Appendix F: Detailed Discussion of Research Studies on Occupant Health, Comfort, and Productivity[1]

This appendix provides details on the studies reviewed for Section 2.6 ("Lower Absenteeism and Improved Productivity") and Section 3 ("The Social Benefits of Sustainable Design"). The studies deal with indoor air quality (Section F.1) and other sustainable design practices (Section F.2).

F.1 Indoor Air Quality

This section describes the studies reviewed on increased ventilation effectiveness, low-emitting materials, indoor chemical and pollutant source control, controllability of systems, thermal conditions, daylight and views, and potential problems with daylight and windows.

F.1.1 Increased Ventilation Effectiveness

Increased ventilation effectiveness includes strategies such as natural ventilation, increased air change rate, increased volume of outdoor air, and increased air filtration. The health benefits, productivity benefits, and comfort and satisfaction of such strategies are discussed below.

Health Benefits

Many large-scale building studies show that increased volumes of outdoor air, natural ventilation, air ventilation rates, and filtration of air and improved cleaning and maintenance of systems are correlated with reduced sick building syndrome (SBS) symptoms as well as reduced allergy and asthma symptoms and transmission of infections diseases (Brightman and Moss 2000; Fisk 2001). Most of the studies cited in the literature are surveys and do not include information on how frequently windows are opened by the workers in naturally ventilated buildings. Therefore, it is not known whether positive impacts are due to psychological factors (e.g., control) or to actual increases in fresh air. Further, in areas where outdoor air has high levels of pollutants or allergens, indoor air quality may actually be compromised. For instance, a study in Norway found that nurses experienced more eye irritation in hospitals near roads with heavy traffic because of the increased dust settlement rates (Smedbold et al. 2001).

A controlled field experiment by Wargocki et al. (2000) in Denmark found that increasing ventilation rates beyond minimum levels prescribed in standards is associated with reduced symptoms. Three outdoor air change rates were studied: 0.6, 2, or 6 air changes (AC)/hr (corresponding to 3, 10, or 30 liters (L)/person/hr). Temperature and humidity were kept constant at 72°F and 40% relative humidity. The researchers found that the workers felt better and had fewer symptoms as ventilation rates increased. The workers also perceived the air as fresher.

A study of 3720 employees in 40 buildings also found reduced symptoms and lower absenteeism in buildings with higher ventilation rates (Milton et al. 2000). The "high" ventilation rate was about 50 cubic feet per minute (cfm)/person outdoor air compared with a "moderate" rate of 25 cfm/person. (This corresponds to 12 L/person/hr and 24 L/person/hr; these data are very consistent with the Wargocki et al. [2000] study.) Milton et al. (2000) estimated the cost of sick leave as $480/person/yr.

[1] This appendix was written by J. Heerwagen, Pacific Northwest National Laboratory.

Productivity Benefits

Performance assessments in work settings are rare because of the difficulty of capturing actual performance measures and linking them to specific environmental features. Nonetheless, a field experiment in Denmark shows that workers performed better on a typing task and perceived themselves as able to think more clearly with increased ventilation (Wargocki et al. 2000). A field experiment by Nunes et al. (1993) looked at the link between SBS symptoms associated with ventilation rates and work performance. They found that workers reporting SBS symptoms worked 7.2% more slowly on a vigilance task and made 30% more errors on a numerical task.

Other studies have assessed self-ratings of productivity. Based on a study of 40 buildings in the United Kingdom, occupants in naturally ventilated or mixed-mode buildings rated their perceived productivity significantly higher than occupants of air-conditioned buildings (Leaman and Bordass 2001). Similar results were found in a study by Rowe et al. in Australia where workers in mixed-mode buildings rated their work performance higher (cited in Leaman and Bordass 2001).

Comfort and Satisfaction

Workers prefer spaces with operable windows compared with completely mechanically ventilated and conditioned spaces, except in hot summer weather (Leaman and Bordass 2001). In the Wargocki et al. (2000) study cited above, workers were more satisfied with the air quality and rated the air as fresher with increased ventilation, from 0.6 AC/hr to 6 AC/hr.

F.1.2 Low-Emitting Materials

The vast majority of research on materials emissions has been conducted in specialized facilities and cannot be generalized to office environments. However, as discussed below, some field studies provide data on occupant health and productivity benefits.

Health Benefits

Brightman and Moss (2001), in a review of large-scale studies of SBS in Europe and the United States, identify carpet as a key risk factor in SBS. Other building factors that show mixed findings (some show increases in symptoms, others do not) are total volatile organic compounds (VOCs), fleecy materials, and formaldehyde. (Work and personal factors affecting symptom occurrence include stress, history of allergy, high use of photocopy machines, and high level of paper work.) A field intervention by Pejtersen et al. (2001) compared symptoms in a newly renovated area of a building with a control group who did not experience the renovation. The upgrades included renovating the HVAC system and replacing the carpet with a low-emitting vinyl floor material. The researchers found significantly improved perceptions and reduced illness symptoms in the renovated space. It is not known, however, to what extent the improvements were due to the HVAC system or to changes in the floor materials.

Productivity Benefits

A field simulation study testing the effects of a 25-year-old carpet on work performance found that when the carpet was absent, performance increased on a variety of clerical as well as complex cognitive tasks requiring mental effort and high attention, including logical thinking, arithmetic, and vigilance (Wargocki et al. 2000). The authors attribute this to airborne particulates, although the exact mechanisms by which particulates might affect cognitive functioning are not discussed.

F.1.3 Indoor Chemical and Pollutant Source Control

Relatively little work has been done on controlling indoor chemicals and pollutant sources. No studies were found on productivity or comfort, and only two studies on health impacts were found. For instance, a Danish experimental office study found an increase in eye and skin irritations in an office with computers, laser printers, and a photocopier than an office without the technologies. The office with the equipment was found to have higher levels of ozone, respirable particulates, and VOCs (Wolkoff et al. 1992). Brown (1999) also found that emissions from dry-process photocopiers increased when temperatures increased from 73ºF to 90ºC and that particle emissions occurred when the copier was idle and copying. Numerous other studies, cited in Hedge (2000), noted that SBS problems increase for workers with high computer use.

F.1.4 Controllability of Systems

A growing body of literature in building science and health care underscores the psychological, functional, and health benefits of having some degree of control over the physical environment, including ventilation, temperatures, lighting, and privacy. The health benefits, productivity benefits, and comfort and satisfaction from such controls are discussed below.

Health Benefits

A field study of an air filtration system integrated into the office furniture system at the breathing zone in a Canadian government building found lower levels of symptoms and reduced absenteeism rates compared with a control floor that did not have the system (Hedge et al. 1993).

A study of 11,000 workers in the Netherlands by Preller et al. (1990) found that absenteeism due to SBS is likely to be 34% lower when workers have control over their thermal conditions. A field study of a furniture-integrated breathing zone system in a Canadian government office building found reduced absenteeism and lower levels of symptoms than a control floor in the same building without the system (Hedge et al. 1993).

Productivity Benefits

Studies have documented increases in work performance on various tasks when occupants have some degree of control over temperature and/or ventilation conditions at their workstations (Kroner et al. 1992; Wyon 1996). Kroner et al. (1992) used organizational performance data to assess the impact of personal control over temperature and ventilation at the workstation level and concluded that the control system increased productivity by 3%.

Drawing on a review of research on indoor air quality and thermal conditions, Wyon (1996) estimated that providing workers with temperature control of just three degrees (plus or minus) would result in performance increases of 7% for typical clerical tasks, 2.7% for logical thinking tasks, 3% for skilled manual work, and 8.6% for very rapid manual work.

A large-scale office study in England also shows that personal control over the environment (as measured by a summary of ratings of perceived control over lighting, noise, temperatures, and ventilation) was one of four key factors affecting occupants' perceived productivity at work (Leaman and Bordass 2001). Of these controls, the most important was control over noise and the least important was control over lighting. The authors also conclude that personal control is less important to workers when ambient conditions are comfortable and when building managers respond promptly to discomfort complaints.

Comfort and Satisfaction

There is evidence that people are more tolerant of conditions the more control opportunities they have, regardless of whether they choose to use the control (Leaman and Bordass 2001). Overall comfort and satisfaction also increases with personal control over ventilation and temperatures (Kroner et al. 1992; Brager and deDear 2000).

F.1.5 Thermal Conditions

The literature on thermal comfort in buildings is voluminous (for instance, see deDear et al. 1993). No attempt is made here to provide a detailed review of this research, much of which focuses on comfort. Key findings from the literature show the following:

- Thermal discomfort is common in buildings.
- Temperature conditions influence symptoms associated with SBS.
- Performance impacts of thermal conditions depend on the nature of the tasks as well as on personal factors.

The health benefits, productivity benefits, and comfort and satisfaction from thermal conditions in buildings are discussed below.

Health Benefits

Elevated temperatures are associated with increases in illness symptoms (Wyon 1996, 2000). As researchers systematically increased indoor temperatures from 68°F to 76.2°F, they found increased incidents of headache and other SBS symptoms. Wyon (1996) also reports increased incidence of headache and fatigue as indoor temperatures increase from 68°F to 76°F. At 76°F, 60% of the workers experienced headache compared with 10% at 68°F.

An extensive review of the epidemiological literature found that "dampness" (a thermal comfort factor) in buildings increases the risks of respiratory symptoms (cough, wheezing, and asthma) as well as other symptoms such as tiredness, headache, and respiratory infections (Bornehag et al. 2001). Unfortunately, the study's data are from worker surveys and do not include actual moisture levels or sources of the problem.

Performance Benefits

Although discomfort is believed to negatively affect productivity, the relationship is complex and is related to the nature of the work itself, time of day, and personal factors such as pre-existing medical conditions (Wyon 1996, 2000). For instance, performance on creative and memory tasks is higher when temperatures are slightly elevated. However, performance decreases on tasks requiring concentration and logical thinking tasks when temperatures are slightly elevated. Performance on these types of tasks is better when temperatures are slightly cool.

Comfort and Satisfaction

Numerous studies in the United States and elsewhere have consistently shown high levels of dissatisfaction and high variability in comfort for any given thermal condition (Heerwagen and Diamond 1992; Leaman and Bordass 2001). Given the high range of variability in comfort, the ability to control temperatures and ventilation at the workstation level may be the single most effective way of increasing thermal comfort (Wyon 1996).

In a study of the costs of dealing with discomforts, Federspiel (2000) estimates that efforts to increase comfort could result in a 12% decrease in labor costs of responding to complaints. His data show that it takes 1.4 hours on average to diagnose a hot complaint and 1.7 hours to diagnose a cold complaint. His data also suggest that complaints are not due to differences among individuals, but rather to HVAC faults or poor control performance.

F.1.6 Daylight and Views

It has long been known that people prefer to be in spaces with windows and daylight (Collins 1975). However, it is only recently that researchers have begun to investigate the health and productivity impacts of daylight and views. The following summarizes the research on daylight and views:

- Daylight and sun penetration may have positive benefits on health.
- The benefits of views depend to a large extent on the view itself (e.g., degree of naturalness and distance of the view).
- Although there is little evidence for direct impacts on work performance, window views have been found to influence a number of mental processes that are associated with performance on complex cognitive tasks.

The health benefits, productivity benefits, and comfort and satisfaction from daylight and views in buildings are discussed below.

Health Benefits

A field study of lighting conditions in a government office building in England found that headache incidence decreased significantly with increased access to daylight (Wilkins et al. 1989). People who suffer from Seasonal Affective Disorder (SAD) may also benefit from access to daylight. Because people with SAD prefer more brightly lighted spaces than people who do not suffer from seasonal variation in mood and well-being, being adjacent to a window where light levels are higher than interior spaces may have therapeutic effects (Heerwagen 1990). Although daylight design generally tries to reduce or eliminate the penetration of direct sunlight into buildings, a modest level of sunlight (sun "spots") may be beneficial to health and well-being.

Two studies are cited in a report prepared by Johns Hopkins researchers on the connection between the built environment and patient outcomes (Rubin et al. 1998). One study compared the length of stay for 174 patients with depression who were randomly assigned to a "sunny" or dull hospital room (Beauchemin and Hays 1996). Those in the sunny rooms stayed an average of 16.9 days compared with 19.5 days for patients in the rooms without sun. The results held true regardless of season. Another healthcare study cited in the Johns Hopkins report found that differences in exposure to natural sunlight affected the serum OH-D concentrations in long-term geriatric patients (Lamberg-Allardt 1984). There is also reason to believe that access to high daylight levels and sunlight for at least part of the day would be beneficial to persons suffering from SAD (Heerwagen 1990). Daylight and sunlight "patches" indoors have been found also to enhance emotional functioning, as long as the sunlight does not increase glare or temperature discomfort (Boubekri et al. 1991; Leather et al. 1998).

Physical benefits of windows and views (especially views of nature) include stress reduction and recovery from illness. In a study of patients recovering from hospital surgery, Ulrich (1984) found that those who had a view of a natural landscape recovered faster and spent fewer days in the

hospital than matched control patients who viewed an adjacent wing of the hospital. Although similar studies have not been conducted in work settings, other research cited above clearly indicates that nature views have positive impacts on stress recovery. In a field study of office workers, Kaplan (1992) found that workers with window views of nature felt less frustrated and more patient and reported more overall life satisfaction and better health than workers who did not have visual access to the outdoors or whose view consisted of built elements only. When deprived of windows, people report more negative moods and a loss of contact with the outdoor world, especially loss of connection to time and weather (Collins 1975; Heerwagen and Orians 1986).

Productivity Benefits

The only current data available on the impact of daylight and views on performance are from a large-scale study of the link between daylight design and test performance in schools (Heschong-Mahone Group 1999). The study found that children scored higher on test scores in schools with the best daylight design. However, many other building factors may have influenced these outcomes. Thus, the results should be taken as preliminary until additional research support is found.

Studies of window views show that people perform better on tasks requiring focused attention (such as proofreading) when they have views of nature compared with views of buildings or windowless conditions (Hartig et al. 1991). Window views may be especially effective in providing micro rest breaks of a few minutes or less. Micro rest breaks have positive impacts on performance and attention (Zijlstra et al. 1999).

Although full spectrum electric light is widely believed to have benefits similar to daylight, no scientific evidence exists for this claim. A major review of the research in this area by Veitch and McColl (1994) found no indications that full spectrum fluorescent lighting was associated with any increases in psychological well-being, health, or productivity.

Comfort and Satisfaction

Numerous office studies in the United States, England, and Europe have found increased satisfaction levels with increases in daylight (Collins 1975; Heerwagen and Diamond 1991; Leaman and Bordass 2001). Although most research on windows has focused on views, the size and location of windows also matters. A series of studies by Butler and Biner (1989) shows that the preferred size, shape, and location of windows are functions of the specific space under consideration. People prefer larger windows in settings for relaxation and smaller windows in settings where privacy is desired (e.g., bedrooms and bathrooms).

F.1.7 Potential Problems with Daylight and Windows

Although windows and daylight have numerous benefits, as identified above, they also have the potential to create discomfort and distractions when not properly designed. Office studies in the United States and elsewhere have consistently found that workers are bothered by glare from windows, and this is especially problematic for computer work. These problems are resolved to a great extent using flat screen computers and indirect lighting (Hedge et al. 1995). The absence of sunlight controls also increases the potential for heat stress. Heat reflective glazing and shading devices do not fully resolve these difficulties (Heerwagen and Diamond 1991; Leaman and Bordass 2001). Furthermore, for facilities with 24-hour operation schedules, the lack of daylight and views may lead to feelings of inequitable distribution of amenities among night-time workers who do not have the same access to daylight and views (Heerwagen and Wise 1998).

F.2 Other Sustainable Design Practices

Although interior design strategies are not included in the current version of the Leadership in Energy and Environmental Design (LEED™) rating system, practitioners are beginning to specify more open plan environments as a way to reduce materials, especially dry wall, and to make daylight and views more broadly available for workers. This section reviews research on open plan layouts and partitions.

F.2.1 Open Plan Layouts and Partitions

Open plan, dense workspaces present serious challenges for sustainable design. On the positive side, the open plan, flexible, condensed workstation layout reduces the overall use of resources, allows more efficient use of space, reduces surfaces that collect dust, and allows daylight to penetrate deeper into the space. It is also evident that open plan design aids communications and information flow that are so important in many work environments. On the negative side, however, an open plan design increases the potential for distractions and interruptions that may reduce productivity for complex cognitive work, as well as the potential for more rapid transmission of illness. These issues are discussed in more detail below.

Comfort and Satisfaction

Open plan layouts, especially those with low partitions, facilitate access to daylight and views. Workers in open plan spaces that facilitate access to windows are more satisfied overall with lighting and with the work environment (Collins 1975; Heerwagen and Diamond 1991). Open plan workspaces also increase people's awareness, information exchange, and general communication levels (Heerwagen and Hunt 2002). Of the factors that contribute to situation awareness, "visible activity" is considered to be the most important (Gutwin and Greenberg 2001). High visual access aids the ability to see others.

Productivity

Szilagyi and Holland (1980) found that increased workstation density increased satisfaction and information exchange and facilitated tasks for new employees and secretarial staff, but not for managers and for workers with many years of tenure. The researchers suggest that when employees are relatively new, they may be using the surrounding social environment as a source of information and feedback about how to successfully accomplish their jobs. For workers whose tasks are repetitive and cognitively simple, the open plan environment may have positive performance impacts. Researchers hypothesize that the beneficial effects are due to social facilitation that may increase stimulation and effort associated with having their work on view to others (Geen and Gange 1977).

Research has also shown that ready access to others in a work group can aid spontaneous problem solving and information flow and reduce the time to market for some products (Teasley et al. 2000). However, the productivity benefits are clearly related to the specific nature of work and cannot be generalized to all contexts because of the potential for serious increases in distractions and loss of privacy.

F.2.2 Problems with the Open Plan Environment

The benefits of open plan, densely packed workspaces need to be carefully balanced with the potential negative impacts on both psychological factors and physical health. Specifically, research shows the following potential problems:

- **Physical health.** Increased density of workstations and open plan environments increase the overall environmental load of airborne microbials and thus facilitates transmission of illness symptoms (Fisk 2001). Open plan spaces also lead to increased distractions. Distractions often lead to increased psycho-physiological activation indicating that some increased effort is needed to maintain performance (Tafalla and Evans 1997). For complex tasks, the increases in effort may be substantial enough to produce physiological stress.

- **Comfort and satisfaction.** Open plan spaces make it more difficult for workers to have private conversations (Sundstrom et al. 1982). This impedes the ability to develop close work relationships and can also lead to increased feelings of stress and dissatisfaction (Gabarro 1987). There is little evidence that providing small, private booths compensates for the loss of privacy at the workstation.

- **Productivity.** Open plan workspaces increase distractions that are especially detrimental to complex cognitive tasks. Distractions interfere with working memory and analytical thought processes. Distractions are also more of a problem for introverts than for extraverts (Morgenstern et al. 1994; Belojevic et al. 2001). Belojevic et al. found that concentration problems and fatigue were more pronounced for introverts working in noise compared with quiet conditions. Researchers believe these results are due to differences in psycho-physiological activity. Introverts have a more pronounced reaction to noise and this may lead to heightened arousal, which interferes with performance on complex mental processing tasks (Eysenck 1982; Stansfeld and Shine 1993). Furthermore, extroverts regularly select higher noise intensities as optimal, compared with introverts (Geen 1984). These results suggest that design and location of people in settings should take into account these personality differences. Introverts may need to have more enclosure or to be located farther away from sources of distracting noise.