Healthy Homes Issues:

Asthma

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Office of Healthy Homes and Lead Hazard Control

HEALTHYHOMES
Healthy Families | Healthy Children

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Asthma

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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.

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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

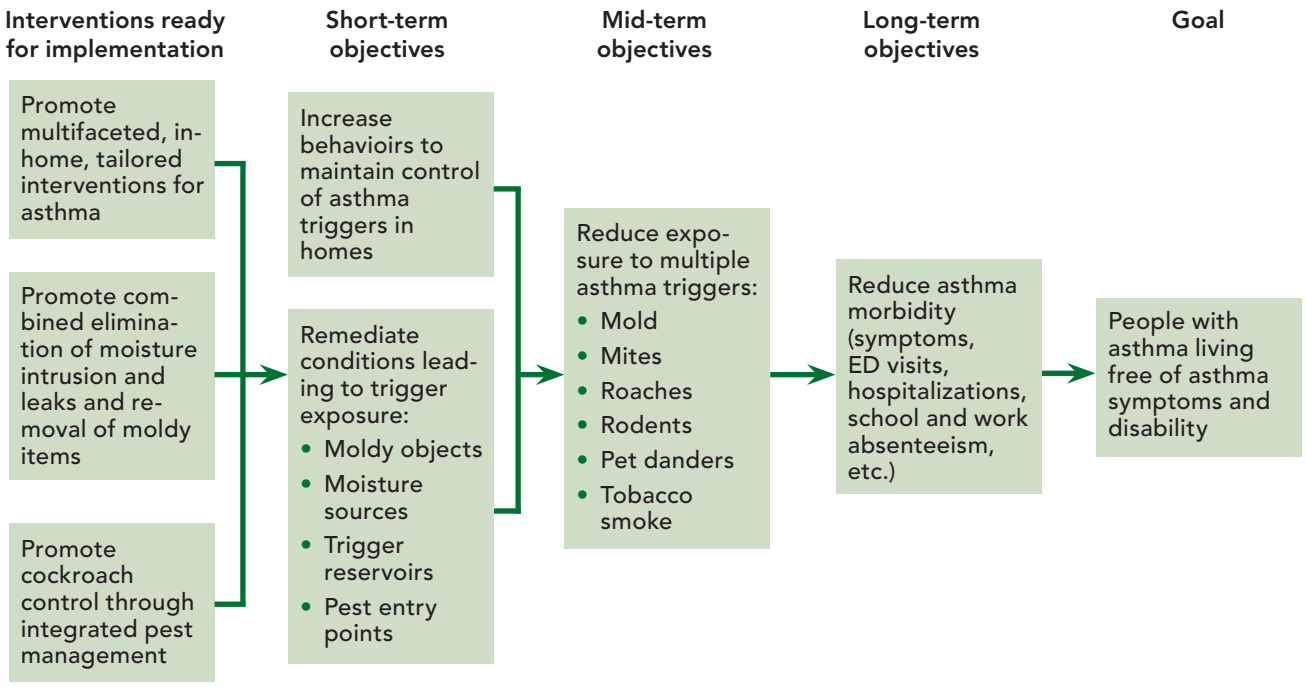
Table 7. Summary of the State of Evidence Related to Home Environmental Interventions for Asthma

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:

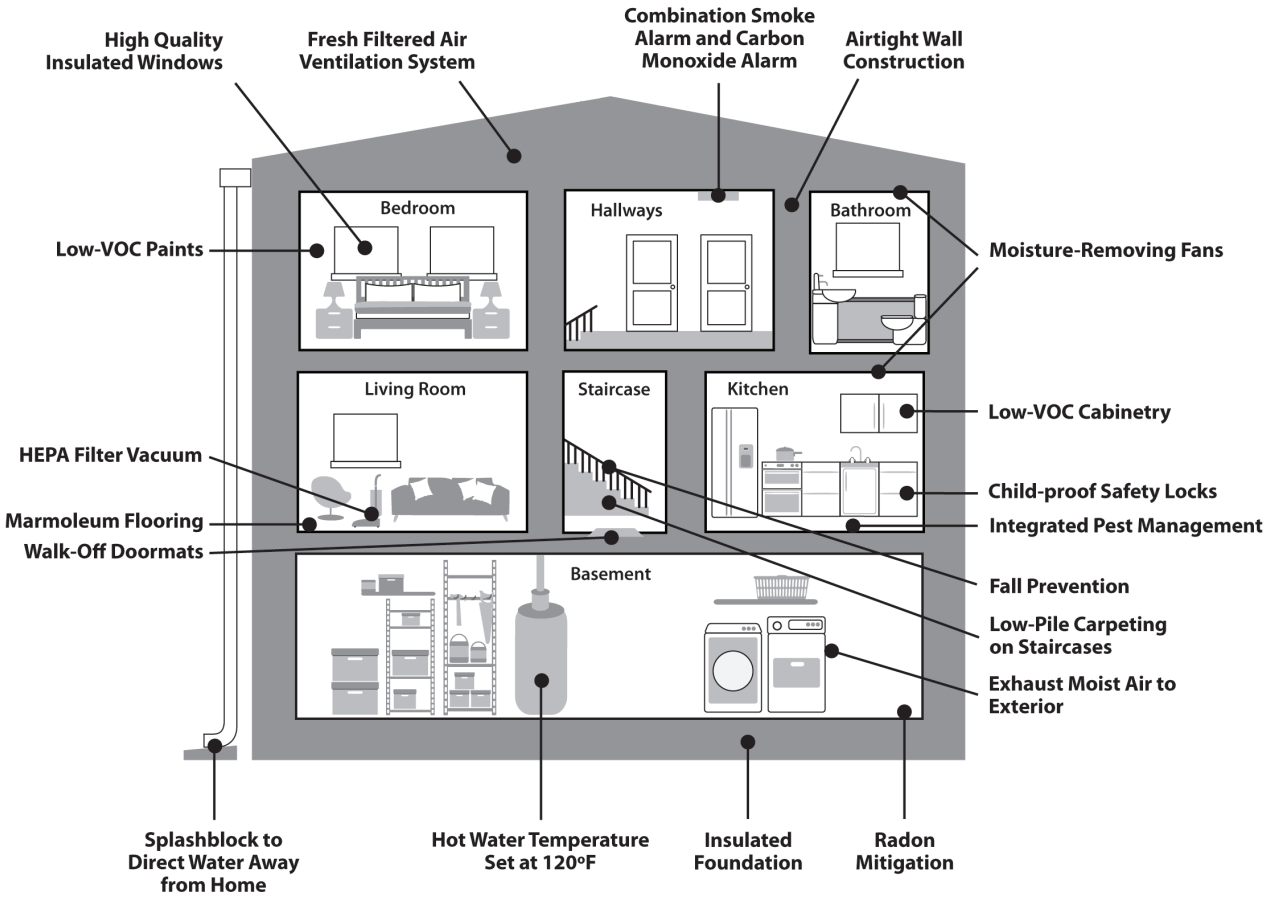
- Enhanced exterior envelope to optimize moisture-proofing;
- Interior finishes, flooring, and other materials that minimized dust accumulation and off-gassing;
- Energy efficient heat-exchange ventilation system with filtration and continuous fresh air supply.

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.

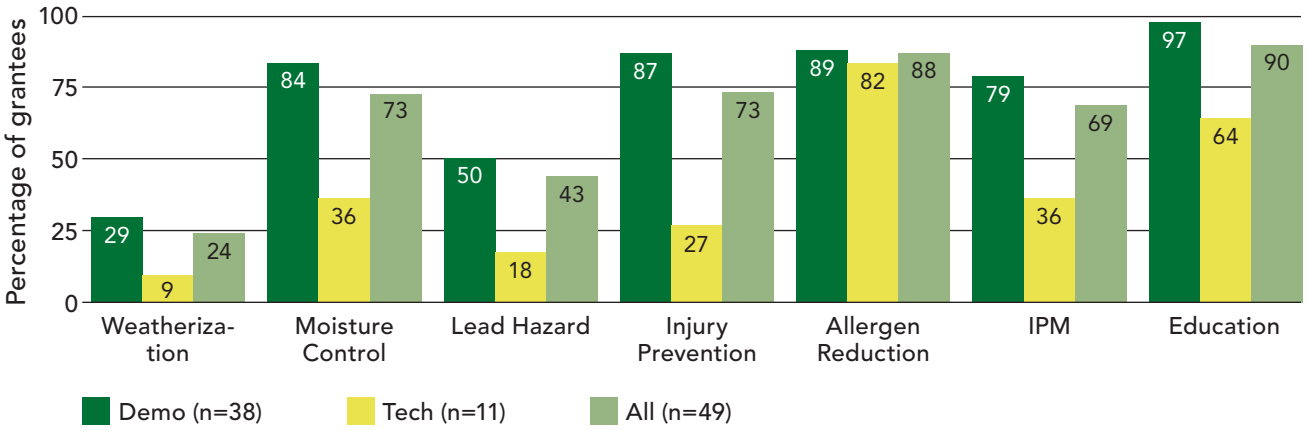
The applicability of these interventions on a wide scale is demonstrated in a recent evaluation of HUD Healthy Homes grantees (HUD 2007). The majority (78%) of Demonstration and Technical Studies grants used remediation of the housing unit and education of the occupants in over 6,268 housing units. While 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