Appendix 1. Summary of findings on Indoor Environmental Quality and Health (organized by type of risk or exposure)

Many review articles or chapters have extensively reviewed aspects of relationships between IEQ and health (none focusing specifically on children in schools, although including articles on this topic). Reviews are available on the following topics:

- Respiratory infections and building environments (Fisk 2000).
- Dampness in buildings and health (Bornehag et al. 2001).
- Moisture and mold as risks for respiratory health effects (Peat et al. 1998).
- Indoor environments and asthma (Committee on the Assessment of Asthma and Indoor Air 2000), including a section on asthma and schools (pp. 321-323).
- Pets and asthma or allergies (Ahlbom 1998).
- HVAC system type and symptoms in buildings (Seppanen and Fisk 2002).
- Ventilation rates and health in buildings (Seppanen et al. 1999).
- Indoor environments and symptoms in offices (Mendell 1993).
- Many other IEQ and health relationships, including indoor chemical and biological pollutants, and effects including building-related illnesses, sensory irritation, eye irritation, and skin responses (Spengler et al. 2000).

The following text summarizes findings in the published scientific literature between aspects of IEQ and the health of occupants of buildings. Much of this research was conducted in office buildings rather than schools; it is unknown how such findings may apply across different types of buildings and occupants.

Measured IEQ factors and relationship to health

This section will summarize available evidence on relationships between measured IEQ factors and health outcomes among occupants. Measured IEQ factors here include specific pollutant exposures (biological, chemical, or particulate, measured indoors or outdoors), pollutant control processes (e.g., ventilation rate), and thermal parameters.

Indoor pollutants and relationship to health

- *Indoor Biological Pollutants*–In recent decades, researchers have rarely found relationships between conventionally measured indoor concentrations of culturable microorganisms and health outcomes (Mendell 1993). Only recently, mostly using new metrics of exposure and response, have researchers begun finding relationships between higher air or dust concentrations of microbiological organisms or related materials and health outcomes. Multiple studies have now reported relationships between concentrations in air or dust of culturable fungi and bacteria or their products or of other biological materials, and allergic, immunologic or inflammatory response, including asthma (Skov et al. 1990; Hodgson et al. 1991; Rylander et al. 1992; Mendell 1993; Gyntelberg et al. 1994; Li et al. 1997; Smedje et al. 1997; Garrett et al. 1998b; Meyer et al. 1999; Norback et al. 2000a; Seuri et al. 2000b). Concentrations of cat and dog allergens in schools, transported there on clothes of pet-owning children, are sufficiently high to cause perennial symptoms among sensitized children with asthma (Munir et al. 1993; Berge et al. 1998; Perzanowski et al. 1999; Elfman et al. 2000). Exposures to molds, bacteria, or their products such as spores or metabolites may cause a variety of health effects, through largely unknown mechanisms. Mold spores and toxins may cause inflammation of mucosal membranes and produce allergic reactions or otherwise influence the immune system, thereby facilitating viral and bacterial infection in the respiratory tract (Flannigan et al. 1991).

- *Indoor Chemical Pollutants*–Studies decades ago documented the presence of hundreds or thousands of chemical compounds in the air of typical indoor environments (e.g., the Total Exposure Assessment and Measurement (TEAM) study) (Wallace et al. 1987). These compounds have been widely suspected of causing the health complaints reported from many buildings during these decades. To document this, many studies have now assessed relationships between summary metrics of chemical compounds in indoor air and irritant or other symptoms among occupants. Few of these studies have found measured chemical exposures, when assessed with summary metrics such as total volatile organicic compounds (TVOC), to be related to symptoms (Mendell 1993), and some have even found inverse relationships (Bluyssen et al. 1996). Studies, however, have found evidence of other relationships and processes that may explain how VOCs can produce irritant responses that are not associated with conventional exposure assessment metrics. The explanations may include the effects of compounds not measured or recognized; the creation of highly irritant but short-lived compounds not identified or readily measured (Weschler and Shields 2000; Wolkoff et al. 2000); inflammatory effects of chemicals like formaldehyde or nitrogen dioxide at typical levels not thought to have health effects (Pazdrak et al. 1993; Wantke et al. 1996; Pilotto et al. 1997 Smedje et al. 1997; Garrett et al. 1999; Franklin et al. 2000; Norback et al. 2000a); and previously unrecognized pulmonary sensitizing effects of chemicals at low levels from cleaning activities (McCoach et al. 1999; Zock et al. 2001). In all these cases, inflammatory effects of exposures may promote sensitization to potential allergens present.

- *Indoor Particulate Pollutants*–Studies have found that airborne or settled indoor dust can produce nasal inflammation, upper-respiratory and mucus membrane irritation, and neuropsychologic effects (Walinder et al. 1999; Mølhave et al. 2000 Norback et al. 2000a).

- *Outdoor Pollutants*.–Higher concentrations of outdoor gaseous or particulate pollutants have been found to be related to diagnosed asthma (Guo et al. 1999), decreased peak expiratory flow (Steerenberg et al. 2001), markers of lung or nasal inflammation (Steerenberg et al. 2001), and asthmatic symptoms (Ramadour et al. 2000) but not atopy as defined by skin prick tests (Charpin et al. 1999). Because many pollutants originating outdoors enter readily into buildings and become indoor pollutants, and people spend most of their time (greater than 90 percent) indoors, primary human exposures to many outdoor pollutants may occur indoors. For example, nitrogen oxides and particulate matter generated by nearby traffic penetrated indoors readily at a day-care center (Partti-Pellinen et al. 2000). Traffic count on streets near schools showed a dose-response relation with sensitization to pollen, determined by skin prick tests and serologic examination, among occupants of schools, suggesting increased allergic sensitization from vehicle exhaust generated outdoors (Wyler et al. 2000). Therefore, the epidemiologic relationships consistently found between outdoor concentrations of key pollutants and human responses *may* be due largely to indoor exposures, with measured outdoor concentrations in available studies having served largely as proxies for unmeasured indoor levels. If this were true, altered characteristics of buildings or ventilation systems might substantially reduce exposures to pollutants originating outdoors.

Control of indoor pollutants and relationship to health

Available findings document that increased outdoor air ventilation rates in buildings are associated with decreased building-related symptoms among occupants, up till at least 20 cubic feet per minute (cfm) per person and possibly up to 30, 40, or more cfm per person (Mendell 1993; Seppanen et al. 1999). Exposures in specific buildings depend on sources, source strengths, pollutant removal, and other factors. These findings therefore suggest that dilution, through outdoor air ventilation, of the indoor air pollutants found in buildings in general, reduces currently uncharacterized indoor exposures that otherwise would cause acute symptoms among occupants. This dilution has been shown to reduce pollutant-related inflammation of mucosal membranes (Walinder et al. 1997; Walinder et al. 1998). Outdoor air ventilation rate *per person* in these studies (Walinder et al. 1997; Walinder et al. 1998) was not associated with the assessed outcomes, suggesting that pollutants produced by the building or its interior rather than those produced by occupants were critical for human health responses. On the other hand, ventilation may also, by reducing indoor concentrations of infectious agents originating from occupants, reduce infectious respiratory disease (Seppanen et al. 1999; Fisk 2000; Menzies et al. 2000; Milton et al. 2000; Mendell et al. 2002a).

Indoor physical parameters and health

Physical parameters in indoor environments that have been related to the health of building occupants include thermal parameters such as temperature, humidity, light, and noise, of which only the first two are reviewed here.

Lower temperatures within the conventional thermal comfort envelope has been associated fairly consistently, in a substantial number of studies, with health benefits such as reduced symptoms (Jaakkola and Heinonen 1989; Skov et al. 1990; Jaakkola et al. 1991b; Wyon 1992; Menzies et al. 1993; Meyer et al. 1999; Reinikainen and Jaakkola 2001; Mendell et al. 2002b), improved performance-related mental states (Mendell et al. 2002b), and reduced nasal congestion and inflammation (Walinder et al. 1998), and rarely with adverse effects such as increased prevalence of asthma (Smedje et al. 1997).

Evidence on humidity, more limited and less consistent, suggests that higher relative humidity within a moderate range may reduce symptoms (Reinikainen et al. 1992; Nagda and Hodgson 2001; Mendell et al. 2002b), whereas lower relative humidities may have benefits such as reduced prevalence of asthma (Smedje et al. 1997) or reduced transmission of common respiratory infections (Milton et al. 2000). However, disagreement exists about the indoor humidity levels best for indirect effects on health of occupants, with respect to survival of infectious organisms, growth of fungi, formation or release of toxic chemicals, and so on (Arundel et al. 1986; Baughman 1996; Milton et al. 2000). (For additional discussion of humidity as related to humidification, see below.)

IEQ-related characteristics of buildings and relationship to health

- *HVAC characteristics and relationship to health*

Research findings on relationships between ventilation systems and health consistently show associations between more complex mechanical ventilation systems and increases in prevalence of various symptoms among occupants, relative to naturally ventilated buildings without ventilation systems. Among mechanically ventilated buildings, an even higher prevalence of symptoms has been found in association with air-conditioned or humidified buildings, with differences between types of humidification systems not clearly evident (Mendell and Smith 1990; Mendell 1993; Seppanen and Fisk 2002). Sufficient information on the nonspecific symptoms assessed is generally not available in these studies to suggest biological mechanisms. One study, however, found mechanical ventilation to be associated not only with nasal congestion but also with objectively measured swelling of nasal mucosal and biomarkers of nasal inflammation (Walinder et al. 1998), suggesting increased exposures to inflammatory substances, either biological or chemical. Overall, findings on this question suggest increased risk of adverse exposures associated with complex ventilation systems, particularly if they involve water. However, some buildings of each kind of ventilation system have prevalence of symptoms as low as naturally ventilated buildings, suggesting that increased risk is not inherent in ventilation systems but may be related to aspects of design, operation, or maintenance.

As mentioned in the section on HVAC characteristics and absenteeism, the findings of Milton et al. (Milton et al. 2000) that suggest increased illness-related absenteeism in offices in relation to humidification contrast with those of several studies that have found humidification of school buildings to be associated with lower rates of respiratory infections or absenteeism (Sale 1972; Green 1974). Humidification of buildings and indoor relative humidity may confound each other's relationships to health and absenteeism among occupants in many reported field studies. Adverse effects of potential microbiological exposures from contaminated humidifiers may diminish any positive effects of higher humidity, or increase apparent positive effects of low humidity. Studies reporting positive effects of humidification or of higher relative humidity may be seeing underestimated net benefits resulting from true positive effects of higher indoor relative humidity lessened by negative effects of microbiologically contaminated humidification systems. Nevertheless, humidification systems have been documented to cause adverse health effects, some serious, and the effective prevention of this risk by use of biocides or of specific types of humidification has not been documented.

Some evidence is available to document health benefits of air filtration in ventilation systems to remove particles or gases from indoor air (Kemp et al. 1998; Mendell et al. 2002b). Relationships have been found between poor design, operation, or maintenance of HVAC systems, particularly those related to potential microbiological contamination, and increased risk of respiratory symptoms or disease (Sieber et al. 1996; Mendell et al. 2003).

- *Building and occupied space characteristics and relationship to health*

Numerous studies have associated dampness, water-damage, mold damage, or related indicators with respiratory, atopic, immunologic, or inflammatory effects (Thörn et al. 1996; Li et al. 1997; Peat et al. 1998; Rudblad et al. 1999; Committee on the Assessment of Asthma and Indoor Air 2000; Taskinen et al. 2000; Bornehag et al. 2001; Walinder et al. 2001a; Meklin et al. 2002; Taskinen et al. 2002). Schools located near high-traffic roads had higher atopic sensitization to pollen among students, with a dose-response relation between traffic count and sensitization (Wyler et al. 2000).

Studies have found relationships between a variety of indoor surface types, including carpet (Hansen 1987; Norback and Torgen 1989; Norback et al. 1990; Skov et al. 1990; Dybendal and Elsayed 1992; Wargocki et al. 1999; Lagercrantz et al. 2000), plastic surface materials (Jaakkola et al. 1999; Oie et al. 1999; Jaakkola et al. 2000b; Jaakkola et al. 2000a), fleecy or fabric surfaces (Skov et al. 1990; Jaakkola et al. 1999), and health effects including bronchial obstruction, asthma severity, release of inflammatory mediators, and neurologic and other symptoms. Also, less frequent cleaning of surfaces and wet mopping of floors were associated with nasal congestion and inflammation (Walinder et al. 1999)