Photo Credit: Paul Sterbentz (Carnegie Institution of Washington)

Mixed-Mode Cooling

By Gail S. Brager, Ph.D., Fellow ASHRAE

Prior to the 1950s, commercial buildings used natural ventilation for cooling. Buildings typically had extended perimeter zones so that every office could have access to windows that opened to the outdoors and provided the primary source of light and fresh air.

However, the availability in the 1950s of large-scale mechanical cooling, along with other technologies such as curtain walls and fluorescent lighting, led to the more common building forms we see today in North America—typically all-glass, flush-skin buildings with large floor plates and no operable windows.

Our technological capabilities allow architects greater design freedom while they can relinquish responsibility for environmental control to the engineers, who use their ingenuity to design mechanical systems that will ensure (ideally) thermal comfort regardless of the loads that are imposed. In air-conditioned buildings, thermal conditions generally are perceived to be predictable and controllable, with the goal of maintaining consistent indoor thermal conditions uniformly across space and throughout the day, regardless of the outdoor climate.

However, this comes at an enormous cost in terms of energy consumption and associated environmental consequences. In addition, occupants who work behind these sealed façades, isolated from the natural rhythms of the day, develop what some consider to be an addiction to the air conditioning that provides this narrow range of constant setpoint temperatures. Although one can find conceptual references to this in the literature, quantitative evidence also is found in the much

About the Author

Gail S. Brager, Ph.D., is a professor at the University of California, Berkeley, and associate director of the Center for the Built Environment.

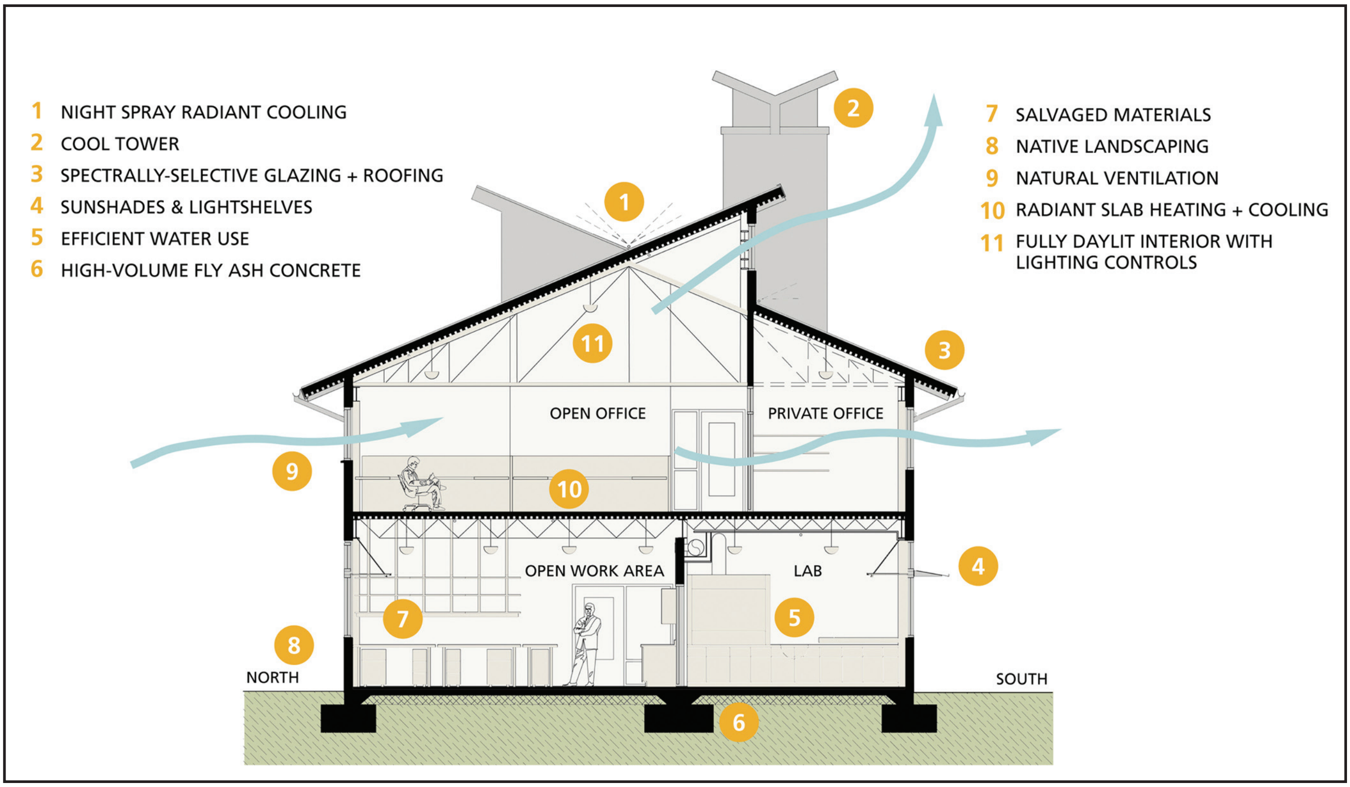

Photo 1 (opposite page): Carnegie Center for Global Ecology in Stanford, Calif. Figure 1 (above): Carnegie Center for Global Ecology, environmental control strategies (Credit: EHDD Architecture).

faster rate at which people express thermal dissatisfaction in air-conditioned buildings as the temperatures deviate from this narrow range.[1]

Growing concerns about energy efficiency, along with the exponential growth of the broader green building movement, has led to renewed interest in naturally ventilated buildings. This interest is natural (excuse the pun), given all the documented benefits of operable windows: thermal comfort over a wider range of temperatures, based on the adaptive comfort zone;[1] reduced energy consumption compared to conventional air-conditioned buildings;[2] and fewer sick building syndrome symptoms.[3] However, this interest also is coupled with a variety of concerns and design challenges. Given our modern expectations, engineers are often uneasy about the lack of predictability and control over indoor thermal conditions in naturally ventilated buildings. As a result, many innovative engineers are exploring mixed-mode buildings, which is a way to combine the best features of naturally ventilated and air-conditioned buildings. This article provides an overview of mixed-mode buildings, and describes some of the research that is investigating their performance.

What is a Mixed-Mode Building?

Mixed-mode refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled) or other passive inlet vents, and mechanical systems that provide air distribution and some form of cooling. A well-designed mixed-mode building allows spaces to be naturally ventilated during periods of the day or year when it is feasible or desirable, and uses air-conditioning for supplemental cooling when natural ventilation is not sufficient. The goal is to provide acceptable comfort while minimizing the significant energy use and operating costs of air conditioning.

Mixed-mode buildings often are classified in terms of their operation strategies, such as concurrent (mechanical cooling and natural ventilation can operate in the same space at the same time); changeover (the building switches between mechanical cooling and natural ventilation on a seasonal or daily basis); or zoned (mechanical cooling and natural ventilation operate in different areas of the building).

Natural ventilation or mixed-mode strategies may not be suitable for all situations, perhaps least so for climates with very high humidities, or sites with excessive levels of outside noise or pollution. However, many climates and sites exist for which it is feasible, and worthy of consideration. And even in the more extreme climates, one might consider whether a sufficient number of swing season months exist when it is worth incorporating operable windows.

Collaborative Design Process

A key to all high-performance design—and no less so for mixed-mode buildings—is an integrated design process where multidisciplinary collaboration happens early and often. A good example of this is the design of the new Federal Building in San Francisco.[4] This is a zoned mixed-mode building where the lower five floors are sealed and fully air conditioned, primarily driven by security reasons, but also programmed so that areas with intensive computer use or other high air-conditioning needs are placed on those floors. The upper 13 floors are zoned such that the perimeter areas are all open plan and exclusively naturally ventilated, while the closed offices and conference rooms are located along the central spine and are exclusively air conditioned. In addition to client meetings with the eight different federal tenant agencies involved with this building, the design process was an excellent example of extremely close collaboration between the architects, mechanical and structural engineers, as well as the involvement of researchers from Lawrence Berkeley National Laboratory and University of California, San Diego, who did extensive modeling of the natural ventilation strategies and various window configurations and control algorithms.[5]

Control Strategies

No standard protocols exist for the operations and control strategies for mixed-mode buildings, nor is there consensus about the relative degree of personal vs. automated controls that one should provide. One facet of this debate is the underlying objectives of trying to optimize both comfort and energy consumption. Adaptive comfort theory demonstrates that greater degrees of personal control allow occupants to fine-tune their thermal environment to match their own personal preferences, while also resulting in a wider acceptable range of temperatures in the building.[1] This might lend support for simpler controls, and relying more on educating occupants about how to operate the building most efficiently to respond to their comfort needs.

Others are proponents of sophisticated integration of the HVAC and building fenestration systems, using window sensors, actuators, and control algorithms that respond to indoor and outdoor climate conditions in an attempt to optimize both energy and comfort. However, as one moves towards a fully automated central control system, there is the risk of losing the adaptive opportunity afforded by personal controls, as well as increasing the inherent cost and maintenance required for a more complex system. Leaman and Bordass[6] have written extensively about mixed-mode buildings, and one publication particularly focuses on the pros and cons of controls complexity in buildings.

Daly[7] used single-zone computer simulations to predict indoor temperatures and energy use for various mixed-mode control strategies, and found that significant energy savings were possible. He investigated scenarios including all mechanical cooling and ventilation, all natural ventilation with different assumptions about window operation, concurrent mixed-mode, and changeover mixed-mode with various alternative scenarios of window switch control, occupancy sensor control, and informed occupant control.

The next step in refining a model such as this would be to develop realistic scenarios about how the changeover mode might operate on a seasonal basis, allowing the building to operate in a purely naturally ventilated mode during the swing seasons, combined with concurrent mode in the more extreme months.

Clearly, more than one right way exists to approach the controls challenge, and the best solution may fall somewhere in the middle of the continuum of possibilities. Perhaps the most important action that engineers can take is to familiarize themselves with the various design and control opportunities, so they can select the one that best fits the needs of the building, client, occupants, and budget. The mixed-mode case studies presented later in this paper describes some of the options.

Analysis Methods

Although no standardized analysis methods exist for assessing the performance or control algorithm for mixed-mode buildings, significant advances have been made in recent years. The International Energy Agency's Annex 35 HybVent is an international collaborative research project involving more than 30 organizations from 15 countries. The consortium's research projects on hybrid ventilation include the development of control strategies and analysis methods, theoretical and experimental studies, and year-round monitoring of thermal comfort, IAQ and energy consumption in pilot study buildings. The project has an extensive Web site (http://hybvent.civil.auc.dk) and has generated many publications offering critical reviews of the literature, describing various design methods and simulation techniques and their applications (ranging from simple analytical and empirical methods, to multizone and CFD techniques) and presenting results of their own work.[8] Some of the projects refer to hybrid ventilation as simply the combination of natural and mechanical ventilation, while others look at the combination of operable windows and mechanical cooling (what is referred to here as mixed-mode).

Axley, et al.,[9] have proposed a multiphase analytical design approach that can be applied at different phases of the design process. It begins with a climate suitability analysis technique based on a general single-zone thermal model, which is applied during the preliminary phases of a project, and estimates design ventilation rates. Then during design development, they use a loop equation design method based on multizone airflow analysis to size ventilation system components, followed by a more detailed multizone coupled thermal airflow analysis to estimate overall building performance and fine-tune system characteristics. As a follow-up to this research, Emmerich and Crum[2] used multizone thermal airflow simulation to model systems in a five-story office building in five U.S. cities, evaluating performance in terms of ventilation, thermal comfort, and energy. They found that the natural ventilation systems performed well in San Francisco and Los Angeles, but poorly in Boston, Minneapolis, and Miami. The mixed-mode operation improved the performance in all climates, with dramatic improvement in some, while saving significant amounts of fan and/or cooling energy compared to the mechanical-only cooling systems.

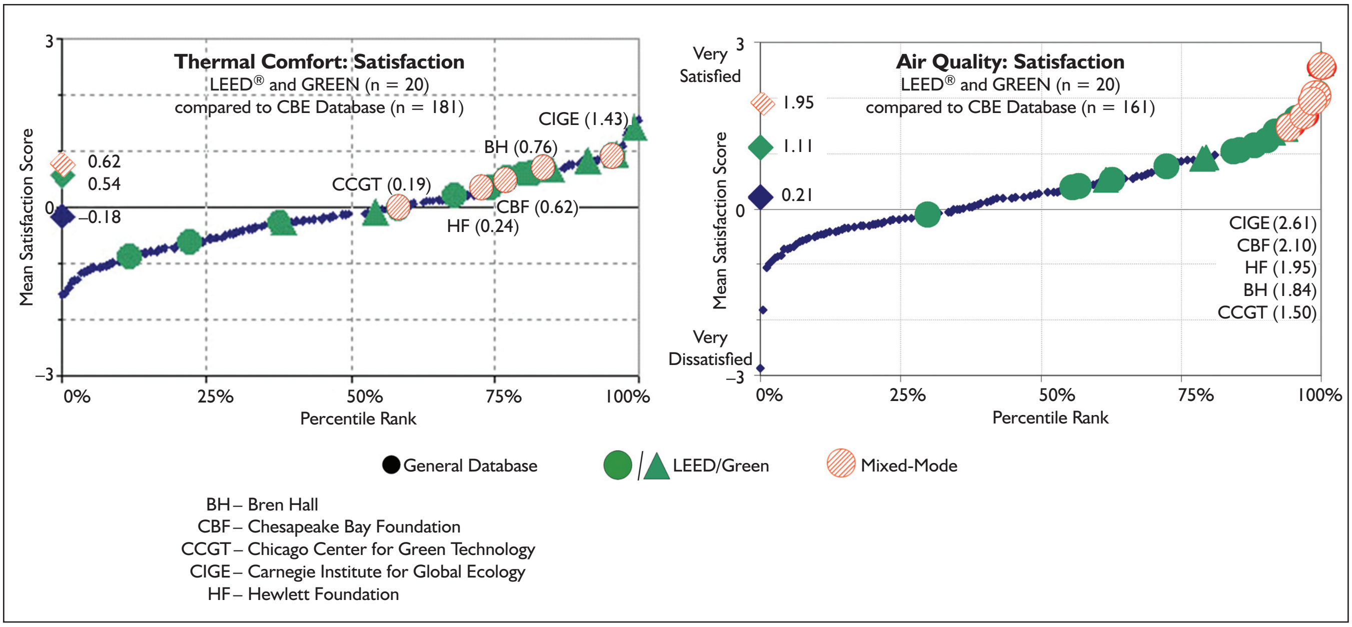

Figure 2: Survey results from five mixed-mode buildings—thermal comfort satisfaction.

Figure 3: Survey results from five mixed-mode buildings—air quality satisfaction.

While beyond the scope of this article, a more extensive review of analysis methods for naturally ventilated and mixed-mode buildings can be found in the literature reviews of the reports mentioned previously.[2,8]

Energy Monitoring

Predictive methods are an essential part of the design process, but there is no substitute for assessing how buildings are performing after they are occupied. The High Performance Buildings Research program at the National Renewable Energy Laboratory has done extensive research on high-performance commercial buildings, including naturally ventilated and mixed-mode buildings, focusing primarily on energy consumption. The informative case studies are nicely organized on its Web site at www.eere.energy.gov/buildings/highperformance/.

In a series of six case studies using physical monitoring and computer simulation, the research group is studying overall energy performance as well as analyzing the integration of specific energy-efficient features, and comparing measured performance to design expectations. As an example, the findings from one of the mixed-mode buildings found that total site energy use was reduced 24.5% compared to a minimally code-compliant building.[10] This was based on actual measured data that was calibrated to a simulation to make the comparison. Those savings included all end uses, including heating, cooling, and fan energy, and as is often the case, it is difficult to determine exactly what percentage of those savings can be attributed simply to natural ventilation alone.

Post-Occupancy Evaluation Methods

In addition to the importance of monitoring energy performance, post-occupancy evaluation (POE) methods are based on the principle that building occupants are an important and often underused source of information about how buildings are performing in practice. The Center for the Built Environment at the University of California, Berkeley has developed a Web-based survey with branching questions and an accompanying online reporting tool that assesses occupant satisfaction with a variety of indoor environmental quality attributes, including office layout, office furnishings, thermal comfort, indoor air quality, lighting, acoustics, and building cleanliness and maintenance.[11] At the time of this writing, the survey has been administered to 36,800 occupants in 240 buildings, including air-conditioned, naturally ventilated, and mixed-mode buildings. The results have been assembled into a database that can be used for benchmarking buildings in comparison to each other.

Case Studies of Mixed-Mode Buildings

While mixed-mode buildings are much more common in Europe, it is a relatively newer concept for U.S. engineers. The U.S. building design industry is generally unfamiliar with mixed-mode cooling strategies, and a lack of published case studies or design and analysis tools exists to facilitate their ability to chart new territory. To address this need, an ongoing research project at UC Berkeley is developing a Web-based library of mixed-mode building case studies, covering a range of climates, design approaches, and control strategies. The purpose is to provide detailed precedents that designers and building owners can learn from and use as examples, to help the building industry better understand how mixed-mode buildings work in practice, and how to overcome barriers to implementation. Another purpose is as a scoping study, to learn from industry about the critical needs in this area from which we can develop a future research agenda. The library can be found at www.cbe.berkeley.edu/mixedmode.

The Web-based library offers two levels of information: 1) a database with a broad list of buildings and basic project information, and 2) more detailed case studies. The database includes approximately 150 mixed-mode buildings, with more than 60 of them in North America. It is downloadable as an Excel spreadsheet to allow for easy sorting, and includes basic information about each project, including location, year built, type of building, owner, architect, engineer, brief comments about the mechanical system, operable windows, and control and operation strategies and Web links for more information.

The eight case studies provide a more detailed narrative and graphic descriptions obtained from literature reviews, drawings and photographs, and interviews with building owners, architects, engineers, and facility managers. The case studies include information about the windows, HVAC system, control strategies, building design process (design tools used, commissioning, relevant code issues), cost (where available), and additional green features of the building. We also were able to administer the CBE Web-based survey of occupant satisfaction in five of the case study buildings.

The case study buildings are all primarily office space, although several of them are multi-use and have academic lab areas as well. Depending on what happens in those labs, some of those spaces are not naturally ventilated. Five of the eight buildings are located in California (primarily resulting from the relative ease of obtaining information from local buildings), two on the East Coast, and one in the Midwest. They represent a range of sizes, from 10,000 ft^2 – 200,000 ft^2 (929 m^2–18 580 m^2), with an average size of approximately 50,000 ft^2 (4645 m^2).

HVAC systems. The case studies reveal that if the architects and engineers have agreed to take on the challenge of designing a mixed-mode building, they are likely to be more innovative in other aspects of the building and system design as well to achieve greater energy efficiency. For example, the Hewlett Foundation building in Palo Alto, Calif., is a changeover system where the windows and mechanical cooling operate at different times, and the operable windows are considered as part of the building mechanical system's economizer cycle. It uses an evaporative cooling chiller with ice storage to minimize peak demand energy costs, combined with an underfloor air-distribution system that provides greater degrees of personal control compared to an overhead system.

Another interesting example is the Carnegie Center for Global Ecology in Stanford, Calif., which is a zoned and concurrent system where first the center's functions (offices vs. laboratories) were zoned into separate categories requiring different levels of ventilation and cooling (*Photo 1* and *Figure 1*). The second floor is concurrent, combining natural ventilation with radiant slab heating and cooling, allowing for the elimination of ducts and fan energy use on that floor. Chilled water for cooling is provided without air-conditioning compressors by using a night-sky roof spray system. It creates a thin film of water on the roof at night using small sprinklers. The water is cooled primarily through radiation to the deep space cold night sky, and collected via the roof drainage system into a 12,000 gallon (45 425 L) storage tank. Chilled water is supplied at 55°F to 60°F (13°C to 15.5°C) using only 0.04 kW/ton (0.14 kW/kW), and using half as much water as a conventional water-cooled chiller.

Control strategies. The buildings also represent a range of control strategies that are possible in mixed-mode buildings. At one end of the spectrum, five of the buildings have no integrated controls and operate exclusively in "concurrent" mode, where windows and air-conditioning operate in the same space at the same time, and occupants can open or close the windows at their own discretion. Two of the buildings have a combination of automatic and what we call "informational" controls. When outdoor climate sensors indicate the building should switch to natural ventilation mode, the cooling system shuts down, the clerestory windows are mechanically opened, and lights in the corridor change from red to green to tell occupants they can open the lower windows. One building has another type of automatic controls where the operable windows and transoms have a small sensor switch on the window frame that turns off the heating system when the windows are open.

Occupant satisfaction. A preliminary review of the findings from our surveys indicates that these buildings are perform-

Advertisement formerly in this space.

ing very well compared to the benchmark data in our database. While a full report of our survey results is beyond the scope of this article, it's worthwhile to present a few examples.

Average thermal comfort scores are presented in *Figure 2*, which is a cumulative frequency graph showing average responses to the thermal comfort satisfaction question for buildings in the database that met our minimum requirements for response rate. Leadership in Energy and Environmental Design (LEED)®-rated or other sustainable buildings are shown as large green solid circles or triangles, respectively, while the five mixed-mode buildings are shown as large red hatched circles. The diamonds on the left axis show the mean score for each group. Although a bit of a range exists across the mixed-mode buildings, they are all performing in the upper half of our database. In all these buildings, thermal dissatisfaction is primarily for the winter months, which generally are viewed as too cold.

Interestingly, it is rare that anyone identifies drafts from the open windows as the source of the discomfort in mixed-mode buildings, but instead point to a problem with the mechanical system and/or lack of access to the thermostat. Similarly, thermal dissatisfaction in the summer is primarily caused by conditions being on the cool side, or more specifically complaints about drafts from the vents. The combination of "too cool" and "drafts from vents" suggests that the air conditioning is perhaps over-cooling the building more than it needs to in these mixed-mode buildings, and even greater comfort and energy savings may be possible.

Figure 3 shows responses for satisfaction with air quality using the same format. The trend here is even more profound, with the mixed-mode buildings all performing in the top 10% of the group. This is particularly interesting given that one of the common criticisms of natural ventilation is that the air is not being filtered, and, therefore, air quality will diminish.

Lessons learned. Several underlying lessons can be learned by investigating the design, operation, and occupant responses in these case study buildings. Regardless of the chosen complexity of the window and HVAC control strategies, from the occupants' point of view, they should be kept simple and easy to understand and use. Automated controls make the most sense for upper windows, such as clerestories, so that you can still provide manual control of the lower windows near the occupants. To ensure that a building is being operated as designed, it's essential that all occupants of the buildings—the facility manager, maintenance staff, and workers—be educated about how the building is designed to interact with the climate, and what the occupants can to do optimize their own comfort while being sensitive to other people's desires and larger concerns such as energy efficiency. The adage "passive buildings require active occupants" is especially true for mixed-mode buildings.

Discussion and Conclusions

It would be a mistake to think of a mixed-mode building as simply a conventional air-conditioned building where the windows open. This is a recipe for trouble.

To begin with, a naturally ventilated or mixed-mode building likely will be successful only if the building has been intelligently designed to incorporate other climate-responsive strategies as well. Particular attention should be paid to shading and daylighting to reduce cooling loads, as well as thermal mass so that direct ventilative cooling during the day might be combined with nighttime cooling. Even in an extreme climate, an integrated design solution likely will extend the times of the year when mechanical cooling can be avoided.

Close collaboration between the building owner and various members of the design team, early and throughout the design and construction process, is essential. All members need to be in agreement about the underlying environmental and performance-based goals of the project, and be willing to challenge conventional design assumptions to realize those goals.

The operation of a mixed-mode building is complex, and requires somewhat of a paradigm shift from the "centralized control" way of thinking. Ideally, operation should allow for natural ventilation as much as possible, and encourage maximum occupant control of the windows to realize the benefits of adaptive opportunity. Where control of the windows is shared, such as in open plan offices, workers need to develop a "good neighbor policy," so they are sensitive to the effect of the open window on others, recognizing that people's personal preferences may differ. This is not unlike several people in a zone sharing a thermostat. When the air conditioning is used, it should be the supplemental, not primary, form of control to keep thermal conditions from rising above the adaptive comfort zone.

The U.S. building industry's interest, experience, and knowledge about mixed-mode buildings has been growing rapidly. However, further research and education is needed before we can fully realize the energy efficiency and comfort benefits from this promising design strategy. In particular, the following activities are needed:

- Further development of multizone, coupled energy and airflow simulation tools;
- Theoretical and experimental studies of airflow patterns and ventilation rates in buildings with operable windows (with and without mechanical ventilation or cooling);
- Theoretical and experimental studies of building control algorithms to optimize both comfort and energy;
- Building energy simulations and physical monitoring to evaluate the energy-savings potential for mixed-mode buildings in different climate zones;
- Detailed field studies that combine subjective surveys with field measurements of thermal conditions, IAQ, and ventilation levels in mixed-mode buildings;
- Field studies to investigate the influence of personal control and natural ventilation on worker performance and associated financial implications;
- Widespread publication of case studies of existing mixed-mode buildings in both the architecture and engineering press;
- Development of design tools and guidelines;
- Revisions of ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy,* Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality,*

and Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings,* to enable more alternative environmental control strategies; and

- Greater collaboration between researchers and professional community.

References

1. De Dear, R. and G. Brager. 1998. "Developing an adaptive model of thermal comfort preference." *ASHRAE Transactions.* 104(1):27 – 49.

2. Emmerich, S.J. and J. Crum. 2005. "Simulated Performance of Natural and Hybrid Ventilation Systems in an Office Building." *Final Report,* Air-Conditioning and Refrigeration Technology Institute, ARTI-21CR/611-40076-01.

3. Seppänen, O. and W. Fisk. 2002. "Association of ventilation system type with sick building symptoms in office workers." *Indoor Air* 12(2):98–112.

4. McConahey, E., P. Haves, and T. Christ. 2002. "The integration of engineering and architecture: a perspective on natural ventilation for the new San Francisco federal building." *Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings.* http://tinyurl.com/zqdvp.

5. Haves, P., G. Carrilho da Graça and P.F. Linden. 2003. "Use of simulation in the design of a large naturally ventilated commercial office building." *Proceedings of Building Simulation '03.*

6. Leaman, A. and B. Bordass. 1994. "Building design, complexity, and manageability." First published in *Facilities* September 1993, July 1994 revision.

7. Daly, A. 2002. "Operable windows and HVAC systems." *HPAC Engineering* (12).

8. Li, Y. and P. Heiselberg. 2003. "Analysis methods for natural and hybrid ventilation—a critical literature review and recent developments." *International Journal of Ventilation, Special Edition: Hybrid Ventilation.* 1(4).

9. Axley, J., S. Emmerich, S. Dols, and G. Walton. 2002. "An approach to the design of natural and hybrid ventilation systems for cooling buildings." *Proceedings Indoor Air 2002.*

10. Griffith, B., M. Deru, P. Torcellini, and P. Ellis. 2005. "Analysis of the Energy Performance of the Chesapeake Bay Foundation's Philip Merrill Environmental Center." Technical Report, NREL/TP-550-34820. National Renewable Energy Laboratory, Golden, Colo.

11. Zagreus, L., C.E. Huizenga, E. Arens and D. Lehrer. 2004. "Listening to the occupants: a web-based indoor environmental quality Survey." *Indoor Air 2004* 14 (Suppl 8):65–74.

Bibliography

CIBSE (Chartered Institution of Building Services Engineers). 2000. *Mixed Mode Ventilation—Applications Manual* AM13:2000.

Chang, J-C. 2002. "Case Studies of Naturally Ventilated Commercial Buildings in the United States." MSc Thesis. Cambridge, Mass.: Department of Mechanical Engineering. MIT.

International Journal of Ventilation. 2003. Special Edition: Hybrid Ventilation. 1(4). (Note: there are many articles in this issue related to the IEA Annex 35-HybVent research projects).

Ring, E.W. 2002. Mixed-Mode Office Buildings: "A Primer On Design And Operating Of Mixed-Mode Buildings and an Analysis of Occupant Satisfaction in Three California Mixed-Mode Office Buildings." MSc Thesis. Dept. of Architecture. University of California, Berkeley.