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Energy Cost and IAQ Performance of Ventilation Systems and Controls

Report # 7

The Cost of Protecting Indoor Environmental Quality During Energy Efficiency Projects for Office and Education Buildings

Integrating Indoor Environmental Quality with Energy Efficiency

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United States Environmental Protection Agency
Washington, D.C. 20460

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INTRODUCTION

Purpose and Scope of this Report

Many building owners and managers are under increased pressure from many circles to provide good indoor environmental quality (IEQ). There are many opportunities to advance IEQ during the course of energy projects without sacrificing energy efficiency. These opportunities could provide the energy service companies and other energy professionals with the ability to gain a competitive edge as they market their services to a clientele that is becoming increasingly sensitive to indoor environmental quality issues. Many energy professionals believe that IEQ necessarily leads to significant energy penalties and therefore deliberately ignore it in their projects.

Relationship between Energy Efficiency and Indoor Environmental Quality

Many actions taken to improve energy efficiency have a secondary effect on the quality of the indoor environment. This secondary effect may be to improve indoor environmental quality (IEQ), leave IEQ relatively unaffected (provided that certain cautions and adjustments are adhered to), or degrade IEQ, sometimes substantially.
The indoor environmental factors that most influence occupant health and welfare are the thermal conditions, the lighting, and the concentrations of indoor pollutants. Thermal control and lighting are familiar subjects in energy management. Accordingly, energy professionals are in a strong position to affect these two important aspects of the indoor environment. However, energy professionals are often less knowledgeable about the third factor–indoor pollutant concentrations. Although they are often responsible for the design, control, and modification of the ventilation systems, energy professionals are often not fully aware of the resulting effects of these systems on IEQ.

Much of the perceived conflict between IEQ and energy efficiency results from just two elements of an energy strategy– the tendency to minimize outdoor air ventilation rates, and the willingness to relax controls on temperature and relative humidity to save energy. Some energy activities that are compatible with IEQ, either because they are likely to enhance or have little effect on IEQ if properly instituted, are suggested in Exhibit 1. The compatibility with IEQ is critically dependent on the cautions and adjustments which are outlined in this exhibit. Some energy projects may inadvertently or needlessly degrade the indoor environment. The energy project activities that are judged to have the greatest potential for degrading the indoor environment are listed in Exhibit 2

The purpose of this report is to help reconcile the desire to provide a quality indoor environment that supports the health and comfort of occupants, with the very important objective of reducing energy use. This report suggests strategies by which energy professionals can design projects for clients that result in both improved energy efficiency and improved indoor environments.

Background

This is a modeling study, subject to all the limitations and inadequacies inherent in using models to reflect real world conditions that are complex and considerably more varied than can be fully represented in a single study. Nevertheless, it is hoped that this project will make a useful contribution to understanding the relationships studied, so that together with other information, including field research results, professionals and practitioners who design and operate ventilation systems will be better able to save energy without sacrificing thermal comfort or outdoor air flow performance

The methodology used in this project has been to refine and adapt the DOE-2.1E building energy analysis computer program for the specific needs of this study, and to generate a detailed database on the energy use, indoor climate, and outdoor air flow rates of various ventilation systems and control strategies. Constant volume (CV) and variable air volume (VAV) systems in different buildings and with different outdoor air control strategies under alternative climates provided the basis for parametric variations in the database.

Seven reports, covering the following topics, describe the findings of this project:

- Project Report #1: Project objective and detailed description of the modeling methodology and database development

- Project Report #2: Assessment of energy and outdoor air flow rates in CV and VAV ventilation systems for large office buildings:

- Project Report #3: Assessment of the distribution of outdoor air and the control of thermal comfort in CV and VAV systems for large office buildings

- Project Report #4: Energy impacts of increasing outdoor air flow rates from 5 to 20 cfm per occupant in large office buildings

- Project Report #5: Peak load impacts of increasing outdoor air flow rates from 5 to 20 cfm per occupant in large office buildings

- Project Report #6: Potential problems in IAQ and energy performance of HVAC systems when outdoor air flow rates are increased from 5 to 15 cfm per occupant in auditoriums, education, and other buildings with very high occupant density

- Project Report #7: The energy cost of protecting indoor environmental quality during energy efficiency projects for office and education buildings

DESCRIPTION OF THE BUILDING AND VENTILATION SYSTEMS MODELED

A large 12 story office building and an L shaped 2 story education building were modeled in three different climates representing cold (Minneapolis), temperate (Washington, D.C.), and hot/humid (Miami) climate zones. The office building has four perimeter zones corresponding to the four compass orientations, and a core zone. The education building has 6 perimeter zones representing the four compass directions, and two core zones. A single duct variable volume (VAV) system was modeled for both buildings. VAV systems alter the supply air volume while maintaining a constant supply air temperature.

Three basic outdoor air control strategies were employed: fixed outdoor air fraction (FOAF), constant outdoor air (COA), and a temperature-controlled air-side economizer (ECONt). The FOAF strategy maintains a constant outdoor air fraction (percent outdoor air) irrespective of the supply air volume, and is commonly represented in field applications by an outdoor damper in a fixed position. The COA strategy maintains a constant volume of outdoor air irrespective of the supply air volume. In a CV system, the FOAF and the COA strategies are equivalent. In a VAV system, the COA strategy might be represented in field applications by a modulating outdoor air damper which opens wider as the supply air volume is decreased in response to reduced thermal demands, or by a dedicated outdoor air fan. Economizers use additional quantities of outdoor air to provide “free cooling” when the outdoor air temperature (or enthalpy when enthalpy economizers are employed) is lower than the return air temperature (or enthalpy). The quantity of outdoor air is adjusted so that the desired supply air temperature (or enthalpy) can be achieved while using as little chiller energy as possible.

A more detailed description of the building and ventilation systems is provided in Report #1.

APPROACH

Energy simulation modeling using the DOE-2.1E computer program was used to estimate the relative energy impacts of various energy efficiency measures and of selected indoor environmental controls. This was done in the context of a staged energy retrofit program for an office building and an education building in the three representative climates. The staged retrofit included operational (tune-up) measures in Stage 1, load reduction measures in Stage 2, air distribution system upgrades in Stage 3, central plant upgrades in Stage 4, and selected IEQ upgrades in Stage 5. The building and HVAC parameters of the base office and education buildings that were modeled are presented in Exhibit 3. Elements of Exhibit 1 that describe adjustments to energy activities required to protect IEQ are implicit in the modeling of these activities of Stages 1-4. Specific improvements to the outdoor ventilation rate and controls to improve IEQ are modeled in Stage 5.

Both buildings were modeled with a variable air volume ventilation system with an air side temperature-controlled economizer. The office building has a fixed outdoor air damper set to circulate 5 cfm of outdoor air per person at design load. The education building was modeled using damper controls to circulate 5 cfm of outdoor air per occupant at all load conditions (constant outdoor air flow). Ventilation rates and controls were adjusted in Stage 5 to meet all the requirements of ASHRAE Standard 62-1999[1].

RESULTS

Energy Savings from Stages 1-4

Exhibits 4 and 5 present the energy cost results from the staged energy activities for the office building and the education building respectively. Exhibit 6 presents the percent savings (from the base and from the previous stage) of total energy costs for both buildings.[2] Stage 1 included only a simple seasonal supply air temperature reset strategy which increased the supply air temperature from 55^{0}F to 65^{0}F from January 1 to March 31 in each climate. Therefore, it does not reflect an optimal control logic for the fans and chiller. As a result, the energy results from stage 1 are not substantial, and do not reflect the values that could be achieved with a more sophisticated control strategy. For example, in the temperate climate of Washington D.C., the seasonal supply air temperature reset strategy in Stage 1 resulted in insignificant reductions (1%) in total energy costs. A greater potential for savings in this stage would exist in buildings with significant pre-existing operational problems. Other measures which are typically included in Stage 1 could either not be modeled or were modeled independently – not part of the staged energy program. These are discussed in a separate section below.

The largest savings resulted in Stage 2 where a further reduction of 31% was achieved through a lighting retrofit and increased efficiency of office equipment. About one fourth of the savings in Stage 2 resulted from reduced loads to the HVAC system. Stage 3 upgrades relied solely on variable speed drives (VSD) which reduced the energy costs an additional 8%. Finally, in Stage 4, central plant upgrades, including down-sizing the equipment because of reduced

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[1] This project was initiated while ASHRAE Standard 1989 was in effect. However, since the outdoor air flow rates for both the 1989 and 1999 versions are the same, all references to ASHRAE Standard 62 in this report are stated as ASHRAE Standard 62-1999.

[2] Total energy costs are defined here to include only energy from HVAC, lighting, and office equipment.

loads[3] added another 13% to the total energy savings, bringing the combined savings to 45%. These results are consistent with EPA's experience in the Energy Star program where typical lighting retrofits result in 25%-30% savings, while other retrofits result in 5%-15% savings depending on the particular retrofit and the context of its application.

The results for the office building in Minneapolis and Miami, also shown in Exhibit 4, are similar with some exceptions. The seasonal supply air temperature reset in Miami added an energy penalty due entirely to the increase in fan energy with no offsetting savings in cooling energy. The lighting retrofit achieved greater overall savings in Miami and lower savings in Minneapolis because of the attendant effects of reduced internal gains on the cost of heating (increase) and on cooling (decrease). Similarly, the savings from the VSD retrofit were greatest in Minnesota, where loads are variable, and lowest in Miami where the loads are more constant.

The results for the education building which are shown in Exhibit 5, are similar to the office building results with some exceptions. Energy savings from lighting and office equipment retrofits were lower compared to the office building. Since the lighting and office equipment in the education building constitute a lower proportion of total loads, the secondary savings on the HVAC system in Stage 2 were less. Finally, the education building experienced greater energy savings from improved central plant efficiencies in Stage 4 because of the larger loads compared to the office building.

While many of these activities implemented in Stages 1 through 4 above could impact IEQ, all the necessary adjustments identified in Exhibit 1 were made or are implicit in the model's algorithms to ensure that IEQ would not be degraded. Thus, this modeling suggests that it is quite feasible to cut the energy budget in the office building by 44% - 45%, and in the education building by 31%-45% (see Exhibit 6, Stage 4) without adversely impacting a building's IEQ, though this does not include the energy impacts of increasing outdoor air ventilation.

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[3] The equipment was downsized, but the final sizing was designed to accommodate increased outdoor air flow of 20 cfm/occ for the office building, and 15 cfm per occupant for the education building as per ASHRAE Standard 62-1999.

Energy Impacts from Stage 5: Increasing Outdoor Air Ventilation to Meet ASHRAE Standard 62-1999

The base buildings provided only 5 cfm of outdoor air per occupant (i.e. does not meet the current ASHRAE ventilation requirements for indoor air quality (ASHRAE Standard 62-1999)). To meet these requirements, a set of IEQ controls were instituted as part of Stage 5. The first control was to raise the outdoor air control setting at the air handler to 20 cfm per occupant in the office building, and 15 cfm per occupant in the education building. This increases the outdoor air design flow rate, but since the office building has a variable air volume system with constant outdoor air fraction (VAV(FOAF)) control strategy, ASHRAE Standard 62-1999 requirements are not met at part- load conditions (see Project Report #3). To solve this problem, the fixed fraction outdoor air strategy was replaced with a constant outdoor air (COA) flow control in the office building. This control allows the outdoor air flow rate to remain at the design level even at part-load.

The education building was already modeled with a constant outdoor air flow control in the base case. However, in order to satisfy the requirement of ASHRAE Standard 62-1999, the following two additional adjustments were implemented in Stage 5. First, the VAV box minimum settings in the education building needed to be adjusted upward. In both the office and education building, the VAV box minimum settings are typically set at about 30% (of peak flow). Unfortunately, because of the high occupant densities in the education building, when the outdoor air flow is raised from 5 to 15 cfm per occupant, the outdoor air requirement was sometimes greater than the supply air needed for thermal comfort alone (see Project Report #6). In other words, the HVAC controls in education buildings and other buildings with high occupant density become ventilation-dominated as opposed to thermally- dominated (Report #6). As a result, the requisite 15 cfm per occupant is only achieved a portion of the time at typical minimum VAV box settings. Therefore, the minimum flow settings in the VAV boxes were adjusted upwards to ensure 15 cfm per occupant during all periods.

The second adjustment required for the education building was to increase control over humidity. The relative humidity at outdoor air ventilation rates of 15 cfm of outdoor air per occupant can sometimes rise above 60% and occasionally above 70% (Project Report #6). This situation causes thermal discomfort and adds to the potential for microbiological contamination. The problem with excess humidity was most dramatic, though not limited, to the Miami climate. Relative humidity was maintained at 60% or less by lowering the cooling coil temperature when required to meet the latent load. The VAV box and humidity controls were instituted for the education building as part of Stage 5.

The results of these ventilation modifications for the office and education building are presented at the end of Exhibits 4 -6**.** For the office building, the energy used to increase outdoor air flows to meet ASHRAE 62-1999 raised total energy cost of the Stage 4 retrofitted building by 3-4% in all climates-- much less than many energy practitioners expect. In fact, when compared to the base (pre-retrofitted) building, the energy savings foregone by instituting these controls was only 2% - 3%. These results are consistent with other studies (Project Report #4, Eto and Meyer, 1988, Eto,1990; Steele and Brown,1990; Ventresca, 1991). This is because, during a large portion of the year, bringing in additional outdoor air provides free cooling and reduces cooling energy use. In HVAC systems with economizers already installed, the energy penalty from higher outdoor air flows is only experienced in extreme weather conditions, and mostly during the summer months. In the winter months, economizer operation may still provide 20 cfm of outdoor air per occupant in office buildings with adequate freeze stat controls, even with outdoor air temperatures as cold as 0° F (Project Report #4; Ventresca, 1991). In HVAC systems without economizers, the higher outdoor air flows act as an implicit economizer by providing some degree of free cooling during most of the year .

In the education building, meeting ASHRAE Standard 62-1999 increased total energy costs of the retrofitted Stage 4 building by 5% - 14%. Compared to the base (pre-retrofitted building), this means that the energy savings foregone as a result of these controls was only 3% - 9%. Interestingly, the adjustments for outdoor air and humidity control for the education building had the highest energy penalty (13–14% from Stage 4) in Washington D.C. and in Minneapolis, but in Miami, the energy penalty was only 5%. This runs contrary to conventional wisdom but is explained by the fact that in temperate and cold climates, there is a substantial heating penalty associated with the outdoor air adjustments which was not present in Miami (Project Report #4). Another counter-intuitive phenomenon is evident in Miami. Increasing the outdoor air setting accounted for a substantial energy penalty (7%) from Stage 4. However, the VAV box and humidity controls reduced the increase to only 5%. This is because by lowering the cooling coil temperature when needed to control humidity, a considerable reduction in fan energy was achieved that more than offset the increase in cooling energy.

Raising the outdoor air flow in this energy retrofit scenario also limits how much equipment can be downsized. The sizing requirements for the boiler and chiller with and without the indoor environmental controls are presented in Exhibit 7. If the outdoor air adjustments and humidity controls identified above were not included in this retrofit (no IEQ controls), the chillers could have been downsized to 75%-77% of the base for the office building and 86% - 90% of the base in the education building. However, by raising the outdoor air design flow rates, insuring that rate is achieved under full and part load conditions, and controlling relative humidity to below 60%, downsizing was limited to 90%-99% of the base in the office building, while in the education building, the size of the chillers had to be increased from 104%-109% of the base. Boiler capacity must generally be increased in energy efficiency projects because of the reduced internal heat gains from more efficient lights, office equipment, and plant, but the IEQ controls add additional boiler size requirements over the base condition.

Measures to Mitigate the Energy Cost of Outdoor Air Ventilation

At higher occupant densities, such as in education buildings, satisfying ASHRAE Standard 62-1999 requires a substantial increase in outdoor air and this can create a substantial energy penalty. Outdoor air ventilation with an energy recovery system thus becomes an attractive method for reducing the energy cost of this ventilation requirement. Unfortunately, DOE-2.1E does not have capabilities which are sufficiently sophisticated to reliably model energy recovery technologies (especially latent heat recovery). However, available literature suggests that energy recovery systems can eliminate or substantially reduce the energy penalty created by raising outdoor air levels to meet ASHRAE Standard 62-1999 in office buildings in hot and humid climates (Rengarajan, et al. 1996; Shirey and Rengarajan, 1996). The efficiency of energy recovery systems range from 50% -75%. Thus, while the cost of increasing outdoor air ventilation rates to15 cfm year round with humidity controlled in education buildings was 5% - 14% over Stage 4, this could well be reduced to 3% to 7% with the use of energy recovery. Reductions in capacity requirements would also be possible.

Stage 1 Measures with Potentially Adverse IEQ Impacts

Many energy measures with significant potential to adversely impact IEQ occur in Stage 1, and involve either relaxing temperature (and humidity) controls and/or reducing HVAC operating hours. Exhibit 3 identifies modeling scenarios for relaxing daytime temperature controls, night time temperature controls, and HVAC operating hours. These scenarios were modeled separately and were not included in the staged energy retrofit project . Exhibit 8 summarizes the results of these modeling runs.

Widening the day time temperature dead band from 71-77^0 F to 68-80^0 F reduced energy costs by 2% -3% in the office building, and by 7%-8% in the education building. Relaxing the night time temperature setback from +/- 10°F to +/- 15°F reduced energy costs from 1% - 2% in the office and from 0% - 1% in the education building. Reducing the HVAC operating time by two hours (including a reduction of startup time from 2 hours to 1 hour), reduced the energy costs by 0%-1% for the office building and by 2%-4% in the education building. Had all these measures been included in Stage 1, the energy reductions in Stage 1 would have increased to 3%-5% for the office building and to 7%-10% in the education building.

In contrast, other operational measures for Stage 1 that do not degrade IEQ can provide significantly greater savings. For example, simply commissioning the building to insure that controls and equipment are functioning properly (not modeled) have been shown to typically reduce total energy costs by 5%-15%, and also tend to improve IEQ (Gregerson, 1997). Reducing lighting and office equipment usage during unoccupied hours can also result in significant savings. The base office building was modeled with lighting during unoccupied hours operated at 20% of daytime use and office equipment operated at 30% of daytime use. Exhibit 9 compares the modeling results for this case (20%/30%) with both greater usage during unoccupied hours (40% /50%) in Stage 1, and reduced usage (10%/15%) after Stage 4 modifications.

As indicated in Exhibit 9, had the usage of the lighting/office equipment during unoccupied hours been at 40%/50% of day time levels and then reduced to the 20%/30% that was modeled in the base building, 12% savings would have been possible in Stage 1 from this activity. This result is consistent with field data which showed that energy savings of approximately 15% on average are associated with operational controls (mostly lighting) during unoccupied hours (Herzog, et al.1992). In addition, an aggressive program to reduce night time use of lights and office equipment after the building is made energy efficient and IEQ compatible could provide additional reductions of equal magnitude.

The energy savings from operational controls that could degrade IEQ amounted to only 3% - 10% of total energy costs. Considering the energy savings of 31% - 45% associated with IEQ-compatible upgrades through Stage 4, plus the potential for additional savings of 12% or more from reduced use of lights, and savings of 5% - 15% from improved equipment performance, the energy savings of 3% - 10% from controls that are incompatible with IEQ are very small in comparison. It appears to make little sense to pursue energy reduction activities that compromise IEQ and run the risk of potential liability of IEQ-related illnesses and complaints, when the energy saving potential for compatible measures is so much greater in comparison.

CONCLUSIONS

This report suggests that indoor environmental quality need not be detractor to achieving substantial energy savings in buildings. Energy savings of 31% - 45% were achieved in a staged energy retrofit program which was designed to prevent degradation of IEQ. Further savings in the range of 5% - 15% are possible through commissioning (not modeled) plus 12% or more from reduced lighting and office equipment use during unoccupied hours. Instituting all the controls needed to meet the outdoor air and humidity requirements of ASHRAE Standard 62-1999 increased the energy cost of the Stage 4 retrofitted building by only 3% - 4% in the office building, but by 5% - 14% in the education building. However, when measured against the base (pre-retrofitted) building, these increases mean that the energy savings foregone because of ASHRAE Standard 62-1999 requirements were only 2% -3% for the office, and 3% - 9% for the education building. Similarly, the outdoor air and humidity requirements limited the degree to which chillers and boilers could be downsized. However, the use of energy recovery technology is likely to either eliminate or substantially reduce that penalty, and allow for greater downsizing of chillers and boilers.

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Exhibit 1
Energy Measures that are Compatible With IEQ

Measure	Comment
Improve building shell	- May reduce infiltration. May need to increase mechanically supplied outdoor air to ensure applicable ventilation standards are met.
Reduce internal loads (e.g. lights, office equipment)	- Reduced loads will reduce supply air requirements in VAV systems. May need to increase outdoor air to meet applicable ventilation standards. - Lighting must be sufficient for general lighting and task lighting needs
Fan/motor/drives	- Negligible impact on IEQ
Chiller/ boiler	- Negligible impact on IEQ
Energy recovery	- May reduce energy burden of outdoor air, especially in extreme climates and/or when high outdoor air volumes are required (e.g. schools, auditoria).
Air-side economizer	- Uses outdoor air to provide free cooling. Potentially improves IEQ when economizer is operating by helping to ensure that the outdoor air ventilation rate meets IEQ requirements. - On/off set points should be calibrated to both the temperature and moisture conditions of outdoor air to avoid indoor humidity problems. May need to disengage economizer during an outdoor air pollution episode.
Night pre-cooling	- Cool outdoor air at night may be used to pre-cool the building while simultaneously exhausting accumulated pollutants. However, to prevent microbiological growth, controls should stop pre-cooling operations if dew point of outdoor air is high enough to cause condensation on equipment.
Preventive Maintenance (PM) of HVAC	- PM will improve IEQ and reduce energy use by removing contaminant sources (e.g. clean coils/drain pans), and insuring proper calibration and efficient operation of mechanical components (e.g. fans, motors, thermostats, controls)..
CO_2 controlled ventilation	- CO_2 controlled ventilation varies the outdoor air supply in response to CO_2 which is used as an indicator of occupancy. May reduce energy use for general meeting rooms, studios, theaters, educational facilities etc. where occupancy is highly variable, and irregular. A typical system will increase outdoor air when CO_2 levels rise to 600-800 ppm to ensure that maximum levels do not exceed 1,000 ppm. The system should incorporate a minimum outside air setting to dilute building related contaminants during low occupancy periods.
Reducing demand (KW) charges	- Night pre-cooling and sequential startup of equipment to eliminate demand spikes are examples of strategies that are compatible with IEQ. Caution is advised if load shedding strategies involve changing the space temperature set points or reducing outdoor air ventilation during occupancy.
Supply air temperature reset	- Supply air temperature may sometimes be increased to reduce chiller energy use. However, fan energy will increase. Higher supply air temperatures in a VAV system will increase supply air flow and vice versa.

Equipment down-sizing	- Prudent avoidance of over-sizing equipment reduces first costs and energy costs. However, capacity must be sufficient for thermal and outdoor air requirements during peak loads in both summer and winter. Latent load should not be ignored when sizing equipment in any climate. Inadequate humidity control has resulted in thermal discomfort and mold contamination so great as to render some buildings uninhabitable. - Energy recovery systems may enable chillers and boilers to be further downsized by reducing the thermal loads from outdoor air ventilation.

Exhibit 2
Energy Activities That May Degrade IEQ

Energy Measure	Comment
Reducing outdoor air ventilation	- Applicable ventilation standards usually specify a <u>minimum</u> <u>continuous</u> outdoor air flow rate per occupant, and/or per square foot, during occupied hours. They are designed to ensure that pollutants in the occupied space are sufficiently diluted with outdoor air. Reducing outdoor air flow below applicable standards can degrade IEQ and has low energy saving potential relative to other energy saving options.
Variable Air Volume (VAV) Systems with fixed percentage outdoor air	- VAV systems can yield significant energy savings over Constant Volume (CV) systems in many applications. However, many VAV systems provide a fixed percentage of outdoor air (e.g. fixed outdoor air dampers) so that during part load conditions when the supply air is reduced, the outdoor air may also be reduced to levels below applicable standards. - VAV systems should employ controls which maintain a continuous outdoor air flow consistent with applicable standards. Hardware is now available from vendors and involves no significant energy penalty.
Reducing HVAC operating hours	Delayed start-up or premature shutdown of the HVAC can evoke IEQ problems and occupant complaints. - An insufficient lead time prior to occupancy can result in thermal discomfort and pollutant-related health problems for several hours as the HVAC system must overcome the loads from both the night-time setbacks and from current occupancy. This is a particular problem when equipment is downsized. Shutting equipment down prior to occupants leaving may sometimes be acceptable provided that fans are kept operating to ensure adequate ventilation. However, the energy saved may not be worth the risk .
Relaxation of thermal control	Some energy managers may be tempted to allow space temperatures or humidity to go beyond the comfort range established by applicable standards. Occupant health, comfort and productivity are compromised. The lack of overt occupant complaints is NOT an indication of occupant satisfaction.

Exhibit 3
Modeling Parameters for the Base Office and Education Building

Building Parameter	Office Building		Education Building	
	Base	**Modification**	**Base**	**Modification**
Stage 1: Operational/Tune-up Measures				
Day Temp. Set Points	71° - 77° F	*(68° - 80° F)*	71° - 77° F	*(68° - 80° F)*
Night Set Back	+/- 10° F	*(+/- 15° F)*	+/- 10° F	*(+/- 15° F)*
Day HVAC Hours	8am - 6pm	*(9am - 5pm)*	7am -10pm	*(8am - 9pm)*
Seasonal Reset	No	Yes	No	Yes
Entries in parentheses were modeled separately–not part of the retrofit project				
Stage 2: Load Reduction Measures				
Lighting	2.5 W/f2	30% reduction	3.0 W/f^2 rms 2.0 W/f^2 corr	30% reduction
Office Equipment	1.0 W/f^2	30% reduction	0.25 W/f^2	30% reduction
Stage 3: Air distribution System Upgrades				
VSD	no	yes	no	yes
Stage 4: Central Plant Upgrades				
Chiller COP	3.0	5.5	3.0	5.5
Boiler Efficiency	70%	85%	70%	85%
Stage 5: IEQ Ventilation Modifications Required to meet ASHRAE 62-1999				
Outdoor Air Setting	5 cfm/occ	20 cfm/occ	5 cfm/occ	15 cfm/occ
Outdoor Air Control	fixed damper	constant flow	constant flow	const. flow-VAV box adjustment
Humidity Control	not needed	not needed	not needed	60% RH

*For the base education building used for the energy retrofit: infiltration rate = 0.5ach; window U value = 0.99 (Btui/hr ft^2 ^0F); and window shading coeff. = 0.90.

Exhibit 4
Energy Cost for Office Building With Energy and IEQ Modifications

Parameter	Washington D.C. (\$/f^2)						Minneapolis (\$/f^2)						Miami (\$/f^2)					
	Fan	Cool	Heat	Total HVAC	Light & Off. Equip	Total	Fan	Cool	Heat	Total HVAC	Light & Off. Equip	Total	Fan	Cool	Heat	Total HVAC	Light & Off. Equip	Total
Base Bldg	0.17	0.42	0.05	0.64	0.94	1.58	0.19	0.39	0.10	0.68	0.94	1.62	0.18	0.56	0.00	0.74	0.94	1.68
Stage 1 Seas. Rset	0.18	0.41	0.04	0.63	0.94	1.57	0.19	0.38	0.08	0.66	0.94	1.60	0.21	0.56	0.00	0.78	0.94	1.72
Stage 2 Ltng/OE	0.15	0.30	0.06	0.52	0.57	1.08	0.17	0.29	0.12	0.58	0.57	1.16	0.17	0.40	0.00	0.57	0.57	1.15
Stage 3 VSD	0.09	0.28	0.06	0.43	0.57	1.00	0.08	0.27	0.12	0.47	0.57	1.04	0.13	0.38	0.00	0.52	0.57	1.09
Stage 4 chllr/boilr	0.09	0.16	0.05	0.30	0.57	0.87	0.08	0.15	0.10	0.33	0.57	0.90	0.13	0.22	0.00	0.35	0.57	0.93
Stage 5 OA setting	0.09	0.18	0.06	0.32	0.57	0.89	0.08	0.16	0.11	0.36	0.57	0.93	0.13	0.24	0.00	0.38	0.57	0.95
OA Control	0.09	0.19	0.06	0.33	0.57	0.90	0.08	0.18	0.11	0.37	0.57	0.94	0.13	0.26	0.00	0.40	0.57	0.97

Exhibit 5
Energy Cost for Education Building With Energy and IEQ Modifications

Building Parameter	Washington D.C. (\$/sf)						Minneapolis (\$/sf)						Miami (\$/sf)					
	Fan	Cool	Heat	Total HVAC	Light & Off. Equip	Total	Fan	Cool	Heat	Total HVAC	Light & Off Equip	Total	Fan	Cool	Heat	Total HVAC	Light & Off. Equip	Total
Base Bldg	0.21	0.62	0.28	1.11	0.97	2.08	0.26	0.55	0.62	1.42	0.97	2.40	0.25	0.97	0.01	1.22	0.97	2.19
Stage 1 Seas. Rset	0.21	0.61	0.25	1.07	0.97	2.04	0.26	0.54	0.58	1.38	0.97	2.36	0.28	0.96	0.00	1.23	0.97	2.21
Stage 2 Ltng/OE	0.19	0.53	0.33	1.04	0.67	1.71	0.26	0.48	0.68	1.42	0.67	2.10	0.24	0.83	0.01	1.08	0.67	1.76
Stage 3 VSD	0.11	0.50	0.33	0.94	0.67	1.62	0.15	0.45	0.69	1.30	0.67	1.97	0.18	0.80	0.01	0.98	0.67	1.65
Stage 4 chllr/boilr	0.11	0.29	0.28	0.67	0.67	1.35	0.15	0.26	0.57	0.98	0.67	1.65	0.18	0.46	0.01	0.64	0.67	1.31
Stage 5 OA Setting	0.12	0.35	0.35	0.82	0.67	1.49	0.16	0.31	0.72	1.19	0.67	1.68	0.18	0.54	0.01	0.73	0.67	1.40

OA Control	0.13	0.36	0.38	0.87	0.67	1.54	0.16	0.31	0.72	1.20	0.67	1.87	0.14	0.55	0.01	0.71	0.67	1.38

Exhibit 6:
Percent Savings in Total Energy Cost from Energy and IEQ Modifications
(Top figure in each cell is for office building; bottom figure is for education building)

	Washington			Minneapolis			Miami		
	$\$/f^2$	From Base	From Prev. Stage	$\$/f^2$	From Base	From Prev. Stage	$\$/f^2$	From Base	From Prev. Stage
Base Bldg	1.58 2.08			1.62 2.40			1.68 2.19		
Stage 1 Seas. Reset	1.57 2.04	1% 2%	1% 2%	1.60 2.36	1% 2%	1% 2%	1.74 2.21	-2% -1%	-2% -1%
Stage 2 Ltng/Off Equip	1.08 171	32% 18%	31% 16%	1.16 2.10	28% 13%	28% 11%	1.15 1.76	32% 20%	33% 20%
Stage 3 VSD	1.00 1.62	37% 22%	7% 5%	1.04 1.97	36% 18%	10% 6%	1.09 1.65	35% 25%	5% 6%
Stage 4 Chiller/boilr	0.87 1.35	45% 35%	13% 17%	0.90 1.65	44% 31%	13% 16%	0.93 1.31	45% 40%	15% 21%
Stage 5 OA setting with OA & RH control*	0.90 1.54	43% 26%	-3% -14%	0.94 1.87	42% 22%	-4% -13%	0.97 1.38	42% 37%	-4% -5%

* *Only the office building required OA control while only the education building required RH control (see text)*

Exhibit 7:
Sizing requirements for chillers and boilers with and without IEQ controls

	Chiller						Boiler					
	Wash. D.C.		Minneapolis		Miami		Wash. D.C.		Minneapolis		Miami	
	MBTU	% of Base	MBTU	% of Base	MBTU	% of Base	MBTU	% of Base	MBTU	% of Base	MBTU	% of Base
	Office Building											
Base	4.29	100	4.33	100	4.35	100	4.67	100	6.19	100	1.96	100
IEQ Control												
yes	4.08	95	3.90	90	4.30	99	5.88	126	8.17	132	2.13	109
no	3.20	75	3.17	73	3.37	77	4.74	101	7.18	116	1.99	102
	Education Building											
Base	1.13	100	1.07	100	1.26	100	2.69	100	3.75	100	0.84	100
IEQ Control												
yes	1.23	109	1.11	104	1.43	113	2.93	109	3.99	106	1.13	135
no	0.98	87	0.92	86	1.13	90	2.76	103	3.89	104	0.81	96

Exhibit 8:
Energy costs ($/ft^2) with operational measures that may adversely affect IEQ

	Washington D.C.						Minneapolis		Miami	
	Fan	Cool	Heat	Total HVAC	Light & Off..Equip	Total	Total HVAC	Total	Total HVAC	Total
Base Office Bldg	**0.17**	**0.42**	**0.05**	**0.64**	**0.94**	**1.58**	**0.68**	**1.62**	**0.74**	**1.68**
Day Temp. Set Pts	0.17	0.40	0.04	0.61	0.94	1.56	0.64	1.58	0.71	1.65
Night Set Back	0.16	0.41	0.04	0.62	0.94	1.56	0.66	1.60	0.72	1.66
Day HVAC Hours	0.17	0.42	0.04	0.63	0.94	1.57	0.66	1.60	0.75	1.69
Base Edu. Bldg.	**0.21**	**0.62**	**0.28**	**1.11**	**0.97**	**2.08**	**1.42**	**2.40**	**1.22**	**2.19**
Day Temp. Set Pts	0.18	0.55	0.22	0.95	0.97	1.93	1.25	2.23	1.06	2.03
Night Set Back	0.21	0.62	0.27	1.10	0.97	2.07	1.40	2.38	1.22	2.19
Day HVAC Hours	0.20	0.61	0.25	1.06	0.97	2.02	1.34	2.31	1.18	2.15

Exhibit 9: Savings from reduced lights and office equipment when unoccupied

Operational Control	**Office Building in Washington D.C.**				
% of daytime use during unoccupied hours	Energy Cost ($/f^2)			Saving	
	HVAC	Light/off equip	Total	$/f^2	%
Stage 1					
40% lights/50% office equipment (base case)	0.71	1.08	1.79		
20% lights/30% office equipment	0.64	0.94	1.58	0.21	12%
Stage 4 (retrofitted building)					
20% lights/30% office equipment	0.33	0.57	0.90		
15%lights/20% office equipment	0.29	0.40	0.70	0.20	22%