Energy Cost and IAQ Performance of Ventilation Systems and Controls

Project Report # 4 Impacts of Increased Outdoor Air Flow Rates on Annual HVAC Energy Costs

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INTRODUCTION

Purpose and Scope of this Report

Conventional wisdom in energy conservation circles suggests that the introduction of outdoor air into the building, while necessary to some extent for indoor air quality, is a major source of energy use in buildings. This is because outdoor air must be conditioned prior to being delivered to the occupied spaces, and since about half of a building's energy budget goes to condition the air, it has been considered wise to minimize the entry of outdoor air. During the energy crises of the 1970's and early 1980's, it was not uncommon for building personnel to close or seal shut the outdoor dampers which provide the building with its outdoor ventilation.

In order to achieve acceptable indoor air quality in office environments, ASHRAE's latest ventilation standard (Standard 62-1999[1]) raised the recommended outdoor air ventilation rates from 5 cfm/occupant to 20 cfm/occupant. This four-fold increase in ventilation rates was contrary to common energy conservation practices and has raised a number of questions concerning the feasibility and cost of implementing this standard.

In contrast to this conventional wisdom, when the outdoor air is cooler than the return air, it is common practice to employ an economizer strategy which provides "free cooling" by *increasing* outdoor air flow. This strategy saves energy by reducing the need for mechanical cooling. Thus, raising outdoor air flow rates may either increase or decrease energy use depending on the outdoor air climate and the thermal demands of the indoor space.

Since outdoor air flow is important to the maintenance of indoor air quality, it is worthwhile to examine the relationship between outdoor air flow and energy use in more detail. This report examines the energy and energy cost impact of raising outdoor air ventilation rates in office

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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.

buildings using both CV and VAV ventilation configurations. A sensitivity analysis is performed to determine how this impact is affected by various building parameters, economizers, and climate. Comparisons are made between ventilation systems that provide a minimum of 5 and 20 cfm of outdoor air per occupant during all occupied hours.

This analysis is applicable to new building construction, and for existing buildings with sufficient equipment capacity to accommodate both outdoor air ventilation rates. The impacts of raising outdoor ventilation rates on ventilation system capacity in existing buildings are examined in a companion report (Project Report # 5).

Background

This report is part of a larger modeling project to assess the compatibilities and trade-offs between energy, indoor air, and thermal comfort objectives in the design and operation of HVAC systems in commercial buildings, and to shed light on potential strategies which can simultaneously achieve superior performance on each objective.

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, with different outdoor air control strategies, in 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 BUILDINGS AND VENTILATION SYSTEMS MODELED

A large 12 story office building (Building A), along with 13 additional parametric variations (Buildings B-N) were modeled in three different climates representing cold (Minneapolis), temperate (Washington, D.C.), and hot/humid (Miami) climate zones. All buildings have an air handler on each floor servicing four perimeter zones corresponding to the four compass orientations, and a core zone. A dual duct constant volume (CV) system, and a single duct variable volume (VAV) system with reheat were modeled using alternative outdoor air control strategies. Constant volume systems control the thermal conditions in the space by altering the temperature of a constant volume of supply air. VAV systems provide control by altering the supply air volume while maintaining a constant supply air temperature. The fourteen building and HVAC configurations used in this analysis are summarized in Exhibit 1.

The CV and VAV systems were each modeled using 5 cfm and 20 cfm of outdoor air per occupant. The system for both runs was sized to accommodate the heating and cooling load of 20 cfm per occupant rather than being separately sized for each case. This analysis therefore applies to existing buildings which may be operating at 5 cfm, but have sufficient excess capacity to operate at 20 cfm per occupant. In addition, this sizing strategy would also apply to new construction. A companion report discusses the HVAC capacity implications of raising outdoor air flow rates in existing buildings (see Project Report # 5).

Comparisons were then made between the two runs (5 cfm and 20 cfm per occupant) to determine the impact of an increased outdoor air flow rate on energy consumption and cost. The basic outdoor air control strategy modeled is one that provides a constant outdoor air flow during all operating conditions. For CV systems, this is accomplished by maintaining a fixed outdoor air fraction [CV(FOAF)]. However, for VAV systems, a constant outdoor air flow strategy VAV(COA) requires that the outdoor air fraction change in inverse proportion to changes in the supply air flow.

While a VAV system with fixed outdoor air fraction control strategy [VAV(FOAF)] is common on VAV systems, it does not maintain a constant outdoor air flow rate into the building, can result in significant reductions in outdoor air during part load conditions, and is not recommended (see Project Report #2). Comparisons between 5 cfm per occupant and 20 cfm per occupant would not be valid for VAV systems with a fixed outdoor air fraction strategy since the designated flow rates are not maintained in these systems. VAV systems with fixed outdoor air fraction [VAV(FOAF)] are therefore not included in this analysis.

The benefits of a temperature air-side economizer strategy is also assessed. The economizer uses additional quantities of outdoor air to provide “free cooling” when the outdoor air temperature is lower than the return air temperature. The quantity of outdoor air is adjusted so that the desired supply air temperature can be achieved while using as little chiller energy as possible. To avoid excess relative humidity indoors during the summer months, the economizer is modeled to shut off at outdoor temperatures above 65°F. The outdoor air flow rate reverts to its base level (5 or 20 cfm per occupant) when the economizer is in the “off” mode.

A more detailed description of all the buildings and ventilation systems modeled in this project is provided in Report #1.

APPROACH

The annual impact of raising outdoor air flow rates on energy use depends mostly on changes in heating and cooling loads. These changes are sometimes positive and sometimes negative depending on the seasonal variations in outdoor climate conditions. For presentation convenience in this section, the DOE-2.1E generated hourly air flow and energy use data were sorted into four bins defined by significant outdoor air temperature conditions.

The first bin includes winter-like outdoor conditions (i.e., 0°F to 55°F). In general, 55°F is the outdoor air temperature at which the outdoor air can no longer completely satisfy the cooling requirements of the building. It is also a temperature threshold above which heating is no longer required in the building. The second bin includes outdoor conditions in the range of 56°F to 65°F. In this bin the total energy content of the outdoor air stream is lower than the energy content of the return air stream. Thus, in this range the HVAC system uses 100 percent outdoor air supplemented with mechanical cooling to meet the buildings cooling load. Above 65°F, high humidity levels may cause the energy content of the outdoor air stream to exceed that of the return air stream. Thus, the economizer is not used. The third bin is 66°F to 79°F. In this range, the outdoor air will provide sensible cooling but may introduce high humidity levels causing a latent cooling burden. The fourth bin is for outdoor temperatures in excess of 79°F. Beyond 79°F, which is approximately the temperature of the return air, the outdoor air is expected to cause both a sensible and a latent cooling burden.

The binned energy analysis allows for comparisons of the combined effects of outdoor air flow rates on annual heating and cooling energy. The annual energy use data are then summarized and converted to energy cost assuming alternative energy price structures for all climates. The price of electricity is assumed to be $0.044 per kilowatt-hour, and $7.89 per kilowatt. The gas, which was used for space heating and DHW service was priced at $0.49 per therm. These prices are meant to reflect “typical” prices based on data collected from actual utilities around the country. A summary of the collected electric and gas utility average rates is given in Report #1.

For comparison purposes, energy costs are also computed for four additional price structures which alter the relative price of gas and electricity, and which alter the electricity demand charge. Unless otherwise noted, energy costs refer to costs under the base price structure. A description of each price structure and how it was determined is also provided in Project Report #1.

RESULTS

By way of example, a binned energy framework is used to summarized results for Building A with a CV system in the Washington, D.C. climate, and for Building A with a VAV system in Minneapolis. Both systems are summarized with and without a temperature economizer. The purpose of this analysis is to demonstrate how the energy impacts of increasing the outdoor air minimum flow rate differs during alternative outdoor climate conditions and how these impacts are effected by the operation of an economizer. Energy costs are then systematically assessed for all buildings, ventilation systems, and climates using energy cost summary tables. A sensitivity analysis of these results using alternative price structures is then presented.

Seasonal Impact of Increasing Outdoor Air Flow

CV System without Economizer

Exhibit 2 summarizes the seasonal energy impacts of raising outdoor air flow rates from 5 to 20 cfm per occupant for a CV system without economizer in the Washington, D.C. climate. As expected, heating energy use increased in the winter (Bin 1) with the higher outdoor air flow rate, while sensible cooling dropped. In the intermediate spring and fall seasons, sensible cooling dropped in Bin 2 with no change in latent load, while latent cooling rose in Bin 3 with no change in sensible load. In the summer (Bin 4) sensible and latent cooling energy use rose. Annually, the building experiences a net increase in heating energy, a net decrease in sensible cooling, and a net increase in latent cooling when the outdoor air flow rate is increased from 5 to 20 cfm per occupant.

CV System with Economizer

The energy results for the same building with economizer is shown in Exhibit 3. Raising outdoor air flow rates had virtually no impact on heating energy use in winter (Bin 1) and in the colder intermediate season (Bin 2) because the economizer was already bringing in more than 20 cfm of outdoor air per person during this period. When the economizer was off (Bins 3 and 4) the cooling penalty (both sensible and latent) was the same as the previous case without economizer. Annually, this building experienced virtually no change in heating energy, and a modest increase in both sensible and latent cooling energy when the outdoor air flow rate was increased from 5 to 20 cfm per occupant.

VAV system without Economizer

Binned energy use results for this system in Minneapolis, are shown in Exhibit 4. This building demonstrates how the added cooling benefit in the cooler months can have a substantial effect on annual energy use. Similar to the CV system, in the winter (Bin 1) the heating energy load was slightly increased while the cooling energy load droped significantly because of the higher outdoor air. In the cooler conditions during the spring and fall season (Bin 2), sensible cooling fell while the latent cooling load showed no change. As the temperature warms (Bin 3), the sensible cooling load fell but the latent cooling load rose, until in the summer conditions (Bin 4), where both sensible and latent cooling loads rose. Since Minneapolis experiences cool weather during a larger portion of the year than Washington, D.C., the large winter cooling benefit tended to dominate the change in energy use when outdoor air flow rates were raised from 5 to 20 cfm per occupant.

VAV System with Economizer

The energy results for the VAV system with an economizer are shown in Exhibit 5. Raising the outdoor air flow rate from 5 to 20 cfm per occupant had no effect on heating energy use or cooling energy use because the economizer was already bringing in more than 20 cfm per occupant in the winter period. In the warmer weather when the economizer was not operating (Bins 3 and 4), this system had the same impact as the VAV system without economizer. With the economizer, the impact of raising the outdoor air flow rate was dominated by a modest increase in latent cooling load. Heating and sensible cooling loads remained virtually unchanged.

Summary of Seasonal Effects

The four examples above show that the effect of increasing outdoor air flow rates in buildings has a varying effect on heating and cooling energy use at various times of the year. In general, increased outdoor air flow rates tended to *increase* winter heating energy use, though it had virtually no impact in mild climates or in systems with economizers.

On the cooling side, increasing outdoor air flow rates tended to *increase* summer cooling energy use and to *decrease* cooling energy use in the winter. Sensible cooling energy use was reduced while latent energy use was increased in the spring and fall. However, in systems with economizers, impacts of increased outdoor air flow settings are negated. This is due to the fact that the economizer over-rides the minimum flow setting. Thus, the system does not experience an increase in outdoor air flow when the economizer is operational. The impacts which are negated included both an increase in heating energy use in temperate and cold climates, and a reduction in cooling costs.

The main effect of climate is to alter the amount of time the system experiences various outdoor temperatures, thereby changing the relative importance of the increases and decreases in energy use described above. In any individual case, the net annual impact of increased outdoor air flow on overall annual energy use depends on the net effect of these counteracting influences.

While large office buildings require minimal heating energy relative to cooling energy, the analysis demonstrates that the impact of increased outdoor air flow on heating energy costs can be as significant as the impact on cooling energy costs. This is due to the countervailing influences on the cooling energy costs (e.g., free cooling effect at mild temperatures which offsets the increase in summer cooling loads) which tend to reduce the net annual impact on cooling energy. .

Annual Energy Cost Impacts of Increasing Outdoor Air Flow

CV System Without Economizers

Exhibit 6 summarizes the energy cost impacts of increasing outdoor air flow rates from 5 cfm per occupant to 20 cfm per occupant for buildings A-N with the CV(FOAF) system without economizer in all three climates.

Raising outdoor air flow rates created a net increase in energy cost for the CV(FOAF) system in all buildings in all climates. In the cold and temperate climates of Minneapolis and Washington, D.C., HVAC costs rose 2% - 14%. The increase in these climates was modest because the increase in outdoor air provided free cooling during the winter and a major part of the transition seasons. Costs rose more (2% - 18%) in the hot humid climate (Miami) because of the extended time period of hot humid weather where the outdoor air created a substantial cooling burden. Buildings with higher occupant densities (Buildings I and J) also experienced the greatest cost increase because the added outdoor air is proportional to occupancy of the building.

It is interesting to note that raising outdoor air flow rates increased the net heating costs almost as much as the net increase in cooling costs, especially in the cold climate, but also in the temperate climate. The heating cost increase was largest for buildings with extended hours of operation (Buildings M and N). These buildings experienced a moderate increase in their cooling costs in the cold and temperate climate, so a net increase in overall HVAC costs was typical. However, the building with high occupant density (building I) experienced a significant rise in both heating and cooling costs, and this amounts to the greatest increase in overall HVAC costs among all the building types.

VAV System Without Economizer

Exhibit 7 displays the energy cost impacts of raising outdoor air ventilation rates for VAV system without economizer. Raising outdoor air flow rates on these systems resulted in a 0% - 9% HVAC energy cost increase in Minneapolis, 1% - 14% increase in Washington, D.C. and an HVAC energy cost penalty of 3% - 20% in Miami. In the Washington, D.C. and Minneapolis climates, the VAV system had a higher basic heating requirement than the CV system because they reheat the supply air after it is cooled. However, since the supply air temperature does not change with the addition of higher outdoor air quantities, no change in heating costs were entailed by the higher outdoor air flow rates[2]. However, in Buildings I and J (the higher occupancy cases), the larger quantities of outdoor air resulted in large heating energy penalties.

VAV systems also provide less supply air than CV systems under part load conditions. Thus, the increase in outdoor air flow rates provides a greater change in the outdoor air fraction than in CV systems during part load. Because of this higher outdoor air fraction, the VAV system without economizer tended to experience a greater cooling energy cost reduction during the winter, spring and fall seasons. Combined with the lack of heating penalty, the energy costs did not increase as much as with the CV system in all three climates.

CV and VAV Systems with Economizers

Exhibits 8 and 9 display the energy cost impact results for the CV and VAV systems with economizers.

Overall, the systems with economizers experienced the greatest energy cost increase due to increased minimum outdoor air flow rates. HVAC costs in both the CV and VAV systems rose 2% - 21%. High occupant density buildings tended to experience the largest cost increase.

The effect of raising outdoor air flow rates on systems with economizers was due almost entirely to the increase in cooling costs. Since economizers already capture the free cooling benefit from increased outdoor air flow, raising the minimum outdoor air flow from 5 to 20 cfm per occupant produced a much more substantial cooling energy cost penalty than for the systems without economizers. Raising outdoor air flow from 5 to 20 cfm per occupant produced no heating energy cost penalty in most buildings modeled. This is due to the fact that even during much of the winter, economizers were already bringing in at least 20 cfm per occupant of outdoor air to provide free cooling to the building core. The one exception to this was for buildings with high occupant densities.

SENSITIVITY OF RESULTS TO ALTERNATIVE UTILITY PRICES

In order to examine whether the conclusions were dependent on the utility price assumptions used, the energy results were converted to energy costs using four additional utility price structures (Exhibit 10). The justification for selecting these prices is provided in Report #1. Exhibit 11 provides the annual HVAC costs for the base building (building A), the high occupant density building (building I), and the building with 24 hour occupancy (building N) for alternative price structures. Exhibit 11 demonstrates the dominance of electric energy over gas energy on HVAC energy costs. For any given HVAC system, going from the base price or from the high gas/low electricity price option to the low gas/high electricity price option

[2] The only exception to this is high occupant density building where higher outdoor air flow rates require a high outdoor air fraction and a preheat requirement in cold weather to avoid coil freezing. This occurs in Minneapolis, and to a lesser extent in Washington, D.C.

significantly raised HVAC energy costs. Likewise, high (or low) demand charges can play a significant role in raising (or lowering) HVAC energy costs.

Exhibit 11 also demonstrates the importance of the price structure in assessing the impact of choosing between HVAC system options. For example, under the low gas/high electricity price option, the economizer systems were much more attractive than on the base price or the high gas/low electricity price options. In fact, because of the heating penalty associated with the CV system economizer that was modeled, high gas prices and low electricity prices resulted in higher HVAC costs (rather than lower costs) from the use of an economizer on that CV system.

Exhibit 12, however, demonstrates that alternative price structures, in general, have little impact on the percentage cost increase associated with raising outdoor air flow rates. The main exception appears to be in the cold climate (Minneapolis) where raising outdoor air flow rates would result in a substantial heating penalty. Thus, raising outdoor air flow rates can be unusually expensive in cold climates when gas prices are high relative to electricity prices. Exhibit 12 also demonstrates that under particular building, climate and utility pricing conditions, raising outdoor air supply may oddly reduce energy costs in unique circumstances.

SUMMARY

Heating Energy Costs

Raising outdoor air flow rates in commercial office space resulted in heating and cooling energy use changes, some resulting in increased cost, and some resulting in decreased cost. In general, heating costs increased in the CV system without economizer in temperate to cold climates. The increase is most dramatic for buildings with high occupant density and buildings that operate 24 hours a day. Otherwise, heating cost impacts tended to be inconsequential.

Cooling Energy Cost

Cooling costs can either increase or decrease when outdoor air flow rates are increased. Raising minimum outdoor air flow rates in cooler weather tended to act as an economizer and provide free cooling. Raising minimum outdoor air flow rates in systems that already had economizers had no effect during cooler weather when the economizer was operating. Raising outdoor air flow rates in the summer always increased the cooling energy costs. The annual effect on cooling energy cost depends on the proportion of the year in which the outdoor climate is cold, temperate or hot/humid. The economizer has little effect in hot humid climates because only a small portion of the year is available for economizing.

The VAV system without economizer experienced an annual *decrease* in cooling energy costs in cold and temperate climates, and an annual increase in hot humid climates. The VAV system with economizer always experienced an annual *increase* in cooling energy costs. The

CV system without economizer in cold climates was most apt to experience a decrease in annual cooling energy costs, but this is not substantial except for buildings that operate 24 hours a day.

Building Characteristics

Of all the building characteristics studied, occupant density and to a lesser extent, hours of operation had the most profound effect on the energy cost impact of increasing outdoor air flow rates. When heating or cooling energy costs increase because of increased coil loads, these increases were magnified as occupant density rose, or to a less extent, as hours of operation were extended to 24 hours a day.

Annual Energy Cost Impact

For the base building, modeled, raising outdoor air flow rates from 5 to 20 cfm per occupant had modest effects on annual energy costs ranging from annual HVAC energy cost increase of 2% - 10% (or an increase of total energy cost of approximately 1% to 4%) under base price conditions. Above this range are buildings with high occupant density. For example, the very high occupant density building (Building I) experienced HVAC cost increases of 9%-21% (approximately 4%-8% increase in total energy) under base price conditions. When alternative pricing structures are applied, the range of energy cost increases widened somewhat, ranging from 0% - 12% for HVAC energy (or approximately 0% to 5% total energy) for the base building, while for the high occupant density building the HVAC energy cost increase ranged from 8% to 24% (or approximately 4% to 10% for total energy) under alternative pricing structures.

The sensitivity of energy cost impacts to high occupant density situations has important implications. In this report, high occupant density is defined as 15 occupants per 1000 square feet. These densities are modest when compared to education buildings, auditoriums, theaters, and similar facilities where occupant densities can be 5 to 10 times that level. It raises special issues about the feasibility of maintaining adequate indoor air quality in these buildings by using the outdoor air ventilation rates recommended in ASHRAE Standard 62-1999. Because of this implication, this issue is addressed separately in detail in a companion report (Project Report #6).

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Exhibit 1: Building and HVAC Characteristics

Building Configuration	Window R-Value	Window Shading Coeffic.	Roof Insulation	Infiltration Rate	Chiller COP	Boiler Effic. (%)	Occup. Density (Occup/ 1000 SF)	P/C Ratio	Exhaust Flow Rate (cfm)	Daily Operating Hours (hrs/day)
A. Base Case	2.0	0.8	10	0.5	3.5	70	7	0.5	750	12
B. High Effic. Shell	3.0	0.6	20	0.75	3.5	70	7	0.5	750	12
C. Low Effic. Shell	1.0	1.0	5	0.25	3.5	70	7	0.5	750	12
D. High Effic. HVAC System	2.0	0.8	10	0.5	4.5	80	7	0.5	750	12
E. Low Effic. HVAC System	2.0	0.8	10	0.5	2.5	60	7	0.5	750	12
F. High P/C Ratio	2.0	0.8	10	0.5	3.5	70	7	0.8	750	12
G. Low P/C Ratio	2.0	0.8	10	0.5	3.5	70	7	0.3	750	12
H. High Exhaust Rate	2.0	0.8	10	0.5	3.5	70	7	0.5	1500	12
I. High Occup. Density	2.0	0.8	10	0.5	3.5	70	15	0.5	750	12
J. Medium Occup. Density	2.0	0.8	10	0.5	3.5	70	10	0.5	750	12
K. Low Occup. Density	2.0	0.8	10	0.5	3.5	70	5	0.5	750	12
L. Very Low Occup. Density	2.0	0.8	10	0.5	3.5	70	3	0.5	750	12
M. Extended Oper. Hours	2.0	0.8	10	0.5	3.5	70	7	0.5	750	18
N. 24 Hour Operation	2.0	0.8	10	0.5	3.5	70	7	0.5	750	24

Exhibit 2
Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with CV (FOAF) in Washington, DC

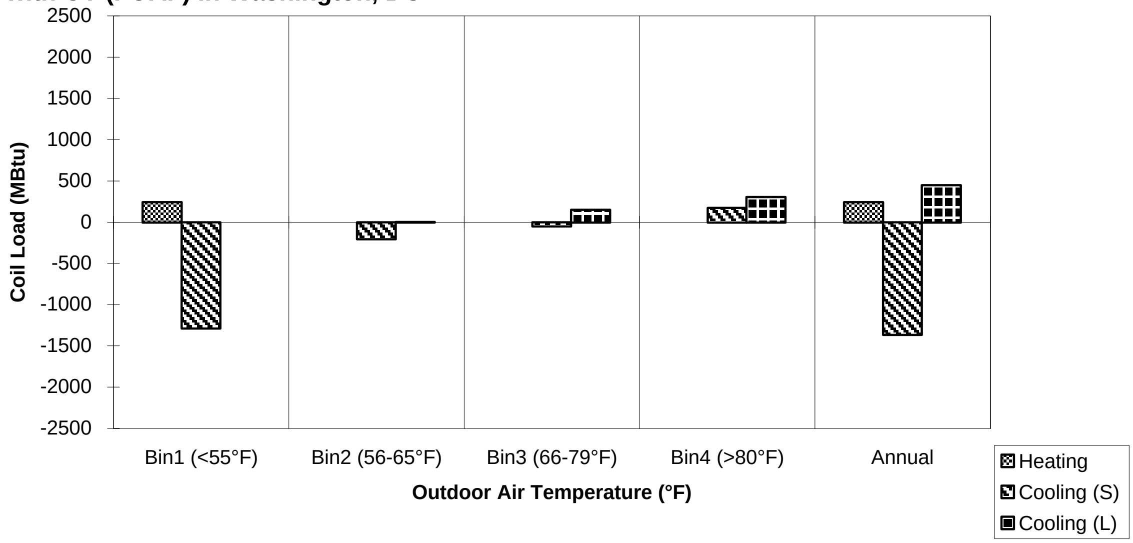

Exhibit 3
Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with CV (FOAF) $Econ_T$ in Washington, DC

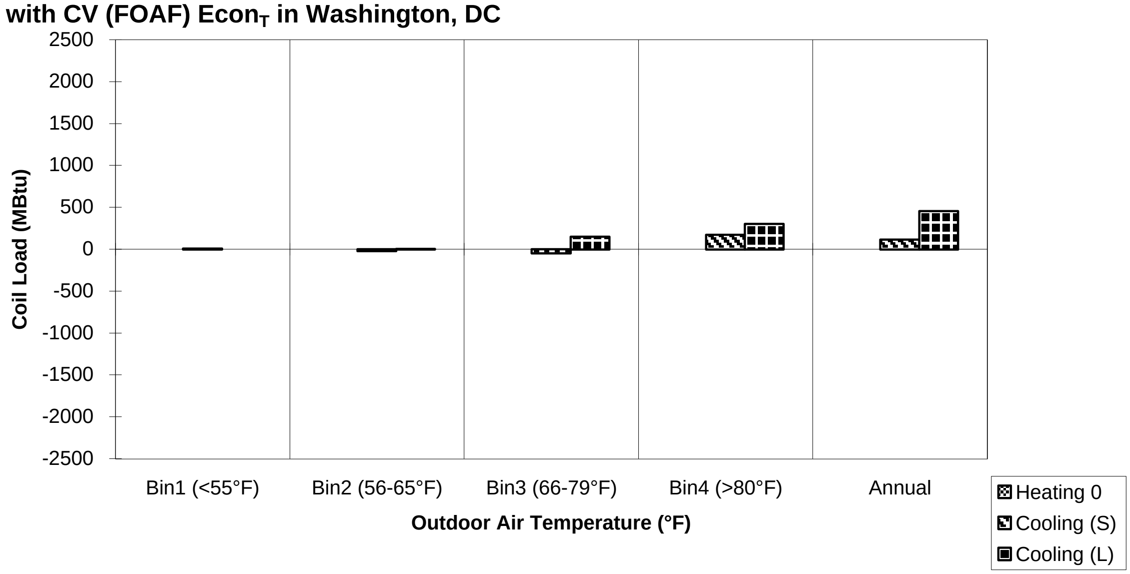

Exhibit 4
Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with VAV (COA) in Minneapolis, MN

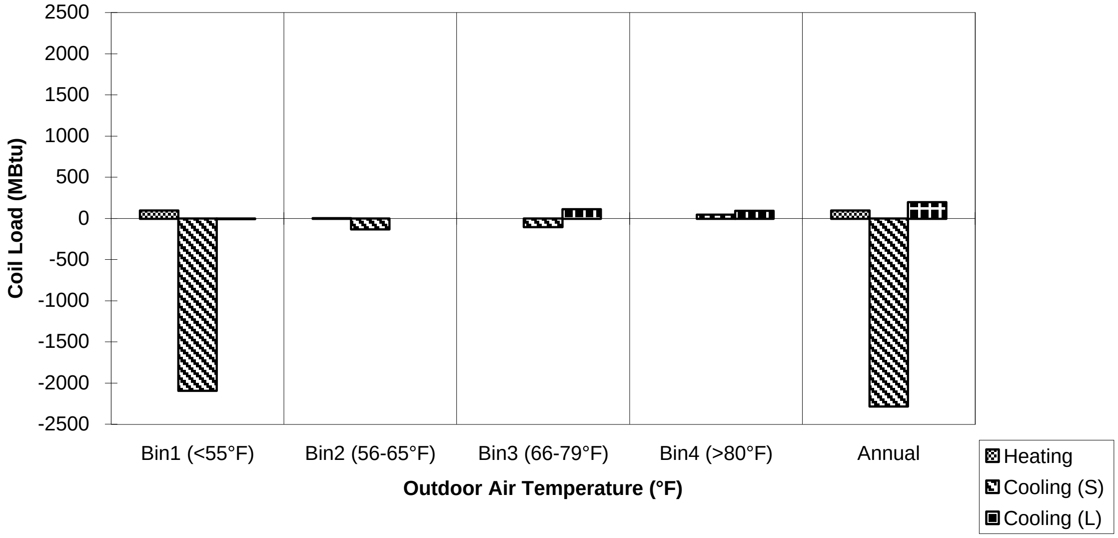

Exhibit 5
Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with VAV (COA) $Econ_T$ in Minneapolis, MN

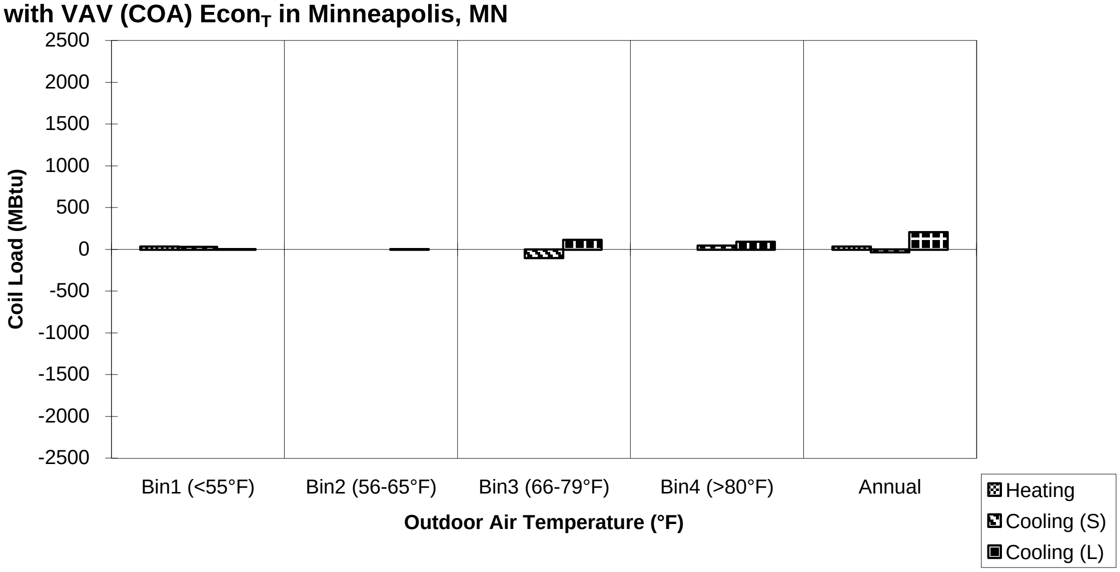

Exhibit 6

Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: CV Systems without Economizers

Building Configuration	Minneapolis, MN Cooling ($/sf)	Minneapolis, MN Heating ($/sf)	Minneapolis, MN Total ($/sf)	Washington, DC Cooling ($/sf)	Washington, DC Heating ($/sf)	Washington, DC Total ($/sf)	Miami, FL Cooling ($/sf)	Miami, FL Heating ($/sf)	Miami, FL Total ($/sf)
A. Base Case @5	0.49	0.02	0.83	0.51	0.00	0.81	0.63	0.00	0.94
Increase	0.03	0.02	0.05	0.05	0.01	0.06	0.08		0.08
Percent Increase	6%	83%	6%	9%	156%	7%	13%	None	9%
B. High Eff. Shell @5	0.46	0.01	0.73	0.48	0.00	0.73	0.59	0.00	0.87
Increase	0.02	0.01	0.04	0.04		0.05	0.08		0.08
Percent Increase	5%	141%	5%	9%	None	6%	14%	None	9%
C. Low Eff. Shell @5	0.52	0.07	0.96	0.55	0.02	0.93	0.69	0.00	1.02
Increase	0.04	0.03	0.06	0.06	0.01	0.07	0.08		0.08
Percent Increase	7%	38%	7%	11%	72%	8%	12%	None	8%
D. High Eff. HVAC @5	0.37	0.02	0.71	0.39	0.00	0.68	0.48	0.00	0.78
Increase	0.02	0.02	0.04	0.04	0.01	0.04	0.06		0.06
Percent Increase	6%	83%	6%	10%	156%	6%	13%	None	8%
E. Low Eff. HVAC @5	0.70	0.03	1.05	0.73	0.01	1.03	0.91	0.00	1.21
Increase	0.05	0.02	0.07	0.07	0.01	0.08	0.12		0.12
Percent Increase	7%	83%	7%	10%	156%	8%	13%	None	10%
F. High P/C Ratio @5	0.53	0.04	0.93	0.56	0.01	0.89	0.69	0.00	1.03
Increase	0.04	0.02	0.06	0.05	0.01	0.05	0.08		0.08
Percent Increase	4%	45%	4%	7%	69%	5%	9%	None	6%
G. Low P/C Ratio @5	0.44	0.01	0.72	0.47	0.00	0.72	0.56	0.00	0.82
Increase	0.03	0.02	0.04	0.04	0.01	0.05	0.09		0.09
Percent Increase	6%	140%	6%	9%	250%	6%	16%	None	11%
H. High Exhaust @5	0.50	0.03	0.86	0.52	0.01	0.83	0.66	0.00	0.97
Increase	0.02	0.01	0.04	0.04	0.01	0.04	0.06		0.06
Percent Increase	4%	50%	4%	7%	102%	5%	9%	None	6%
I. High Occ. Dens. @5	0.54	0.03	0.91	0.60	0.00	0.99	0.72	0.00	1.05
Increase	0.07	0.05	0.13	0.10	0.02	0.11	0.19		0.19
Percent Increase	14%	199%	14%	17%	408%	11%	27%	None	18%
J. Medium Occ. Dens. @5	0.51	0.02	0.86	0.54	0.01	0.84	0.66	0.00	0.98
Increase	0.05	0.03	0.08	0.07	0.01	0.08	0.13		0.13
Percent Increase	10%	129%	10%	13%	226%	10%	19%	None	13%
K. Low Occ. Dens. @5	0.48	0.03	0.81	0.50	0.01	0.79	0.62	0.00	0.92
Increase	0.02	0.01	0.04	0.03		0.03	0.05		0.05
Percent Increase	4%	51%	4%	6%	None	4%	8%	None	6%
L. Very Low Occ. Dens. @5	0.46	0.03	0.79	0.49	0.01	0.78	0.60	0.00	0.90
Increase	0.01	0.01	0.01	0.01		0.01	0.02		0.02
Percent Increase	2%	19%	2%	2%	None	2%	3%	None	2%
M. Extended Op. Hours @5	0.50	0.04	0.88	0.53	0.01	0.86	0.65	0.00	0.97
Increase	0.02	0.03	0.06	0.04	0.02	0.05	0.09		0.09
Percent Increase	5%	81%	7%	7%	117%	6%	15%	None	10%
N. 24 Hour Operation @5	0.52	0.06	0.96	0.55	0.02	0.94	0.69	0.00	1.07
Increase	0.01	0.06	0.07	0.03	0.03	0.06	0.10		0.10
Percent Increase	2%	91%	7%	5%	128%	6%	15%	None	10%

Exhibit 7

Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: VAV Systems without Economizers

	Minneapolis, MN			Washington, DC			Miami, FL		
Building Configuration	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)
A. Base Case @5	0.48	0.10	0.77	0.49	0.05	0.71	0.57	0.00	0.76
Increase	0.01		0.02	0.03		0.03	0.07		0.07
Percent Increase	3%	None	2%	6%	None	4%	13%	None	10%
B. High Eff. Shell @5	0.44	0.05	0.64	0.45	0.02	0.62	0.54	0.00	0.71
Increase	0.01		0.01	0.03		0.03	0.08		0.08
Percent Increase	2%	None	2%	7%	None	5%	14%	None	11%
C. Low Eff. Shell @5	0.51	0.20	0.92	0.54	0.11	0.85	0.62	0.01	0.82
Increase	0.01		0.02	0.03		0.04	0.07		0.07
Percent Increase	3%	None	2%	6%	None	4%	11%	None	8%
D. High Eff. HVAC @5	0.36	0.09	0.64	0.37	0.04	0.59	0.43	0.00	0.62
Increase	0.01		0.01	0.02		0.02	0.06		0.06
Percent Increase	3%	None	2%	6%	None	4%	13%	None	9%
E. Low Eff. HVAC @5	0.68	0.12	0.99	0.70	0.06	0.93	0.82	0.00	1.01
Increase	0.02		0.02	0.05		0.05	0.11		0.11
Percent Increase	3%	None	2%	7%	None	5%	13%	None	11%
F. High P/C Ratio @5	0.52	0.14	0.86	0.53	0.07	0.79	0.62	0.00	0.82
Increase	0.01		0.02	0.03		0.03	0.07		0.07
Percent Increase	2%	None	2%	4%	None	3%	9%	None	7%
G. Low P/C Ratio @5	0.42	0.06	0.65	0.44	0.03	0.62	0.52	0.00	0.68
Increase	0.01		0.02	0.03		0.03	0.08		0.08
Percent Increase	3%	None	2%	7%	None	5%	15%	None	12%
H. High Exhaust @5	0.48	0.10	0.78	0.50	0.05	0.73	0.60	0.00	0.79
Increase	0.01		0.01	0.02		0.02	0.05		0.05
Percent Increase	2%	None	2%	5%	None	3%	9%	None	7%
I. High Occ. Dens. @5	0.52	0.10	0.82	0.56	0.06	0.83	0.65	0.00	0.84
Increase	0.04	0.03	0.07	0.08	0.01	0.11	0.17		0.17
Percent Increase	8%	31%	9%	14%	23%	14%	26%	None	20%
J. Medium Occ. Dens. @5	0.49	0.10	0.79	0.51	0.05	0.74	0.60	0.00	0.79
Increase	0.02	0.01	0.03	0.04		0.04	0.11		0.11
Percent Increase	5%	8%	4%	8%	None	6%	19%	None	15%
K. Low Occ. Dens. @5	0.46	0.10	0.74	0.48	0.05	0.70	0.56	0.00	0.74
Increase	0.01		0.01	0.02		0.02	0.05		0.05
Percent Increase	2%	None	1%	4%	None	3%	8%	None	6%
L. Very Low Occ. Dens. @5	0.45	0.10	0.72	0.47	0.05	0.69	0.55	0.00	0.72
Increase				0.01		0.01	0.02		0.02
Percent Increase	None	None	None	2%	None	1%	3%	None	3%
M. Extended Op. Hours @5	0.49	0.15	0.84	0.51	0.09	0.79	0.60	0.02	0.81
Increase		0.01	0.01	0.02		0.02	0.07		0.07
Percent Increase	None	5%	1%	4%	None	3%	12%	None	9%
N. 24 Hour Operation @5	0.51	0.20	0.94	0.54	0.14	0.90	0.64	0.05	0.91
Increase	-0.02	0.01		0.01		0.01	0.08		0.08
Percent Increase	-4%	7%	None	2%	None	2%	13%	None	9%

Exhibit 8

Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: CV Systems with Economizers

Building Configuration	Minneapolis, MN Cooling ($/sf)	Minneapolis, MN Heating ($/sf)	Minneapolis, MN Total ($/sf)	Washington, DC Cooling ($/sf)	Washington, DC Heating ($/sf)	Washington, DC Total ($/sf)	Miami, FL Cooling ($/sf)	Miami, FL Heating ($/sf)	Miami, FL Total ($/sf)
A. Base Case @5	0.40	0.10	0.82	0.43	0.06	0.79	0.62	0.00	0.93
Increase	0.05		0.05	0.07		0.06	0.09		0.08
Percent Increase	13%	None	7%	15%	None	8%	14%	None	9%
B. High Eff. Shell @5	0.36	0.07	0.69	0.40	0.04	0.69	0.58	0.00	0.85
Increase	0.05	0.01	0.05	0.06		0.06	0.09		0.08
Percent Increase	13%	7%	8%	16%	None	9%	15%	None	10%
C. Low Eff. Shell @5	0.44	0.15	0.97	0.48	0.09	0.93	0.68	0.01	1.02
Increase	0.05		0.06	0.07		0.07	0.08		0.08
Percent Increase	12%	None	6%	15%	None	8%	12%	None	8%
D. High Eff. HVAC @5	0.30	0.09	0.71	0.33	0.06	0.67	0.47	0.00	0.78
Increase	0.04		0.04	0.05		0.05	0.06		0.06
Percent Increase	13%	None	6%	15%	None	7%	14%	None	8%
E. Low Eff. HVAC @5	0.58	0.12	1.01	0.62	0.07	0.98	0.89	0.01	1.20
Increase	0.07		0.08	0.10		0.09	0.12		0.12
Percent Increase	13%	None	8%	16%	None	10%	14%	None	10%
F. High P/C Ratio @5	0.44	0.13	0.93	0.48	0.08	0.89	0.68	0.01	1.02
Increase	0.05		0.05	0.06		0.06	0.08		0.08
Percent Increase	9%	None	4%	11%	None	6%	9%	None	6%
G. Low P/C Ratio @5	0.35	0.06	0.68	0.39	0.04	0.68	0.55	0.00	0.82
Increase	0.05		0.06	0.06		0.06	0.09		0.09
Percent Increase	15%	None	8%	15%	None	9%	16%	None	11%
H. High Exhaust @5	0.42	0.10	0.84	0.45	0.06	0.81	0.65	0.00	0.96
Increase	0.04		0.04	0.05		0.05	0.06		0.06
Percent Increase	8%	None	4%	11%	None	6%	10%	None	6%
I. High Occ. Dens. @5	0.45	0.10	0.89	0.51	0.05	0.94	0.70	0.00	1.04
Increase	0.11	0.02	0.13	0.13		0.13	0.19		0.19
Percent Increase	25%	19%	15%	26%	None	14%	28%	None	18%
J. Medium Occ. Dens. @5	0.42	0.10	0.84	0.46	0.06	0.82	0.65	0.00	0.97
Increase	0.08	0.01	0.08	0.09		0.09	0.13		0.13
Percent Increase	19%	6%	10%	20%	None	11%	20%	None	13%
K. Low Occ. Dens. @5	0.39	0.10	0.79	0.43	0.06	0.78	0.61	0.00	0.91
Increase	0.03		0.04	0.04		0.04	0.05		0.05
Percent Increase	9%	None	5%	9%	None	5%	9%	None	6%
L. Very Low Occ. Dens. @5	0.38	0.09	0.77	0.42	0.06	0.76	0.59	0.00	0.90
Increase	0.01		0.02	0.02		0.02	0.02		0.02
Percent Increase	4%	None	2%	4%	None	2%	3%	None	2%
M. Extended Op. Hours @5	0.38	0.14	0.85	0.42	0.09	0.83	0.63	0.01	0.96
Increase	0.05	0.01	0.06	0.06		0.06	0.10		0.10
Percent Increase	14%	7%	7%	14%	None	8%	15%	None	10%
N. 24 Hour Operation @5	0.36	0.19	0.93	0.41	0.11	0.89	0.66	0.01	1.05
Increase	0.05	0.02	0.07	0.06	0.01	0.07	0.10		0.10
Percent Increase	13%	12%	8%	14%	12%	8%	16%	None	10%

Exhibit 9
Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: VAV System with Economizer

Building Configuration	Minneapolis, MN Cooling ($/sf)	Minneapolis, MN Heating ($/sf)	Minneapolis, MN Total ($/sf)	Washington, DC Cooling ($/sf)	Washington, DC Heating ($/sf)	Washington, DC Total ($/sf)	Miami, FL Cooling ($/sf)	Miami, FL Heating ($/sf)	Miami, FL Total ($/sf)
A. Base Case @5	0.39	0.10	0.69	0.42	0.05	0.65	0.57	0.00	0.75
Increase	0.04		0.04	0.05		0.05	0.07		0.08
Percent Increase	10%	None	6%	12%	None	8%	13%	None	10%
B. High Eff. Shell @5	0.36	0.05	0.57	0.39	0.02	0.56	0.53	0.00	0.70
Increase	0.04		0.04	0.05		0.06	0.08		0.08
Percent Increase	11%	None	7%	14%	None	10%	15%	None	11%
C. Low Eff. Shell @5	0.43	0.20	0.84	0.47	0.12	0.79	0.61	0.01	0.81
Increase	0.04		0.04	0.05		0.05	0.07		0.07
Percent Increase	9%	None	5%	11%	None	7%	11%	None	9%
D. High Eff. HVAC @5	0.30	0.09	0.58	0.32	0.04	0.54	0.43	0.00	0.61
Increase	0.03		0.03	0.04		0.04	0.06		0.06
Percent Increase	10%	None	5%	12%	None	7%	13%	None	9%
E. Low Eff. HVAC @5	0.57	0.12	0.88	0.61	0.06	0.84	0.82	0.00	1.00
Increase	0.06		0.06	0.07		0.08	0.11		0.11
Percent Increase	10%	None	7%	12%	None	9%	13%	None	11%
F. High P/C Ratio @5	0.43	0.14	0.79	0.47	0.07	0.73	0.62	0.00	0.82
Increase	0.04		0.04	0.05		0.05	0.07		0.07
Percent Increase	7%	None	4%	8%	None	5%	9%	None	7%
G. Low P/C Ratio @5	0.35	0.07	0.57	0.38	0.03	0.56	0.51	0.00	0.67
Increase	0.04		0.04	0.05		0.05	0.08		0.08
Percent Increase	11%	None	7%	13%	None	9%	15%	None	12%
H. High Exhaust @5	0.41	0.10	0.71	0.44	0.05	0.67	0.59	0.00	0.78
Increase	0.03		0.03	0.04		0.04	0.05		0.05
Percent Increase	7%	None	4%	9%	None	6%	9%	None	7%
I. High Occ. Dens. @5	0.44	0.10	0.75	0.50	0.06	0.76	0.64	0.00	0.84
Increase	0.09	0.03	0.12	0.11	0.01	0.14	0.17		0.17
Percent Increase	20%	26%	16%	22%	21%	19%	27%	None	21%
J. Medium Occ. Dens. @5	0.41	0.10	0.71	0.45	0.05	0.68	0.59	0.00	0.78
Increase	0.06	0.01	0.07	0.07		0.07	0.12		0.12
Percent Increase	15%	6%	9%	15%	None	10%	19%	None	15%
K. Low Occ. Dens. @5	0.38	0.10	0.66	0.42	0.05	0.64	0.55	0.00	0.73
Increase	0.03		0.03	0.03		0.03	0.05		0.05
Percent Increase	7%	None	4%	7%	None	5%	8%	None	6%
L. Very Low Occ. Dens. @5	0.37	0.10	0.65	0.41	0.05	0.63	0.54	0.00	0.72
Increase	0.01		0.01	0.01		0.01	0.02		0.02
Percent Increase	3%	None	2%	3%	None	2%	3%	None	3%
M. Extended Op. Hours @5	0.38	0.15	0.73	0.42	0.09	0.70	0.59	0.02	0.80
Increase	0.04		0.04	0.05		0.05	0.07		0.08
Percent Increase	10%	None	6%	11%	None	7%	13%	None	9%
N. 24 Hour Operation @5	0.36	0.22	0.80	0.41	0.15	0.78	0.62	0.05	0.89
Increase	0.04	0.01	0.05	0.05		0.05	0.09		0.09
Percent Increase	11%	4%	6%	12%	None	6%	14%	None	10%

Exhibit 10
Alternative Utility Rate Structures

	Rate Class			Rate Structure			
Rate Structures	Gas Rate	Electric Rate	Electric Demand	Gas Rate	Electric Rate	Electric Demand	Ratchet Clause
Base	Average	Average	Average	$0.490	$0.044	$7.890	No
1	Low	High	Average	$0.330	$0.063	$7.890	No
2	High	Low	Average	$0.650	$0.025	$7.890	No
3	Average	Average	High	$0.490	$0.044	$11.710	No
4	Average	Average	Low	$0.490	$0.044	$4.070	No

Exhibit 11
Comparison of Annual HVAC Energy Costs Under Alternate Price Structures
With Outdoor Air at 20 cfm per occupant

HVAC System / Building	Minneapolis, MN					Washington, DC					Miami, FL				
	Base $/sf	Lo Gas Hi Elc $/sf	Hi Gas Lo Elc $/sf	Hi Dmd $/sf	Lo Dmd $/sf	Base $/sf	Lo Gas Hi Elc $/sf	Hi Gas Lo Elc $/sf	Hi Dmd $/sf	Lo Dmd $/sf	Base $/sf	Lo Gas Hi Elc $/sf	Hi Gas Lo Elc $/sf	Hi Dmd $/sf	Lo Dmd $/sf
CV(FOAF)															
A	0.88	1.08	0.69	1.05	0.72	0.86	1.07	0.65	1.03	0.69	1.02	1.30	0.74	1.20	0.84
I	1.04	1.24	0.83	1.25	0.83	1.10	1.36	0.84	1.33	0.87	1.24	1.56	0.91	1.47	1.00
N	1.03	1.24	0.82	1.19	0.87	1.00	1.25	0.75	1.17	0.84	1.17	1.53	0.82	1.35	1.00
VAV/COA															
A	0.78	0.91	0.66	0.93	0.63	0.74	0.89	0.60	0.90	0.59	0.83	1.04	0.62	0.99	0.67
I	0.89	1.02	0.77	1.08	0.71	0.94	1.12	0.77	1.14	0.74	1.01	1.26	0.77	1.23	0.80
N	0.94	1.05	0.83	1.08	0.79	0.92	1.07	0.76	1.06	0.77	0.99	1.24	0.73	1.14	0.84
CV(FOAF)/$Econ_t$															
A	0.87	1.02	0.72	1.04	0.71	0.85	1.02	0.68	1.02	0.68	1.01	1.29	0.74	1.19	0.84
I	1.02	1.19	0.85	1.23	0.82	1.07	1.30	0.85	1.30	0.85	1.23	1.55	0.91	1.46	1.00
N	1.00	1.13	0.87	1.16	0.84	0.96	1.14	0.79	1.13	0.80	1.16	1.49	0.82	1.33	0.99
VAV/COA/Econ T															
A	0.73	0.83	0.63	0.88	0.58	0.70	0.82	0.57	0.85	0.54	0.83	1.04	0.62	0.99	0.66
I	0.86	0.97	0.75	1.05	0.68	0.91	1.06	0.75	1.11	0.70	1.01	1.25	0.77	1.22	0.80
N	0.84	0.91	0.78	0.99	0.70	0.83	0.95	0.72	0.98	0.68	0.98	1.23	0.73	1.13	0.83

Exhibit 12

Comparison of Percent Increase in Annual HVAC Energy Costs when Increasing Outdoor Air Flow Rates from 5 to 20 cfm per Occupant under Alternate Price Structures

HVAC System / Building	Minneaplis, MN					Washington, DC					Miami, FL				
	Base $/sf	Lo Gas Hi Elec $/sf	Hi Gas Lo Elec $/sf	Hi Demand $/sf	Lo Demand $/sf	Base $/sf	Lo Gas Hi Elec $/sf	Hi Gas Lo Elec $/sf	Hi Demand $/sf	Lo Demand $/sf	Base $/sf	Lo Gas Hi Elec $/sf	Hi Gas Lo Elec $/sf	Hi Demand $/sf	Lo Demand $/sf
CV(FOAF)															
A	6%	4%	10%	7%	5%	7%	5%	10%	8%	5%	9%	8%	11%	10%	7%
I	14%	9%	21%	15%	12%	11%	9%	16%	14%	8%	18%	16%	21%	20%	15%
N	7%	3%	13%	8%	6%	6%	4%	10%	7%	5%	10%	9%	10%	10%	9%
VAV/COA															
A	2%	1%	4%	4%	0%	4%	3%	7%	6%	2%	10%	9%	12%	11%	8%
I	9%	5%	14%	11%	5%	14%	11%	17%	16%	10%	20%	18%	24%	23%	17%
N	0%	-3%	3%	1%	-2%	2%	0%	4%	3%	0%	9%	8%	10%	10%	8%
CV(FOAF)Econ$_T$															
A	7%	6%	7%	7%	5%	8%	8%	9%	9%	6%	9%	8%	11%	10%	8%
I	15%	13%	17%	16%	13%	14%	12%	16%	16%	11%	18%	16%	21%	20%	15%
N	8%	6%	9%	8%	7%	8%	7%	10%	9%	7%	10%	10%	11%	10%	9%
VAV(COA)Econ$_T$															
A	6%	5%	7%	7%	4%	8%	7%	9%	9%	6%	10%	9%	12%	11%	8%
I	16%	14%	19%	17%	14%	19%	17%	21%	20%	16%	21%	19%	24%	23%	17%
N	6%	6%	7%	7%	5%	6%	6%	7%	7%	5%	10%	9%	10%	10%	8%