation of allergens associated with airborne particles (Gaffin and Phipatanukul 2009). Common indoor allergen sources include dust mites, cockroaches, animals (domestic animals and pests such as rodents), and mold. Particular allergens identified in animals include proteins found in the urine (for rodents), saliva (for cats), feces (for house dust mites and cockroaches), and skin flakes or body casing particles (for dog, cat, and cockroach) (Salo et al. 2008; Erwin et al. 2003; Katial 2003). Sensitization to a substance is the development of the potential for an allergic reaction to that substance. Sensitization occurs in susceptible individuals when repeated exposure to an allergen (also called an antigen in immunological science) results in the production of the immunoglobulin E (IgE) antibody. An antibody is a protein that is manufactured by lymphocytes (a type of white blood cell) to neutralize an antigen or foreign protein. An allergic response may result when the individual is again exposed to the substance that caused IgE antibody formation. IgE represents a class of antibodies normally present in very low levels in humans but found in larger quantities in people with allergies and certain infections. Evidence suggests that it is the primary antibody that mediates the classic allergic reaction (see American Academy of Allergy, Asthma and Immunology (AAAI) at http://www.aaaai.org).

Of the tests used to determine whether an individual is sensitive to an allergen, the skin prick is the most common method. A small amount of allergen is introduced into the skin by making a small puncture through a drop of allergen extract. Swelling occurs if the patient is allergic to the specific allergen. A blood test, called a RAST (radioallergosorbent test) which measures the amount of specific IgE antibodies in the blood which are present if there is a "true" allergic reaction, may sometimes be used. This is a more expensive method, is generally less sensitive than skin testing, and requires more time for results to be available. It is generally used only when skin tests cannot be performed. Allergen extracts are produced commercially according to Food and Drug Administration (FDA) standards.

Exposure to house dust mite allergens in childhood has been linked to an increase in the relative risk of developing asthma, and numerous other allergens are associated with asthma exacerbation in sensitized individuals (Salo 2008; NAS 2000). However, the mechanisms underlying this relationship are subject to further investigation. Silvestri et al. (2010), for example, note that total and House Dust Mite (HDM)-specific IgE levels are more tightly linked to allergic inflammation than to pulmonary functions.

Data regarding critical ages for sensitization toward allergens are not well defined in the literature. Health risks for infants from exposure to pollutants in house dust may be 100 times greater than those for adults (Roberts et al. 2009). Research findings are mixed on the introduction of allergen avoidance measures before and early after birth. While early research (Bergmann et al. 1998), supported

The HUD- and National Institute of Environmental Health Sciences (NIEHS)-sponsored National Survey of Lead and Allergens in Housing (NSLAH), a cross-sectional survey of a nationally representative sample of 831 homes in 75 locations, found that 51.5% of the homes had detectable levels of six allergens and 45.8% had at least three allergens that exceeded levels considered to be elevated (Salo et al. 2008). For individuals with a genetic predisposition to develop allergic reactions (atopy), high allergen levels increased the odds of having asthma symptoms .The survey also found that over 80% of homes in the United States have detectable levels of mite allergen in the bedroom, 46% have levels associated with sensitization, and 24% have levels associated with asthma morbidity (Arbes et al. 2003a).

recommendations that avoidance measures for allergens be introduced for high-risk infants (e.g., those with family histories of allergic diseases, atopic dermatitis in the first three months of life, or sensitizations to specific food allergens in the first three years of life), later studies showed mixed results on the impact of environmental interventions (Arshad et al. 2007). For example, the Canadian Childhood Asthma Primary Prevention Study found that interventions during infancy were associated at age seven with a significantly lower prevalence of pediatric allergist-diagnosed asthma in the intervention group than in the control group (Chan-Yeung et al. 2005). More recent studies of an at-risk group of pregnant women in Chicago found that general modifications of the home environment during pregnancy (such as use of mattress covers and washing linens in hot water) did not produce significant differences in symptoms from those achieved by intensive in-home education (Persky et al. 2009). A longitudinal study of Michigan children's prenatal indoor exposure to pets was associated with similar mixed results (Havstad et al. 2011).

Research in the U.S. and Europe found evidence that exposure to microbial organisms via lifestyle characteristics such as day care attendance, having multiple siblings, and close proximity to farming practices may decrease the risk of atopy

Another concept, known as the "hygiene hypothesis," has spawned a number of studies. The hygiene hypothesis suggests that children's immune systems are not being developed normally at a young age due to a general lack of exposure to infectious agents (Ball 2000; Arruda et al. 2001).

and asthma (Omland et al., 2011; Liu and Szefler 2003; Alm et al. 1999; von Mutius 2002; Braun-Fahrlander et al. 2002), but the support for the "hygiene hypothesis" is mixed. For example, a study of children in rural Germany, Austria, and Switzerland, found that children from farming households who are routinely exposed to high levels of environmental endotoxin have a significantly decreased risk of hay fever, sensitization to six common aeroallergens, atopic wheeze, and atopic asthma. This effect was seen in children from both farming and non-farming households, indicating that even low levels of exposure to endotoxin may protect against atopic diseases in early life (Braun-Fahrlander, 2003). However, Perzanowski et al. (2006) in a prospective birth cohort study of children of Dominican and African-American mothers in New York City found that children in homes with higher endotoxin concentrations were less likely to have eczema at age one but more likely to wheeze at age one. Celedon et al. (2003) found that the protective effect of day care attendance was only observed in children without maternal history of asthma.

Other research casts doubt over the hygiene hypothesis in its entirety. Results of the International Study of Asthma and Allergies in Childhood (ISAAC) showed that there wasn't a lower prevalence of asthma in some underdeveloped countries (i.e., countries with high infection rates) compared with those in the developing world (ISAAC Steering Committee 1998; Arruda et al. 2001). After extensive review of studies investigating the relationship between the number of siblings in a family and allergic disorders, Karmaus and Botezan (2002) concluded that the hygiene hypothesis failed to explain inconsistent study results. It is possible that children in developing countries are exposed to different sensitizing agents, thereby changing their risk level and subsequent expression of disease. Eldeirawi et al. (2009)

surveyed parents of 2,023 US school children of Mexican descent and examined the associations of asthma with nativity, age at immigration, and length of residence in the U.S. after adjusting for potential confounding variables. They found that Mexican-born participants who moved to the US before two years of age were almost twice as likely to experience asthma compared with Mexican-born children who moved to the US at or after two years of age. These associations were not explained by factors such as: place of residence in infancy; exposure to animals/pets; history of infections; breastfeeding; exposure to environmental tobacco smoke; daycare attendance: number of siblings; and language use.

Less is known about asthma among the elderly. Reed (2010) reports that the prevalence of asthma in the elderly is similar to that in all other adult age categories (i.e., 5–10%). The few studies focusing on asthma in elderly persons indicate that it is a significant problem, that much of the cause of morbidity may be sensitivity to indoor allergens, and that the pattern of sensitivity appears to be similar to that reported in children and young adults in urban areas of the United States if asthma is developed prior to age 65 (Hanania et al. 2011; Huss et al. 2001a; Rogers et al. 2002). However, Reed (2010) suggests that late-onset asthma (i.e., asthma whose onset occurs after age 40) rarely is IgE- mediated and is often a component of irreversible airway obstruction, in addition to airway changes associated with cigarette smoking. He notes that elderly individuals with a diagnosis of intrinsic asthma are more likely to have a higher rate of decreased lung function and to die of asthma than those with allergic asthma. Busse et al. (2010) also found in the 245 patients in a cohort of inner city adults with persistent asthma that 73%, 61%, and 41% of patients ≤35, 36–59, and ≥60 years old, respectively, were sensitized to at least one indoor allergen (p=0.01). Multivariate analysis showed that patients older than 60 years of age were significantly less likely to be sensitized compared to younger adults after controlling for potential confounders.

Regardless of the cause, the health consequences of negative control of asthma in the elder are great. Elderly participants in the National Asthma Survey had poorer short and long-term symptom control and less education about appropriate interventions (Talreja et al. 2011).

Research also indicates that many other environmental factors can exacerbate asthma symptoms, such as respiratory tract infections, bacterial endotoxins, indoor pollutants (environmental tobacco smoke, nitrogen oxides/indoor combustion products, formaldehyde, phthalates, VOCs, pesticides), outdoor pollutants that penetrate the indoor environment (sulfur oxides, ozone, particulate matter), cold air, and the presence of wood burning stoves and fireplaces. These substances act by an irritant mechanism which sets off the body's inflammatory response as opposed to the allergic mechanism described above.

Both adults and children are at risk from environmental tobacco smoke, which has a direct link to multiple respiratory symptoms and increases the risk of other adverse health outcomes (USDHHS 2010 and 2006; Gronenberg-Kloft et al. 2007). Both secondhand smoke (such as close proximity to tobacco smoke by non-smokers) and "third hand" exposure (i.e., exposure to smoke residues that adhere to surfaces) contributes to these risks (Butz et al. 2010; Matt et al. 2011).

In addition to home environmental exposures, medications, viral infections, and dietary factors, such as Vitamin D deficiency (Brehm et al. 2012) and lowered consumption fruits and vegetables rich in vitamin C, selenium, and zinc (Peroni et al. 2012), may play a role in the development of asthma or its exacerbation. A summary of this research is beyond the scope of this paper.

Trupin et al. (2009) found that multivariate models covering a range of individual and environmental factors (including neighborhood socioeconomic status, proximity to traffic, land use, and ambient air quality) explained nearly a third of FEV_1 variability and, taking into account lung function, one quarter of variability in their study of adult asthma severity. Positive neighborhood characteristics, such as community vitality, neighborhood stability, neighborhood

Neighborhood characteristics, such as presence of serious housing code violations per 1000 rental units. proximity to major highways and railroads and stress related to crime and violence, also contribute to asthma exacerbations (Patel et al. 2011; Rosenfeld et al. 2010; Lindberg et al. 2010; Juhn et al. 2010; Gupta et al. 2009; Sandel and Wright 2006).

interaction, and economic potential, were found to be associated with lower asthma prevalence rates in Chicago urban neighborhoods. These positive neighborhood characteristics explained 21% of asthma variations (Gupta et al. 2010). They conclude that the data support an integrated approach to modeling adult asthma outcomes, including both the physical and the social environment. While individual-level factors, such as stress, obesity/body mass and physical exercise, may play a role in asthma severity, many of these factors are also influenced by the wider social context (such as neighborhood safety, access to lower fat foods, fruits and vegetables, and the "walkability" of the neighborhoods). The evidence is mixed on whether asthma severity can be reduced through weight loss or exercise alone (Ma et al. 2010; Clerisme-Beary et al. 2009).

In 2007, the National Heart, Lung and Blood Institute's National Asthma Education and Prevention Program (NAEPP) Expert Panel Report 3 (EPR3) presented guidelines for the diagnosis, management, and control of asthma. The Guidelines specify that asthma control requires regular monitoring of symptoms and medical management. Environmental controls are an important adjunct to a combination of long-acting controller medication and short-acting inhaled corticosteroids to relieve muscle spasms and open airways. These medications are adjusted on a stepwise basis according to the severity of symptoms at different age levels. EPR3 recommended environmental controls include:

- Reduce, if possible, exposure to allergens to which the patient is sensitized and exposed.

The EPR3 recommended that individuals with asthma *at any level of severity* should take actions on environmental exposures.

- Know that effective allergen avoidance requires a multifaceted, comprehensive approach; individual steps alone are generally ineffective.
- Avoid exposure to environmental tobacco smoke and other respiratory irritants, including smoke from wood-burning stoves and fireplaces and, if possible, substances with strong odors.
- Avoid exertion outdoors when levels of air pollution are high.
- Consider allergen immunotherapy when there is clear evidence of a relationship between symptoms and exposure to an allergen to which the patient is sensitive.

The EPR3 report recommendations are also supported by the pooled analysis of multi-faceted tailored asthma interventions in the home environment conducted by CDC (Crocker et al. 2009), which showed that housing-based interventions that target multiple triggers are associated by clear symptom improvements.

2.0 Extent and Nature of Asthma Triggers in the Home

Analysis of national survey data found that occupants' race, income, housing type, presence of smokers, pets, cockroaches, rodents, and moisture problems were all independent predictors of high allergen burden. Total house dust weight, which serves as an index of total dust exposure, was associated with greater odds of current asthma and wheeze, even when adjusting for allergen and endotoxin exposures (Arbes et al. 2007).

General conclusions about the comparative risk of various indoor agents associated with asthma are difficult, largely due to the dependency of the particular risk on the characteristics of a given environment (e.g., climate, urban setting) and its occupants (e.g., smoking status, genetics). In addition, the literature on indoor risks associated with asthma generally focuses on single agents; in reality, however, occupants

of houses receive exposures to multiple agents that may interact physically or chemically with each other or their environment, or that may act synergistically (e.g., endotoxins or diesel exhaust and various household allergens) (NAS 2000; Pandya et al. 2002; Miller et al. 2004).

In support of the U.S. Environmental Protection Agency's (EPA) efforts to develop an asthma outreach strategy, the National Academy of Sciences' Institute of Medicine (IOM) conducted a review of available data on asthma and indoor air exposures published in the literature through 1999 (NAS 2000). In this assessment, a number of biological and chemical exposures in the home were categorized according to the strength of their relationship with asthma development and/or exacerbation, as based on a uniform set of criteria regarding sufficiency of evidence. Table 1 summarizes general findings and conclusions of the assessment committee regarding the association between exposure to an indoor agent and asthma development and exacerbation.

Selected key studies relevant to the major indoor agents associated with asthma, and the residential factors that affect these agents, are discussed later in this section.

The major independent risk factor that has been identified to date for asthma causation is dust mite sensitization, although many other agents are associated or otherwise related to development and exacerbation of asthma (Table 1). Michel et al. (1996) found that the presence of endotoxin in house dust was significantly related to the severity of asthma symptoms in individuals sensitized to the dust mite. Thorne et al. (2005) using cross-sectional data from NSLAH found that endotoxin levels in settled dust were significantly related to diagnosed asthma, asthma symptoms in the past year, current use of asthma medications, and wheezing, but not allergy.

The relationships were strongest for dust on bedroom floors and bedding in adults and they indicate that "endotoxin exposure worsens symptoms in adults, regardless of whether an individual has allergies or not."

Since the IOM report, research indicates that pest exposures also contribute significantly in specific regional and housing contexts. Various studies have shown that sensitization to mouse or cockroach allergens follow the same dose response relationship. Donohue et al. (2008) found this association in an inner-city birth cohort followed up to age three, with the odds of early wheeze higher in children with IgE to cockroach, mouse, or both exposures. Moreover, cockroach and mouse exposures can be more or equally important in certain areas (e.g., urban), and risk factors can depend on the region's climate and the socioeconomic status of the household (Platts-Mills et al. 1997, 2000a and 2000b; Phipatanakul 2000a and 2000b). For example, asthmatics living in low income, urban housing have been found to have patterns of specific sensitivities that differ from those of other populations, with a higher frequency of sensitivity to cockroaches, mice, and molds and less frequent sensitivity to cats, dogs, and house dust mites (Eggleston 2000; Eggleston et al. 1999a; Phipatanakul 2000a and 2000b; Gruchalla et al. 2005). Residence in public housing and especially high-rise buildings appears to be associated with higher levels of cockroach and mice allergens (Rosenfeld et al. 2011; Northridge et al. 2010) In very low humidity climates in the mountains of New Mexico (i.e., where dust mites and fungi are less prevalent), sensitization to dog and cat allergens has been observed to be more strongly associated with respiratory symptoms (Sporik et al. 1995 and Ingram et al. 1995 as cited in Platts-Mills et al. 1997). The Inner City Asthma Study (ICAS), which was conducted

The World Health Organization/International Union of Immunological Societies (WHO/IUIS) Allergen Nomenclature Sub-Committee has developed systematic nomenclature for describing all characterized allergens (Smith, 1999; WHO/IUIS Allergen Nomenclature Subcommittee, 1994). In this system, allergens are generally designated according to the accepted taxonomic name of their source as follows: the first three letters of the genus, followed by a blank space, followed by the first letter of the species, followed by a blank space, and finally an Arabic number. The Arabic numerals are assigned to allergens in the chronological order of their identification. For example, the first cat (Felis domesticus) allergen to be successfully purified is Fel d 1. (WHO/IUIS Allergen Nomenclature Subcommittee 1994).

Table 1. Summary of NAS Findings Regarding the Association between Biological and Chemical Exposures in the Home and the Development and Exacerbation of Asthma in Sensitive Individuals.

Development of Asthma		Exacerbation of Asthma	
Biological Agents	Chemical Agents	Biological Agents	Chemical Agents
Sufficient Evidence of a Causal Relationship[1]			
Dust mite	**No agents met this definition**	**Cat** Cockroach Dust mite	**ETS (in preschool-aged children)**
Sufficient Evidence of an Association[2]			
No agents met this definition	**ETS (in preschool-aged children)**	**Dog** Fungi or mold Rhinovirus	**Nitrogen oxides (high-level exposures)[3]**
Limited or Suggestive Evidence of an Association[4]			
Cockroach (in preschool-aged children) Respiratory Syncytial virus	**No agents met this definition**	**Domestic birds** *Chlamydia pneumoniae* *Mycoplasma pneumoniae* Respiratory Syncytial virus	**ETS (in older children and adults)** Formaldehyde Fragrances
Inadequate or Insufficient Evidence to Determine Whether or Not an Association Exists[5]			
Cat, Dog, Domestic Birds Rodents Cockroaches (except for preschool-aged children) Endotoxins Fungi or molds *Chlamydia pneumoniae* *Mycoplasma pneumoniae* Chlamydia trachomatis Houseplants Pollen	**Nitrogen oxides** Pesticides Plasticizers VOCs Formaldehyde Fragrances ETS (in older children and adults)	**Rodents[6]** Chlamydia trachomatis Endotoxins Houseplants Pollen Insects other than cockroaches	**Pesticides** Plasticizers VOCs
Limited or Suggestive Evidence of No Association[7]			
	No agents met this definition	**No agents met this definition**	**No agents met this definition**

Source: NAS. 2000. Clearing the Air: Asthma and Indoor Air Exposures. National Academy of Sciences Institute of Medicine

[1] Sufficient Evidence of a Causal Relationship: Evidence fulfills association criteria and in addition satisfies criteria regarding the strength of association, biologic gradient (dose-response effect), consistency of association, biologic plausibility and coherence, and temporality used to assess causality.

[2] Sufficient Evidence of an Association: Association has been observed in studies in which chance, bias, and confounding factors can be ruled out with reasonable confidence (e.g. several small bias free studies showing an association that is consistent in magnitude and direction

[3] At concentrations that may occur only when gas appliances are used in poorly ventilated kitchens

[4] Limited or Suggestive Evidence of an Association: Evidence is suggestive of an association but is limited because chance, bias, and confounding cannot be ruled out with confidence (e.g., one high quality study shows association, but results of other studies are inconsistent)

[5] Inadequate or Insufficient Evidence to Determine Whether or Not an Association Exists: Available studies are of insufficient quality, consistency, or statistical power to permit a conclusion; or no studies exist

[6] Since the time of the NAS review and assessment, analysis of a subset of data from the National Inner-City Asthma Study indicates that mouse allergens may be an important indoor allergen in inner-city children with asthma, with exposure and hereditary disposition being risk factors contributing to mouse sensitization (Phipatanakul 2000a and 2000b).

[7] Limited or Suggestive Evidence of No Association: Several adequate studies are mutually consistent in not showing an association (but limited to the conditions, level of exposure, and length of observation covered in the study).

in seven metropolitan inner city areas in the United States, found that cockroach exposure and sensitivity predominated in the Northeast, whereas dust-mite exposure and sensitivity were predominant in southern and northwestern cities (Gruchalla et al. 2005). However, these national data may still mask exposure differences within a geographic region. For example, while the ICAS reported that Dallas had high levels of Bla g 1 in fewer than 50% of the homes studied, post-Hurricane Katrina research in New Orleans found 56.6% of the homes studied had high levels of Bla g 1 (Rabito et. al. 2007). The association between allergens and asthma is further complicated by the issue of genetics, which is known to predispose children to asthma and related conditions. Lanphear et al. (2001) observed an association between asthma and both parental atopy and African-American race. Results from another study suggest that children may be genetically predisposed to be more or less susceptible to certain indoor pollutants (Belanger et al. 2003).

2.1 Dust Mite Allergens

Evidence supporting an association between exposure to dust mite allergens and asthma exacerbation is well documented in the general literature (Gaffin and Phipatanakul 2009; Celedon et al. 2007; NAS 2000; Custovic et al. 1998; Platts-Mills et al. 1997). For example, in a review of studies on middle-class or mixed economic-class asthmatic children, Kattan et al. (1997) report that 50–60% of children had positive skin test results to dust mites. Huss et al. (2001b) reported that analysis of early cross-sectional data from 1,041 children in the Childhood Asthma Management Program (a five-year study sponsored by the National Heart, Lung and Blood Institute) show that, for house dust mites, the higher the level of allergen exposure, the more likely patients were to have positive skin test responses.

House dust mites are the only home allergen source for which the National Academies' IOM report found sufficient evidence in the literature of a causal relationship between exposure and the development of asthma in susceptible children.

The primary determinants of dust mite growth in homes are food source (i.e., skin scales), temperature, humidity and the availability of upholstered furniture, carpets, mattresses, and pillows (Vaughan and Platts-Mills 2000). Of these, humidity is generally the limiting factor (NAS 2000). Critical humidity level for mite survival is temperature dependent and ranges from 55% to 73% for temperatures between 15°C and 35°C (Arlian et al. 2001).

Mites are a very common exposure source in temperate and humid regions such as the southeastern United States. Based on results from the NSLAH, Arbes et al. (2003a) concluded that over 80% of U.S. homes have detectable levels of house dust mite allergen in the bedroom and that allergen levels associated with allergic sensitization and asthma exacerbation are common. Other features of houses that can increase levels of mite growth include poor ventilation, excess production of water in the house (e.g., humidifiers, unvented cooking), water leakage, poor cleaning habits, and being on the ground floor level (NAS 2000). Most dust mite exposure is thought to occur as mite fecal pellets and aggregates associated with larger (~10–25 μm) dust particles that become airborne during and immediately after disturbance of dust reservoirs (NAS 2000).

Some of the major mite allergens identified and isolated to date include those from *Dermatophagoides farinae* (Der f 1, 2, 3, 5, 7, and 10), *D. pteronyssinus* (Der p 1), and *Blomia tropicalis* (Blo t 5). *Dermatophagoides farinae*, *D. pteronyssinus*, and other *Dermatophagoides* species comprise most of the mite species present in U.S. homes, although *Blomia tropicalis* may also be common in the southern states of the U.S. (Curtis et al. 1997).

2.2 Cockroach Allergens

The literature indicates that allergens derived from the cockroach are an important source of sensitization, particularly in areas where cockroach infestation is common (Litonjua et al. 2001; NAS 2000; Chapman et al. 1997). ICAS researchers reported that both cockroach

Cockroach allergens may be an important factor in asthma exacerbation in any area where substandard housing permits cockroach infestation, including rural areas, suburbs, and small towns and cities across the United States (Arruda et al. 2001). Cohn et al. (2005), analyzing data from NSLAH, found cockroach allergen (Bla g 1) concentrations exceeding 2.0 U/g (a level associated with allergic sensitization) in 13% of kitchen floors and 11% of living room floors nationwide. Concentrations exceeding 8.0 U/g (a level associated with asthma morbidity) were found in 10% of kitchen floors and 3% of living room floors. Concentrations of cockroach allergen are typically highest in kitchens and bathrooms (i.e., where food and water sources are plentiful), although high levels have also been observed in bedrooms (NAS 2000; Eggleston and Arruda 2001).

allergen exposure and dust mite allergen exposure were risk factors for the development of positive skin test reactions, but reduction in cockroach allergen exposure was associated with a greater decrease in the number of symptom days by year two of the study (Morgan et al. 2004). More recent data on New Orleans children (Rabito et al. 2011) also found that that cockroach exposure increased the odds of hospitalization whereas exposure to house dust did not. Cockroach allergens and sensitivity were predominant in northeastern cities and dust mite exposure and sensitivity were higher in the south and northwest (Gruchalla et al. 2005). As noted earlier, these national data may still mask exposure differences within a geographic region. Cockroaches, like dust mites, thrive in temperate and humid regions, but may also proliferate in northern states (Chapman et al. 1997)

Differences in socioeconomic status and housing type appear to be associated with cockroach exposure and sensitization. Matsui et al. (2003) observed that over 40% of a middle-class, suburban study population had elevated levels of cockroach allergens in the home and that sensitization may occur at levels as low as one Unit/g. Cohn et al. (2005) found that elevated concentrations were associated with high-rise buildings, urban settings, pre-1940 construction, and household incomes of less than $20,000.

The humidity in a home may be an important factor in cockroach infestations for some species, such as the German and American cockroaches, which tend to aggregate in warm, humid crevices such as those around water heaters, laundries, bathrooms, appliances, and plumbing fixtures, and the Oriental cockroach, which prefers damp areas such as basements, plumbing, and sewers (Eggleston and Arruda 2001).

Other studies have also found that cockroach allergens are generally more likely to be found at higher levels in multi-family homes, often in high-poverty regions of large metropolitan areas (Kitch et al. 2000; Arruda et al. 2001). In the National Cooperative Inner City Asthma study (NCICAS), the second highest prevalence of sensitization was to cockroach allergen (36%) in 1,286 asthmatic children tested via prick skin tests (Kattan et al. 1997). In contrast, in their review of studies of middle-class or mixed economic-class asthmatic children, Kattan et al. (1997) report that positive skin tests to cockroach were uncommon, and were instead dominated by sensitivity to dust mites and cat or dog. Leaderer et al. (2002) observed similar results in a study of a socioeconomically-diverse New England population, which found independent associations between low socioeconomic status, African-American or Hispanic ethnicity, low maternal education, and residence in densely populated areas with increased likelihood of elevated cockroach allergen levels in the home.

Although there are over 70 cockroach species that occur in the U.S., only five species are commonly found in residential settings: the German cockroach (*Blatella germanica*), the American cockroach (*Perplaneta americana*), the Oriental cockroach (*Blatta orientalis*), the smoky brown cockroach (*Periplaneta fuliginosa*), and the brown-banded cockroach (*Supella Longipalpus*) (Eggleston and Arruda 2001). Some of the major cockroach allergens identified and isolated to date include those from *Blatella germanica* (Bla g 1 and Bla g 2) and *Periplaneta americana* (Per a 3). Sources of cockroach allergen include body parts, the GI tract, saliva, and feces. Like house dust mite allergens,

cockroach allergens are also thought to be associated with larger particles that are airborne during and immediately after disturbances of dust reservoirs (Esposito et al. 2011).

2.3 Pet Allergens

Studies of the characteristics of cat, dog, and rodent allergens show that they are carried on smaller (<10µm) airborne particulates, and in contrast to larger particulate sizes of dust mite and cockroach allergens, may remain suspended in the air for long periods of time (Chapman and Wood 2001; NAS 2000).

The major pet allergens identified and isolated to date include those from the domestic cat (*Felis domesticus*, Fel d 1) and dog (*Canis familiaris*, Can f 1 and Can f 2). The IOM Report found sufficient evidence for the role of cat and dog allergen in asthma exacerbation, but not for either allergen in terms of asthma development (NAS 2000). In studies of pet exposure in early life and asthma development, conflicting results have been observed (Chapman and Wood 2001). In some settings (e.g., where cockroach and dust mite allergen exposure is rare), pet allergens have been shown to be the dominant indoor allergens (Chapman and Wood 2001). A more recent meta-analysis of 32 studies that included relative risk analyses of exposure to cats, dogs, and other furry animals and subsequent asthma indicates that the pooled relative risk related to exposure to any furry animal was 1.39. The researchers concluded there might be a small preventive effect on asthma from cat exposure but a slight risk of asthma related to dog exposure (Takkouche et al. 2008).

Due to the adherent nature of cat and dog dander, these allergens may also be transported easily from room to room and deposited in high levels on walls and other surfaces within the home (Chapman and Wood 2001; NAS 2000). In addition to the traditional reservoirs in homes, research has also indicated that clothing can be a major source of inhaled cat and dog allergens (O'Meara and Tovey 2000). Although a number of studies have shown that the vast majority of homes contain cat and dog allergen even if a pet has never lived there (due to small particle size and ease of transport), levels of these allergens in homes are clearly highest in homes housing these animals (Chapman and Wood 2001). Therefore, occupant choice plays the primary role in determining indoor exposure to pet allergens.

Studies have shown that the relationship between exposure to cat allergen and the risk of sensitization does not follow the same pattern of increasing risk with an increase in exposure that has been reported for dust mite (as indicated by settled dust concentrations).

Many questions about cat exposure remain. For example, evidence has suggested that high-dose exposure to cat allergen early in life may produce a form of immunologic tolerance to cats, rather than cause sensitization (Kelly, Erwin, and Platts-Mills, 2012; Platts-Mills et al. 2000a and 2000b; Platts-Mills et al. 2001; Ronmark et al. 2003). Furthermore, it has been suggested that avoidance of cat allergens by removing the cat from the family home, especially within a community where many other cats are present (i.e., moderate ambient levels of cat allergen are present), might achieve the opposite of the intended effect for children in the early stages of immune system development (i.e., immunologic tolerance might have occurred at higher exposure levels; sensitization can occur at moderate levels) (Platts-Mills et al. 2000a and 2000b; Platts-Mills et al. 2001). However, the hypothesized protective effect of high-level cat allergen exposure may diminish when combined with certain genetic factors, such as maternal history of asthma (Celedon et al. 2002). Additional research is needed to better characterize the complex relationship between pet ownership and asthma. Specifically, intervention studies in which pets are removed from the home may help to determine the effect of animal removal on asthma development (Apter, 2003).

2.4 Rodent Allergens

The IOM Report found evidence of an association between exposure to rodents and asthma exacerbation from occupational exposure in a laboratory setting only (NAS 2000). In the analysis of NCICAS data, children

Since the IOM assessment, a subset of data from NCICAS has been analyzed and found a significant association between exposure to mouse (*Mus musculus*) allergen (Mus m 1) and asthma sensitization, particularly in inner city, multi-family dwellings (Phipatanakul 2000b).

whose homes had mouse allergen levels above the median (1.60 µg/g) in the kitchen had a significantly higher rate of mouse sensitization. Mouse allergens were also found to be widely distributed in inner-city homes, with 95% of all homes assessed having detectable mouse allergen in at least one room (Phipatanakul 2000a). Chew et al. (2003) observed that mouse allergen was common in low income, inner-city apartments, even where sightings were not reported. Higher mouse allergen levels have also been associated with evidence of cockroach infestation in any room (Phipatanakul 2000a). Recent evidence lends additional credence to the association between rodent allergen exposure and asthma. An investigation of inner-city homes found detectable levels of rat allergen in 33% of the dwellings assessed and observed significantly higher asthma morbidity in children sensitized to rats (Perry et al. 2003). Findley et al. (2003) also documented a strong association between the presence of rats or mice in the home and asthma, particularly among Puerto Rican residents.

Less is known about the effect of exposure to rodents and adult asthma. Sheehan et al. (2010), cites Phipatanakul's (2007) research in inner-city Boston showing women with mouse sensitization have twice the odds of an asthma diagnosis.

2.5 Molds

There are over 200 species of fungi, including those commonly called "mold," to which people are routinely exposed indoors and outdoors. Molds can obtain nutrients and moisture sufficient for growth from water-affected building materials such as wood, insulation materials, cellulose in the paper backing on drywall, and glues used to bond carpet to its backing, as well as furniture, clothing, and dust and dirt (CDC and HUD 2006).

Molds are thought to play a role in asthma in several ways. They are known to produce proteins that are potentially allergenic, and there is evidence of associations between fungal allergen exposure and asthma exacerbation. In addition, molds may play a role in asthma via release of irritants that increase potential for sensitization, or release of toxins that affect immune response (NAS 2000).

Mold exposure in homes primarily occurs as airborne spores and hyphal fragments, but molds are also present in household dust and on surfaces. Release of mold spores or fragments into indoor air is usually dependent on some sort of mechanical disturbance, although for some types of molds slight air movement may be sufficient (e.g., air movement by a fan), or spores may become airborne through natural spore discharge mechanisms. Most molds release spores ranging in size from 2 µm to 10 µm, although some may be released as chains or clumps of spores (NAS 2000). Green et al. (2003) found that germination of the spores releases greater quantities of allergen, and that more research needs to be conducted as to whether the clinical responses to allergen exposure were more related to the inhalation of spores or the hyphae that germinate after deposition in the respiratory tract.

In 2004, the IOM published a comprehensive review of the scientific literature on the relationship between damp or moldy indoor environments and the manifestation of adverse health effects, particularly respiratory and allergic symptoms (IOM, 2004). IOM found sufficient evidence of an association with symptoms of the upper respiratory tract (nasal and throat), asthma symptoms in sensitized asthmatic persons, hypersensitivity pneumonitis (inflammation in the lungs) in susceptible persons (i.e., persons with a family history of sensitivity), wheeze, and cough. They found limited or suggestive evidence of an association with lower respiratory illness in otherwise healthy children. However, the Institute did not find sufficient evidence of a *causal* relationship with any health outcomes, and they concluded that evidence was inadequate or insufficient

to determine an association with many health effects, including asthma development, dyspnea (shortness of breath), airflow obstruction (in otherwise healthy persons), mucous membrane irritation syndrome, chronic obstructive pulmonary disease, lower respiratory illness in otherwise healthy adults, and acute idiopathic pulmonary hemorrhage in infants. These conclusions are not applicable to immuno-compromised persons, who are at increased risk for fungal colonization or opportunistic infections.

More recent research continues to show mixed results. Research conducted in New Orleans following hurricane Katrina (Rabito et al. 2010) found no evidence that extensive exposure to mold and moisture was associated with increased sensitivity to mold allergens. These results did not change when asthma status was added to the analysis. Moreover, the Children's Respiratory Health Study to examine the respiratory health of children aged seven to fourteen in a sample of children who returned to New Orleans immediately after Katrina found that there was no increase in respiratory symptoms at baseline or two months after return to their homes (Rabito et al. 2008).

Based on a more definitive longitudinal study design, Reponen et al. (2011) reported that children at age one living in a home with extensive mold, as assessed by a DNA-based analysis for the 36 molds that make up the Environmental Relative Moldiness Index (ERMI), had more than twice the risk of developing asthma by age seven than those in low ERMI value homes (adjusted odds ratio [aOR], 2.6; 95% confidence interval [CI], 1.10–6.26). Also, a meta-analysis of 16 published studies found statistically significant associations between asthma development and measures of home dampness, visible mold, and mold odor (Quansah et al. 2012).

The primary factor affecting fungal growth in homes is moisture level. In general, most molds require fairly wet conditions (near saturation), lasting for many days, to extensively colonize an environment (NAS 2000). Some of the major mold allergens identified and isolated to date include those from *Aspergillus fumigatus* (Asp f 1, 2, 6, and 12), Alternaria alternata (Alt a 1, 2, 3, 6, 7, and 10), and *Cladosporium herbarum* (Cla h 1, 2, and 3), as well as others such as *Aspergillus oryzae, Penicillium citrinum, Penicillium chrysogenum, Trichophyton tonsurans, Malassezia furfur*, and *Psilocybe cubensis* (NAS 2000). NHANES III data estimated 12% of the general population (Arbes et al. 2005) were sensitized to Alternaria; 15–50% of those who are genetically susceptible (atopic) are sensitized to mold allergens (NAS 2000). The clearest association between mold exposure and asthma is sensitization to *Alternaria*, although this may be because the allergens of this genus (Alt a 1 and Alt a 2) are well characterized relative to other mold species, thus allowing this association to be more easily established (NAS, 2000). NCICAS skin test results of 1,286 children with asthma showed that the most common positive allergen sensitivity was to *Alternaria* (38%) (Eggleston et al. 1999a; Kattan et al. 1997). Data from NSLAH suggest that higher levels of *A. alternaria* in vacuumed dust samples collected from a bed, sofa, or chair and on bedroom, living room and kitchen floors increased the odds of having asthma symptoms in the past year (Salo et al. 2006).

For further information on mold, see the HUD background paper, "Healthy Homes Issues: Mold."

Features of houses that can increase moisture levels and fungal growth include being on the ground floor level, poor ventilation, excess production of water in the house (e.g., humidifiers, unvented cooking), and water leakage or flooding.

Some of the most abundant fungi genera found in homes without severe water damage include: *Alternaria, Cladosporium, Penicillium*, yeasts, and *Aspergillus* (Burge and Otten 1999; American Academy of Pediatrics 1998; Bush and Portnoy 2001; Gravesen 1999). Most of these molds do not typically produce toxins (mycotoxins) (Etzel 2000), but may be important as sources of mold irritants or allergens. In contrast, under wet conditions (i.e., in the presence of water-soaked cellulosic materials), toxin producing molds (e.g., *Stachybotrys chartarum*) may be prominent (Flannigan 1997). The role of *Stachybotrys* in asthma is not known.

2.6 Endotoxins

In residential indoor environments, bacterial endotoxins, cell wall components of gram-negative bacteria (GNB), contribute to asthma through increased airway inflammation. Rabito et al. (2010) suggest that the numerous reports of adverse respiratory health effects post-Katrina may be associated with non-allergic responses to mold exposure. Sordillo et al. (2011 and 2010) found that GNB biomarkers are predicted by home characteristics such as dampness and presence of dogs and cats. They reported that later childhood exposure to GNB may be associated with an independent protective effect against asthma. However, this linkage is difficult to study, since an individual's personal endotoxin exposure reflects not only the house dust exposure but also ambient levels of pollution, geographic region, and seasonal weather conditions, as well as other environments to which he/she is exposed such as day care (Delfino, Stiamer, and Tjoa 2011; Maier et. al, 2010). Moreover, the home airborne exposure concentration may not be reliably predicted by the dustborne concentrations (Singh et al. 2011).

2.7 Indoor Chemical Air Pollutants

Although the body of evidence regarding respiratory symptoms and exposure to chemical agents is primarily based on data from occupational settings with much higher level exposures than those found in residential settings, research has suggested indoor exposure to ETS, formaldehyde and certain other volatile organic compounds (VOCs), phthalates (found in many plastics), some household products such as pesticides, and various combustion products (nitrogen oxides, sulfur oxides, carbon monoxide (CO) can be related to asthmatic symptoms in susceptible individuals (Mendell 2007; Becher et al. 1996; Garrett et al. 1999; Bornehag et al. 2004).

In the IOM review of the available literature (NAS 2000), no indoor chemical exposures were conclusively linked with asthma development, but ETS and other chemicals were associated with asthma symptomology. Sufficient evidence was found to support an association between high level exposures to nitrogen dioxide and asthma exacerbation, and limited

The IOM found sufficient evidence of a causal relationship between environmental tobacco smoke (ETS) exposure and asthma exacerbation. ETS exposure was also found to be associated with asthma development in preschool aged children, and limited evidence of an association was observed between ETS exposure and asthma exacerbation in adults and older children. The relationship is now further supported in the 2006 Surgeon General's report on involuntary exposure to tobacco smoke (USDHHS 2006).

evidence was found of an association between formaldehyde and fragrance exposures and asthma exacerbation. Inadequate or insufficient evidence was available for determination of the exact role of other indoor pollutants, such as pesticides and VOCs in asthma exacerbation or development (NAS 2000).

Since the IOM report was published, Hulin et al. (2010) conducted a case controlled comparison of asthmatics and non-asthmatics in a rural and a city environment. In the entire population, they found exposure to acetaldehyde and toluene significantly associated with a higher risk of asthma. In the urban population, the association with toluene was significant in children studied during winter, and with toluene, xylenes, and ethylbenzene when cases were restricted to current asthmatics. In rural settings, a relationship between asthma and formaldehyde exposure was observed (OR=10.7; 95% CI 1.69–67.61). The researchers suggest that daily continuous exposures to pollutants may be implicated in asthma, even in the case of low exposure, as those found in rural areas.

Common indoor sources of formaldehyde include particle board, plywood, paneling, certain types of foam insulation, and some carpets and furniture (Garrett et al. 1999).

McGwin et al. (2010) reviewed seven peer-reviewed studies on the relationship between formaldehyde exposure and asthma in children. They found an Odds Ratio of 1.17 per 10-μg/m^3 increase in formaldehyde and suggest that when compared with individuals with no formaldehyde

exposure, those with the highest levels of exposure reported in the seven studies (i.e., 80 µg/m^3) would have had 3.5-times higher odds of asthma. A strong relationship has also been found between formaldehyde concentration and exacerbation of wheezing illness in a U.K. study (Venn et al. 2003).

Nitrogen oxide and particulates have been the subject of intensive research since the IOM study. McCormack et al. (2011) found that both fine and coarse particulate levels were associated with increased asthmatic symptoms in both atopic and non-atopic children McCormack et al. (2009) found that particulate exposure in the home, especially $PM_{2.5–10}$ and $PM_{2.5}$, were associated with increased respiratory symptoms and rescue medication use in preschool Baltimore asthmatic children, while increased in-home and ambient PM levels were associated with exercise-induced asthma.. High-level, short-term exposure to nitrogen dioxide, which occurs as a result of poorly ventilated kitchens or the use of a gas appliance for heating purposes, may be particularly detrimental to asthmatic individuals (NAS 2000). A cross-sectional analysis of data from the Third National Health and Nutrition Examination Survey (NHANES III) found a significant association between doctor-diagnosed asthma and the use of a gas oven or stove for heat (Lanphear et al. 2001). Hansel et al. (2008) found that even when adjusting for the effect of other indoor air pollutants, each 20 ppb increase in NO_2 was significantly associated with an increase in the number of days on limited speech, cough, and nocturnal symptoms.

The primary sources of nitrogen and sulfur oxides, CO, VOCs, and particulates include tobacco smoke, vehicle start-up and idling in attached garages, and combustion appliances that are either unvented or that have improperly installed or malfunctioning ventilation.

Swedish researchers have reported an association between asthma and allergies in children and concentrations of n-butyl benzyl phthalate (BBzP) and di (2-ethylhexyl) phthalate (DEHP) in dust collected from the children's bedrooms (Bornehag et al. 2004).

Phthalates are widely used as plasticizers in polyvinyl chloride (PVC) flooring, wall materials, vinyl tile and vinyl toys (Bornehag et. al. 2005).

The same researchers have found associations between dust concentrations of those two phthalates and the amount of PVC used as flooring and wall material in the home. High concentrations of BBzP were associated with reported water leakage in the home, and high concentrations of DEHP were associated with buildings constructed before 1960 (Bornehag et al. 2005). Larsson et al. (2010), using data from the Swedish Dampness in Buildings and Health study (DBH), examined the relationship between exposure to PVC flooring in the rooms of children ages one to three and their parents, and asthma five years later. Adjusted analyses showed that the incidence of asthma among children was associated with PVC-flooring in the child's bedroom, but these data were of borderline statistical significance. There was also a positive relationship between the number of rooms with PVC-flooring and the cumulative incidence of asthma, and a greater risk factor for incident asthma in multifamily homes and in smoking families. The researchers note that earlier results from the DBH study showed that PVC-flooring is one important source for phthalates in indoor dust, and exposure to such phthalates was found to be associated with asthma and allergy among children.

Although there is currently no conclusive evidence of a link to indoor exposure to pesticides and exacerbation of childhood asthma, limited evidence does exist for a link between pesticide exposure and asthma in adults in occupational settings (Etzel 1995). Pesticides may be of particular concern in low-income, inner-city areas, where conditions favor pest infestation. For example, Whyatt et al. (2002) found that 85% of pregnant women in minority communities reported the use of insecticidesduring pregnancy.

For further information on Pesticides, see the HUD background paper, "Healthy Homes Issues: Pesticides."

Researchers in California found a link between herbicides and childhood asthma (Salam et al. 2004). While rarely an indoor source, herbicides may be an environmental factor affecting homes in some communities just as vehicle exhaust is in others.

2.7.1 Ambient Nano/Ultra Fine particles (UFP)—Extent and Nature

Various activities around the home, such as gas or electric stove cooking, smoking cigarettes, burning candles etc., and household electronic devices such as vented gas clothes dryer, air popcorn popper, electric mixers, toasters, hair dryers, curling irons, steam irons etc generate nano-particles or ultra-fine particles (UFP). UFP concentrations within the home may further be increased through infiltration from outdoor sources such as traffic-related fuel combustion if the home is located close to a major highway (Lwebuga-Mukasa 2004 and 2005; Buzea 2007; Brugge 2007; Wallace and Ott 2011). Using electric and gas burners during cooking hours increases UFPs levels up to ten times compared to non-cooking hours. Once generated, they may stay suspended in ambient air for three or more hours (Buzea, 2007; Lwebuga-Mukasa, 2009). Examples of UFPs found in the residential environment are textile fibers, skin particles, spores, dust mite droppings, chemicals and smoke (Buzea 2007). The potency of UFPs is basically due to their smallness, normally between 10–700 nm in diameter, thus having a large surface area even at low mass concentrations. They are polydispersed, soluble or poorly soluble, have high pulmonary system deposition ability, able to evade destruction (through macrophage phagocytosis) and stick to the airway walls of the lungs when inhaled (Chalupa 2004; Frampton 2004; Peters 2005; Lubick 2009; Li 2010; Win-Shwe 2011). They also have the ability to transport large amounts of redox-active organic chemicals to their deposition sites, which induce pulmonary inflammation or oxidative stress in the lungs (Chalupa 2004; Lubick 2009; Li 2010). Several studies have associated UFPs with asthma and airway inflammations (Buzea 2007; Mühlfeld 2008; Lwebuga-Mukasa 2009; Yarris 2010; Li 2010).

Chalupa et al. (2004) in their studies showed that UFP deposition in lungs was greater than larger particulate matter and the quantity retained in the lungs were higher in asthmatic than non-asthmatic subjects, thus contributing to airway inflammations. Lwebuga-Mukasa et al. (2005) in investigating the role of home environmental and local ecological factors in the prevalence of asthma in Buffalo, NY neighborhoods monitored UFPs and showed that asthma prevalence in the west side was influenced by UFP concentrations mostly from traffic-related fossil-fuel combustion. A study by Brugge et al. (2007) on near-highway pollutants in motor vehicle exhaust and cardiac and pulmonary health risks of area residents concluded that there is elevated risk for the development of asthma and lung function reduction in children. In their study of the impacts of ambient UFP on traffic-related asthma flares from a Los Angeles, CA highway, Li et al. (2010) found out that UFP provides a strong adjuvant effect in secondary immune response, thus ambient UFPs heightens allergic inflammation in asthmatics. Another study by researchers at Lawrence Berkeley National Laboratory (CA) showed that ozone reacts with nicotine to create a UFP, which is more potent than nicotine and can cause more serious problems for asthmatics than nicotine (Yarris, 2010).

3.0 Methods of Assessing Asthma Triggers in the Home

The level of rigor involved in assessing asthma triggers in a research setting surpasses what is needed for programmatic or public health use, and is generally not required for home intervention programs. From a housing or public health perspective, a home assessment is generally constrained by the need for cost-effective methods that are sufficient to allow for the identification of a substance that may be at levels of concern in the home environment.

While most of the discussion in this section focuses on quantitative methods, other methods such as lower cost visual inspection

> The HUD background paper, "Healthy Homes Issues: Residential Assessment," contains a lengthy discussion of environmental sampling and analysis of air, settled dust and bulk building materials.

A pooled analysis of nine asthma studies found that that a number of housing conditions are consistently associated with increased allergen dust concentrations and concluded that screening for housing-based asthma triggers should include presence of cats, dogs, cockroaches, or rodents; water leaks; mold or mold odor; holes or cracks in walls; and below average housekeeping. Single family houses that have basements or crawl spaces or are built before 1951 are also important predictors for increased dust mite allergen levels (Wilson et al. 2010).

or questionnaires or checklists can also provide a qualitative assessment of the potential asthma hazard in a home. Visual measures such as dampness, visible mold growth, signs of cockroach or rodent activity, the presence of pets, the presence and condition of upholstery and carpets, the presence of sources of CO or VOCs, and general cleanliness, can all be used to identify particularly obvious sources of potential triggers. This section summarizes information from the HUD background paper, "Healthy Homes Issues: Residential Assessment" focused on environmental data collected to assess allergen hazards. Quantitative assessment of indoor allergens typically involves air and/or settled dust sampling in the home. Following extraction in the laboratory, the allergen levels in that sample can be directly measured through lab methods such as immunoassays. Levels of the allergen source material may also be estimated via some other marker, such as by estimating the total fungal biomass from (1→3) ß-d-glucan analysis.

In the absence of an independent visual assessment, caregiver self-report of the presence of pests and pets can be predictive of clinically meaningful levels of Bla g 1, Mus m 1, Can f 1, and Fel d 1 in settled dust. However, parent self-report of the absence of pests are not predictive of low levels of these allergens (Curtin-Brosnan et al. 2008).

A program evaluation found that most HUD Healthy Homes grantees (83%) routinely conducted multiple assessments or interviews of clients. These assessments/interviews often focused on behavioral information (e.g., smoking or cleaning habits), health data (e.g., asthma symptoms), household/ resident/ family characteristics, or client's knowledge of the focus area. The most commonly collected health data included information reported by the family on asthma, emergency room visits, doctor visits, and health-related absences from school or work (HUD 2007). HUD's 2007 evaluation of its Healthy Homes grantees found that 81% of grantees conducted visual assessments of the housing unit. The majority (94%) used a standardized assessment tool to conduct the assessment and conducted at least two or more assessments. The five most frequently reported hazards assessed included the presence of visible mold and moisture problems, pest infestation; lead hazards; fire hazards; and carbon monoxide hazards.

Examples of commonly-used assessment tools that combine visual assessment and interviews are included in Table 2 (HUD, *Healthy Homes Program Guidance Manual*, 2012). Also included are questionnaires related to improved asthma control.

3.1 Allergen Sampling and Analysis

3.1.1 Allergen Sampling

Depending on dust-disturbing activity, only a very small amount is usually airborne at a given time (with the exception of cat and other animal allergens, which may also have relatively high airborne levels). The primary route of exposure to allergens is presumed to be inhalation of airborne particles. Settled dust may contribute to airborne levels through re-suspension of settled dust particulate. Settled dust sampling is much simpler and less expensive than air sampling; therefore, settled dust sample results

Indoor environments may contain large reservoirs of allergens in settled dust accumulated in carpets, bedding, and upholstery. Reservoir levels are more reflective of an integrated chronic exposure rather than being markers for short-term exposures. Therefore, environmental allergen assessment primarily involves measuring allergen levels in dust samples obtained from reservoir sources within the house.

Table 2. Comparison of Leading Healthy Housing Assessment Tools

Tool Name	Link or Source	Comprehensiveness/Topics (see key below)	Validation/ Used in Published Evaluation	Practicality and Ease of Adaptation	Burden
Childhood Asthma Control Test—Measure of asthma control of children 4–12 years of age	http://download.journals.elsevierhealth.com/pdfs/journals/ 0091-6749/PIIS 0091674907001674.pdf	Medium AS	Validated	Medium	Low
Asthma Core Caregiver Survey—Allies Against Asthma	http://asthma.umich.edu/mediaeval_autogen/core_caregiver.pdf	Medium AS	Uses Juniper plus other questions	Medium	Low
EPA Asthma Home Environmental Checklist	http://www.epa.gov/asthma/pdfs/home_environment_checklist.pdf	Medium MM, PA,OP	No	High	Low
Seattle-King County HomeBASE	http://www.kingcounty.gov/healthservices/health/chronic/asthma/homebase/questionnaires.aspx	High AS, HC, IS, MM, PA, OP, TC	Evaluation published (prev. edition)	Medium	Medium
Cuyahoga County Mold and Moisture Project: Visual Assessment and Testing	http://www.ehw.org/Healthy_House/HH_VAT.pdf	High HC, MM, PA, OP, TC	Evaluation published	High	Medium
Home Moisture Audit	http://www.ehw.org/Healthy_House/HH_Moist_Audit.htm	Medium MM	No	Medium	Medium
Allergen Trigger Screening Questions—NCHH	National Center for Healthy Housing http://www.nchh.org	Low HC, MM, PA	Evaluation publication pending	High	Low
Assessment Questions for Environmental and Other Factors that can Make Asthma Worse—NIH	http://www.nhlbi.nih.gov/guidelines/asthma/06_sec3_comp3.pdf (Figure 3-17)	Low MM, PA, OP	No	High	Low
Community Environmental Health Resource Center	http://www.cehrc.org/res/res_cehrc.htm	Medium HC, MM, OP, PA	Evaluation publication pending	High	Low
Pediatric Environmental Health Assessment	http://www.healthyhomestraining.org/Nurse/PEHA_Start.htm	Medium HC, IS, MM, OP, PA, TC	No	High	Low
British Healthy Housing Rating System	http://www.communities.gov.uk/documents/housing/pdf/propertyquestionnairegeneral.pdf	Medium HC, MM	No	Medium (May only be applicable to UK Housing)	--
LARES	http://www.euro.who.int/Housing/LARES/20080506_3	High AS, GH, HC, IS, MM, PA, TC	Evaluation published	Low (May only be applicable to European housing)	--

Survey Topic Key: AS: Asthma Symptoms and Health Effects; GH: General Health; HC: Housing Conditions—General; IS: Injury/Safety Conditions; MM: Mold/Moisture; OP: Other Pollutants/Irritants; PA: Pests/Animals; and TC: Temperature/Comfort

Table 3. Overview of Assessment Strategy Options for Selected Residential Asthma Triggers

Residential Trigger	Assessment Strategy					
	Sampling		Analysis		Test Applicability	
	Method	Reliability	Method (units)	Quality assurance	Important Species	Data Obtained
Allergens: dust mite, cockroach, pet, rodent	Dust sampling by vacuum	Spatially and temporally variable; most cockroach and mite allergens in settled dust	ELISA (µg/g) (Units/g for Bla g2)	Accurate quantitation, sensitive; each species must be analyzed separately	*Dermatophagoides species; Blomia tropicalis; blatella germanica; periplaneta americana; Felis domesticus, Canis familiaris, Mus musculus; rattus norveticus*	Allergen levels: • Dust mite:Group 1 (Der p 1 & Der f 1) and Group 2 (Der p 2 and Der f 2); Blo t 5 • Cockroach: Bla g1 & Bla g2 • Cat: Fel d1 • Dog: Can f1 • Mouse: Mus m1 • Rat: Rat n1
			MARIA (µg/g) (units/g for Bla g2)	More accurate, precise and better sensitivity over ELISA; can analyze multiple species simultaneously	*Dermatophagoides species; blatella germanica; Felis domesticus, Canis familiaris, Mus musculus, rattus norveticus*	Allergen levels: Der p1, Der f1, Mite Group 2, Fel d1, Can f1, Rat n1, Mus m1, Bla g2
	Air sampling with static or personal sampler	Spatially and temporally variable; air levels variable with disturbance; high levels of pet and rodent allergen airborne	ELISA (pg/m3) (units/m3 for Bla g2)	Accurate quantitation, sensitive	*Dermatophagoides species; Blomia tropicalis; blatella germanica; periplaneta americana; Felis domesticus, Canis familiaris, Mus musculus, rattus norveticus*	Allergen levels: • Dust mite:Group 1 (Der p 1 & Der f 1) and Group 2 (Der p 2 and Der f 2); Blo t 5 • Cockroach: Bla g1 & Bla g2 • Cat: Fel d1 • Dog: Can f1 • Mouse: Mus m1 • Rat: Rat n1
	Dust or air (sampled as above)	See above	Particle immunostaining	Extremely sensitive	*D. pteronyssinus; Blatella germanica; Canis familiaris and Felis domesticus*	Allergen levels (Der p 1; Der p 2; Bla g 1; Can f 1; Fel d 1

Residential Trigger	Assessment Strategy					
	Sampling		Analysis		Test Applicability	
	Method	Reliability	Method (units)	Quality assurance	Important Species	Data Obtained
Cockroach allergens	Trapping		Cockroach counts		Nonselective	Estimates of cockroach population
Mold Allergens and Surrogate Mold Measures	Dust or surface sampling by vacuum, surface wipe, swab, or tape Bulk sampling of contaminated materials Air sampling with static or personal sampler *Also see Table 4 for additional pros/cons of the various types of mold sampling/assessment strategies	Spatially and temporally variable; air levels variable with disturbance	ELISA 3 (µg/g) or pg/m3)	Not currently reliable for fungi (e.g., Alternaria counts must be very high)	*Aspergillus fumigatus, Aspergillus versicolor, Stachybotris chartarum, Alternaria alternata*	Allergen levels: (Asp f 1, AveX, SchX, SchY, Alt a 1
			Spore Count	Intact spores may not account for total allergen load	All (*Aspergillus and Penicillium* species difficult to identify)	Concentration of spores; spore identification
			Culture	Viable fungi may not account for total allergen load	All (may miss poorly competing species of low viability, e.g. Stachybotrys chartarum.)	Species identification; Estimates of fungal concentrations
			Chemical biomarkers (ergosterol, beta-D-glucan, mycotoxins, VOCs)	Good indicators of total biomass; cannot identify species	Not species specific: Components in all fungal hyphae and spores (as well as some algae and yeasts) Beta d-glucan is biologically active	Concentration of chemical biomarker; Estimates of fungal biomass
			Polymerase chain reaction (PCR) based technologies (i.e., genetic probes)	Accurate: Based on targeting species-specific sequences of DNA for the 130 species for which probes have been developed	Species specific, including but not limited to: *Alternaria, Aspergillus, Cladosporium and Penicillium*	Mold identification to the species level
			Particle immunostaining	Extremely sensitive	*Alternaria*	Allergen levels

are often used as a surrogate of exposure, although studies are underway to determine which metric is most predictive. HUD currently has two studies underway that examine which rooms and which sampling methods within those rooms are most predictive of asthma clinical status in children (Sandel et al. 2011a and b, unpublished manuscripts) Bedroom concentrations and/or loadings are sometimes used as markers of allergen exposure because activity pattern analyses indicate that bedroom areas are where the majority of exposure usually occurs (NAS 2000).

Factors to be considered when collecting settled dust allergen samples include:

- **Repeated sampling of dust over time:** Gives better information on long-term exposures and helps account for seasonal variation but is expensive. Season is expected to have a much lower impact on allergen concentrations than other factors such as type of building and region (e.g., urban vs. rural).
- **Sampling locations with the highest expected allergen levels:** Allergen dust concentrations can vary significantly over short distances; therefore, it is important to choose areas where levels are expected to be highest.
- **Concentration versus loading:** Results are typically expressed as concentration (units of weight of substance per weight of dust) or loading (units of weight of substance per unit of area sampled). If the surface area is measured, it is possible to derive both concentration and loading from the same sample.

Dust samples are usually collected using a vacuum device. A hand-held portable electric-powered vacuum cleaner with a dust collection device (e.g., filter, sleeve, or thimble) is recommended. Another type of dust vacuum sampling device is the High Volume Surface Sampler (HVS3 and HVS4) developed by Envirometrics for EPA to collect surface dust for measurement of lead, pesticides, allergens, and other contaminants. HUD's Healthy Homes Issues: Residential Assessment, discusses in detail the pros and cons of various dust sampling methods and equipment, and various factors (e.g., design of the vacuum device, characteristics of the surface sampled (e.g., carpet vs. smooth floor, type of carpet),

HUD has developed a recommended "Vacuum Dust Sample Collection Protocol for Allergens" for use by HUD Healthy Homes Initiative grantees (HUD 2008). The protocol is adapted from sampling methods used in NSLAH and the Inner-City Asthma Study, and it is supported by a companion HUD document, "Background and Justification for a Vacuum Sampling Protocol for Allergens in Household Dust" (HUD 2004).

and other environmental characteristics (e.g., relative humidity) that may affect the efficiency of vacuum dust collection The Residential Assessment document also discusses the feasibility of having subjects collect their own home dust samples.

For investigations of mold contamination in homes, source sampling methods, including bulk, air and surface sampling, may also be used. In bulk sampling techniques, portions of environmental materials (e.g., settled dust, sections of wallboard, pieces of duct lining, carpet segments, or return air filters) are collected and tested to determine if mold has colonized a material and are actively growing, and to identify surface areas where previously airborne mold spores and fragments have settled and accumulated (Martyny et al. 1999). Simple surface sampling techniques, accomplished by either pressing a collection material (e.g., a contact plate or adhesive tape) against a surface, or by wiping an area with a wetted swab, cloth, or filter, may also be used in mold contamination investigations (Martyny et al. 1999).

The pros and cons of collecting air samples versus settled dust samples for allergens are summarized in Table 4.

General considerations for air sampling are summarized below and discussed in detail in HUD's "Healthy Homes Issues: Residential Assessment:"

- **Active sampling.** Active sampling, in which a pump pulls contaminated air into the sampling device (e.g., filter) for a fixed amount of time and known flow rate, is most likely to achieve the best detection limits. Although more expensive than passive sampling, active

Table 4. Pros and Cons of Settled Dust versus Air Sampling for Allergens

Sampling method	Pros	Cons
Settled dust sampling	• Better indicator of time-integrated exposure. Less temporally variable. • Better indicator of exposure to easily settled house dust mite and cockroach allergens. Relatively fast, easy, inexpensive sample collection.	• May be poor indicator of short-term exposures. • Inhalation is primary exposure mechanism so may not be best indicator of actual exposure.
Air Sampling	• Captures inhalable particles. Better indicator of short-term exposure. • Allows fluctuations in exposure to be assessed over a week or a day. • Possibly better indicator of exposure to animal allergens, because smaller particles remain airborne relatively long. • May be useful if ventilation system contamination is suspected.	• Airborne concentrations for many allergens are generally low, analytical sensitivity is problematic. • Allergen levels in air vary with activity/disturbance. • To assess long-term exposure, large number of samples must be collected. • Sample collection may be relatively slow, complex, and expensive. • May provide poor representation of exposure to house dust mite and cockroach allergens, because particles tend to remain airborne for relatively short time periods.

methods are most likely to yield samples with enough mass to allow reliable lab analysis (Lippmann 2009). For airborne particulates, collection media may run through impactors or cyclones that select particle sizes that reach the filter. For gases and vapors, dry collection media, such as carbon, silica gel, or other adsorptive surfaces are far more common than liquid-based samplers (e.g., impingers) (Lippmann 2009). Both high-volume (60 to 1100 L/min) and low-volume (4 to 20 L/min) filter samplers can be used, although low-volume samplers may better approximate breathing volumes of humans and thus better represent exposure.

- **Passive Sampling.** Passive static samplers, normally kept in a fixed location, rely on particle deposition to collect contaminants on a filter or settling plate. Passive methods are more commonly used for gases and vapors than for particulate and need longer sampling times than active sampling to obtain enough mass. Settling techniques are non-volumetric and, due to large temporal and spatial variations, may not necessarily be readily compared to one another or to active samples (Martyny 1999; O'Meara and Tovey 2000).
- **Air Sampling Location.** Air samples are collected from either fixed locations in a home or from the breathing zone of a person wearing the sampler. Fixed location samplers provide a less accurate measure of personal exposure. Breathing zone samplers often yield higher levels of collected allergens than static samplers, likely due to the varying levels of dust that are re-suspended in the personal

breathing zone as a result of human activity; however, only minor differences are observed during high levels of dust disturbance (O'Meara and Tovey 2000).

3.1.2 Endotoxin Sampling

Endotoxin aerosols are ordinarily collected on filter media because they are easy to use and allow long sampling times. Dust samples are collected using a vacuum cleaner equipped with a special nozzle to collect dust on a paper filter; then gravimetric measurements and endotoxin extractions are performed. Both floor and mattress samples are common (Douwes et al. 1998). Collection with all-glass impingers has also been reported, but this method may underestimate endotoxin levels. More information on the characteristics and health effects of endotoxins, as well as filter type, handling, and storage suggestions for sample collection, can be found in Martyny et al. (1999).

3.1.3. Methods for Identifying Mold Levels

Direct observation of visible fungal growth is usually sufficient to warrant a recommendation for mitigation, and current guidance generally discourages collecting and analysis of environmental samples for mold in most situations (USEPA 2001b; CDC 2005) due to high analysis costs, wide spatial and temporal variability in mold sampling results. HUD (2011) does not recommend mold sampling because a visual examination and odor detection is usually adequate to determine a mold problem. For example, in their study of bacterial and fungal distribution in 15 US homes, Nasir and Colbeck (2010) found a wide variation in total concentration and size of bioaerosols in different residential settings, due to variable airborne behavior and resulting in different estimates of respiratory exposure risk. Air sampling may sometimes be used if the source of mold contamination is not visible.

Testing procedures do exist to determine the species of mold that are present in a house, yet most healthy homes programs and others involved in mold remediation have come to the conclusion that such speciation does not yield the kind of information needed to determine remediation (AIHA 2008). Similarly, measuring the mold spore concentrations in air is generally not recommended by HUD because results can be very variable and difficult to interpret. The HUD *Healthy Homes Issues: Mold* background paper contains a detailed discussion of mold sampling and analysis options that may be conducted (1) as part of research studies (i.e., for documentation purposes and to record the types of fungi that predominate (Burge and Otten 1999)), (2) when needed to identify the source of mold, or (3) to support litigation.

3.2 Allergen and Endotoxin Analysis

Various analytical methods for allergen analysis are summarized in Table 5. The reader is referred to HUD's "Healthy Homes Issues: Residential Assessment," which contains a detailed discussion of the immunoassay and particle immunostaining methods used to analyze allergen samples. There are two primary methods to measure allergen levels: enzyme-linked immunosorbent assays (ELISAs) and fluorescent multiplex array for indoor allergens (MARIA). Immunoassays generally provide very accurate quantification (Chapman et al. 2000); however, although immunoassays for numerous dust, animal, and mold allergens have been developed, only relatively few are readily available from commercial laboratories (see allergens listed in Table 5). Immunoassay technology for molds is not as highly developed as that for house dust mite, animal, or cockroach allergens (Bush and Portnoy 2001), with standard for only a few mold allergens available. There are limited external QA/QC programs to assess laboratory performance at this time. The pros and cons of ELISA versus MARIA analysis methods are provided in HUD's "Healthy Homes Issues: Residential Assessment" and are summarized below:

- ELISA methods have been widely used in large national studies such as NSLAH and Inner City Asthma Study; therefore, more comparable ELISA-based data are available across published studies than MARIA-based data available across published studies.
- ELISA requires a separate test for each allergen in a sample and is therefore more labor-intensive, time-consuming, and expensive than MARIA analyses, which combine multiple analytes into a single lab test.

Table 5. Threshold Levels Routinely Used as Comparison Values for Residential Allergens

Allergen	Threshold Level		Typical Sample Characteristics
	Allergic Sensitization	Asthma Exacerbation	
Dust mite allergen Der f 1 + Der p 1	2 µg/g[a]	10 µg/g[a]	**Collection:** Dust, by vacuuming (bed and bedroom) **Analysis:** ELISA assay (µg/g) or dust mite count
Cockroach allergen Bla g 1	2 Units/g[b]	8 Units/g[b]	**Collection:** Dust, by vacuuming (bedroom, kitchen, bathroom); trapping **Analysis:** ELISA assay (Units/g) or cockroach identification and counts
Cockroach allergen Bla g 2	0.2 µg/g[c]	0.4 µg/g[c]	Conversion of Bla g 1 values from Units/g to µg/g
Cat (Fel d 1)	1 µg/g[d]	8.0 µg/g[d]	**Collection:** Dust, by vacuuming (living room floor and furniture); air sampling **Analysis:** ELISA assay (µg/g)
Dog (Can f 1)	2 µg/g[d]	10 µg/g[d]	**Collection:** Dust, by vacuuming (living room floor and furniture); air sampling **Analysis:** ELISA assay (µg/g)
Mouse (Mus m 1)	1.6 µg/g[d]	--	**Collection:** Dust, by vacuuming (whole house); air sampling **Analysis:** ELISA assay (µg/g)
Fungal allergen	No allergen specific thresholds		**Collection:** Air sampling; surface sampling **Analysis:** Spore counts, culturable fungi, total biomass/biomarker

[a] *Eggleston and Bush 2001.*

[b] *Eggleston and Arruda 2001.*

[c] *Indoor Biotechnologies 2009.*

[d] *Cat and dog threshold levels used by Ingram et al. (1995) and Custovic et al. (1998b). Mouse levels based on Phipatanakul et al. (2000b).*

- More laboratories across the country are currently capable of running ELISA tests than MARIA; however, for both ELISA and MARIA, few standard protocols exist to ensure consistent analysis both within and across labs. There is a need for validation of assays for allergen measurements.
- When allergen concentration values obtained using individual ELISA allergen standards were compared with those obtained using the MARIA 5-plex or the 8-plex, considerable differences were found, meaning that allergen data generated using different standards are not directly comparable and must be corrected for known differences between the standards. This problem and its solution are discussed in detail in HUD's Healthy Homes Issue: Residential Assessment.

Particle immunostaining, a rarer allergen analysis method, involves a protein-binding membrane, immunostaining of bound allergens, and examination of stained samples under a microscope where the density of staining is determined using image analysis (O'Meara and Tovey, 2000). This technique has been used in research settings to measure airborne dust mite (Der p 1 and Der p 2), cockroach (Bla g 1), cat (Fel d 1), dog (Can f 1) and *Alternaria* allergens in undisturbed indoor environments (Poulos et al. 1998; De Lucca et al. 1998; Tovey et al. 1998; and O'Meara et al. 1998, as cited in O'Meara and Tovey 2000). It is extremely sensitive (on the order of sub picograms of allergen) and appears to have high repeatability in combination with nasal air samples (O'Meara and Tovey 2000).

Endotoxin analysis uses a kinetic limulus assay (specifically, a Limulus amebocyte lysate assay). Endotoxin levels are expressed as either concentration (units per gram of house dust) or loading (units per square meter of surface area) (Braun-Fahrlander 2002). Douwes et al. (1998) found that the highest endotoxin levels were detected on living room floors, while the lowest levels were found for mattresses, when results were expressed as concentration or loading. More information on limulus amebocyte lysate (LAL) assays and sample analysis (quantitative LAL assays, parallel-line LAL assays, interferences with LAL assays, and variability in LAL reagents) can be found in Martyny et al. 1999.

3.3 Interpretation of Results

The challenge in interpreting results from visual assessment and occupant surveys or from environmental sampling is twofold: first, determining the degree to which the results indicate potential for human exposure and subsequent health effects, and second, determining the relative severity of different individual hazards. An extensive discussion of the factors associated with exposure and risk for asthma associated with residential exposures is beyond the scope of this paper.

3.3.1 Comparison Values for Allergens

Comparison values exist to suggest a level of potential hazard posed by allergen sampling results. These comparison values are estimated threshold settled dust concentration levels for (1) the level representing a risk of becoming sensitized to an allergen (allergic sensitization) and (2) the level at which asthmatic individuals may begin to experience symptoms (asthma exacerbation) (see Table 5).

3.3.2. Comparison values for Particulate Matter

There are no U.S. regulatory standards for indoor residential particulate matter concentrations. EPA standards for outdoor exposures and Canada's guidelines for indoor exposures are summarized in Table 6. Health Canada notes that indoor particulate matter differs in both size and chemical composition from that originating outdoors; thus, it may not be appropriate to compare EPA's outdoor standards with indoor PM sampling results. Health Canada also notes that indoor concentrations of small particulates tend to be higher than those outdoors, with average indoor concentrations of particles under 3.5 μm ranging from 20 to 30 $\mu g/m^3$. In homes with smokers, levels can be raised by 12 to 40 $\mu g/m^3$ per smoker (Health Canada 2010).

3.3.3 Interpretation of Mold Values

Currently in the US, there are no numerical standards or widely accepted guidelines for mold contamination (USEPA 2001b). Various governmental and private organizations have

Table 6. Selected Standards and Guidelines for Particulate Matter

Standard	Agency & Purpose
15 µg/m^3	EPA's National Ambient (outdoor) Air Quality Standard for $PM_{2.5}$—annual arithmetic average (*Federal Register*, August 1, 1994)
40 µg/m^3	Health Canada's Exposure Guideline for Residential Indoor Air for $PM_{2.5}$ —acceptable long-term exposure, 24-hr average
100 µg/m^3	Health Canada's Exposure Guideline for Residential Indoor Air for $PM_{2.5}$—acceptable short-term exposure, 1-hr average
150 µg/m^3	EPA's NAAQS for PM10—24-hour average

proposed guidance on the interpretation of fungal measures of environmental media in indoor environments (quantitative limits for fungal concentrations).

Recommendations reported in Rao et al. (1996) vary widely, with quantitative standards/guidelines ranging from less than 100 CFU per m^3 to greater than 1,000 CFU per m^3 as the upper limit for airborne fungi in non-contaminated indoor environments (Rao et al. 1996). Bush and Portnoy (2001) suggest that indoor spore counts equal to or greater than 1,000/m^3 and colony counts on the order of 1,000 to 10,000 CFU per m3 likely represent indoor fungal contamination. In a review article, Portnoy et al. (2005) concluded that, "it seems reasonable to expect that total airborne spore counts attributable to indoor sources greater than 1,000 spores/m^3 indicate a concern and those greater than 10,000 spores/m^3 indicate a definite problem."

Such guidelines based on total spore counts are only rough indicators, and other factors should be considered including, for example, the number of fungi indoors relative to outdoors, whether the fungi are allergenic or toxic, if the area is likely to be disturbed, whether there is or was a source of water or high relative humidity, if people are occupying the contaminated area or have contact with air from the location, and, whether there are immune compromised individuals or individuals with elevated sensitivity to molds in the area (University of Minnesota 1996).

3.4 Ambient Nano/Ultra Fine Particles (UFP)—Methods of Assessment

Due to their size and nature, no visual methods exit to identify UFPs. They are usually detected and measured through the use of Condensation Particle Counters (CPC). The technology involves the use of condensation (using water or alcohol as the fluid) to enlarge the UFP to a size that can easily be optically detected. Since they are ultra light weight and their potency depends on the quantity, the CPC counts the number concentration per cm^3. Most of them have the ability to detect UFPs between 2.5 and 3000nm (SCAQMD 2009; TSI 2012).

4.0 Methods Being Used to Mitigate Asthma Triggers in the Home

A variety of research studies support the effectiveness of a multifaceted approach to home-based interventions, combining education with efforts to address a variety of triggers (Jacobs et al. 2010; Krieger 2010; Krieger et al. 2010; Crocker et al. 2008; Eggleston et al. 2010; Platts-Mills et al. 2007; Roberts et al. 2009; Clark et al. 2009; USEPA 2007; Centers for Managing Chronic Disease 2007; Diette et al. 2008; Canino et al. 2009). Crocker et al. (2008) reviewed 25 intervention studies with more than one home-based intervention. The systematic review showed that there were significant reductions in asthma symptom days, missed school days,

and number of asthma acute care visits when multiple home interventions were employed. More recently, Jacobs et al. (2010), Krieger et al. (2010) and Sandel et al. (2010), used approaches similar to that employed by the IOM to assess the strength of the evidence for individual home interventions; they found strongest support for multifaceted interventions. Table 7 summarizes those findings for biological and chemical agents. Figure 1 shows the relationship between multiple home interventions and expected asthma outcomes. As noted earlier, the National Asthma Education and Prevention Program (NAEPP) Expert Panel Report 3 guidelines specify that environmental controls are an important adjunct to medication management.

Research also supports the effectiveness of Community Health Workers (CHWs) in the delivery of education and low-intensity home environmental interventions, especially with rural, Latino, and low-income urban communities (Butz et al. 2011; Postma et al. 2011; Krieger et al. 2010; Bryant-Stephens and Li 2008). Postma et al. (2009), reviewed the findings of seven randomized controlled trials that involved home-based interventions delivered by CHWs to families of children with asthma and that addressed multiple environmental triggers. All of the studies identified decreases in asthma symptoms and daytime activity limitations and reductions in emergency room and urgent care visits. However, they found inconsistent effects

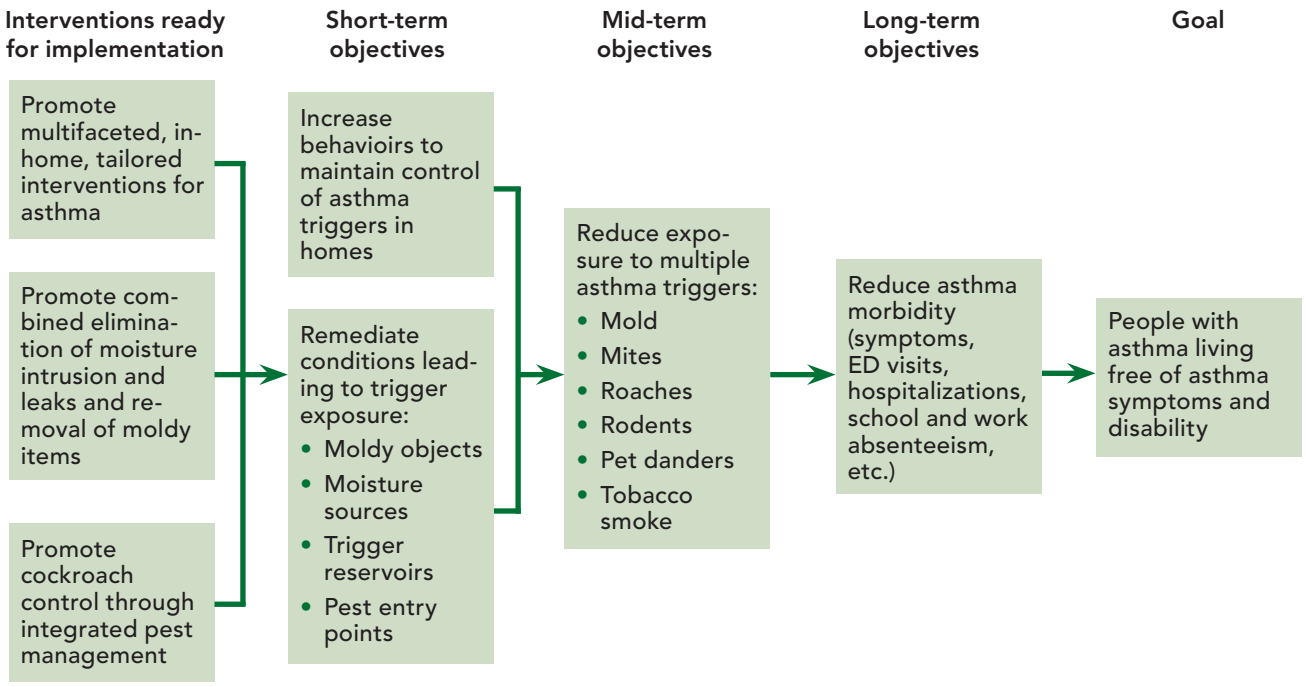
Table 7. Summary of the State of Evidence Related to Home Environmental Interventions for Asthma

Type of Agent	Sufficient Evidence	Needs More Field Evaluation	Needs Formative Research	No Evidence or Ineffective
Biologic Agents[a]	• Multi-faceted tailored asthma interventions • Integrated Pest Management (allergen reduction) • Moisture intrusion elimination	• Dehumidification • General & local exhaust ventilation (kitchens and baths) • Air cleaners (to reduce asthma) • Dry steam cleaning • Vacuuming	• Carpet treatments • Education only • One-time professional cleaning • Acaracides	• Bedding encasement alone • Sheet washing alone • Upholstery cleaning alone • "Air cleaners" that release ozone
Chemical Agents[b]	• Integrated Pest Management (pesticide exposure reduction) • Smoking bans	• Portable HEPA air cleaners to reduce particulate • Attached garage sealing to limit VOC intrusion • Particulate control by envelop sealing	• Smoking ban compliance in residential • Improved residential ventilation • VOC avoidance	• Portable HEPA air cleaners to reduce environmental tobacco smoke • "Air cleaners" that release ozone

[a] *Krieger et al. 2010.*

[b] *Sandel et al. 2010.*

Figure 1. Relationship Between Home Environmental Interventions and Asthma Outcomes[a]



[a] *Krieger et al. 2010.*

on trigger reduction behavior and allergen levels, which they attributed to differences in the study-provided resources for trigger control.

Finally, the research suggests there are critical partnership elements to multifaceted interventions studies. For example, the Centers for Managing Chronic Disease Asthma Health Outcomes Project (AHOP 2007) reviewed 223 evaluations of asthma programs worldwide that demonstrated improvement in at least one asthma-related health outcome. US EPA's National Asthma Forum, Communities in Action for Asthma-Friendly Environments, in its review of high-performing asthma management programs, similarly found that committed leaders, strong community ties, high-performing collaborations, and integrated health care services were critical adjuncts to tailored environmental interventions. Moreover the research suggests that tailored interventions need to be extended to all areas where asthmatics can be exposed to triggers: work, school, and home.

Table 8 summarizes six recent multifaceted interventions in the homes of asthmatic children. The largest, The Inner City Asthma Study enrolled 937 children, aged five to eleven years, with asthma, living in generally

AHOP's (2007) review found programs were most likely to have a positive health impact if they were:

- Community-centered;
- Collaborative with many agencies and institutions;
- Clinically-connected;
- Responsive to individuals' triggers; and
- Included actions to address triggers, including provision of materials, demonstrations, and direct remediation. Triggers most likely to be addressed in interventions included ETS, cat and dog dander and dust mites. One-third of the programs studied measured change in trigger reduction, and all reported decreases of at least 50% in the triggers measured.

Table 8. Summary of Recent Multi-faceted Environmental Intervention Studies

Study	Study Cohort	Interventions	Results	Costs
Inner City Asthma Study (a)	937 asthmatic children, aged 5–11, living in low-income neighborhoods of 7 American cities	Individualized actions tailored to children's sensitivities and exposures in home. Major effort to educate and equip caregivers in environmental remediation. Bedding encased. HEPA vacuum provided. Air purifier provided for ETS, pet allergens, & mold. Pest extermination for cockroaches. Research assistants made a median of 5 visits to intervention-group homes over a 12-month period.	Intervention group had fewer symptom days and greater declines in allergen levels than control group. Reductions in cockroach and dust-mite allergens were correlated with reduced asthma morbidity. Cockroach allergens appeared to have a greater effect on asthma morbidity than dust mites or pet allergens in inner city children. Intervention group had significant reductions in the disruption of caregivers' plans, caregivers' and children's lost sleep, and school days missed. Cockroach exposure and sensitivity predominated in northeastern cities; dust mite exposure and sensitivity were greater in the south and northeast.	Kattan et al. (2005) reported that the intervention used in the Inner City Asthma Study cost $1,469 per family and that over the year of intervention and a year of follow-up, the cost was $27.57 per additional symptom-free day (95% confidence interval, $7.46–$67.42). The authors concluded that the intervention was cost-effective.
Seattle-King County Healthy Homes Project (b)	274 low-income households with asthmatic children aged 4–12	Individualized actions. Major effort to educate and equip caregivers in environmental hazard reduction, and to support them in dealing with difficulties of life. Bedding encasements provided. Low-emission vacuum provided. Door mats and cleaning kits provided. Roach bait and rodent traps provided. Community health workers made 5–9 visits to high-intensity intervention homes over a 12-month period.	The high-intensity intervention group improved significantly more than the low-intensity group in urgent health services use and in caregiver quality-of-life index. Asthma symptom days declined more in the high-intensity group, but not statistically significant. The high-intensity group had a decrease in the asthma trigger composite score that was significantly greater than that for the low-intensity group. Improvements in mean scores for condensation, roaches, moisture, and dust weight were significant for the high-intensity group but not for the low-intensity group.	

Study	Study Cohort	Interventions	Results	Costs
Seattle-Kings County Breathe Easy Homes (c)	35 English-, Spanish- or Vietnamese-speaking low income households with asthmatic children aged 2–17, 2 years if successful tenancy, and no household members with criminal convictions.	Units-level interventions (1) Enhanced exterior envelope to optimize moisture-proofing; (2) Interior finishes, flooring, and other materials that minimized dust accumulation and off-gassing; (3) Energy efficient heat-exchange ventilation system with filtration and continuous fresh air supply. Individualized actions. Major effort to educate and equip caregivers in environmental hazard reduction and symptom recognition and management, and to support them in dealing with difficulties of life. which was provided by CHWs using standard protocols, information specific to operation and maintenance of a BEH, high-efficiency particulate-air-filter vacuums, allergen impermeable bedding encasements, and cleaning supplies. Allergy skin-prick testing was provided to all participants to determine their sensitization to common indoor allergens and 22 of the 34 participants received the test. CHWs used this information to prioritize educational interventions based on sensitivities and to motivate parents to address allergen sources. Finally, families signed a lease agreement that prohibited pets and tobacco smoke in the home. Smoking in child's presence was discouraged.	The clinical response after 1 year of residence in BEH unit showed improvements in primary and secondary outcomes: Primary outcome improvements: Increase in asthma-symptom-free days in the previous 2 weeks, decrease in urgent clinical visits over the previous 3 months, and improvement in caretaker quality of life all. Secondary outcomes also improved significantly. The proportion of participants with well-controlled asthma increased; the proportions with rescue medication use, activity limitations, symptom nights in the previous 2 weeks, and asthma attacks in the previous 3 months all decreased. Lung function measured by FEV1 improved. Exposure to asthma triggers as measured by home inspection declined substantially and significantly after moving into a BEH. At the end of the study, only 1 home continued to have a household member who smoked inside. The average number of asthma triggers per home (presence of rodents, roaches, pets, mold, moisture, or smoking) decreased from 1.5 in the old homes to 0.03 in the BEHs.	The total additional cost of BEH-specific upgrades ranged from $5000 to $7000 per home.

Study	Study Cohort	Interventions	Results	Costs
Study of effects of home moisture remediation on asthma morbidity, metropolitan Cleveland (e)	62 asthmatic children, aged 2 to 17 years, living in homes with indoor mold.	All participants received medical and behavioral information and support. Remediation-group homes received construction repairs focused on reducing water infiltration, removal of water-damaged materials, HVAC alterations, and environmental cleaning. The mean cost of remediation was $3,458.	Results after one year were: Remediation-group subjects had fewer symptom days than control-group children, and the difference was significant when adjusted for baseline asthma severity and season. Remediation group children had significantly fewer acute care visits. Reductions in endotoxins were greater in the remediation group, as were reductions in mold scores. Allergen concentrations for dust mite, cockroach, and rodent did not decline significantly.	The mean cost of remediation was $3,458.
Community-based participatory study of effects of environmental interventions on asthmatic children in Boston public housing (f)	50 asthmatic children in Boston public housing.	Asthma education for caregivers and limited case management. Provision of new mattress with microfiber technology. Integrated pest management (IPM). Industrial cleaning. Sealing of possible pest penetrations. Education of residents about IPM and provision of tools for reducing clutter and pest access to food.	No control group. Respiratory symptoms improved significantly. With logistic regression, the following variables were predictors of improvements in respiratory health: number of allergens with high concentration reductions, reductions in cockroach allergen levels, and improvements in neighborhood social cohesion or individual social support.	

Sources:
(a)Morgan et al. 2004; Gruchalla et al. 2005.
(b)Krieger et al. 2005; Takaro et al. 2004; Krieger et al. 2002.
(c)Takaro et al. 2011; Krieger 2010.
(d)Klinnert et al. 2005.
(e)Kercsmar et al. 2005.
(f)Levy et al. 2006.

lower income neighborhoods in the Bronx, NY; Boston, MA; Chicago, IL; Dallas, TX; New York, NY; the Seattle and Tacoma area, WA; and Tucson, AZ. It focused on reducing exposure to dust mites, passive smoking, cockroaches, pets, rodents, and mold. Interventions were tailored to the allergic sensitivities of each child and environmental exposures observed in the home. After two years, children in the intervention group had significantly fewer days with symptoms than those in the control group, and their homes had greater declines in allergens. Reductions in the levels of cockroach allergen and dust-mite allergen on the bedroom floor were significantly correlated with reduced complications of asthma (Morgan et al. 2004; Gruchalla et al. 2005).

An early study in the Seattle-King County area used an approach similar to that in the Inner City Asthma Study. Home asthma triggers were reduced, caregiver quality-of-life improved, and asthma-related urgent health services declined due to the intervention. Asthma symptom days declined significantly in both the high-intensity and the low-intensity (or control) groups, but the effect due to the intervention did not reach statistical significance in this measure (Krieger et al. 2005; Takaro et al. 2004; Krieger et al. 2002). Two differences between this Seattle study and the Inner City Asthma Study (ICAS) are: (1) the Seattle study did not provide HEPA air purifiers whereas the ICAS did if the child was exposed to passive smoking, sensitized and exposed to cat or dog allergens, or sensitized to mold; and (2) home visits in the Seattle study were made by community health workers, whereas the ICAS used research assistants. Both studies emphasized educating and equipping caregivers for environmental remediation, but the Seattle study may have given greater emphasis to providing support to the caregiver in other difficult aspects of life.

Breathe Easy Homes (BEH), the most recent Seattle-King County study, took a more intensive approach to interventions (Takaro et al. 2011; Krieger 2010). The study focused on the High Point development of the Seattle Housing Authority, an ethnically-diverse mixed community with 1,600 public and privately-owned units. High Point residences were built to green building standards, including improved energy efficiency and use of sustainable materials. Thirty-five apartments were renovated to include specific asthma-friendly features:

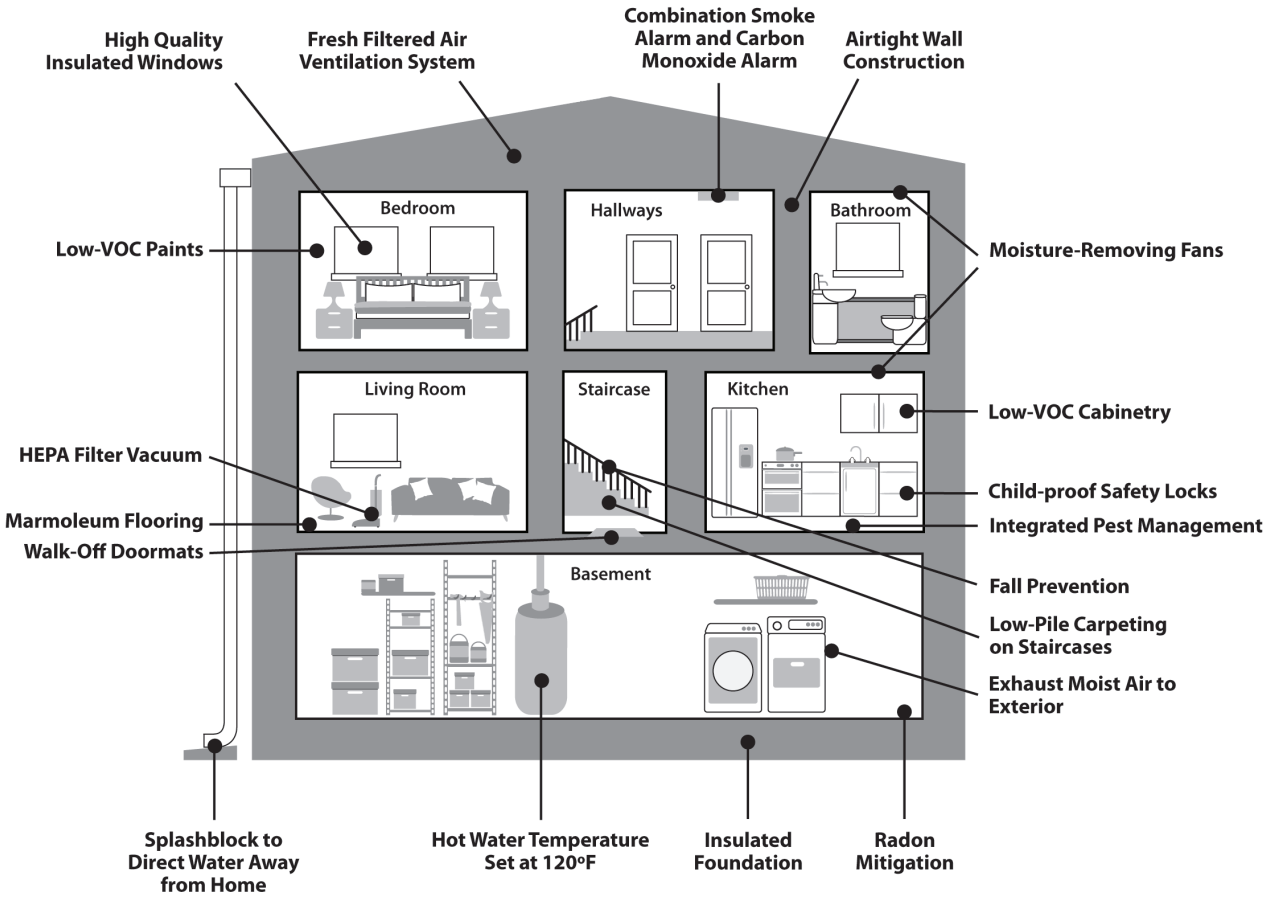
- Enhanced exterior envelope to optimize moisture-proofing;
- Interior finishes, flooring, and other materials that minimized dust accumulation and off-gassing;
- Energy efficient heat-exchange ventilation system with filtration and continuous fresh air supply.

BEH families also received in-home asthma education addressing self-management and trigger reduction, which was provided by CHWs using standard protocols, information specific to operation and maintenance of a BEH, high-efficiency particulate-air-filter vacuums, allergen impermeable bedding encasements, and cleaning supplies. Allergy skin-prick testing was provided to all participants to determine their sensitization to common indoor allergens and 22 of the 34 participants received the test. CHWs used this information to prioritize educational interventions based on sensitivities and to motivate parents to address allergen sources. Finally, families signed a lease agreement that prohibited pets and tobacco smoke in the home.

The BEH residents were compared to a matched cohort of 68 participants in the Healthy Homes II randomized control trial of children who received asthma education delivered by nurses in a clinical setting and home visits by CHWs (enrolled from 2002–2004), The Healthy Homes II project provided bedding encasements, a low emission vacuum with power head and embedded dirt finding, door mat, cleaning kit, and medication boxes.

Both projects collected asthma outcomes through interviews with caregivers and spirometry and visual assessments of triggers. BEH collected house dust allergen samples from the child's bedroom floor at three time points: in the participant's old home; after three months in the BEH home, and after one year in the BEH home. Asthma primary outcome measures included asthma-symptom-free days (self-reported number of 24-hour periods during the previous two weeks without wheeze, tightness in chest, cough, shortness of breath, slowing down of activities because of asthma, or nighttime awakening because of asthma), Pediatric Asthma

Figure 2. Breathe Easy Homes Home Interventions[a]



[a] *Takaro et al. 2011, p.56*

Caregiver's Quality of Life Questionnaire score (ranging from one to seven, with higher scores indicating better quality of life), and proportion of participants with self-reported asthma-related urgent health service use during the previous three months (emergency department, hospital, or unscheduled clinic visit). Secondary outcomes included asthma attack frequency (a time when asthma symptoms were worse, limiting activity more than usual or making you seek medical care) and rescue medication use. Pulmonary function measurements included FEV_1 (forced expired volume in first second), PEF (peak expiratory flow), FVC (forced vital capacity), $FEF_{25–75}$ (force expiratory flow between 25th and 75th percentiles), and FEV_1/FVC were collected for participants aged six years and older who could consistently perform the maneuver.

Both groups also showed improvement in primary outcomes between exit and baseline, with the degree of improvement in the BEH group higher for all measures except improved FEV_1.but no statistically significant differences. Both also showed improvement in secondary outcomes at exit, with a statistically significant improvement for nocturnal symptoms in the BEH group. Rescue medication use and asthma attack rates were marginally significantly improved for the BEH group. Exposure to mold, dampness, smoking in the home, and rodents decreased for both groups. There was a statistically significant reduction in mean trigger score for both groups, with statistically significant change in Odds Ratio for BEH (OR 0.69; 95% CI 0.21,1.17; p=0.005).

Another earlier study in Denver reported less successful results, although these findings are considered preliminary (Klinnert et al. 2005). In this study, the enrolled children were aged 24 months to nine years, whereas the ICAS and Seattle studies enrolled children aged 5–11

and 4–12 years, respectively. Vacuum cleaners were provided, but not HEPA air purifiers. Nurse home visitors provided caregivers with education on respiratory illness management and continual support for mental health. At 12 months, the study was effective in reducing several environmental exposures and improving illness management, but it failed to reduce respiratory symptoms or medical use in the intervention group relative to the control group.

In the Cleveland area, researchers took an approach that was different from the three studies described above (Kercsmar et al. 2006). While all 62 participants received medical and behavioral intervention, the remediation group received construction repairs focused on reducing water infiltration, removal of water-damaged building materials, HVAC alterations, lead hazard reduction, and environmental cleaning. Households with no visible mold were excluded from the study. Examples of intervention work include cleaning mold from hard surfaces, removing mold exposure pathways, stopping rainwater intrusion, exhausting water vapor from kitchen and baths, repairing plumbing leaks, repairing a faulty cold-air return, disconnecting and redirecting downspouts, and reducing moisture in crawlspaces and basements. Subjects in the remediation group had fewer symptom days than those in the control group, but the difference was not statistically significant. However, when adjusted for baseline asthma severity and season, the difference was significant. Children in the remediation group had significantly fewer acute care visits than those in the control group. Reductions in endotoxin concentrations were greater for the remediation group, as were reductions in mold scores. Allergen concentrations for dust mite, cockroach, and rodent did not decline significantly.

Researchers in Boston measured the effects of a community-based multi-faceted approach in homes of 50 asthmatic children in public housing (Levy et al. 2006). Although this study lacked a control group, it did find, with logistic regression, that the following variables were among the most significant predictors of improvements in respiratory health: the number of allergens with high concentration reductions, reductions in cockroach allergen levels, and improvements in neighborhood social cohesion or individual social support. The authors point out that, "significant reductions in symptoms among those who had improved perceptions about their neighborhood, who had improved social support, and who had enough reduced fear of violence to allow their children to play outside, may indicate that the social connections made during the study had a direct or indirect health benefit."

4.1. An Overview of Common Mitigation Methods

The two primary components of an integrated approach are removal or cleaning of allergen reservoirs and control of new sources of exposure. Based on a review of the literature, Chapman et al. (2000) suggested that a reduction in allergen levels in key reservoirs (bedrooms, living rooms, and basements) by more than 50% could reduce the risk of asthma development and severity. However, the authors also noted that even if removal of new sources reduces allergen exposure by up to 80% or 90%, allergen levels in reservoirs in homes with very high allergen levels (e.g., >10 µg/g for mite allergens) may still remain higher than the proposed threshold levels for sensitization (e.g., 2 µg/g for mite allergens). Platts-Mills et al. (1997) suggested that, where possible, mitigation protocols should be evaluated using measurements of both reservoir dust concentration and quantity together with airborne levels during disturbance.

An overview of common mitigation methods and their relationship with multiple asthma triggers in the home is presented in Table 9. While the

The Seven Principles of Healthy Homes provide a good structure for planning asthma-related environmental interventions:

- Keep it Dry
- Keep it Clean
- Keep it Safe
- Keep it Ventilated
- Keep it Pest-Free
- Keep it Contaminant-Free
- Keep it Maintained

Table 9. Major Mitigation Methods and Asthma Triggers Potentially Affected[1]

Mitigation Method	Asthma Triggers Potentially Affected[2]				
	Dust mites	Cockroaches	Pets and Rodents	Molds	Chemical Agents
Moisture control	●	●		●	
Ventilation			●	●	●
Cleaning	●	●	●	●	●
Air filtration			●	●	
Minimization and/or replacement of soft interior furnishings[3]	●	●	●	●	
Encasement of mattresses and pillows	●	●	●		
Behavior modification	●	●	●	●	●

[1] *See below for additional discussion of each mitigation technique*

[2] *Only selected triggers are listed*

[3] *Soft interior furnishings might include items such as carpeting and upholstered furniture*

following discussion is structured by type of allergen, the reader should bear in mind that the major studies described above indicate that an integrated multi-faceted tailored approach that addresses all the identified sensitivities of a subject seems to have the best chance of effectiveness; interventions with a single focus are far less likely to be effective. Most patients with asthma are sensitive to and exposed to multiple allergens. Also, as research suggests that children and lower-income inner city residents are particularly vulnerable populations for asthma sensitization, morbidity, and mortality, much mitigation research has focused on finding ways to mitigate asthma triggers for these populations.

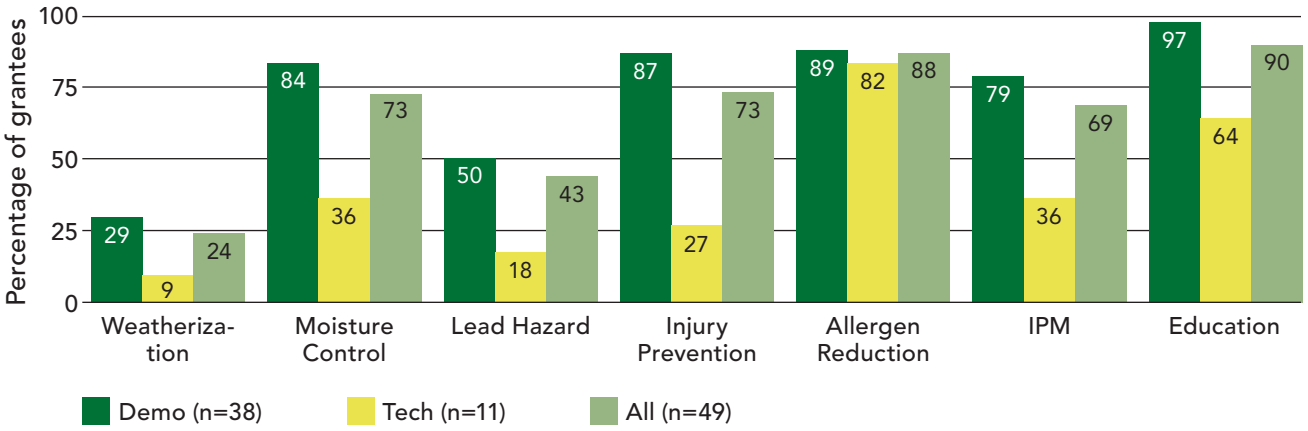
The applicability of these interventions on a wide scale is demonstrated in a recent evaluation of HUD Healthy Homes grantees (HUD 2007). The majority (78%) of Demonstration and Technical Studies grants used remediation of the housing unit and education of the occupants in over 6,268 housing units. While interventions often addressed potential physical hazards, such as high allergen concentrations, injury hazards, excess moisture, and pests, they also focused on increasing community awareness of healthy homes issues by providing education to the tenant or homeowner (See Figure 3).

4.2 Dust Mite Allergens

Common intervention methods reported in the literature for residential mitigation of dust mite allergens include:

- Maintaining a relative indoor humidity less than 50%.
- Encasement of mattresses and pillows in covers (<10 μm in pore size) and washing of bedding in hot (>120°F) water.
- Removal of fitted carpets (especially in humid zones).
- Replacement with non-VOC containing flooring (e.g., Marmoleum or hardwood floors).
- Dry vacuuming and dry steam cleaning (carpets, floors, and upholstered furniture).
- Removal or cleaning of upholstered furnishings and drapes.

Figure 3. Percentage of HUD Healthy Homes Grantees Focusing on Specific Intervention Categories[a]



[a] *HUD 2007, p. E-S 6.*

- Removal of soft toys for children, or periodically (e.g., monthly) freezing them.
- Regular year-round cleaning protocol.

Recent research suggests that the use of impermeable bedding covers, combined with frequent washing of bedding materials, can be effective in reducing house dust mite allergen levels in the bed (Vojta et al. 2001; Vaughan et al. 1999a; Mihrshahi et al. 2003), but does not by itself reduce asthma symptoms unless included in a more comprehensive approach to trigger control (de Vries et al. 2007; Krieger et al. 2010).The most effective coverings for bedding have been shown to be permeable to air and water vapor, but tightly woven and impermeable to mites. In a study that tested the effectiveness of different "allergen proof" bedding encasement materials (Vaughan et al. 1999a), tightly woven fabrics (e.g., Pristine from Allergy Control Products, Inc. and Microfiber from Priorities, Inc.) with an estimated pore size of 10 µm or less were found to be effective at blocking mite allergen particles. To block the smaller particles of cat allergens, fabrics needed to have a pore size of 6 µm or less (Vaughan et al. 1999a). In addition, these tightly woven fabrics only reduced airflow slightly, and thus would not promote moisture buildup in the bedding or cause discomfort sometimes felt with vinyl covers due to heat build-up. In general, the durability and effectiveness of these encasement materials in situations where frequent washing is occurring is also a factor that should be considered. One tightly woven fabric (Pristine) was tested by washing the material 22 times before testing, and showed very little change in performance (Vaughan et al. 1999a).

Evidence suggests that the use of encasement materials may be more effective in preventing allergen exposure among children than it is among adults. Woodcock et al. (2003) found that allergen-impermeable bed covers were ineffective as the sole method of dust mite allergen avoidance in adults, contradicting the findings in numerous studies on children. These results indicate that early intervention (i.e., during childhood) may be crucial to obtaining long-lasting effects through allergen removal (Woodcock et al. 2003).

Studies have shown that physical and chemical interventions can also be effective in reducing dust mite allergen levels in homes. Krieger et. al (2010) found the need for more formative research on the effectiveness of acarcides and more field research needed on the use of dry steam cleaning, but did not find sufficient evidence to determine they were ineffective

treatments. The use of acaricides to kill mites and use of tannic acid to break down allergens, each use followed by cleaning, may be effective in reducing mite allergen levels for short times (i.e., reductions have been observed to last up to a few months) (Vaughan and Platts-Mills 2000). Therefore, chemical treatments may require frequent re-application (Vaughan and Platts-Mills 2000). The effectiveness of physical interventions, including intensive vacuuming and dry steam cleaning plus vacuuming, was evaluated by Vojta et al. (2001). (In dry steam cleaning, hot steam is applied to the carpet. This method differs from standard hot water extraction cleaning in that the surface is said to be completely dry within 15 minutes after application and the carpet backing remains dry throughout the procedure.) Results of treatments showed that both vacuuming plus dry steam cleaning and vacuuming alone resulted in significant reductions in dust mite allergen concentrations and loads in carpets. Furthermore, reductions in carpet mite allergen levels persisted longer with the vacuuming plus steam cleaning than for the vacuuming alone (e.g., eight weeks versus four weeks). They also observed that intensive vacuuming and steam cleaning resulted in modest reductions in mite levels in upholstered furniture. Based on the observed reductions, the authors concluded that these physical interventions offer practical, effective means of reducing house dust mite allergen levels in low-income home environments, although long-term control would likely include frequent repetition of the vacuuming and dry steam cleaning treatments (Vojta et al. 2001).

Vacuum cleaners used in allergen cleaning are recommended to have high efficiency particulate air (HEPA) or electrostatic filtration systems on the exhaust air (Platts-Mills et al. 1997; Vaughan et al. 1999b). Krieger et al. (2002) reported improved effectiveness of vacuuming by study participants when they used power-head HEPA vacuums with a "dirt detector" that indicated when nearly all the dust was removed. Such vacuums are available commercially. Not all such vacuums have the same collection efficiency. Vaughan et al. (1999b) found that although the majority of vacuum cleaners and vacuum cleaner bags specially designed for allergic patients assessed in their study reduced allergen leakage, there was still room for improvement.

In general, most of the two- and three-layer microfiltration bags recommended for allergic patients performed well compared to traditional single-layer bags. However, large ranges in performance of the two-layer bags highlighted variability found between manufacturers. Corsi et al. (2008) found that use of vacuums without HEPA filtration produced redeposition of PM_{10} over background levels but had an insignificant impact on $PM_{2.5}$ mass concentrations. Their findings also reinforced the message that asthmatics should not be present during the vacuuming. Koh et al. (2009) found that the act of vacuuming could itself increase sensitivity to dust mites, but not cockroach allergens, but the nature of the vacuum used was not discussed.

4.3 Cockroach Allergens

Common intervention methods reported in the literature for residential mitigation of cockroach allergens include:

- Regular year-round cleaning protocol and limiting open food-stuffs (e.g., enclosing food in plastic containers).
- Eliminating water sources (leaky pipes/faucets, pet water bowls etc.).
- Safe (targeted) insecticide use and/or extermination.
- Sealing holes and cracks in the home.
- Encasement of mattresses and pillow in covers and washing of bedding in hot (>130°F) water.
- Dry vacuuming and dry steam cleaning (carpets, upholstered furniture).
- Removal of fitted carpets.

Until recently, researchers had not demonstrated that reductions in cockroach allergens resulted in reductions in asthmatic symptoms. The Inner City Asthma Study found a significant correlation between cockroach and dust-mite allergen reduction and a decrease in asthma-related morbidity during a multi-intervention study that addressed multiple allergens in the home. However, the correlation was particularly strong between reduced exposure to cockroach allergen and asthma morbidity reduction (Sever et al. 2011; Morgan 2004). Basic issues in effective cockroach allergen abatement are (1) the difficulty in reducing allergen levels

below suggested thresholds of concern (2) the difficulty in maintaining low allergen levels over the long term. Suggested reasons for limited effectiveness include: the presence of residual cockroach allergens (due to carcasses remaining in areas that are not easily accessible or lack of thorough cleaning following extermination) and re-infestation problems (especially in multi-family dwellings). As part of the National Cooperative Inner-City Asthma Study (NCICAS), controlled clinical home intervention trials were conducted in 265 homes where children were sensitized to cockroach allergen. Interventions included mattress and pillow coverings, professional pest control, provision of cleaning supplies, and education on further cockroach allergen removal. Although cockroach allergen levels were temporarily reduced, levels were still well above those reported to cause respiratory symptoms in asthmatics (i.e., >8 Units/g) (Gergen et al. 1999). The authors of the study concluded that cockroach allergens are not easily removed from inner-city homes, especially in multifamily units, and will require further study of cockroach ecology, pest control techniques, and follow-up cleaning methods to allow for successful remediation of cockroach infested houses (Gergen et al. 1999; Eggleston, 2000). In addition, this research emphasizes the importance of addressing multi-family dwellings as a whole, rather than as individual apartments. Wood et al. (2001) also reported that although cockroach allergen levels can be reduced by 80% to 90%, many homes may still have allergen levels exceeding the proposed threshold of 8.0 U/g of dust. In a study of thirteen homes in inner-city Baltimore, Maryland, Eggleston et al. (1999b) found that although cockroach extermination was feasible, standard housecleaning procedures were only partially effective in removing residual cockroach allergen over eight months.

The most effective type of cockroach control typically includes using several of these methods concurrently to reduce cockroach populations (Wang and Bennett 2009; Ogg et al. 1994). This multiple tactics approach, which can be applied to any pest population, is called Integrated Pest Management (IPM). For residential cockroach control, an IPM approach should include monitoring suspected infestation areas before and after treatments (e.g., using sticky traps). The primary features of an IPM program for cockroaches include: removal of food, water, and harborages, in combination with careful placement of the least toxic baits and insecticides necessary (Wang, and Bennett 2009; Ogg et al. 1994). Recommended treatments include: implementing structural improvements (such as plugging major holes around plumbing, sealing cracks and crevices to prevent entry and limit hiding places), and improved housekeeping/use of good sanitation practices (i.e., to eliminate food and water resources) (CMHC 1998; Ogg et al. 1994). Following initial intervention, IPM approaches emphasize continued monitoring in the same areas to assess the success of the control program and whether additional intervention is necessary (Wang, and Bennett 2009; Ogg et al. 1994).

Ongoing research has indicated that IPM techniques can be effective for cockroach control (Wang and Bennett 2009; Frantz et al. 1999; Campbell et al. 1999). IPM approaches emphasize the use of "least toxic" pesticides only as needed and confining the area of pesticide application (e.g., with targeted gels, baits, and powders) to reduce the probability of human exposure (Campbell et al. 1999; CMHC 1998). Results of a study which assessed the effectiveness of a pilot IPM program in controlling cockroaches in an apartment complex, without pesticide sprays, showed that education can influence building residents to accept and comply with an IPM program, and that the program can be effective in controlling cockroaches (Campbell et al. 1999). Another successful urban IPM program credited its effectiveness to strong community involvement at each stage of the project, comprehensive guidance and education by experts, and the cooperation of building managers and others responsible for providing support services to apartments (Brenner et al. 2003). Wang and Bennett (2009) conducted a community-wide IPM program in two Gary, IN low income apartment complexes, with one complex treated by state-licensed entomologists from Purdue University, and the other by pest management professionals. Both complexes received the same resident and staff education. While cockroach trap counts reduced more quickly in the entomologist-intervention group, by 12 months the trap count was reduced by 74% in both groups. Bla g a 1 concentrations were also reduced at 12 months. Professional cleaning (as

opposed to resident cleaning) has been shown to greatly enhance the effectiveness of IPM approaches, based on the results of a three-pronged intervention to reduce cockroach allergen levels in infested urban homes through resident education, professional cleaning, and insecticide bait placement (Arbes et al. 2003b). In a follow-up study of homes that participated in this six-month intervention, Arbes et al. (2004) found that reductions in cockroach allergen concentrations could be maintained through 12 months with the continued application of insecticide bait alone. IPM can lead to greater sustainability in keeping cockroach populations down, in contrast to extermination only, which typically needs to be repeated.

Insecticides, including inorganic compounds (e.g., boric acid), pyrethrins, avermectins/abamectin (e.g., Raid®, Combat®), and newer compounds (e.g., fipronil, hydramethylnon, and sulfluramid) are often used in the home to kill cockroaches (Katial 2003; Vaughan and Platts-Mills, 2000; Eggleston and Arruda, 2001). Boric acid and a less processed form (disodium octoborate tetrahydrate) may be appropriate for persons who are chemically sensitive, and its low mammalian toxicity is consistent with IPM philosophy (Katial 2003; Vaughan and Platts-Mills 2000). Studies reviewed by Eggleston (2000) indicated that pesticides can be effective in reducing cockroach populations by as much as 90% for as long as three months. Although these pesticides may be applied in almost any form, gel forms of many roach insecticides are available and can be applied to cracks and other critical areas in a manner that will reduce potential exposures to pets and children (Eggleston and Arruda 2001). Gels may also be preferred because they have a longer duration of effectiveness and because the insecticides can be carried back to areas of heavy infestation (Katial 2003). Bait traps that limit access to the pesticide have also been developed (Eggleston and Arruda 2001) but may require frequent replacement to provide long-term benefit (Katial 2003).

Regardless of the level of reliance on insecticides for controlling cockroach populations, thorough household cleaning is essential for successful cockroach allergen removal (Eggleston and Arruda, 2001). The cockroach allergen (*Blatella germanica*) Bla g 1 is extremely stable; therefore allergens not removed by cleaning may remain indefinitely (Vaughan and Platts-Mills 2000). It is recommended that general cleaning to remove any food sources be conducted before insecticide application, and that the entire house be intensively cleaned about a week following extermination, including vacuuming, scrubbing walls, floors, countertops and other hard surfaces with water and detergent, and washing bedding, curtains, and clothing, (Eggleston and Arruda 2001). The effectiveness of different methods of cleaning following extermination has not been well tested; however, vacuum cleaning and tannic acid (to break down allergens) applications have been effective in experimental settings (Eggleston 2000). Use of a bleach solution (sodium hypochlorite) when cleaning does not seem to improve allergen reduction (Wood et al. 2001). Cockroach allergens located in areas that are not easily accessible (e.g., between cabinets and walls) often cannot be reduced by traditional cleaning techniques.

Interventions requiring carpet removal and replacement with smooth flooring have been shown to be effective in cockroach allergen mitigation, although this method may be impossible in rental units where tenants do not have control of the flooring. Overall, cleaning and extermination (use of acaricides) effectiveness has been supported for dust mite and cockroach allergen control.

4.4 Pet and Rodent Allergens

Common intervention methods reported in the literature for residential mitigation of pet allergens include:

- Removal of the pet from the home.
- Removal of fitted carpets and upholstery.
- Dry vacuuming and a regular cleaning protocol.
- HEPA air filtration.
- Encasement of mattresses and pillows in covers (<6µm in size).
- Frequent pet washing.
- Use of topical sprays on pets.

Although observed effective in some cases, the extent to which the mitigation measures listed above can control pet allergens is inconclusive

(Platts-Mills et al. 1997; NAS 2000; Chapman and Wood 2001). Reductions achieved via pet washing and other pet applications have generally been observed to be temporary or insignificant (NAS 2000). High-efficiency particulate or electrostatic air cleaners are often recommended, especially in bedrooms, although studies on their effectiveness have yielded conflicting results (Chapman and Wood 2001). For example, van der Heide et al. (1999) observed that the use of air cleaners in bedrooms and living rooms resulted in significant improvements in respiratory symptoms of asthmatic children sensitized to pet allergens, while Wood et al. (1998) found that although HEPA air cleaners reduced airborne allergen levels, no significant improvements in respiratory symptoms occurred. Thus, although airborne levels may be temporarily reduced, reservoirs of pet allergens (e.g., in floor dust) may affect the ability of air cleaners to effectively improve symptoms. As noted earlier in the section on dust mite reduction, in-duct forced air systems with high efficiency filtration may provide positive benefits on pet allergen control.

Even following pet removal, research has shown that pet allergen levels may remain elevated for substantial periods of time (NAS, 2000). For example, following cat removal, levels of cat allergen in settled dust may take four to six months to return to levels normally seen in houses without cats, although levels may fall much more quickly if carpets, upholstered furniture and other reservoirs in the home are removed (Chapman and Wood 2001). Therefore, additional measures that address reservoir sources (e.g., intensive cleaning of furnishings, beds) are typically required (NAS 2000).

High mouse allergen levels have been correlated with cockroach infestation (Phipatanakul et al. 2000a), and both types of pests have similar environmental requirements (e.g., a means of access to the home, food, water). IPM approaches discussed above for cockroaches can also be effective for controlling rodent populations (Frantz et al. 1999). Phipatanakul et al. (2004) were successful in significantly reducing mouse allergen in 12 intervention homes compared with six control group homes in inner-city Boston using an intervention consisting of filling holes with copper mesh, vacuuming and cleaning, and using low-toxicity pesticides and traps. Median levels in intervention homes fell to 2.8 µg/g in kitchens, 2.2 µg/g in bedrooms, and 0.9 µg/g in living rooms at month five.

4.5 Mold and Moisture

Given evidence that young children may be especially vulnerable to certain mycotoxins (American Academy of Pediatrics 1998) and in view of the potential severity or diseases associated with mycotoxin exposure, some organizations support a more precautionary approach to limiting mold exposure (Burge and Otten 1999). For example, the American Academy of Pediatrics recommends that infants under 1 year of age not be exposed at all to chronically moldy, water-damaged environments (American Academy of Pediatrics 1998).

Various guidance documents for remediation of mold contamination have been developed.

- The New York City Department of Health has a set of guidelines, "Assessment and Remediation of Fungi in Indoor Environments," that are widely recognized. The document, originally developed for *Stachybotrys* but expanded to be inclusive of all molds, addresses health effects, environmental assessment, remediation techniques, and hazard communication (available at http://www.nyc.gov/html/doh/html/epi/moldrpt1.html).

- 2010 NY State Toxic Mold Task Force Final Report to the Governor and Legislators identifies a number of treatments and policy changes, including recommendations to agencies about mold remediation training (available at http://www.health.ny.gov/environmental/indoors/air/mold/task_force/docs/final_toxic_mold_task_force_report.pdf).

- The Institute of Inspection Cleaning and Restoration Certification produced guideline S500: Standard and Reference Guide for Professional Water Damage Restoration (available by contacting the IICRC headquarters at (360) 693–5675 or through e-mail at supplies@iicrc.org).

- The American Conference of Governmental Industrial Hygienists (ACGIH) bioaerosols committee published in 1999, "Bioaerosols: Assessment and Control," a compilation of

information on investigation strategies, sampling and analysis, and control of indoor bioaerosols, including molds (can be ordered through ACGIH at http://www.acgih.org/home.htm).

- The American Industrial Hygiene Association (AIHA) is in the process of developing a document with explicit guidelines for mitigation of mold hazards and some general guidelines for "clearance."
- U.S. Environmental Protection Agency published guidance for "Mold Remediation in Schools and Commercial Buildings," which includes many general principles also applicable to residential mold mitigation efforts (available through EPA at http://www.epa.gov/iaq/molds/mold_remediation.html).
- U.S. Environmental Protection Agency published guidance, "A Brief Guide to Mold, Moisture, and Your Home," for homeowners and renters on how to clean up residential mold problems and how to prevent mold growth (available from EPA online at http://www.epa.gov/iaq/molds/images/moldguide.pdf).
- The Canada Mortgage and Housing Corporation published, "Clean-up Procedures for Mold in Houses," which provides qualitative guidance for mold mitigation, (can be ordered from CMHC at https://www.cmhc-schl.gc.ca:50104/b2c/b2c/init.do?language=en).
- Health Canada published its "Fungal Contamination in Public Buildings" guide to assist investigators in recognizing and managing fungal contamination (available through Health Canada at http://www.hc-sc.gc.ca/hecs-sesc/air_quality/pdf/fungal.pdf).
- The Institute of Medicine of the National Academies report, *Damp Indoor Spaces and Health*, provides a summary of mitigation methods for mold (IOM 2004).
- The Centers for Disease Control and Prevention recently published a report entitled "Mold: Prevention Strategies and Possible Health Effects in the Aftermath of Hurricanes Katrina and Rita," which provides advice on responses to flooded homes with an emphasis on worker protection (CDC 2005).
- D. M. Weekes, and J. D. Miller. 2008. Recognition, Evaluation, and Control of Indoor Mold. IMOM08-679. Fairfax, VA: American Industrial Hygiene Association.

Common intervention methods reported in the literature for residential mitigation of mold hazards include:

- Location and removal of sources of moisture (control of dampness and humidity and repair of water leakage problems).
- Increasing ventilation.
- Cleaning of mold contaminated materials that can be salvaged.
- Physical removal of materials with severe mold growth.
- Use of high-efficiency particulate air (HEPA) filters.
- Maintenance of heating, ventilation, and air conditioning systems.
- Prevention of spore infiltration from outdoors by closing doors and windows and by using air conditioning.
- Proper worker protection.

Because one of the most important factors affecting mold growth in homes (as well as other asthma related triggers such as dust mites) is moisture level, controlling this factor is crucial in abatement strategies. It is critical to find the source of moisture and remove it. Many simple measures can significantly control moisture, for example: maintaining indoor relative humidity at less than 50% through the use of dehumidifiers, fixing water leakage problems, increasing ventilation in kitchens and bathrooms by using exhaust fans, venting clothes dryers to the outside, using air conditioning at times of high outdoor humidity, heating all rooms in the winter to avoid temperature variations that cause condensation, and adding heating to outside wall closets, and using a sump pump in basements prone to flooding (Johnson et. al. 2009; Bush and Portnoy 2001; ACGIH 1999).

Remediation of the causes of moisture sources in homes may be effective in reducing indoor mold and symptomatic days of asthmatic children living in the homes, but results have been

modest and the studies have been hampered by small samples sizes and/or methodological issues (Rabito et al. 2010; Kercsmar et al. 2005).

When mold contamination does occur, non-porous (e.g., metals, glass, and hard plastics) and semi-porous (e.g., wood and concrete) materials contaminated with mold and that are still structurally sound can often be cleaned with detergent or bleach solutions or by using quaternary amine preparations; however, in some cases, the material may not be easily cleaned or may be so severely contaminated that it may have to be removed. (Do not mix detergents and bleach. Some detergents have ammonia, which can produce toxic gases when mixed with bleach.) It is recommended that porous materials (e.g., ceiling tiles, wallboards, and fabrics) that cannot be cleaned be removed and discarded (NYC 2000; USEPA 2001). Physical removal interventions have proven effective, although additional research is needed regarding the containment of mold spores during the renovation process (NAS 2000). It is recommended that rooms being remediated be isolated, using plastic sheeting, from the remainder of the home.

The use of biocides is discouraged by many experts because little research has been conducted on their effectiveness for this use and because of the potential human health hazards associated with this use (USEPA 1997b; Foarde 1998; Cole and Foarde 1999). In addition, research indicates that dead mold material often retains the allergenic or toxic properties of the mold (Foarde 1998; NAS 2000), and thus removal is often cited as the best mitigation option.

Worker protection is required when conducting cleaning or removal of mold contaminated materials in homes. Activities such as cleaning or removal of mold-contaminated materials in homes, as well as investigations of mold contamination extent, have the potential to disturb areas of mold growth and release fungal spores and fragments into the air. This suggests that residents should not attempt repairs without the proper protection, or preferably should employ a contractor trained in environmental remediation (Vesper et al. 2000). Recommended measures to protect workers during mold remediation efforts depend on the severity and nature of the mold contamination being addressed, but include the use of well fitted particulate masks or respirators that retain particles as small as 1μm or less, disposable gloves and coveralls, and protective eyewear (ACGIH 1999).

4.6 Indoor Chemical Air Pollutants

Occupant choice plays the primary role in determining indoor exposure to environmental tobacco smoke (ETS). Caregivers and other household members can be urged to quit smoking or to smoke outside, and those with contact with the patient can be urged to wear a smoking jacket if they continue to smoke and/or to wash smoke-contaminated clothing that may come in contact with the patient. But engendering such behavioral change is difficult. Data from the National Asthma Survey suggests that African-American children were less likely to be in smoking-avoidance households than nonminority children (Roy et al. 2010). Northridge et al. (2009) preliminary findings from the Harlem Children's Zone Asthma Initiative indicate that adult family members of children with asthma were aware of the hazards of secondhand smoke, took some measures to reduce exposure in their homes, but used smoking as a stress-reliever and believed that outdoor pollutants were just as bad for their children's health as indoor pollutants.

For further information on pesticides and carbon monoxide remediation, see the HUD background papers: "Healthy Homes Issues: Pesticides" and "Healthy Homes Issues: Carbon Monoxide."

Reduction of pesticide exposure in the home can be achieved through alteration of consumer behavior and implementation of practices such as integrated pest management. Other indoor pollutants, such as emissions from products (e.g., phthalates) or appliances, may be minimized with changes in product use (e.g., using paints formulated to have low VOC emissions and pressed woods with reduced formaldehyde content) and increased ventilation (e.g., increasing the overall home air exchange rate and installing ventilation fans in areas containing sources) (NAS 2000). Regular

inspection of gas and wood burning appliances, correction of improper appliance ventilation systems, and installation of ventilation systems where unvented sources are present (e.g., unvented stoves in the kitchen), can reduce the potential hazard associated with emissions (including nitrogen and sulfur oxides, VOCs, CO, and particulates) from these sources. For example, in the National Cooperative Inner-City Asthma Study (NCICAS), air-monitoring measurements indicated that levels of nitrogen dioxide in inner-city homes investigated were often in excess of EPA environmental standards. These high levels, which could be expected to contribute to asthma aggravation, were thought to be related to gas use for 89% of the families and to the fact that 24% of the kitchens did not have functioning windows (Eggleston 2000, citing Kattan et al. 1997).

Air cleaning methods such as HEPA air filtration are more likely to be effective for allergens associated with smaller particles (e.g., cat allergens), because they tend to remain airborne longer than those associated with larger particulates (e.g., dust mite or cockroach allergens) (Chapman 1998). Both Sandel et al. (2010) and the US Surgeon General (USDHHS 2006) concluded that portable air cleaners alone were not sufficient to address ETS. More recent research (Butz et al. (2011) found that decreases in mean $PM_{2.5}$ and $PM_{2.5-10}$ were greatest in the randomized clinical intervention group that received an air cleaner and "health coach" home visits to reduce ETS, but that there were also decreases in $PM_{2.5}$ for the intervention group that only received air cleaners, and both were greater than that for a control group. Eggleston et al. (2005) found as part of the ICAS randomized clinical trial that the combination of cockroach extermination and HEPA air cleaners reduced by 39% particles of PM_{10} or smaller. Myatt et al. (2008) modeled peak and time-integrated concentrations of common indoor air asthma triggers over a one year period as a function of natural ventilation, portable air cleaners, and forced air ventilation with conventional or high efficiency filtration. They found that forced air systems with high efficiency filtration provided the best control of cat allergens and fungal spores, as well as a significant reduction in ETS levels. Macintosh et al. (2010) also found that whole house in-duct air cleaning reduced indoor concentrations of ambient $PM_{2.5}$ more than central air conditioning with conventional ventilation or natural ventilation. Sublett's (2011) recent review of the literature on the effectiveness of air filters and air cleaners on the control of allergic respiratory conditions concluded that most cost-effective approach may be whole house filtration combined with a portable room air cleaner in the bedroom.

4.6.1 Ambient Nano/Ultra Fine particles (UFP)—Methods of Mitigation

The toxic effects and physiochemical characteristics of UFP justify the need to limit exposure, especially for asthmatics, to prevent airway inflammation. Due to their size and nature, UFPs are more of a problem to asthmatics if they are suspended in ambient air and inhaled. Also, the concentration of UFPs is usually greater indoors than outdoors (Wallace and Ott 2011). Thus, the effective means of controlling their levels in the home is through source control, air filtration or cleaning and ventilation (Air Quality Sciences 2011).

Controlling the sources of production of UFPs in the home can be an effective means of reducing indoor concentrations. These include the use of building materials, furniture, electronic products and cleaning materials that emit low or no VOCs since VOCs are a key component in generating UFPs. Another means of reducing UFP concentrations indoors is the use of mechanical or electronic filtration. Through the use of Ultra Low Penetration Air (ULPA) or High Performance Panel Filter (HP-PF) filters, which are manufactured using "nano fibers", about 75% of UFPs or more can be removed from the indoor environment (SCAQMD 2009; Air Quality Sciences 2011).

A well designed passive or active ventilation system will help reduce their concentration by improving air exchange between indoors and outdoors. For example, using a hood ventilation system that vents outside can effectively remove most of the UFPs generated during cooking. A properly designed HVAC system can condition and dilute as well as transport the suspended pollutants, including UFPs, outside (Air Quality Sciences 2011).

4.7 The Costs of Interventions

The cost of asthma to society has been the subject of numerous studies (see Bennett and Nurmagambetov, 2011; Nurmagambetov et al. 2011; Sullivan et al. 2011; and Mason and Brown 2010 for summaries of those studies). Bennett and Nurmagambetov, for example, estimated the total cost of asthma to society in 2007 at $56 billion, with productivity losses from work days and school days lost because of morbidity and productivity losses from mortality representing 8% to 12% of annual total costs from 2002–2007. They noted that this estimate does not include nonmedical direct costs and the intangible costs of asthma to society. Sullivan et al. used the 2003 and 2005 Medical Expenditure Panel Surveys to specifically estimate the effect of asthma on medical expenditures, use, productivity, and chronic co-morbidity among adults. Of the over 40,000 adults with expenditure data, 2,003 had an asthma diagnosis. Productivity-related outcome variables included employment, annual wages, missed work days, days spent sick in bed, and activity limitations, Compared to those without asthma, the asthmatics studied were significantly less likely to be employed (odds ratio, 0.78), spent 1.4 more days sick in bed annually, and were significantly more likely to have activity limitations or to be unable to work. Adults with asthma incurred an additional $1,907 (2008 US dollars) annually and experienced higher health care use and co-morbidity. The researchers also found that cost to government was higher for adults with asthma, since more were likely to be covered by Medicaid (30%) than the general adult population (10%). Mason and Brown also noted that the costs associated with substandard housing are not equally distributed throughout society, as low-income families are more likely to experience the health burdens associated with deteriorate housing stock Mudarri and Fisk (2007) estimated the total annual asthma cost attributable to dampness and mold in homes at $4.0 billion.

CDC's Task Force on Community Preventive Services reviewed twelve studies to estimate costs and benefits for asthma interventions in 2007 US dollars. The average cost per participant ranged from $231 to $14, 858. Interventions with major environmental remediations had a per participant cost of between $3,796 and $14,858; those with education and a minor to moderate remediation component ranged from $231–$1,720. Studies with minor to moderate remediation demonstrated that these interventions provide good value for money invested ($5.30 to $14.00 for each dollar invested) and a cost per symptom free day of ($12 to $57) (See Nurmagambetov et al. 2011 and http://www.thecommunityguide.org/asthma/multicomponent.html for more information.) Environmental Improvements for Children with Asthma served 255 low-income households from 2005–2008. The program reported that a two-home visit home assessment and installation of allergen-reducing products cost on average $320 for the home visit and $301 for the products. Based on health plan claims data that compared the 12 months prior to interventions to the 12 months post-intervention, the return on investment was $2.19:$1:00 for total health care costs and $1.76: $1:00 for asthma related total health care costs (American Lung Association in Minnesota).

The study of HUD Healthy Homes grantees found that the average cost of allergen reduction in housing was $1,292/housing unit. Most of the interventions were relatively low in cost, averaging approximately $3,700 per unit (Table 10).

IPM is likely to have a higher initial cost than more traditional methods, according to two recent studies conducted in public housing. Wang and Bennett (2006) reported that the median costs per apartment during a 29-week period were $65 for IPM and $35 for bait treatment. They expected, however, that over the long term IPM would continue to provide better control at a similar cost compared with bait treatment. In their 2009 study, the mean monthly estimated cost of the treatments, excluding education, was $7.50 per apartment. Miller and Meek (2004) reported that the average cost per apartment of IPM was $14.60 in the first month compared to $2.75 per unit for a more traditional treatment of baseboards and cracks and crevices with spray and dust formulation insecticides, but that after four months the costs of the two treatments were no longer significantly different because many of the IPM apartments were shifted to a quarterly treatment schedule. For an entire year, the

Table 10: Average Cost[a] of Intervention Materials per Housing Unit[b,c]

Intervention Category	Cost per Housing Unit	
	Range	Average
Weatherization (n=8)	$47–$7,250	$2,266
Moisture control (n=13)	$4–$4,200	$1,272
Lead hazard control (n=8)	$600–$13,000	$5,312
Injury prevention (n=14)	$7–$850	$233
Allergen reduction (n=17)	$5–$6,000	$1,292
IPM (n=14)	$39–$800	$290
Education (n=16)	$20–$600	$211
Average total cost per unit for all interventions (n=10)	$450–$7,028	$3,705

[a] *Average cost includes both cost of materials and labor.*

[b] *Numbers presented in the table include both estimated and actual quantities provided by grantees. 33 of 44 grantees reported that their numbers were estimates.*

[c] *n=number of grantees who answered questions concerning the costs of various interventions.*

average per unit cost of IPM was $4.06 per month compared to $1.50 for the traditional treatment, which was much less effective (as measured by cockroach-trap catches).

5.0 Current Research and Information Gaps

The state of research knowledge on effective home interventions for asthma has improved greatly in the last decade, but as Brugge (2010) has observed, there are still questions about when there has been enough research, and of the most rigorous type. The CDC 2008 Task Force on Community Preventive Services and the CDC-funded 2010 Systematic Review of Housing Interventions and Health also highlight a number of areas where more research in needed. Possible areas of consideration for future research include:

Methodological Issues Related to Assessment

- Inter-rater reliability for visual assessments tools.
- Assessment of correlation between visual inspection methods and environmental sampling.
- Determination of performance criteria for analytic methods (e.g., detection limits etc.).
- Relation of environmental samples (vacuum dust etc.) to actual exposure.
- Research on accuracy of home allergen tests and development of better sampling and analytical techniques.
- Standardized methods for assessment and measurement of allergens.
- Standardization of assays for measuring allergen levels to allow for comparison.
- Characterization of sources of variability in analytical results and development of quality control samples.
- Standardization of threshold values for allergens.

Methodological Issues Related to Mitigation

- Most effective intervention implementers (CHWs, nurses, respiratory therapist etc.) and does this change depending on intervention setting.
- Integrating interventions into the health care system to insure appropriate access and sustainability.

- Required intensity (number of home visits, intensity of remediation, intensity of education) needed for an effective home intervention program
- The impact of household member smoking on the effects of interventions (i.e., should smoking cessation counseling be a necessary component of all home-based environmental interventions for asthma).
- Intervention studies that introduce "sham interventions" in order to test the effectiveness of specific interventions in the context of intervention and control group studies, and the ethical issues they raise.
- Research on the relative cost-effectiveness of different intervention strategies and prioritization of mitigation alternatives.
- Research on the effect of insecticides on allergen levels (for dust mites and cockroaches) and effective methods of clean up after use of insecticides.
- Establishment of standards of quality for indoor allergen control products.
- Effectiveness of integrated pest management methods for controlling pest/rodent allergen levels.
- Feasibility of effectively reducing allergen levels below thresholds.

Health and Exposure Issues

- Identification of threshold levels for sensitization to major residential allergens and for asthma exacerbation in both children and adults, especially the elderly.
- The role of stress, depression, or other mental health factors on asthma.
- Additional data on the role of rodent allergen exposure, particularly in socially disadvantaged populations.Information on additional allergens and irritants of importance in the home.
- Information on the relationship between indoor exposure to pesticides and exacerbation of asthma.
- Feasibility of preventing childhood sensitization to allergens through intervention.
- Policy and cost implications of preventing asthma by intervening in the home environment at birth versus later in childhood.
- Information on factors that affect exposure, including research on how risk factors vary by region, by housing type or population characteristics, and by neighborhood-level factors.
- Research on the "hygiene hypothesis" and potential effects on intervention methods.
- Intervention studies in which pets are removed from the home to determine the effect of removal on asthma development.
- Additional data on the health effectiveness of moisture and mold reduction.
- Impact of the infiltration of outdoor air pollutants to indoors.

Issues Related to Housing Structure

- Data to quantify which aspects of household water damage are related to respiratory illness.
- Health impacts of building design and management.
- Areas of potential impact in building code and design to improve the indoor environment for asthmatics.
- Improved labeling of health building materials and home furnishings.
- Relationship between the type of dwelling (apartment, duplex, single family home) and the effectiveness of the intervention.

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Appendix A. Additional Internet Resources

In addition to the references and links appearing in the reference list above, the following table provides selected links with additional information on asthma and related healthy homes issues.

Sponsoring Organization-Topic	Internet Web Site Address
Aerotech Laboratories, Inc. (Indoor air quality testing)	http://www.aerotechlabs.com/
Air Quality Sciences	http://www.aqs.com/
Allergy, Asthma & Immunology Online	http://www.allergy.mcg.edu/
Allergy and Asthma Network—Mothers of Asthmatics, Inc.	http://www.aanma.org/
American Academy of Allergy, Asthma and Immunology	http://www.aaaai.org/
American Conference of Governmental Industrial Hygienists	http://www.acgih.org/home.htm
American Indoor Air Quality Council	http://www.iaqcouncil.org/
American Industrial Hygiene Association (AIHA) Environmental Microbiology Proficiency Analytical Testing (EMPAT) Program	http://www.aiha.org/LaboratoryServices/html/empat1.htm
American Lung Association	http://www.lungusa.org
American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.	http://www.ashrae.org/
Assessment Guide for Building Owners (EPA and NIOSH)	http://www.cdc.gov/niosh/baqtoc.html
Asthma and Allergy Foundation of America	http://www.aafa.org/
California Department of Health Services Indoor Air Quality Program	http://www.cal-iaq.org/
Canada Mortgage and Housing Corporation (Healthy Housing & Sustainability Project Information))	http://www.cmhc-schl.gc.ca/en/index.cfm (http://www.cmhc-schl.gc.ca/en/imquaf/hehosu/index.cfm)
Canada Mortgage and Housing Corporation (Publications on dealing with moisture and eliminating the mold that can result)	http://www.cmhc-schl.gc.ca/en/imquaf/hehosu/hehosu_002.cfm

Sponsoring Organization-Topic	Internet Web Site Address
Center's for Disease Control and Prevention (CDC)	http://www.cdc.gov/
CDC's publications related to various types of mold	http://www.cdc.gov/nceh/airpollution/mold/default.htm
Center's for Disease Control and Prevention (CDC) Air Pollution and Respiratory Health Branch	http://www.cdc.gov/nceh/airpollution/default.htm
Children's Environmental Health Network	http://www.cehn.org/
DHHS Agency for Toxic Substances and Disease Registry	http://www.atsdr.cdc.gov/
DHHS Agency for Healthcare Research and Quality	http://www.ahrq.gov/
Environmental Health Watch	http://www.ehw.org/
Environmental Microbiology Laboratory, Inc.	http://www.emlab.com/
Health House Project of the American Lung Association	http://www.healthhouse.org/
Healthy Homes Partnership—USDA and HUD	http://www.uwex.edu/healthyhome/
HUD's Healthy Homes for Healthy Children	http://www.hud.gov/consumer/hhhchild.cfm
HUD's Office of Healthy Homes and Lead Hazard Control	http://www.hud.gov/offices/lead/
IBT Reference Lab	http://www.ibtreflab.com/
Indoor Air Pollution: An Introduction for Health Professionals (USEPA)	http://www.epa.gov/iedweb00/pubs/hpguide.html
Indoor Biotechnologies, ltd.	http://www.inbio.com/
Institute of Inspection Cleaning & Restoration (fire and flood restoration)	http://www.iicrc.org/
International Union of Immunological Societies/Allergen Nomenclature Sub-Committee	http://www.allergen.org
Johns Hopkins Asthma & Allergy	http://www.hopkins-allergy.org/
Master Home Environmentalist	http://www.alaw.org/air_quality/master_home_environmentalist/
Medscape's Allergy & Clinical Immunology Online	http://www.medscape.com/allergy-immunologyhome

Sponsoring Organization-Topic	Internet Web Site Address
Minnesota Department of Health Children's Environmental Health	http://www.health.state.mn.us/divs/eh/children/index.html
Minnesota Department of Health—Mold in Homes	http://www.health.state.mn.us/divs/eh/indoorair/mold/index.html
National Lung Health Education Program (NHLEP)	http://www.NLHEP.org/
National Safety Council Indoor Air Program of the Environmental Health Center	http://www.nsc.org/ehc/indoor/iaq.htm
New York City Department of Health (Guidelines on Assessment and Remediation of Fungi in Indoor Environments)	http://www.ci.nyc.ny.us/html/doh/html/epi/moldrpt1.html
NIH National Institute of Allergy and Infectious Diseases	http://www.niaid.nih.gov/default.htm
NIH National Heart, Lung, and Blood Institute	http://www.nhlbi.nih.gov/
NIH National Institute of Environmental Health Sciences Asthma Homepage	http://www.niehs.nih.gov/airborne/home.htm
North Carolina State University Extension Service, Mold, dust mites, fungi, spores, and pollen: Bioaerosols in the human environment	http://www.ces.ncsu.edu/depts/fcs/housing/pubs/fcs3605.html
Pure Air Control Services, Inc.	http://www.pureaircontrols.com/
Safer Child, Inc.—Indoor Air Pollution	http://www.saferchild.org/indoor.htm
STL P & K Microbiology (Environmental Microbiology and Mycology)	http://www.stl-inc.com/Labs/P&K/Contacts.htm
University of California Indoor Air Quality Tools: Education, Prevention and Investigation	http://ehs.ucdavis.edu/ftpd/ucih/iaqtools.pdf
University of Minnesota, Department of Environmental Health and Safety, Fungi in Buildings	http://www.dehs.umn.edu/iaq/fungus/
University of Montana Healthy Indoor Air	http://www.montana.edu/wwwcxair/
USEPA Indoor Air Quality Homepage	http://www.epa.gov/iaq/
USEPA Mold Resources	http://www.epa.gov/iaq/molds/moldresources.html
USEPA Office of Children's Health Protection	http://yosemite.epa.gov/ochp/ochpweb.nsf/homepage
USEPA Mold Remediation in Schools and Commercial Buildings	http://www.epa.gov/iaq/molds/mold_remediation.html

Notes

HUD Office of Healthy Homes and Lead Hazard Control

VACUUM DUST SAMPLE COLLECTION PROTOCOL FOR ALLERGENS

For use by:

HUD's Healthy Homes Program Grantees

May, 2008

Original by:
BATTELLE
(Version 1.0)

Revised by:
QuanTech
(Version 2.0)

Acknowledgements:

The persons listed below provided valuable input into this revised sampling protocol and are recognized as contributing authors:

Peter Ashley, DrPH, HUD Office of Healthy Homes and Lead Hazard Control
Gary Dewalt, PhD, QuanTech, Inc.
Robert Hamilton, PhD, Johns Hopkins University School of Medicine
Jeff Jones, City of San Diego
Eugene Pinzer, MS, CIH, HUD Office of Healthy Homes and Lead Hazard Control

For questions or comments please contact Peter Ashley at Peter.J.Ashley@hud.gov

HUD Healthy Homes Grant Program
Vacuum Dust Sample Collection Protocol for Allergens

1.0 Background

This protocol is intended for use by HUD's Healthy Homes (HH) grantees for collecting household dust samples for allergen analyses. Unlike traditional field sampling protocols, this protocol has flexibility built into it with the understanding that different grantees may have different goals and/or resource limitations that require a customized protocol to better suit their needs. As a result, some sections of this protocol describe a specific procedure to be followed whereas other sections provide different guidance options from which the grantees can select.

This protocol has been adapted from the April 30, 2004 (Version 1.0) using lessons learned from the 2006 American Healthy Homes Survey (AHHS). It incorporates procedures for the use of an integrated sample nozzle with removable filter collection sleeve that is being commercially sold as a sampling device for the collection of dust for allergens and other related analyses. Because the collection filters fitting these nozzles are small (typically about 60mm long by 15 mm in diameter), the dust holding capacity is also small. This size issue is a potential limitation in a household environment where animal (pet) hair is found. To combat this problem, this revised protocol includes monitoring the loading of the filter sleeve during sample collection and use of multiple filter sleeves (when needed) to complete sample collection of a selected area.

This protocol also includes the collecting surface area measurements combined with specific sample handling and extraction directives to the laboratory so that allergen-loading results (amount of allergen per surface area sampled) can be determined from laboratory reported results. Although most estimates on the effect thresholds are in concentration (such as mass of allergen per mass of dust), allergen-loading results provide a much better indicator of the amount available for exposure. Therefore, it is important to collect the surface area measurements and for the laboratory processing the collected dust sample to obtain a total sample mass (weight) after sieving the entire collected sample to 300 um.

2.0 Personnel Training

Sampling technicians should undergo a formal training program prior to beginning home visitations and allergen dust sampling. Grantees should document the names of those taking this training and where and when the training took place. Each grantee should devise a program-specific training program to cover the following areas:

- Overview of protocol and purpose
- Code of conduct in homes
- Orientation to data collection forms and appropriate completion
- Orientation to sampling devices to be used
- Handling of sampling materials
- Handling and transport of collected samples (valid and invalid samples)
- Troubleshooting of problems that are likely to be encountered

Sampling technicians must satisfactorily display proficiencies in the areas described above prior to being sent to the field. Before beginning the collection of the official samples for the program, technicians should practice the field-sampling protocol in several dry runs to become comfortable with it. In addition, a handbook should be created by the grantee outlining all of the information necessary to conduct successful field sampling of each housing unit. Copies of this handbook should be given to each sampling technician to use as a reference when needed.

3.0 Vacuum Sampling Materials and Supplies

Prior to visiting a housing unit, each sampling technician should be supplied with the following materials and supplies needed to conduct dust sampling:

> **USEAGE NOTE 1:** It is suggested that you "stage" all of your field supplies (containers, gloves, labels, etc.) so that you have a standard box of supplies that will serve to collect all the samples you might need at one house or at one site. In this box, along with other sampling supplies, you can place a plastic bag containing the replicate labels that are planned for use at a given house. (See section 3-10 below).

3.1 Portable, canister-type vacuum cleaner with hose that will accommodate the selected collection nozzle (no battery operated or rechargeable models), fitted with new/clean vacuum bag.

> **USEAGE NOTE 2:** Battery-operated or rechargeable models are not considered powerful enough to be effective for this sample collection. Vacuum bag is used as a safety measure to capture any dust that might pass through the sample collection filter. It is generally recommended that you have one spare vacuum bag for each vacuum (to use in the case that original becomes clogged or is inadvertently torn such as can occur if a wet area is sampled by accident).

3.2 Collection device: Either Type A (2.1 below) or Type B (2.2 listed below):

- **3.2.1 Type A.** Two collection nozzles with small sample filter sleeve inserts (MiTest, Duststream or similar, see Figure 1). Place the collection nozzle itself in a resealable bag. Place each filter sleeve targeted for use in collecting dust samples into a hard walled sample container along with a filter cap (if available). Include one quart-sized resealable bag for holding together multiple samples collected for the same location (See Note 3).
- **3.2.2 Type B**. Two of each type of vacuum attachments planned for use (floor or upholstery tool, as needed) along with a large disposable one-use "sock" filter sleeve per sample to be collected such as the type available from the Johns Hopkins DACI Reference Laboratory Asthma and Allergy Center [Dupont Hysurf Material: 1 micron exclusion disposable sampling bag, See Figure 2]. Place the vacuum attachments themselves in a resealable bag. Place each large disposable one-use "sock" filter sleeve into a hard walled sample container (See Note 4).

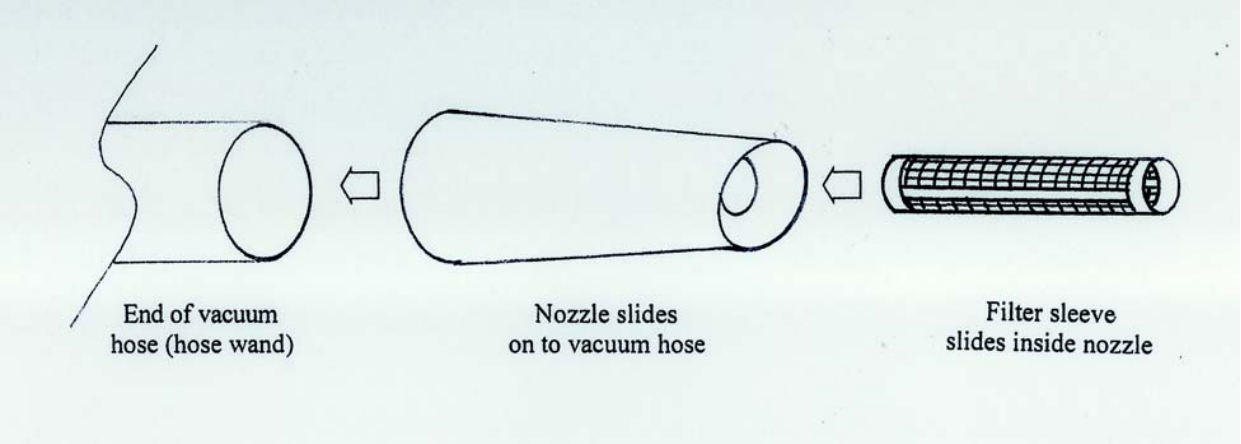

Figure 1. Example Diagram of Type A Collection Device

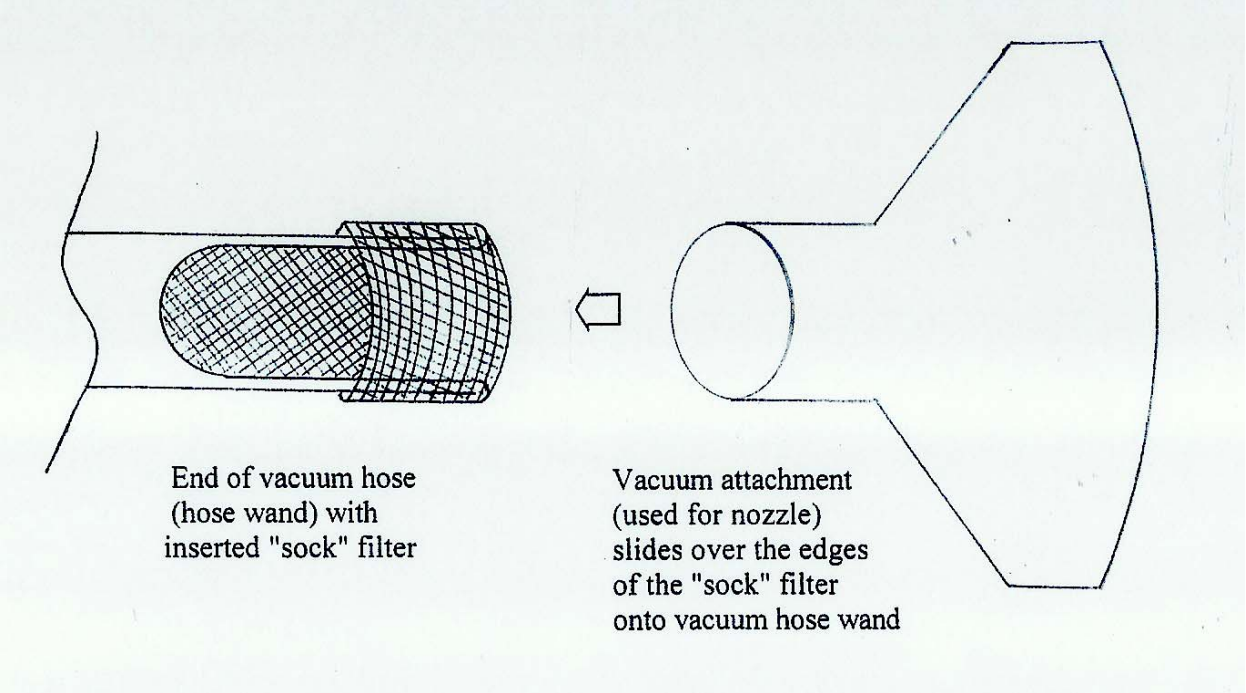

Figure 2. Example Diagram of Type B Collection Device

USEAGE NOTE 3: For Type A collection devices, it is recommended that you use 2 nozzles (per operator) so that one can be drying (after cleaning with a pre-moistened wipe) while the other is being used for collection. Otherwise you have to wait between samples (undesirable). The resealable plastic bag is NOT for holding the sample filters. Plastic bags should never be used to collect dust samples. Static cling is a serious problem when using plastic bags and you will likely lose sample if they are used. For hard-wall containers using Type A collection devices, we suggest using screw top centrifuge tubes big enough to hold the entire filter plus collected dust (50mL, 30mL or 15mL depending on the filter sleeve size). Type A collection devices generally have small filter sleeves. (Typically about 60mm long by 15 mm in diameter). Therefore, they will rapidly clog if you plan to collect samples in anything other than a fairly clean environment. Therefore, we recommend having at least 1 filter sleeve available (not necessarily used) for every 9 square feet (or 1 square meter) of surface collected (two should be considered for floors, while 1 is probably enough for sheets and relatively clean upholstery). This means that the total number of filter sleeves preloaded into hard walled sample containers needed onsite is dependent on the amount of surface area you plan on sampling. All filters that come from a specific sampling location must receive the same sample ID and the total number of sleeves collected for a sample should be placed on the field data collection form (Vacuum Dust Sample Collection Log). Multiple containers containing the used sleeves from the same sample location can and should be placed into a resealable plastic bag to hold them together. Therefore, all those samples inside the hard shell container within the plastic bag must have the same sample ID on them. Then, the lab is directed to combine (before sieving) all the dust contained in all the filters having the same sample ID (collectively stored inside the bag). The plastic bags are not a critical item, but it will help ensure that the lab combines all the collected filter sleeves that belong to one sample location. For example, if the lab misses one of the filters, you are never going to know and it will increase the variability of the pooled results in your study. Therefore, use the plastic bag to direct the lab as to which sample filter sleeves are to be combined for analysis.

USEAGE NOTE 4: For Type B collection devices, this protocol assumes that: (a) the disposable one-use "sock" filter sleeve is sufficiently large (approximately 6 inches long by 2 to 3 inches diameter) to capture all the sampled dust likely to be in selected sampling location without replacement; and, (b) the "sock" filter sleeve can be fitted into the vacuum wand (tube) of the vacuum as needed to collect the sample. It is recommended that you use 2 sets of attachments (per operator) so that one can be drying (after cleaning with a pre-moistened wipe) while the other is being used for collection. Otherwise you have to wait (undesirable). Avoid using attachments that have brushes in them, as these are hard to clean and could represent a source of cross-contamination between samples. For hard-wall containers, we suggest using screw top centrifuge tubes big enough to hold the entire "sock" filter plus collected dust (50mL should be big enough for most sample collection).

3.3. Extension cord (25 feet) with 2-prong adapter.

3.4. Box of disposable wipes for cleaning hands and sampling tools.

3.5. Non-sterilized, non-powdered disposable gloves.

3.6. Surgical booties (optional, as needed to protect residents floors)

USEAGE NOTE 5: The primary technical augment for booties is to prevent cross-contamination of material from one sampling site to another (whether in the same house or between houses). However, the downside to using booties is that they may alarm the residents. From a practical point of view, field staff must be trained to not walk over a sampling area until it has been sampled. Wearing booties does not protect the sampling site if walked on (the booties will pick up dust). Given that one should never be walking into an area where your feet are really dirty (or muddy), use of booties to cover shoes is optional. Use them if needed to protect the resident's floors from your (potentially) muddy feet.

3.7. Timer or stopwatch

3.8. Temperature/relative humidity gauge.

3.9. Vacuum Dust Sample Collection Logs (forms), clipboard and ink pens.

3.10. Sample labels.

USEAGE NOTE 6: It is suggested that you create a defined format for your sample IDs and to create pre-printed sample labels for use in marking sample containers and field forms. By creating them in advance of the fieldwork, you can ensure that all the numbers are truly unique and eliminate potential transposition errors in the field. Sample labels are easy to create using a spreadsheet that can be copied to a pre-formatted Word document (using matching commercially available label sheets). Be sure that your selected label fits on all the sample containers and sheets planned for use. It is generally recommended to create rows of labels with identical numbers on each row. That way one label can be used on the container, one on the field form, one on a chain of custody, etc. When using Type A collection devices, you will have to make a decision as to the maximum number of filters you are ever going to collect for a given location. If you end up using 4 filter sleeves for a single sample, you might need up to 6 identical labels (possibly more than one row of labels).

USEAGE NOTE 7: The sample ID format numbering system you select is somewhat dependent on the numbers and different types of samples you pan on collecting at a given house. Some researchers like to imbed a lot of information into the ID numbers and that can be useful. However, it is worth noting that there is a need to balance the size of the sample ID with the potential for transposition errors: the more complex the number, the easier it will be to make an error when keying it. Simple ID numbers that have a sequential order are useful because you can sort a set of data connected to those ID numbers and rapidly identify gaps in the data (and possibly missing samples). If you are collecting data from housing units, it can also be very useful to assign each house with a unique (base) ID number and each sample collected in that house is given a different sub number. For example, sample IDs X001-01, X001-02, X001-03 are the 1st, 2nd, and 3rd samples that are all collected from a house tagged X001. To use this scheme, all you have to do is label each "box" of supplies to be used at a house with a unique base number (like X001). Then be sure all the pre-

printed labels that you place in that box have that same prefix number. This way, you do not need to assign numbers in advance to the houses...they get assigned automatically by the box that is used for the sampling. Just be sure that the field staff is trained to label the box OPENED once they start using a box for sampling so that it never gets used again for another house.

3.11. Permanent marker

3.12. Low-tack painters tape (blue or green, 1/2 or 3/4 inch)

3.13. Measuring tape, 20 foot showing units in inches

3.14. Trash bags

4.0 Step-by-Step Sampling Procedure

The steps for taking dust samples within a room are as follows.

4.1. Locate area to sample. Upon entering the room to be sampled, establish an area for sampling on the designated components using a measuring tape and low-tack painters tape (if possible) to mark off the chosen area (for rectangular areas, not perimeters). Avoid disturbing or walking in area to be sampled. Avoid disturbing or walking in area to be sampled.

4.2. Plug in vacuum. Plug vacuum into a dedicated outlet and assure that the cord length will be long enough to reach the area to be sampled. Use an extension cord if necessary. Do not plug the vacuum into a circuit believed to be supplying electricity to an air conditioner or water heater. This will avoid overloading and tripping of the breaker or blowing of the fuse. If something must be unplugged in order to plug in the vacuum cleaner, try not to unplug electric clocks, computers that are in use, etc., and be sure to plug items back in after vacuuming is completed.

4.3. Check vacuum. Check to be sure a new vacuum bag is in the unit and that it is clean and not torn.

4.4. Don clean gloves. Put on disposable latex gloves. Booties are optional if shoes are dirty or muddy. If booties are used, they should be put on at the entrance doorway when first entering the house.

4.5. Connect nozzle (Type A collection devices only). Place a clean nozzle on the end of the vacuum hose (hose wand). Use blue painters tape if needed to ensure that the nozzle will not come off during sampling. All clean nozzles are stored in a resealable bag. After collecting a sample at a sampling location, clean the nozzle with pre-moistened wipe and allow to air dry before collecting the next sample or before storing it a in resealable bag. The vacuum can be used to help air dry the nozzle by pointing the nozzle upwards and allowing clean air to flow across it. Do not place a nozzle back into the resealable bag unless it is completely

dry. Do not clean the nozzle when switching a filled filter sleeve for an empty filter sleeve for a single sample location.

4.6. Insert/attach filter sleeve.

4.6.1 Type A collection devices. With the hose wand in the vertical position (pointing up) use a clean, gloved hand to insert the filter sleeve into the nozzle. Turn on the vacuum before pointing the nozzle down to the sampling location (or the filter may fall out).

4.6.2 Type B collection devices. With the hose wand in the vertical position (pointing up) use a clean, gloved hand to insert the "sock" filter sleeve into the end of the hose wand as needed to secure it inside with the edges of the sock overlapping to the outside of the hose wand and then slide on a clean vacuum attachment to hold it in place (see Figure 2).

4.7. Start sample collection. Begin vacuuming the specific sampling area established in the room. *See Section 5, subsections A-F* for specific details on sampling from selected components in designated rooms.

USEAGE NOTE 8: If large debris is encountered in the selected sample area, carefully remove the material by hand first so as not to clog the filter tube and adversely affect the collection of smaller dust allergen particles of interest.

4.8. Tilt the nozzle/vacuum attachment during collection and cover selected area twice. The efficiency of dust collection from a surface is directly related to the air velocity through the nozzle or vacuum attachment at the surface. For flat hard surfaces, no dust will be collected if the nozzle is completely pressed against the surface so that no air can flow. Technicians may have to tip the nozzle slightly to one side while they cover the sampling area so that air is always flowing across the nozzle or vacuum attachment. For surfaces that are porous, such as carpet or upholstery, the amount of the tilt should be reduced but there should still be a visible gap between the nozzle and the sampling surface. Move the nozzle across the sampling area to cover the entire area and then repeat the sampling in a direction perpendicular (90 degrees) to the original direction.

USEAGE NOTE 9: Many vacuum attachments are constructed with small ridges on the face of the attachment so that a gap always exists between the sampling surface and the vacuum attachment. For these types of "nozzles" the technician will not have to tilt the nozzle.

4.9. Complete sample collection:

4.9.1 For Type A collection devices: Change filters when full. While collecting dust, listen to the draw by the vacuum for subtle sound changes that might indicate a clogged filter. If you suspect the filter is full, note the stopping place on the surface being sampled and then point the hose wand in the vertical position (up toward the ceiling), turn off the vacuum and look into the end of the nozzle. If you cannot tell whether it is full, lean over the sampling location and use your gloved little finger to tease the filter out of the nozzle and examine it. If not full, push the filter back into the nozzle. If full, cap the filter (with the supplied cap, if any), place the filter into the hard shell container (where it came from) and re-seal that container, and insert a new filter into the nozzle. Turn on the

vacuum and continue where you left off making sure to vacuum up any dust that might have spilled out of the filter onto the sample location during your examination. Repeat this filter checking and replacement exercise as needed until either the entire sample location has been vacuumed or until the total maximum number of filter sleeves for use on a single location has been reached. In the case that the maximum number of filter sleeves is reached before completing collection at the selected sample location, mark the stopping point using a piece of tape and after storing the last full filter sleeve, measure and record the sample area that takes into account that the sample location was smaller than originally planned.

4.9.2 For Type B collection devices: Continue sample collection at the selected sample location until the desired sampling area has been reached. Point the hose wand in the vertical position (up toward the ceiling), turn off the vacuum and carefully separate the vacuum attachment from the wand at the junction where the filter sleeve is located. Hold down the edges of the "sock" filter sleeve against the wand to ensure that dust is not spilled when removing the attachment. Carefully fold the top of the sock filter to trap the dust inside and place the "sock" filter with dust into the designated hard-shelled sample container. Record the sample area.

4.10. Clean nozzle/vacuum attachment after collection. After collecting a sample at a sampling location, clean nozzle or the attachment and wand with pre-moistened wipe and allow to air dry before collecting the next sample or before storing it a in resealable bag. The vacuum can be used to help air dry the nozzle or the attachment and wand by pointing the nozzle/attachment upwards and allowing clean air to flow across it. Do not place a nozzle/attachment back into the resealable bag unless it is completely dry.

4.11. Label samples and record data. Label each hard-walled container that contains used filter sleeve that came from the same sample location with the same ID number. This ID number must be unique from all others from other sampling areas for a given research program. Record the sample ID, sample location, and sampled area on the Vacuum Dust Sample Collection Log along with all other needed project data (see example form at the end of this protocol). For Type A collection devices where multiple filter sleeves were collected for one sample location, place all the labeled hard-walled containers representing that sample into a single resealable bag.

4.12. Store sample. Place the labeled samples into a suitable container for short-term storage while completing the remaining work in the house. If you used a separate sampling materials box for each house, then this same box can be useful for holding collected samples until the house is completed. At the end of the sampling day, the samples should be relocated to a cool location such as a refrigerator, freezer or cooler. You do not need to put these samples immediately on ice after collection. But for any long-term storage (greater than 2 days), these samples must be stored either refrigerated or frozen to stop the microbial growth.

USEAGE NOTE 10: The purpose to cooling the samples is to stop the microbial growth. Samples can be transported to a storage site or the lab without having to be kept cold provided that such transport does not involve an extended period of time (such as more than several days).

4.13. Record Collection Data. Complete required information on the Vacuum Dust Sample Collection Log for each sample.

4.14. Cleanup. Dispose of any trash generated in the supplied trash bags. No trash generated by the sampling may remain in the housing unit. All trash should be placed in supplied trash bags and properly disposed of off-site.

4.15. Check electrical. After collecting the sample(s) in a room, re-connect lamps or other electrical devices that were disconnected.

USEAGE NOTE 11: Avoid vacuuming wet or damp areas or collecting moist materials.

5.0 Dust Sample Collection Sites (Guidance only)

Table 1 provides a matrix of possible sampling sites within the selected household unit. As mentioned in the background section above, it is up to the grantee to determine the specific number of rooms and components to be sampled. The room(s) selected for sampling depends upon the project objectives. For example, the kitchen should be sampled if reduction in cockroach or mouse allergen loading is a major objective.

Table 1. Potential Rooms and Components for Dust Sampling

Room	Surface	Sampling Area
Kitchen	floor	perimeter (wall/cabinet edge)
Common Living Area	sofa/chair or floor immediately in front of sofa/chair	rectangular areas
Bedroom	floor immediately next to side of bed most commonly used or bedding	rectangular areas
Basement (if present)	floor at bottom of stairs	rectangular areas

Allergen dust samples may be collected from the floor in one or all of the specified rooms (See Notes 12 and 13).

USEAGE NOTE 12: Collection of composite samples (more than one location sampled as a single sample) can be used to reduce analysis costs and field time. However, these gains are generally offset by reduced information that may not be suitable for some research goals and should only be done with care. For example, composite sampling of the floors between a kitchen and bedroom for mouse allergen may advertently assign a rodent risk to the bedroom when the real primary source of this allergen is in the kitchen where food is more often spilled. Additionally, in this example that assumes that mice are more often associated with kitchens, the true magnitude of the allergen in the kitchen is diluted from contributions from the bedroom.

USEAGE NOTE 13: It is important to ensure that enough dust is collected to meet all the analysis requirements for all the target allergens (as required by your laboratory). Differences the cleanliness and surface floor type between different units can impact the amount of dust that is actually collected. Flexibility should be given to the technician conducting the sampling to expand the area of collection should the amount of dust being collected appear to be below that needed to meet the project needs for analysis. However, the technician should take care that such expansions of sampling area (when needed to obtain more dust) still represent the general locations of similar comparative sampling being done in different units. For example, if the target sampling location of 1 square meter on the floor in front of the couch or other most commonly used seat is the common living area, then a needed expanded area should still be centered around the target location.

The room and component combinations that may be sampled in a housing unit include the following:

5.1 <u>Sampling Suggestions Common to All Room Locations</u>: The following suggestions apply to all sampling locations:

- Use a new filter and clean nozzle for each separate sample collected.
- For type A collection devices, swap out filters as needed to collect dust from the entire surface area targeted for sample collection.
- Sample the designated area and record the collected area data and the sample surface type(s) in the Vacuum Dust Sample Collection Log.
- Sample for 5 minutes total.
- For floor samples, do not over sample cracks between floorboards and linoleum or tile. If there is a choice between sampling a rug, carpeting, or smooth floor, consider that the rug and/or carpeting likely will provide a much higher dust yield.
- For (non-perimeter) floor samples, collect rectangular samples and record the length and width dimensions of the sampled area in the Vacuum Dust Sample Collection Log.
- Record the room temperature and relative humidity in the Vacuum Dust Sample Collection Log

5.2. <u>Kitchen Floor</u>: Vacuum the entire perimeter of the kitchen (i.e., along base of walls, appliances, cabinets, etc.). If the counter is formed as a peninsula or island, vacuuming should follow the base of it as appropriate. Do not move appliances to vacuum behind or between them. Vacuuming should be performed for a minimum of 5 minutes. The perimeter of the floor area sampled (including all turns) must be measured to the nearest inch (or centimeter, if these units are used in the Log) and recorded in the Vacuum Dust Sample Log. The total sampled area is equal to the width of the nozzle times the perimeter length. The width of the nozzle must be measured to the nearest one-eighth inch (or millimeter, if these units are used in the Log) and recorded in the Vacuum Dust Sample Collection Log.

Suggestions specific to kitchen floor sampling:

- For perimeter floor samples in the Kitchen, sample the entire perimeter, including edges and around appliances. Push one edge of nozzle against wall while sampling. Record perimeter length sampled and the nozzle width in the Vacuum Dust Sample Collection Log. Do not sample inside cabinets and underneath refrigerators and other appliances.

5.3. <u>Common living area floor</u>: For this room, vacuum at least 9 square feet (or 1 square meter) of surface directly adjacent to a frequently used sofa (or chair) for 5 minutes total.

5.4. <u>Common living area sofa (or chair)</u>: Collect a dust sample from the sofa (or chair) most often used in the selected common living area. Only upholstered sofas (or chairs) should be sampled. Vacuum the seat cushions, seat back, and arms of the sofa (or chair). Vacuum approximately 9 square feet (or 1 square meter) of upholstered surface. This typically corresponds to an entire chair, about ½ of a love seat, or about 1/3 of a sofa. If a cushion is present on a wooden or metal sofa (or chair), the cushion should be sampled. If the cushions within the targeted surface collection area are reversible, vacuum both sides. Also vacuum any throw pillows in the area. The sample should be collected for 5 minutes.

Suggestions specific to upholstery sampling:

- Sample designated area. Define a set of rectangular areas that add up to the total targeted sample area. Use low-tack tape to mark either the corners or the entire parameter of each area.
- Do not vacuum the area under the cushions or deep into the crevices of the sofa where large particles tend to collect.
- Record the dimensions of each and every rectangular area making up the total sample area in Vacuum Dust Sample Collection Log.
- Record the upholstery type in the Vacuum Dust Sample Collection Log.
- Sampling of upholstered surface may be performed in an alternate manner (e.g. sampling only seat cushions, not sampling pillows, etc.). If so, details of collection should be specified in an alternate protocol to be used by all technicians for sampling of sofa (or chair), and sampled surface area(s) should be recorded in sample log.

5.5. <u>Bedroom Floor</u>: For this room, vacuum at least 9 square feet (or 1 square meter) of surface directly adjacent to the side of the bed most often used by the resident for 5 minutes total. If possible, arrange the sampling area so that about one-quarter of the area to be vacuumed is under the bed. If this is not possible (i.e., because the mattress is on the floor, or objects under the bed prevent access), include as much of this desired area as possible under the bed.

5.6. <u>Bedroom Bedding</u>: Collect the bedding sample from the bed most often slept in. Occasionally, a bed may not be a conventional bed (i.e., it may be a couch or a pad). Sample these in a manner similar to a conventional bed. Handle all bedding layers with care and do not step on them. Occupants may be asked to assist in the sampling of the bedding. Vacuum all layers of the bedding (i.e., covers, blankets, top sheets, bottom sheet, mattress pad, "egg-carton" style pads, mattress, and pillows) for a total of **5 minutes**. Vacuum at least **2 square meters** of the bedding: if the bed is a single bed, vacuum the entire surface; if it is a double bed or larger, measure one meter width and vacuum down the length of the bed within the 1-meter wide area. The breakdown of the bedding sample follows:

1. **30 seconds** - one pillow (preferable the primary sleeping pillow) inside the pillowcase (if possible) without removing the pillowcase, and both sides of the pillow
2. **2.5 minutes** - all of the bedding layers described above.
3. **2 minutes** - mattress surface (impermeable, fully encapsulated mattresses should be sampled by vacuuming the top layer. Do not remove the cover).

Handle all bedding sensitively. Do not put it on the floor or in a place where it can get dirty or stepped on. Ask the family for assistance or suggestions, if necessary. Remake the bed as closely as possible to the way the family had it made up originally.

> **USAGE NOTE 14**: Bedrooms are rooms that people sleep in on a regular basis. Rooms that are designed as bedrooms, but are being used for another purpose (e.g., as a guest room, office, playroom, sewing room, or storage room) are not included as bedrooms.

Suggestions specific to sampling bedding:

- The following items should not be vacuumed in the bedroom: stuffed animals, areas under the mattress, towels, and box spring surfaces.
- Rolled up blankets that serve as pillows should be vacuumed if they are on the bed at the time of sampling.
- To the degree possible, record total sample area in sample log.
- Record bedding layers sampled in the sample log.

5.7. <u>Basement Floor:</u> A finished basement also may be sampled at the discretion of the investigator. However, finished basements are generally considered as low priority locations for sampling for allergens. Suggestions for locating this sample include: the center of the largest open area of the floor or the floor at the bottom of the stairs. Wherever the sample is located, this information should be clearly defined in the final protocols used by all technicians collecting these samples. For this room, vacuum at least 9 square feet (or 1 square meter) of surface for 5 minutes total.

6.0 Dust Sample Collection Logs

Examples of three Dust Sample Collection Logs are provided in Appendix A: one for floors, one for upholstery and one for bedding. These are adapted from the dust sample logs used in the HUD sponsored National Survey for Lead and Allergens in Housing (completed) and the HUD sponsored American Healthy Homes Survey (nearly completed). These logs are intended for use in collecting a single sample in a specific room. The comments section of these example logs can be reduced and the space used to add other information that you may wish to collect on a room-by-room basis. When in use to collect an actual sample, the technician should make an entry in each and every block shown on these logs. If no comments are applicable, then the technician should make an entry of "no comment". Clarifications on the various entry blocks on the forms are provided in the front of Appendix A.

7.0 Shipping Samples to Laboratories

Collected dust samples should be stored cold or frozen until they can be batched together with an Allergen QC Sample (provided by HUD) and then shipped to the laboratory for processing and analysis (See Note 10). Because of the potential to inadvertently introduce moisture into collected samples, ice should never be used to keep collected dust samples cold. Allergen QC samples should be incorporated in with your collected field samples at a minimum rate of 1 per every 20 field samples.

8.0 Laboratory Processing Directives

Laboratories provide allergen results as a concentration by weight (amount of allergen per gram of dust). In order to determine a loading value (amount of allergen per area of surface collected), you must measure the area being collected and the total sieved weight of the entire collected sample. Obtaining this information is a key element often missing from laboratory processing of dust samples for allergen testing. Normally, the lab only extracts 100mg of the sample. The lab is not likely to extract the entire collected sample when the weight is larger than 100mg and they may not sieve the samples unless directed to do so. The only way to convert laboratory reported results (in amount of allergen per gram of sample) to a loading is to multiple the reported results by the total sieved sample weight and divide it by the collected sample area (see Note 13). The total sieved weight is desired because real-world dust samples often have a lot of larger material that will not be extracted into the solution the laboratory creates from the dust sample to perform the testing. Therefore, you must direct the laboratory to sieve the entire collecting sample and measure the sieved weight of the total sample that you collected in the field. If more than one filter is used to collect dust from a single selected location, then all the material in those filters must be combined and then filtered as one sample. If you follow the directives in this protocol, then the sample filters to be combined by the laboratory are all those that have the same sample ID and are grouped together in one resealable plastic bag. At the time this revision of this protocol was prepared, HUD is recommending to all grantees that they ensure that they give their lab a directive to sieve all submitted samples to 300 µm (Sieve Size No. 50), obtain and report a total sample mass (weight) along with the allergens results, and extract all (sub-) samples overnight with agitation before testing for allergens.

Chain of custody forms should be completed for all samples shipped to a laboratory in order to maintain of record of the parties responsible for the sample integrity at any given time and to provide a written record of the specific samples shipped to the laboratory for analyses. An example chain of custody form is provided in Appendix A.

USEAGE NOTE 15: An example of converting ug/g to ug/square foot is:A = [(B)(C)]/D
where: A= results in ug per square foot
B= results in ug/g
C = total sieved sample weight in grams
D= total sample collection area in square feet

9.0 Additional Suggestions

In addition to the protocol specifications outlined above, the following optional procedures might also prove useful.

Photographs. The taking of photographs might be helpful in later interpretation or to serve as a record in longitudinal studies where repeat measurements might need to be taken over time. If photos are to be taken, then a camera and supplies should be added to the grantee supply list for all sampling. Photos taken should be organized and adequately documented in order to ensure that they will be useful at a later point in time.

Site Plan. A site plan or drawing of the housing unit, including indications of sample areas and room measurements also may be useful in later interpretation or as a record for repeat measures over time in longitudinal studies. If a site plan is to be drawn for each housing unit then adequate supplies to measure and record such a rendering should be added to the supply checklist for each housing unit.

Appendix A - Example Vacuum Dust Collection Logs

Two example logs are provided in this Appendix: one for sampling dust from floors and one for sampling dust from upholstery. These forms each have 12 data entry blocks roughly arranged (top to bottom, left to right) in the likely order of completion during data collection. Also included at the end of this appendix is an example chain-of-custody log that may be used to track the custody of the samples from creation in the field to delivery to the lab targeted for processing the samples. When in use to collect an actual sample, the technician should make an entry into each and every data entry block on the forms. Clarifications for these 12 data enter blocks are provided below:

House ID. This is a unique identification (ID) for this house. Example IDs range from a full street address to an assigned sample ID number that is identified on some other project form.

Competed by. This is the name of the technician collecting the sample.

Date. This is the date when the sample was collected.

Sample ID. This is a unique identification (ID) for the collected vacuum dust sample. The block is sized to accept most sample ID labels.

Sample Collected? This is used to indicate whether a sample was collected and why not if it was not collected. If a sample is not collected, the technician should complete the header of the form (House ID, Completed by, and date), the "Room Location" block and circle "2" under the "Sample Collected?" block indicating that no sample was collected. They should also enter a code as to why the sample was not collected. Defined codes are shown at the bottom of the form. If none of the codes are suitable, the technician should create a new unique code and define it under the comments block of the form.

# of Filters Collected for this Sample. This is used to indicate the total number of filters used to collect the entire dust sample at the targeted sample location. The laboratory may need this information to be sure that they know how many filters need to be combined together to process the entire collected sample. One method to transferring this data to the lab (other than sending the lab a copy of this form) is to note this number under the Comments column of chain-of-custody form that accompanies the sample to the lab.

Room Location Code. This is used to indicate which room was sampled.

Sample Surface Code. This is used to indicate the type of sampling surface.

Vacuumed Sample Area. This is used to indicate the dimensions of the sampled area. The form is currently setup for using inches (not meters, centimeters and millimeters). Use of these units reflects the more commonly available tape measures that can be purchased in the U.S and the fact that most U.S. residents think in terms feet and inches (not meters). Please note that only the dimensions of the sampling areas are recorded on the form and not the calculated sample areas. This is done because it is generally safer to avoid having

technicians do calculations in the field as the potential for introducing error increases, as the field efforts get more complex.

- For a perimeter sample, both the nozzle width and perimeter length must be recorded. The total sample area for a perimeter sample is the nozzle width times the perimeter length.
- For a typical rectangular floor sample, both the length and width must be recorded and the technician must be cautioned to be careful to make the corners as close to right-angles (90º) as possible. In general, most technicians are quite capable of getting the corners close enough to 90º using only their eyes as tools. The total sample area for a rectangular floor sample is the length times the width.
- For upholstery samples, the total sampling area is comprised of a series of rectangular areas. Therefore, there are multiple entries for recoding the length and width dimensions of each of these areas. The total sample area for upholstery samples is the sum of all the separate rectangular sample areas (sum of length times width of each rectangular area).

Room Temperature. This is used to indicate the room temperature. Allow the probe or measuring device to equilibrate (as required by the manufacturer) before taking a reading and avoid areas that are not representative of the temperature of the room (such as near a heating or cooling device).

Room Humidity. This is used to indicate the relative room humidity. Allow the probe or measuring device to equilibrate (as required by the manufacturer) before taking a reading and avoid areas that are not representative of the humidity of the room.

Comments. This block is used to record general comments about the sampling. In the case where there are no comments, then the technician should make an entry of "no comment". However, as a general rule, technicians should be encouraged to make comments about the conditions found and any other issue that could impact the validity or value obtained from the collected sample. Part of this space of the form can also be edited to hold questions aimed at obtaining relevant answers about the room being sampled. The questions asked are often project specific but may include the questions listed below in Table 2:

Table 2. Example Room Observation Questions

Room Observations [circle one for each row]		Room Observations [circle one for each row]	
1 Mildew observed?	1=Yes 2=No	7 Evidence of rodents?	1=Yes 2=No
2 Other moisture evidence?	1=Yes 2=No	8 Room air conditioner?	1=Yes 2=No
3 Food debris observed?	1=Yes 2=No	9 Dehumidifier?	1=Yes 2=No
4 Evidence of smoking?	1=Yes 2=No	10 Air cleaning device?	1=Yes 2=No
5 Cockroach stains?	1=Yes 2=No	11 Humidifier/vaporizer?	1=Yes 2=No
6 Live/dead cockroaches?	1=Yes 2=No	12 Musty or moldy smell?	1=Yes 2=No

Vacuum Dust Sample Log for Floors

House ID: _____

Completed by: _____ (*name*) on _____ (*date*)

Sample ID: _____

Sample Collected?: [circle one]
Yes 1
No 2
If No, reason code:_____

# of Filters Collected for this Sample: _____

Room Location Code (circle one)	Sample Surface Code (circle all that apply)	Vacuumed Sampled Area (Measure in units shown below)
Kitchen.....1 Common Living Area .....2 Bedroom .....3 Other.....4 enter:_____	Smooth/cleanable.....1 Not smooth .....2 Carpeted.....3	**Perimeters only:** Nozzle width: |___||___| and |___|/8 inches Perimeter length: |___||___||___||___|inches **Rectangular Areas only:** |___||___|inches X |___||___|inches

Room Temperature ºF: _____ Room Humidity: _____

Comments:

No Reason Codes: I=Inaccessible, NO=Note allowed to sample, O=other:_____

Vacuum Dust Sample Log for Upholstery

House ID: _____

Completed by: _____ on _____

(name) *(date)*

Sample ID: _____

Sample Collected?: [circle one]
Yes 1
No 2
If No, reason code:_____

# of Filters Collected for this Sample: _____

Room Location Code (circle one)	Sample Surface Code (circle all that apply)	Vacuumed Sampled Area (Measure in units shown below)
Kitchen.....1 Common Living Area .....2 Bedroom .....3 Other.....4 enter:_____	Leather .....1 Plastic/vinyl.....2 Velvet/velour.....3 Woven Fabric .....4 Other.....5 enter:_____	**Rectangular Areas only:** |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches

Room Temperature ºF: _____ Room Humidity: _____

Comments:

No Reason Codes: I=Inaccessible, NO=Note allowed to sample, O=other:_____

Vacuum Dust Sample Log for Bedding

House ID: _____

Completed by: _____ on _____

(name) *(date)*

Sample ID: _____

Sample Collected?: [circle one]
Yes 1
No 2
If No, reason code:_____

# of Filters Collected for this Sample: _____

Room Location Code (circle one)	Sample Surface Code (circle all that apply)	Vacuumed Sampled Area (Measure in units shown below)
Kitchen.....1 Common Living Area .....2 Bedroom .....3 Other.....4 enter:_____	Pillows .....1 Sheets .....2 Blankets.....3 Woven Fabric .....4 Other.....5 enter:_____	**Rectangular Areas only:** |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches |___||___|inches X |___||___|inches

Room Temperature ºF: _____ Room Humidity: _____

Comments:

No Reason Codes: I=Inaccessible, NO=Note allowed to sample, O=other:_____

Field Chain-of-Custody for Vacuum Dust Samples

House ID:

Completed by: _____ on _____

(name) *(date)*

Sample ID	Comments
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	
Field sample ID label here	

Relinquished by: Date / Time:	Relinquished by: Date / Time:
Received by: Date / Time: Condition Acceptable? ❒ Yes ❒ No	Received by: Date / Time: Condition Acceptable? ❒ Yes ❒ No