MONITORED PERFORMANCE OF AN OFFICE BUILDING WITH AN UNDER-FLOOR AIR DISTRIBUTION SYSTEM

Christine E. Walker — PhD Research Assistant
Leslie K. Norford — Professor of Building Technology
Massachusetts Institute of Technology, Building Technology Program
Cambridge, MA 02139

ABSTRACT

This paper documents the long-term detailed monitoring, short-term measurements, and observations in a commercial office building with an under-floor air distribution system (UFAD). The data collected over a 16-month period were used to evaluate the whole building performance, with a focus on the ventilation system, and were compared to existing building energy standards. The performance of the heating, ventilation, and air-conditioning equipment was assessed and energy and ventilation improvements suggested. The building was found to fall within good practice and standard practice for energy usage in air-conditioned commercial office buildings for the United Kingdom.

INTRODUCTION

Underfloor air distribution systems (UFAD) have been growing in popularity, particularly in commercial office buildings. These systems introduce fresh air into the occupied space from an underfloor plenum, forcing old air out through ceiling plenums. This type of ventilation system has the potential ability to improve occupant comfort, improve the indoor environment and reduce energy usage if engineered and installed properly (Bauman, 2001). A UFAD also provides flexibility for office configurations by having all of the heating, ventilation, and air-conditioning (HVAC) equipment, voice and data outlets, and power outlets in the underfloor plenum. These spaces remain readily accessible through the use of floor panels to adjust the location of floor diffusers and for maintenance. UFAD systems do not promote lateral mixing, thereby isolating pollutants, and result in a stratified thermal environment that provides fresh air at the occupied level, removing old, stale air at the ceiling level. This provides a good indoor environment for occupants.

This provides a substantial benefit over the typical ducted HVAC system, which takes up valuable space, is not easily reconfigured, and provides a well-mixed environment. However, if not installed or designed properly, these systems can use as much or more energy than a conventional HVAC system. The results of long-term monitoring and short-term measurements in a commercial office building with a UFAD are presented along with the performance of this ventilation system type. Additionally, suggestions for improved operation and pitfalls to avoid are discussed.

Building Description

Located at Sunbury-on-Thames, approximately twenty miles southwest of London, the building was the first of several new office buildings, completed as part of the redevelopment of an office park. The building has three occupied floors that all open onto a central atrium, which runs the entire length of the building. The net internal floor area for the building is 5,100 square meters (54,900 square feet). The atrium level is raised an additional 2.5 meters (8.2 feet) to accommodate roof access and a clerestory, allowing natural daylight to penetrate the central core of the building. The mechanical room is located on the roof above the atrium. The façade is nearly 100% glazing, with fixed shading devices installed to reduce solar heat and glare. On the south and west façades, photovoltaics are integrated into the shading device. Each floor of the building has two major zones: north and south, which are separated by the atrium. Throughout this paper, these zones will be referred to as half floor plates, and referenced by orientation (North or South) and floor level (ground, first, and second). A typical floor plan is shown in Figure 1, and a section through the building in Figure 2.

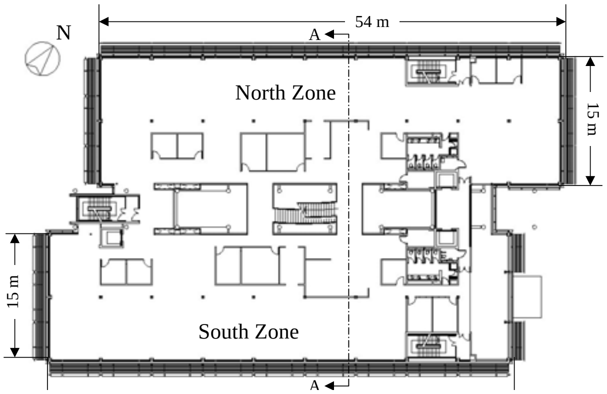

Figure 1. Typical Building Floor Plan

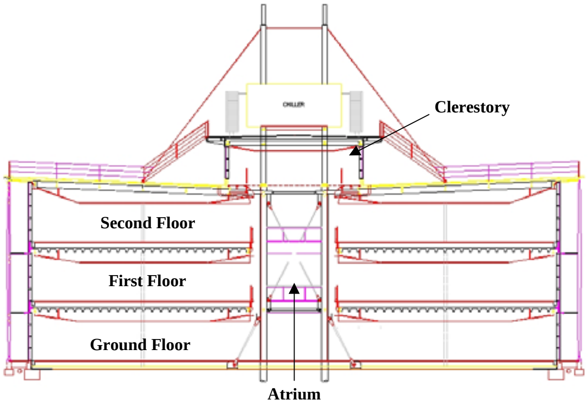

Figure 2. Building Section

The following sections briefly describe the internal loads within the building and HVAC systems that condition the building.

Internal Loads. The building is a standard open floor plan office building. It is occupied five days per week, 52 weeks per year, except for holidays. The internal loads in the building, including lighting, plug loads such as computers, and occupants, contribute to the overall cooling requirements. High efficiency fluorescent lamps are used throughout the building. Each fixture is outfitted with a combination photometric and occupancy sensor and is continuously dimmable from 100 to 10 percent. A small percentage of light fixtures remain on year round for safety reasons. Meeting rooms each have manual switches to operate the lights. Common plug loads found in the building include desktop and laptop computers, monitors, printers, fax machines and desktop task lights. Most of the equipment located in the building had energy saving modes that were in use.

There are approximately 360 occupants in the building, as counted during a site visit in January 2002. The occupant density varies by area, with more people on the second floor and less on the ground and first floor. Most of the occupants arrived between 7 and 9AM, left the building between 11AM and 1PM for lunch, and finished for the day between 5 and 7PM.

HVAC System. The existing building system consists of a UFAD system with chilled ceilings, perimeter chilled beams, and perimeter trench heaters. Fairly complex chilled and hot water loops are used to add and remove heat to these components. The building air system consists of two air handling units that deliver fresh air through two independent supply risers. The supply risers deliver the air to all six supply plenums serving the six half-floor plates. Air is exhausted through the return plenums to two return risers that exhaust air through the air handling units. The air handling unit is a constant volume system and includes supply and return fans, a preheat coil, economizer, cooling coil, and a reheat coil. In the building, the dampers are controlled such that 100% outdoor air is used from 8AM until 7PM, 50% outdoor air from 6–8AM, and 100% return air before 6AM and after 7PM. The entire mechanical system is off during the night and weekends. Electrical monitoring showed that the building system was generally turning on at 4AM and off at 7PM. on weekdays.

Upon leaving the air handling unit the air is distributed to six supply plenums, one for each half-floor plate. The air in the supply plenum enters the space at 18°C through numerous circular floor diffusers. The air leaves the space and enters the return plenums through the ceiling-mounted ventilated light fixtures. The supply flow rate for the entire system and each zone is constant. One hundred percent outside air is conditioned and supplied to the occupied space during occupied hours, then exhausted outside.

The entire ceiling of the central zone of each half-floor plate is composed of chilled ceiling panels. The chilled ceiling consists of metal chilled water tubing bonded to a thin metal panel. The back side of the ceiling panel is lined with insulation. The chilled ceiling control is based on the zone mean air temperature. The control varies the flow rate linearly from zero flow at 24.5°C (76.1°F) to the maximum flow rate at 25.5°C (77.9°F). This corresponds to a 1°C (1.8°F) throttling range centered on 25°C (77°F). Flow to the panel is turned on if the proportional-integral temperature error exceeds some set value.

In the perimeter zone, the chilled ceiling is replaced with chilled beams, mounted near the ceiling, which have a higher cooling capacity. The chilled beam is essentially a long and narrow finned tube heat exchanger. Hot air rises and passes through the chilled beam, where it is cooled and sinks due to the change in buoyancy. The chilled beams are controlled to maintain a set-point temperature of 25°C (77°F). If the temperature is below 25°C (77°F), there is no flow to the chilled beam. When the temperature reaches 25°C (77°F), the flow through the chilled beam is varied to maintain this set-point. As with the chilled ceilings, the flow to the beam is turned on if the proportional-integral temperature error exceeds some set value.

The perimeter zones also have trench heaters to overcome heat losses due to window conduction during the winter. The heater is placed in a trench at the base of the window. Air is cooled as it comes in contact with the window and flows downward into the trench. It then rises upwards after it is heated. The trench heaters are controlled to maintain a set-point temperature of 20°C (68°F). If the temperature is above 20°C (68°F), there is no flow to the trench heater. When the temperature falls to 20°C (68°F), the flow through the trench heater is varied to maintain this set-point, using three-way valves.

Plant. The building plant loops consist of the hot water loop, serving the air handler heating coils and trench heaters, and the cold water loop, serving the cooling coil, chilled ceilings, and chilled beams. The only heat source is from the two boilers operating in parallel. From the boiler, water can flow through a bypass, either of the heating coils, or into the secondary loop. The secondary loop is maintained at a lower temperature than the primary loop and is fed with water from the primary loop as necessary to maintain a set temperature. The secondary loop supplies the trench heaters.

The primary hot water loop is maintained at a set-point temperature of 80°C (175°F); the secondary loop in the building has a variable set-point temperature dependent on the outside air temperature. The secondary loop flow rate varies in the building in order to save pumping energy.

The only cooling source is the chiller. From the chiller, water can flow through a bypass or the cooling coil. The warmer water exiting the cooling coil and bypass then flows through either another bypass or through the secondary loop. The secondary loop is maintained at a higher temperature than the primary loop and is fed with water from the primary loop as necessary to maintain a 15°C (59°F) set-point temperature. The secondary loop supplies the chilled ceilings and beams.

As with the hot water loops, both cold water loops operate at constant flow rates. The primary loop is maintained at a set-point temperature of 6°C (11°F) when dehumidification is required; and 10°C (50°F) at other times. The secondary loop flow rate varies in the building in order to save pumping energy. The building uses two 500 kW air-cooled chillers.

METHODOLOGY

The building was evaluated through a combination of long-term monitoring, short-term measurements, and spot measurements and the UFAD system assessed, as described in this section. The building was outfitted with a variety of equipment to best monitor the overall performance of the building, not only in energy usage, but in thermal comfort as well.

Electrical Monitoring. Electrical sub-metering equipment was installed to better understand how much each sub-system contributed to the overall electrical usage, and to verify the schedule of these systems. Power data were acquired from a multiplexed set of watt-transducers. Current transducers (CTs) were used in locations throughout the building, and were connected to data loggers set up to record the electrical usage every 15 minutes. Monitoring equipment was placed in the main electrical switch-room to monitor the building mechanical systems, including the chillers, air handlers, elevators, photovoltaics and landlord services. This included six data loggers, and 32 CTs for all of the systems. Additional electrical monitoring equipment was installed at each half floor plate in order to obtain more detailed information for lighting and plug load usage in the building.

Temperature. Temperature and relative humidity sensors were determined to be necessary to monitor the occupied space climate conditions for the building, recording data at 15 minute intervals. These compact, discrete sensors were placed throughout the building, six per floor, with the exception of the second floor south side, which had a total of nine sensors to obtain a more accurate horizontal temperature distribution. The sensors located in the occupied space were placed at desk level height, as most occupants spend much of their day working at a desk. Six additional sensors were strung in the atrium, measuring temperature and relative humidity at interstitial spaces, and providing stratification data.

Carbon Dioxide. Carbon dioxide sensors were used in conjunction with measurement of supply air introduced into the building to determine ventilation effectiveness. The meeting rooms located on each floor use under floor transfer fans in order to introduce fresh air into these spaces. The design engineers stated that it was the fresh air requirement of the meeting rooms, and a minimum of 8 liters per second per person, that determined the ventilation rate for the building. Therefore measurements of the carbon dioxide levels were used to determine ventilation effectiveness. The carbon dioxide sensor had an unobtrusive data collector attached to it, and was set up to log the carbon dioxide levels every ten minutes. The sensor was placed in meeting rooms, left in place for a week, and then relocated to another meeting room. This provided information on meeting rooms throughout the building, for a weeklong period.

Airflow. A hot wire anemometer was used to measure the airflow for the building, both at a local level and an overall airflow rate for the building. Measurements were recorded around several diffusers, at various radial positions along the floor plane, as well as at distances above the floor plane. Duct traverses for the supply and return ducts at each floor level were taken, using existing holes drilled into the ductwork. A grid pattern was set up to get an accurate airflow velocity profile at each branch location.

Temperature Stratification. In studying occupant comfort, vertical temperature measurements were recorded every 1-5 minutes to determine the variation of temperatures from floor to ceiling. Thermocouples were placed at 35-40cm (14-16 in.) intervals along a vertical pole that reached the height of the occupied space of 2.7 meters (8.9 ft), and attached to a data logger. Measurements were taken over the period of a few weeks during occupied hours at each floor level.

Weather Station. External conditions were collected using a weather station with attached data logger. Temperature, relative humidity, barometric pressure, and wind speeds were monitored. Solar radiation measurements were taken using two pyranometers, one of which was used with a shadow band to gather diffuse solar radiation, while the other was used alone to measure total solar radiation. The weather station was located on the roof of the building, away from any obstructive points, including boiler exhaust and items that could produce shadows. Data were recorded every 15 minutes, and the shadow band was adjusted once every four months in order to ensure that it continued to point due north.

Ultrasonic Flow Meter. The design flow rates for the building were provided by the facility manager. An ultrasonic flow meter was used to verify the constant flow rates of the primary hot and chilled water systems. The secondary flow loops for both the hot and chilled water systems use variable speed drives, and the ultrasonic flow meter was used to obtain the range of flow rates for the building. Measurements were taken every minute for a 48 hour period to gather typical weekday usage data.

Airflow Visualization. To evaluate the types of floor supply diffusers installed in the building and the lateral and vertical airflow patterns, several airflow visualization techniques were used. Smoke pencils were used to determine flow patterns around single diffusers to determine if the air was supplied in a more lateral or vertical direction. Smoke pencils, though useful for localized flow pattern, diffuse too quickly to observe overall airflow patterns in the whole office space. Helium balloons, made neutrally buoyant for the mid-height location in the occupied space (Glicksman, 2004), were used to determine overall airflow patterns in the vertical and lateral directions.

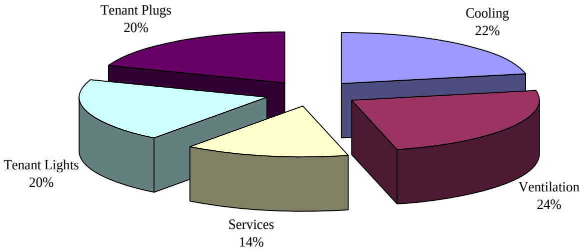

Figure 3. Electricity Usage by Sub-System

RESULTS

Data from sixteen months were analyzed to determine the overall performance of the building, as well as assess the building operation by sub-system. The energy usage, lighting usage, and ventilation were evaluated and the results presented in this section.

Electrical Sub-metering. The recorded energy usage data were compared to monthly energy usage data provided by the facility. Total annual usage derived from measurements was within 10% of the actual usage, and provided important information on the energy usage of the sub-systems within the building. Both chillers and the cooling motor control panel data were categorized as cooling, while the landlord services, lifts (elevators) and atrium lights were put under the title of services. The ventilation category includes the humidifiers and the HVAC motor control panel, while the tenant lighting and plug loads category includes all six half-floor plates of data. The energy end-use is provided in Figure 3.

Typical weekday and weekend profiles of each subsystem were created based on the data that was collected, which verified the schedules that were supplied by the facility manager, and showed that improvements in energy usage could be made. The typical weekday profile for the lighting and plug loads by half floor plate is show in. Figure 4. It was found that during the winter, and part of the fall and spring, there was a requirement for heat at the perimeter of the building, while cooling was still required to control the internal loads. This resulted in both the chillers and boilers being in operation at the same period of time.

The contribution of the photovoltaics, integrated with the exterior shading devices on the southern and the western façades, to the energy consumption of the building could be determined from the detailed sub-metering data. The monthly contribution of the photovoltaics ranged from 885 kWh in July 2002 to 126 kWh in December 2002. During the winter months, the solar cells do not generate as much energy, due to the reduced number of hours of daylight, as well as the fixed position of the photovoltaics. The annual contribution of the solar cells to the building energy is almost 9,000 kilowatt-hours, which represents 1.7 percent of the annual energy usage for the building.

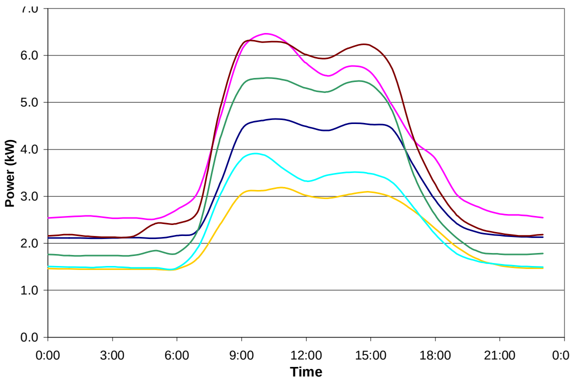

Figure 4. Energy Consumption by Half-Floor

Lighting. In the building, each light fixture has an occupancy- and photo-sensor, so that the lights will automatically turn off after a period of time when the space under the fixture is unoccupied, and so that if there is enough natural daylight from the windows, that the lighting fixtures are not on unnecessarily.

Because detailed sub-metering was conducted by half floor plate, the effectiveness of these sensors due to building orientation was determined. On the ground and second floors, there is some reduced energy consumption of the lighting system, on the south versus the north half-floor plate of the building. However, the first floor shows very similar usage patterns for the south versus the north side of the building, as shown in Figure 5. This is due to blind position on the southern façade, where the blinds remain in a partially to mostly closed position. The blind positions were recorded over a period of days when short term monitoring was being completed in the building. It was observed that some blinds were always closed, particularly on the south façade, and others remained always open, and that some occupants varied the blind position with the amount of perceived glare due to the window.

The discrepancies between floors can be explained as follows. The energy usage of the first floor is generally lower than either the ground or second floor due to a lounge area and smoking room that are not in use all day long, but for shorter periods of time. Additionally, the ground floor had more meeting rooms, located on the north half of the floor, than either of the other two floors.

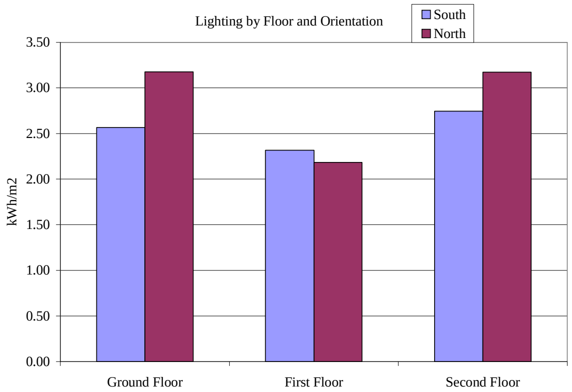

Figure 5. Lighting Energy Usage by Orientation

Ventilation. Duct traverse measurements were taken while on site, during a typical weekday in January 2002, and the data are presented in Table 1.

Table 1. Supply Duct Traverse Measurements

	South Ground	North Ground	South First	North First	South Second	North Second
m^3/s	2.23	2.23	2.41	2.49	3.67	2.77
cfm	4,725	4,725	5,100	5,275	7,775	5,900

The overall air flow rate for the building, based on the occupancy and duct traverse measurements, was determined to be 40 liters per second per person (85 cfm/person). This is four times higher than the United States and United Kingdom minimum required fresh air rates, which are 8-10 liters per second per person (17-20 cfm/person). Part of the reason for the high air flow rates was that the building was originally designed for twice the number of people. However, because there is a constant volume system installed, the flow rate cannot be varied based on the current occupancy.

Airflow Patterns. Through spot measurements taken on site, two types of diffusers were found throughout the building; ones that moved air in a more lateral direction and ones that introduced the air into the space in a slightly more vertical direction. There was an even distribution of these diffusers throughout the office space. Smoke pencils assisted in determining which type of diffuser was used in a particular location. The configuration of the diffuser indicated its type; how the two slotted plates that make up the diffuser were aligned.

It was found through on-site experiments that the occupants would lift up the floor diffusers and put tape or paper beneath those diffusers that provided discomfort due to cold drafts. This would block the flow of supply air to the occupied space, but reduce some of the discomfort experienced by the occupants, including cold feet. Though the diffusers were adjustable to change the direction of the flow of supply air, often this was not done due to lack of knowledge, perceived difficulty or modification of the diffuser.

Helium balloons were used to evaluate lateral air movement throughout the occupied space, as well as determine larger scale airflow patterns. It was determined that there was little lateral movement, except for locations in close proximity to the restrooms, where exhaust fans tended to draw office air towards intake grills located over the entry door to the restroom. Some convective heat loops were found near window locations on the southern façade due to the warm air near the window surface caused by solar gain, causing the balloons to rise near the window, and then drop when nearing the chilled beams located at the ceiling. Additionally, when experiments were carried out in the evening hours, a large convective loop was observed in the atrium, which has little supply air, when the western end of the atrium was warmer than the eastern end, causing the balloon to rise on the western end and slowly drop on the eastern end.

<u>Carbon Dioxide Measurements</u>. After determining that the building was providing too much fresh air, the engineering design team was consulted. The meeting rooms are supplied with fresh air through under-floor ducts using transfer fans. The fans turn on when the room is occupied, and turn off when unoccupied. Because the meeting rooms were the limiting factor with the desired air flow rate, carbon dioxide (CO_2) measurements were recorded. The CO_2 sensor was placed outside, on the roof of the building in order to obtain accurate data on the outside CO_2 level, which was measured at 415 parts per million (ppm). The small CO_2 sensor was then placed in each of four meeting rooms for a week at a time, over the period of a month. A sample week from one meeting room is shown in Figure 6. The hourly average is represented by the varying black line, while the average outside CO_2 level for Sunbury is indicated by the horizontal black line. During times when there is no occupancy, the CO_2 levels drop below the average outside level, as there is a degree of uncertainty in measurements and the outside level actually varies over time.

Both the United States and the United Kingdom have maximum allowable levels of carbon dioxide and the corresponding exposure times for people in the workplace. The UK guidelines (CIBSE, ems-online.co.uk) recommend that levels above 1000 ppm is not to be exceeded for longer than 8 hours, before problems with lethargy and headaches can occur. The American Society of Heating, Refrigeration, and Air-conditioning Engineers Standard 62-1989 contains a guideline value for carbon dioxide of 1000 ppm. However it is based on the association of higher levels of carbon dioxide concentrations with unacceptable levels of body odor, not on any health or comfort impacts due to the carbon dioxide itself. From Figure 6, the meeting rooms in the building are well below the allowable limits, even when the meeting rooms are fully occupied.

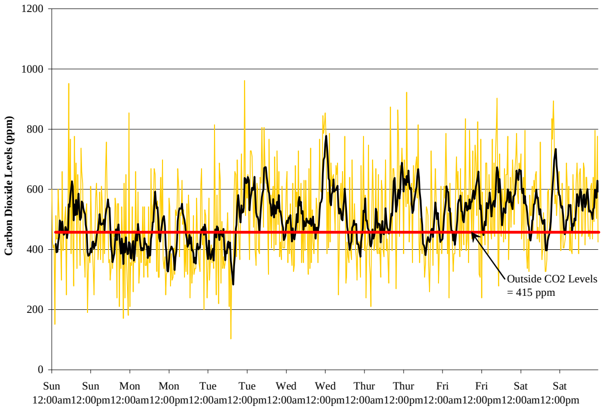

Figure 6. Carbon Dioxide Measurements

<u>Temperatures</u>. Vertical temperature measurements were taken over the period of a day in a single location in order to determine the amount of stratification and vertical temperature variation in the occupied space, which is the design intention of the UFAD systems. For thermal comfort, a maximum variation within the occupied zone should not be more than 2.0-3.0°C (3.6-5.4°F). In the building, the maximum measured temperature stratification during occupied hours was 1.8°C (3.2°F). Sample vertical temperature distribution profiles are presented in Figure 7. The stratification height, or horizontal plane above which there exists well-mixed warm air, occurs approximately at 1.8 meters, above the seated height of 1.3 meters.

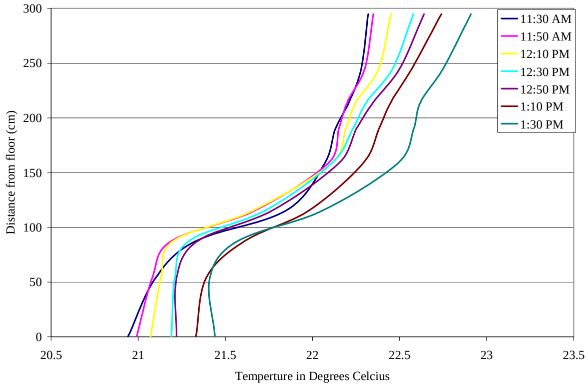

Figure 7. Vertical Temperature Stratification

On the horizontal plane, the space temperatures throughout the building did not vary much, except on weekends, when the HVAC system is turned off. On the weekends during the summer months, the internal space temperatures can raise to uncomfortable levels (up to 28°C, 82.4°F), while during the winter months, the temperatures can be rather cool (down to 18°C, 64.4°F) as shown in Figure 8. In general, during occupied hours, the temperature is constant throughout the building. However, on weekends, the southern half-floor plate tends to be slightly warmer than the northern half-floor plate, particularly on sunny weekends. This trend was most apparent on the second floor, which had the most sun exposure, and least apparent on the ground floor, which had more shading by trees and buildings across the street. The atrium became somewhat stratified during the weekends, but less so during the week, with a maximum temperature variation of 5°C (9°F), as shown in Figure 9.

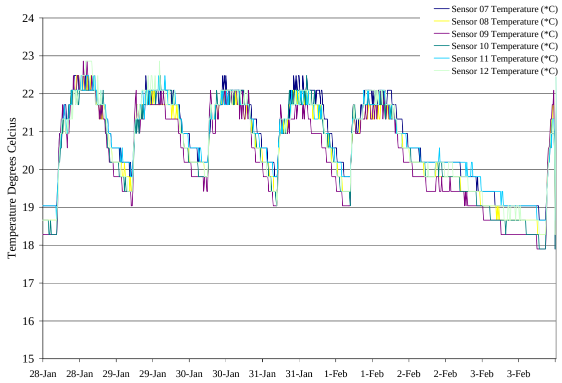

Figure 8. Office Winter Week Temperature Distribution

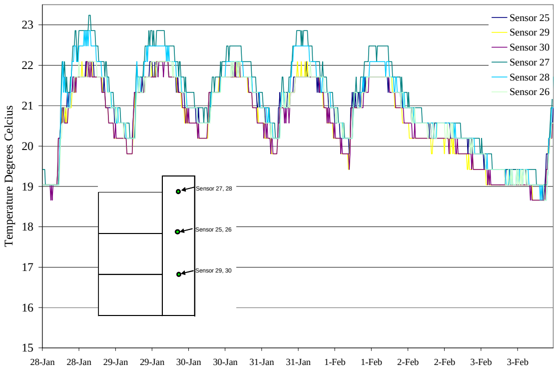

Figure 9. Atrium Winter Week Temperature Stratification

IMPROVED OPERATIONS

One of the benefits of the UFAD system is the ability to supply the minimum amount of outside air required to meet ventilation standards and a low velocities, thereby providing a good indoor environment for occupants. However the current operation of the HVAC system for the building includes bringing in 100% outside air during occupied hours, 8AM to 7PM, using four times the minimum required amount of outside air, and not recovering any of the heat from the exhaust air stream to preheat the incoming outside air. The building was originally designed and built with a heat recovery loop. During the monitoring period the heat recovery loop was found to not be in use, so calculations were performed to determine how much natural gas could be conserved if the heat recovery loop were repaired. Saving natural gas usage would in turn, reduce the overall emissions from the building, which corresponds with the building owner's goals of reducing carbon dioxide emissions from its building stock. Calculations were performed using specification data regarding the heat recovery loop, measurements of air flow taken on site in January 2002, hourly weather bin data for the London area, the energy equations, and the NTU method for heat-exchanger calculations.

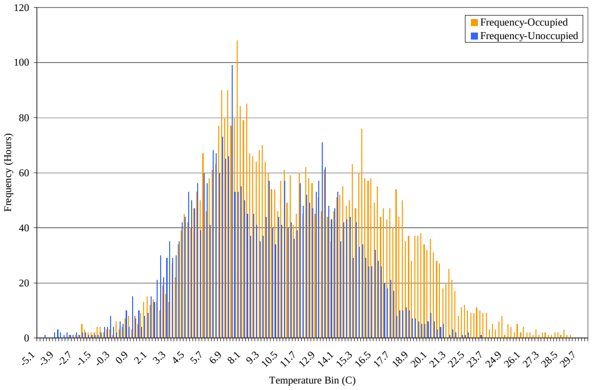

Figure 10. London Temperature Bin Data

The bin method was used to analyze the weather data in terms of heat recovery potential. The bin method divides outdoor temperature data into various temperature increments, or bins, and further separates these data into various times of the day. The results are the number of hours in a given time interval (over the year in this case) that the outdoor temperature falls within a 0.2 °C (0.4 °F) increment, or bin. The data was further subdivided into hours during the day, occupied and unoccupied. This is presented graphically in Figure 10. The total number of hours that the outdoor temperature was below 18.4 °C (65°F) (the supply air temperature for the building) during occupied hours (8AM to 7PM during the week) was calculated. This was determined to be 36,089 degree hours for the year. The data used for the calculations are presented in tabular format in Table 2.

The calculations for the heat recovery potential involved the properties of the air at the supply temperature, the number of hours that the outside temperature was below the supply air temperature during occupied hours, thereby requiring additional heating, and the volume of air being conditioned. The effectiveness of the heat recovery loop using the provided design specifications was calculated in order to provide the most accurate results. Calculations were made to determine the impact on heat recovery due to reducing the supply airflow in half, given its large per-occupant value.

Table 2. Heat Recovery Calculation Variables

Heating Energy	162	kWh/m^2
	15.1	kWh/ft^2
Boiler Efficiency	0.8	estimated
Annual Heating Degree Hours	36,089	hours
Occupants	385	
Volume of Air	15.86	m^3/s
	33,600	cfm
Reduced Flow	7.93	m^3/s
	16,800	cfm
Supply Temperature	18.4	°C
	65.1	°F
Return Temperature	22.3	°C
	72.1	°F
Conversion Natural Gas	0.19	kg CO_2/kWh
	0.42	lb CO_2/kWh
Conversion Electricity kWh	0.46	kg CO_2/kWh
	1.01	lb CO_2/kWh

The results for heat recovery loop calculations are presented in Table 3. It was determined that 35.5 percent of the natural gas usage and associated carbon dioxide emissions due to natural gas usage for the building could be conserved if the heat recovery loop were repaired. The meeting rooms, which drive the building air flow rates, reached a maximum level of approximately 950 ppm for any single data point, but averaged 650 ppm for any length of time. Due to the carbon dioxide measurements, it was determined that the building could operate with a reduced air flow of 50%, resulting in 20 liters per second (40cfm) per person to still accommodate the requirements of the meeting rooms. With reduced airflow and related fan energy reduction, the carbon dioxide emission savings for the building are 32% annually. The carbon dioxide reduction for the building as it currently operates would be reduced by 35 percent due to repairing the heat recovery loop. The annual fan energy and natural gas usage for the three cases, current conditions, current conditions with heat recovery, and reduced airflow rate with heat recovery, are presented graphically in Figure 11. There is a slight increase in natural gas usage due to the reduced fan energy.

Table 3. Heat Recovery Calculation Results

Heat Recovery based on Current Air Flow (40 l/s/person)		
Efficiency of Heat Recovery	0.43	efficiency
Heat Recovery Potential-Occupied	57.6	kWh/m^2
	5.35	kWh/ft^2
CO_2 Emission Reduction-Occupied	11.0	kg CO_2/m^2
	2.25	lb CO_2/ft^2
Heat Recovery based on Half Air Flow (20 l/s/person)		
Efficiency of Heat Recovery	0.55	efficiency
Heat Recovery Potential-Occupied	37.3	kWh/m^2
	3.47	kWh/ft^2
CO_2 Emission Reduction-Occupied	7.1	kg CO_2/m^2
	1.45	lb CO_2/ft^2

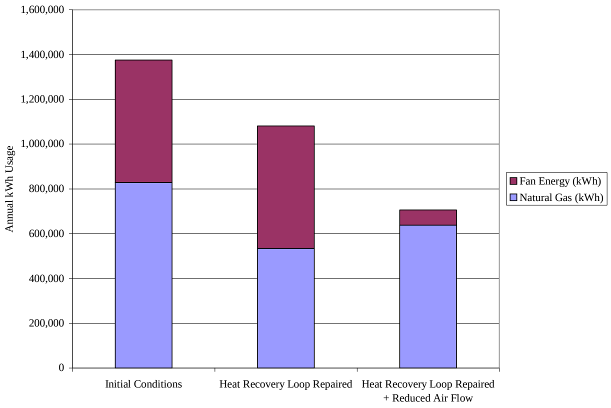

Figure 11. Improved Operation Energy Consumption

BUILDING PERFORMANCE

As part of evaluating the performance of the building, there were a couple of benchmarks to which the data collected could be compared. These benchmarks were the Post-occupancy Review of Buildings and their Engineering (PROBE) Studies, and the UK Energy Consumption Guide 19 for Office Buildings (ECG019). A summary of each of these methods is provided in the following sections.

PROBE Study

William Bordass Associates (WBA) has been performing PROBE studies of buildings for the past several years. This method is intended to determine energy-performance indicators for the building and its major end-uses, which can be compared among many buildings. An energy survey method is used, whereby no comprehensive monitoring of sub-systems is performed. It is based on the Office Assessment Method, a prototype for evaluating office buildings energy usage, developed by the UK Department of the Environment. It is an iterative approach, originally divided into three stages, but expanded into a multi-stage method by WBA. The PROBE assessment is a two day visit in order to understand the original design intentions, obtain sub-metering data if available, take spot measurements, and perform blower door (pressure) tests if possible. The three stage assessment is divided as follows:

•Stage 1: broad-brush analysis against annual consumption by fuel (presented per unit floor area)

•Stage 2: influencing factors are considered, such as extended occupancy, extreme weather, unusual end-uses (e.g. computer rooms)

•Stage 3: load in kilowatts is multiplied by the number of occupied hours to determine initial consumption estimations by item, area, or subsystem. This is then compared to metered data for the building. This can include day/night, summer/winter, and weekday/weekend load pattern analysis.

The PROBE data are the results of a 2-3 day walk through of the building during the first year of occupation. Between then and when the current study was completed, adjustments in controls and operation had been implemented, resulting in a more efficient operation of the plant equipment.

ECON 19

This set of benchmarks was derived from energy consumption measurements in a wide range of occupied office buildings. The buildings surveyed were organized into four categories based on the manner in which the building was ventilated and the energy density of the building. Data were presented by end-use and total energy consumption in kilowatt-hours per square meter, and carbon emissions in kilograms of carbon per square meter for each of the four building types, defined as follows:

•Naturally ventilated cellular office buildings have individual lighting and heating controls, and operable windows, allowing the occupant to have more control over their environment.

•Naturally ventilated open-plan office buildings have higher illuminance levels, lighting power densities and occupied hours than for the cellular type. The controls often serve a larger area, and tend to operate for longer periods of time.

•Air-conditioned, standard office buildings are based on a variable-air-volume ventilation system with air-cooled chillers, and have a deeper floor plan than do the naturally ventilated buildings, and often use tinted glazing in order to reduce glare, which in turn reduces natural daylighting.

•Air-conditioned, prestige office buildings have similar operation and systems to the standard air-conditioned office building, but with longer operating hours, conditioned central computer rooms, and more energy intensive amenities, such as food preparation areas.

Measured Building Performance

The building data gathered through monitoring was compared with the standard and prestige air-conditioned office buildings from the ECON 19 standard, and the initial PROBE study conducted for the building. The long-term monitoring provided more accurate presentation of how the building was performing. The building was compared to the standard office building type, as it did not meet the extended hours or additional energy intensive amenities that are present in the prestige office buildings. The building falls between typical and good practice standards for the ECON 19 for the standard AC-type building. The results are presented in Table 4.

Reduced airflow to provide conditioned fresh air based on the number of occupants, rather than a constant-volume system, would reduce the amount of fan energy required. The other option of recovering heat from the exhaust air stream would also reduce the amount of heating energy required by the building, bringing the monitored building closer to the good practices end of the building performance scale.

Table 4. Building Energy Usage Comparison to Benchmarks

		PROBE	ECG019-Typ	ECG019-GP	Monitoring
Total Natural Gas Consumption	kWh/m^2 (kWh/ft^2)	230 (21.4)	178 (16.5)	97 (9.0)	162 (15.1)
Annual Electricity Consumption	kWh/m^2 (kWh/ft^2)	193 (17.9)	226 (21.0)	128 (11.9)	155.9 (14.5)
Lighting	kWh/m^2 (kWh/ft^2)	41 (3.8)	54 (5.0)	27 (2.5)	27.7 (2.6)
Office Equipment	kWh/m^2 (kWh/ft^2)	34 (3.2)	31 (2.9)	23 (2.1)	27 (2.5)
Refrigeration	kWh/m^2 (kWh/ft^2)	36 (3.3)	31 (2.9)	14 (1.3)	29.3 (2.7)
Fans, Pumps, Controls	kWh/m^2 (kWh/ft^2)	48 (4.5)	60 (5.6)	30 (2.8)	49.8 (4.6)
Humidification	kWh/m^2 (kWh/ft^2)	3 (0.3)	18 (1.7)	8 (0.7)	0.3 (0)
PV Contribution	kWh/m^2 (kWh/ft^2)				-1.7 (-0.2)

CONCLUSIONS

Through measurement and monitoring, several issues of energy usage and thermal comfort arose regarding the building. Some of these issues are readily solvable, while others require some additional investigation. All of the issues will be presented below.

The building used an UFAD system for ventilation, with several types of diffusers to introduce the fresh air into the occupied space. However, because of the high air velocities and cool inlet temperatures, the occupants have covered up diffusers with paper to reduce cold drafts that they were feeling, particularly at foot level. Of the energy related issues, repairing the heat recovery loop is the option with the greatest rate of return. Because the building uses 100% outside air, there is great potential to recover some of the waste heat during the winter. The building is currently over-ventilated, providing 40 l/s/person (85 cfm) of outside air for the occupants. By reducing the airflow rate, additional fan energy savings could be achieved.

The energy usage in the building by the lighting system could be reduced in two ways. One method is leaving blinds in the open position more often. Through the measurements taken, there should be more significant difference in lighting power between the north and south sides of the building. Second, the blinds were closed in the clerestory area, preventing natural light from penetrating the central atrium. This would trigger some of the lights on the perimeter of the atrium to either dim, or turn completely off during certain times of the day; current practice has them on during the day, when no additional lighting was needed. Control over these lights is achieved by a manual switch, which requires an occupant to determine when the lights should be on or off.

The temperature of the supply air is 18°C (64.4 °F), which can feel very cold in the winter on people's feet, particularly with the high ventilation rate. Raising the supply air temperature would assist with this issue, however further studies would need to be completed to determine if raising the supply air temperature would adversely effect the chilled ceiling operation. The diffusers used in the UFAD system had the ability to be adjusted to better control the way the supply air was introduced into the space. Instructing the occupants of this would help avoid their blocking diffusers as the only way to improve comfort. Though the office layout was flexible and changed several times per year as needed, the locations of the diffusers were not necessarily altered to accommodate the newer layout. One of the benefits of the UFAD system is the ability to introduce supply air where it is needed and change the configuration as required.

In general, monitoring of the building allowed the unique opportunity to study in detail the energy, ventilation, and overall performance of a commercial office building. The level of detail attained is unusual, due to personnel and equipment requirements and cost. Most commercial facilities have building energy management systems, to assist in operating the building. With sub-metering capabilities, an additional level of information can be provided. An accurate representation of the energy usage by sub-systems over the period of a year, though more expensive, can better benchmark the energy usage of a building, and track energy savings due to the implementation of energy-efficiency measures. Monitoring space temperatures can help to ensure occupant comfort, while monitoring systems can help in evaluating their efficiency and effectiveness.

REFERENCES

[1] Action Energy. 2003. Energy Consumption Guide-ECG019: Energy Use in Offices. Best Practices Programme. Crown.

[2] ASHRAE Handbook: 2001. Fundamentals. SI Units.

[3] Bauman, F. and T. Webster. 2001. *Outlook for Underfloor Air Distribution*. ASHRAE Journal, June 2001.

[4] Bordass, William. 2000. *Building A Probe Study*. June 2000.

[5] Glicksman, L. 2004. *Monitoring Airflow in Occupied Buildings, the Dynamics of Balloon*s. *Proceedings of RoomVent 2004*. Coimbra, Portugal.

[6] Kays & London. 1964. Compact Heat Exchangers. McGraw Hill Press, New York.

[7] Krepchin, I. 2001. *Underfloor air systems gain foothold in North America*. E Source Report. ER-01-1, Boulder, Co. January 2001.

[8] Lienhard, John. 2001. A Heat Transfer Textbook, 3rd Edition. Phlogiston Press, Cambridge, MA.

[9] Olsen, Erik. 2002. Performance Comparison of UK Low-Energy Cooling System by Energy Simulation. M.S. Thesis. Massachusetts Institute of Technology.