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SIMULATED PERFORMANCE OF NATURAL AND HYBRID VENTILATION SYSTEMS IN AN OFFICE BUILDING
Final Report

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USE OF NON-SI UNITS IN A NON-NIST PUBLICATION

It is the policy of the National Institute of Standards and Technology to use the International System of Units (metric units) in all of its publications. However, in North America in the HVAC&R industry, certain non-SI units are so widely used instead of SI units that it is more practical and less confusing to include values for customary units only in certain figures and tables.

ABSTRACT

A key finding of past research on natural ventilation is that the potential application of pure natural ventilation systems may be limited in the United States by issues such as climate suitability, humidity control, and reliability. However, hybrid (or mixed-mode) ventilation systems offer the possibility of attaining energy savings in a greater number of buildings through the combination of natural ventilation systems with mechanical equipment. Although a recent surge of interest in Europe has advanced natural and hybrid ventilation technology, much work is needed to identify and realize its potential in the United States. Innovators in this field are learning by doing, but there is only limited design and analysis data available – partially due to a lack of adequate engineering methodologies and tools. The objective of this study is to investigate the potential energy and indoor environmental performance of natural and hybrid ventilation alternatives in low- to mid-rise U.S. commercial buildings in a variety of U.S. climates. In this effort, NIST reviewed hybrid ventilation approaches and existing applications and conducted simulations to predict and compare the indoor environmental and energy performance of natural, hybrid, and mechanical systems in an otherwise similar building. Limitations of this study include the simulation of only one building with only one system of each type. Additionally, some important issues were not evaluated, such as indoor air quality impacts of outdoor and indoor sources of contaminants, purchased building energy, and humidity control.

Due to the strong interaction of airflow and heat transfer in naturally ventilated buildings, CONTAMR, a coupled multi-zone airflow and thermal simulation tool, was used to model the systems in a 5-story office building for cold, moderate and hot months in five U.S. cities. Performance was evaluated in terms of ventilation (i.e., ventilation rates and indoor carbon dioxide (CO_2) concentrations), thermal comfort (i.e., zone temperatures), and energy (i.e., fan energy and thermal conditioning loads).

Overall, the natural ventilation system performed adequately in San Francisco and Los Angeles although some tolerance for imperfect thermal and IAQ control is required. Natural ventilation system performance was poor in the more challenging climates of Boston, Minneapolis, and Miami due to poor thermal control, unreliable ventilation, or high heating loads. The hybrid ventilation system improved on the performance of the natural ventilation system in all climates with dramatic improvement in some.

Compared to the mechanical system, the hybrid system saved significant amounts of fan energy, reduced cooling loads or both in all climates but often resulted in higher heating loads. Although the hybrid system provided acceptable thermal control, the mechanical system provided more consistent control as expected. The hybrid ventilation system provided better IAQ control, as indicated by CO_2 concentrations, in most but not all cases.

Key recommendations include further development of engineering methodologies and tools for improved design and analysis of hybrid ventilation systems, field studies of hybrid ventilation system performance in U.S. buildings, follow-up studies on potential barrier issues and ancillary technologies, and development of specific performance standards for natural and hybrid ventilation systems.

Key Words: 21CR, analysis, ARTI, design, energy efficiency, hybrid ventilation, indoor air quality, modeling, natural ventilation, mixed-mode ventilation, simulation, thermal comfort, ventilation.

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1. INTRODUCTION

1.1 Background

Natural ventilation systems have been increasingly applied in European commercial buildings, and interest in applying these systems in U.S. commercial buildings is growing. However, implementation of natural ventilation in the United States suffers from a lack of adequate design and analysis methodologies and tools and a lack of knowledge of the performance in U.S. climates. Recent NIST reports (Axley 2001, Emmerich et al. 2001) reviewed the application of natural ventilation to commercial buildings, the potential advantages of these systems, and some of the design and operational challenges that must be considered. In these reports, an approach to the analysis of climate suitability is presented and applied to a number of North American climates, European design strategies and the analytical methods developed to support them are reviewed, and a modeling study of a naturally ventilated building located in the Netherlands is presented. A coupled multizone thermal/airflow simulation tool (CONTAM97R) was used for a limited investigation of the performance of this building in two North American climates. A key finding of the reports is that the potential application of pure natural ventilation systems may be limited in the United States by issues such as climate suitability, humidity control, and reliability. However, hybrid ventilation systems offer the possibility of attaining energy savings in a greater number of buildings through the application of natural ventilation systems in combination with mechanical ventilation, mechanical cooling and heat recovery. In this effort, NIST reviewed hybrid ventilation approaches and existing applications, and then conducted simulations to evaluate the performance of natural and hybrid ventilation systems in commercial buildings in multiple U.S. climates. Predicted indoor environmental and energy performance were compared to predicted performance of buildings with single mode natural ventilation and mechanical systems.

The objective of this study is to investigate the potential energy and indoor environmental performance of natural and hybrid ventilation alternatives in low- to mid-rise U.S. commercial buildings in a variety of U.S. climates. Simulations are used to compare the performance of natural, hybrid, and mechanical systems in an otherwise similar building. Performance aspects investigated include ventilation and space conditioning (primarily cooling) energy savings, ventilation rates, air distribution, and thermal comfort.

1.2 Contents

This report is organized into three main sections – Literature Review, Simulation Plan, and Results. The first section contains a literature review on hybrid ventilation in commercial buildings, which was conducted in order to provide a sound base for the simulation effort by assessing the current state-of-the-art and by identifying potential case study buildings. The second section describes the simulation plan developed for the study, and the third section discusses the results of the simulation study.

1.3 Scope and Limitations of Study

This project presents a unique study comparing the performance of natural, mechanical and hybrid systems for a commercial building in U.S. climates. However, it must be recognized that available resources and the state-of-the-art of building simulation limited the scope of this study. One important limitation is the consideration of only one building (both in configuration and parameters) and of only one system of each type (i.e., one natural ventilation system, etc.), which cannot capture the diversity of possible combinations of different buildings and systems. Additionally, important aspects such as indoor air quality impacts of outdoor and indoor sources of contaminants, purchased building energy, and humidity control were not evaluated.

2. LITERATURE REVIEW

A literature search was conducted on the topic of hybrid ventilation of commercial buildings in order to provide a sound base for the simulation effort by assessing the current state-of-the-art and by identifying potential case study buildings. In addition, the review addressed fire safety and smoke control code issues. See Section 7.0 References for the references considered in the literature review.

2.1 General and Design

This section contains a review of publications on the topic of hybrid ventilation of commercial buildings. The reviewed publications cover such topics as definitions, categorizations, pros and cons, and design information. Most of these efforts were performed under the International Energy Agency (IEA) Annex 35 on Hybrid Ventilation. Although definitions of hybrid ventilation vary, most authors include almost any combination of natural ventilation with mechanical ventilation and cooling. Some emphasize that hybrid ventilation (also referred to as mixed-mode) systems must have a purposeful design and operational integration of the natural and mechanical components as opposed to the simple inclusion of operable windows in a mechanically cooled and ventilated building. Many reports note that current existing methodologies and tools are inadequate for the design and analysis of hybrid ventilation systems.

Heiselberg (1999) provides an early but limited overview of hybrid ventilation including a definition (which does not include concurrent use of natural and mechanical ventilation in different building zones) and discussions of climate data, pressure distribution on surfaces, airflow characteristics of openings and other elements, airflow in and between rooms, and airflow processes for whole systems.

Heiselberg and Tjelflaat (1999) describe preliminary ideas on a design procedure for hybrid ventilation systems including consideration of the various design phases (conceptual design, basic design, detailed design, design evaluation, and commissioning). It is emphasized that suitable design tools for all phases do not exist yet, that methods suitable for mechanical-only systems are not adequate for hybrid systems, that the building and hybrid system must be consider together with efficient iteration schemes, and that a major focus must be on combining thermal and airflow simulation models. They observe:

> "Suitable methods as we know them from mechanical systems are not available for hybrid ventilation systems yet. Valid methods would give architects and engineers the necessary confidence in system performance, which in many cases is the decisive factor for choice of system design. …
>
> As the hybrid ventilation process and the thermal behaviour of the building are linked the development of design methods for hybrid ventilation must take both aspects into consideration at the same time and include efficient iteration schemes. This is the case for all types of methods from simple decision tools, analytical methods, zonal and multizone methods to detailed CFD analysis methods. A major focus will be on combining thermal simulation models with existing multizone airflow models. In this way, the thermal dynamics of the building can be taken into account and this will improve the prediction of the performance of hybrid ventilation considerably. The combined model will be capable of predicting the yearly energy consumption for hybrid ventilation and will therefore be the most important design tool for hybrid ventilation systems."

Tjelflaat (2001) updates this work and expands the design phases to initial considerations, building initial design, first design of room environment, building/system first design, final design of room environment, building/system final design, validation of room environment design, building/system commissioning, and commissioning of room environment. Existing tools and methods are listed to address the various phases. Similarly, Li (2001) discusses the design process for hybrid ventilation systems with emphasis on the primary modeling methods available for analysis, i.e., simple, multizone, and computational fluid dynamics (CFD).

Wouters et al. (1999) define hybrid ventilation, differentiate between IAQ and cooling purposes of ventilation, briefly describe seven case studies of hybrid ventilated buildings, and discuss the categories of possible hybrid ventilation systems (alternating operation, mechanical assist to primary natural ventilation, supplemental mechanical cooling) with examples. They also list design criteria (draft control, security, air preheating, outdoor air pollution, acoustical problems, and fire regulations) and discuss levels of design integration (industrial hybrid ventilation, fully integrated design, and moderate integration level).

Kosik (2001) provides an overview of hybrid ventilation including a definition which emphasizes built-in strategies as opposed to coincidence of operable windows and differentiates between two types of hybrid systems, i.e., changeover or complementary and concurrent or zoned. Kosik also discusses potential advantages (reduced energy usage, higher occupant satisfaction, and building flexibility) and design challenges (most research and practice in Europe, U.S. design/construction industry unfamiliar, U.S. codes and standards sparse on topic, occupants used to current methods). Numerous design strategies are considered including operable windows, integral building openings, atria, heat stacks, double-skin glazing systems, fan assist, low pressure HVAC components, as well as additional design considerations – thermal mass, natural light, solar shading, natural ventilation, prevailing winds, mechanical cooling and ventilation, control strategies, air distribution, clustering of high heat gain spaces, life safety issues, control of infiltration, control of outdoor pollutants.

Brager et al. (2000) provide another overview of hybrid ventilation (referring to it as mixed-mode) including definition, categorization, potential benefits (reduced energy consumption, higher occupant satisfaction, and highly ‘tunable’ buildings), and barriers (design issues, operations and controls issues, fire and safety concerns, and energy code concerns. They also briefly describe three buildings being studied by the Center for the Built Environment at the University of California, Berkeley and list research and development needs (theoretical and experimental quantification of benefits, building energy simulations, detailed field studies including subjective surveys, development of design tools and guidelines, revisions of key industry standards, and greater collaboration between researchers and practitioners).

Heinonen and Kosonen (2000) describe three hybrid ventilation concepts: hybrid ventilation with mechanical exhaust, hybrid ventilation with supply air ducts, and a low-pressure hybrid ventilation system. The three concepts are described in general terms while briefly addressing design aspects, advantages, and disadvantages. One feature stressed is occupancy and/or carbon dioxide (CO_2) sensors for system control. Slotboom (2001) discusses the design of a hybrid ventilated school building from an architectural perspective and emphasizes that a key aspect of hybrid ventilation may be in decentralization of the cooling system, thus leading to better architectural use of building space.

Bourgeois et al. (2000) discuss the desirability of natural ventilation but notes problems with application to commercial buildings in Canada due to the wide range of ambient conditions. Hybrid ventilation systems are proposed as a potential solution. One unique suggestion is that the act of an occupant opening a window could be a switch to turn off mechanical systems. Hybrid ventilation strategies suggested including operation as a function of ambient thermal conditions. Also discussed is the application of current modeling programs for evaluating IAQ, thermal comfort, and energy without using coupled airflow/thermal modeling. Bourgeois et al. (2002a) continues this analysis by considering the pros and cons of applying specific Annex 35 pilot study designs to Montreal.

Li and Heiselberg (2003) present an extensive review of the literature and recent developments in analysis methods for natural and hybrid ventilation in buildings. Available design and analysis methods reviewed range from simple analytical and empirical methods to multi-zone and CFD techniques. The authors conclude that a fully integrated, combined multi-zone airflow and thermal modeling is the most promising analysis approach but challenging issues remain before such models are well-established.

2.2 Case Study Buildings

If possible, it would be advantageous to base the building model investigated in the simulation stage of this project on an actual hybrid building with well-documented building features and measured performance data. Numerous reports describing a wide range of buildings with hybrid ventilation were reviewed, but the vast majority of these reports provide very brief, general descriptions of the buildings and systems and have minimal, if any, performance data.

The majority of case study buildings in the reviewed literature are located in the U.K. or Northern Europe. Delsante et al. (2000) report on the initial phase of the International Energy Agency Annex 35 research effort on hybrid ventilation and include short descriptions of 22 buildings with hybrid ventilation systems. The buildings are a mix of mostly low-rise office and education buildings with dominant skin-load and a range of thermal mass. In addition, they are mostly recent construction and located above 50° N latitude. Limited performance data are available. The report also discusses critical barriers to hybrid ventilation (including synopses of relevant building codes in various countries, but not the United States), control strategies for hybrid ventilation, and analysis tools Aggerholm (2001 and 2002) describes control strategies for hybrid ventilation in these and other office and educational buildings in Northern Europe. Lessons learned include satisfactory operation can be achieved with occupant control in cellular offices during occupied hours, automatic control is needed during unoccupied hours and at all times in open floorplan offices, and inlet air may need to be preheated to control the sensation of draft. Risks to be considered include high CO_2 concentration in classrooms if occupants have control, mechanical cooling may remain on when not needed, and complex controls may not be operated and maintained properly in the long term.

Hendriksen (2001 and 2002) and Brohus et al. (2003) describe a year-long monitoring study (CO_2, temperatures, ventilation parameters, ambient conditions, fan and space heating energy use) in a hybrid ventilated 3-story office building in Denmark. Limited tracer gas studies of building air movement were also conducted. The hybrid ventilation system features a combination of stack- and wind-driven natural ventilation, fan assist, CO_2 control, night cooling, and displacement ventilation distribution. Extensive data are presented including sample daily CO_2 concentration and vertical temperature distribution plots, cumulative frequency distributions of average room temperatures and CO_2 concentrations for each floor of the building, seasonal mean values for thermal comfort parameters, annual hours of temperature over design criteria and annual energy use. Problems encountered in the building included noise from the assist fans and operational problems with the systems that consisted of many distributed components. It was also observed that the CO_2 control system operated effectively but ventilation was dominated by uncontrolled infiltration. Thermal comfort design criteria were not always met, as hours with temperatures above desired limits often exceeded the design criteria on the third floor. The high level of infiltration also resulted in higher than expected heating energy use. The tracer gas studies showed significant exchange of air between floors of the building in both directions.

Schild (2001) describes 17 hybrid-ventilated buildings in Norway. Most of the buildings are schools and employ hybrid ventilation based on potential IAQ improvement rather than energy savings. Over 70 % feature buried intake ducts or a culvert in the basement to provide summer cooling. The systems can be categorized into seasonally adjusted flow rate systems or heat recovery systems. In general, the buildings are viewed as successful, with good air quality and low operating costs. However, it is also noted that these hybrid-ventilated buildings have proven to be an operation and maintenance challenge. While this may be due to a lack of experience with designing, building, and operating such systems, this is an issue to monitor in the future as some claim traditional mechanical systems are too complicated to maintain and operate correctly.

Arnold (2000) describes a five story commercial building in the U.K. that features vents for air quality control, occupant-controlled windows, an atrium with exhaust vents, night ventilation for cooling the exposed concrete floor/roof, hydronic heating, a low-pressure underfloor supply-only mechanical ventilation system for supplemental cooling/ventilating, and a supplemental chilled beam cooling system with a cooling pond. The design and control principles of the building are also discussed. Although insufficient data are presented to independently evaluate the performance, it is reported that while numerous ‘teething’ problems occurred in the first two years of operation (attributed to discrepancies between control software and design intent, delays in commissioning the second of two chillers, and defects in the control actuators for the roof-light vents), the building cost less to construct than a similarly prestigious air-conditioned building, will cost significantly less to operate and maintain, and scored very well for overall building design and comfort in an occupant survey. The survey did reveal some dissatisfaction with summer temperatures (attributed to the ‘teething’ problems), drafts from trickle vents (inlet vents intended to provide continuous background ventilation) during strong northerly winds (remedied with deflectors), and ventilation control for those not near a window. An issue of omitted CO_2 sensors is dismissed by stating ‘there have been no problems with underventilation of the building’.

Braham (2000) compares U.K. buildings with three low-energy alternative concepts. The first building features natural ventilation with exposed ceiling slabs and options of low-pressure hot water or electric heating. The second building features natural ventilation via wind towers with solar assist and supplemental CO_2-controlled fans, core cooled slabs, and supplemental hydronic floor heating and cooling. The third building features mechanical ventilation supplied via a core slab cooling and exhaust air heat recovery system. Although minimal performance data are presented, it is concluded that the third option achieves better year-round comfort with significantly lower annual delivered and primary energy consumption (due to heating energy savings) and with lower maintenance requirements.

Wahlstrom and Nielsen (2001) describe a two-story, 20-classroom school building in Sweden that was retrofitted with a hybrid ventilation system controlled by a building energy monitoring system. The ventilation system primarily consists of 6 m high solar chimneys with supplemental low-energy exhaust fans. The system also has CO_2 sensors that can control both damper opening and fan operation. Continuous monitoring of the following variables was performed for a year: space heating energy use, electricity use, room and duct air temperatures, relative humidity, CO_2, air speed and direction in ducts, manual or central control, position of dampers, and weather conditions. Additional short term testing of air change rates and thermal comfort was also performed. It was reported that electricity use for ventilation was reduced by 55 % and space-heating energy use was reduced by 32 % after the retrofit. Note that other changes were made to the building at the same time as the ventilation system retrofit.

Van der Aa (2002) describes a new school building with a hybrid ventilation system in the Netherlands and presents some initial operating results. The building consists of six connected sections 1-2 stories tall and features high levels of thermal insulation, good air tightness, a high efficiency natural gas boiler, high frequency lighting with daylight adjustment, and a building energy management system (BEMS) system that controls natural ventilation inlets and assist fans based on CO_2 and temperature. Initial results indicated IAQ met design expectations but thermal comfort suffered from complaints of drafts. Meinhold and Rosler (2002) also describe a school with a hybrid ventilation system. The existing building was retrofitted by converting courtyards to atria, which functioned as part of a natural ventilation system. The occupants controlled switching between the natural and mechanical ventilation system. Some operating problems were reported including overheating, an ineffective night cooling system, and inadequate ventilation during low outdoor temperatures.

Principi et al. (1999, 2002 and 2003) describe measurements of thermal comfort and ventilation performance parameters in a four-story building with a hybrid ventilation system in Italy. The building features a central atrium, large glazing areas with cross ventilation openings and a shading roof, exposed thermal mass to enable night cooling by natural ventilation flows, and supplemental fan coil units. The authors conclude that the system provided acceptable ventilation for air quality as indicated by CO_2 concentrations but allowed overheating during some seasons due to inadequate solar shading. However, only very limited measured data are presented. Additionally, the authors state the mechanical system was found to operate too frequently, but this statement is not supported by the presented data.

Rowe (2003) and Rowe and Dinh (1999) report on observations of occupant behavior in utilizing supplementary cooling in naturally ventilated rooms in the offices of a 5-story educational building in Sydney, Australia. The natural ventilation is primarily wind driven via operable windows although some offices may use stack driven flow through corridor connections to a small atrium or an open central stairwell. In addition to window opening, office occupants have control over individual office heating and cooling units. No night cooling is utilized. At various times over several years, the study included occupant surveys, energy use measurement, cooling unit operation, CO_2 and particle concentration measurements, and occupant clothing and metabolic activity observation. The surveys of occupant perceptions of perceived air quality, thermal comfort, overall comfort, and effect of workspace on performance of work, which were conducted during mild weather months, yielded high ratings compared to similar surveys from 33 other buildings that employed mechanical, natural, and hybrid ventilation systems. Additionally, the occupant ratings in one office space improved after installation of the supplementary mechanical cooling equipment. Occupant ratings for prevalence of eight symptoms associated with sick building syndrome resulted in scores at or near the low end of scores for the 33 buildings with averages for the study building spaces being below nearly all of the air-conditioned buildings studied. Despite these favorable occupant ratings, very limited measurements indicated higher CO_2 and particle concentrations in the study building than in two offices with mechanical systems. Based on simulation estimates, it was also found that the hybrid system with occupant control of supplementary cooling used much less energy than an equivalent mechanical-only system. Also, operation of the supplementary mechanical equipment was strongly related to outdoor conditions with little use in mild weather. While the study concludes that the availability of operable windows in combination with occupant-controlled supplementary cooling results in a high quality indoor environment with considerably lower energy consumption than a conventionally air-conditioned building with full-time mechanical ventilation, the data are not sufficient for a firm conclusion to be drawn independently.

Chikamoto et al. (1999) describe a high-rise education building with a hybrid ventilation system in Tokyo. Features of the building and system include a ‘wind-core, a ‘wind-floor’, automatically controlled natural ventilation windows, automatically controlled outdoor air intake, and a building environment and energy management system. The wind-core is an open core formed by the escalator space from the 1st to the 17th floor. The wind-floor on the 18th floor is open to the wind in all four directions. CFD simulations indicated that the wind -floor increased the building air change rate by more than 4 h^{-1} compared to a similar building without the wind-floor. Long-term and short-term monitoring efforts are described but no results are presented, thus no conclusions can be drawn on the effectiveness of the system performance.

Only a few U.S. buildings with hybrid ventilation systems were found in the review. Ring and Brager (2000) describe three modern office buildings in California that combine occupant-controlled operable windows with conventional mechanical HVAC systems. No physical performance data are presented but results of occupant surveys indicated that access to operable windows has a significant positive impact on reported satisfaction with air quality. However, concerns about the impact of outdoor noise and air pollution were also raised. Also, the Philip Merrill Environmental Center of the Chesapeake Bay Foundation is a modern office building with operable windows and a conventional mechanical system (www.cbf.org/merrillcenter). The energy management system includes a feature to alert occupants when outdoor conditions are favorable for opening windows. Non-accessible windows are opened automatically.

2.3 Simulation Studies

Several recent simulation studies of the performance of hybrid ventilation systems in commercial buildings were reviewed for information relevant to planning the simulation study. This review does not include a review of CFD simulation studies of detailed single room conditions such as described by Kato et al. (2000).

Eriksson and Wahlstrom (2002) describe the use of a multizone airflow simulation tool to evaluate the performance of a hybrid ventilation system in a Swedish school building. Wahlstrom (2001) described the school building and ventilation system (discussed above). Simulations were performed to evaluate the sensitivity of the system to changes in the wind conditions, to study the transport of air relative to the designed paths under various combinations of opened and closed doors and a range of damper authority, and to evaluate the performance of the solar chimney. Measured data was used to calibrate the 17-zone airflow model by tuning the flow characteristics of the exhaust system between the rooms and the solar chimney and then tuning the capacity of the discharge terminal. The researchers concluded that multizone airflow modelling showed clear benefits in studying these issues but that simultaneous coupled thermal and airflow simulation is needed for detailed design of features such as the solar chimney.

Vuolle and Heinonen (2000) describe a simulation study of the performance of a hybrid ventilation system in a seven-story office building in Finland using the IDA Simulation Environment (Vuolle and Sahlin 2000). The modeled system, designed for a cold climate, features a central supply air stack system with assist fans and dampers controlled by occupancy and CO_2. Very limited detail is provided on the modeling and results, but the following conclusions are reported:

- The system without demand control or heat recovery increases heating energy use more than fan energy savings.
- The investment and space costs are high compared to traditional systems.
- Controlling pressure losses in the system is critical.
- The system is sensitive to installation and design errors.
- Air distribution requires attention.
- Traditional particle filters cannot be used.

- The minimum number of floors for sufficient stack effect is five.
- A large basement is needed for the supply stack system.
- Tightness of the envelope is not critical.

Heinonen et al. (2002) describe a similar simulation study of the performance of a hybrid ventilation system in a five-story office building in Finland. Four types of systems were compared for a building with an atrium including:

- Mechanical constant air volume (CAV) system with radiators, cooled ceiling, and heat recovery.
- Mechanical variable air volume (VAV) system with demand controlled ventilation, radiators, cooled ceiling, and heat recovery.
- Hybrid ventilation with demand controlled ventilation, radiators, cooled ceiling, no ductwork, and exhaust fans (concept #1).
- Hybrid ventilation with demand controlled ventilation, fan coils, supply ductwork, supply and exhaust fans, and heat recovery (concept #2).

Preliminary simulations were performed with a single-zone model to determine appropriate ranges of building airtightness and ventilation system pressures. Detailed coupled thermal and airflow simulations were then performed with an 11-zone model using the IDA Simulation Environment. Conclusions include:

- A hybrid ventilation system may reduce energy costs compared to mechanical system – mainly by reducing the electricity consumption of fans.
- Adequate ventilation is achievable with hybrid ventilation.
- Ventilation openings should be controllable (e.g., via CO_2 control) for hybrid concept #1 to enable control of the airflows to account for weather and load changes.
- Optimal performance for the hybrid system requires advanced, fast, and individually tuned control systems.
- A tight building envelope is required to achieve the expected performance.

Jeong and Haghighat (2002) describe an effort to model a hybrid ventilated school building using the simulation tool ESP-r's coupled building thermal and airflow capability. The school building modeled is a single-story with ventilation supplied through an underground duct and exhausted through an exhaust tower. The system has both supply and exhaust assist fans that are controlled by CO_2 and temperature. The building model employed 21 thermal zones and 32 airflow nodes. The model did not have the capability to model CO_2 control and only a winter condition was considered. The results indicate that modeling a hybrid-ventilated building is possible with this integrated model but limitations of the study prevented any conclusions about model performance.

Cron et al. (2003) report on a simulation study of a hybrid ventilation system for a classroom in 10 cities in France. The simulations were conducted with the SPARK program. The hybrid system studied was essentially a fan-assisted natural ventilation system with inlet vents controlled by room CO_2 concentrations, operable windows, and an exhaust stack. The mechanical systems simulated were an exhaust-only system and a balanced fan system with heat recovery. Neither the hybrid nor mechanical systems included air-conditioning but both included night cooling strategies. The authors concluded that the hybrid system provided better IAQ based on predicted CO_2 concentrations but the mechanical system with heat recovery generally used the least energy. One shortcoming of the study was the assumption of constant airflow rates due to infiltration and open windows.

2.4 Safety and Other Issues

As mentioned earlier, one objective of the literature review was to obtain information addressing fire safety and smoke control code issues for buildings with hybrid or natural ventilation systems. While many reports reviewed above (e.g., Delsante et al. (2000), Kosik (2001), Wouters et al. (1999), Brager et al. (2000)) mention life safety, security, noise and other issues as design challenges, they provide little practical information addressing these issues.

Del Sante et al. (2000) reviewed building codes and standards in 12 countries for potential barriers to the application of hybrid ventilation in educational and office buildings, including fire safety and smoke control issues. Regulations on fire, smoke and noise are identified as the most serious barriers to hybrid ventilation. Specific issues included compartmentalization (size, layout, and content), penetration of fire-separating constructions (e.g., doors, windows, ducts, and other ventilation openings), smoke ventilation and escape routes, and compensating measures. The specific requirements were noted to vary widely from country to country. Implications of the restrictions include separate ventilation systems for compartments, limited opening area and/or automatic closing for ventilation paths, and high fire resistance for ventilation components. Some restrictions may be satisfied through the use of compensating measures such as sprinkler systems or smoke ventilation. Bourgeois et al. (2002b) published a similar but more detailed review of relevant building regulations in Canada. The topics covered include building size and construction, spatial separation and exposure protection, fire separations and closures, mezzanines, safety within floor areas, and additional requirements for tall buildings.

A design handbook for natural ventilation systems (Allard 1998) contains a chapter discussing similar barriers to natural ventilation, including fire safety and smoke control issues. Other barriers discussed include noise, rain penetration, and intruder prevention. Two types of fire regulations are discussed: 1) Requirements at the façade level (grilles, louvers, operable windows, etc.) must not decrease the fire resistance of sectioning element of which they are a part when closed, and 2) Requirements regarding zoning (may be a function of building height).

2.5 Discussion of Literature Review

While hybrid ventilation of commercial buildings is still an emerging topic, there is a rapidly growing body of published literature covering topics including general/design information, case study buildings, and simulation studies. As indicated by many of the general reports, innovators in this field are learning by doing and there is a minimum of hard design and analysis data available, partially due to a lack of adequate engineering methodologies and tools. While there is no obvious candidate building on which to base a building model, there are many descriptions of buildings and systems available to guide the definition of the building and systems to be studied. At this time, commercial buildings with hybrid ventilation in the U.S. seem to be limited to a few buildings with operable windows accessible to the occupants. Further research is needed into perceived barrier issues such as fire safety and security.

3. SIMULATION PLAN

A simulation plan was developed to specify the key variables to be studied (including ventilation system type and controls, climate, and building description including physical properties, operating schedules, internal heat gains, and occupancy) and to define the thermal and IAQ criteria that will be used in the analysis. While fire safety and smoke control code issues are important, these issues are outside the scope of this project but should be considered in follow-up studies. A preliminary simulation plan was developed based on earlier work by NIST and the literature review performed as Task 1 of this project. The preliminary plan was revised after consideration of comments received from the ARTI Project Monitoring Subcommittee (PMS) and in response to simulation program limitations.

3.1 Testable Hypotheses

As stated earlier, the objective of this study is to investigate the potential energy and indoor environmental performance of natural and hybrid ventilation alternatives in low- to mid-rise U.S. commercial buildings in a variety of U.S. climates. In order to focus the simulation effort, a set of hypotheses to be tested by the simulation plan was developed. The final set of hypotheses included:

- Natural ventilation is not reliable in terms of providing adequate ventilation rates for air quality control
- Natural ventilation will result in unacceptable thermal comfort in typical U.S. climates
- Hybrid systems will provide reliable ventilation (both rates and distribution) and acceptable thermal conditions (during occupied hours) and use less energy than mechanical systems

3.2 Evaluation Criteria

Evaluation criteria to judge the above hypotheses and address the performance aspects to be investigated were also defined. The original evaluation criteria included:

- Ventilation performance
    - Office zone CO_2 concentrations (i.e., used as a surrogate for occupant-generated contaminants) for natural and hybrid ventilation systems are at or below peak levels reached with mechanical ventilation meeting ASHRAE Standard 62.1 outdoor air requirements (determined to be 1400 mL/m^3 (1400 ppm(v))) during at least 98 % of occupied time
- Thermal performance
    - Average hourly office zone air temperatures are below 20 °C fewer than 2 % of occupied hours and above 26 °C fewer than 2 % of occupied hours
- Energy-related performance
    - Fan energy use relative to mechanical system
    - Heating and cooling loads relative to mechanical system

While useful in evaluating many performance aspects of the natural and hybrid ventilation systems, these hypotheses and evaluation criteria do not cover all aspects of system performance. Important performance factors not evaluated include humidity control, effective temperatures, and contaminant concentrations for the range of internal and external contaminant sources. These performance aspects remain important issues and need to be pursued in future simulation and field studies.

3.3 Simulation Method

Due to the significant interactions between airflow and heat transfer in naturally ventilated buildings, the recent literature has emphasized the need for a coupled thermal and airflow simulation method to model such buildings (Axley 2001, Eriksson and Wahlstrom 200, Heiselberg and Tjelflaat 1999, Heinonen et al. 2002). Therefore, these simulations were performed using CONTAMR, a version of the CONTAM multizone IAQ modeling program that provides the essential coupled thermal/airflow modeling capability. A version of CONTAMR was used in a previous modeling study of a naturally ventilated building (Axley et al. 2002). However, this program lacks tools enabling convenient performance of typical annual energy use calculations. Presently, CONTAMR provides thermal components to model dynamic one-dimensional conductive heat transfer (accounting for both conductivity and heat capacity of the building envelope), dynamic one-dimensional thermal storage heat transfer (accounting for internal thermal mass), advective heat transfer (accounting for infiltration and interzonal airflow), and internal sensible gains (accounting for occupants and equipment, solar gains, and sensible space conditioning).

3.4 Building Parameters

Several guiding principles played a role in defining the building to be modeled. These include:

- The model should be based on a real building that's been monitored for airflow and thermal performance to increase the credibility of the simulation results.
- The building should employ good energy efficiency practice to reflect the "forward-thinking" owners/architects/engineers likely to consider a natural or hybrid system.
- The building should not be too exotic relative to mainstream U.S. construction.
- The natural, hybrid and mechanical buildings should be very similar but need not be identical.

Although it was considered desirable to base the modeled building on one in the U.S., no building was identified that met these criteria. Therefore, based on these principles and to leverage previous NIST work, the baseline building selected is the Enschede office building located in the Netherlands (see Figure 1). This building is a five story, 4300 m^2 office building organized around a "slot" atrium (see Figures 2 and 3), which was designed to be a low-energy building.

Figure 1 Enschede Office Building, the Netherlands

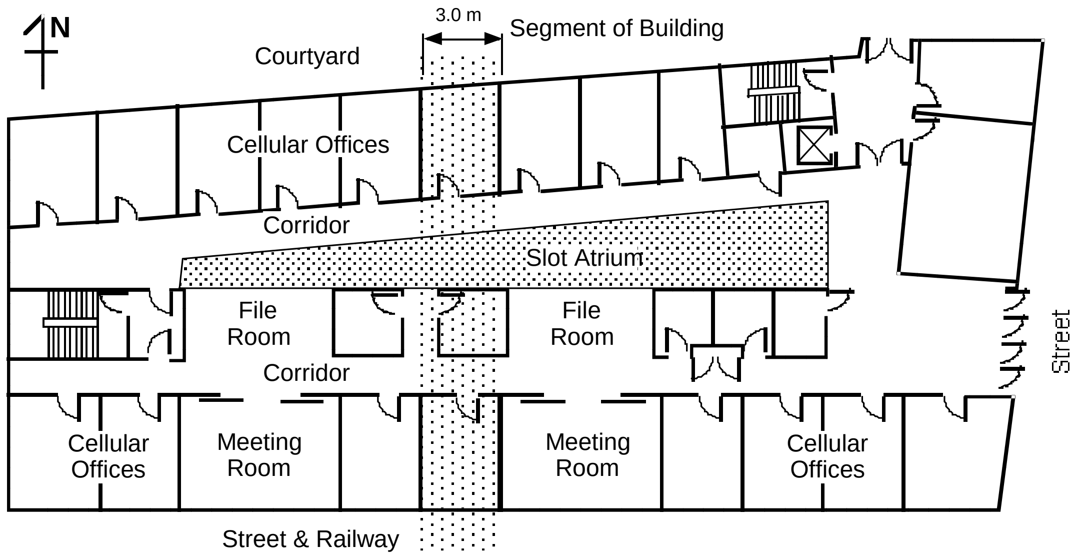

Figure 2 Floorplan of Office Building

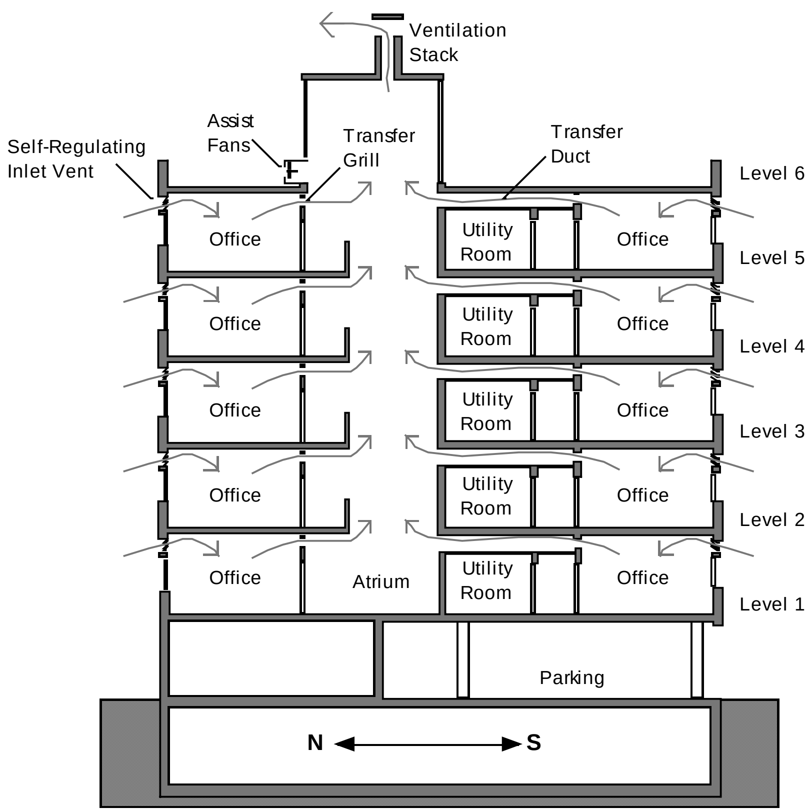

Figure 3 Section of office building (as built with natural ventilation system)

The Enschede building was modeled previously with the CONTAMR program in an earlier study of natural ventilation (Axley 2001 and Axley et al. 2002). No significant changes to the baseline building are needed to incorporate the natural, hybrid and mechanical configurations. Thermal properties were taken from the 1997 ASHRAE Handbook of Fundamentals (ASHRAE 1997). Some of the important features of the simulated building include:

- Envelope leakage: Effective leakage area, 1 cm^2/m^2 at 4 Pa
- Occupancy: 2 persons per 15 m^2 office
- Total daytime internal heat gain in offices: 27.5 W/m^2 (accounting for both internally generated loads and a variable solar thermal load; reduced to 0 W/m^2 during unoccupied hours)
- Daytime internal heat gain in halls, atrium, etc.: 5 W/m^2
- Windows: 45 % glazed area with low-e glazing
- Wall: brick tile/plywood/fiberglass/gypsum system
- Thermal mass: 150 mm concrete with area 150 % of nominal combined ceiling and floor areas

Some rooms were combined to limit the total number of thermal and airflow zones to a more manageable number as shown in Figure 4. The CONTAMR model has 6 floors with 56 zones including 6 atrium zones, 45 office zones and 5 elevator/stairwell shaft zones. The atrium (which includes the corridor, file rooms, and other non-office spaces) is divided vertically at each floor to more accurately account for the stack effect due to vertical temperature gradients. The 45 office zones represent 110 offices. Note that the total office floor area in the model is 1650 m^2. The elevator shaft, like the atrium, is also divided by floor to better model the stack effect. While these auxiliary spaces are included in the model, the results presented are for the office space only.

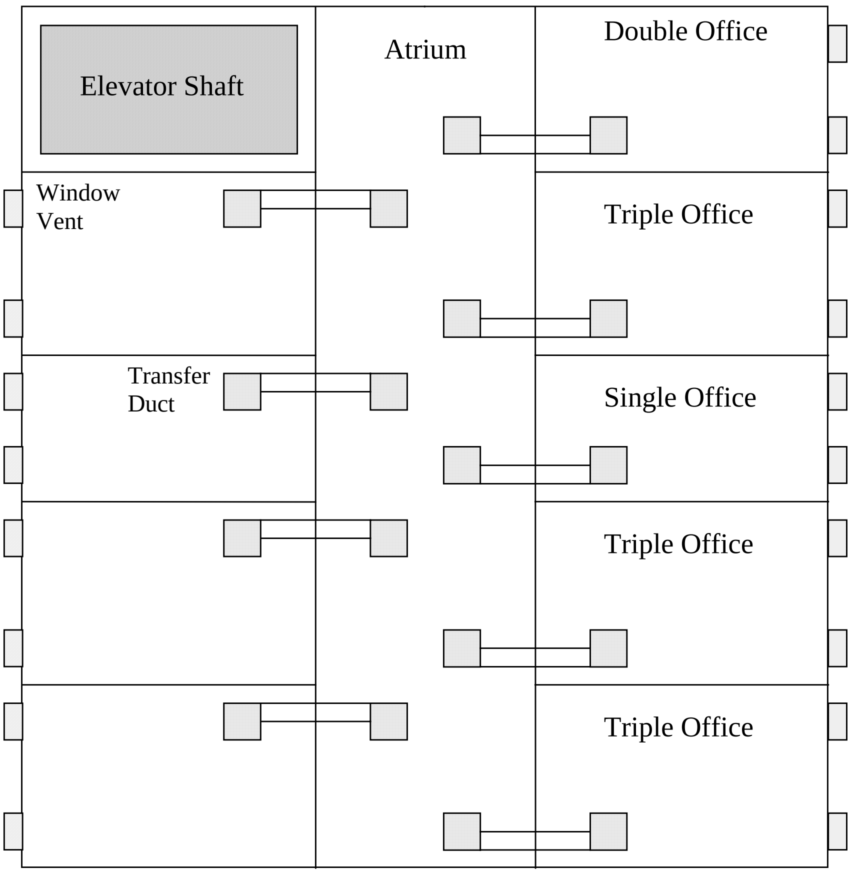

Figure 4 Floorplan of office building as modeled

3.5 HVAC Systems

As described earlier, the performance of the baseline building was simulated with a natural ventilation system, a conventional mechanical system, and a hybrid ventilation system. The modeled systems are simple and idealized because CONTAMR does not have detailed equipment models available. Fan energy use was estimated from simulation flow rates using the fan power limitation of 0.48 W/(m^3/h) (1.1 x 10^{-3} hp/cfm) per Table 6.3.3.1 of ASHRAE Standard 90.1 (ASHRAE 2001b).

Natural ventilation

The natural ventilation system is based on the earlier model of the actual Enschede building. This natural ventilation system is one of the typical configurations currently used in a number of modern European buildings (Axley 2001). Features of the modeled system include:

- Adjustable self-regulating inlet vents to provide outdoor air for ventilating and cooling the offices
- Slot atrium with ventilation stacks
- Transfer ducts and grills connecting offices to the atrium
- Thermally massive slabs to reduce daytime cooling loads
- Night cooling strategy tailored to the climate and season

The only significant changes from the model described by Axley are deletion of the stack assist fan and modification of the self-regulating inlet vent sizes to provide climate-specific target ventilation rates. The natural ventilation system is intended to rely primarily on stack effect to drive ventilation flows and to utilize night cooling when direct ventilative cooling is likely to be insufficient. One potential concern with such a night cooling strategy is the risk of condensation. As mentioned earlier, humidity control was not analyzed in this study but does need to be considered in future work to support the evaluation and implementation of these strategies. Each office zone includes an outdoor air intake vent drawing from the ambient outdoor air and a transfer duct that links the office zone to the atrium. The atrium has an extended stack above the top (fifth) floor of the building to assist the stack effect. It also has large stack vents in the atrium ceiling. Sizing of the system components was performed using the LoopDA natural ventilation design tool (Dols and Emmerich 2003) and is described later in this section. Each office also includes a heater.

A key to the success of the natural ventilation system is using an effective ventilation and temperature control strategy. Different strategies were used in the different climates during different seasons. The first strategy, used for hot periods, has the heaters remaining off at all times and the window vents opened for minimum ventilation during the day and closed completely at night. The second strategy is used in the milder climates during the summer periods and in the warmer climates during shoulder seasons. It consists of the heaters being always off and the natural ventilation inlet vents being kept at the minimum during the day and maximum during the night. The third strategy is used for the milder climates' shoulder season and cold climates' summer season. It consists of temperature-controlled heaters running with setbacks during the night and weekend hours. The window vents are set at the minimum during occupied hours and, if night cooling is needed, also during nights and weekends. The fourth strategy is used for the winter periods in the mild climates and the shoulder and winter periods in the colder climates. It consists of the heater being run on temperature control with setbacks at night and on the weekends. The inlet vents are kept at the minimum during the day and are closed at night.

The two controllable components of the natural ventilation system, the individual office heaters and the natural ventilation inlet vents, are controlled independently. The inlet vents are controlled by schedules but must remain at least partially open during the occupied hours in an attempt to comply with the outdoor air requirements in ASHRAE Standard 62.1-2004. At night and on the weekend the window vents can be opened fully, closed completely or left partially open depending on the climate and season. The heaters are controlled individually for each office by a system of temperature sensors and schedules. A schedule is set for the minimum indoor temperature for occupied hours and for nights and weekends, creating the setback for the heating system. A sensor then detects the indoor temperature for the zone and compares it with the value from the schedule of minimum temperatures. If the detected temperature is below the minimum temperature then the heater is switched on. The heater has a dead band of 2 °C, which means that the zone temperature must be raised 2 °C above the minimum temperature from the schedule before the heater is switched off. In certain climates and seasons the heater is off at all times.

In all cases, the operating strategy for the natural ventilation system was limited to opening the vents when occupants arrive in the morning and closing them when they leave in the afternoon. The specific strategies used for each modeled city/season combination are described in the results section. A more sophisticated strategy could be employed based on either weather-driven automatic controls or manual controls operated in response to measured indoor or ambient conditions. However, the simple strategy modeled is based on the one actually used in the Enschede building and is sufficient for this study's objectives.

Mechanical system

The mechanical system is an all-air system with temperature-based economizer and ventilation rates that meet ASHRAE Standard 62.1 (ASHRAE 2004). It is modeled with a simple air handling system for each floor. The air handling system has a supply vent in every office zone and a return vent located in the atrium at the level of the floor. The system is operating constantly during occupied hours and is off during night and weekend hours. The supply airflow rate is four air changes per hour in the offices and brings in the minimum amount of outdoor air per ASHRAE Standard 62.1. The outdoor air rate used was 34 m^3/h per single office with two occupants based on Standard 62.1 requirements of 2.5 L/s per person plus 0.3 L/s per m^2 of floor area. It is equipped with an economizer that switches to 100 % outside air when the temperature outside is within a set range. In the model, each individual office includes a heater and an AC unit, both controlled by the individual zone temperatures with setbacks or setups during the night and weekend hours. While such a system would be atypical in practice, it serves the modeling purpose of calculating the minimum total amount of office zone cooling and heating loads required to meet the setpoints in each office zone.

There are two main control strategies used with the mechanical system. In the heating strategy, used during the winter periods and some shoulder periods, the air handling system runs during occupied hours and is off at night. This heating strategy utilizes the economizer, if needed, when the outdoor temperature falls within the designated range. Also, the heaters are controlled based on the individual zone temperatures with a setback during the night and weekend hours. For the winter in cold climates, the AC units are off at all times. The summer strategy has the air handing system on with an economizer during occupied hours and off at night. The individual zone temperatures control the AC unit with a set-up at night and on the weekend. The heaters are off at all times.

The three controllable components of the mechanical ventilation system are the air handling system, the heaters and the AC units. The air handling system is controlled independently of the heaters and AC units. Two schedules for controlling heating and cooling are used - one with the maximum temperature allowed in the zone for the occupied hours and for the nights and weekends, and another with the minimum temperature allowed in the room for the nights and weekends. A sensor detects the temperature in the zone. If the temperature in the zone falls below the minimum temperature set by the heating schedule the heater is switched on. The heater uses a dead band of 2 °C. Similarly, if the zone temperature is above the maximum temperature set by the cooling schedule, then the air conditioner is switched on. The AC unit also has a dead band of 2 °C. This means that once the AC unit is switched on the zones temperature must fall 2 °C below the maximum temperature before the air conditioners are switched off. Either heating or cooling, but not both, is enabled during a simulation period. The air handling system is controlled by both schedules and sensors, and is only operated during occupied hours. During all occupied hours there are four air changes of air per hour of supply air being moved by the air handling system and at least the minimum amount of outdoor air required by Standard 62.1. The air handling system is equipped with an economizer that works by sensing the outdoor temperature. If the outdoor temperature falls between 15 °C and 20 °C, then the system switches from the minimum required outdoor air to 100 % outdoor air, i.e., four air changes per hour.

Hybrid system

There are many possible combinations of natural and mechanical components that can make up a hybrid ventilation system. The literature review performed in Task 1 of this project details a number of systems currently operating in buildings throughout the world. However, only one hybrid system was modeled, representing a ‘state-of-the-art’ hybrid ventilation system with automatic control of individual zone temperature and ventilation. The natural ventilation components of the system are the same as the single-mode natural ventilation system described earlier, with the exception of the target airflow in some cases. The mechanical system is intended to be capable of providing ventilation or thermal conditioning as needed to individual zones of the building. Such an idealized system might be more expensive to install but likely provides an upper bound to the potential energy savings.

The ventilation fans are controlled individually in each office and are switched on and off according to the CO_2 concentration in the individual office. The heaters from the hybrid system are operated in the same manner as in the natural ventilation system (described earlier) but AC units are added to supplement the direct natural cooling and night cooling effects. The strategies used by the hybrid systems are tailored to the individual climate and season. In warmer climates during the summer periods the strategy involves setting the natural ventilation inlets to the minimum during the day and closing them completely at night while the air-conditioners are operated based on the individual offices temperature, utilizing setbacks during the night and weekend hours. The shoulder season strategy is to use the inlet vents to provide cooling without causing a need for supplemental heating. Supplemental cooling was used when needed. The winter season strategy consists of using the natural ventilation inlets at minimum during the day and closing them at night while using the heaters controlled by the individual office temperatures to regulate those spaces. For the coldest climates, the winter strategy involves closing the natural ventilation inlets at all times to reduce the heat load while allowing the mechanical fan to provide controlled ventilation.

The hybrid ventilation system has four components: natural ventilation inlet vents, local ventilation assist fans, heaters, and AC units. The natural ventilation inlet vents are controlled by schedules in the same manner as in the natural ventilation system. During occupied hours, the vents may either be open to provide ventilation and cooling or closed to allow the mechanical fan to provide all needed ventilation. At night and on the weekend, the inlets can be opened fully, closed completely or left partially open depending on the climate and season. The local assist fans are controlled individually for each office. The concentration of CO_2 in the zone is sensed and compared with the CO_2 setpoint of 1200 mL/m^3 (1200 ppm(v)). If the level of CO_2 in the room is higher than the CO_2 setpoint, then the assist fans are turned on with a flow rate of 34 m^3/h per single office. The assist fan controls have a dead band of 100 mL/m^3 (100 ppm(v)). This means that once the assist fan is activated the level of CO_2 has to drop 100 mL/m^3 (100 ppm(v)) below the maximum level before the fans are switched off. The heating and cooling equipment is operated in much the same manner as the heaters in the natural system. Two schedules are used - one with the maximum temperature allowed in the zone for the occupied hours and for the nights and weekends, and another with the minimum temperature allowed in the room for the nights and weekends. A sensor detects the temperature in the zone. If the temperature in the zone falls below the minimum temperature established by the schedule, the heater is switched on. The heater uses a dead band of 2 °C. The AC unit is controlled by comparing the maximum temperature schedule and the zone temperature. If the zone temperature is above the maximum temperature set by the schedule, then the AC unit is switched on. The AC unit also has a dead band of 2 °C. In certain climates and seasons, the heater or AC unit is always off.

3.6 Simulation Periods and Climates

The simulation periods were selected to represent typical weather events in several U.S. climates. This approach enables modeling of events such as an extended summer heat wave, mild shoulder season, or long cold spell without having to simulate and analyze and entire year of 8760 hours. Each of the simulation periods lasted six weeks, with the first two weeks simulated but not included in the analysis of results due to the large thermal mass of the building. While modeling an entire year has some appeal, it adds far more data analysis without adding any truly useful knowledge. Additionally, the shorter periods allow more focus on far more important details such as operational strategies.

Given the simulaton approach, the specific climates in which the buildings are modeled is not critical provided the wide range of U.S. climate is considered. Therefore, the simulations employed TMY2 weather files (Marion and Urban 1995) for hot (July), cold (February) and moderate (April) periods in Boston, Los Angeles, Miami, Minneapolis, and San Francisco. Given the three systems modeled, this resulted in a total of 45 simulation cases (5 cities x 3 periods x 3 systems).

3.7 Climate Analysis and Sizing of Natural Ventilation System Components

As described above, the natural ventilation system modeled is based on the actual system for a naturally ventilated building in the Netherlands. However, the system components (i.e., self-regulating inlet vents, transfer ducts, and ventilation exhaust stacks) must be sized for the climates being simulated. This was accomplished with a two-step process. First, the climates were analyzed to estimate the required day and, if required, night ventilation rates. Then, component sizes were specified to achieve the needed ventilation rates under chosen ambient conditions.

In earlier work (Axley 2001), NIST developed a climate suitability analysis technique to evaluate the potential of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling, i.e., of a building's thermal mass. The direct ventilative cooling may be provided by either a natural ventilation system or a fan-powered economizer system. As such, this climate analysis is a useful pre-design analytical technique. It also establishes first order estimates of design ventilation rates needed for preliminary design calculations, i.e., given knowledge of the likely internal heat gains in a building and local climatic conditions. Specifically, a designer may estimate the ventilation rate needed to offset internal gains when direct ventilation can be effective and the internal gains that may be offset by nighttime ventilation when direct ventilation will not work. However, since the technique requires no building-specific information other than estimated thermal loads, it may be applied to evaluate the potential impact of natural ventilation in a given climate for buildings over a range of thermal loads.

The climate suitability analysis technique is based on a general single-zone thermal model of a building configured and operated to make optimal use of direct and/or nighttime ventilative cooling. With this model, an algorithm was defined to process hourly annual weather data, using established thermal comfort criteria. The details of this approach are presented in earlier reports (Axley 2001, Emmerich et al. 2001, Axley and Emmerich 2002).

This method was applied to the five U.S. locations using TMY2 hourly annual climatic data (Marion and Urban 1995) to evaluate the potential applicability of natural ventilation and to estimate needed ventilation rates for the building being studied. The results of this analysis include the fraction of hours for which direct ventilative cooling is estimated to be effective at a total building internal heat gain of 27.5 W/m^2, the average required air change rate to directly cool the building, the 25th and 90th percentiles of required air change rates to directly cool the building (calculated as guides for design ventilation rates in cooler and hotter seasons), the number of overheated days (i.e., days when night cooling or supplemental cooling may be required), the fraction of overheated days for which night cooling is expected to be effective, and the average required air change rate at night to meet the daily building internal gain.

While the climate analysis method is only expected to provide rough estimates due to its many limiting assumptions, the results in Table 1 provide useful insights into the potential natural ventilation system performance for the various climates in addition to ‘design’ ventilation rates. For example, its not surprising that the San Francisco climate is most suited to natural ventilation as seen by the prediction that direct natural ventilation cooling can meet the cooling load 99 % of all hours (i.e., % effective value in Table 1) at a modest average ventilation rate of 3.1 h^{-1} and very small number of potential overheated days. The range of required ventilation rates, i.e., from the 25th percentile rate of 2.1 h^{-1} to the 90th percentile rate of 4.3 h^{-1}, may indicate the potential for successfully providing thermal comfort with simple operating strategies. A natural ventilation strategy without night cooling is therefore likely to be effective in this climate.

While requiring larger ventilation rates than San Francisco, the Los Angeles climate has a similarly high effectiveness (i.e., Table 1 shows that an average rate of 4.5 h^{-1} will meet the cooling requirement for 97 % of hours) and a fairly flat required ventilation rate profile. However, there are many more potentially overheated days (55) but a very high percentage effectiveness is predicted for a night cooling strategy at a reasonable average night ventilation rate of 4.2 h^{-1}. Therefore, a natural ventilation system with a night cooling strategy may be effective in Los Angeles.

Boston and Minneapolis both differ from San Francisco and Los Angeles in several ways that lead to lower effectiveness for a natural ventilation strategy. First, the percent effectiveness is significantly lower at 88 % and 81 % for Boston and Minneapolis, respectively. Second, the required ventilation rates in hotter weather are much higher than they are for cooler weather. Finally, a night ventilation strategy is needed for 80 or more potential overheated days but is likely to be ineffective for about a quarter of those days due to excessive humidity as the analysis assumes night cooling cannot be used if the dew point is higher than 17 °C. Thus, while a pure natural ventilation system is likely to be effective for a large fraction of the year in Boston and Minneapolis, it is unlikely to effectively provide thermal comfort for a significant portion of the year even with a night cooling system. However, a hybrid ventilation system may be more effective in these climates.

In contrast, the Miami climate is far too hot for a natural ventilation system to provide thermal comfort for more than a small fraction of the year (percent effectiveness of 28 %) and even that requires a large average ventilation rate of 7.2 h^{-1}. Additionally, a night cooling strategy is likely to provide sufficient supplemental cooling for only about a quarter of the overheated days.

Table 1 Natural Ventilation Analysis for Five U.S. Locations (Internal Gain of 27.5 W/m²)

	Direct Cooling				Night Cooling[1] rate (h^{-1})
	% Effective	Average rate (h^{-1})	25th percentile rate (h^{-1})	90th percentile rate (h^{-1})	
Boston					
Ventilation Rate		3.4	1.4	5.5	4.4
% Effective[2] (Overheated days)	88 %				78 % (82 days)
Los Angeles					
Avg. Vent. Rate or Cooling Potential		4.5	2.7	6.7	4.2
% Effective[2] (Overheated days)	97 %				100 % (55 days)
Miami					
Avg. Vent. Rate or Cooling Potential		7.2	3.7	16.5	5.9
% Effective[2] (Overheated days)	28 %				26 % (80 days)
Minneapolis					
Avg. Vent. Rate or Cooling Potential		4.0	1.2	6.1	4.4
% Effective[2] (Overheated days)	81 %				71 % (77 days)
San Francisco					
Avg. Vent. Rate or Cooling Potential		3.1	2.1	4.3	3.2
% Effective[2] (Overheated days)	99 %				100 % (12 days)

[1] Night cooling for days when direct cooling is not effective.

[2] For direct cooling % effective = # of hours that direct natural cooling can meet the cooling load ÷ 8760 h. For night cooling % effective = days effective ÷ overheated days.

Sizing of System Components

As described above and shown in Figures 3 and 4, the natural ventilation system components include self-regulating inlet vents, transfer ducts and grills, and exhaust stacks above the atrium. For the building model, these ventilation system components were sized using the Loop Equation Design Method (Axley 2001) as implemented in NIST's LoopDA program (Dols and Emmerich 2003).

The loop equation design method is based on the same theory currently used in multi-zone airflow analysis programs like CONTAMW (Dols and Walton 2003). The approach taken is both fundamental and simple; equations are written for the changes of pressure that must occur along each ventilation loop of a building ventilation system following a ventilation flow path from inlet to exhaust and back to the inlet again. The sum of these pressure changes around any loop must necessarily equal zero. The resulting loop equations define combinations of system component sizes that will provide desired ventilation flow rates given specific environmental design conditions. Therefore, these equations may be used directly to size ventilation system components. Furthermore, as the loop equations generally do not define a unique design solution, specific non-technical design constraints (e.g., selecting component sizes from commercially available units) may be specified and operational strategies (e.g., for with-wind and without-wind conditions) formulated when applying the loop equation design method. A representative section and partial plan of the office building is illustrated in Figure 5, showing diagrammatic representations of each of ten ventilation flow loops.

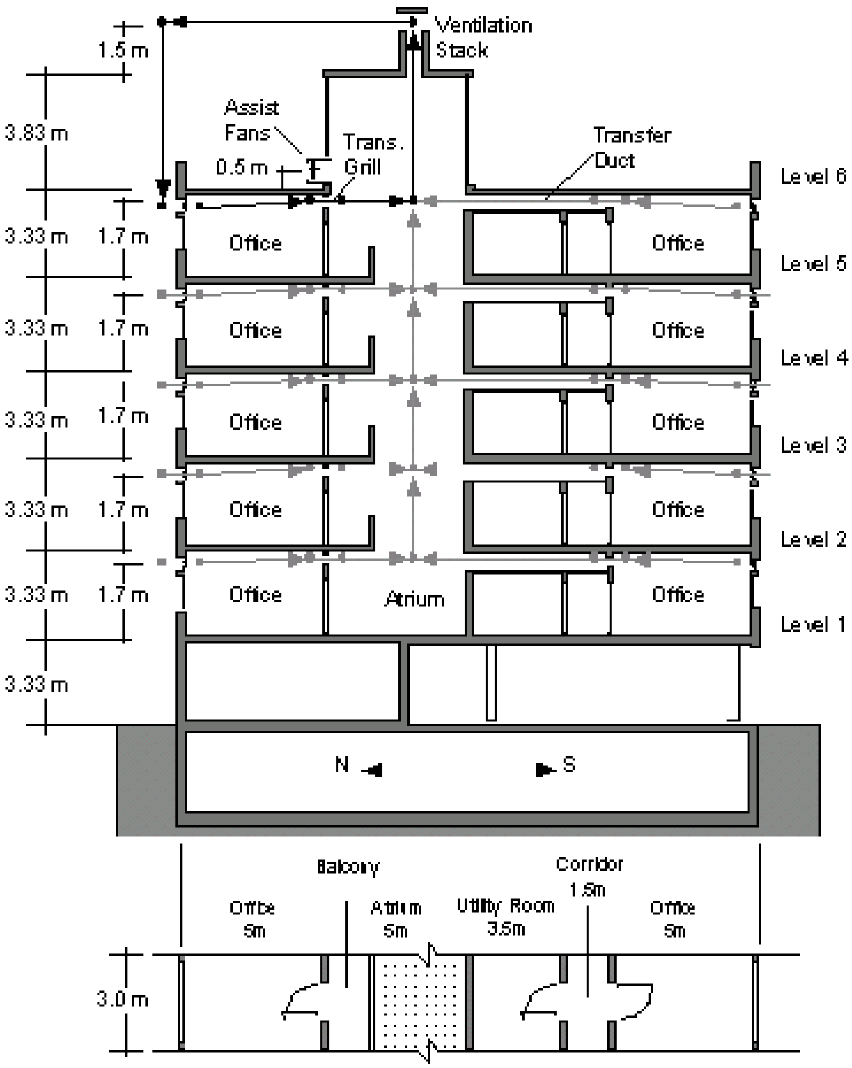

Figure 5 Plan and section of the Enschede Tax Office building. (Solid dots and linking arrows indicate, diagrammatically, pressure nodes and airflow paths of all ventilation loops.)

The sizing of the components was simplified through the use of the self-regulating inlet vents and by sizing the systems once for all climates based on the largest design flow condition. Self-regulating inlet vents (Knoll and Kornaat 1991, Wouters and Vandaele 1990, Cavannal et al. 1999, Schultz 1993) provide relatively constant airflow rates over the range of air pressure differences likely to be encountered. Consequently, they provide the means to achieve controlled design airflow rates for the varying natural driven conditions that exist in the field. However, they cannot sustain design airflow rates when wind and buoyancy forces drop to negligible values. The self-regulating inlet vents used in the Enschede Tax Office were designed to provide a near-constant flow rate of 50 m^3/h for driving pressure differences between 1 Pa and 25 Pa at their lowest setting and 100 m^3/h at their highest setting. The following power-law relation using an unusually low exponent of n = 0.1 was used to model one of the two vents placed in the offices set at its lowest setting:

$$\dot{V} = 39\Delta p^{0.10} \tag{1}$$

where $\dot{V}$ (m^3/h) is the volumetric airflow rate through the component and Δp (Pa) is the pressure difference across the component. Relative to the power law model with an exponent of n = 0.5, which is commonly used to model openings in building envelopes, the relation chosen to model the self-regulating inlet vents provides a fairly constant airflow rate over a range of pressure differences likely to be encountered in practice (i.e., from 0 Pa to 25 Pa). Axley (2001) provides a more complete description of such self-regulating inlet vents.

Use of the self-regulating inlet vents simplifies the design and modeling of the inlet vents for the project as the desired maximum desired flow can be provided in the design by including the appropriate number of inlet vents. Then, the desired operating strategy can be implemented by simply ‘opening’ and ‘closing’ the required number of vents via a schedule in CONTAMR. For convenience, the airflow provided by each vent is approximately 1 h^{-1} at the minimum setting and 2 h^{-1} at the maximum setting for the single 50 m^3 office. This represents a target outdoor airflow rate that is 50 % above the required rate per ASHRAE Standard 62.1 at the minimum setting for a single vent. Since it is desired that the inlet vents maintain control authority over the ventilation airflow, and the needed number of vents will be set during the simulations for the various locations and seasons, the LoopDA program was used to size the remaining natural ventilation system components to be sufficiently large to meet the largest desired design flow. Based on the estimated required airflow rates in Table 1, 4 h^{-1} was selected as the design value as it meets most of the values except for the very high values in Miami and the high values for the summer in several other locations. However, those locations will be modeled with a night cooling ventilation strategy during the hottest season and thus will not rely on direct ventilative cooling.

In addition to selecting design ventilation flow rates, the sizing procedure requires specifying ambient conditions for the design calculation. Since a night ventilation strategy will be used during the hottest months in all climates except San Francisco, it is not necessary to size the components to provide the design flow rate in those extreme conditions. The warmest simulation period for which direct ventilative cooling might be effective is the Los Angeles shoulder season. Therefore, the 90th percentile hourly ambient temperature (20 °C) from April during the Los Angeles TMY2 file was selected as the design point for the sizing calculations. The design wind speed was conservatively set to 0 m/s although this extreme rarely occurs. The selected component sizes based on the LoopDA design effort are summarized in Table 2. Note that the exhaust stack area listed is for a single office section – the whole building model has a total of 11 such atrium exhaust stacks.

Table 2 Design sizes of natural ventilation system components

Component	Atrium Exhaust Stack Area (m^2)	Transfer Duct Diameter for single office (mm)	Transfer Duct Diameter for double office (mm)	Transfer Duct Diameter for triple office (mm)	Transfer Grill Diameter for single office (mm)	Transfer Grill Diameter for triple office (mm)
Design size	2	400	600	700	250	360

4. Results

As discussed in Section 3, the key performance aspects predicted in the simulation study include ventilation flow rates, indoor temperatures, CO_2 concentrations, heating and cooling loads, and fan energy use. Since the performances of the natural and hybrid systems are very dependent on climate, this section presents those results organized by location. Sample plots are presented for all three system types in all three seasons for San Francisco. Plots for all other locations are included in Appendix A. As mentioned earlier, results are presented only for the office zones within the building.

4.1 San Francisco

4.1.1 Natural Ventilation System

February

During the cool weather in February, the ventilation system is operated at its minimum target of approximately 50 m^3/h per single office during occupancy with no night ventilation. Air temperatures for 10 office zones for the building with natural ventilation system for February in San Francisco are shown in Figure 6. The office zones in the figure are the single offices on opposite sides of the atrium from the 1st through 5th floors (refer to Figures 2, 3 and 4). The office temperatures fall in the desired 20 °C to 26 °C range most of the time. However, on several afternoons, the temperature exceeds the desired maximum by about 1 °C in several offices. Increasing the ventilation rate could control these temperatures but would increase the heating load during the cooler portion of the month. As stated earlier, a more sophisticated control strategy could improve the control relative to the simple strategy modeled.

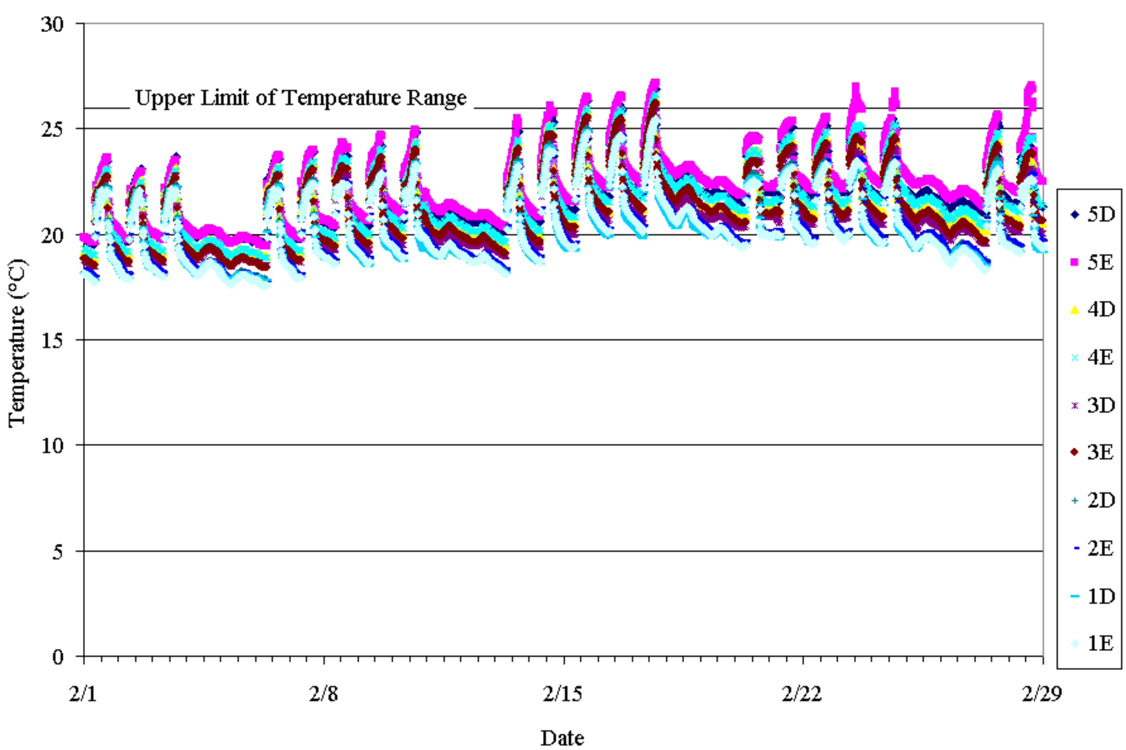

Figure 6 Office zone temperatures for natural ventilation in February, San Francisco

Natural ventilation system inlet airflow rates for the same 10 office zones for the building with natural ventilation system for February in San Francisco are shown in Figure 7. Although the inlet flow is fairly stable due to the control of the self-regulating inlet vents, the flow does drop below the target of 50 m^3/h when the stack and wind driving forces are low. Occasionally, the flows through the inlet vents reverse in some office zones due to a combination of reduced stack effect and opposing wind effect on the leeward side of the building. This effect has also been observed in the Enschede building and in earlier modeling studies (Axley 2001). For this case, the flow reversals only occurred on the 5^{th} floor of the building.

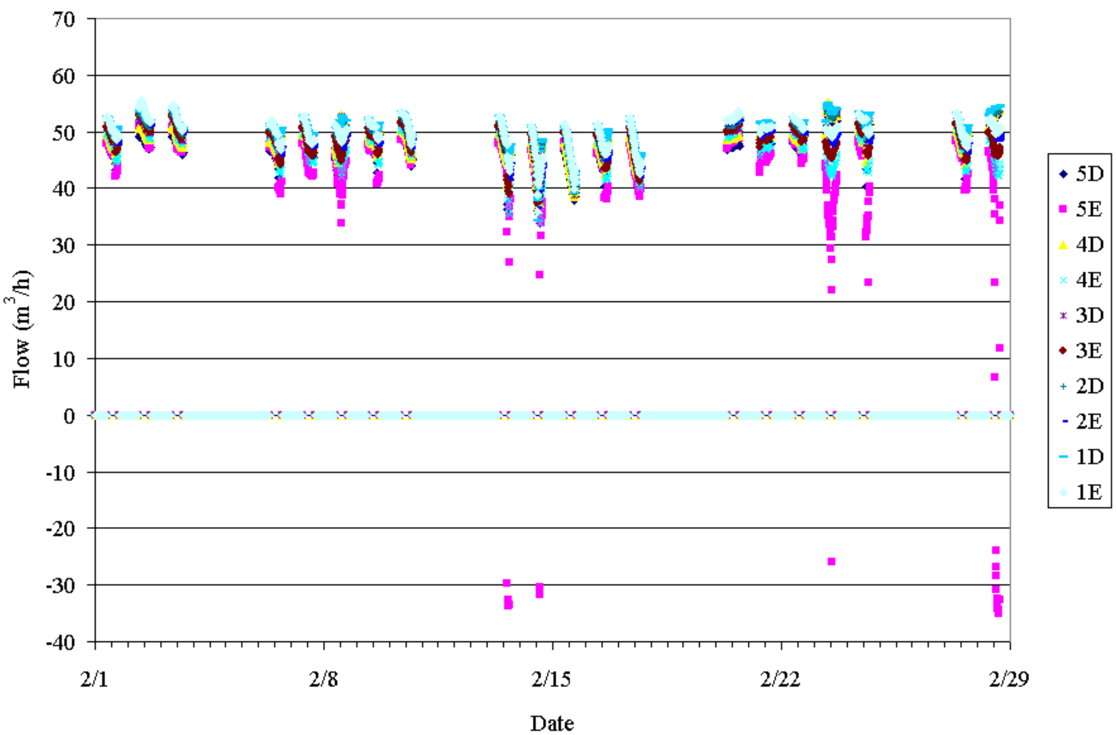

Figure 7 Natural ventilation inlet flow rates in February, San Francisco

Carbon dioxide concentrations for the same 10 office zones for the building with natural ventilation system for February in San Francisco are shown in Figure 8. Although the flow reversals show the natural ventilation system failing relative to its design intent, ventilation is still being provided to those zones via the atrium. The calculated CO_2 concentrations can be compared relative to a level of approximately 1400 mL/m^3 (1400 ppm(v)) which corresponds approximately to the steady-state concentration for the mechanical system operated at the Standard 62. minimum ventilation rate (e.g., as shown later in Appendix A for the mechanical system during July in Boston). The CO_2 concentrations for the natural ventilation system exceed that level in one or more zones during three days of the month.

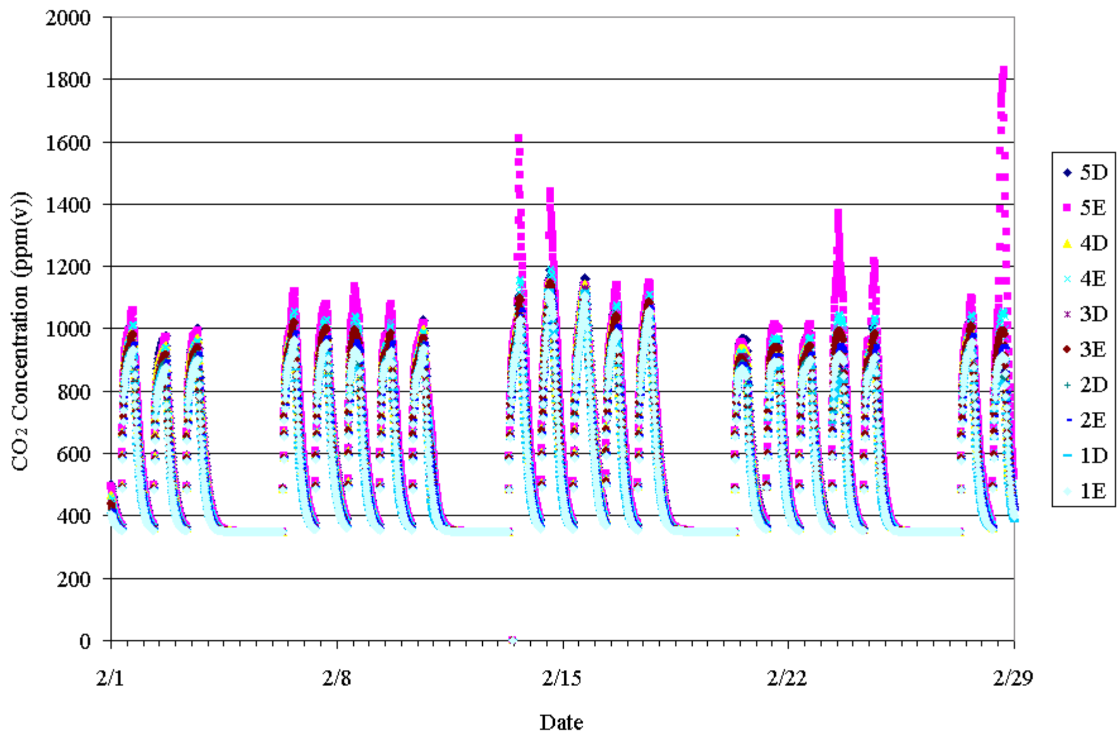

Figure 8 Office zone CO_2 concentrations for natural ventilation case in February, San Francisco

April

Given the modest change in weather in San Francisco in April relative to February, the operational strategy for the natural ventilation system is very similar. The only change is an increase in the target ventilation rate during occupied hours to 100 m^3/h per single office to provide additional direct cooling. For thermal control, the natural ventilation system performance in April is also similar to February as there are once again a few hours during the month when temperatures exceed the desired upper limit (see Figure 9). There are several more days during which ventilation flow reverses (see Figure 10) in February than in April due to the warmer temperatures that result in lower stack forces. However, since the ventilation setting during occupied periods is doubled, the resulting CO_2 concentrations in April are much lower than in February (see Figure 11). In fact, the peak concentrations never exceed 1300 mL/m^3 (1300 ppm(v)).

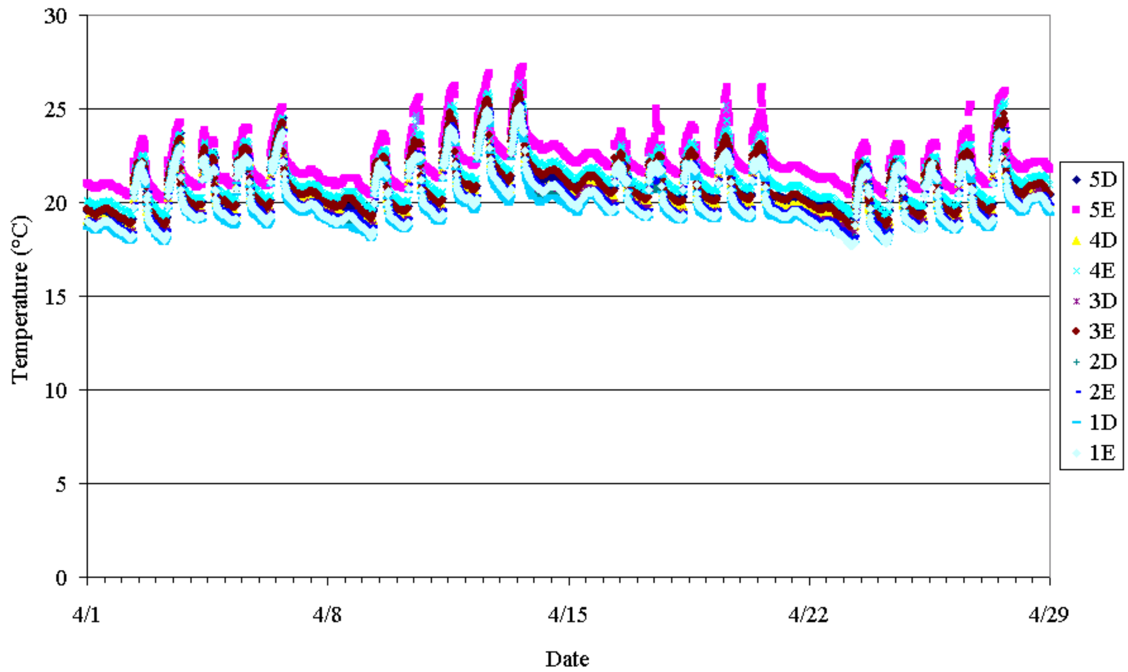

Figure 9 Office zone temperatures for natural ventilation in April, San Francisco

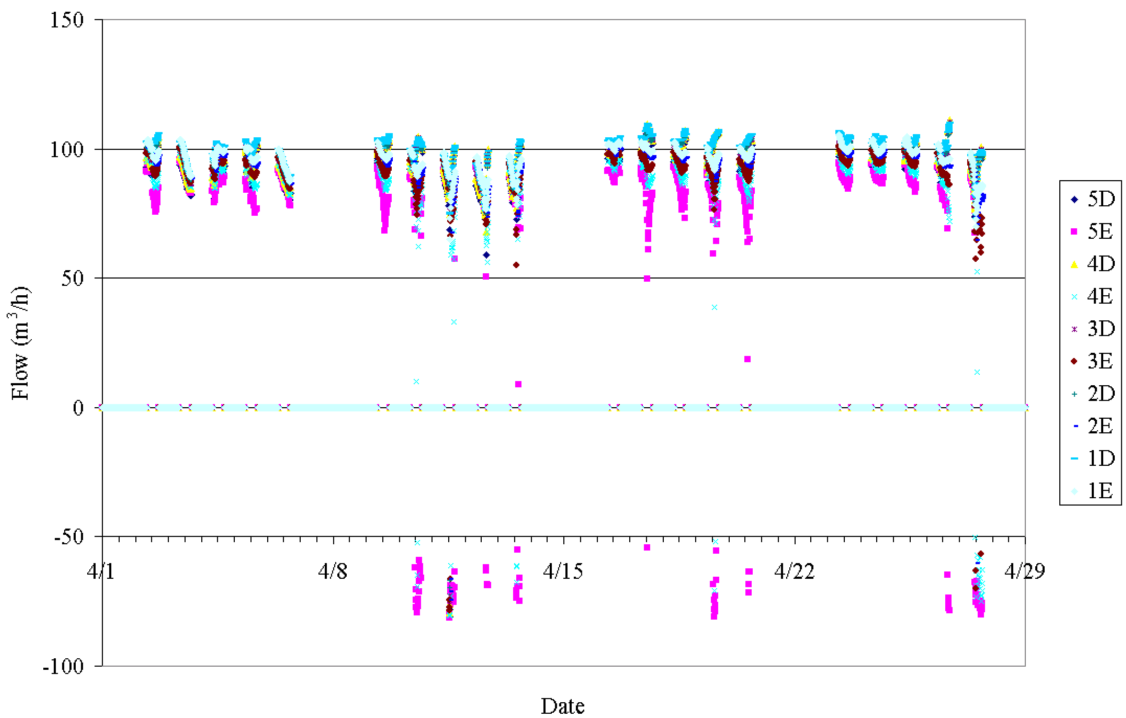

Figure 10 Natural ventilation inlet flows in April, San Francisco

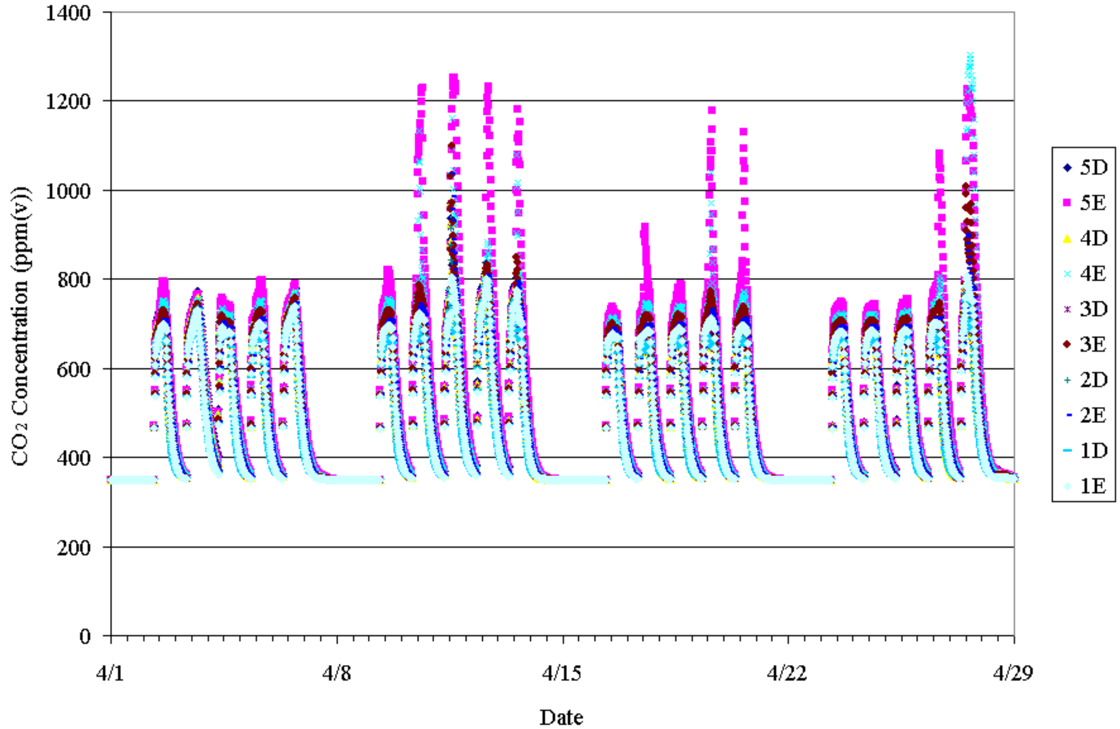

Figure 11 Office zone CO_2 concentrations for natural ventilation in April, San Francisco

July

The operational strategy for the natural ventilation system for July in San Francisco maintains the same occupied ventilation rate of 100 m^3/h per single office but adds night ventilation for supplemental cooling. The night target rate is also 100 m^3/h. As seen in Figure 12, the supplemental night cooling allows the system to maintain the office zone temperatures within the desired range throughout the month. Figure 13 shows that the resulting inlet flow rates during the night met the target but the flow rates were below target during the day and flow reversals occurred for some zones nearly every day. Once again, ventilation flow was adequate to keep peak CO_2 concentration rates at about 1100 mL/m^3 (1100 ppm(v)) to 1300 mL/m^3 (1300 ppm(v)) despite the flow reversals (see Figure 14).

As discussed later, the night cooling strategy, which is necessary to limit temperature increases during occupied hours, results in a small amount of heating energy use when the building is occasionally overcooled at night. A more sophisticated control system or a strategy based on anticipated temperatures could likely avoid or reduce the need for this heating.

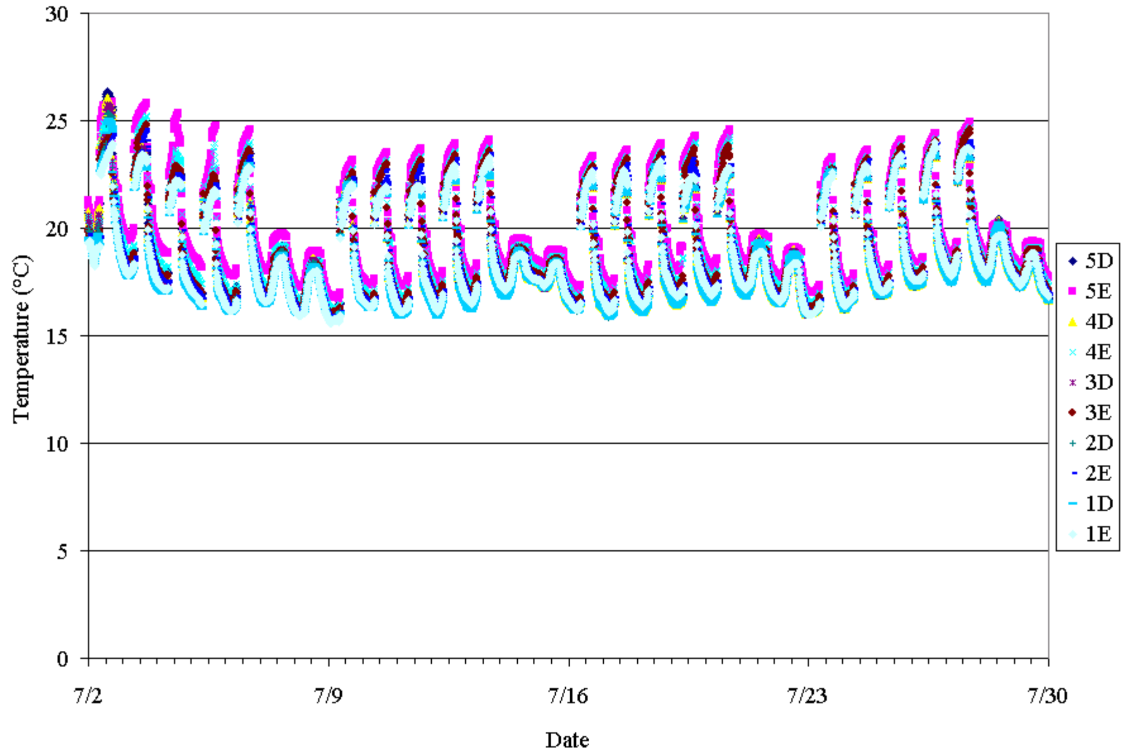

Figure 12 Office zone temperatures for natural ventilation in July, San Francisco

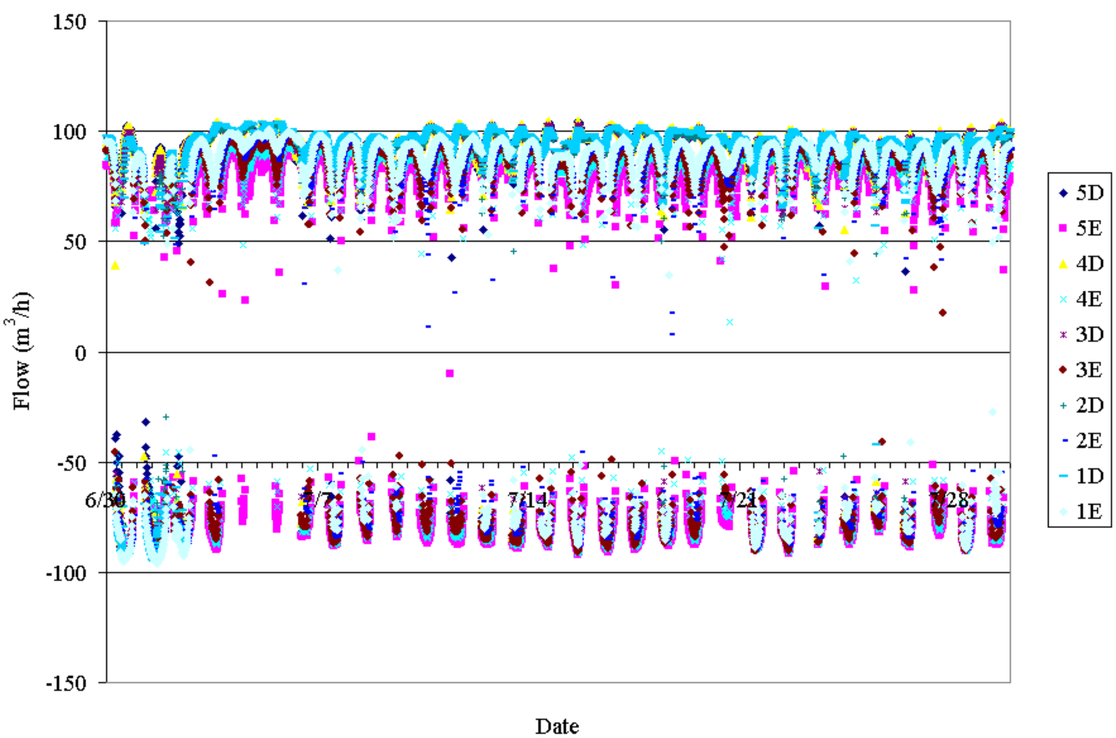

Figure 13 Natural ventilation inlet flow rates in July, San Francisco

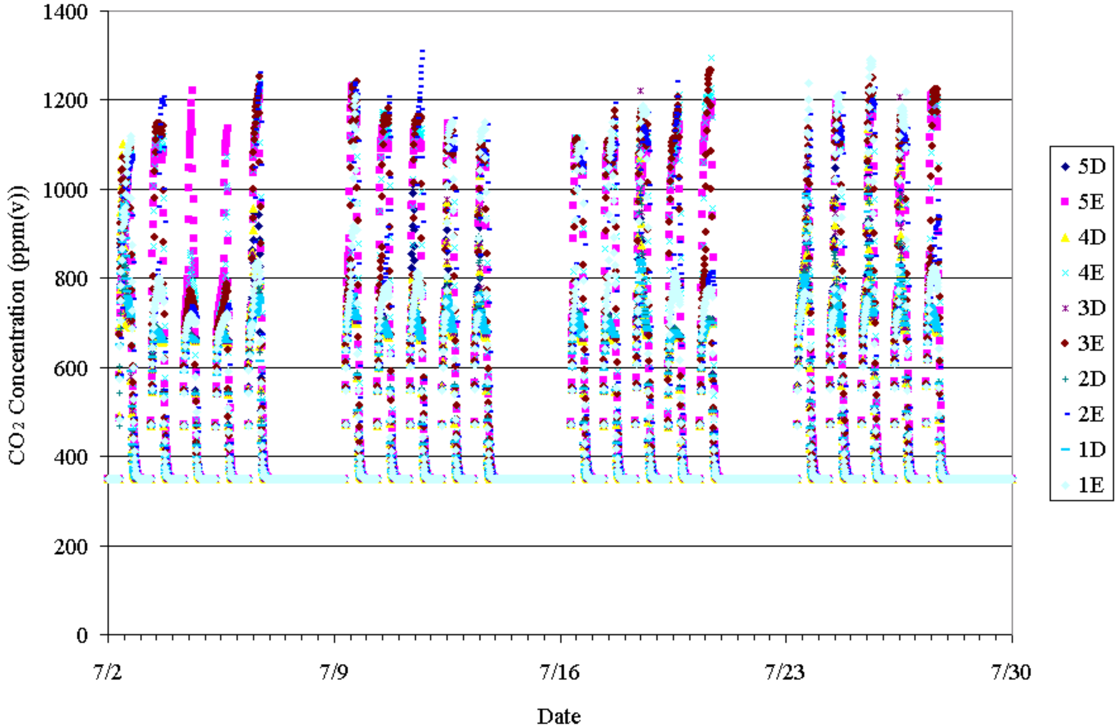

Figure 14 Office zone CO_2 concentrations for natural ventilation case in July, San Francisco

4.1.2 Mechanical Ventilation System

As expected the mechanical ventilation system with air-conditioning maintains the office zone temperatures within or very near the desired range during all three periods (see Figures 15, 17, and 19). The CO_2 concentration results are not very revealing either, as they are determined almost entirely by whether the economizer was operating or not (see Figures 16, 18, and 20). When the system was operating at the constant design minimum outdoor air rate of 34 m^3/h per single office, the CO_2 concentrations peak in the range of 1200 mL/m^3 to 1300 mL/m^3 (1200 ppm(v) to 1300 ppm(v)). When the economizer operated to provide free cooling, the CO_2 concentration peaks were much lower, below 600 mL/m^3 (600 ppm(v)) when the economizer operated much of the day.

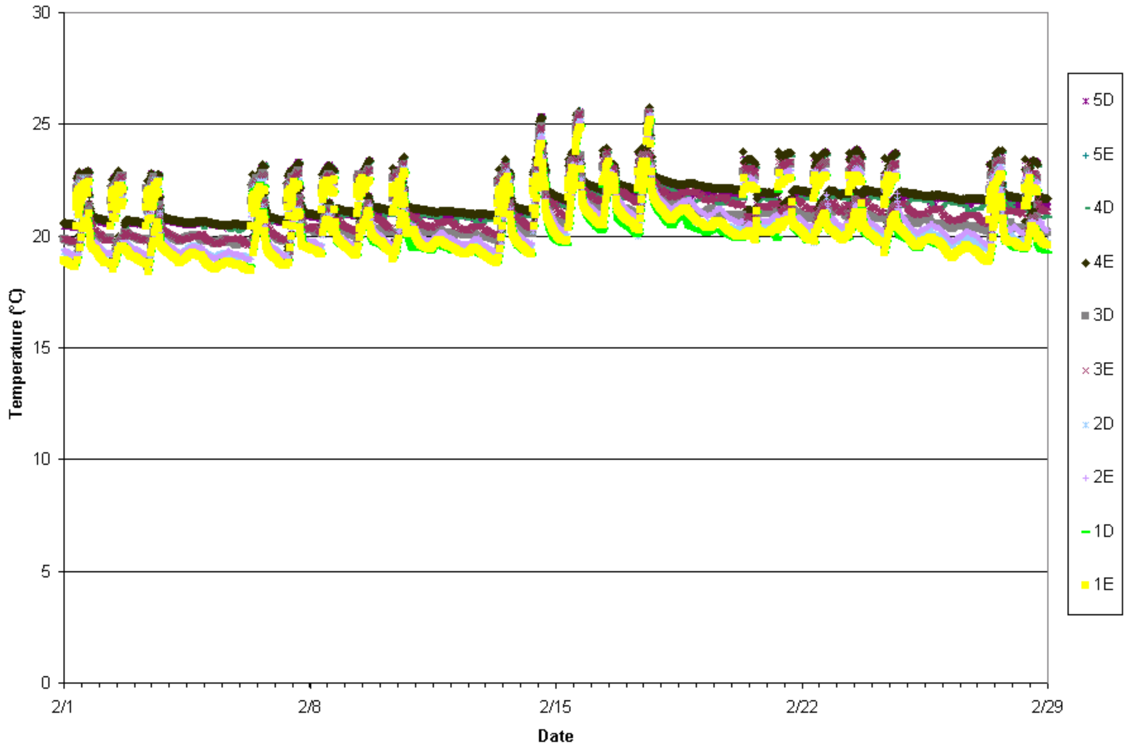

Figure 15 Office zone temperatures for mechanical ventilation in February, San Francisco

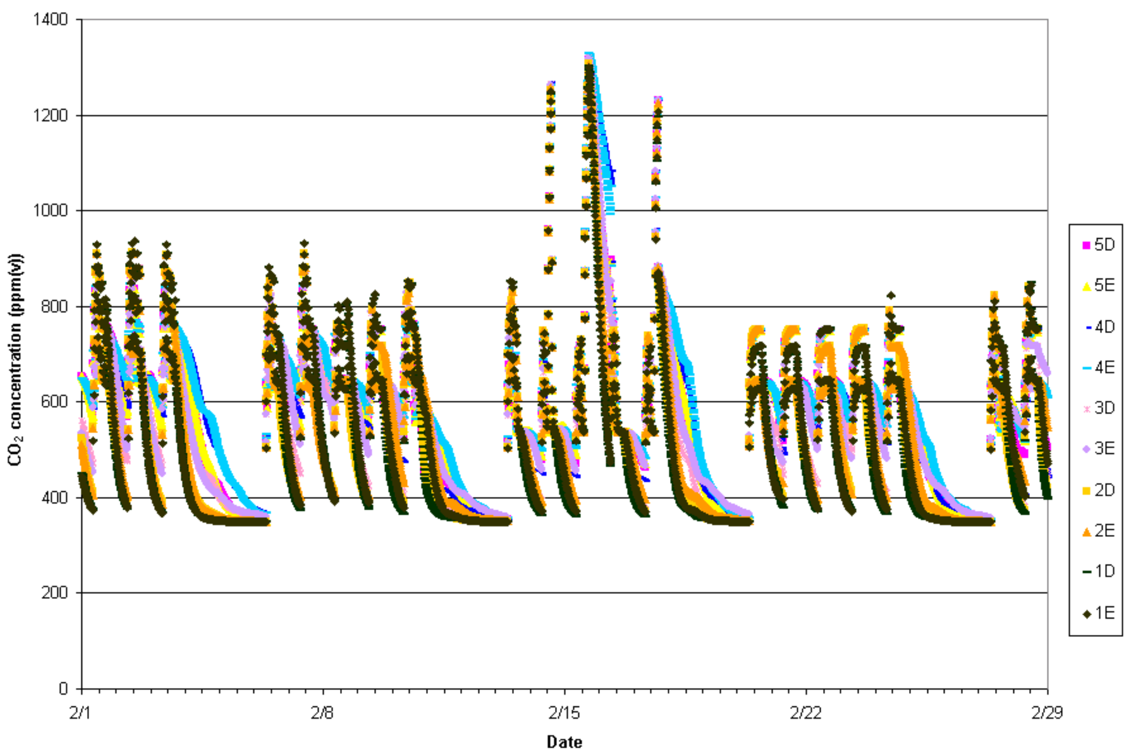

Figure 16 Office zone CO_2 concentrations for mechanical system in February, San Francisco

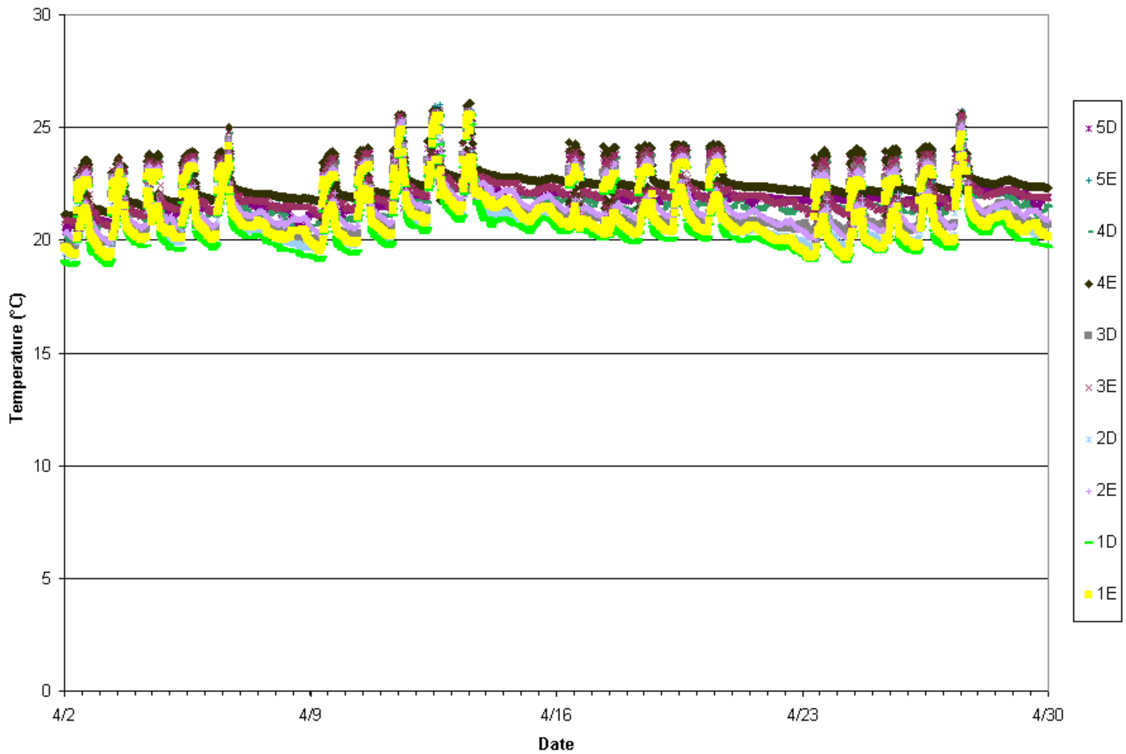

Figure 17 Office zone temperatures for mechanical ventilation system in April, San Francisco

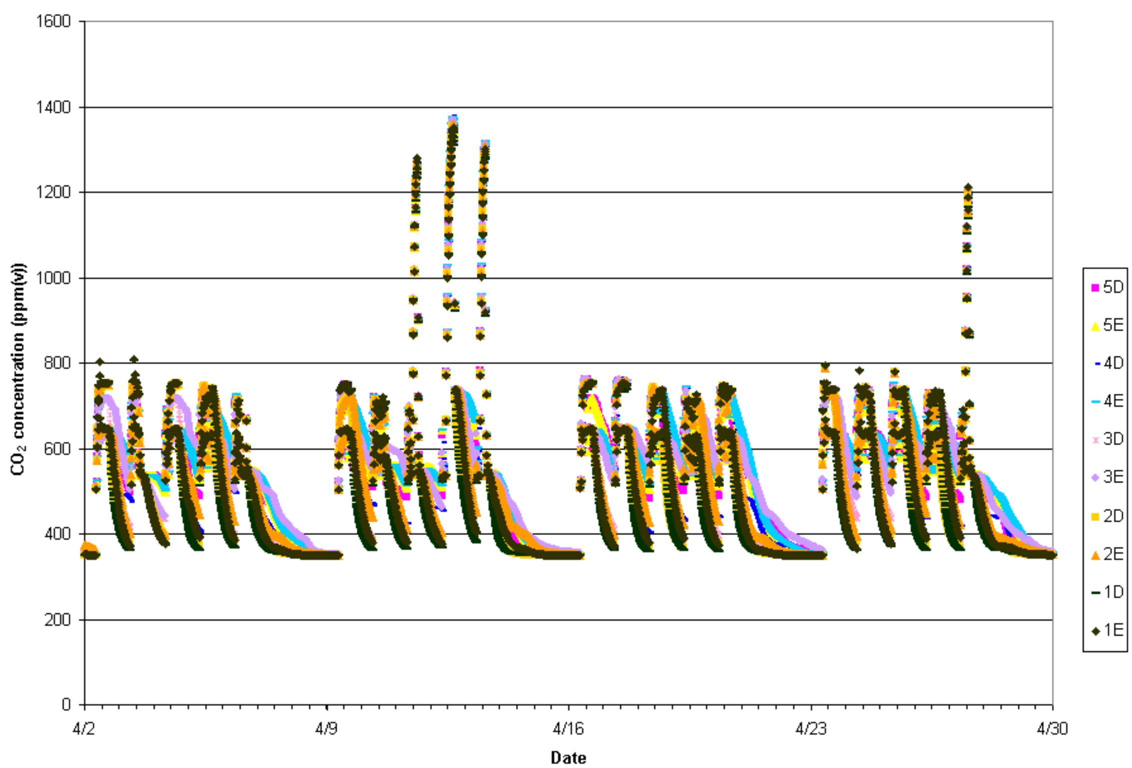

Figure 18 Office zone CO_2 concentrations for mechanical system in April, San Francisco

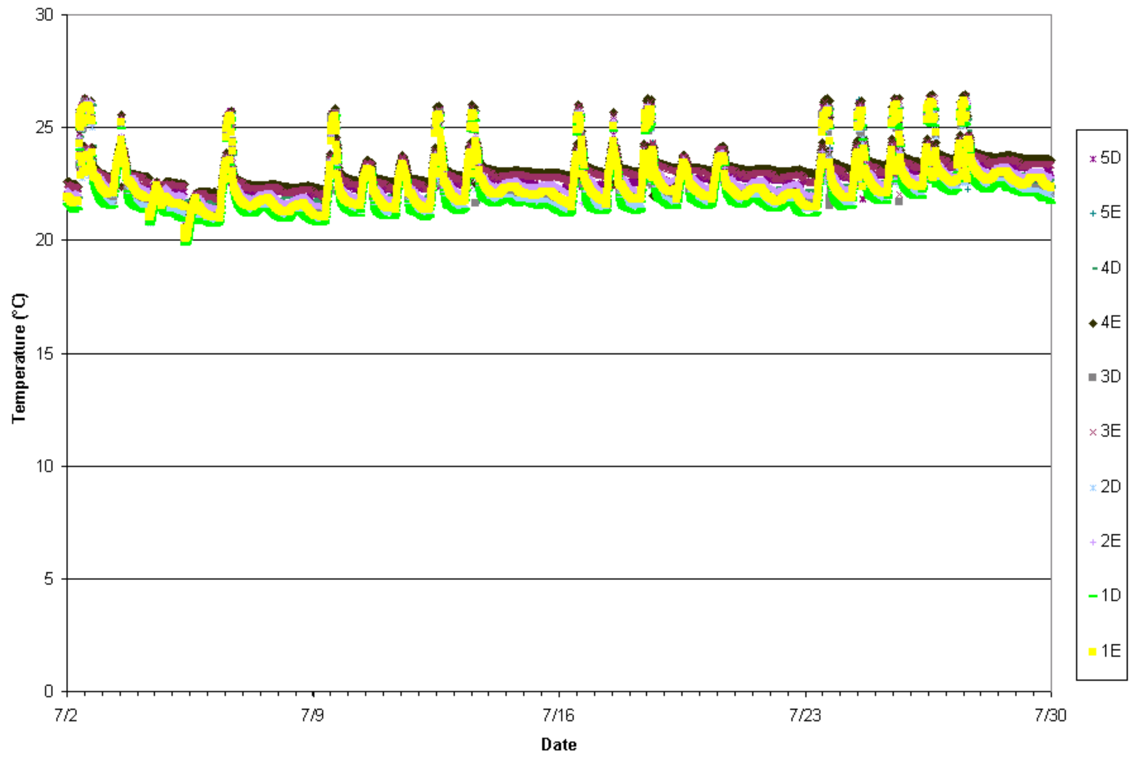

Figure 19 Office zone temperatures for mechanical ventilation system in July, San Francisco

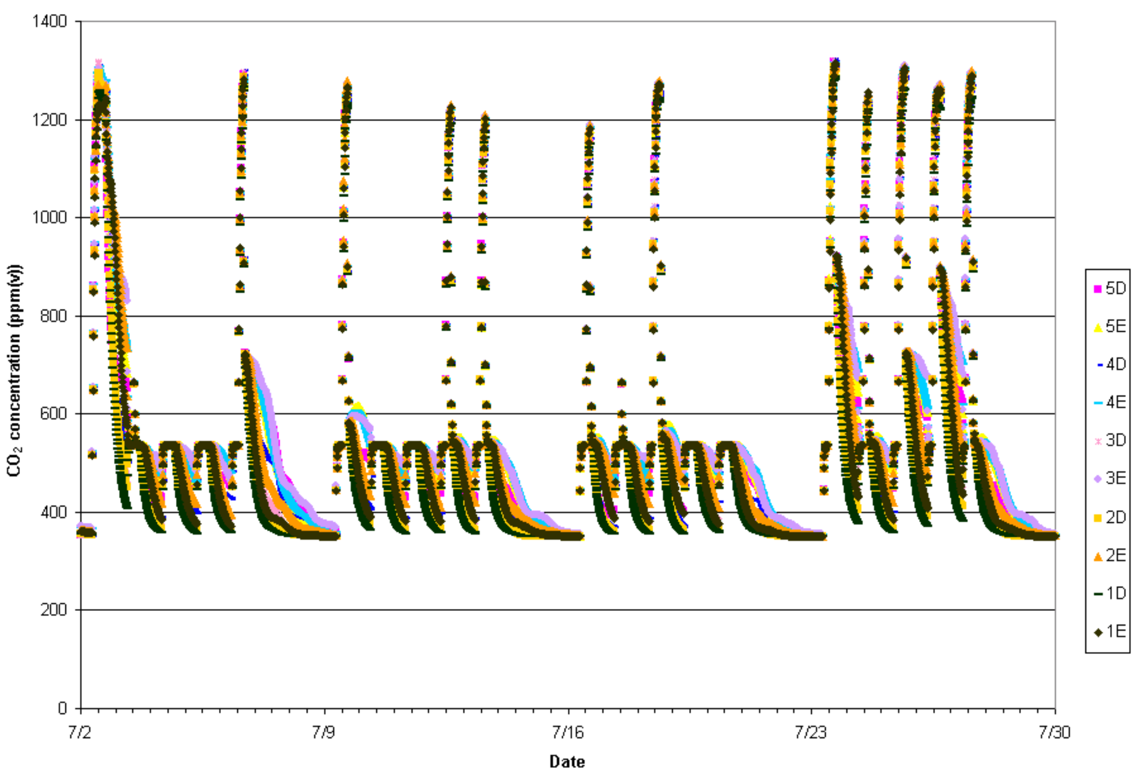

Figure 20 Office zone CO_2 concentrations for mechanical system in July, San Francisco

4.1.3 Hybrid Ventilation System

February

The hybrid ventilation system strategy for February in San Francisco included operating the natural ventilation inlets with a target flow rate of 50 m^3/h per single office during occupied hours and closing them during unoccupied hours with the heaters used as needed. Additionally, the system has mechanical assist ventilation operated based on CO_2 concentrations as described previously. As seen in Figures 21 through 22, the hybrid system maintains temperatures within the desired range and limits CO_2 concentration peaks to no higher than about 1200 mL/m^3 (1200 ppm(v)) for most zones during most hours.

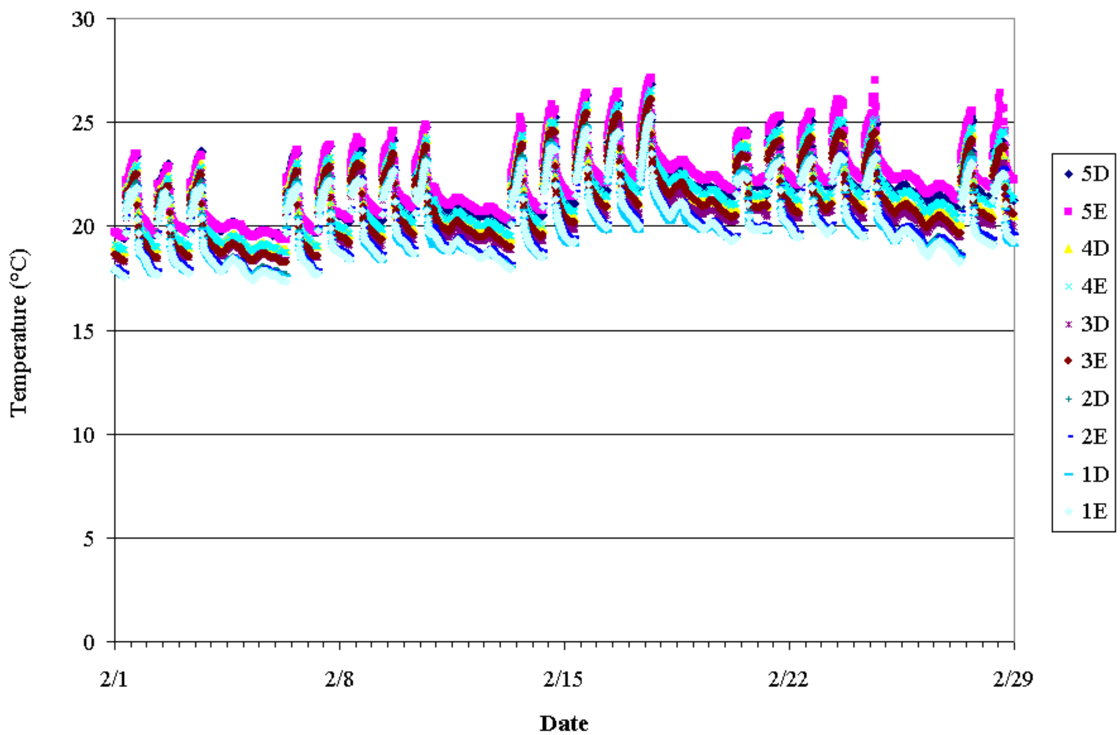

Figure 21 Office zone temperatures for hybrid ventilation system in February, San Francisco

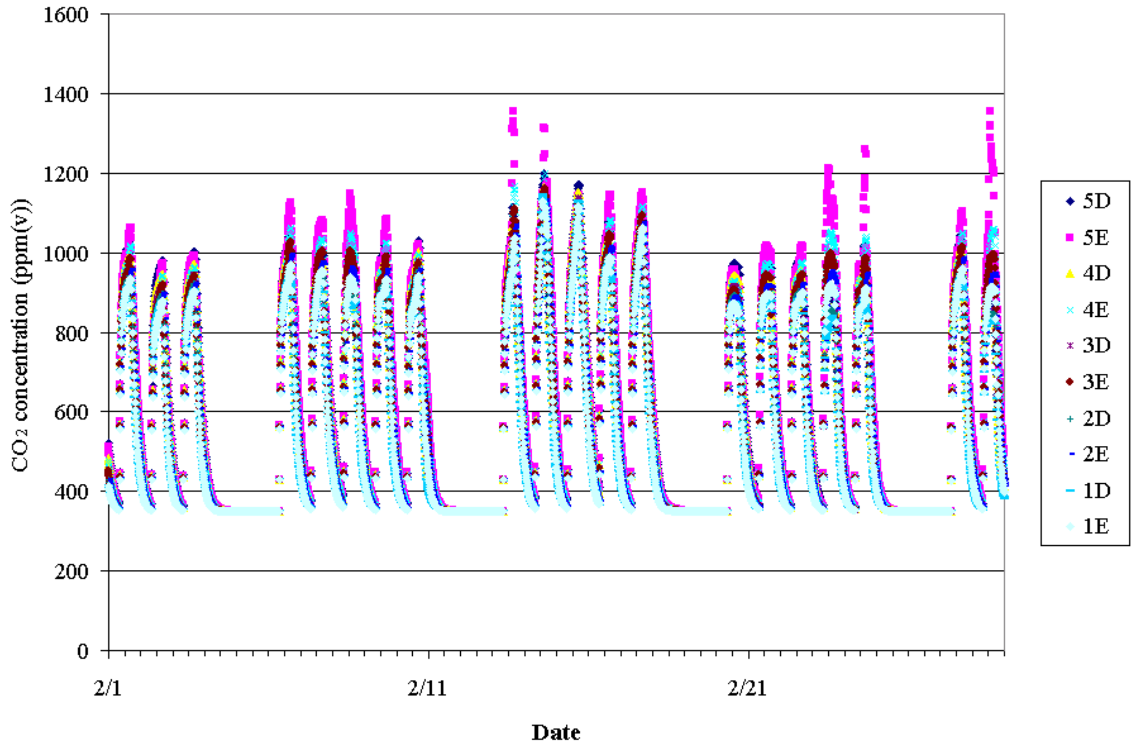

Figure 22 Office zone CO_2 concentrations for hybrid system in February, San Francisco

April

The operating strategy for the hybrid ventilation system for April in San Francisco included operating the natural ventilation inlets with target flow rate of 50 m^3/h per single office during occupied hours and keeping them closed during unoccupied hours. Additionally, the system has supplemental mechanical ventilation available based on CO_2 concentrations and supplemental mechanical cooling available based on individual zone temperatures as described previously. As seen in Figures 23 and 24, the hybrid system maintains temperatures within the desired range and also limits CO_2 concentration peaks to the range of 1100 mL/m^3 to 1400 mL/m^3 (1100 ppm(v) to 1400 ppm(v)).

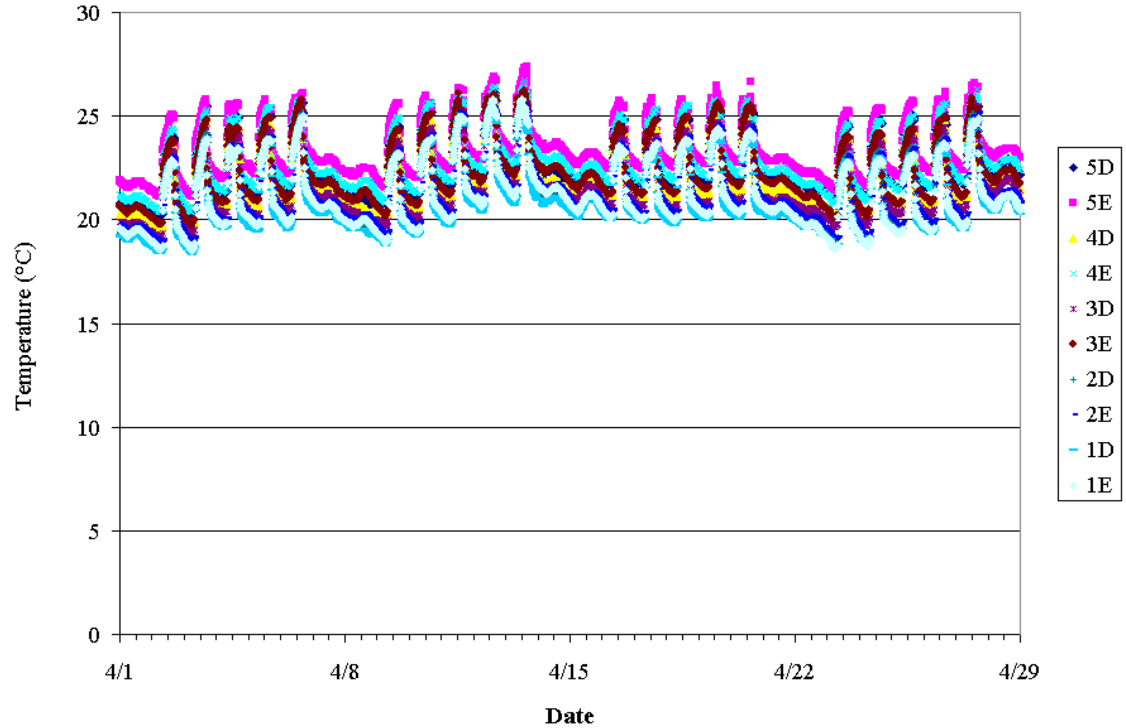

Figure 23 Office zone temperatures for hybrid ventilation system in April, San Francisco

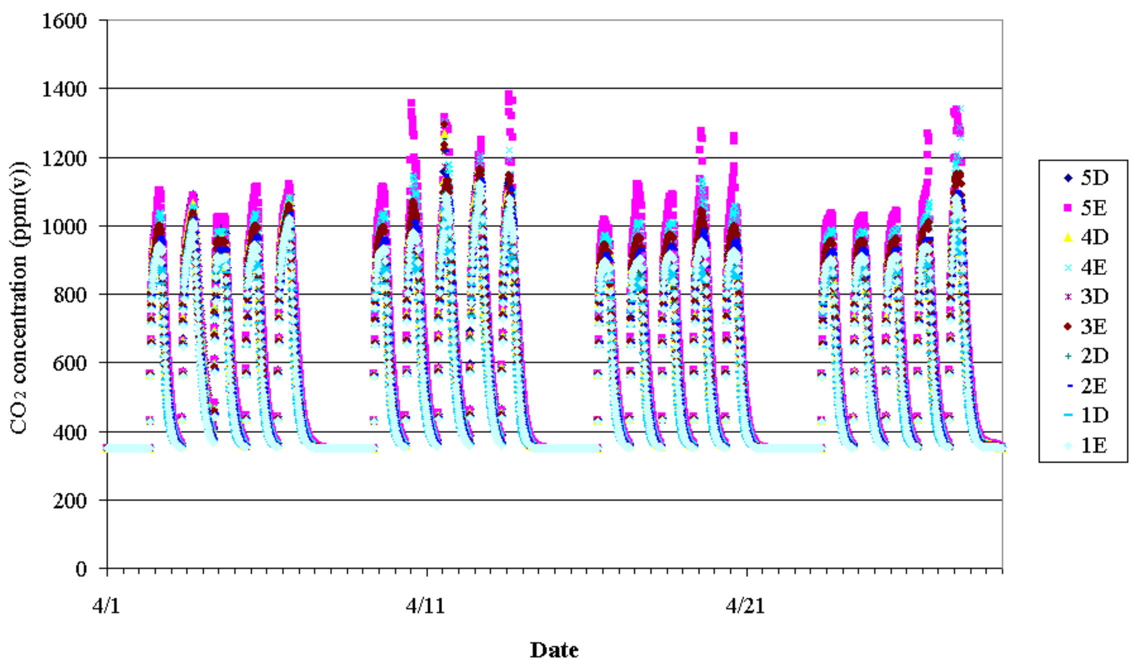

Figure 24 Office zone CO_2 concentrations for hybrid system in April, San Francisco

July

For July in San Francisco, the target ventilation rate for the natural ventilation openings is 200 m^3/h during occupied hours. In contrast to the pure natural ventilation system strategy, the hybrid ventilation system uses supplemental air-conditioning instead of a night cooling strategy so the natural ventilation openings are closed during unoccupied hours. As shown in Figure 25, the hybrid ventilation system successfully controls the office temperatures although the temperatures approach or slightly exceed 26 °C each afternoon before the supplemental cooling limits the temperature rise. Figure 26 shows that the large target ventilation rate provides effective control of CO_2 concentrations at all times, with peaks never exceeding 1000 mL/m^3 (1000 ppm(v)).

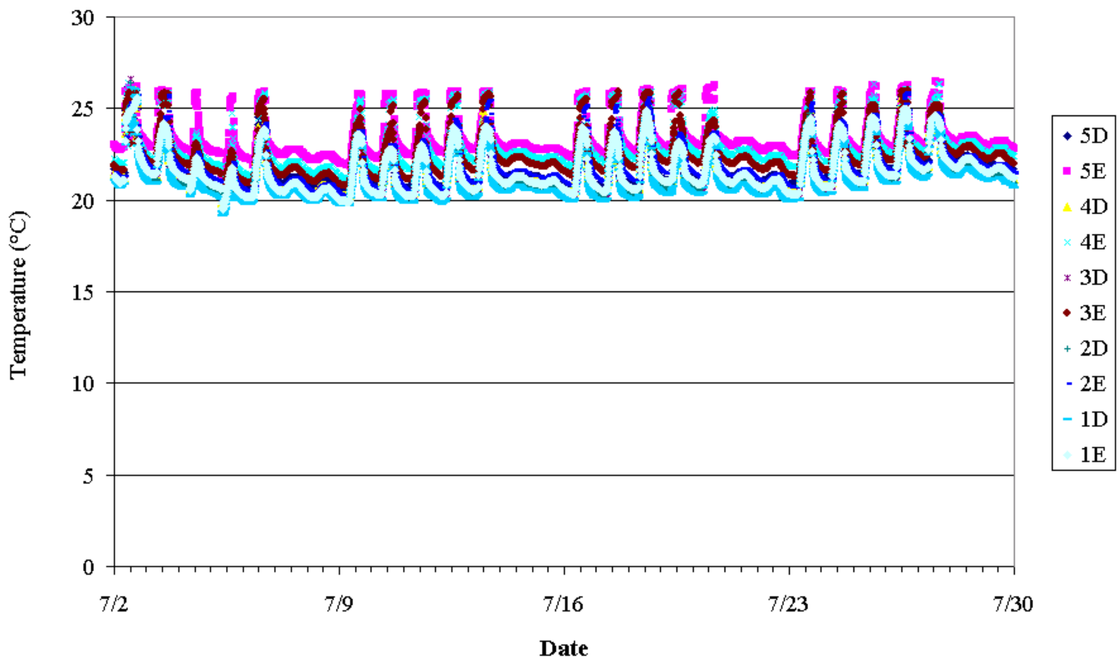

Figure 25 Office zone temperatures for hybrid ventilation system in July, San Francisco

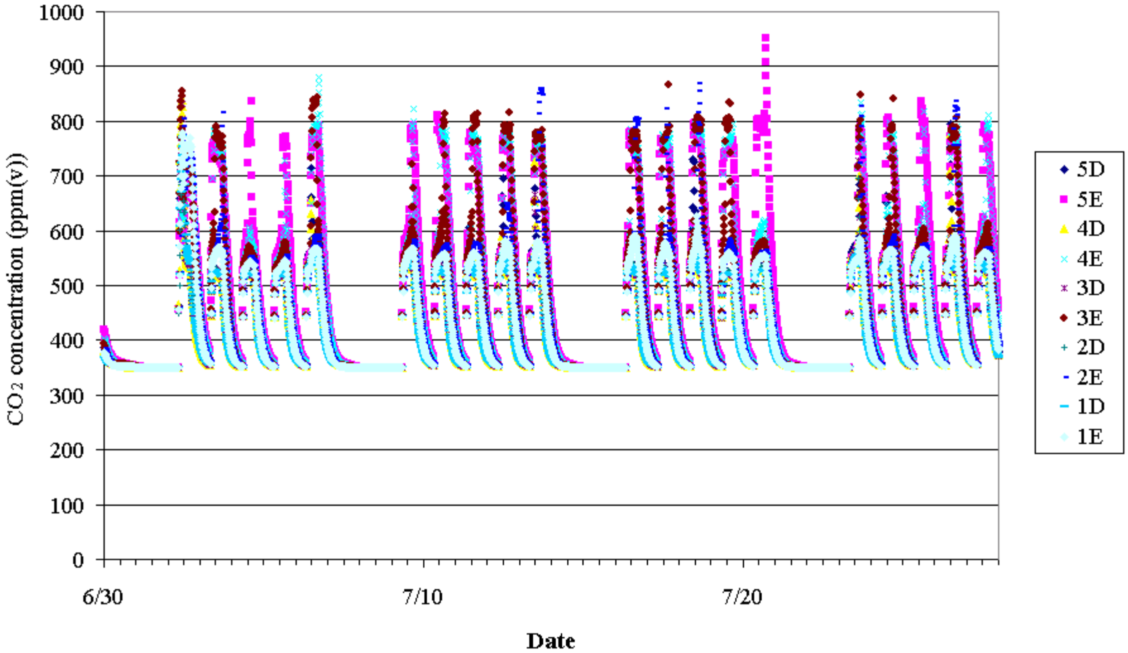

Figure 26 Office zone CO_2 concentrations for hybrid system in July, San Francisco

Summary for San Francisco

Zone temperatures, CO_2 concentrations and system loads are summarized for all cases in San Francisco in Tables 3 through 5.

Table 3 presents the average temperatures and the percent of hourly average temperatures during occupied hours that were outside the range of 20 °C to 26 °C for all office zones for all nine system and season combinations. All three strategies provided acceptable control of temperatures in all three time periods, compared to the evaluation criteria of fewer than 2 % of hours below 20 °C and fewer than 2 % of hours above 26 °C. Small improvements in the heating system control (modeled with a simple on-off capability at 15 min time steps) would likely eliminate the hours below the 20 °C minimum without any significant impact on heating load. A strategy involving larger ventilation rates may have eliminated any hours with temperatures exceeding 26 °C maximum during this period, however, such a strategy would have resulted in larger heating loads.

Table 3 Zone temperatures for San Francisco

System:	**Natural**			**Hybrid**			**Mechanical**		
	T_{Avg} *(°C)*	% of hours below criteria	% of hours above criteria	T_{Avg} *(°C)*	% of hours below criteria	% of hours above criteria	T_{Avg} *(°C)*	% of hours below criteria	% of hours above criteria
February	22.8	1.5	1.5	22.6	1.9	1.0	21.8	1.4	0
April	22.2	1.7	0.4	23.7	1.2	1.4	22.5	0.2	0
July	22.3	0.3	0.05	23.1	1.5	0	23.4	0.2	0

Table 4 presents the average CO_2 concentrations and percent of time that CO_2 concentrations exceeded 1400 mL/m^3 (1400 ppm(v)) during occupied hours for all office zones for all nine system and season combinations. Despite occasionally higher CO_2 concentrations (e.g., see Figure 8), all systems kept the time with CO_2 concentrations over 1400 mL/m^3 (1400 ppm(v)) at less than the 2 % evaluation criteria during all seasons.

Table 4 CO_2 concentrations for San Francisco

System:	**Natural**		**Hybrid**		**Mechanical**	
	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria
February	870	0.4	860	0	690	0
April	680	0	870	0	680	0
July	800	0	560	0	720	0

Table 5 summarizes the cooling and heating loads and fan energy use predicted for the nine system and season combinations for San Francisco. The cooling and heating loads are the amounts of energy (in kWh) that the systems must provide to meet the cooling and heating loads in the office zones, as the equipment itself was not modeled. These loads were not converted to primary energy use since detailed equipment models were not available in the simulation tool. The fan energy use includes energy required to supply heating and cooling air and ventilation air calculated as described earlier, based on the assumed value of 0.48 W/(m^3/h). All values listed in the table are totals for all office zones.

Since the natural ventilation system includes no fans or air-conditioning, the only loads are heating loads. In contrast, the mechanical system for this climate with a low-energy building design has no heating load but a small cooling load and significant fan load. The hybrid system modeled in San Francisco uses much less fan energy than the mechanical system during all seasons, much less cooling energy in July but incurs a heating load in February not seen with the mechanical system.

Table 5 Fan and thermal load summary for San Francisco

System:	**Natural**			**Hybrid**			**Mechanical**		
	Cool Load	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*
	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h
February	0	490	0	0	300	240	50	0	1900
April	0	660	0	180		140	180	0	1900
July	0	470	0	220	0	30	1040	0	1900

4.2 Los Angeles

Although obviously warmer than San Francisco, the Los Angeles climate is similar in that it lacks extreme high and low temperatures and has moderate daily swings in temperature. Therefore, the natural ventilation strategy applied was similar but employed higher target ventilation rates to handle the larger cooling load. Also, a heating system was used only during February for both the natural and hybrid systems. To provide the cooling needed in February, the target ventilation rate was 100 m^3/h per single office during occupied hours only. In April, it was increased to 200 m^3/h per single office during occupied hours only. In July, the target ventilation rate was 200 m^3/h per single office at all times to provide supplemental night cooling. The hybrid ventilation system strategy uses the same target ventilation rate settings as the natural ventilation system but has supplemental fans and cooling available as described earlier.

Predicted average zone temperatures and CO_2 concentrations, percent of values above and below evaluation criteria, and system loads are summarized for all cases in Los Angeles in Tables 6, 7, and 8. Detailed plots of office zone temperatures and CO_2 concentrations for Los Angeles (similar to the ones presented above for San Francisco) are located in Appendix A. As shown in Table 6, the modeled natural ventilation strategy is unable to keep the hourly average office temperatures below 26 °C more than 3 % of hours for both April and July. As desired, the hybrid ventilation system significantly improves the thermal control relative to the natural ventilation system by limiting hours with high temperature to fewer than 2 % of occupied hours per the evaluation criteria.

Table 6 Zone temperatures for Los Angeles

System:	**Natural**			**Hybrid**			**Mechanical**		
	T_{Avg} *(℃)*	% of hours below criteria	% of hours above criteria	T_{Avg} *(℃)*	% of hours below criteria	% of hours above criteria	T_{Avg} *(℃)*	% of hours below criteria	% of hours above criteria
February	22.7	1.7	1.1	22.8	1.4	0.8	22.6	0.1	0
April	22.8	0.9	3.8	22.6	0.9	0.8	22.9	0.04	0
July	24.3	0	3.2	24.1	0	0	24.4	0	0.7

As shown in Table 7, all three ventilation systems provide acceptable dilution of occupant-generated contaminants, as indicated by both the average CO_2 concentrations and the lack of times with concentrations above the desired limit of 1400 mL/m^3 (1400 ppm(v)). In July, the relatively high target inlet ventilation rates of both the natural and hybrid ventilation systems result in much lower average CO_2 concentrations than the mechanical ventilation system.

Table 7 CO_2 concentrations for Los Angeles

System:	**Natural**		**Hybrid**		**Mechanical**	
	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria
February	690	0.01	680	0	660	0
April	550	0	550	0	640	0
July	600	0	580	0	1090	0

Table 8 summarizes the cooling and heating loads and fan energy use predicted for the nine system and season combinations for Los Angeles. The natural ventilation system incurs a heating load only in February. Compared to the mechanical system, the hybrid system saves a significant amount of cooling load in all three periods in addition to reducing fan energy use by more than 90 %. However, the night cooling strategy employed does cause a very small heat load in February that is not seen with the mechanical system. An improved control strategy that limits overcooling by the passive inlet vents might eliminate this heat load.

Table 8 Fan and thermal load summary for Los Angeles

System:	Natural			Hybrid			Mechanical		
	Cool Load	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*
	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h
February	0	40	0	0	20	20	270	0	1900
April	0	0	0	160	0	130	670	0	1900
July	0	0	0	160	0	20	5830	0	1900

4.3 Boston and Minneapolis

Since identical operating strategies were used in the similar Boston and Minneapolis climates, they are presented together. For both the cold month of February and the cool month of April, the natural ventilation system had a target ventilation inlet rate of 50 m^3/h per single office during occupied hours with closed inlets during unoccupied hours. During the hot month of July, the system was simulated with a target ventilation rate of 200 m^3/h per single office at all times in an attempt to provide sufficient cooling.

In February, the hybrid ventilation system was operated with the natural ventilation inlets closed at all times to limit the amount of cold air entering to only that needed to control CO_2 concentrations, which is provided by the assist fans. In April, the hybrid ventilation system was operated with a target natural ventilation rate of 100 m^3/h. In July, the system was simulated with a target ventilation rate of 200 m^3/h per single office at all times, but with supplemental mechanical cooling also available.

Predicted average zone temperatures and CO_2 concentrations, percent of values above and below evaluation criteria, and system loads are summarized for all cases in Boston and Minneapolis in Tables 9 through 14. Detailed plots of zone temperatures and CO_2 concentrations for Boston and Minneapolis are located in Appendix A.

As seen in Tables 9 and 10, the natural ventilation system is unable to maintain temperatures close to the desired limit in July in these locations, with the average temperature being above the desired range. Hourly average temperatures are above 26 °C more than 60 % of the time. However, the hybrid ventilation system is effective at reducing the July office temperatures and limiting the hours with average temperatures above 26 °C to less than 2 %.

Table 9 Zone temperatures for Boston

System:	Natural			Hybrid			Mechanical		
	T_{Avg} (°C)	% of hours below criteria	% of hours above criteria	T_{Avg} (°C)	% of hours below criteria	% of hours above criteria	T_{Avg} (°C)	% of hours below criteria	% of hours above criteria
February	22.8	1.3	0	22.4	0.06	1.6	23	0.2	0.2
April	21.5	1	0	22.8	1	0	22.4	0.5	0
July	26.3	0	62.8	24.5	0.7	1.3	24.2	0	0

Table 10 Zone temperatures for Minneapolis

System:	Natural			Hybrid			Mechanical		
	T_{Avg} (℃)	% of hours below criteria	% of hours above criteria	T_{Avg} (℃)	% of hours below criteria	% of hours above criteria	T_{Avg} (℃)	% of hours below criteria	% of hours above criteria
February	22.4	0.5	0	23.1	0.01	0.2	22.8	0.01	0
April	21.8	0.1	0	22.9	0.6	0	22.5	0.6	0.7
July	26.9	0	70.1	24.7	0.04	0.4	24.3	0	0

As seen in Tables 11 and 12, all three systems adequately controlled CO_2 concentrations most of the time. However, the natural ventilation system resulted in concentrations above the limit of 1400 mL/m^3 (1400 ppm(v)) 2 % of the time in Minneapolis and 2.9 % of the time in Boston. The hybrid ventilation system with its CO_2-controlled assist fans is effective at eliminating these times with excessive CO_2 concentrations. During the cooler months, the mechanical ventilation system results in much lower average concentrations than the hybrid system but the reverse is true during the hot month of July.

Table 11 CO_2 concentrations for Boston

System:	Natural		Hybrid		Mechanical	
	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria
February	800	0.9	1200	0	1100	0
April	880	2.9	830	0	680	0
July	580	0	590	0	1140	0

Table 12 CO_2 concentrations for Minneapolis

System:	Natural		Hybrid		Mechanical	
	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria
February	740	0	1180	0.0	730	0
April	880	2	860	0	690	0
July	620	0	640	0	1240	3.7

Tables 13 and 14 summarize the cooling and heating loads and fan energy use predicted for the nine system and season combinations for Boston and Minneapolis, respectively. Compared to the mechanical system, the natural ventilation system results in a substantial energy penalty in the form of high heating loads in both Boston and Minneapolis. The hybrid system strategy reduces this heating energy penalty while still resulting in substantial reductions in cooling loads compared to the mechanical ventilation system in July. Fan energy is somewhat higher for the hybrid system in

February and April but is greatly reduced in July in both Boston and Minneapolis.

Table 13 Fan and thermal load summary for Minneapolis

System:	Natural			Hybrid			Mechanical		
	Cool Load	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*
	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h
February	0	73100	0	0	35860	3130	0	32120	2880
April	0	10780	0	0	9160	1950	0	3140	1900
July	0	0	0	4140	0	660	7810	0	1900

Table 14 Fan and thermal load summary for Boston

System:	Natural			Hybrid			Mechanical		
	Cool Load	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*
	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h
February	0	44660	0	0	18480	2240	0	16340	2060
April	0	10010	0	0	8130	1730	0	3050	1900
July	0	0	0	3850	0	610	7260	0	1900

4.4 Miami

The operating strategies for the natural and hybrid ventilation systems were significantly different for the much hotter Miami climate. In February, the natural ventilation inlets were set for target ventilation rates of 200 m^3/h per single office during occupied hours and 100 m^3/h per single office for night cooling for the natural ventilation system and 100 m^3/h per single office during occupied hours and for night cooling for the hybrid system. For the natural ventilation system in both April and July, the inlets were set to target ventilation rates of 100 m^3/h per single office during occupied hours and 400 m^3/h per single office during the night in an attempt to provide sufficient ventilation during the day and as much cooling as possible at night. The same target settings were used for the hybrid system in April, but for July the inlets were set to the minimum ventilation setting of 50 m^3/h per single office during the day and closed during the night, as the temperatures were not cool enough for night cooling to be effective.

Predicted average zone temperatures and CO_2 concentrations, percent of values above and below evaluation criteria, and system loads are summarized for all cases in Miami in Tables 15 through 17. Detailed plots of zone temperatures and CO_2 concentrations for Miami are in Appendix A.

As seen in Table 15, the natural ventilation system as operated is unable to provide adequate thermal comfort during any of the time periods with average hourly temperatures above 26 °C over 50 % of the time even in February. However, the hybrid system performs much better than the natural ventilation system with less than 1 % of hourly average temperatures outside the criteria range during all seasons.

Table 15 Zone temperatures for Miami

System:	Natural			Hybrid			Mechanical		
	T_{Avg} (℃)	% of hours below criteria	% of hours above criteria	T_{Avg} (℃)	% of hours below criteria	% of hours above criteria	T_{Avg} (℃)	% of hours below criteria	% of hours above criteria
February	26.1	1	51.4	24.4	1	0	24.1	0	0
April	28.5	0	90.1	24.4	0	1	24	0	0
July	33.1	0	100	24.2	0	0.06	23.3	0	0

As seen in Table 16, the mechanical system resulted in the highest CO_2 concentrations since the system was typically operated without the economizer due to the Miami weather. However, all three systems met the evaluation criteria, with CO_2 concentrations above 1400 mL/m^3 (1400 ppm(v)) much less than 2 % of the time.

Table 16 CO_2 concentrations for Miami

System:	Natural		Hybrid		Mechanical	
	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria	Avg *CO_2 concentration ppm(v)*	% of hours above criteria
February	730	0.05	750	0	1070	0
April	620	0.01	670	0	1050	0
July	740	0.04	1110	0.01	1260	0.24

Table 17 summarizes the cooling and heating loads and fan energy use predicted for the nine system and season combinations for Miami. The natural ventilation system has almost no energy use since it has no fans or air-conditioning and the heating load is trivial. The hybrid system significantly reduces the cooling loads compared to the mechanical system in February with a smaller load reduction in April and a small increase in July. Fan energy for the hybrid system is substantially reduced relative to the mechanical system in all periods.

Table 17 Fan and thermal load summary for Miami

System:	Natural			Hybrid			Mechanical		
	Cool Load	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*
	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h
February	0	130	0	3520	0	580	6160	0	1900
April	0	0	0	8360	0	680	8800	0	1900
July	0	0	0	10770	0	950	10010	0	1900

4.5 Summary of Simulation Results

Overall, the pure natural ventilation system meets the evaluation criteria in San Francisco in terms of both thermal control (i.e., average hourly office temperatures) and dilution ventilation for occupant-generated contaminants (i.e., CO_2 concentrations) while reducing cooling and fan loads to zero. However, there is an energy cost in terms of an increased heating load. A more sophisticated control strategy could likely reduce this heating load while further improving the system's performance.

Additionally, the design of the natural ventilation system in San Francisco may not have been ideal, as the stack driving forces did not always dominate over wind forces, which were consistently in opposition on the leeward side of the building. An alternative configuration for this climate with its moderate temperatures and consistent wind might be an open floorplan with a cross-flow design. Since the pure natural ventilation performed well in this climate, the hybrid ventilation system might be considered unnecessary. However, the hybrid system did result in modest improvements in performance for a small amount of cooling load and fan energy. Relative to the mechanical ventilation system, the hybrid system reduced both cooling load and fan energy significantly while providing thermal and ventilation performance that met the evaluation criteria. However, as modeled, the hybrid system did incur a heating load that was not present for the mechanical system.

Performance of the natural ventilation system in Los Angeles was mixed, as it met the dilution ventilation criteria but did not meet the thermal criteria. However, the thermal performance improves dramatically with the hybrid ventilation system while still reducing loads significantly compared to the mechanical ventilation system.

Overall, the pure natural ventilation system does a poor job in Boston and Minneapolis as it results in a large heating load in February, provides inadequate dilution ventilation in April, and cannot control temperatures in July. Better dilution of internally generated contaminants could be provided in April by increasing the target ventilation rate, but the heating load would increase as a result. In contrast, the hybrid ventilation strategy is a more promising option as the more flexible system with supplemental cooling and fans improves over the performance of the natural ventilation system in all three aspects (i.e., thermal comfort, IAQ, and heat loads). However, while the hybrid system reduces both cooling load and fan energy relative to the mechanical system, it also increases the heating load for the modeled building. Although increasing heating loads might be a fair trade-off for reduced mechanical cooling loads, the decision for a specific building will depend on careful analysis of the specific building configuration, systems, occupancies and loads.

The natural ventilation system performs very poorly in Miami with unacceptably high temperatures. On the other hand, the hybrid system met both the thermal and ventilation evaluation criteria while reducing both cooling loads and fan energy during most of the periods simulated. However, as noted earlier, concerns about potential humidity control problems need to be resolved before considering a natural or hybrid ventilation system in any humid climate.

5. Discussion

As previously stated, the objective of this study was to investigate the energy and indoor environmental performance of natural and hybrid ventilation alternatives in low- to mid-rise U.S. commercial buildings in a variety of U.S. climates. Also as described previously, three hypotheses were developed as a means of accomplishing the objective. These hypotheses are repeated below along with discussion of the relevant insights gained from the study. However, it is important to remember that any conclusions drawn from this simulation study should not be taken as definitive and extended to other buildings and climates without consideration of additional simulation and field studies.

1. *Natural ventilation is not reliable in terms of providing adequate ventilation rates for air quality control.*

   The natural ventilation system as simulated was not completely reliable per the specified criteria as the predicted reliability of the ventilation rates depended on both the ambient conditions and the specific strategy used for a given simulation period. For the majority of the periods simulated, the ventilation rates were acceptable per the stated evaluation criteria. However, there were periods, such as April in Boston and Minneapolis, where the low ventilation inlet setting and the moderate driving forces resulted in high CO_2 concentrations. The CO_2 concentrations in these cases could have been limited by increasing the target ventilation rates but that would result in higher energy costs. The reliability of the natural ventilation rates was helped greatly by the use of self-regulating inlet vents, which enable the setting of a target ventilation rate which can be achieved under modest driving forces yet limit excessive ventilation when driving forces increase, i.e., under very cold or windy conditions.

2. *Natural ventilation will result in unacceptable thermal comfort in typical U.S. climates.*

   Again, this hypothesis must be evaluated separately for the various climates studied, and the conclusions should not be extrapolated far beyond the specific simulation scenarios. However, the results indicate that unacceptable thermal comfort occurred for the hot periods in Boston and Minneapolis and for much of the year in Miami. However, in the moderate coastal climates, the thermal performance of the natural ventilation systems as modeled was only acceptable if one is willing to tolerate excursions outside the specified temperature range.

3. *Hybrid systems will provide reliable ventilation (both rates and distribution) and acceptable thermal conditions (during occupied hours) and use less energy than mechanical systems.*

   The simulation results support this hypothesis as the hybrid systems provided acceptable ventilation and thermal performance per the defined criteria while saving cooling and fan energy for nearly all cases studied. In cold climates, the hybrid system often resulted in increased heating loads relative to the mechanical system. While the trade-off between increased heating loads and decreased fan and cooling loads should be evaluated in detail for buildings and systems located in specific climates, such a trade-off would likely be favorable in many cases. Additionally, further improvement in the hybrid system strategies may lower the impact of such increases in heating loads.

Some general conclusions may be drawn for the natural ventilation system. First, if one is to apply a pure natural ventilation system in a commercial building, one must have some tolerance for less than perfect control of ventilation rates, temperatures, and other aspects of indoor environmental performance. Second, even more than with other systems, the design and operation of natural ventilation systems involves trade-offs, i.e., decisions must be made regarding which performance aspect takes priority. For example, utilizing a higher target ventilation rate to ensure adequate ventilation will likely result in higher heating energy use.

As demonstrated in this simulation study, hybrid ventilation systems can improve on many of the limitations of pure natural ventilation systems while still providing the potential for significant savings in fan energy and cooling loads. However, these potential savings need to be evaluated in detail for the specific building and system design, climate and performance requirements and may involved a trade-off with higher heating loads. Additionally, as stated earlier, indoor humidity control is a concern that needs to be evaluated before any natural or hybrid ventilation strategy is employed in a humid climate.

Recommendations

Based on the results of this study, the following additional research and follow-up activities are recommended:

- Further develop coupled building energy and airflow simulation tools for research, design and analysis.
- Monitor the IAQ, thermal comfort and energy performance of U.S. commercial buildings employing hybrid ventilation systems
- Verify the reliability of humidity predictions and perform an analysis of humidity levels in natural and hybrid ventilated commercial buildings.
- Conduct a study on fire safety, smoke control, noise control, internal and external chemical or biological releases, and other potential barriers to natural or hybrid approaches.
- Conduct a study of the performance of hybrid systems featuring operable windows in commercial buildings with mechanical ventilation systems.
- Study the potential application and/or define the needed development of ventilation components, heat recovery, air cleaning, controls and other ancillary technologies to enhance the performance of hybrid ventilation systems.
- Study the impacts on employee satisfaction and productivity in commercial buildings with hybrid ventilation systems.
- Sponsor a symposium and/or design workshop on hybrid ventilation systems for commercial buildings in the U.S. similar to ones held in Europe with a focus on climates with significant heating and cooling loads.
- Develop standards and guidelines for IAQ, thermal comfort, and energy performance of natural and hybrid ventilation systems.
- Consider the application of a hybrid ventilation system in a small commercial building as a demonstration of the technology.

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7. REFERENCES

Aggerholm, S. Control Strategies for Hybrid Venilation,in HybVent Forum '01. 2001. Delft University of Technology, The Netherlands.

Aggerholm, S. Hybrid Ventilation Principles and Control Strategies. Proceedings of Hybrid Ventilation 2002. 2002. Concordia University.

Allard, F. (ed.) Natural Ventilation in Buildings – A Design Handbook. 1998. James & James, London.

Arnold, D., Thermal Storage Case Study: Combined Building Mass and Cooling Pond ~. ASHRAE Transactions, 2000. Vol. 106(Part 1).

ASHRAE. 1992. Thermal Environmental Conditions for Human Occupancy. ASHRAE Standard 55; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1997. 1997 ASHRAE Handbook—Fundamentals, SI edition. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE.2004. Ventilation for Acceptable Indoor Air Quality. ASHRAE Standard 62.1; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE.2001b. Energy Standard for Buildings Except Low-Rise Residential Buildings. ASHRAE Standard 90.1; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Axley JW. 2001. Application of Natural Ventilation for U.S. Commercial Buildings – Climate Suitability, Design Strategies & Methods, Modeling Studies. GCR-01-820. National Institute of Standards and Technology.

Axley, J.W. and S.J. Emmerich. 2002. "A Method to Assess the Suitability of a Climate for Natural Ventilation of Commercial Buildings", Proceedings of Indoor Air 2002.

Axley, J.W., Emmerich, S., Dols, S., and G. Walton. 2002a. "An Approach to the Design of Natural and Hybrid Ventilation Systems for Cooling Buildings", Proceedings of Indoor Air 2002.

Axley JW, Emmerich SJ, and Walton GN. 2002b. "Modeling the Performance of a Naturally Ventilated Commercial Building with a Multizone Coupled Thermal/Airflow Simulation Tool." 2002. ASHRAE Transactions V. 108, Pt. 2.

Bourgeois, D., F. Haghighat, and A. Potvin. On the Applicability of Hybrid Ventilation in Canadian Office and Educational Buildings: Part 2 – Implementing Annex 35 Pilot Study Projects in Canada. Proceedings of Hybrid Ventilation 2002. 2002a. Concordia University.

Bourgeois, D., F. Haghighat, and A. Potvin. On the Applicability of Hybrid Ventilation in Canadian Office and Educational Buildings: Part 1 – Barriers and opportunities stemming from building regulation. Proceedings of Hybrid Ventilation 2002. 2002b. Concordia University.

Bourgeois, D., A. Potvin, and F. Haghighat. Hybrid Ventilation Of Canadian Non-Domestic Buildings : A Procedure For Assessing IAQ, Comfort And Energy Conservation. in RoomVent 2000. 2000. University of Reading: Elsevier.

Brager, G. S., Ring, E., and K. Powell. 2000. Mixed-mode ventilation: HVAC meets Mother Nature, Engineered Systems, May 2000.

Braham, G.D., Comparative Performance of U.K. Fabric Energy Storage Systems. ASHRAE Transactions, 2000. Vol. 106(Part 1).

Brohus, H., Frier, C., Heiselberg, P. and O.J. Hendriksen, Measurements of Hybrid Ventilation Performance in and Office Building, The International Journal of Ventilation, February 2003.

Chikamoto, T., S. Kato, and T. Ikaga. Hybrid Air-Conditioning System at Liberty Tower of Meiji University. in HybVent Forum '99. 1999. Sydney, Australia.

Cron, F., Inard, C., and R. Belarbi. 2003. Numerical Analysis of Hybrid Ventilation Performance Depending on Climate Characteristics, The International Journal of Ventilation, February 2003.

Delsante, A. and Tor Arvid Vik, (ed.) Hybrid Ventilation State-of-the-Art Review.2000, International Energy Agency Annex 35 Report.

Dols, W.S. and S.J. Emmerich. *LoopDA – Natural Ventilation Design and Analysis Software*. National Institute of Standards and Technology. 2003.

Dols, W. S. and G. N. Walton 2003. CONTAMW 2.0 User Manual: Multizone Airflow and Contaminant Transport Analysis Software. NIST.

Emmerich, S.J., Dols, W.S., and J.W. Axley. 2001. Natural Ventilation Review and Plan for Design and Analysis Tools. NISTIR 6781, National Institute of Standards and Technology.

Emmerich, S.J. and A.K. Persily. 2001. State-of-the-Art Review of CO_2 Demand Controlled Ventilation Technology and Application. NISTIR 6729, National Institute of Standards and Technology.

Eriksson, J. and A. M. Wahlström, Use of Multizone Air Exchange Simulation to Evaluate a Hybrid Ventilation System, 2002, ASHRAE Annual Meeting.

Heinonen, J. and R. Kosonen. Hybrid Ventilation Concepts for Commercial Buildings. in Healthy Building 2000. 2000. Espoo, Finland: SIT Indoor Air Information Oy, Helsinki, Finland.

Heiselberg, P., The Hybrid Ventilation Process - Theoretical and Experimental Work. Air Infiltration Review, 1999. Vol. 21(No. 1): p. 1-4.

Heiselberg, P., and Tjelflaat, P. O., Design Procedure for Hybrid Ventilation, in HybVent Forum '99. 1999. Sydney, Australia.

Heinonen, J., Vuolle, M., Heikkinen, J., and Seppanen, O. Performance Simulations of Hybrid Ventilation Systems in a Five-Story Office Building. 2002, ASHRAE Annual Meeting.

Hendriksen, O.J., Long-term Monitoring at Bang & Olufsen Office Building, in HybVent Forum '01. 2001. Delft University of Technology, The Netherlands.

Hendriksen, O.J., Characteristics of Ventilation and Control Strategy in Bang & Olufsen Office Building. Proceedings of Hybrid Ventilation 2002. 2002. Concordia University.

Jeong, Y., and F. Haghighat. Modeling of a Hybrid Ventilated Building “Grong School”. Proceedings of Hybrid Ventilation 2002. 2002. Concordia University.

Kato, S., Murakami, S., Chang, H., Chikamoto, T., and Kim, T. Room Air Distribution and Cooling Load of Hybrid Air-Conditioning System Utilizing Natural Ventilation in an Office. in RoomVent 2000 - 7th International Conference on Air Distribution in Rooms. 2000. University of Reading, UK: Elsevier.

Kosik, W.J., Design Strategies for Hybrid Ventilation, ASHRAE Journal, October 2001.

Li, Y., Analysis Methods and Tools for Hybrid Ventilation Systems, in HybVent Forum '01. 2001. Delft University of Technology, The Netherlands.

Li, Y. and P. Heiselberg. Analysis Methods for Natural and Hybrid Ventilation - a Critical Literature Review and Recent Developments, The International Journal of Ventilation, February 2003.

Marion, W. and K. Urban. User’s Manual for TMY2s. National Renewable Energy Laboratory, 1995.

McDowell, T.P., Thornton, J.W., Emmerich, S., and G. Walton. 2003. “Integration of Airflow and Energy Simulation Using CONTAM and TRNSYS”, ASHRAE Transactions Vol 109 Pt 2.

Meinhold, U. and M. Rosler, Hybrid Ventilation in the Bertolt-Brecht-Gynmasium Results of the Monitoring Phase. Proceedings of Hybrid Ventilation 2002. 2002. Concordia University.

Principi, P., Di Perna, C. and E. Ruffini. Measurements in Situ of Fluid Dynamic Parameters in the Buildings with Natural and Hybrid Ventilation in HybVent Forum '99. 1999. Sydney, Australia.

Principi, P., Citterio, M., Romio, C. and E. Ruffini.. Monitoring Analysis and Performance Evaluation of a Hybrid Ventilated Office Building: “Iguzzini” Case Study. Proceedings of Hybrid Ventilation 2002. 2002. Concordia University.

Principi, P., Di Perna, C. and E. Ruffini. Five Years of Laboratory and In Situ Test Experiences to Verify Thermal Comfort Conditions in an Innovative Hybrid Ventilated Building, The International Journal of Ventilation, February 2003.

Ring, E., and G.S. Brager, 2000. “Occupant Comfort, Control, and Satisfaction in Three California Mixedmode Office Buildings.” Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy.

Rowe, D. and C. T. Dinh, Experience with Occupant Control of Supplementary Cooling in a Naturally Ventilated Environment: Preliminary Results from Work in Progress, in HybVent Forum '99. 1999. Sydney, Australia.

Rowe, D. A Study of a Mixed Mode Environment in 25 Cellular Offices at the University of Sydney, The International Journal of Ventilation, February 2003.

Schild, P.G., An Overview of Norwegian Buildings with Hybrid Ventilation, in HybVent Forum '01. 2001. Delft University of Technology, The Netherlands.

Slotboom, E. Hybrid Ventilation, Application of Installation Technics from Architectural Perspective, in HybVent Forum '01. 2001. Delft University of Technology, The Netherlands.

Van der Aa, A. Hybrid Ventilation Waterland School Building The Netherlands – First Results of the Monitoring Phase. Proceedings of Hybrid Ventilation 2002. 2002. Concordia University.

Vuolle, M. and J. Heinonen. Hybrid Ventilation Simulations in IDA Modular Simulation Environment. in Healthy Building 2000. 2000. Espoo, Finland: SIT Indoor Air Information Oy, Helsinki, Finland.

Vuolle, M. and P. Sahlin. IDA Indoor Climate and Energy – a New Generation Simulation Tool. in Healthy Building 2000. 2000. Espoo, Finland: SIT Indoor Air Information Oy, Helsinki, Finland.

Wahlström Å. M.., Nielsen J. R., Hybrid Ventilation Retrofit in a School Setting, 2001, Proceedings of Performance of Exterior Envelopes of Whole Buildings VIII.

Wouters, Demeester, 1999, The NatVent project of the European Union (EU) JOULE Program, Contract Nr:JOR3-CT95-0022

Wouters, P., Heijmans, N., Delmotte, C. and Vandaele, L.. Classification of Hybrid Ventilation Concepts. in HybVent Forum '99. 1999. Sydney, Australia.

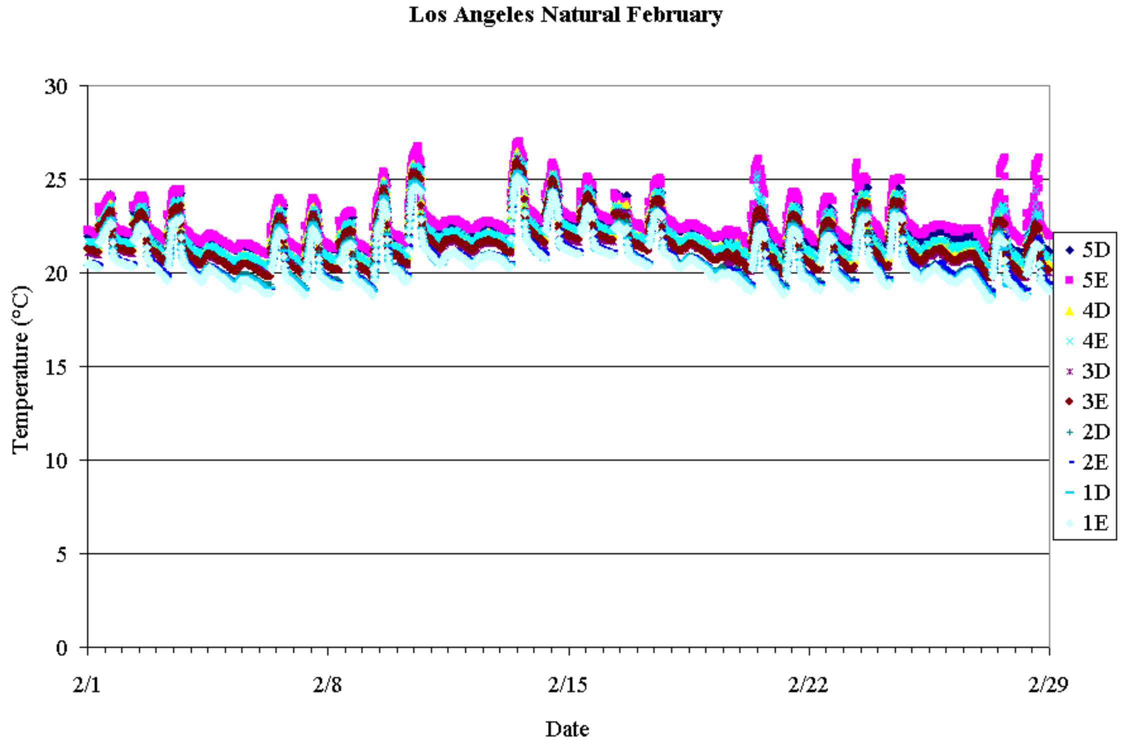
Appendix A Zone Temperature and Concentration Figures

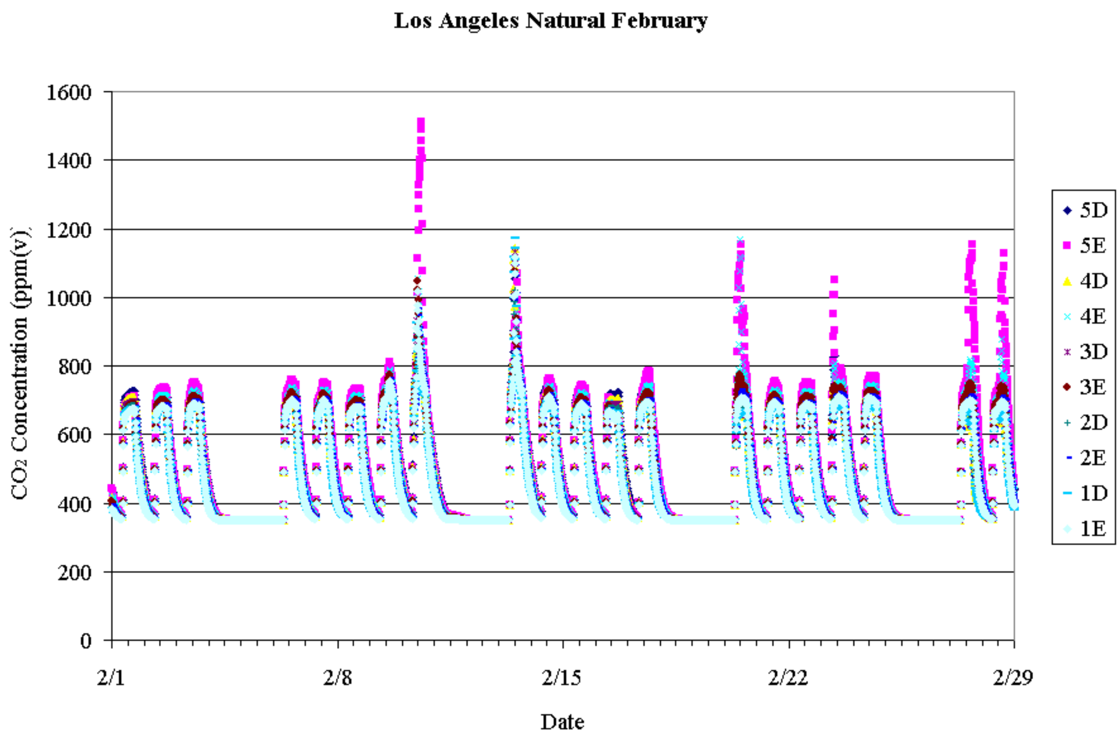
This Appendix presents the zone temperature and CO_2 concentration results plots for Los Angeles, Boston, Minneapolis, and Miami.

Los Angeles

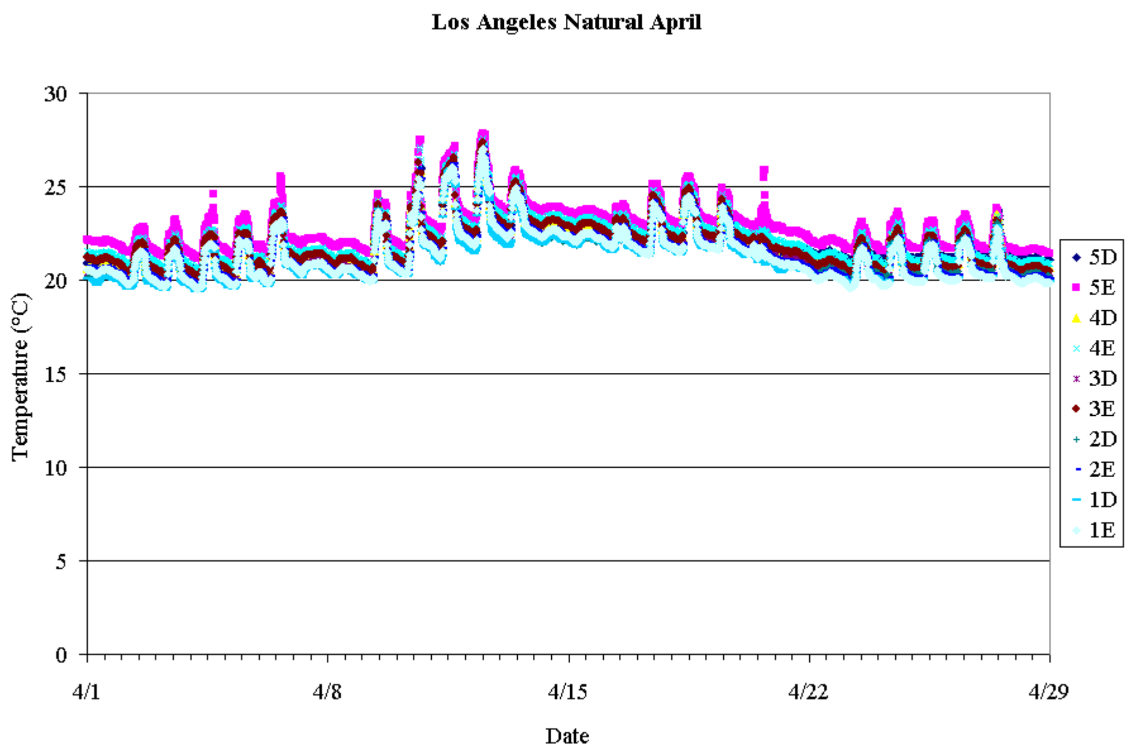
Natural Ventilation System

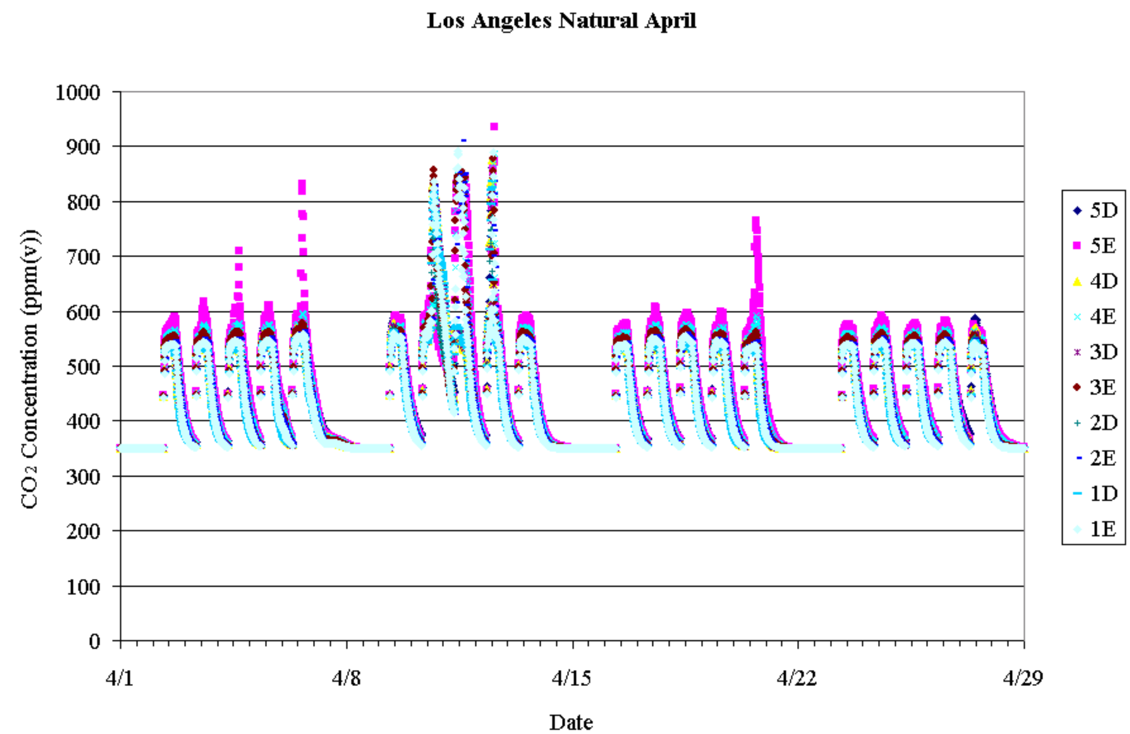
February



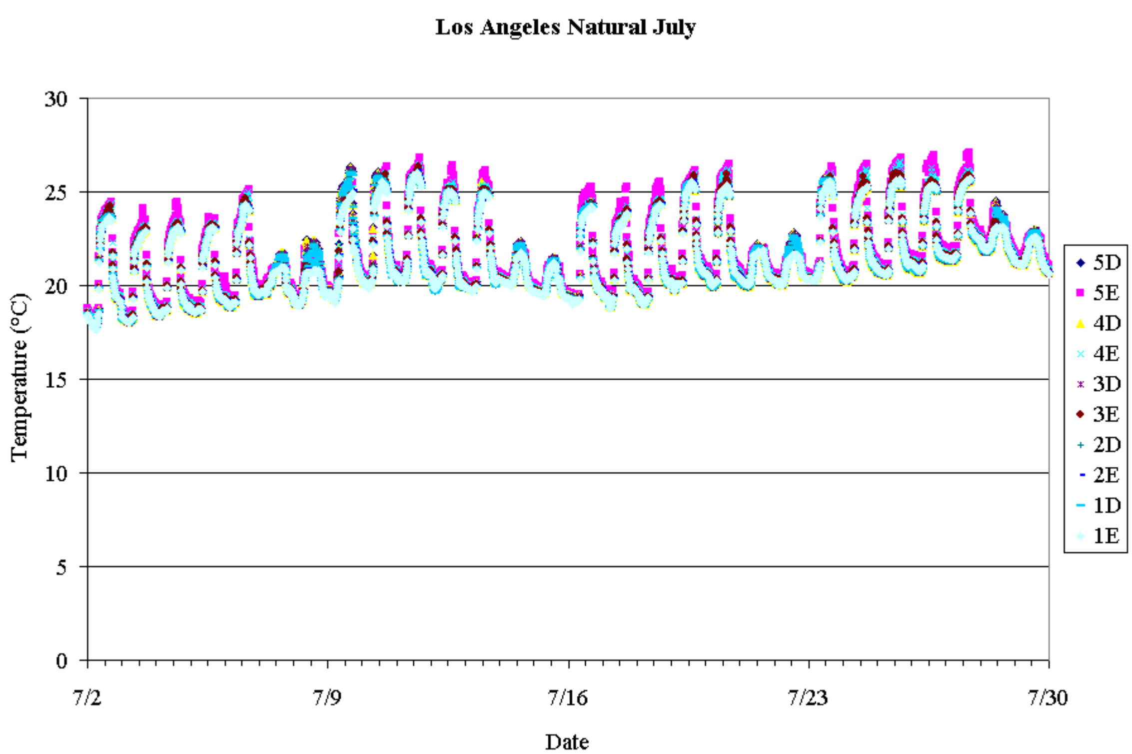

Los Angeles Natural February
1600
1400
1200
1000
800
600
400
200
0
CO2 Concentration (ppm(v))
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

April


Los Angeles Natural April
30
25
20
15
10
5
0
Temperature (°C)
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Los Angeles Natural April
1000
900
800
700
600
500
400
300
200
100
0
CO2 Concentration (ppm(v))
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July


Los Angeles Natural July
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
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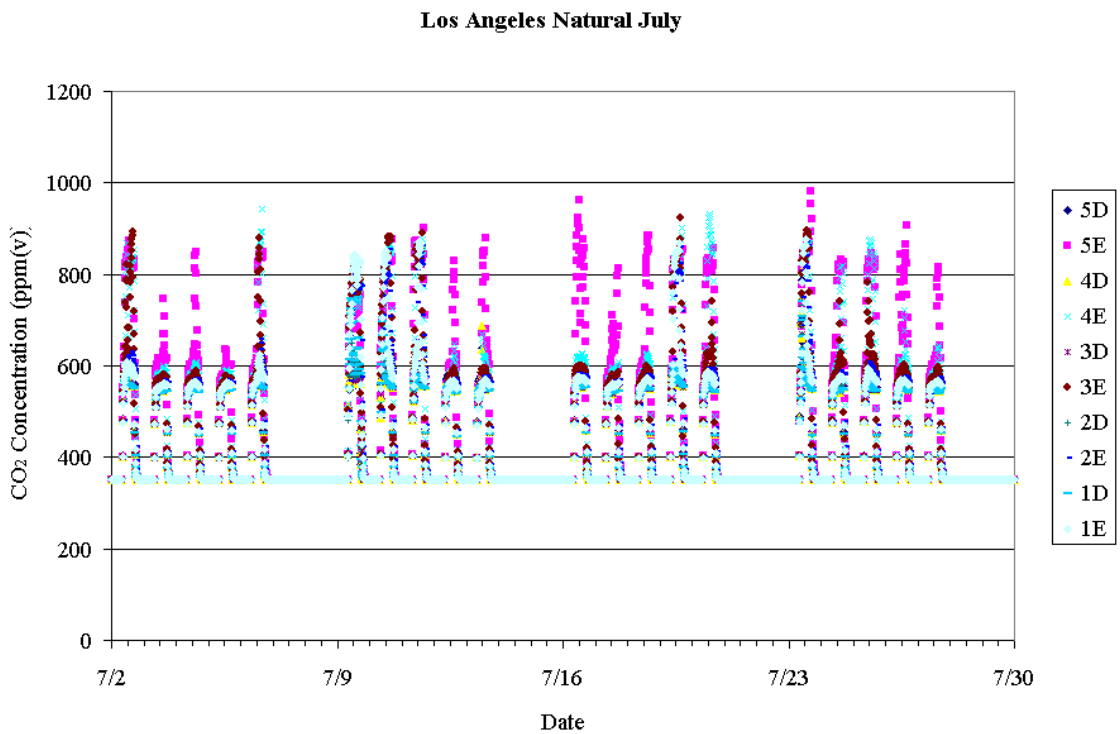
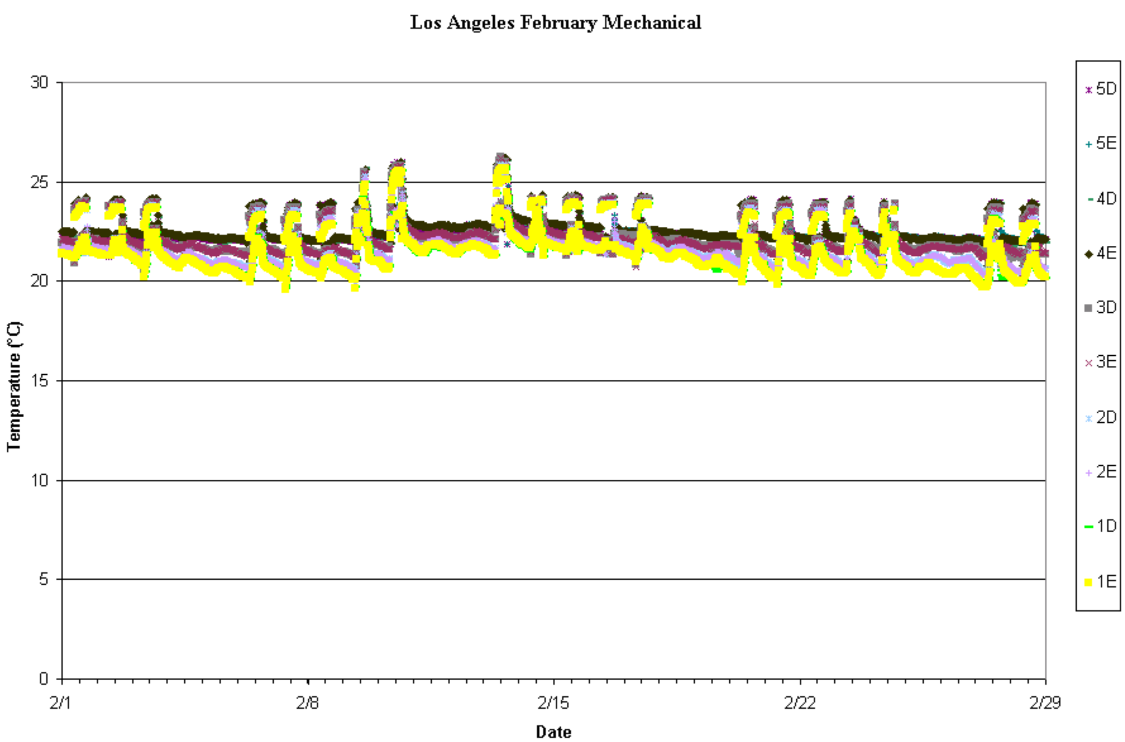
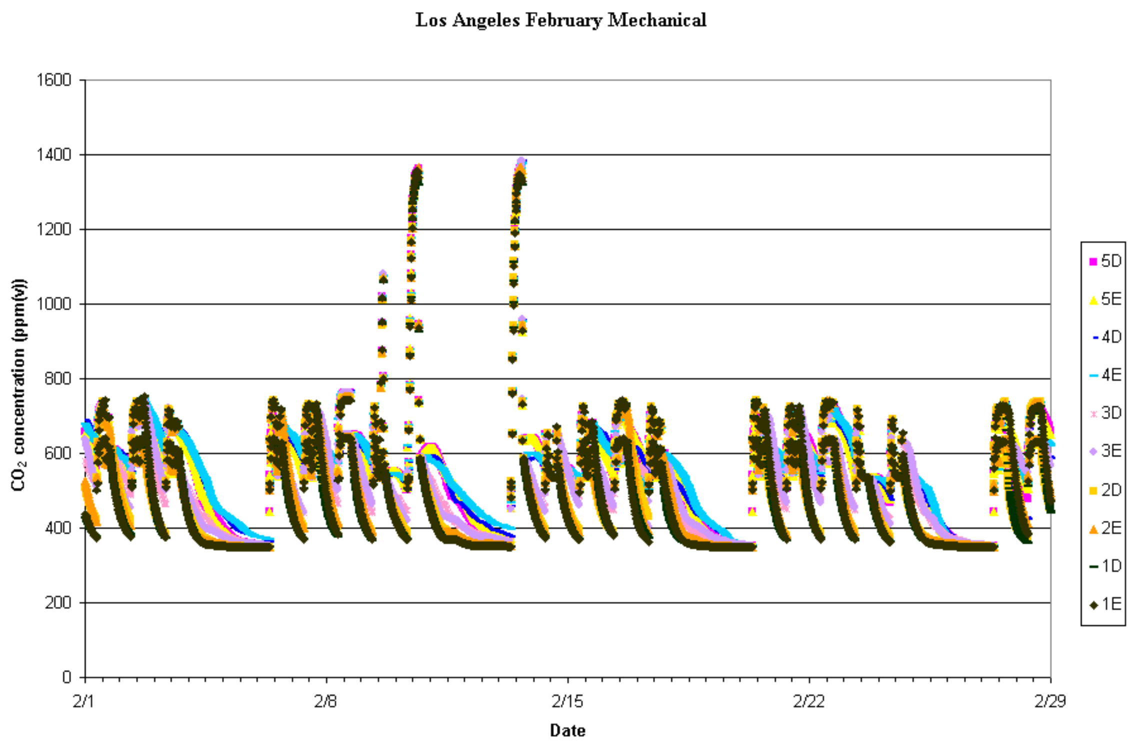
2D
2E
1D
1E



Mechanical Ventilation System

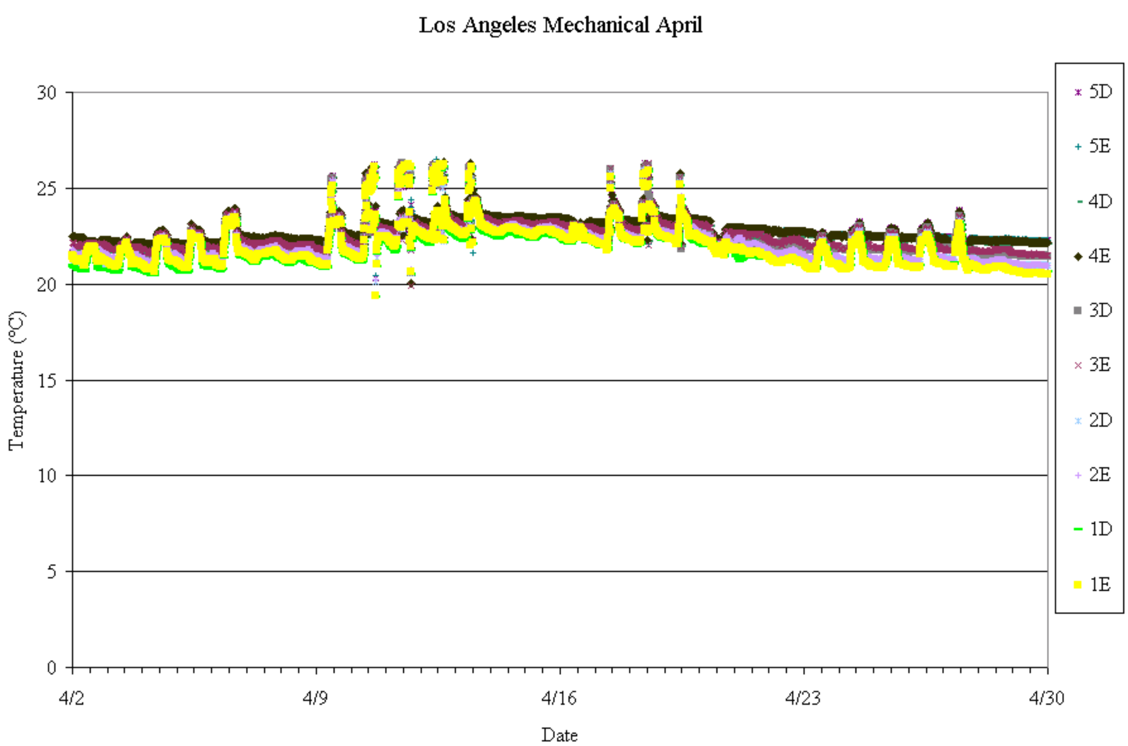
February



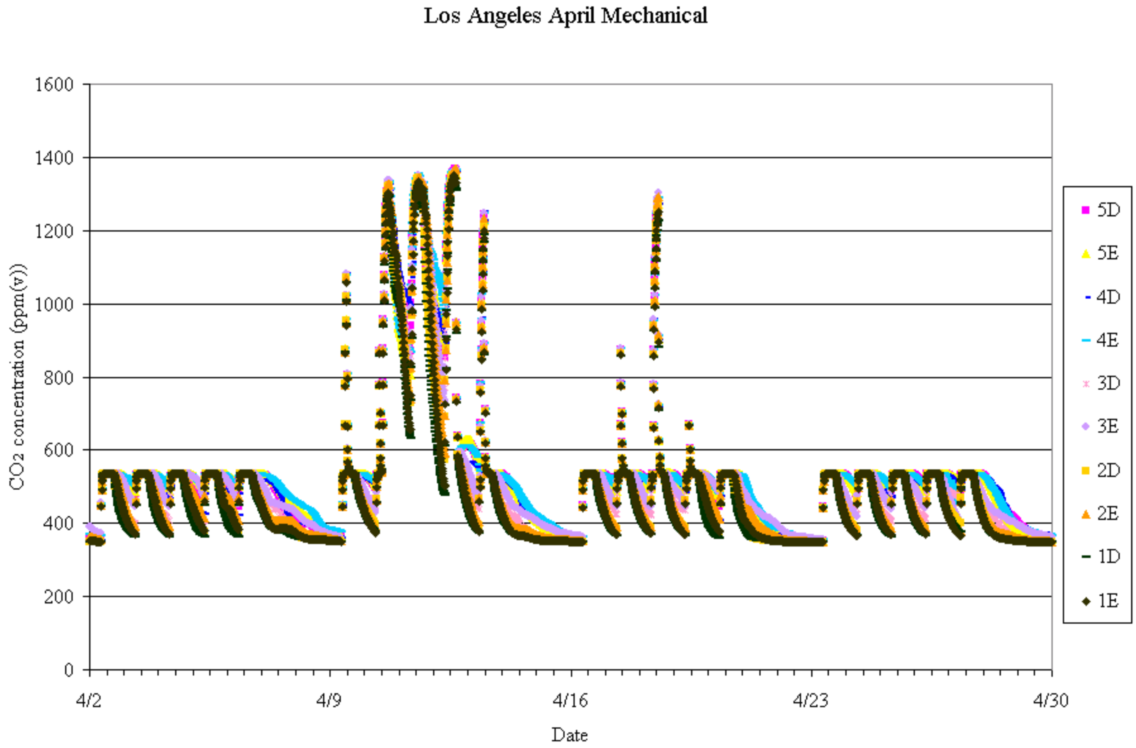


Los Angeles February Mechanical
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

April

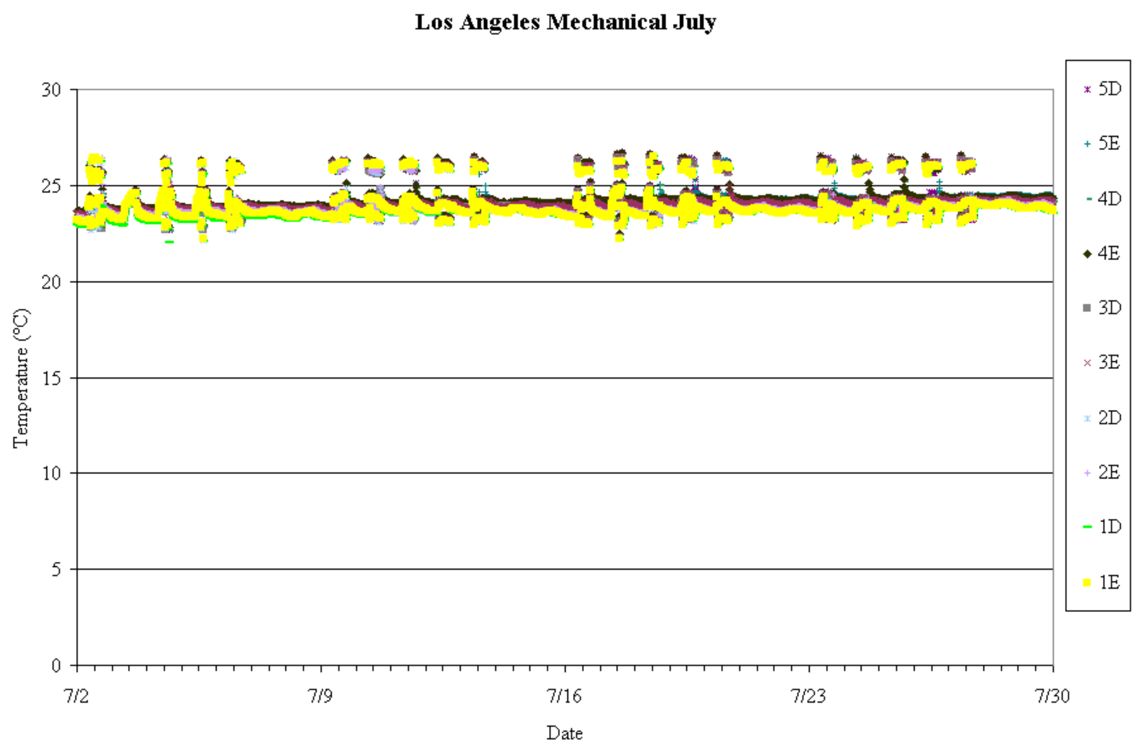


Los Angeles Mechanical April
30
25
20
15
10
5
0
Temperature (°C)
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

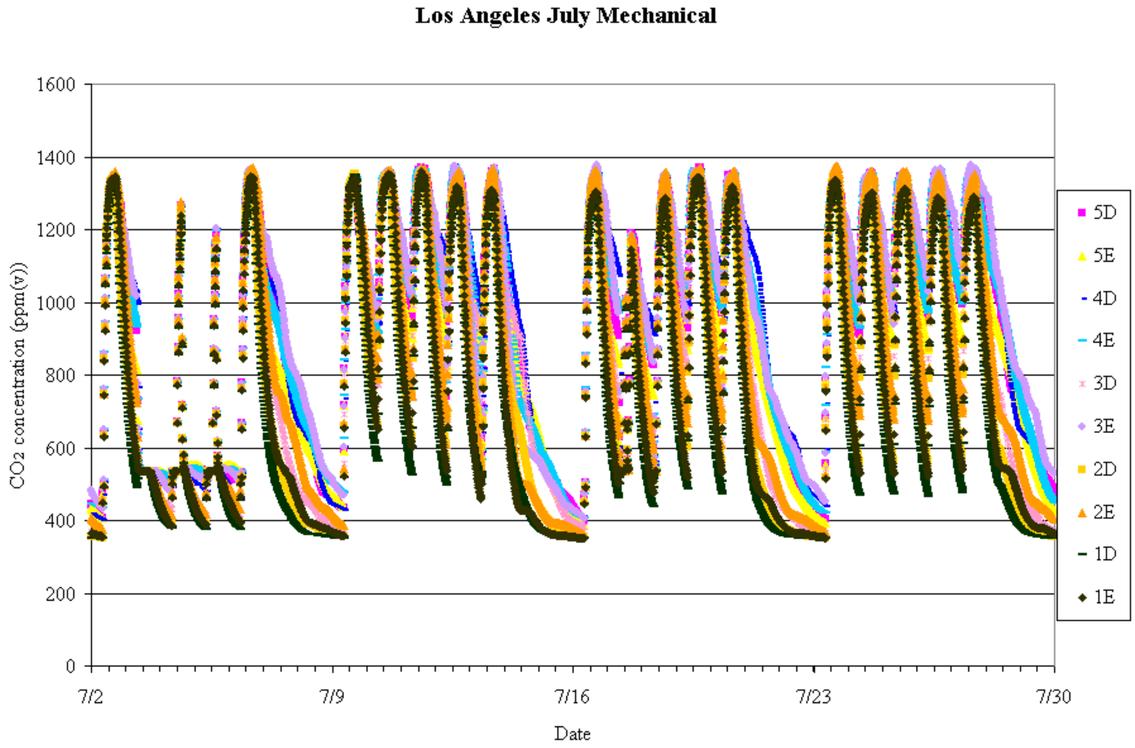


Los Angeles April Mechanical
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July

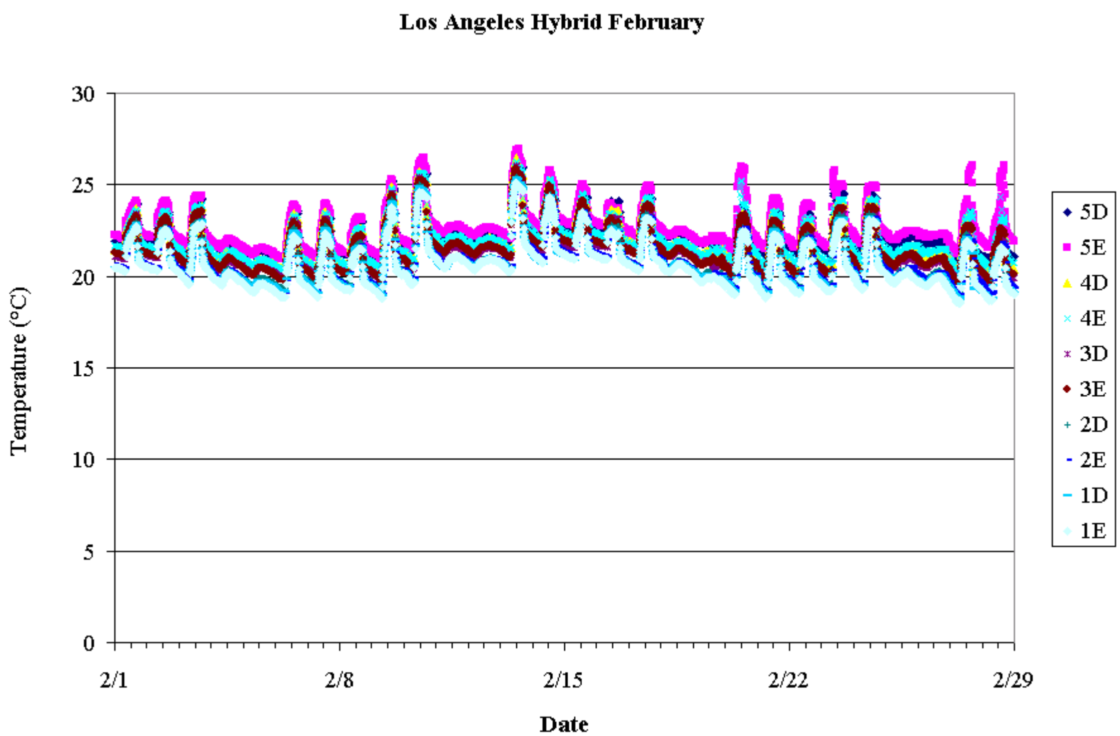


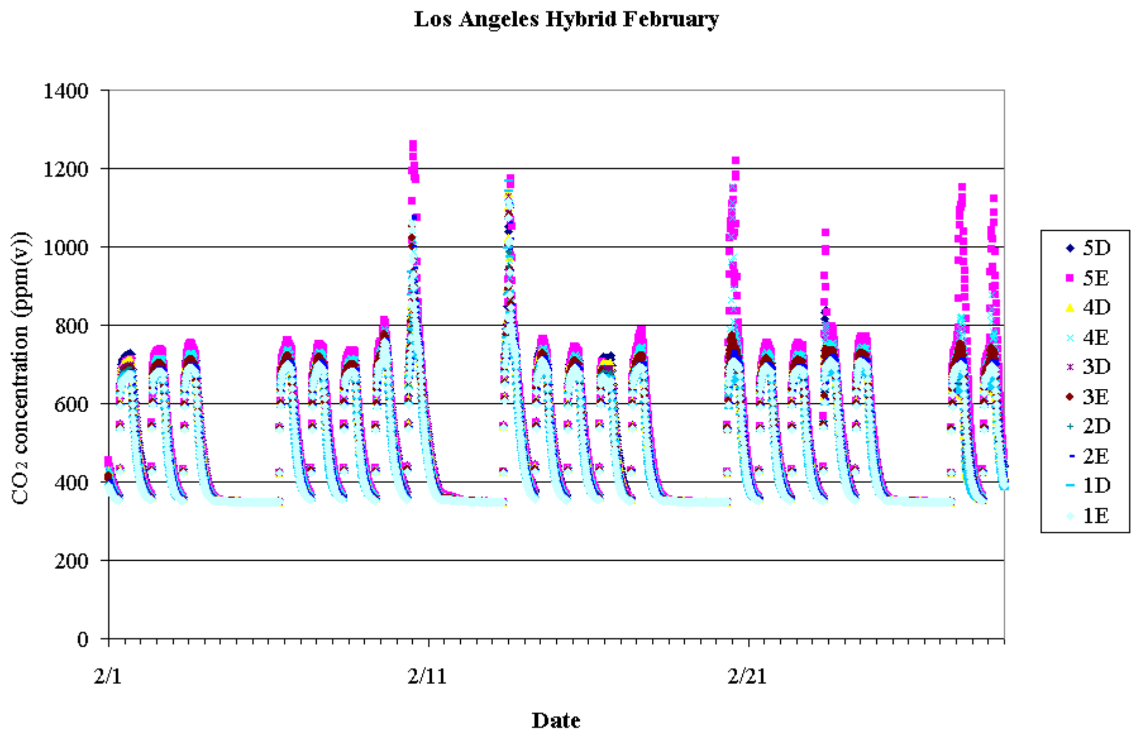
Los Angeles Mechanical July
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



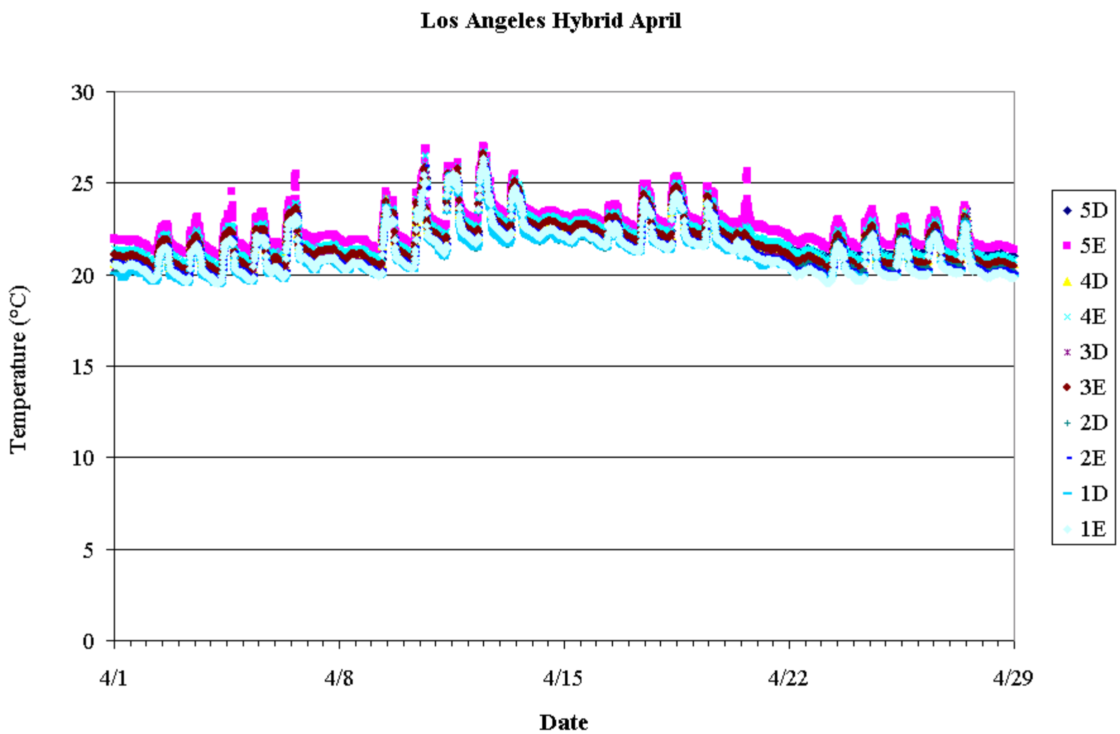
Hybrid Ventilation System

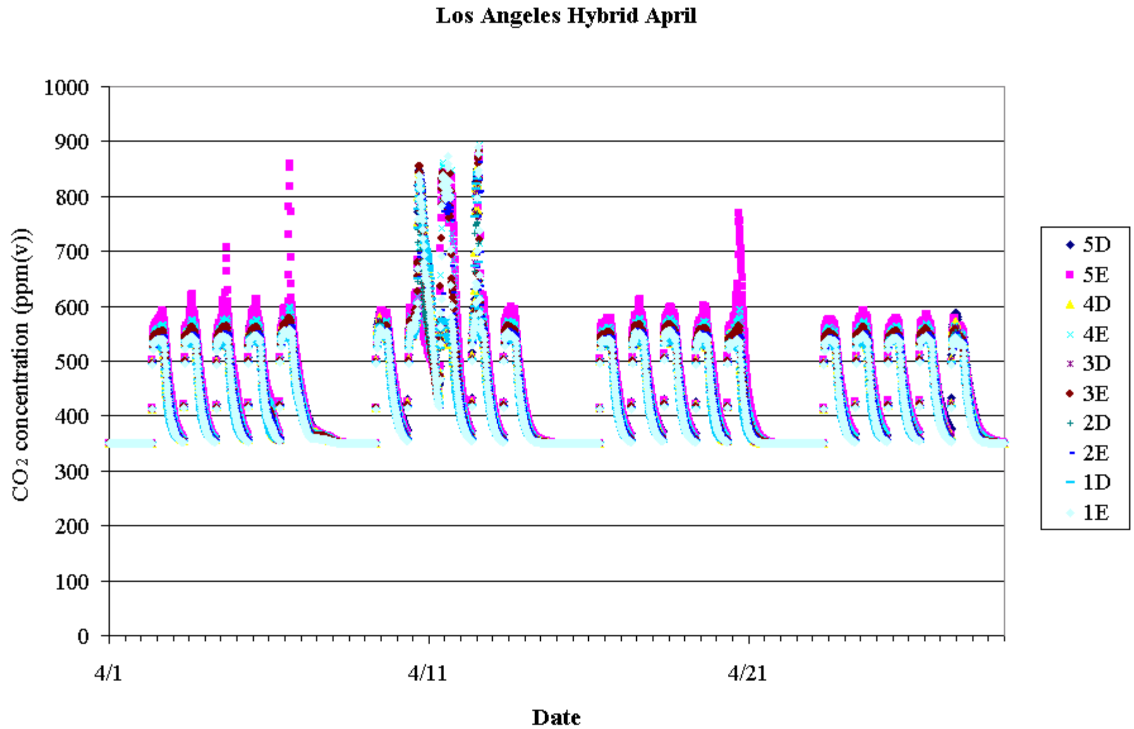
February




Los Angeles Hybrid February
CO2 concentration (ppm(v))
1400
1200
1000
800
600
400
200
0
2/1
2/11
2/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

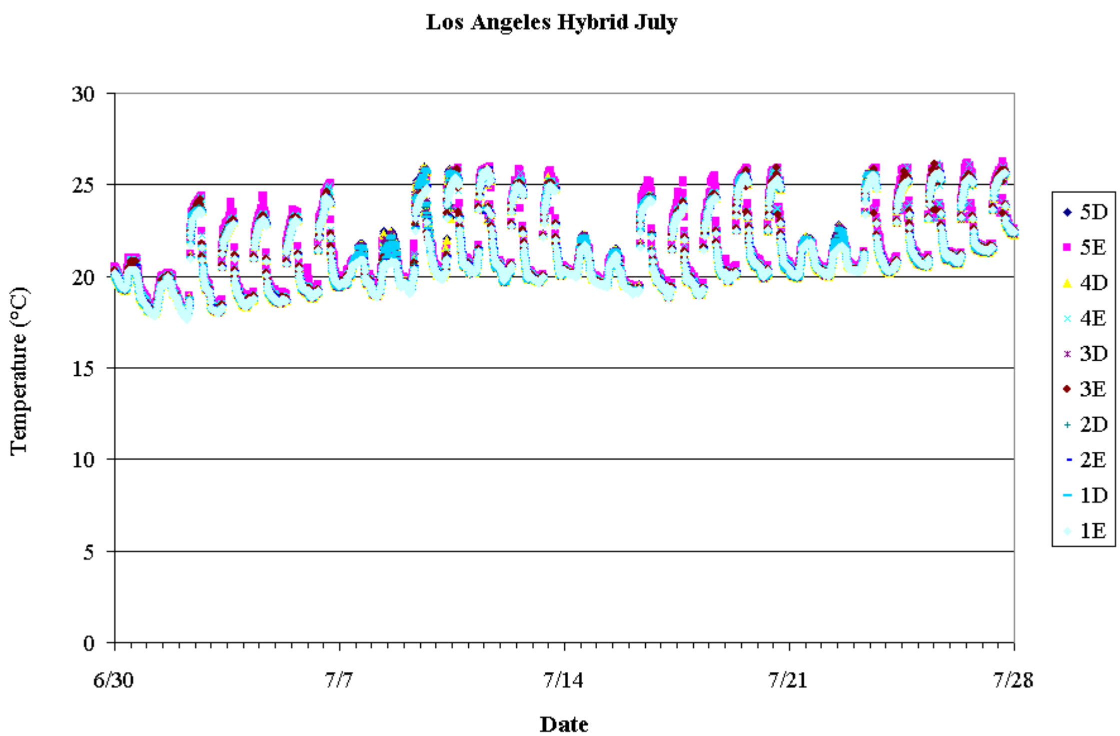
April


Los Angeles Hybrid April
Temperature (°C)
30
25
20
15
10
5
0
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

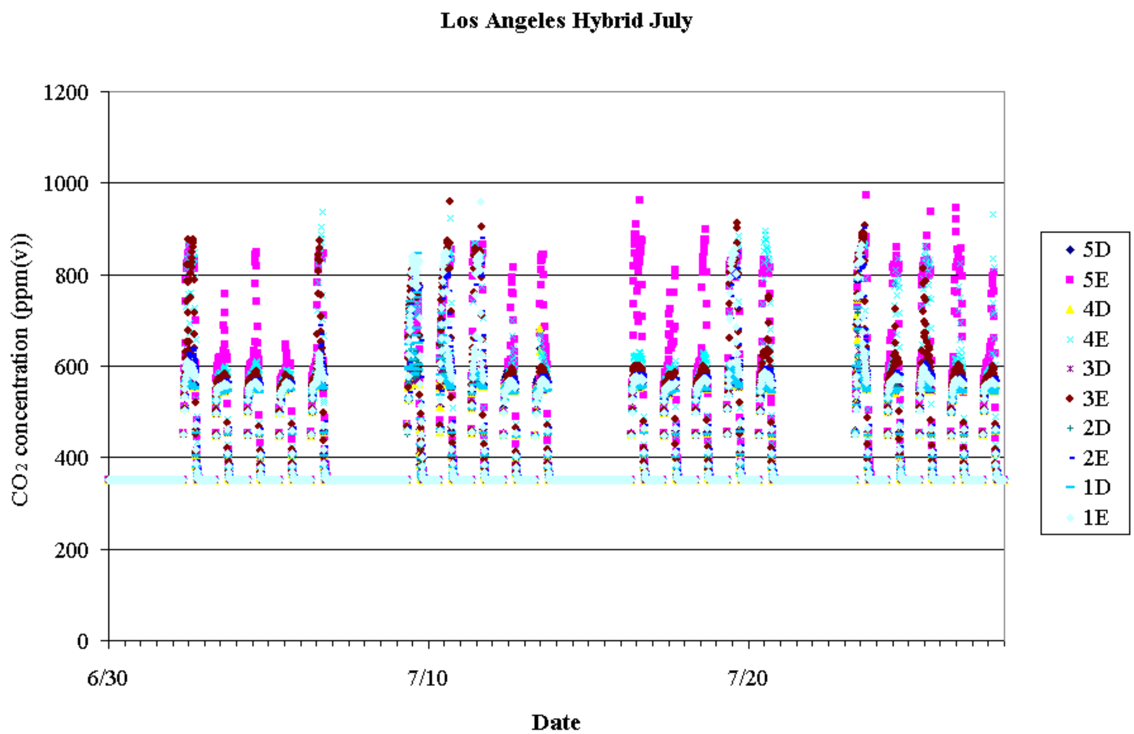


Los Angeles Hybrid April
1000
900
800
700
600
500
400
300
200
100
0
CO2 concentration (ppm(v))
4/1
4/11
4/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July



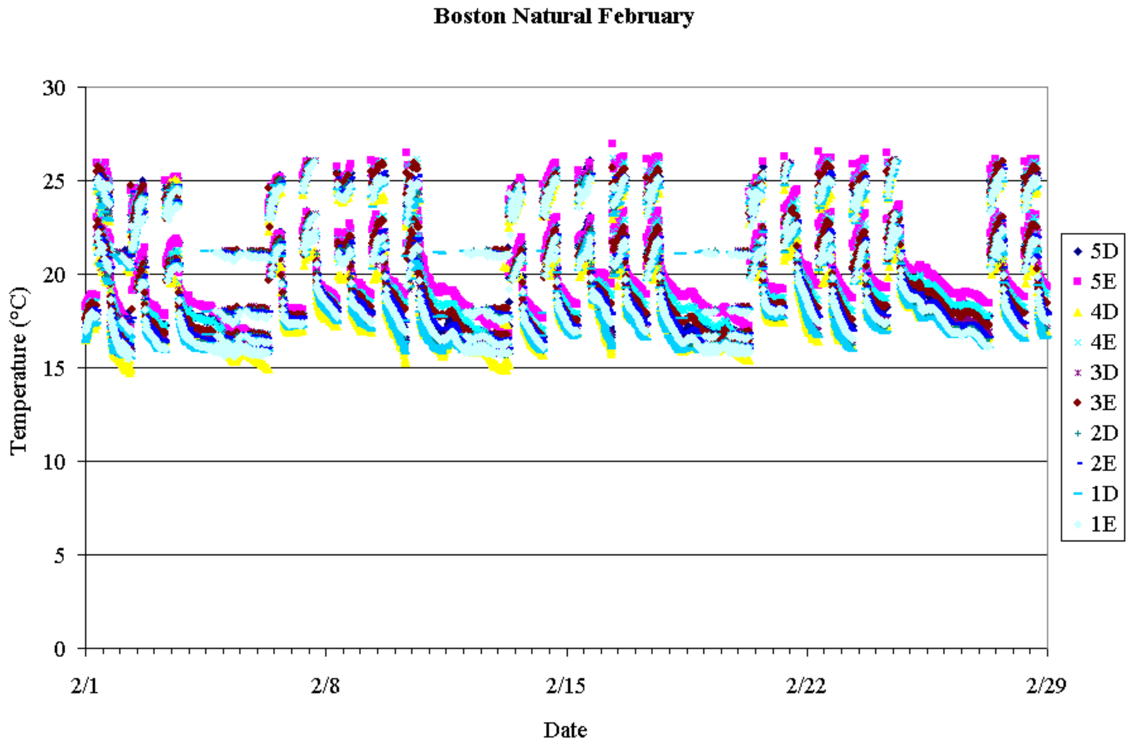
Los Angeles Hybrid July
30
25
20
15
10
5
0
Temperature (°C)
6/30
7/7
7/14
7/21
7/28
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

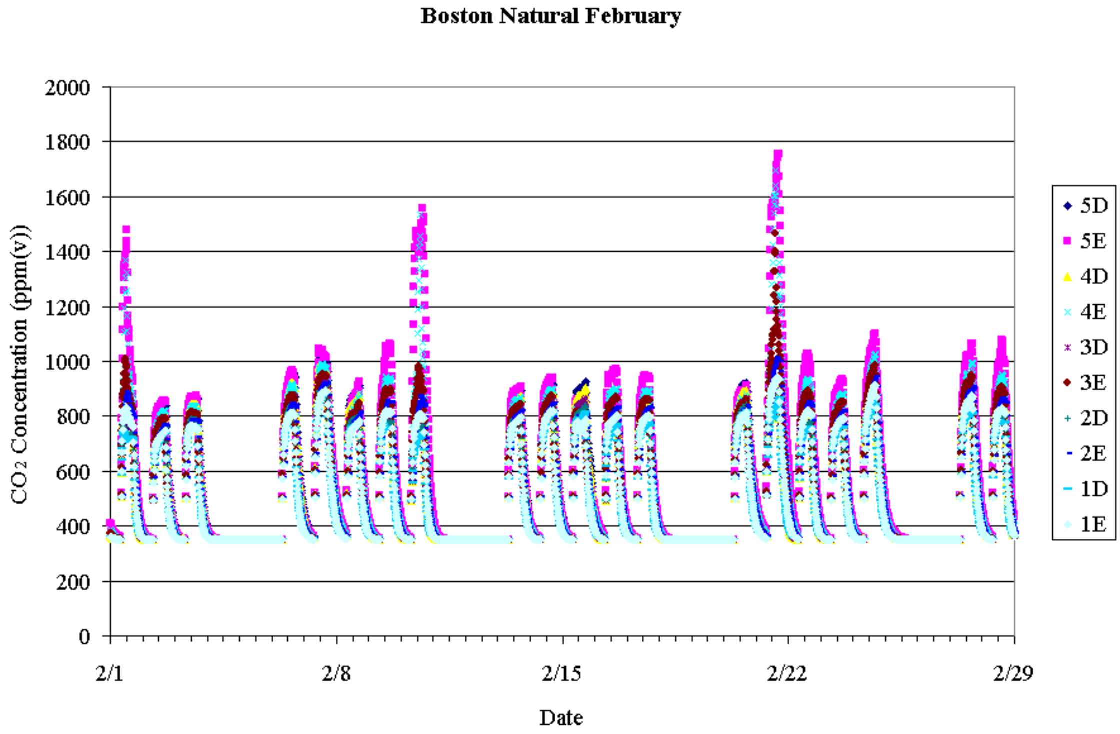

Los Angeles Hybrid July
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
6/30
7/10
7/20
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

Boston

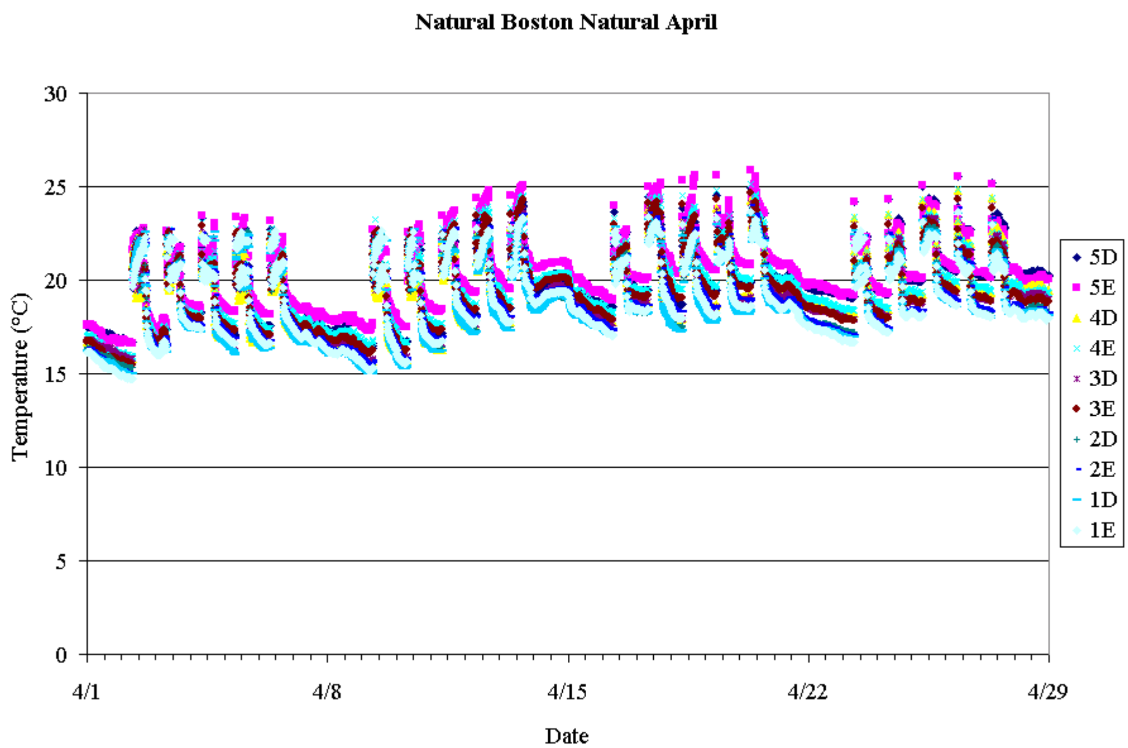
Natural Ventilation System

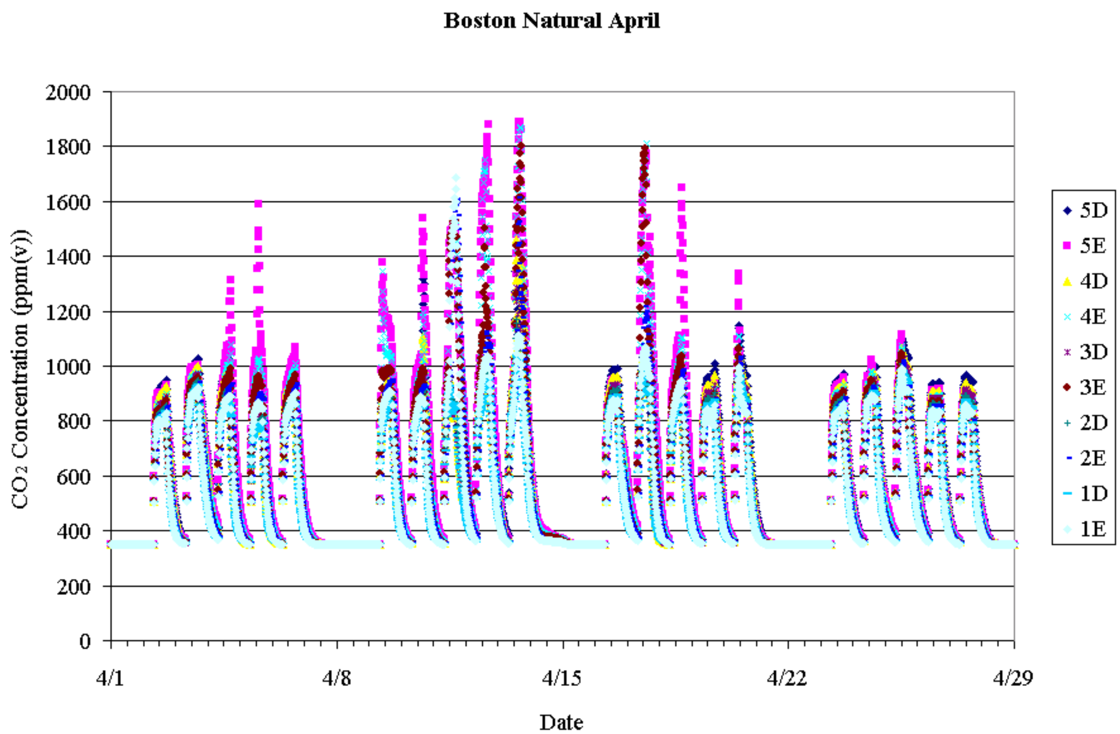
February



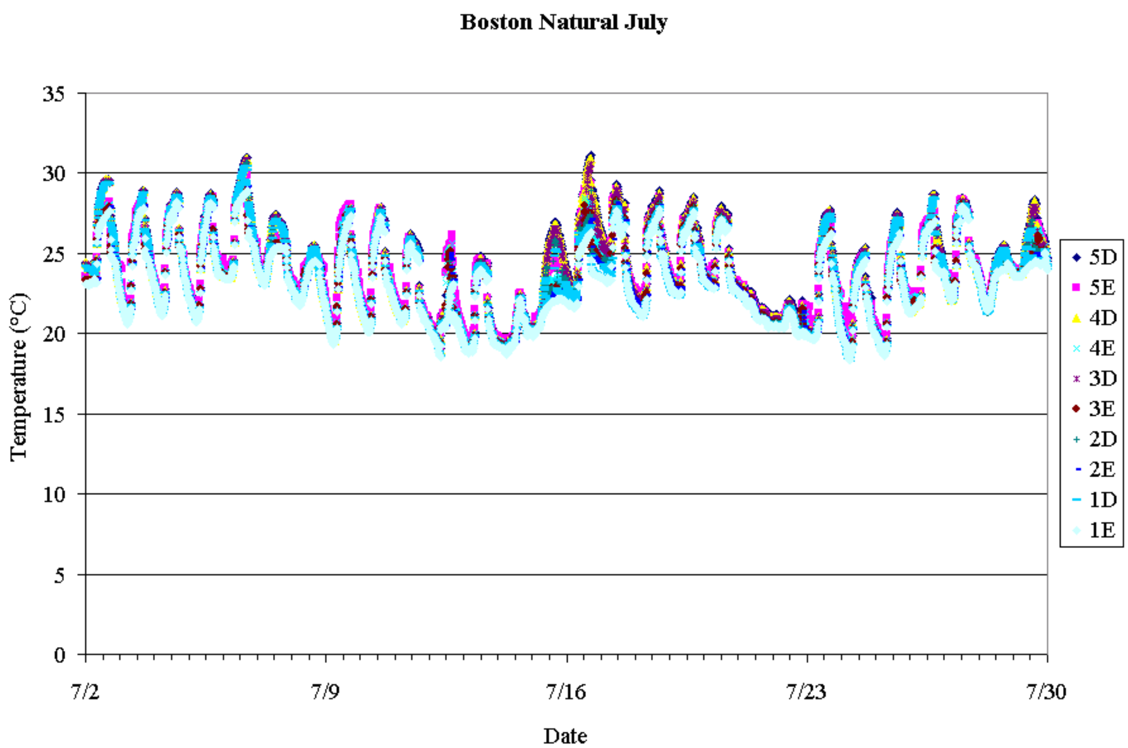

Boston Natural February
CO_2 Concentration (ppm(v))
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

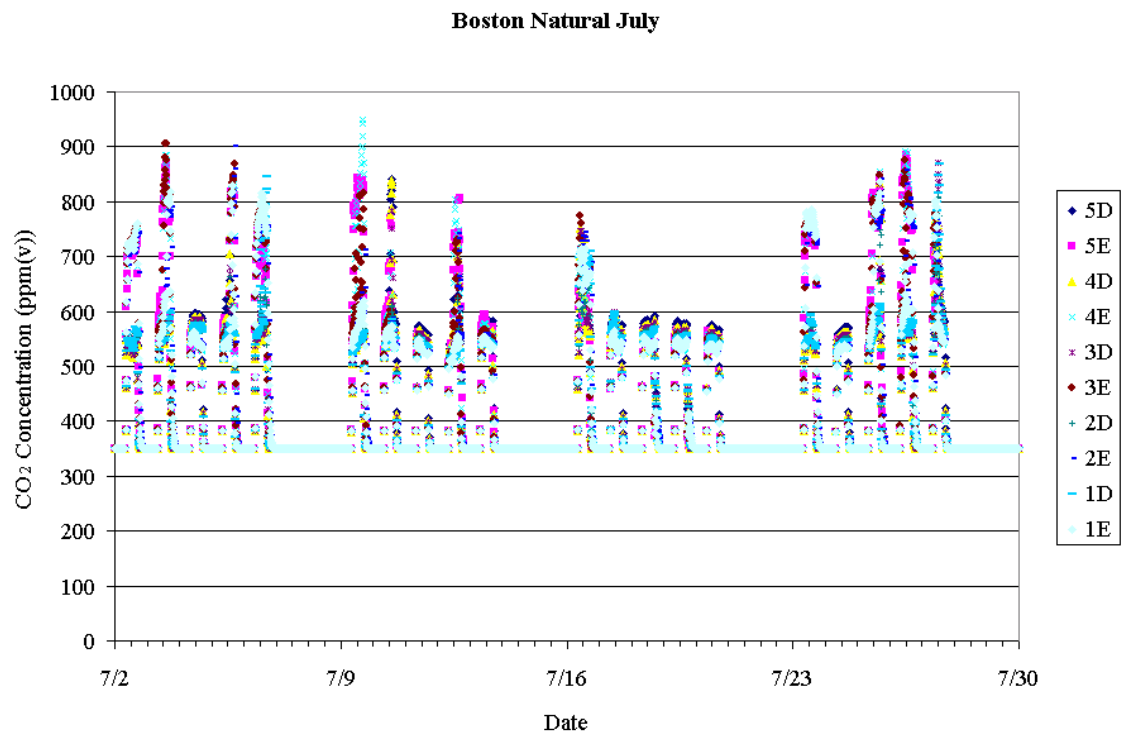
April


Natural Boston Natural April
Temperature (°C)
30
25
20
15
10
5
0
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Boston Natural April
2000
1800
1600
1400
1200
1000
800
600
400
200
0
CO2 Concentration (ppm(v))
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

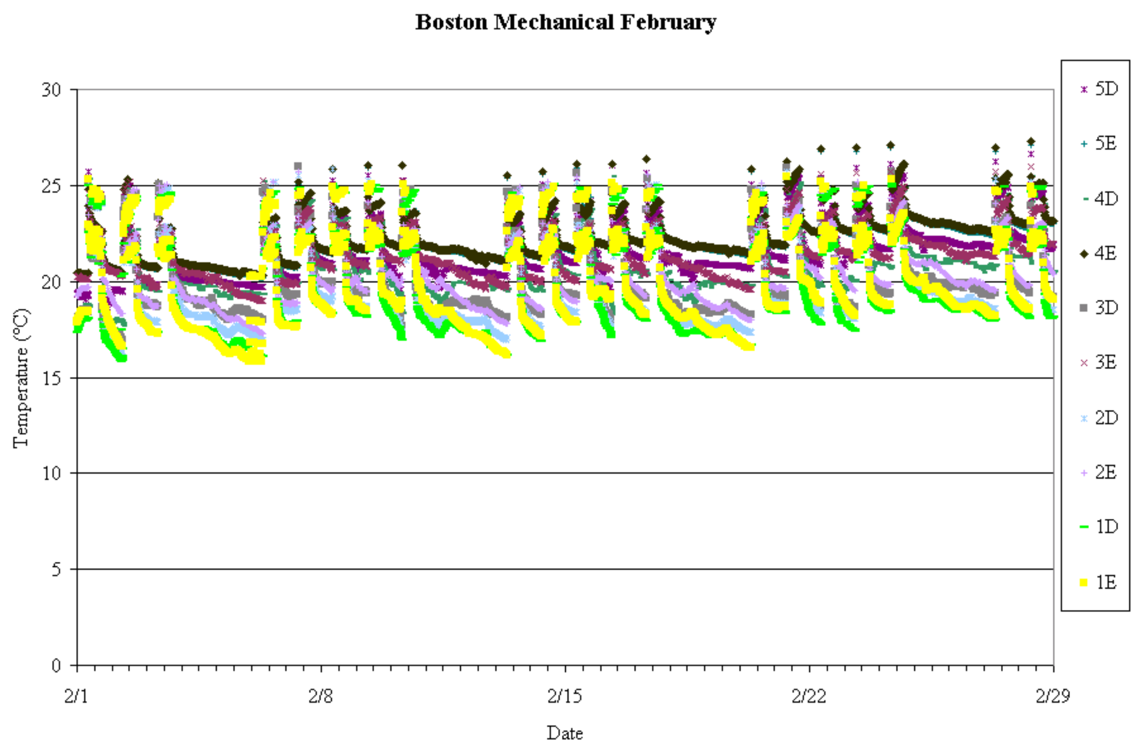
July

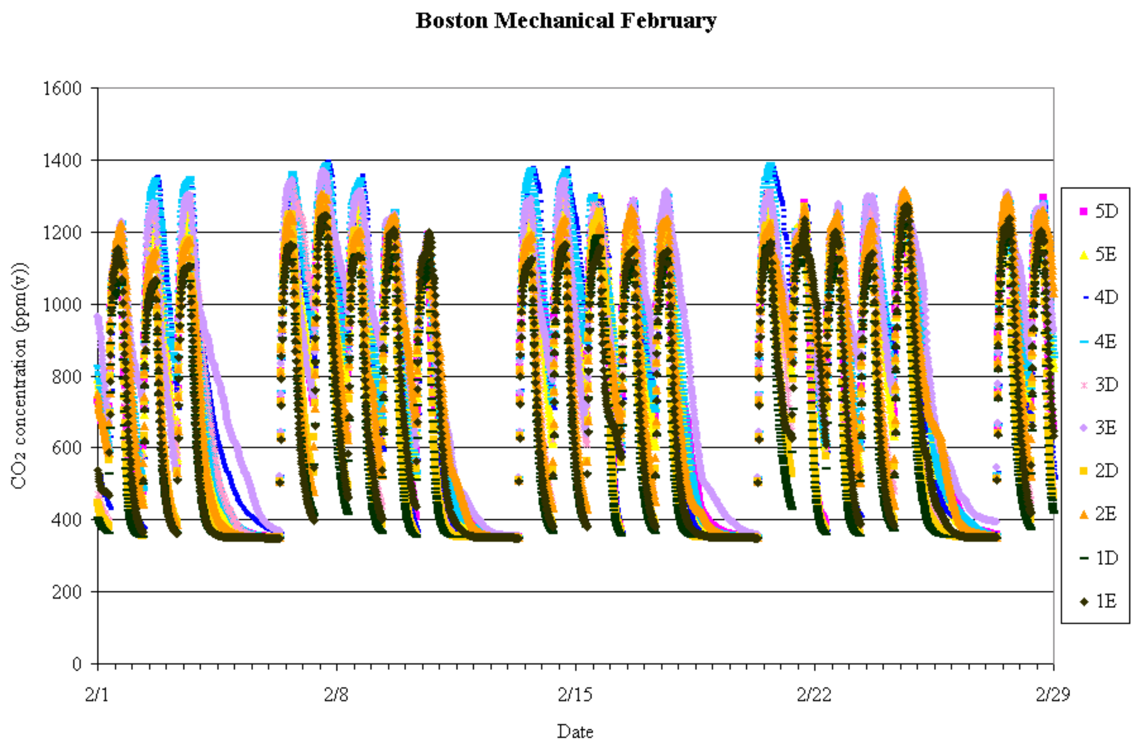

Boston Natural July
35
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



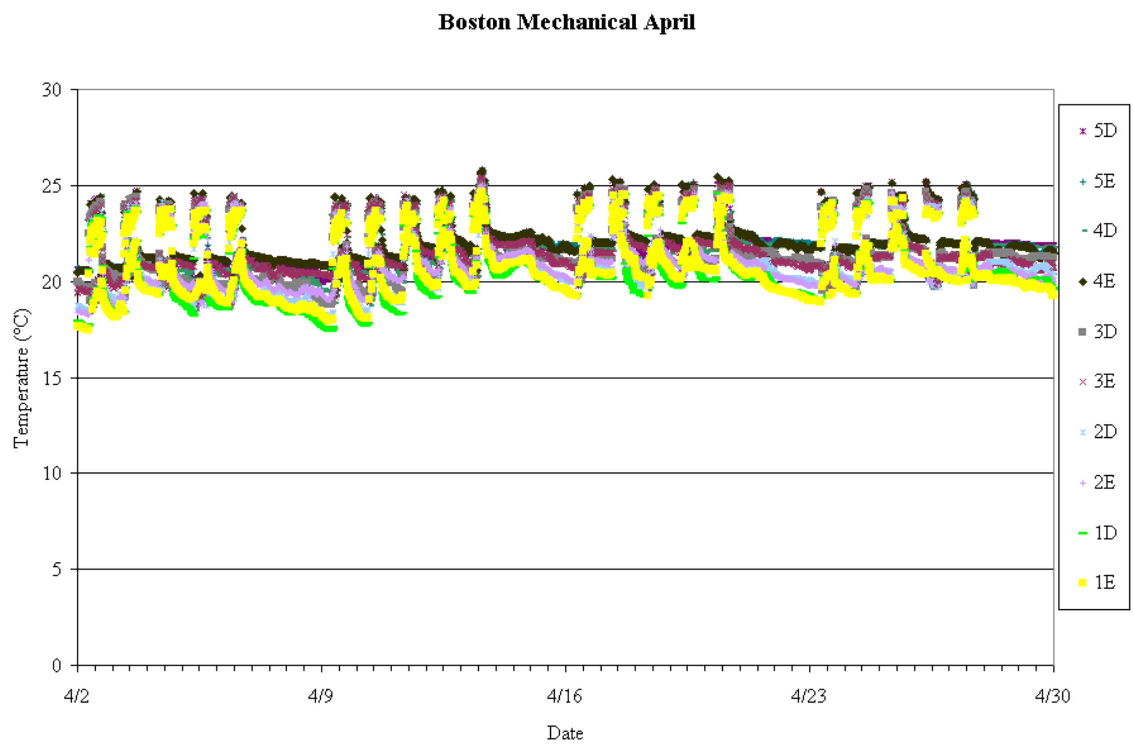
Mechanical Ventilation System

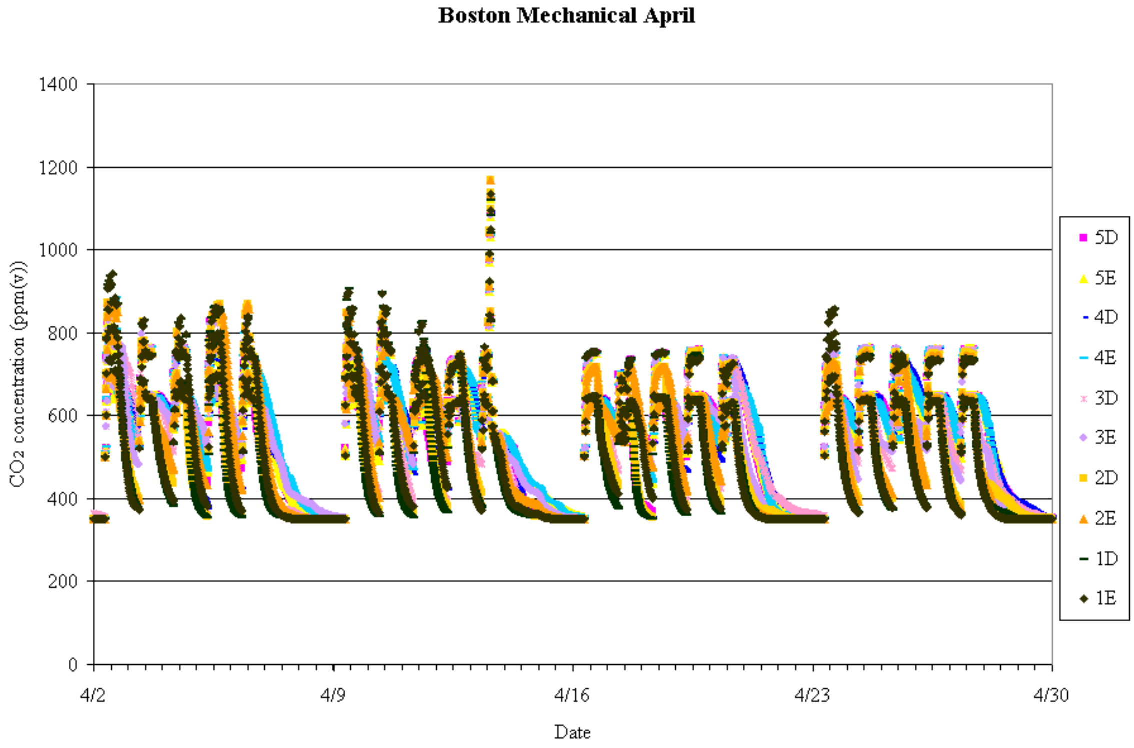
February




Boston Mechanical February
CO2 concentration (ppm(v))
1600
1400
1200
1000
800
600
400
200
0
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

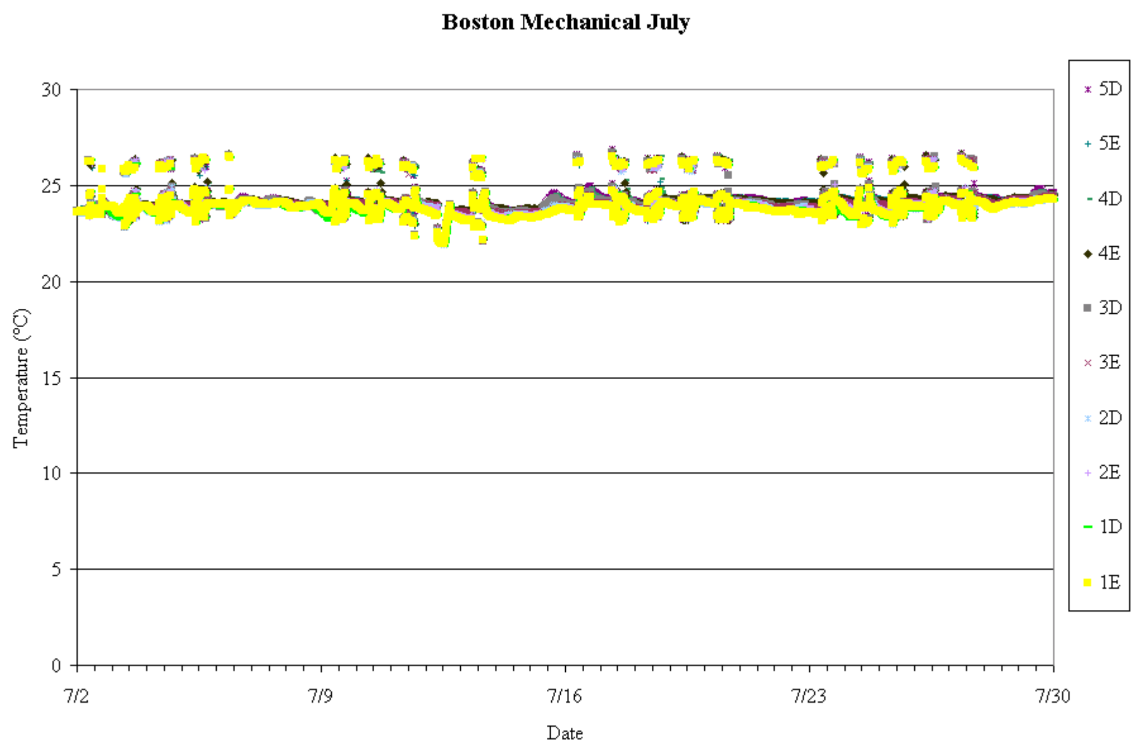
April


Boston Mechanical April
Temperature (°C)
30
25
20
15
10
5
0
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



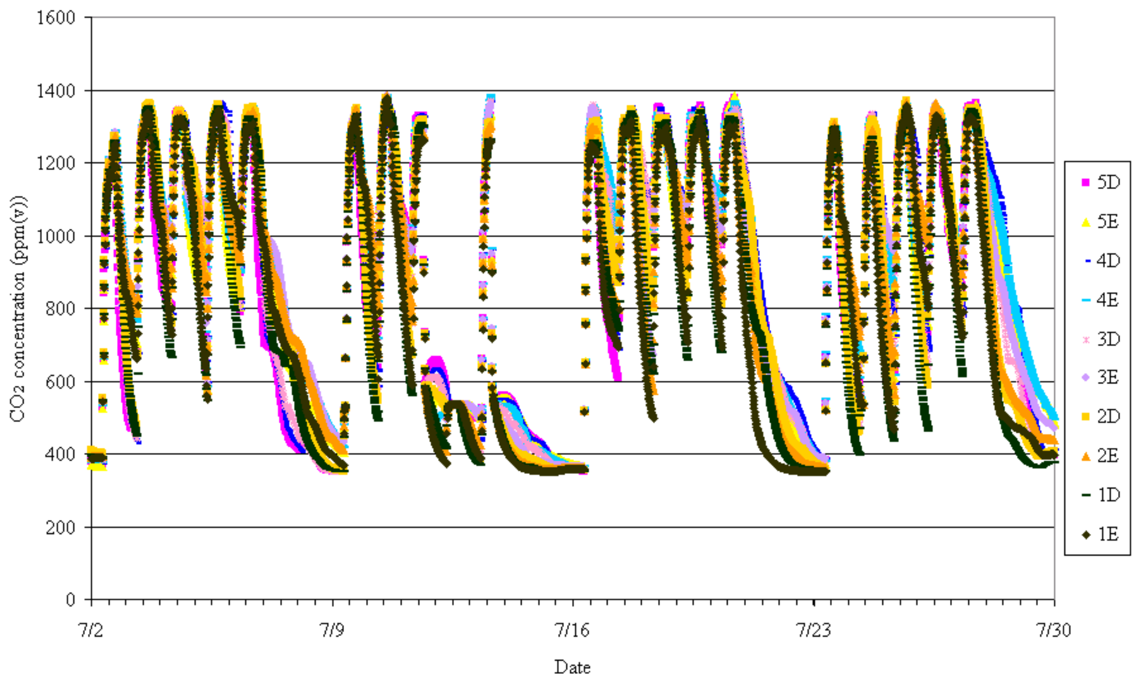
Boston Mechanical April
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July



Boston Mechanical July
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

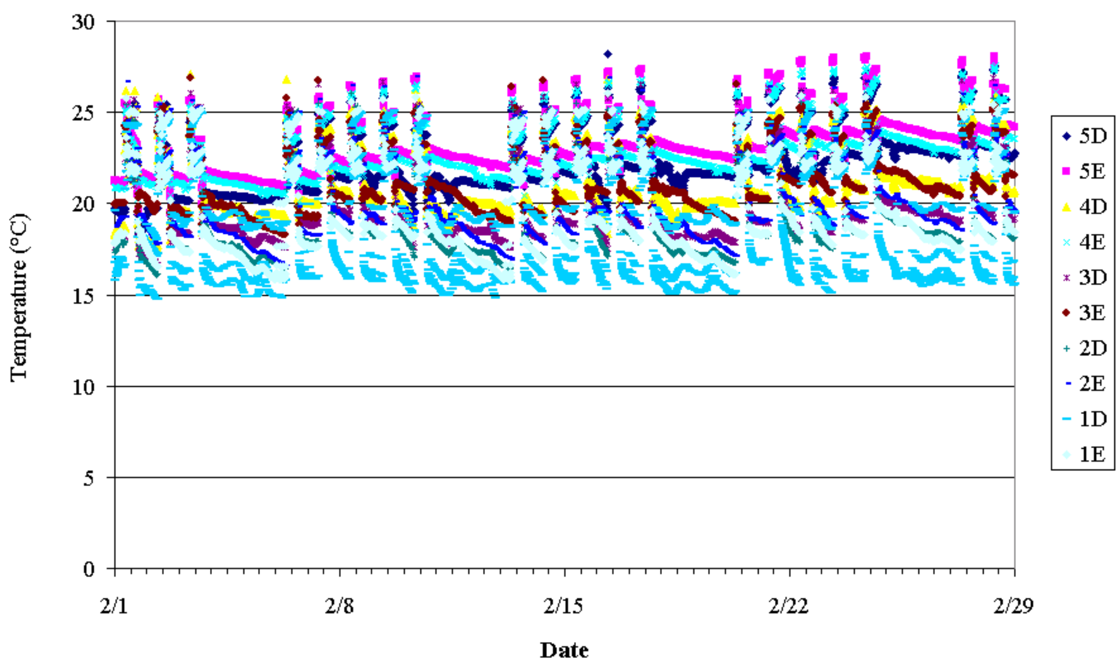
Boston Mechanical July

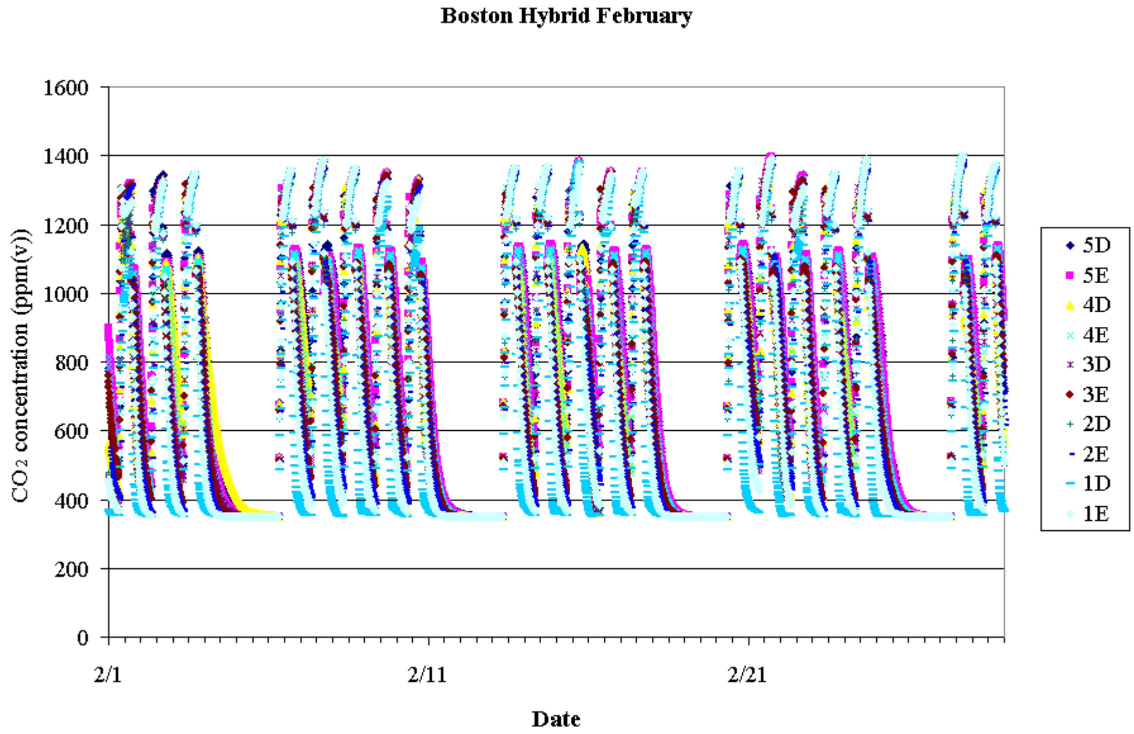


Hybrid Ventilation System

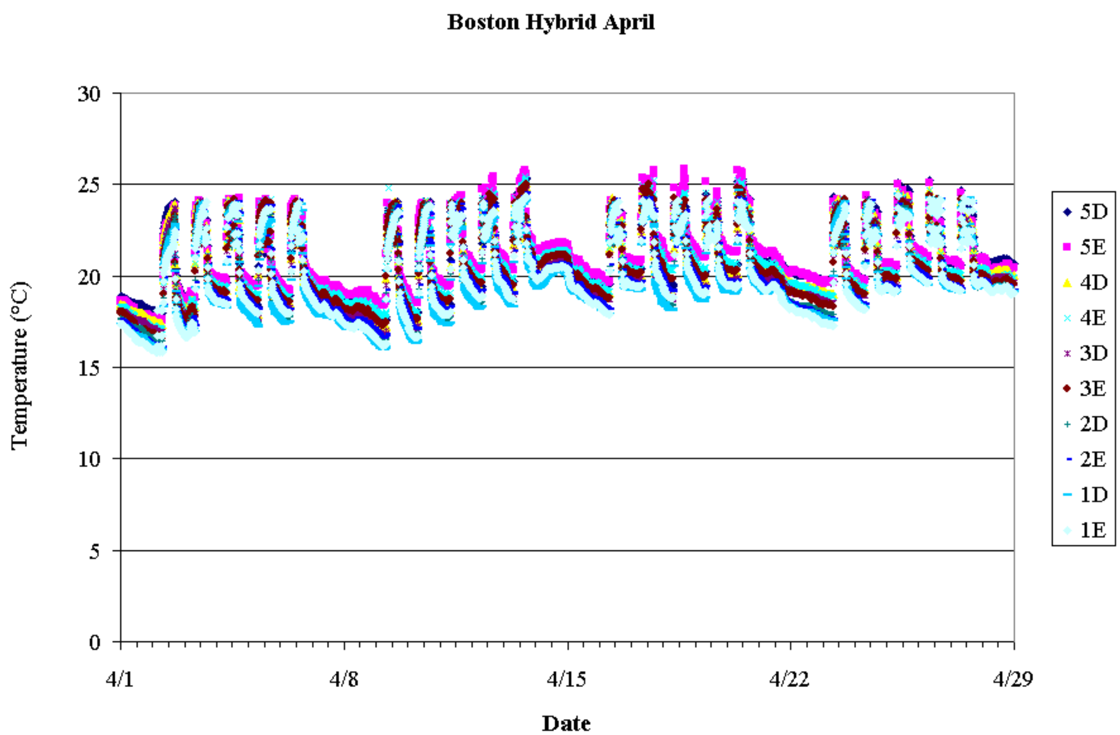
February

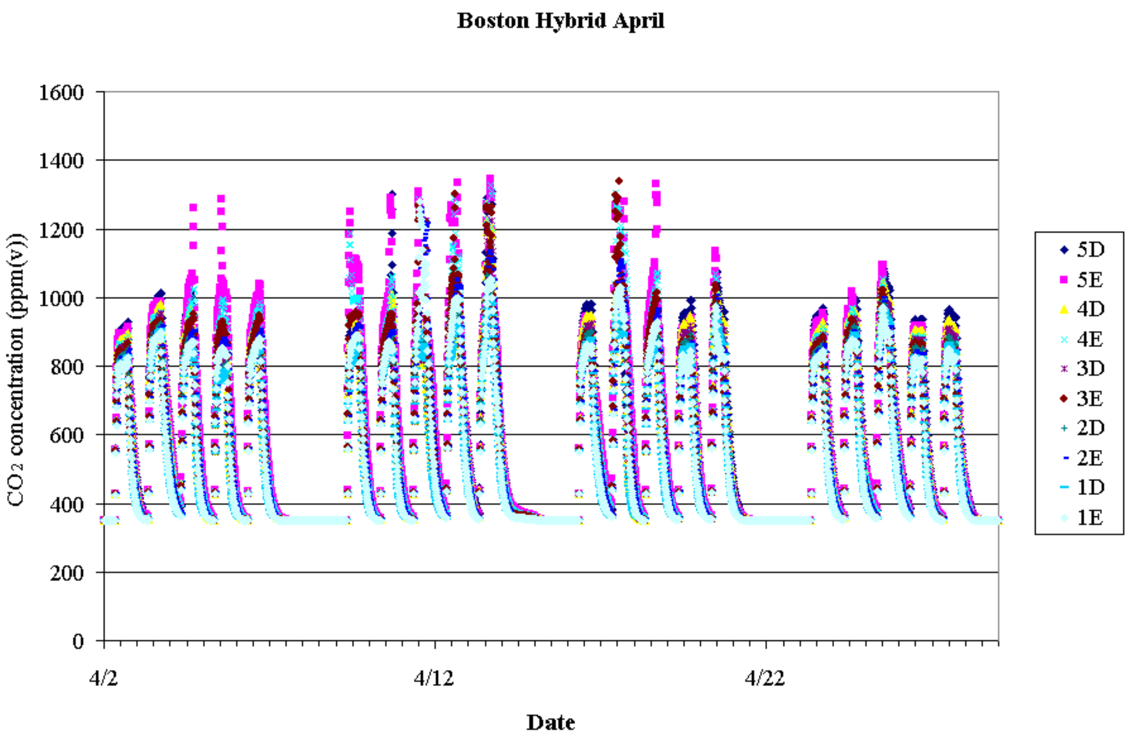
Boston Hybrid February



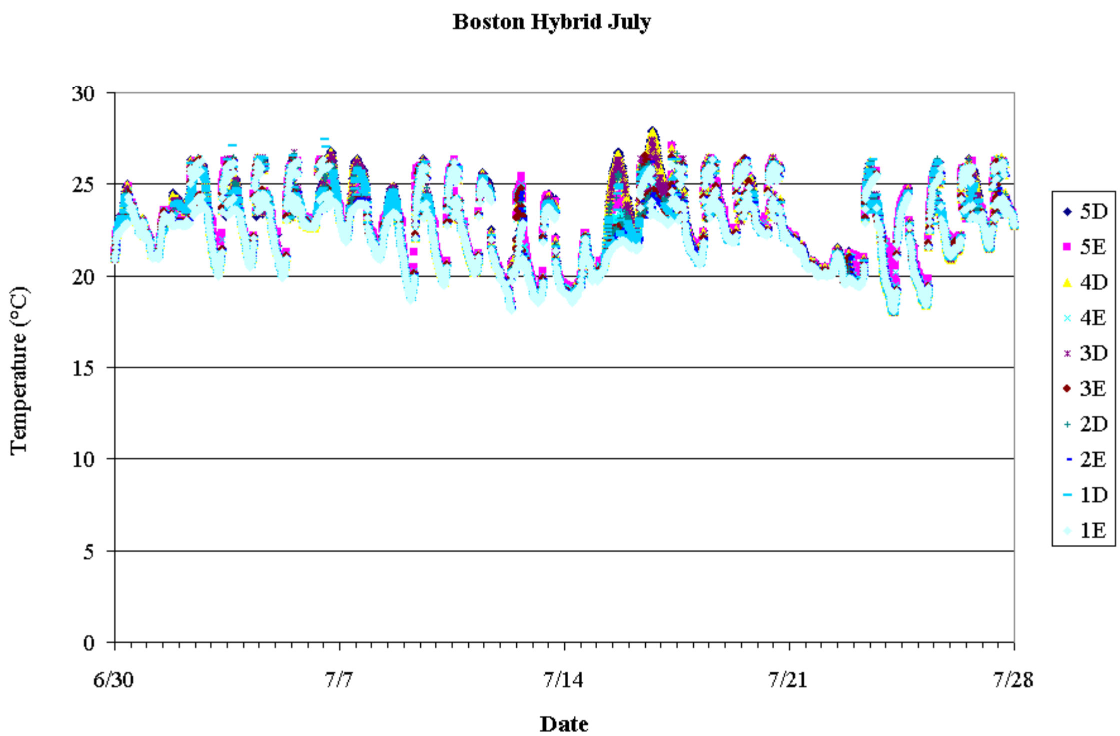

Boston Hybrid February
CO₂ concentration (ppm(v))
1600
1400
1200
1000
800
600
400
200
0
2/1
2/11
2/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

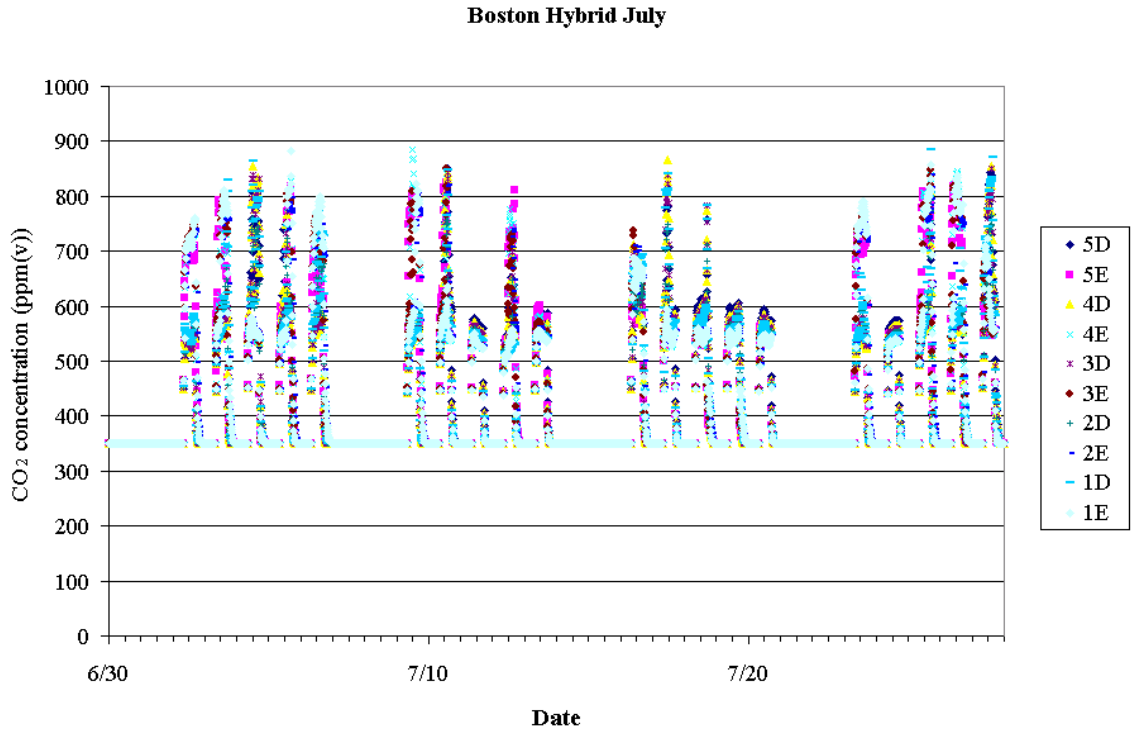
April


Boston Hybrid April
Temperature (°C)
30
25
20
15
10
5
0
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Boston Hybrid April
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
4/2
4/12
4/22
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July

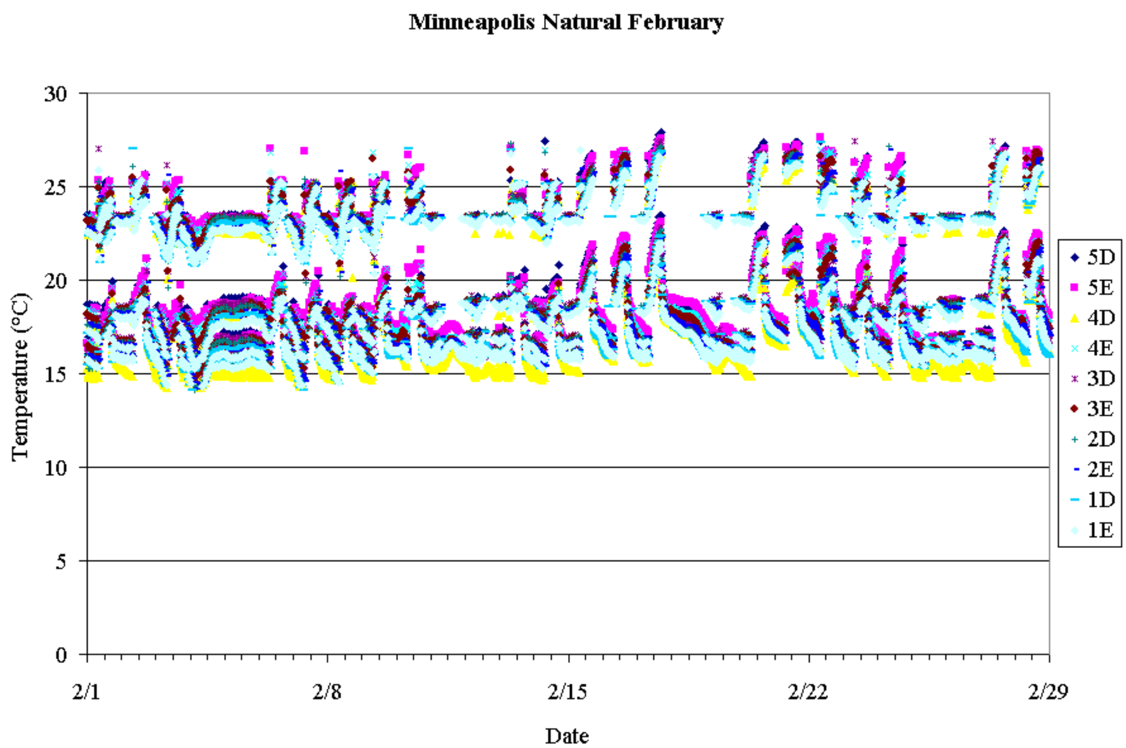

Boston Hybrid July
30
25
20
15
10
5
0
Temperature (°C)
6/30
7/7
7/14
7/21
7/28
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



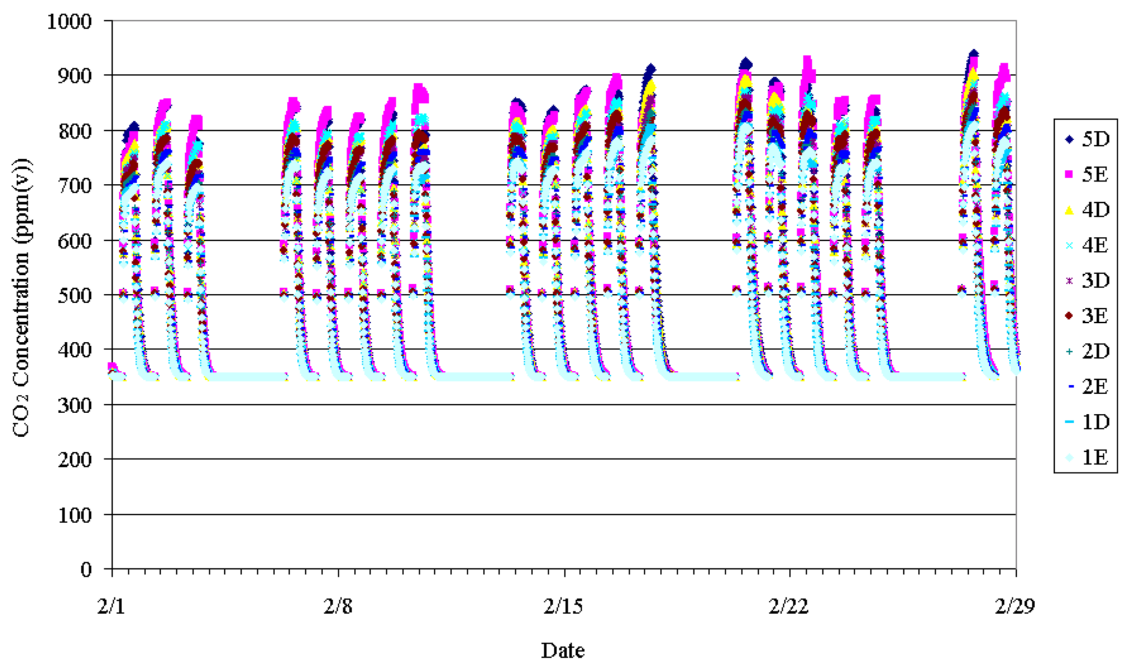
Minneapolis

Natural Ventilation System

February

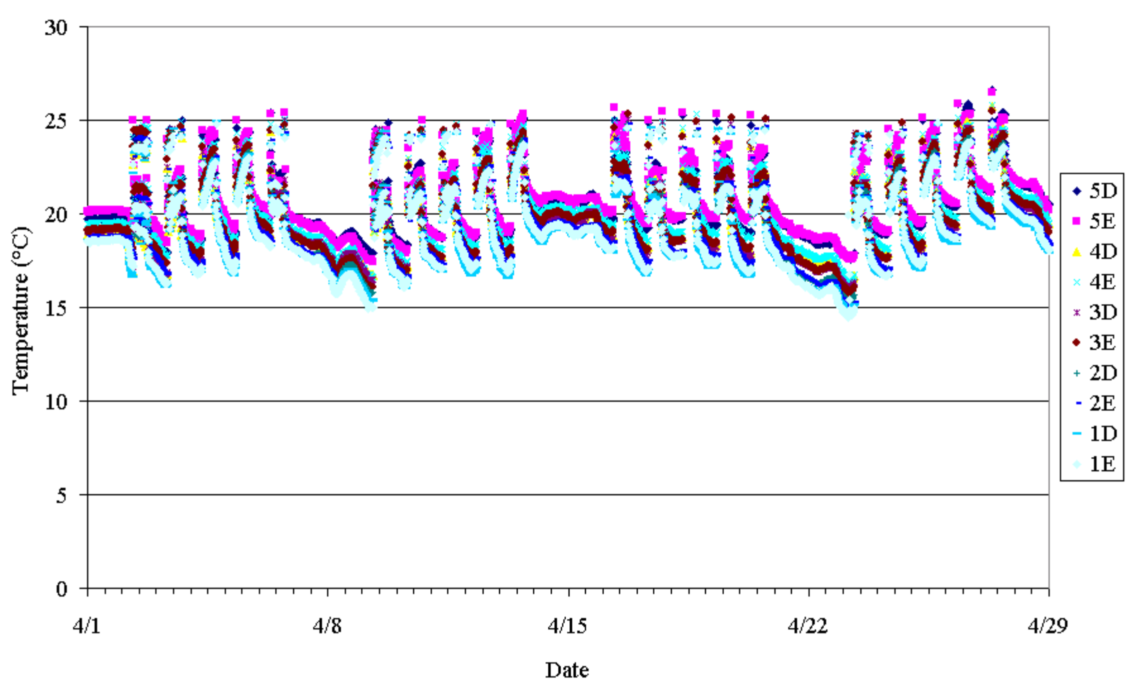


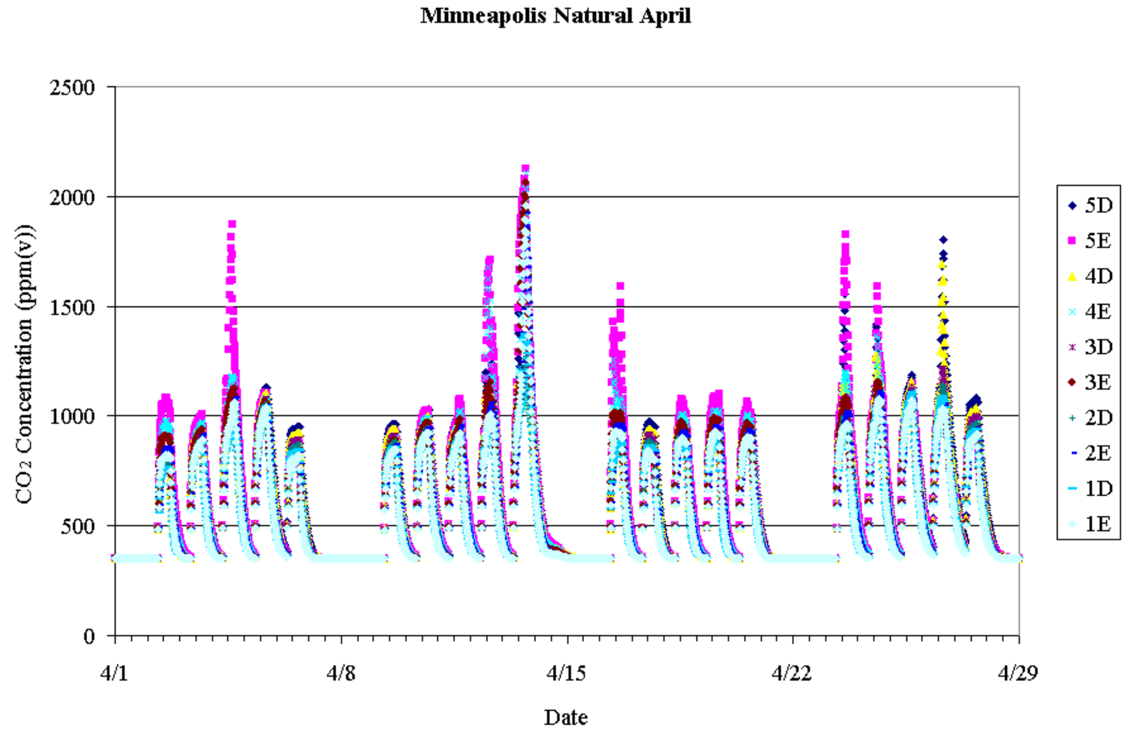
Minneapolis Natural February



April

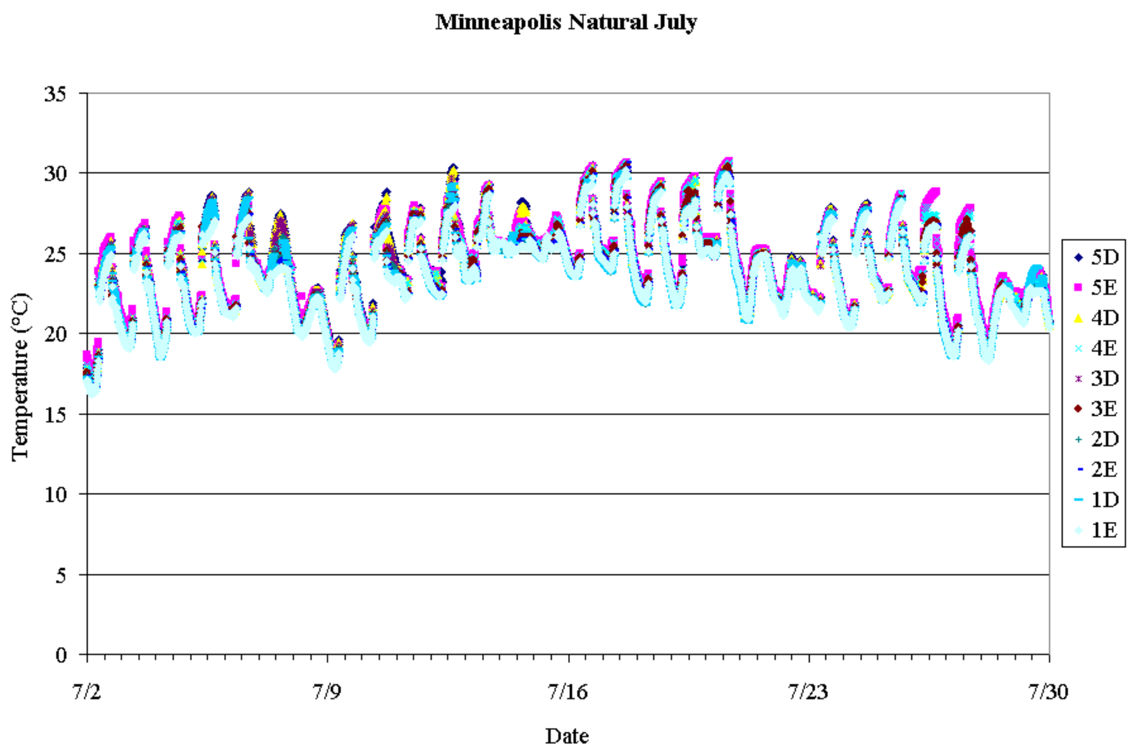
Minneapolis Natural April



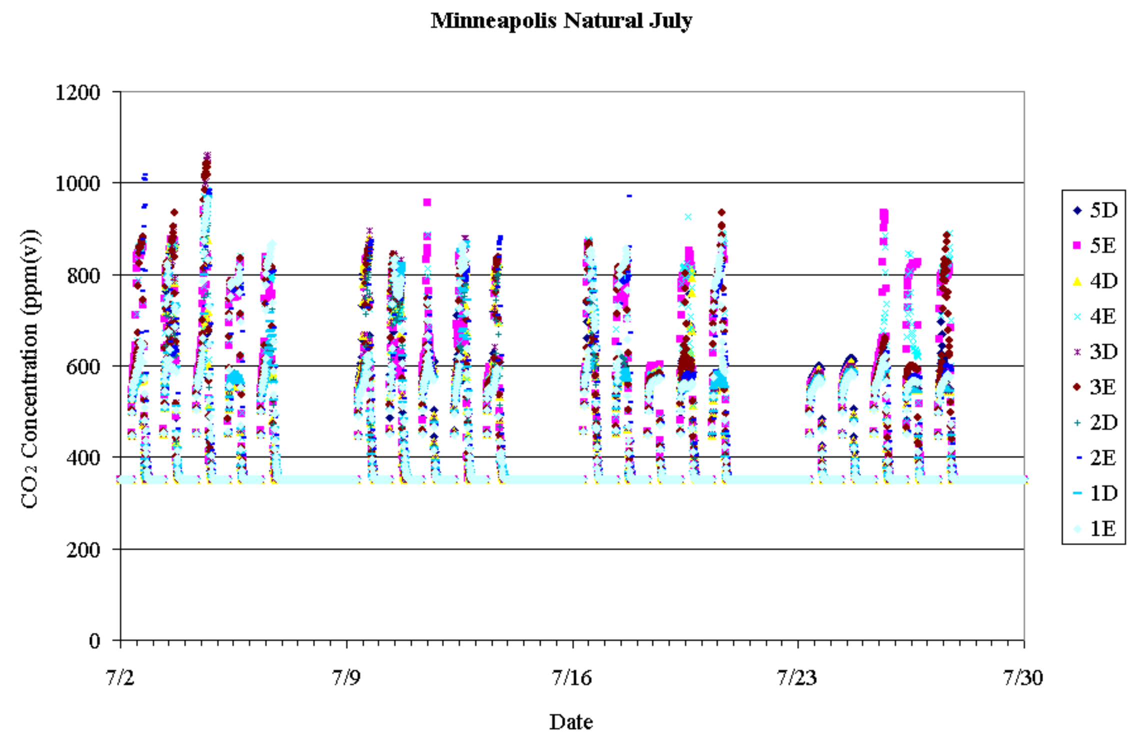


Minneapolis Natural April
2500
2000
1500
1000
500
0
CO2 Concentration (ppm(v))
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July

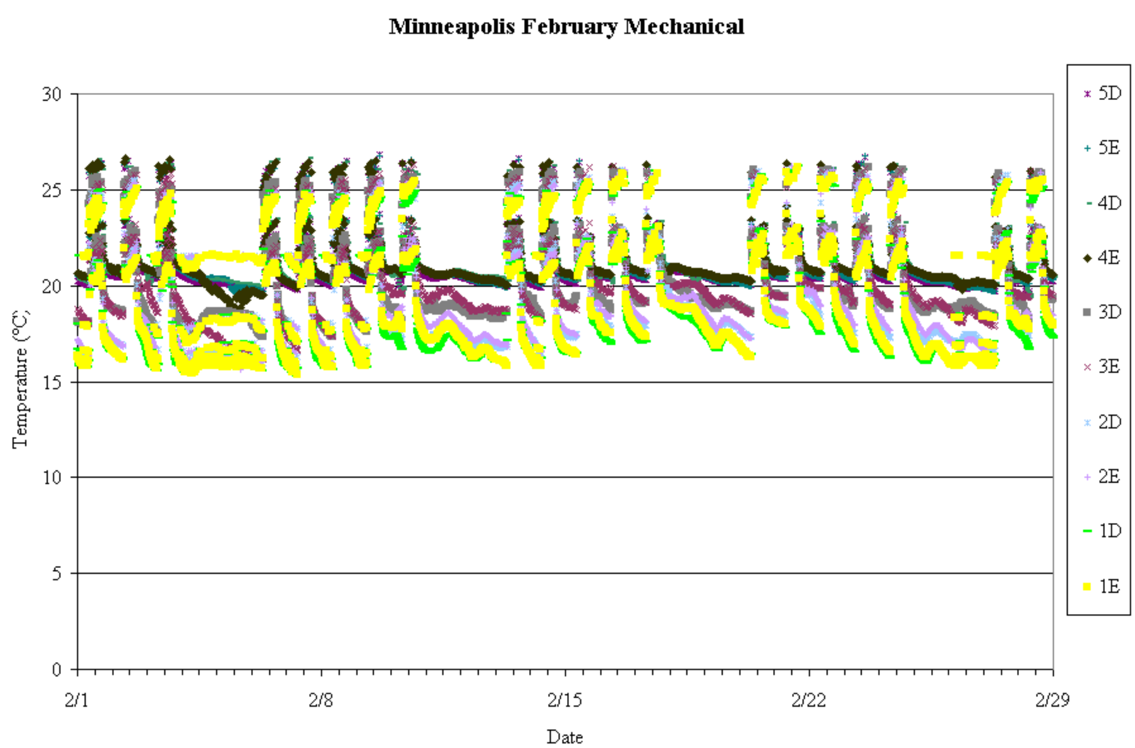


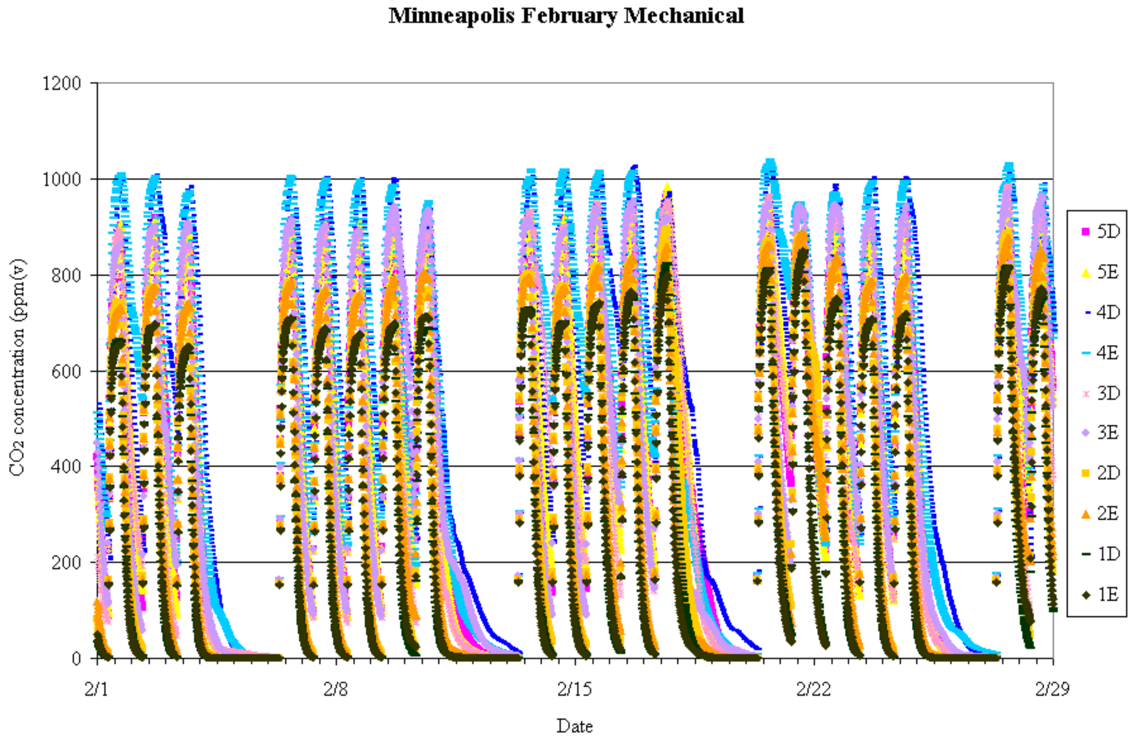
Minneapolis Natural July
35
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



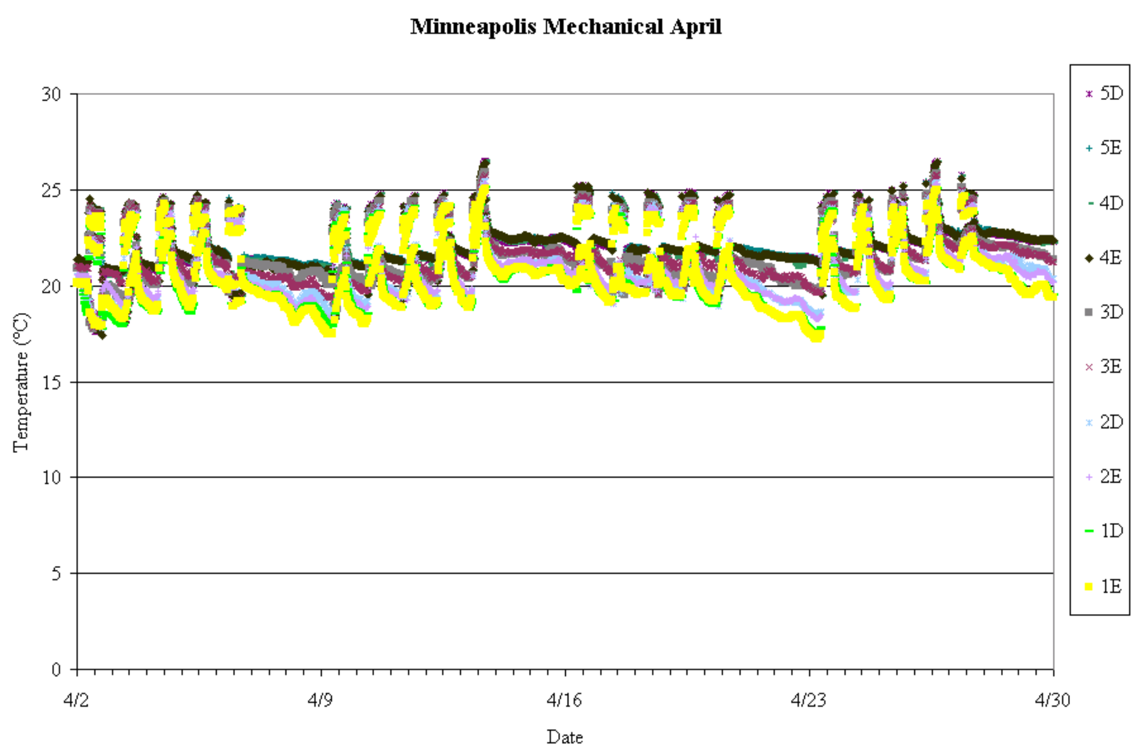
Mechanical Ventilation System

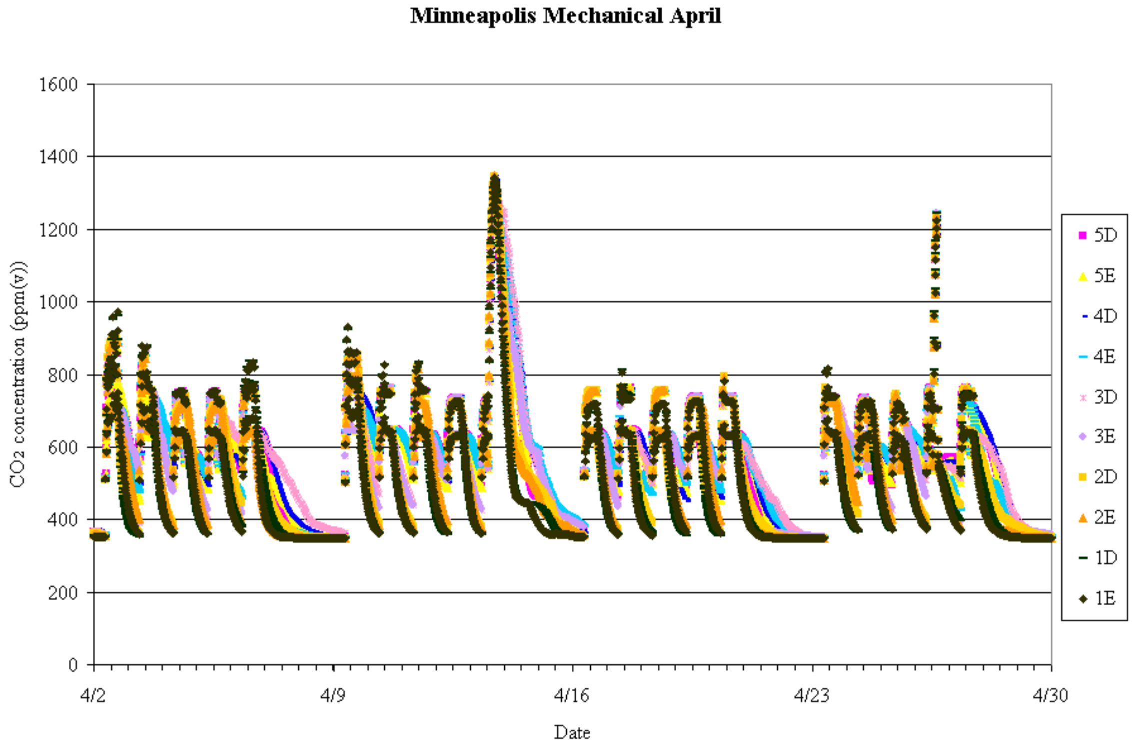
February



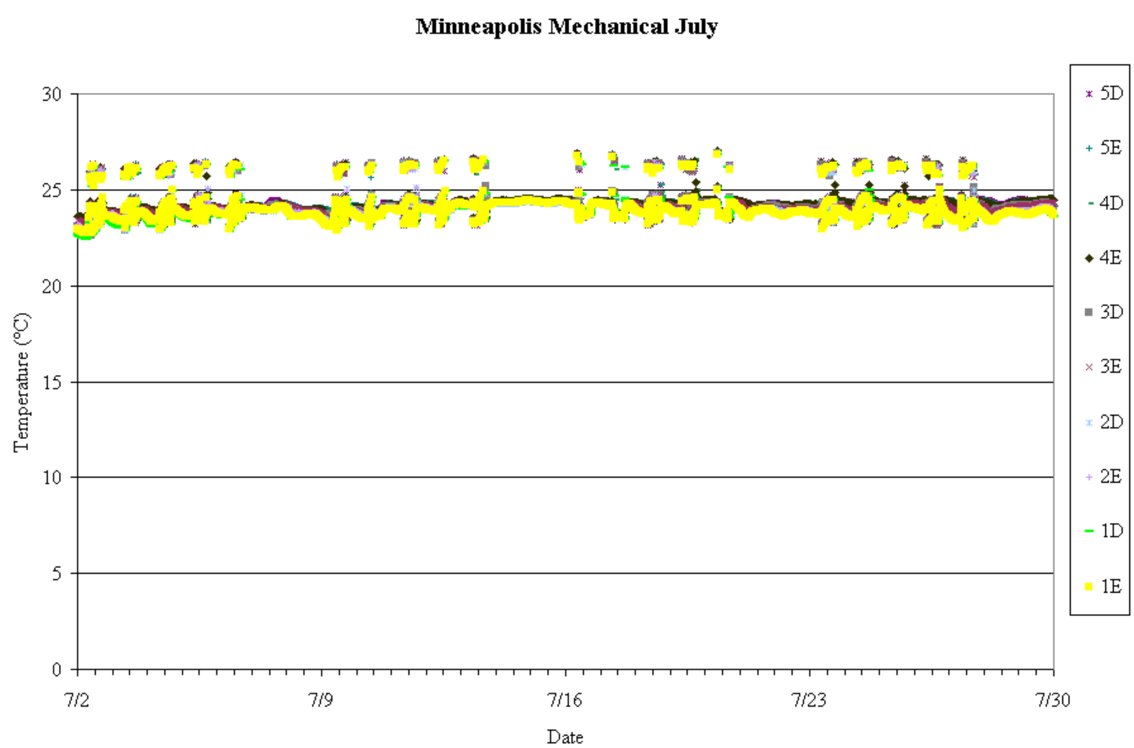

Minneapolis February Mechanical
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v)
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

April

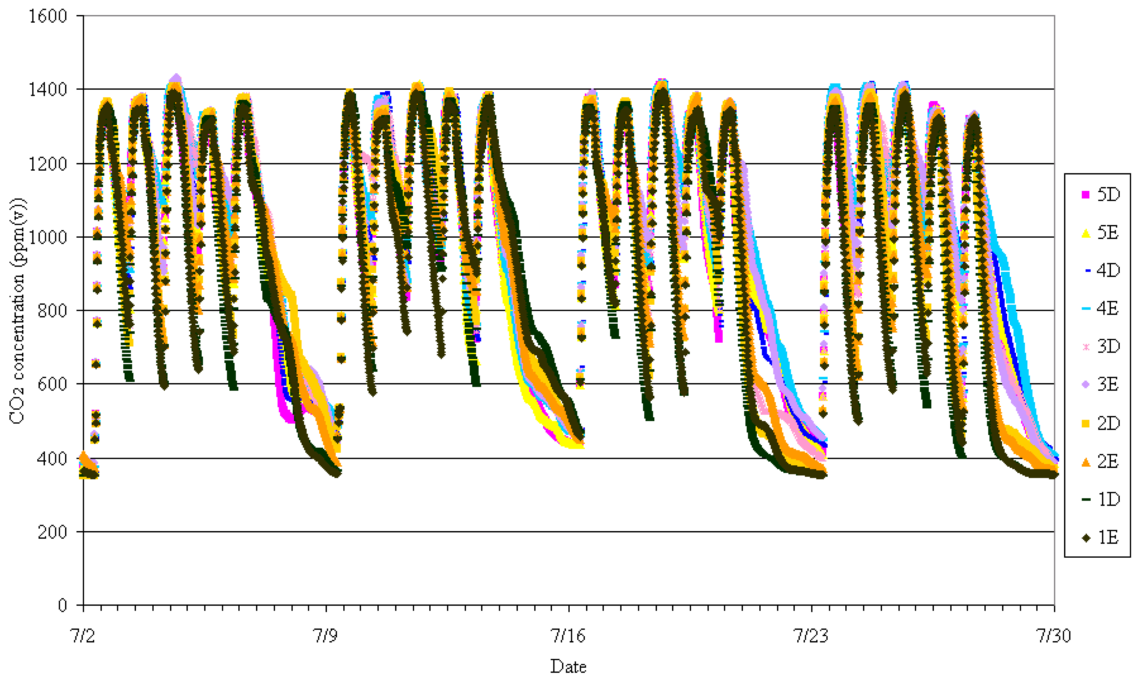

Minneapolis Mechanical April
30
25
20
15
10
5
0
Temperature (°C)
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Minneapolis Mechanical April
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July


Minneapolis Mechanical July
30
25
20
15
10
5
0
Temperature (ºC)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

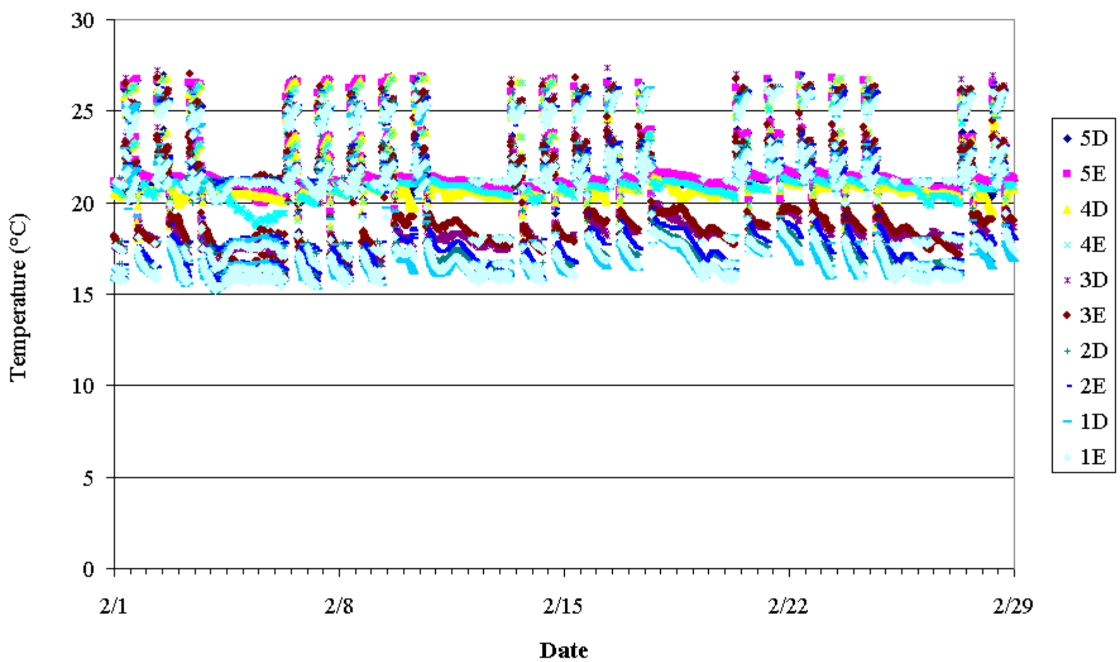
Minneapolis Mechanical July

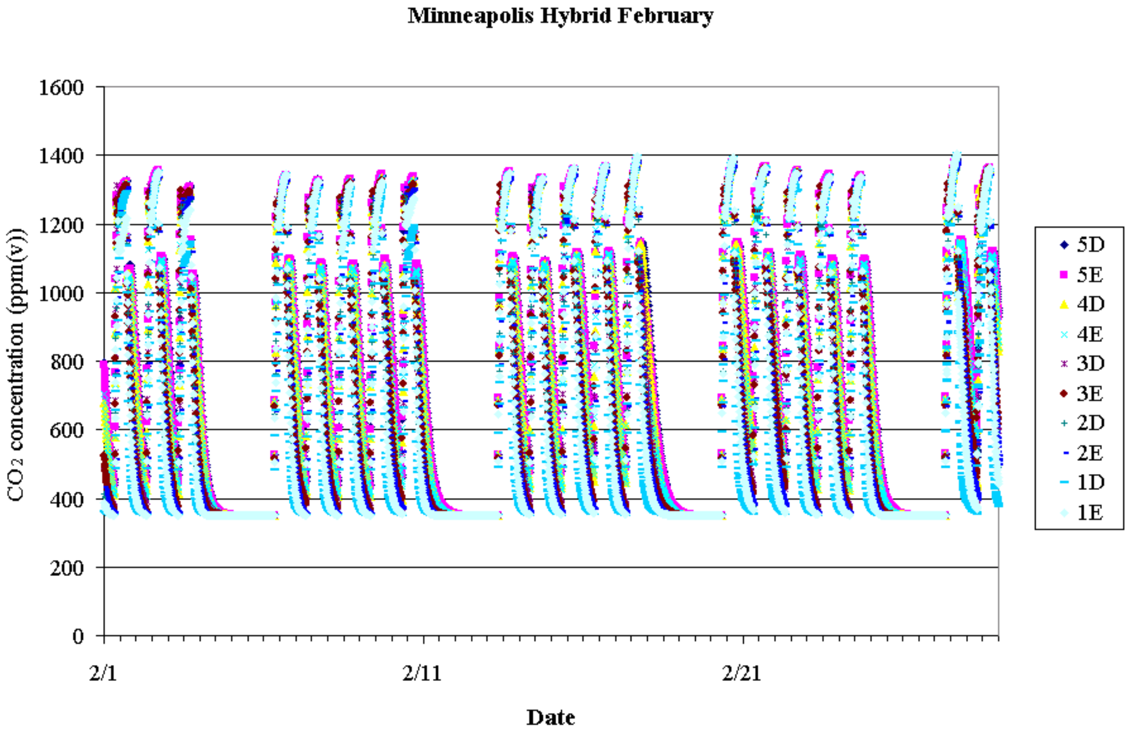


Hybrid Ventilation System

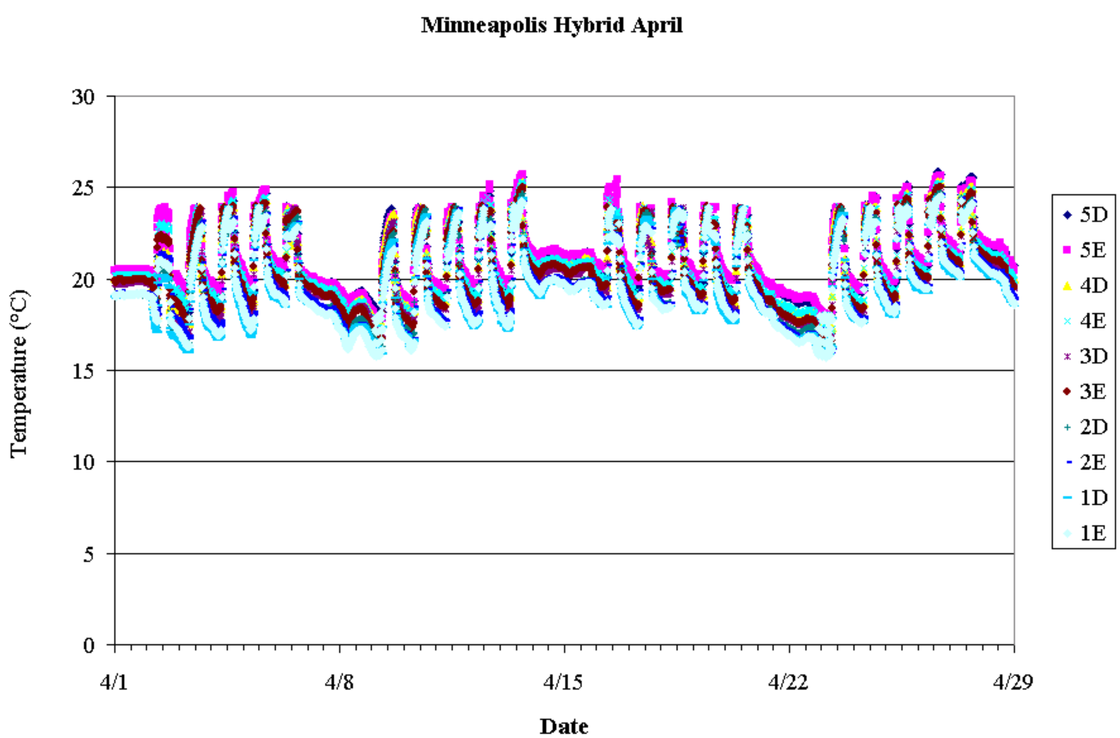
February

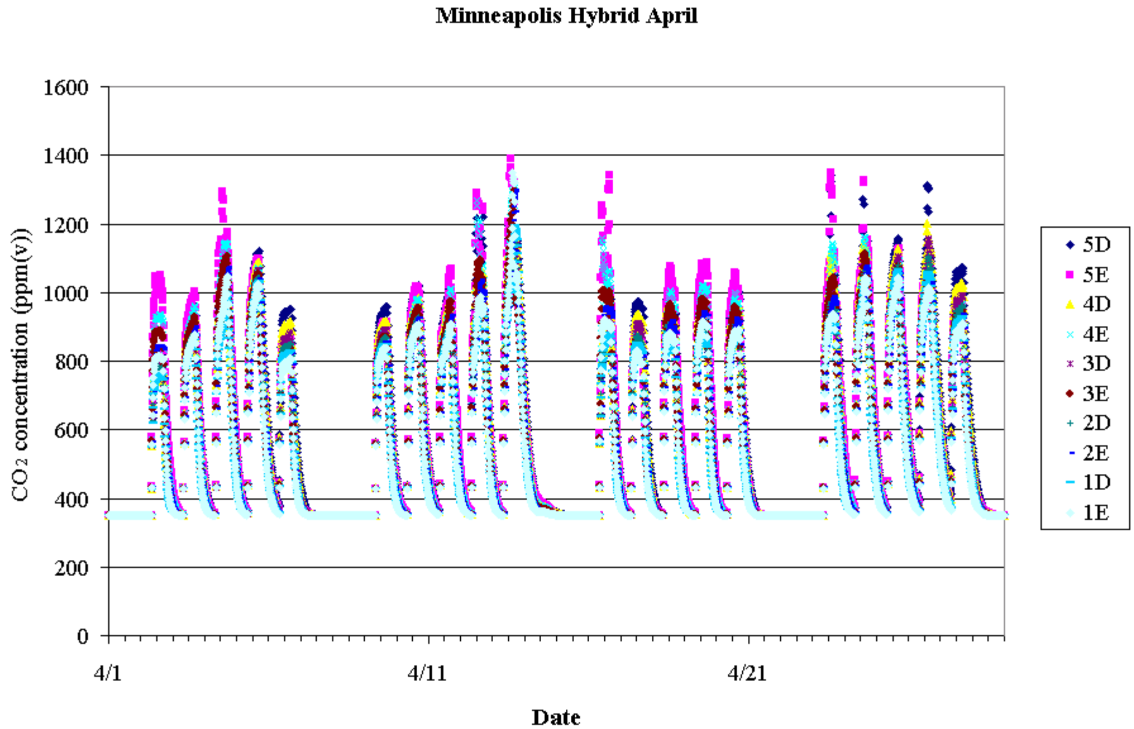
Minneapolis Hybrid February




Minneapolis Hybrid February
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
2/1
2/11
2/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

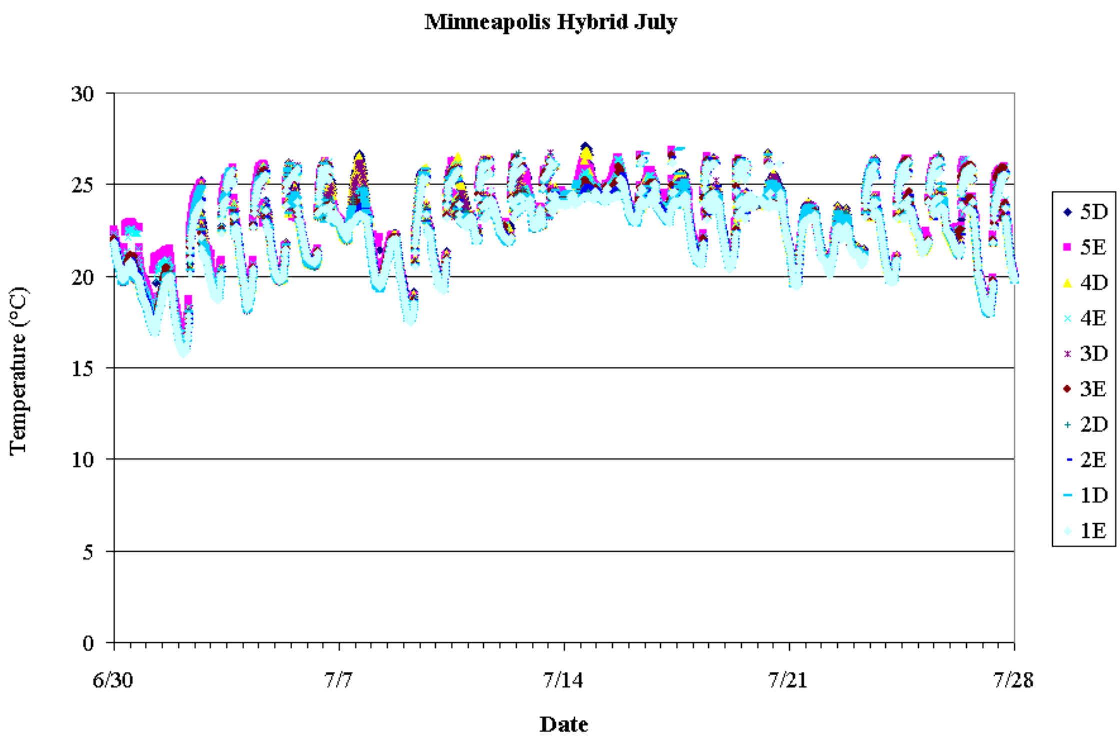
April


Minneapolis Hybrid April
30
25
20
15
10
5
0
Temperature (°C)
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

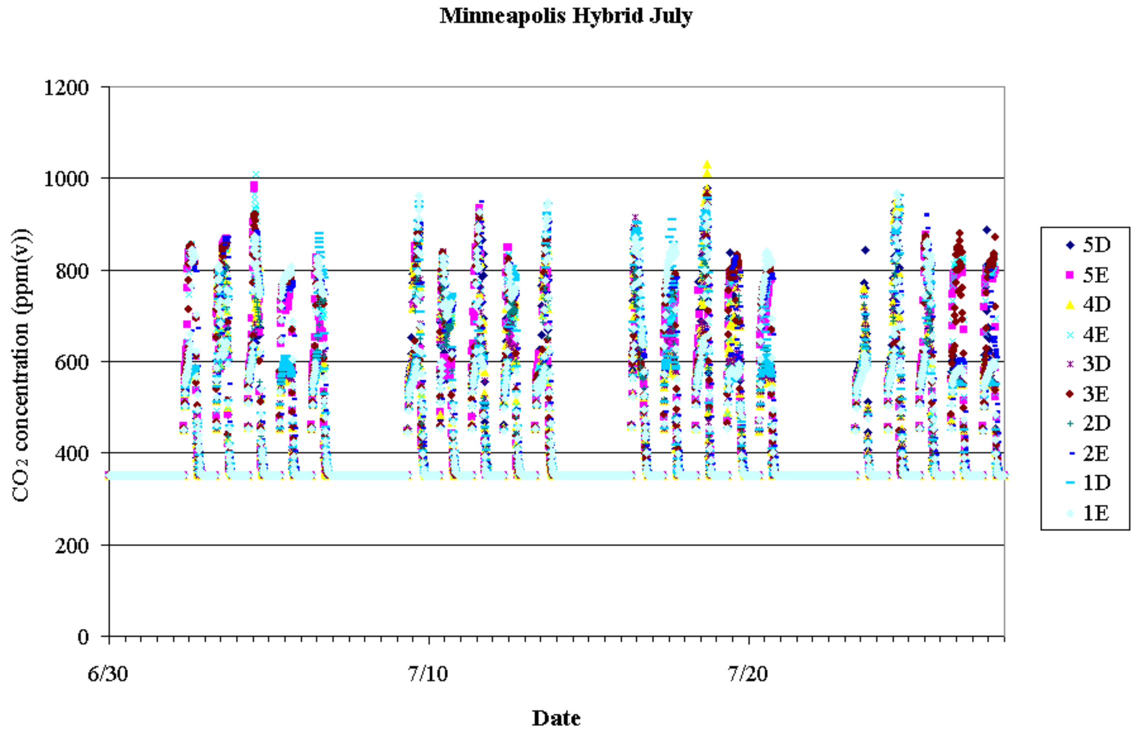


Minneapolis Hybrid April
CO2 concentration (ppm(v))
1600
1400
1200
1000
800
600
400
200
0
4/1
4/11
4/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July



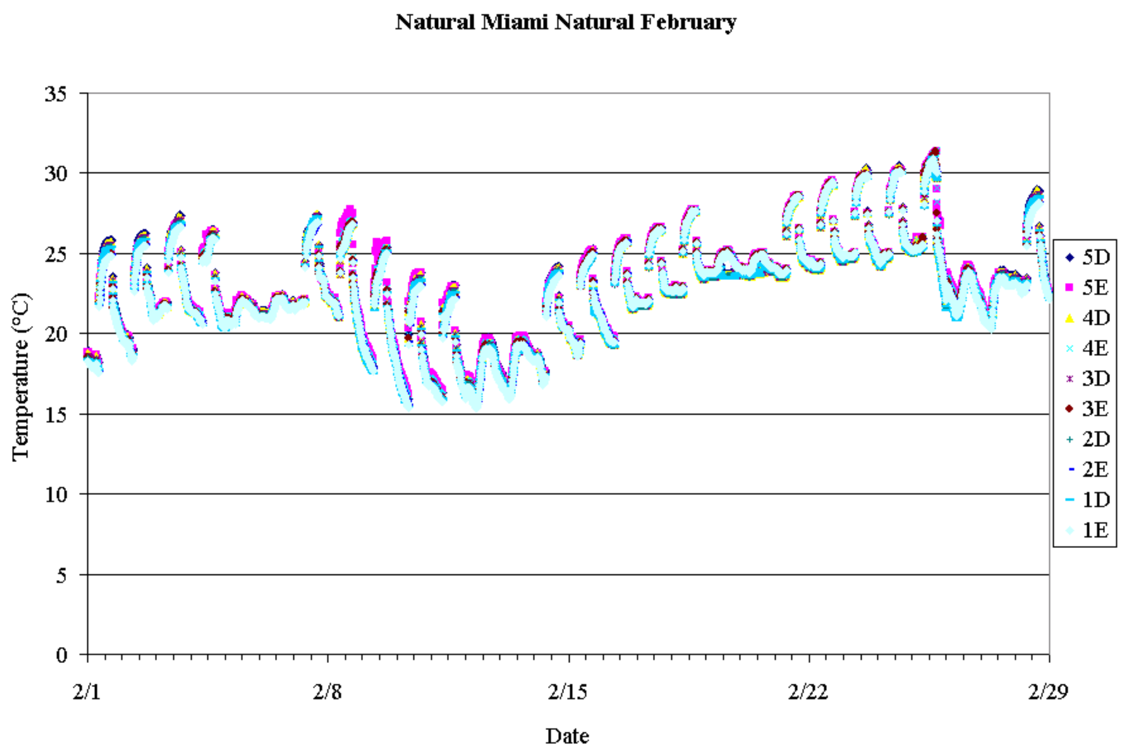
Minneapolis Hybrid July
Temperature (°C)
30
25
20
15
10
5
0
6/30
7/7
7/14
7/21
7/28
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

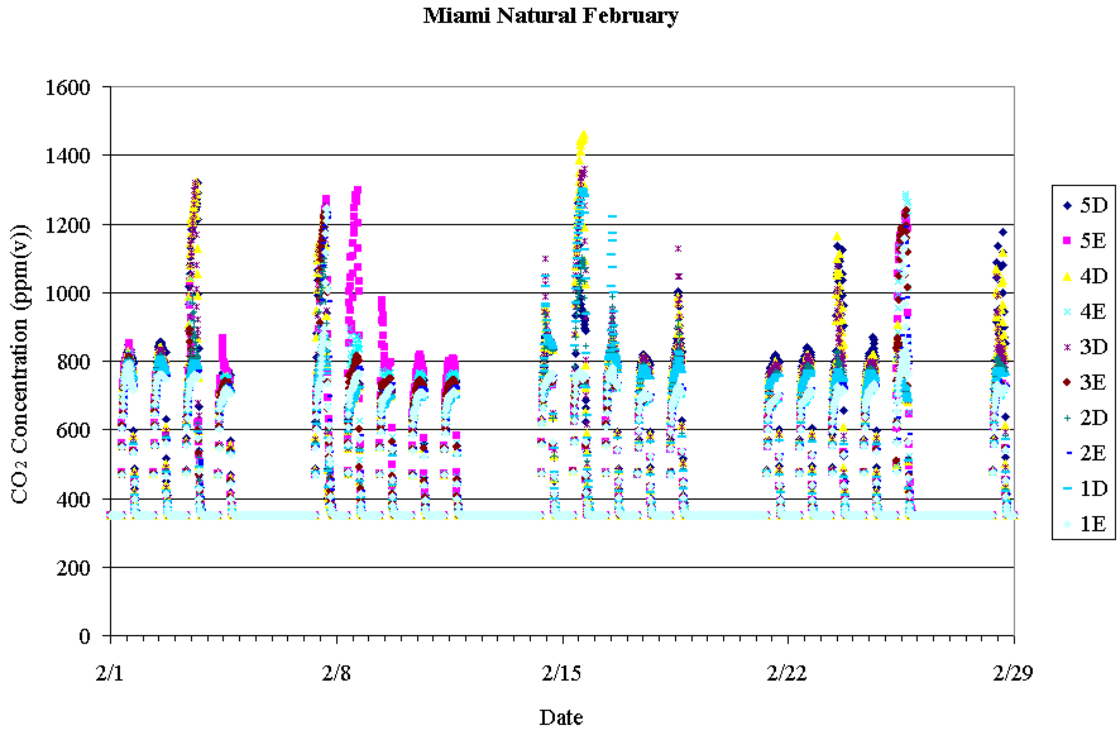


Miami

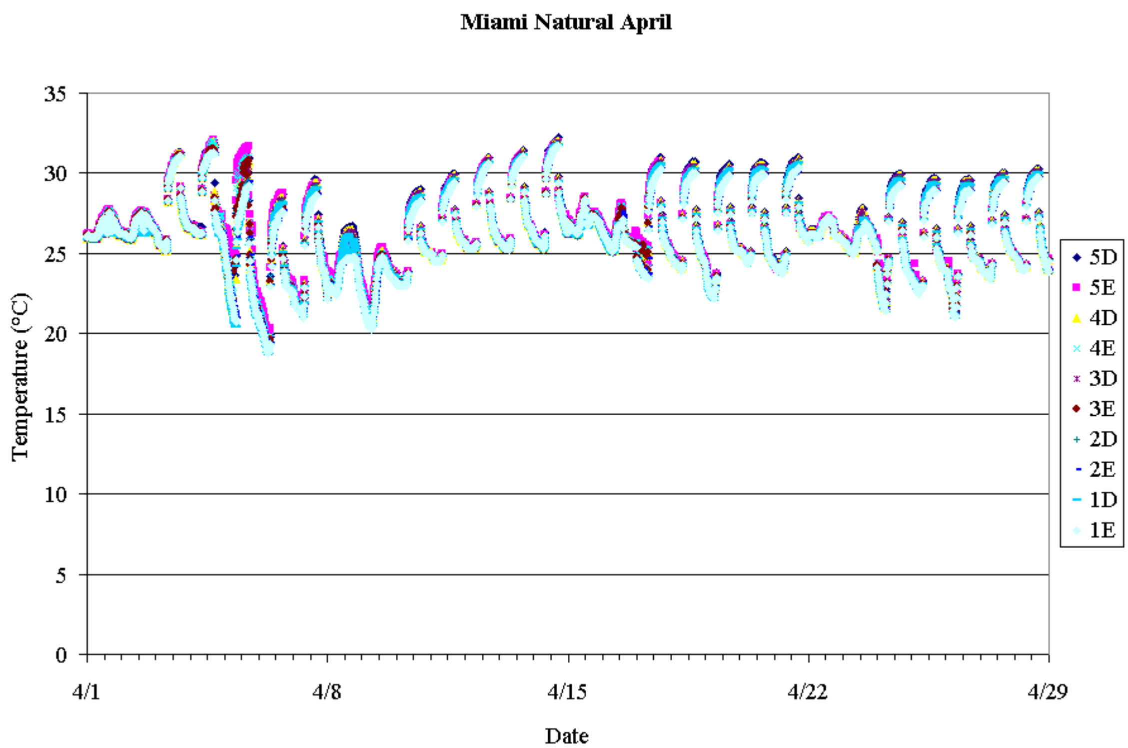
Natural Ventilation System

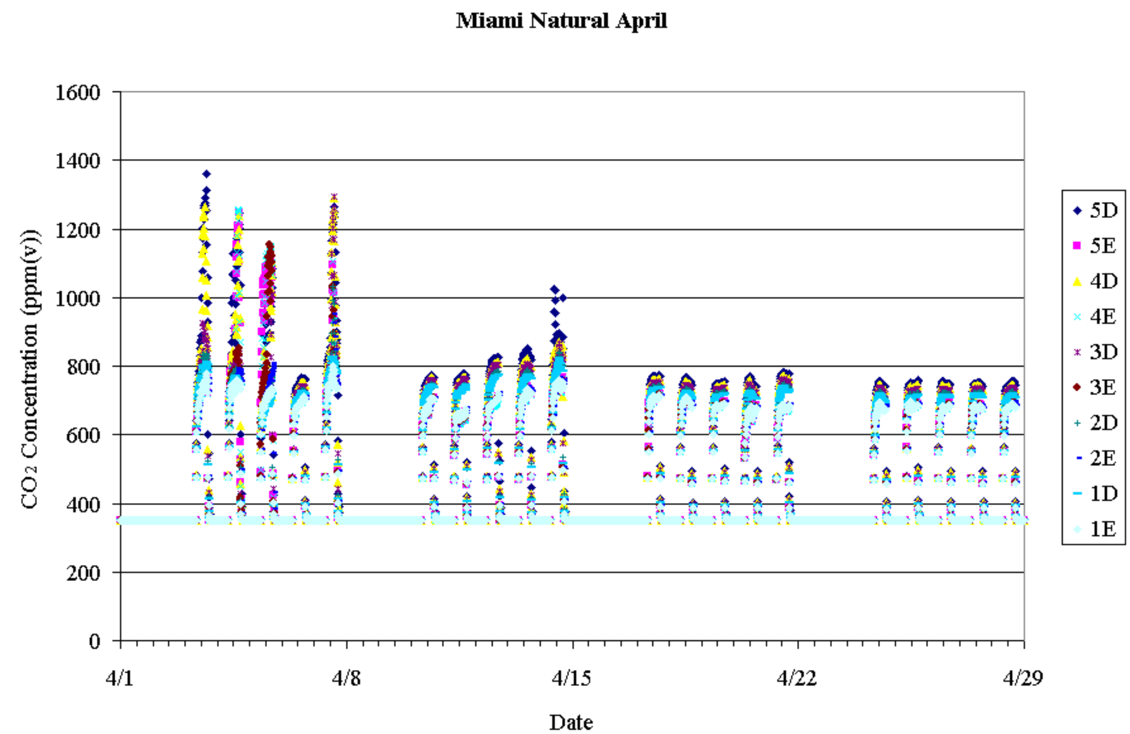
February




Miami Natural February
1600
1400
1200
1000
800
600
400
200
0
CO2 Concentration (ppm(v))
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

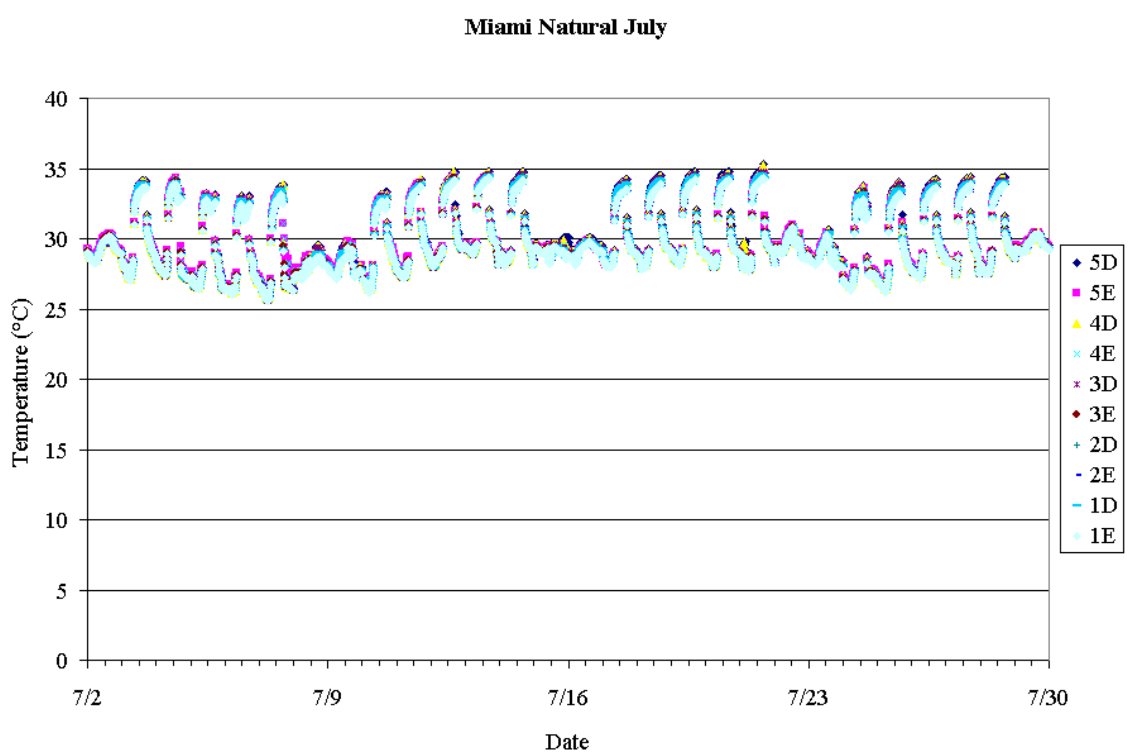
April


Miami Natural April
35
30
25
20
15
10
5
0
Temperature (°C)
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

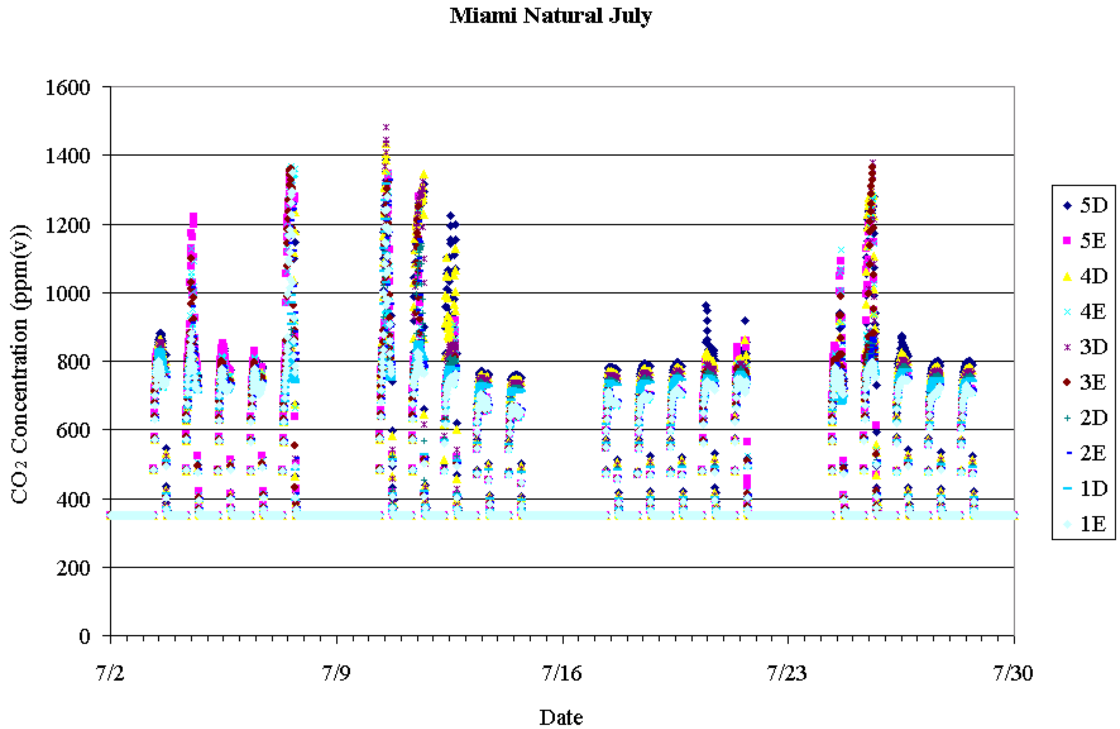


Miami Natural April
1600
1400
1200
1000
800
600
400
200
0
CO2 Concentration (ppm(v))
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July

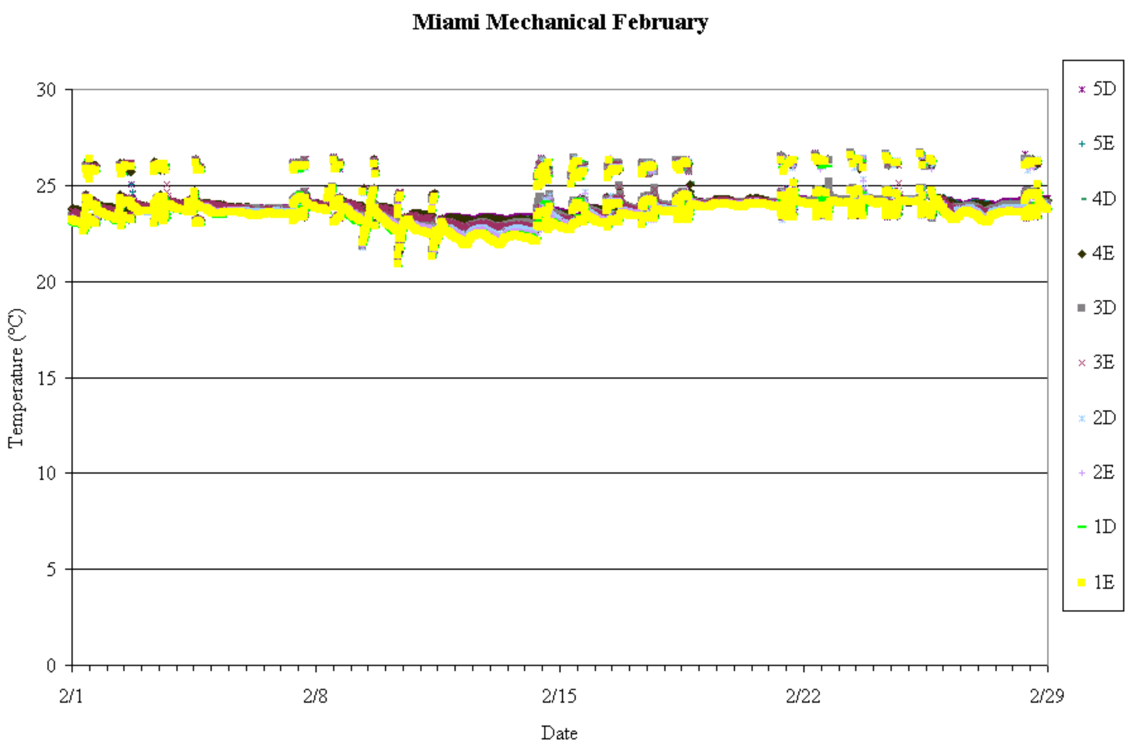


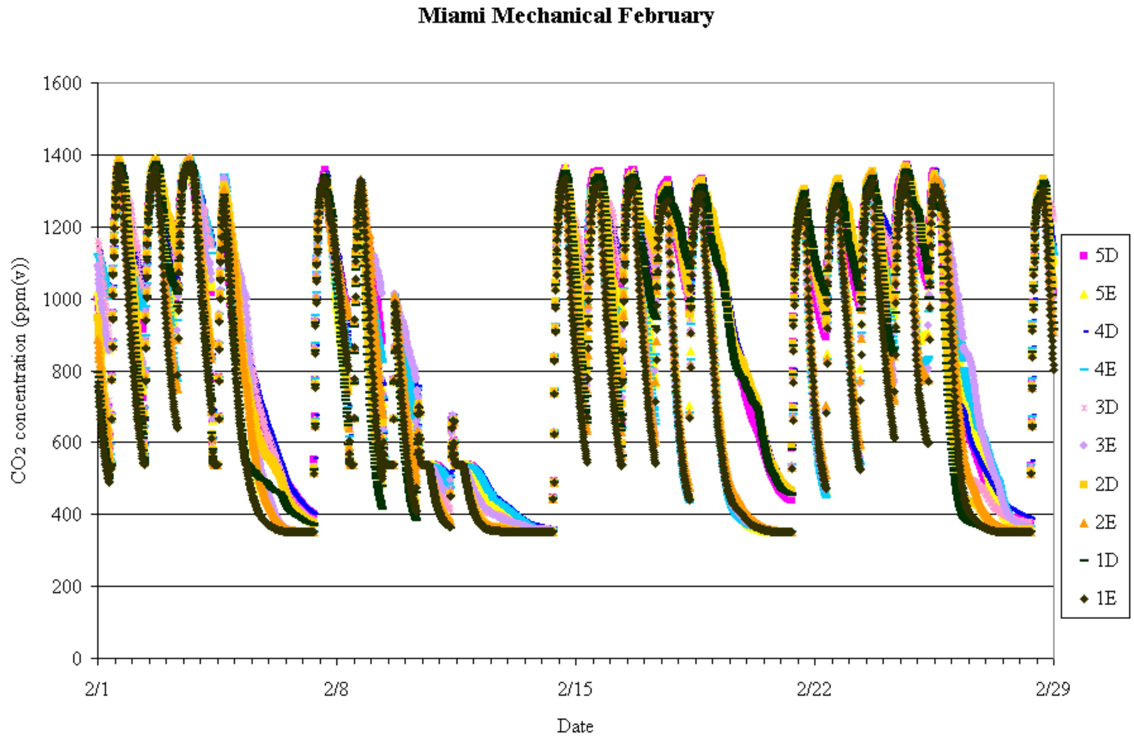
Miami Natural July
40
35
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



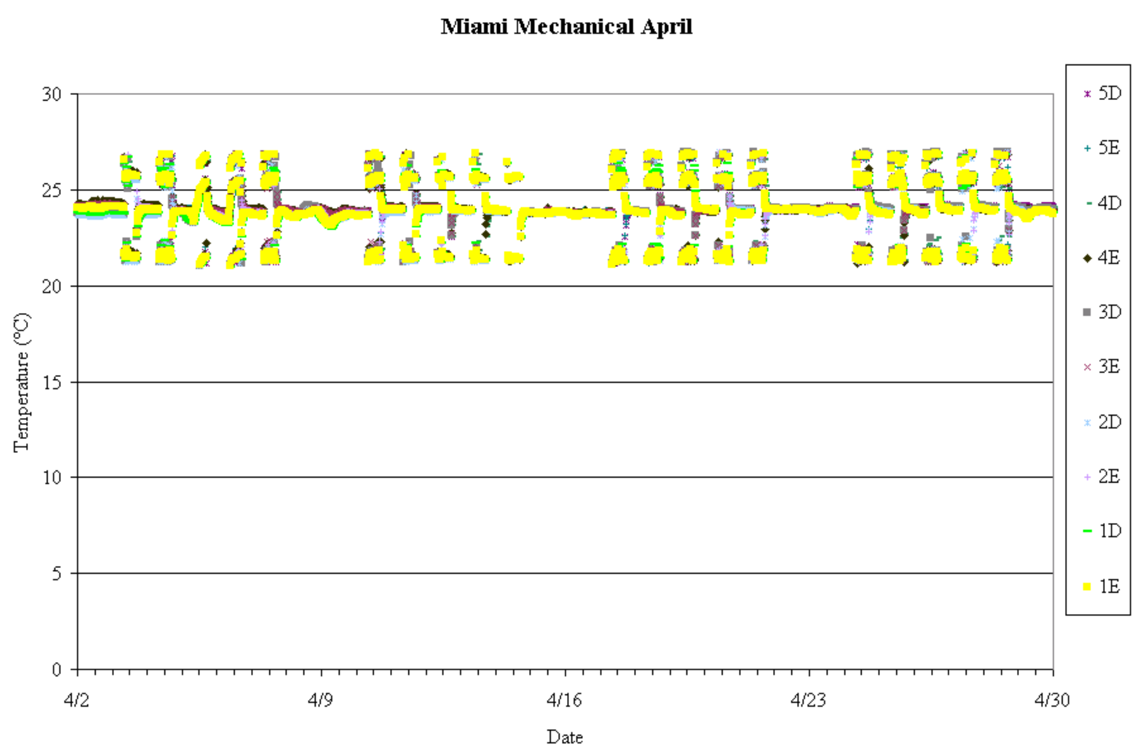
Mechanical Ventilation System

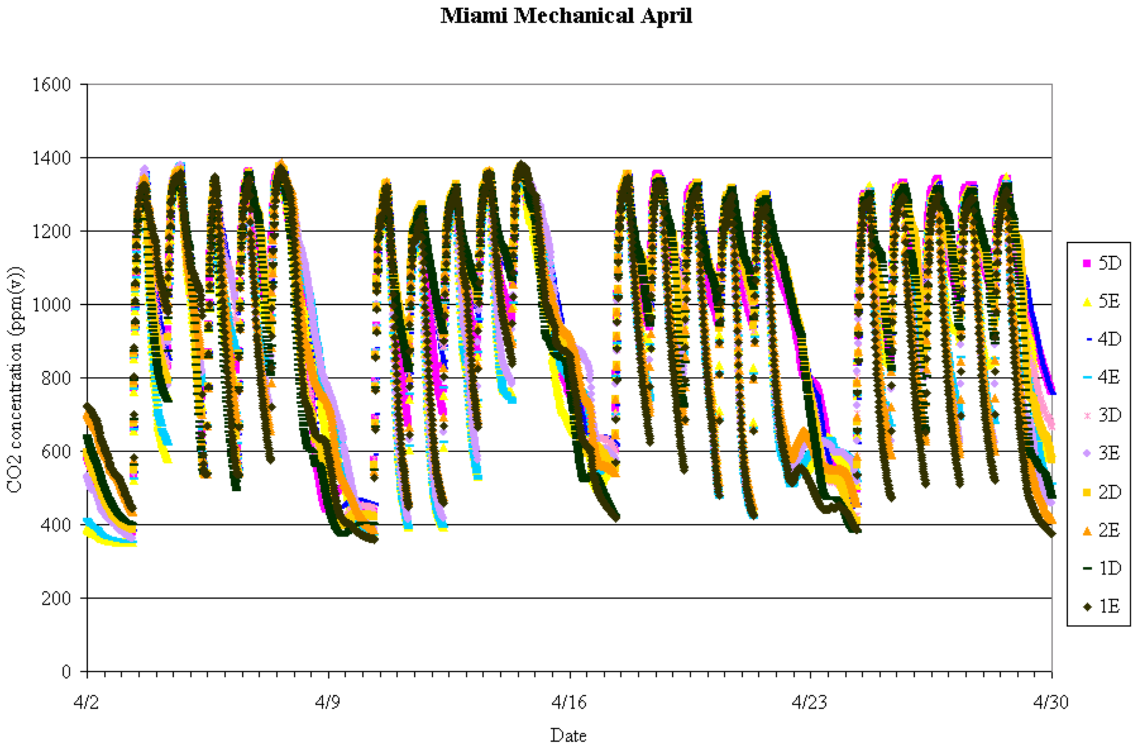
February



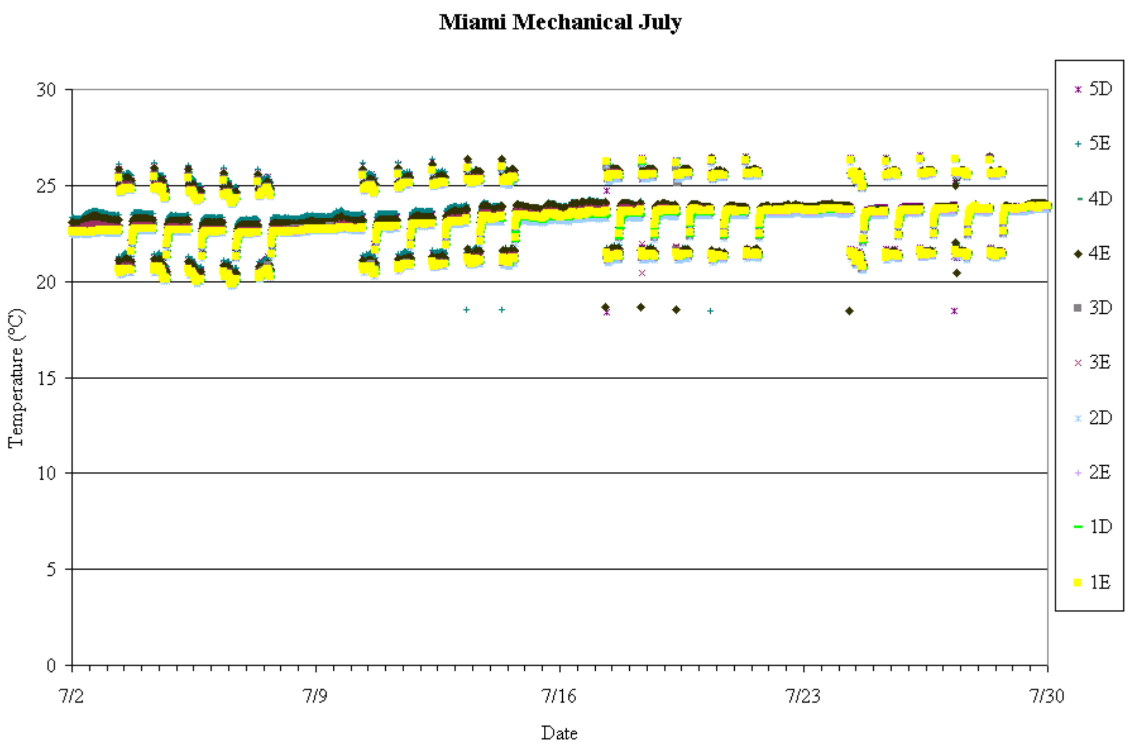

Miami Mechanical February
CO2 concentration (ppm(v))
1600
1400
1200
1000
800
600
400
200
0
2/1
2/8
2/15
2/22
2/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

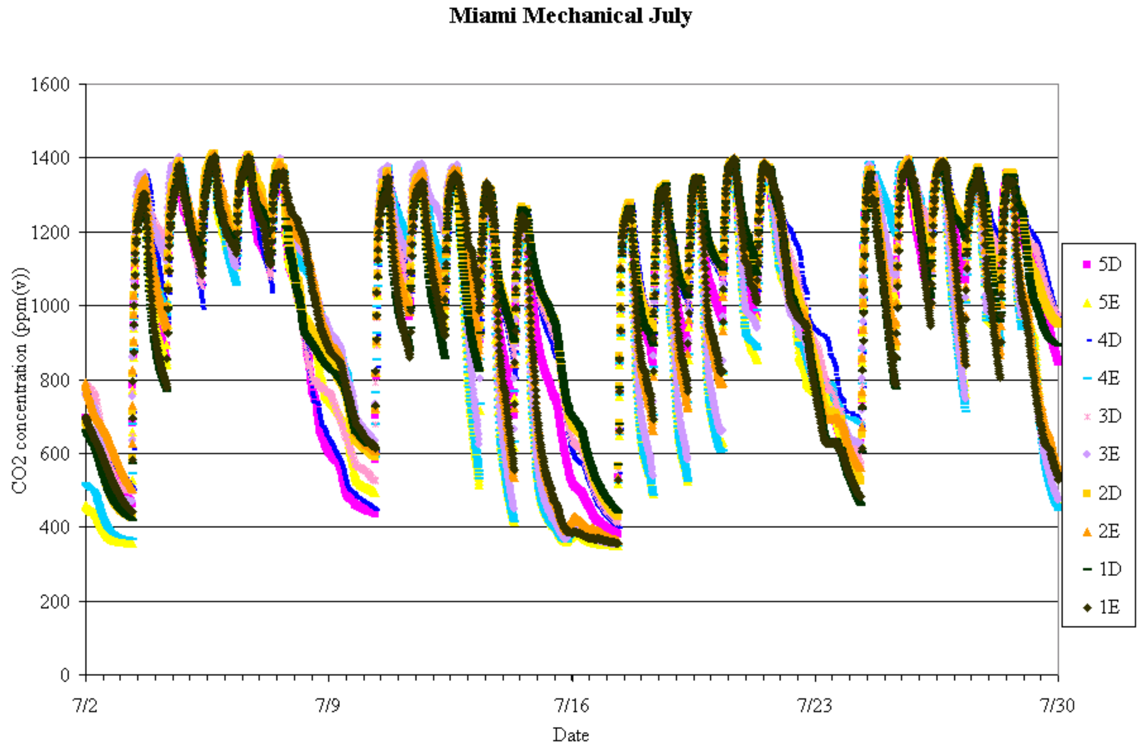
April


Miami Mechanical April
Temperature (ºC)
30
25
20
15
10
5
0
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Miami Mechanical April
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
4/2
4/9
4/16
4/23
4/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

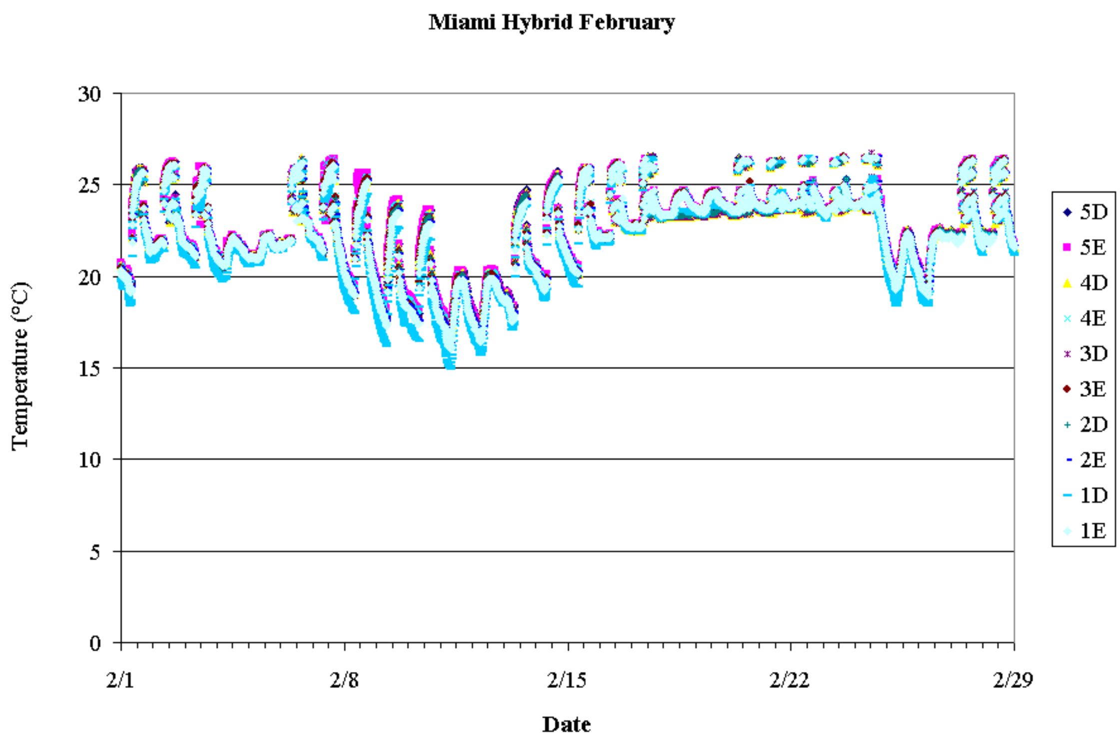
July

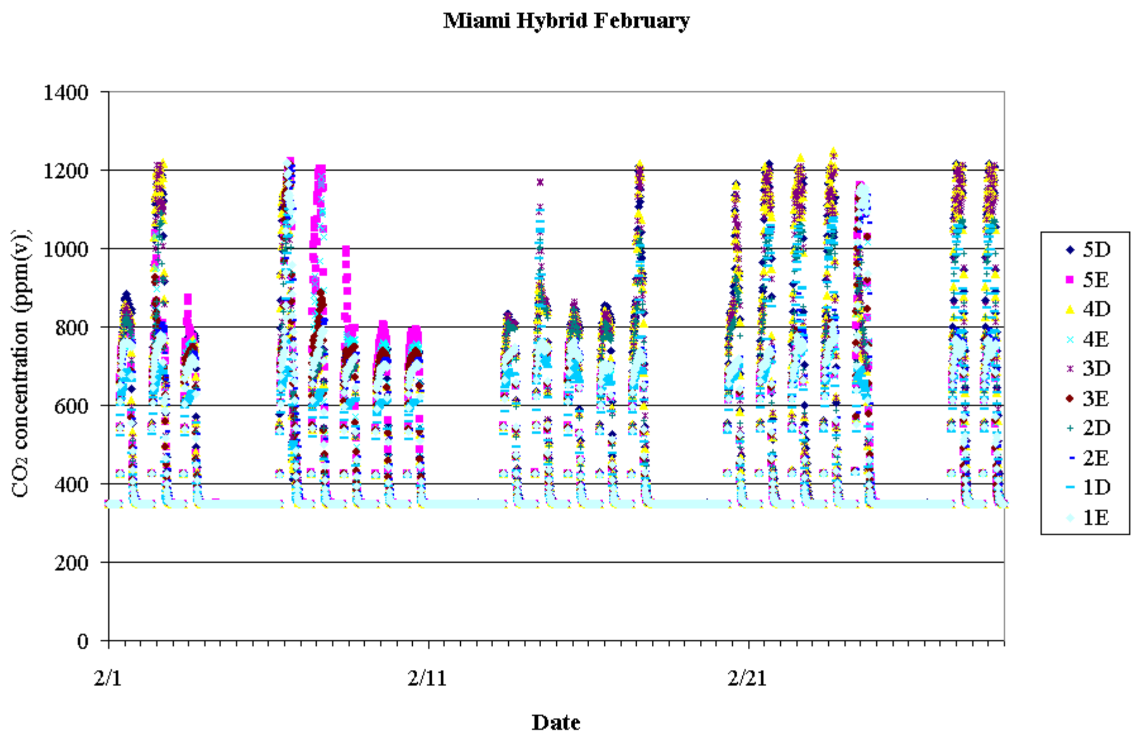

Miami Mechanical July
30
25
20
15
10
5
0
Temperature (°C)
7/2
7/9
7/16
7/23
7/30
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E



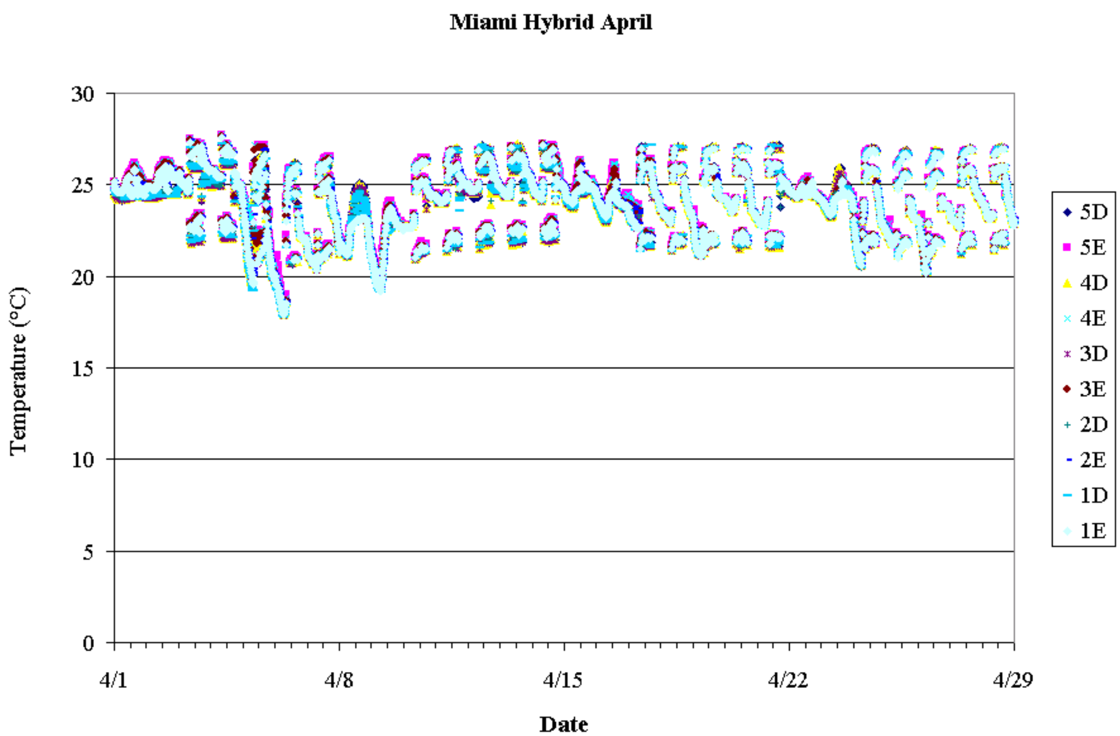
Hybrid Ventilation System

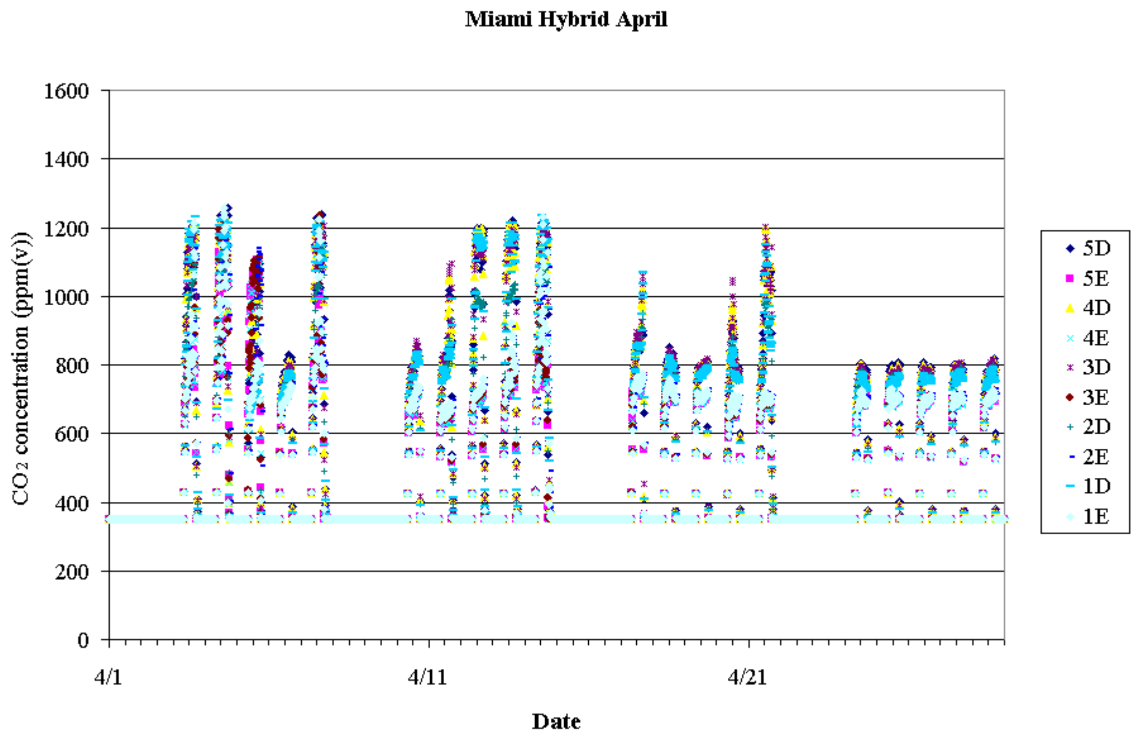
February



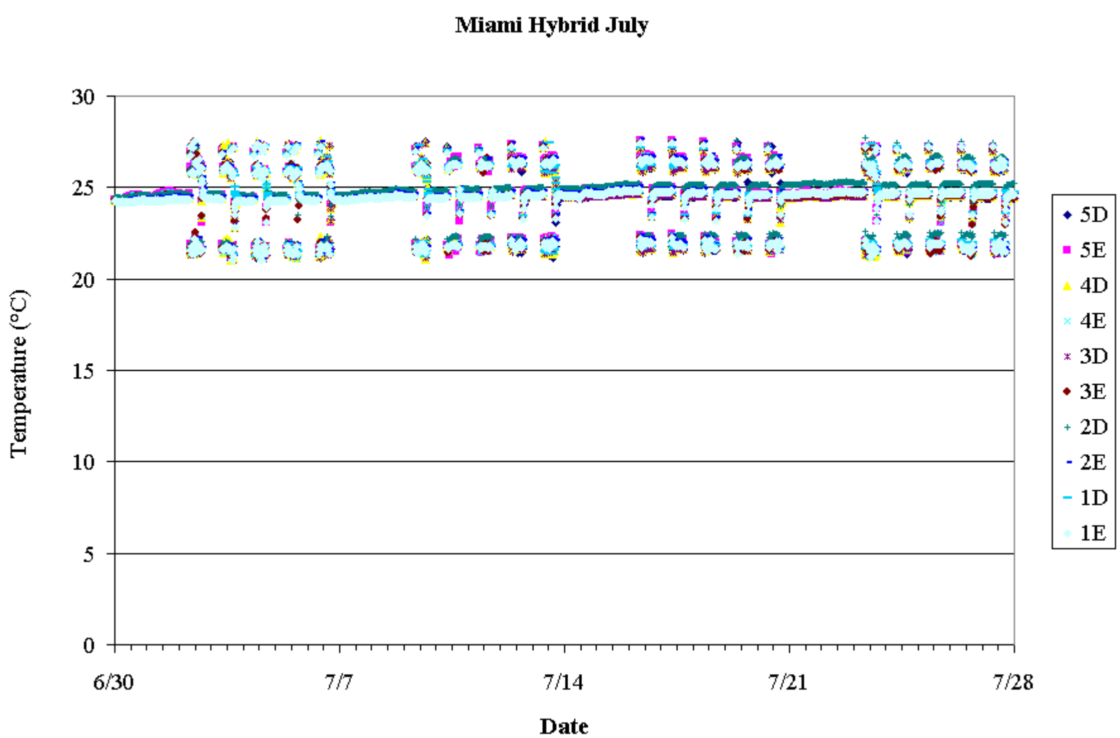

Miami Hybrid February
1400
1200
1000
800
600
400
200
0
CO_2 concentration (ppm(v))
2/1
2/11
2/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

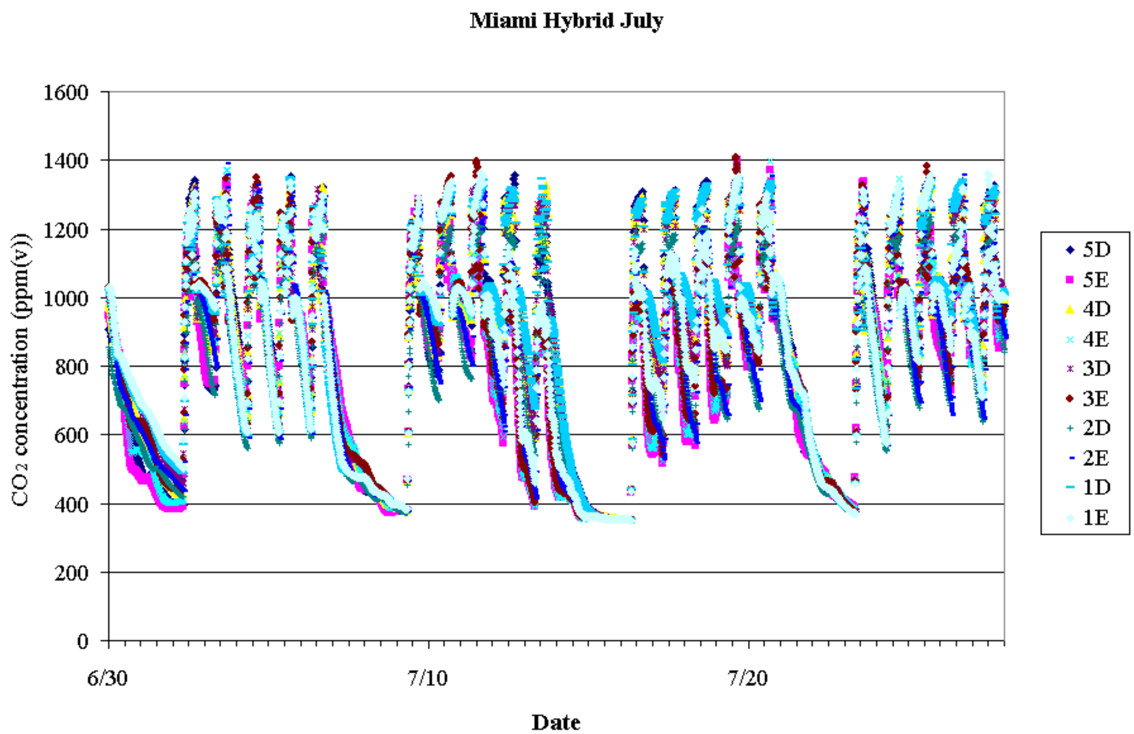
April


Miami Hybrid April
30
25
20
15
10
5
0
Temperature (°C)
4/1
4/8
4/15
4/22
4/29
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Miami Hybrid April
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
4/1
4/11
4/21
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E

July


Miami Hybrid July
30
25
20
15
10
5
0
Temperature (°C)
6/30
7/7
7/14
7/21
7/28
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E


Miami Hybrid July
1600
1400
1200
1000
800
600
400
200
0
CO2 concentration (ppm(v))
6/30
7/10
7/20
Date
5D
5E
4D
4E
3D
3E
2D
2E
1D
1E