Energy Cost and IAQ Performance of Ventilation Systems and Controls

Project Report # 2 **Assessment of CV and VAV Ventilation Systems and Outdoor Air Control Strategies for Large Office Buildings**

Outdoor Air Flow Rates and Energy Use

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INTRODUCTION

Purpose and Scope of this Report

Constant volume (CV) air handling systems provide a constant flow of ventilation air at all operating conditions, and were the staple of the HVAC design community for many years. Because the ventilation air quantities in these systems do not change, maintaining a minimum outdoor airflow is a matter of establishing a minimum outdoor air damper setting. In the last fifteen years, variable air volume (VAV) ventilation systems have become more popular with design engineers because of their improved energy efficiency over CV systems. When VAV systems were introduced as being more energy efficient, they often employed outdoor air controls similar to those of the older CV systems. However, since the total supply air flow in a VAV system varies in response to varying thermal loads, the outdoor air flow rate into the building may also be expected to vary, unless specific provisions are introduced to maintain a constant outdoor air flow rate. Thus, the variations in air flow have created new challenges for maintaining minimum outdoor air flow.

Using the DOE-2.1E energy simulation model, this report systematically compares the outdoor air flow quantities of CV and VAV air handling systems in a large office building under a variety of outdoor air control and economizer strategies, and examines the energy implications of these strategies. This assessment is conducted for three climate regions representing cold (Minneapolis), temperate (Washington, D.C.) and hot/humid (Miami) weather conditions. A companion report (Project Report #3) examines how these systems distribute outdoor air and control thermal comfort in individual zones.

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 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 was modeled in three different climates representing cold (Minneapolis), temperate (Washington, D.C.), and hot/humid (Miami) climate zones. The building has 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 with temperature reset, and a single duct variable volume (VAV) system with reheat were modeled. 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.

Three basic outdoor air control strategies were modelled: fixed outdoor air fraction (FOAF), constant outdoor air (COA), and air-side economizer (ECON). The FOAF strategy maintained a constant outdoor air fraction (percent outdoor air) irrespective of the supply air volume. The FOAF strategy maintained a constant outdoor air fraction (percent outdoor air) irrespective of the supply air volume. For VAV systems, the FOAF may be approximated in field applications by an outdoor damper in a fixed position (Cohen 1994; Janu 1995; and Solberg 1990), but specific field applications are not addressed in this study. The FOAF strategy was modeled so that the design outdoor air flow rate is met at the design cooling load, and diminishes in proportion to the supply flow during part-load. 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, and are referred to in this report as CV (FOAF). 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. Specific control mechanics which would achieve a VAV (COA) have been addressed by other authors, (Haines 1986, Levenhagen 1992, Solberg 1990) but are not addressed in this modeling project.

Two air-side economizer strategies are used, one based on temperature ($ECON_t$) and one on enthalpy ($ECON_e$). The economizer strategies override the outdoor air flow called for by the prevailing strategy (FOAF or the COA) by bringing in additional quantities of outdoor air to provide “free cooling” when the outdoor air temperature (or enthalpy) is lower than the return air temperature (or enthalpy). The quantity of outdoor air is adjusted so that the desired supply air discharge temperature (or enthalpy) can be achieved with minimum mechanical cooling. Because outdoor air humidity levels are sometimes high during warm weather, the temperature economizer in this project is shut off at outdoor temperatures above 65^o F.

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

APPROACH

In this report, the outdoor air quantities for each HVAC system and OA control strategy are determined over the full range of thermal loads. The systems design setting is 20 cfm of outdoor air per occupant, which is prescribed for office spaces by ASHRAE Standard 62-1999[1]. The outdoor air flow rates were established for design occupancy levels and were not changed as occupancy varied during the day.

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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.

Annual energy use (KBtu/ft^2) is converted to energy cost under the base price structure of $.044 per kilowatt-hour, and $7.89 per kilowatt and $0.49 per therm. A sensitivity analysis is also conducted to determine how sensitive the conclusions are to relative utility prices. Since Minneapolis, Washington, D.C. and Miami are used only to represent different climate conditions, no attempt was made to use the actual energy prices in these individual cities. Derivation of the pricing scenarios is provided in Report #1

RESULTS

The presentation of results is organized to shed light on the following questions:

a. Do the energy savings in VAV systems justify the potential shortfall in delivering desired quantities of outdoor air? What are optimal outdoor air control strategies for CV and VAV systems?

b. How significant are advantages of economizer strategies in energy savings and outdoor air flow rates? When do enthalpy economizers make sense?

c. How might operating engineers change outdoor air flow settings to improve the performance of existing HVAC systems?

Comparing CV and VAV Systems

Energy Advantage of VAV Systems

Exhibit 1 presents the annual energy use and annual energy costs for operating each of the CV and VAV systems modeled without economizers. The data confirm the energy savings associated with VAV systems. For example, the annual energy cost of the CV(FOAF) system is $.86/sf, while the annual cost of VAV(FOAF) system is only $.74/sf, or 14% less for the Washington, D.C. climate. The VAV(FOAF) system is 10% less in Minneapolis and 21% less in Miami compared to the CV (FOAF) system. As expected, most of the savings results because fan energy is cut almost in half. The modeled CV system is a dual duct system with temperature reset capabilities, which is much more energy efficient than other CV systems, and therefore the results tend to underestimate the advantages of conversion from CV to VAV systems.

Except in Miami where heating is negligible, more heating energy is used in the VAV than in the comparable CV systems. This is because the VAV system modeled reheats the supply air at the VAV box after it is cooled at the central air handler.

Outdoor Air Shortfall with VAV(FOAF) Systems

Exhibit 2 compares the outdoor air flow rate of CV(FOAF), VAV(FOAF) and the VAV(COA) systems set to deliver 20 cfm of outdoor air per person at the design cooling load. This plot is based on hourly data over the full year, and shows the average OA flow rate delivered by the air handler for all the hours associated with each outdoor air temperature - Winter at the left end of the horizontal axis, Spring/Fall in the middle, and Summer at the right end.

Since the CV system operates on a constant supply air volume, the CV(FOAF) strategy brings in a constant supply of outdoor air, and is therefore comparable to the VAV(COA) system. Most of the year, the VAV(FOAF) system operates at considerably less than the design setting of 20 cfm per person and only approaches this value as the supply air increases toward its design cooling flow rate (far right of the graph). At off-peak conditions (periods of mild or cool weather), the requirement for supply air is reduced, and the OA flow rate is reduced proportionately. At Spring and Fall conditions, the amount of OA delivered from the air handler is almost one half of this design value. The OA flow rate in the summer is at or near the required 20 cfm per occupant which is reached at design load[2].

How often the flow of outdoor air in the VAV(FOAF) system is significantly below design depends on the outdoor climate - the proportion of the year that the outdoor temperature is substantially below summer design temperature. Exhibits 3A and 3B presents this information for the three climates, along with the proportion of time the VAV(FOAF) system delivered outdoor air flow rates at various levels. In this case, the performance was worse in the colder climate (Minneapolis)[3] where the system almost never delivered more than 15 cfm of outdoor air per person, delivering only 6 - 10 cfm per person 42% of the time, and 11 - 15 cfm per person 56% of the time. The performance was marginally better in the temperate climate of Washington, D.C., but even here, the VAV(FOAF) system exceeded 15 cfm of outdoor air only 5% of the time. The ventilation system performed best in Miami because of cooling load dominance, where it never delivered less than 10 cfm, and most often delivered more than 15 cfm of outdoor air per occupant. But in no case did the VAV(FOAF) system provide the 20 cfm of outdoor air per person that the system was “designed” to achieve.

Outdoor Air and Energy Trade-offs

What, if any, of the energy savings of VAV(FOAF) system can be associated with this shortfall in the delivery of outdoor air? To examine this question, it is useful to compare the energy performance of the VAV(COA) system which continuously provides 20 cfm/occupant to that of the VAV(FOAF) system which delivers considerably less outdoor air. A glance at Exhibit 1 reveals that the diminished outdoor air flow of the VAV(FOAF) system did not reduce energy consumption

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[2] The design load is an estimate of the peak or close to peak load based on anticipated internal loads, and outdoor temperature and relative humidity which is published for major cities and climate regions. Since the design load is an estimate, it may never be experienced in a given year.

[3] It would not always be worse in the colder climates, because as the outdoor temperature gets colder, the supply air and outdoor air volumes may rise. When the heating load rises sufficiently in cold weather to offset the declining cooling load, the VAV(FOAF) system would increase the supply air volume, and consequently the outdoor air volume. This did not occur to any substantial degree in the base building for the Minneapolis climate. The outdoor temperature at which this offset point occurs is colder for more efficient building shells or for buildings with low perimeter to core ratios.

or reduce energy costs. In fact, for the cold and temperate climates of Minneapolis and Washington, D.C., energy use and energy costs of the VAV(FOAF) system were marginally greater than the VAV(COA) system, and only marginally less than the VAV(COA) system in Miami.

This result is consistent with the fact that additional outside air during cooler weather provides some degree of free cooling, which is the concept underlying the economizer outdoor air control strategies. This added cooling benefit of the additional outdoor air in the VAV(COA) system was more than enough to offset the added cooling burden during the hot summer season. The VAV(COA) system, therefore, provided net energy advantages equivalent to the VAV(FOAF) system while providing quantities of outdoor air equal to the older CV systems. It appears, therefore, to be highly advantageous to design control mechanisms to achieve the VAV(COA) strategy for both energy efficiency and indoor air quality purposes in all climates.

Conversely, the VAV system with fixed fraction outdoor air offered no energy or indoor air quality advantage to recommend it. Rather, the analysis suggests reasons for avoiding control mechanisms that approximate the VAV(FOAF) system[4].

Economizer Strategies

Both temperature economizers and enthalpy economizers were modeled with the CV(FOAF), VAV(FOAF), and VAV(COA) systems. The energy data for the economizer systems is presented in Exhibit 4. Exhibit 5 presents the percent difference in HVAC energy use and energy costs associated with each economizer over its base system. Economizers on the CV systems modeled offered energy cost savings on the order of 1% - 2% in the cold and temperate climate, while economizers in VAV systems offered savings of 6% - 10% in these climates. Enthalpy economizers provided only marginal increased savings over the temperature economizer modeled.

Economizers offered significant energy savings in the cold and temperate climates of Minneapolis and Washington, D.C., but have no meaningful affect on energy use in the hot humid climate of Miami. This is because hot humid climates offer little opportunity for economizing. Exhibit 3B shows the proportion of time each climate experiences cold, temperate, and hot weather conditions. Opportunities for economizers to provide “free cooling” exist only about 10% of the time in Miami compared to approximately 70% of the time in Minneapolis and 60% of the time in Washington, D.C.

Since air-side economizers both increase the quantity of outdoor air and, in most cases, save energy, they would appear to be advantageous. However, temperature economizers can create humidity problems in some climates. In this modeling study, the temperature economizer was shut

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[4] All the central HVAC systems studied created an unequal distribution of outdoor air to different occupied zones where the core zone received a lower than average airflow. Because of this, the reduced outdoor airflow at the air handler with the VAV(FOAF) system exacerbated potential problems caused by this outdoor air shortfall in the core zone (see Project Report #3).

off at temperatures above 65^0 F to avoid bringing in excessively humid air in the spring and summer periods (See Project Report #1). Economizers also increase the potential for contaminating the indoor environment with outdoor pollutants. Where outdoor pollution is a problem, the indoor air quality impact of economizers would have to be carefully examined.

High Outdoor Air Flow and Heating Penalties of CV Economizers

The energy use data on Exhibit 5 shows that for the CV system, economizers actually increased the energy use by up to 13% even while the energy costs were reduced. This is because, particularly in cold climates, increasing outdoor air quantities carries with it a heating penalty, even while the cooling burden is reduced. The cost savings for cooling exceeded the added costs for heating and thus a net energy cost savings was achieved. This is particularly significant for the CV systems modeled. Exhibit 6 compares the outdoor air flow rates at various outdoor temperatures for the temperature economizers of a CV and a VAV system in the Minneapolis climate[5]. In both the CV and VAV system, more than 20 cfm of outdoor air per occupant is brought into the building, even at sub-zero temperatures as a means of cooling the supply air to achieve a desired discharge temperature[6]. However, the economizing outdoor air flow rates are considerably higher in the CV system than in the VAV system. This is because the part-load supply air flow in the CV system is higher, and therefore requires a higher outdoor air quantity to achieve the desired mixed air temperature.

The added quantity of cool outdoor air in the CV system provided free cooling for the core of the building, but it carried with it a heating penalty for the perimeter zones. This added heating penalty diminished the advantage of the economizer in overall energy costs for the CV system. However, this would not likely be the case for dual fan, dual duct CV systems with separate economizers for the hot and cold coils. Since the heating energy in the systems modeled is gas rather than electricity, the energy cost advantage of economizers is sensitive to the relative price of these two fuels. Exhibit 7 demonstrates that with relatively high gas and low electricity prices, economizers on the CV system modeled could actually increase energy costs when gas prices are high relative to electricity prices.

Outdoor Air and Energy Performance of VAV Economizers

Exhibit 8 presents economizer outdoor air flow rates for the VAV systems in Minneapolis. The outdoor air flow rates for both temperature and enthalpy economizers are identical below 65° F at

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[5] The pattern is similar for all climates. The differences in annual average outdoor air flow rates between climates depends mostly on the proportion of the year that a climate will experience cold, temperate, or hot outdoor temperatures.

[6] In cold weather, the economizer causes the outdoor air damper to open sufficiently to provide a mixed air temperature of about 55°F, so theoretically, there should be no problem in freezing the coil. However, because of imperfect mixing, coil freezing may still occur. Therefore, the outdoor air flow is sometimes purposely reduced in extreme cold conditions, or the outdoor air may have to be preheated, to avoid freezing of the coil. See Project Report #5 for a discussion of the capacity constraints associated with raising outdoor air flow rates.

which point the temperature economizer is modeled to shut off. The enthalpy economizers continue to operate to temperatures as high as 80º F, bringing in additional outdoor air[7]. The pattern is similar for all climates.

The annual average outdoor air performance of the VAV(FOAF) system was considerably improved when an economizer was added but significant shortfalls still remained. Exhibit 9 compares the outdoor air flow rates of VAV systems. Without the economizer, the VAV(FOAF) system never achieved the design 20 cfm of outdoor air, and was below 11 cfm per person 42% of the occupied hours for Minneapolis and 17% of the occupied hours for Washington, D.C. Adding the temperature economizer kept the outdoor air flow rate above 10 cfm/occupant during all occupied hours, but still showed significant shortfalls. Adding the enthalpy economizer improves the performance more, but the outdoor air flow rate was between 11 and 15 cfm per occupant 19% of the time in Minneapolis and 28% of the time in Washington D.C.

As was the case without economizers, the shortfalls in outdoor air supply of the VAV(FOAF) system with economizers were not counterbalanced by meaningful energy savings when compared to economizers applied to the VAV(COA) system. This suggest that a control mechanism which approximates the VAV(FOAF) system, even with economizer operation, is not a mechanism which is easily justified based on its performance characteristics.

Systems which approximate the VAV(COA)(ECON) strategy appear to offer the best overall performance in terms of providing requisite outdoor air flow over the full year while attaining significant energy advantages or no meaningful energy disadvantage over alternative systems. In hot humid/climates, the VAV(COA) system is equally advantageous since there is little opportunity for economizer operations. All economizers may need to incorporate humidity controls, and economizer advantages may be compromised when outdoor air pollution levels are high.

Possible Corrections for Existing VAV(FOAF) Systems

Increasing Outdoor Air Flow Setting

Short of installing a new outdoor air control system, owners of buildings with VAV(FOAF) systems may wish to improve the ventilation and/or energy performance of this system by simply resetting the system to bring in larger amounts of outdoor air. In addition to the design load setting of 20 cfm per occupant, higher design load settings of 30, and 45 cfm per occupant were also modeled to determine the impact on both outdoor air flow rates and energy consumption. Exhibits 10 and 11 display the outdoor air flow rates in graphical and tabular formats. Exhibit 12 show the energy implications of these settings.

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[7] The temperature economizer is modeled to shut off at 65ºF. Above 65ºF, the outdoor humidity could be too high. In practice, this shut off temperature would be climate dependent (e.g., in dry climates it might be set at 75ºF. The enthalpy economizer has no automatic shut off since it will automatically shut off when the outdoor humidity is too high. Exhibit 8 shows the *average* outdoor air flow rate for the economizer systems at each outdoor air temperature. *On average*, the enthalpy is operational between 65ºF and 80ºF even though it does not operate under high humidity conditions.

The results are surprising. Raising the design outdoor air flow rate to 30 cfm per occupant improved the outdoor air performance of the VAV(FOAF) system considerably at a cost of only $0.01 - $0.02 per square foot in Minneapolis and Washington, D.C. and $0.03 per square foot in Miami. At a design setting of 45 cfm per occupant in Minneapolis and Washington, D.C. energy costs rose by $0.05 - $0.06 per square foot, while 20 cfm of outdoor air was provided all year round.

These cost increases are modest, and may be worthwhile to insure adequate outdoor air flow. A potential problem is that raising the design outdoor air setting requires large increases in the outdoor air flow rate at peak cooling and heating conditions. The additional burden of this outdoor air on the heating and cooling coils could exceed the original coil design loads. If this should happen in the summer, space conditions may become excessively warm. Increasing the outdoor air flow on very cold winter days could cause freezing and permanent damage to the coils in the central air handlers.

Resetting the Outdoor Air Flow Rate Each Season for VAV(FOAF)

A more effective strategy might be to reset the outdoor air control system at each season in an attempt to mimic a VAV(COA) enthalpy economizer. This could avoid some of the capacity problems mentioned above, while improving the energy performance of the system. For ease of interpretation by operating engineers, Exhibit 13 translates the outdoor air flows of the VAV(COA) enthalpy economizer to percent outdoor air. Exhibits 8 and 13 suggest that using a setting of 40% outdoor air during the winter (e.g., below 40º F) a setting of 85 % outdoor air during the spring and fall, (e.g., 40-79º F), and a setting of 20% outdoor air during the hot summer period (e.g., above 80º F and above), would approximately mimic the VAV(COA) enthalpy economizer. To model this strategy, the settings specified in Exhibit 14 were used.

The effects of this outdoor air flow reset strategy, relative to the VAV(FOAF) control strategy, are presented in Exhibits 15 and 16. These Exhibits suggest that a four season reset strategy has the potential of achieving improved outdoor air performance at little energy expense in temperate climates like Washington, D.C. In Exhibit 15, the energy used by the two control strategies is almost identical in all three climates. However, the cooling costs were 10 to 20 percent higher in Minneapolis and Miami. This increase is due to the increase in peak loads and peak demand in these two climates. As expected, Exhibit 16 shows that the outdoor air flow rates were significantly improved when the reset strategy was used. The reset strategy is less effective in Miami, since the economizer is not operational during a large part of the year (i.e., when the outdoor air temperature is above 75°F) .

Summer Reset for VAV(FOAF)(ECON)

For existing VAV(FOAF) systems with temperature or enthalpy economizers, a simple improvement would be to reset the system to bring in 20 cfm per occupant (18% outdoor air) for a modest summer load (e.g., 90º F), rather than at design load. Effectively, this amounts to resetting the design load damper setting to 30 cfm per occupant. Exhibits 17 and 18 present the results of this modification. Provided that there is sufficient capacity in the cooling system, this should not have a significant effect on energy, but it would improve the outdoor air performance of this system during summer months.

This simple resetting of the outdoor air flow to achieve 20 cfm per person at 90ºF rather than at design load improved the outdoor air performance in all climates, insuring that this system achieved at least 15 cfm per occupant all year round. The cost for such an improvement ranged from $0.02 to $0.03 per square foot (3-4%) in Minneapolis and Washington, D.C. and from $0.03 to $0.05 per square foot (4-6%) in Miami. A major portion of this increment occurred during very hot summer days. Some reduction in cost would likely be achieved if the damper were manually reset to its original minimum position during these very hot days.

EFFECTS OF UTILITY RATES ON ENERGY COSTS

Exhibits 19-24 compares the energy costs of the base office building under the different utility price structures outlined in Exhibit 7a. As expected, the results reflect the greater sensitivity of energy costs to electric prices relative to gas, because the HVAC systems employed use gas only for heating, while most commercial buildings are cooling dominated. However, as previously demonstrated with CV economizers, when alterations to the HVAC system dramatically change the relative use of heating and cooling energy, the effect on energy costs can be substantial.

These exhibits also demonstrate the relative importance of electric demand charges. For example, in Exhibit 7a which shows the utility prices used under the different rate structures, there is a 48% difference between the high (or low) demand charges and the base rate. Exhibit 20 shows that this increase (or decrease) in demand charges resulted in an increase (or decrease) in energy costs of about 20% in Miami where gas usage is minimal, and somewhat lower in Washington D.C. and Minneapolis where gas usage is higher. Thus, approximately 40% of electric energy cost (20/48 = 0.20), was from electric demand charges, which reflect peak load rather than actual kilowatt hours of electricity consumed.

SUMMARY & CONCLUSIONS

Constant volume ventilation systems provide a constant flow of ventilation air at all operating conditions, and were the staple of the HVAC design community for many years. The fact that ventilation air quantities in these systems do not change both simplifies the task of maintaining system balance, and assures that designated quantities of outdoor air enter the building under ***all*** operating conditions.

In the last fifteen years, variable air volume ventilation systems have become more popular with design engineers because of their improved energy efficiency over constant volume systems. These systems vary the amount of supply air in response to variations in thermal demand, and use less energy primarily because they move less air. This report suggests that the energy cost savings are are conservatively 10% -21% compared with CV systems. However, the variations in air flow can create new challenges for maintaining system balance, and have raised a number of issues concerning the ability of these systems to adequately dilute indoor contaminants at ***part load*** conditions.

Maintaining system balance in VAV systems is a challenge which is not addressed in this project. However, the ability of VAV systems to adequately dilute contaminants with outdoor air is addressed. Serious questions regarding VAV system outdoor air control relate to whether commonly used control mechanisms approximate a fixed outdoor air fraction or a constant outdoor air flow. The results of this study suggest that the implications of this question are more related to indoor air quality than they are related to energy consumption.

This report suggests that the outdoor air quantities actually supplied by systems which approximate VAV(FOAF) can be significantly less than the design quantity. When set to deliver 20 cfm of outdoor air at design conditions, VAV(FOAF) actually deliver only 6-10 cfm a substantial portion of the time in cold and temperate climates, and almost never exceeded 15 cfm in those climates. In warmer climates, the outdoor air performance was improved, but was only between 10 and 15 cfm per occupant almost half the time. Adding an economizer improved the overall outdoor air performance, but still left the buildings with less than design quantities of outdoor air during a significant portion of the year.

This study suggests that the energy cost savings of VAV systems are not compromised if the outdoor control strategy provides 20 cfm of outdoor air under all operating conditions. In fact, only in the cold climate of Minneapolis, was the energy cost of the VAV(FOAF) system greater than for the VAV(COA) system, and the difference was marginal. In the temperate climate of Washington, D.C., and in the Miami climate, providing 20 cfm of outdoor air year round, resulted in a marginal energy cost saving. It is therefore not likely that the systems which approximate VAV(FOAF) could be justified on either energy or indoor air grounds. Control mechanisms which approximate the VAV(COA) system, on the other hand, appear to be a highly advantageous for both energy efficiency and indoor air quality. It would appear to be the preferred system for both retrofit and new construction.

Adding either an air-side temperature or enthalpy economizer to the VAV(COA) strategy provided significant additional savings in energy cost of $ 0.04 - $0.06 per square foot (6% - 8%) in the cold and temperate climates of Minneapolis and Washington, D.C. Economizers did not offer advantages in hot/humid climates where there is little opportunity for economizer operations.

Provided that humidity is controlled and outdoor pollution is not excessive, economizers appear to offer the advantages from both energy conservation and indoor air quality perspectives.

Operational modifications for existing VAV(FOAF) systems could improve their outdoor air performance without retrofit, at what appears to be little to no energy cost, and in some cases could possibly result in an energy savings. For VAV(FOAF) systems, a four season reset strategy was modeled and produced favorable results. The operation of the VAV(FOAF) system with temperature and enthalpy economizers were modified with a simple reset of the outdoor air damper during the summer period when the economizers are not operating to improve their outdoor air performance. Doing this likely to increased energy costs only marginally 3 - 4% per square foot in cold and temperate climates.

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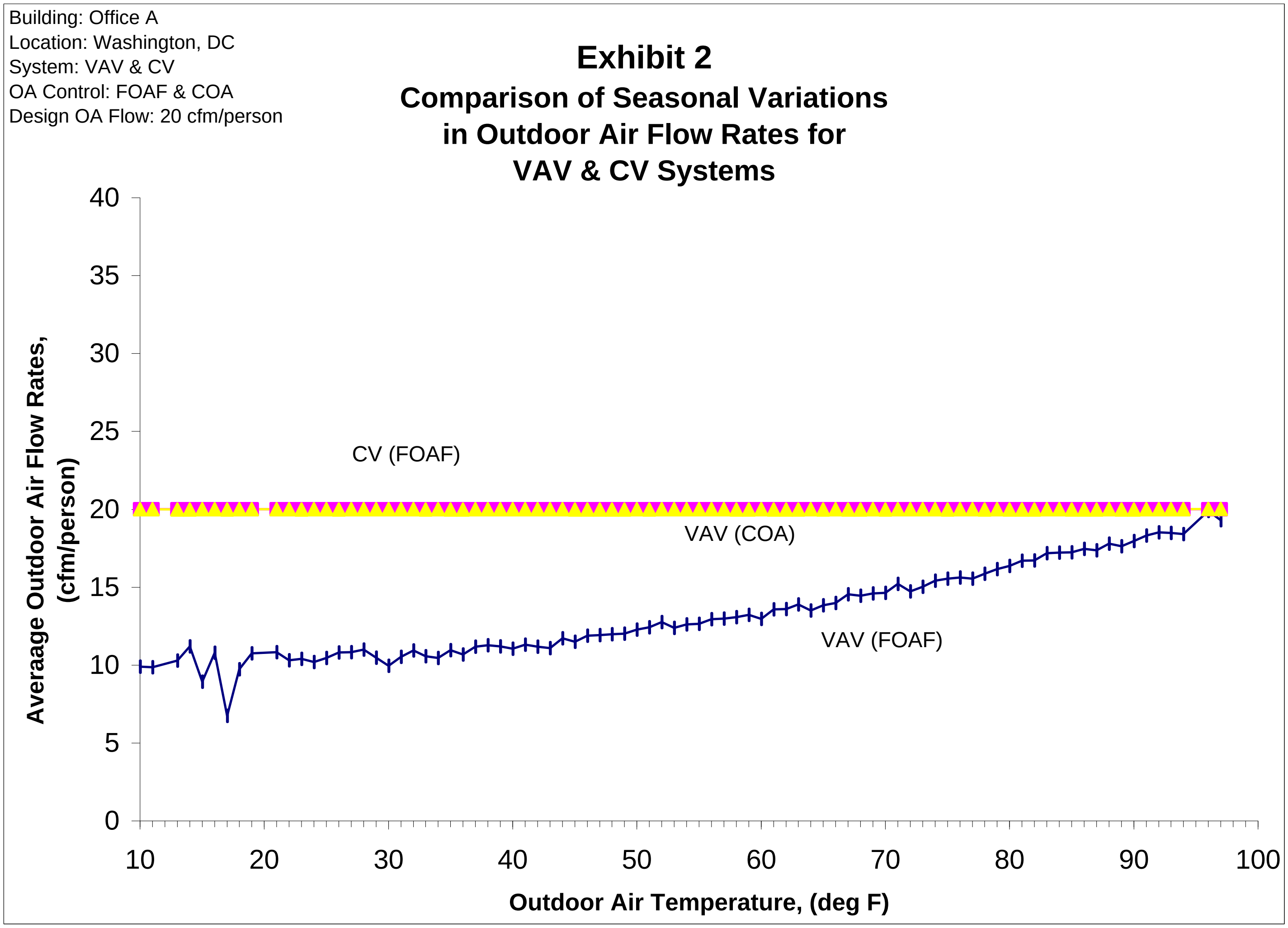
Exhibit 1
Variations in Annual Energy Use
for HVAC Systems
in Three Climate Locations

HVAC System Type and Climate Location	Annual HVAC Energy Use Summary							
	Fan		Cooling		Heating		Total	
	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf
CV (FOAF)								
Minneapolis, MN	0.32	18.3	0.52	19.9	0.04	9.2	0.88	47.4
Washington, DC	0.29	16.4	0.56	22.2	0.01	2.4	0.86	41.1
Miami, FL	0.30	17.6	0.72	33.0	0.00	0.1	1.02	50.6
VAV(FOAF)								
Minneapolis, MN	0.19	9.8	0.49	20.0	0.10	20.9	0.79	50.6
Washington, DC	0.17	8.7	0.52	21.0	0.05	9.8	0.74	39.5
Miami, FL	0.18	9.3	0.62	28.5	0.00	0.5	0.81	38.3
VAV(COA)								
Minneapolis, MN	0.19	9.8	0.49	18.7	0.10	21.2	0.78	49.7
Washington, DC	0.17	8.7	0.52	20.3	0.05	9.9	0.74	38.9
Miami, FL	0.18	9.3	0.65	29.0	0.00	0.5	0.83	38.9



Building: Office A
Location: Washington, DC
System: VAV & CV
OA Control: FOAF & COA
Design OA Flow: 20 cfm/person
Exhibit 2
Comparison of Seasonal Variations
in Outdoor Air Flow Rates for
VAV & CV Systems
Averaage Outdoor Air Flow Rates,
(cfm/person)
0
5
10
15
20
25
30
35
40
CV (FOAF)
VAV (COA)
VAV (FOAF)
10
20
30
40
50
60
70
80
90
100
Outdoor Air Temperature, (deg F)

Exhibit 3A
Variation in OA Flow Rates for VAV(FOAF)
in Three Climate Locations

HVAC System Type and Location	Outdoor Air Flow Rates Achieved (cfm per person)				
	<= 5	**6-10**	**11-15**	**16-19**	**>= 20**
VAV(FOAF)					
Minneapolis, MN	0.0%	42.0%	56.3%	1.7%	0.0%
Washington, DC	0.0%	16.6%	78.1%	5.3%	0.0%
Miami, FL	0.0%	0.0%	42.5%	57.5%	0.0%

Exhibit 3B
Variation in Temperature for VAV(FOAF)
in Three Climate Locations

Location	Outdoor Air Temperature Bins					
	Winter <10 - 39°F		Spring/Fall 40 - 69°F		Summer 70 - >90°F	
	# of hours	% of hours	# of hours	% of hours	# of hours	% of hours
Minneapolis, MN	979	41.4%	736	31.1%	649	27.5%
Washington, DC	411	17.4%	1028	43.5%	925	39.1%
Miami, FL	0	0.0%	219	9.3%	2145	90.7%

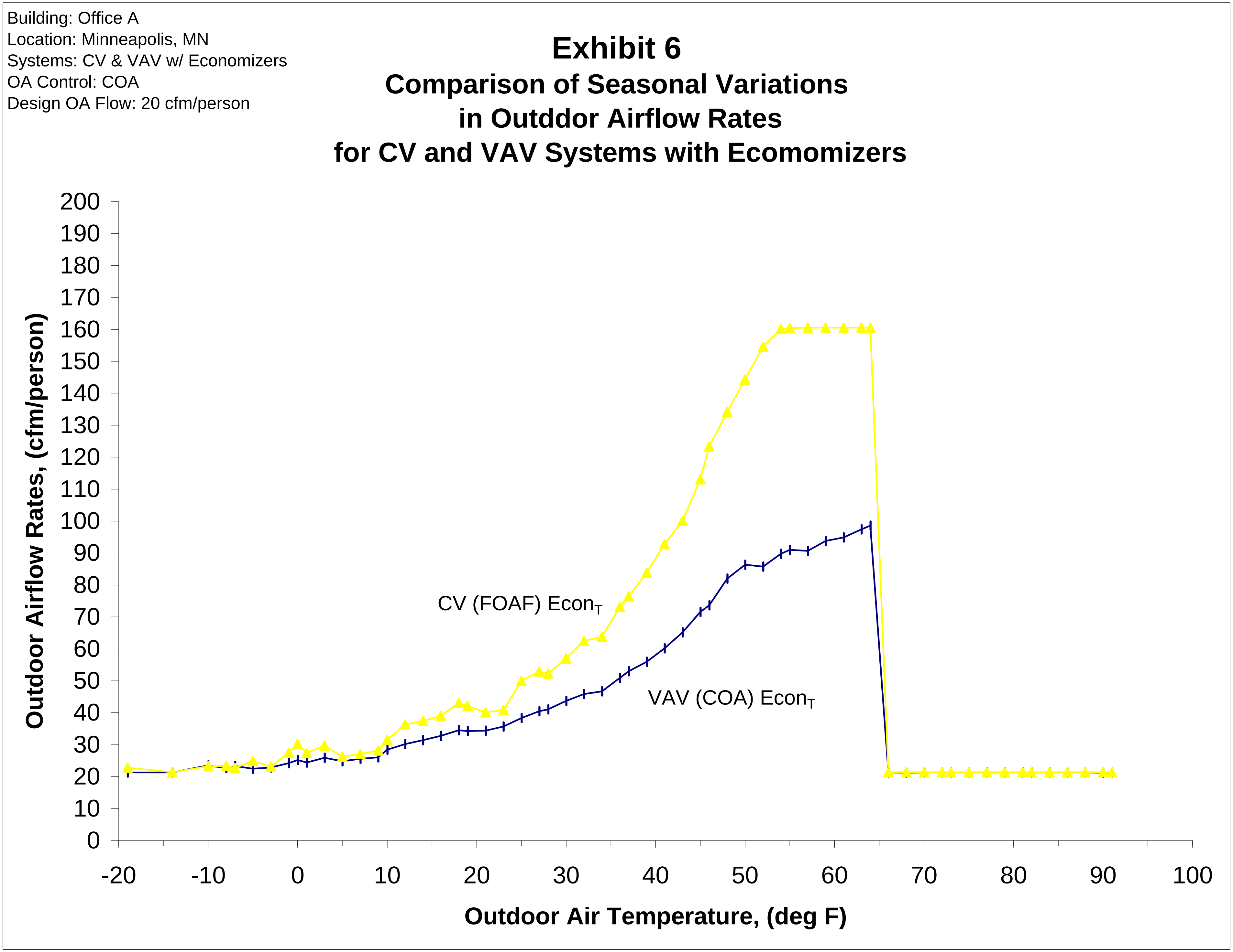
Exhibit 4
Variations in Annual Energy Use
for HVAC Systems with Economizers

HVAC System Type and Climate Location	Annual HVAC Energy Use Summary							
	Fan		Cooling		Heating		Total	
	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf
CV (FOAF) $Econ_T$								
Minneapolis, MN	0.32	18.2	0.45	14.7	0.10	20.7	0.87	53.7
Washington, DC	0.29	16.4	0.50	17.4	0.06	12.5	0.85	46.4
Miami, FL	0.30	17.5	0.71	32.3	0.00	0.9	1.01	50.7
CV (FOAF) $Econ_E$								
Minneapolis, MN	0.32	18.2	0.45	14.1	0.10	20.7	0.87	53.1
Washington, DC	0.29	16.4	0.49	16.8	0.06	12.5	0.84	45.7
Miami, FL	0.30	17.5	0.70	31.9	0.00	0.8	1.01	50.2
VAV(FOAF) $Econ_T$								
Minneapolis, MN	0.19	9.7	0.42	14.2	0.11	21.8	0.71	45.7
Washington, DC	0.17	8.6	0.46	16.4	0.05	10.4	0.68	35.5
Miami, FL	0.18	9.3	0.61	27.9	0.00	0.5	0.80	37.8
VAV(FOAF) $Econ_E$								
Minneapolis, MN	0.19	9.7	0.41	13.8	0.11	21.8	0.71	45.3
Washington, DC	0.17	8.6	0.45	15.8	0.05	10.4	0.68	34.9
Miami, FL	0.18	9.3	0.61	27.6	0.00	0.5	0.79	37.4
VAV(COA) $Econ_T$								
Minneapolis, MN	0.19	9.7	0.43	14.3	0.11	21.8	0.73	45.9
Washington, DC	0.17	8.6	0.47	16.7	0.05	10.4	0.70	35.8
Miami, FL	0.18	9.3	0.64	28.6	0.00	0.5	0.83	38.5
VAV(COA) $Econ_E$								
Minneapolis, MN	0.19	9.7	0.43	14.0	0.11	21.8	0.72	45.5
Washington, DC	0.17	8.6	0.47	16.1	0.05	10.4	0.69	35.2
Miami, FL	0.18	9.3	0.64	28.3	0.00	0.5	0.82	38.2

Exhibit 5
Annual HVAC Energy and HVAC Energy Cost Savings* of Temperature and Enthalpy Economizers Compared to the Base Case

	Minneapolis, MN		Washington, DC		Miami, FL	
System	Temp	Enth	Temp	Enth	Temp	Enth
Energy (kBTU/sq ft)						
CV (FOAF)	-13.3%	-12.0%	-13.0%	-11.3%	-0.2%	0.8%
VAV(FOAF)	9.8%	10.6%	10.1%	11.6%	1.5%	2.5%
VAV(COA)	7.7%	8.4%	8.0%	9.5%	1.0%	1.9%
Energy Costs ($/sq ft)						
CV (FOAF)	1.3%	2.1%	1.4%	2.4%	0.5%	1.1%
VAV(FOAF)	9.3%	9.9%	7.8%	8.9%	1.2%	1.8%
VAV(COA)	6.9%	7.5%	6.0%	7.0%	0.6%	1.2%

*** Negative values represent increases**



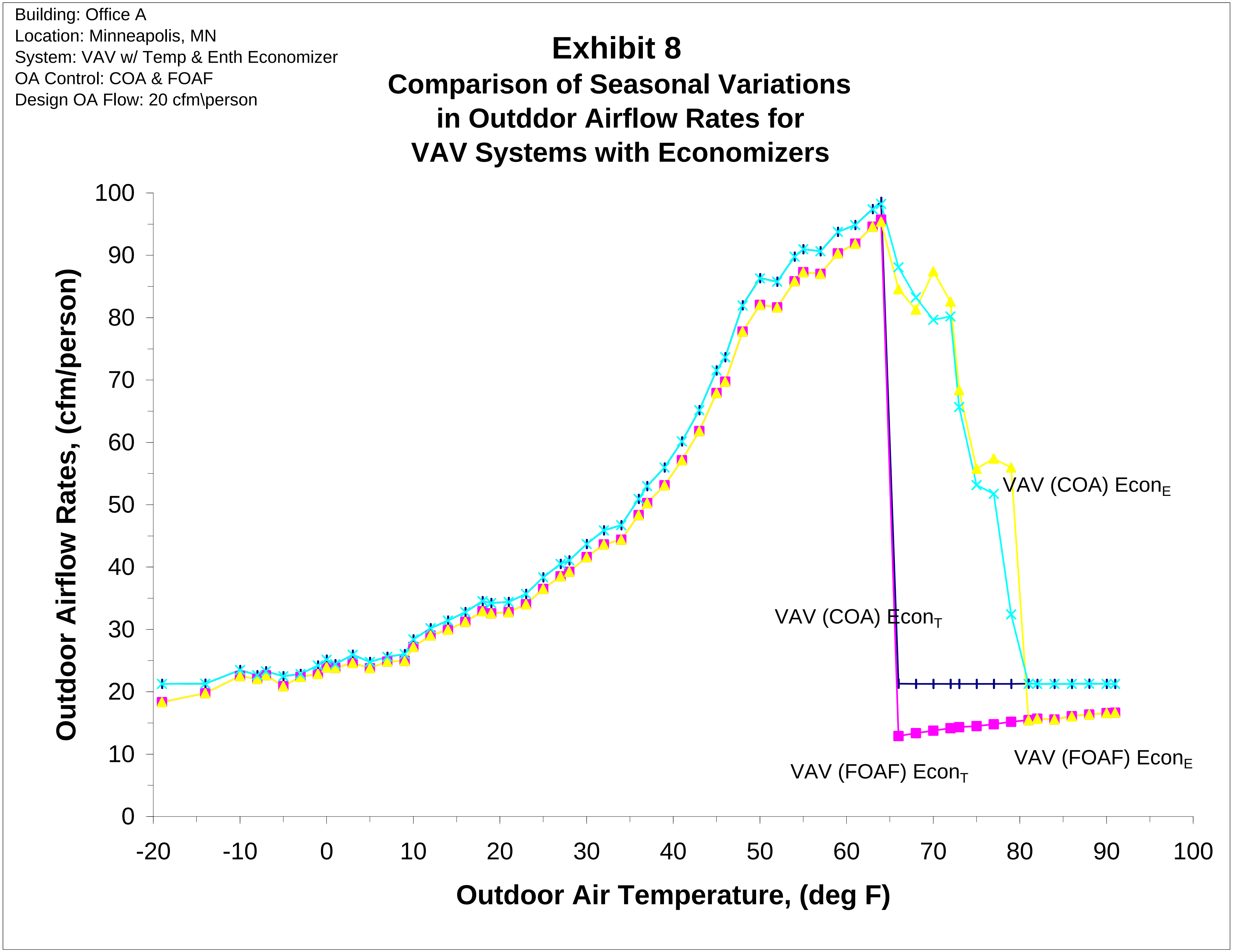
Building: Office A
Location: Minneapolis, MN
Systems: CV & VAV w/ Economizers
OA Control: COA
Design OA Flow: 20 cfm/person
Exhibit 6
Comparison of Seasonal Variations
in Outddor Airflow Rates
for CV and VAV Systems with Ecomomizers
CV (FOAF) Econ$_T$
VAV (COA) Econ$_T$
Outdoor Airflow Rates, (cfm/person)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
-20
-10
0
10
20
30
40
50
60
70
80
90
100
Outdoor Air Temperature, (deg F)

Exhibit 7a
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
Option1	Low (-33%)	High (+43%)	Average	$0.330	$0.063	$7.890	No
Option 2	High (+33%)	Low (-43%)	Average	$0.650	$0.025	$7.890	No
Option 3	Average	Average	High (+48%)	$0.490	$0.044	$11.710	No
Option 4	Average	Average	Low (-48%)	$0.490	$0.044	$4.070	No

Exhibit 7b
Price Sensitivity of CV Systems with Economizers in Three Climates

Location and Utility Price Structure	CV (FOAF) System with Temperature and Enthalpy Economizers				
	Base	**$Econ_T$**		**$Econ_E$**	
	$/sf	$/sf	% Change	$/sf	% Change
Minneapolis, MN					
Base	1.02	1.01	-0.5%	1.01	-1.1%
Lo Gas/Hi Elec	1.30	1.29	-0.8%	1.28	-1.4%
Hi Gas/Lo Elec	0.74	0.74	0.0%	0.74	-0.5%
Hi Demand	1.20	1.19	-0.5%	1.19	-0.9%
Lo Demand	0.84	0.84	-0.6%	0.83	-1.3%
Washington, DC					
Base	0.88	0.87	-1.3%	0.87	-2.1%
Lo Gas/Hi Elec	1.08	1.02	-5.5%	1.01	-6.4%
Hi Gas/Lo Elec	0.69	0.72	5.3%	0.72	4.7%
Hi Demand	1.05	1.04	-1.1%	1.03	-1.8%
Lo Demand	0.72	0.71	-1.6%	0.70	-2.6%
Miami, FL					
Base	0.86	0.85	-1.4%	0.84	-2.4%
Lo Gas/Hi Elec	1.07	1.02	-5.1%	1.01	-6.3%
Hi Gas/Lo Elec	0.65	0.68	4.7%	0.68	4.0%
Hi Demand	1.03	1.02	-1.2%	1.01	-2.0%
Lo Demand	0.69	0.68	-1.8%	0.67	-3.0%



Building: Office A
Location: Minneapolis, MN
System: VAV w/ Temp & Enth Economizer
OA Control: COA & FOAF
Design OA Flow: 20 cfm\person
Exhibit 8
Comparison of Seasonal Variations in Outddor Airflow Rates for VAV Systems with Economizers
Outdoor Airflow Rates, (cfm/person)
Outdoor Air Temperature, (deg F)
VAV (COA) Econ$_E$
VAV (COA) Econ$_T$
VAV (FOAF) Econ$_E$
VAV (FOAF) Econ$_T$
100
90
80
70
60
50
40
30
20
10
0
-20
-10
0
10
20
30
40
50
60
70
80
90
100

Exhibit 9
Variation in OA Flow Rates for VAV Systems
in Three Climate Locations

HVAC System Type and Location	Outdoor Air Flow Rates Achieved (cfm per person)				
	<= 5	**6-10**	**11-15**	**16-19**	**>= 20**
VAV(FOAF)					
Minneapolis, MN	0.0%	42.0%	56.3%	1.7%	0.0%
Washington, DC	0.0%	16.6%	78.1%	5.3%	0.0%
Miami, FL	0.0%	0.0%	42.5%	57.5%	0.0%
VAV(FOAF) $Econ_T$					
Minneapolis, MN	0.0%	0.0%	32.5%	0.0%	67.4%
Washington, DC	0.0%	0.1%	48.6%	0.5%	50.8%
Miami, FL	0.0%	0.0%	62.3%	31.9%	5.8%
VAV(FOAF) $Econ_E$					
Minneapolis, MN	0.0%	0.0%	18.9%	0.0%	81.1%
Washington, DC	0.0%	0.0%	28.1%	0.5%	71.4%
Miami, FL	0.0%	0.0%	48.2%	29.7%	22.1%
VAV(COA)					
Minneapolis, MN	0.0%	0.0%	0.0%	0.0%	100.0%
Washington, DC	0.0%	0.0%	0.0%	0.0%	100.0%
Miami, FL	0.0%	0.0%	0.0%	0.0%	100.0%

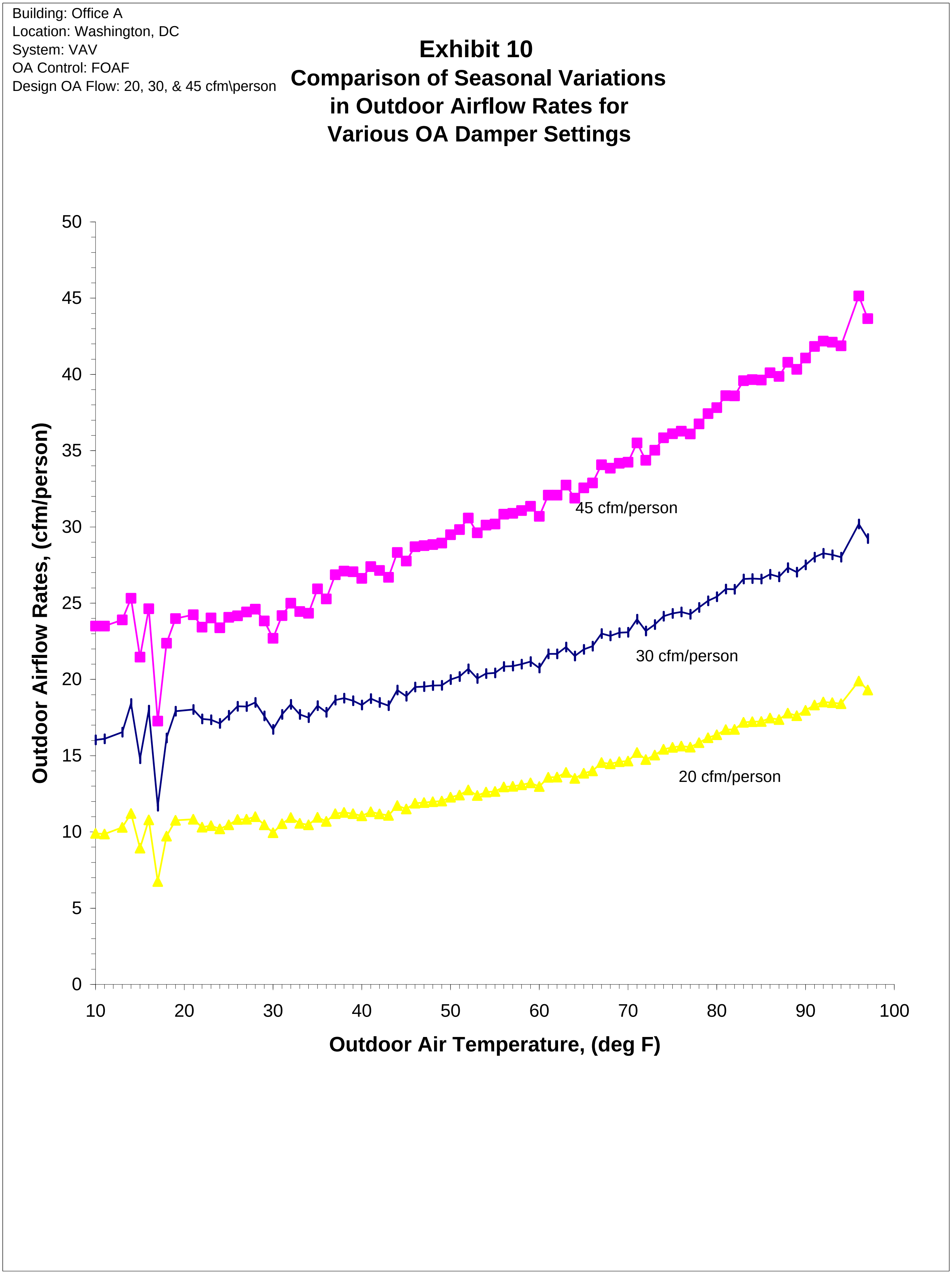
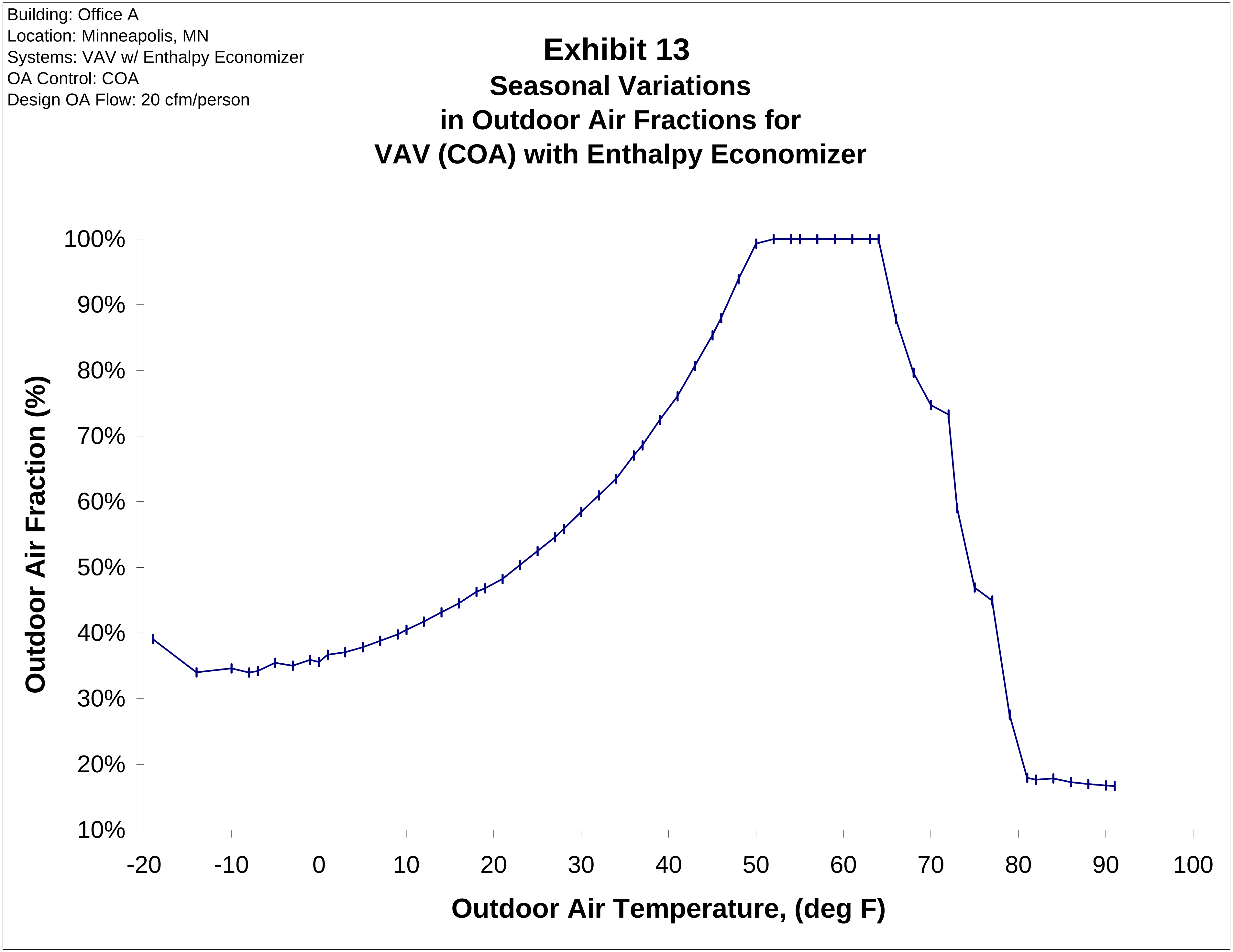

Building: Office A
Location: Washington, DC
System: VAV
OA Control: FOAF
Design OA Flow: 20, 30, & 45 cfm\person
Exhibit 10
Comparison of Seasonal Variations in Outdoor Airflow Rates for Various OA Damper Settings
45 cfm/person
30 cfm/person
20 cfm/person
Outdoor Airflow Rates, (cfm/person)
Outdoor Air Temperature, (deg F)
0
5
10
15
20
25
30
35
40
45
50
10
20
30
40
50
60
70
80
90
100

Exhibit 11
Comparison of Variations
in Outdoor Air Flow Rates for VAV (FOAF) Systems
with Various OA Damper Settings
in Three Climate Locations

OA Damper Setting and Location	Outdoor Air Flow Rates Achieved (cfm per person)				
	<= 5	**6-10**	**11-15**	**16-19**	**>= 20**
20 cfm/person					
Minneapolis, MN	0.0%	42.0%	56.3%	1.7%	0.0%
Washington, DC	0.0%	16.6%	78.1%	5.3%	0.0%
Miami, FL	0.0%	0.0%	42.5%	57.5%	0.0%
30 cfm/person					
Minneapolis, MN	0.0%	0.9%	39.5%	30.2%	29.3%
Washington, DC	0.0%	0.1%	14.1%	41.3%	44.5%
Miami, FL	0.0%	0.0%	0.0%	7.6%	92.4%
45 cfm/person					
Minneapolis, MN	0.0%	0.0%	1.0%	19.2%	79.8%
Washington, DC	0.0%	0.0%	0.3%	1.8%	98.0%
Miami, FL	0.0%	0.0%	0.0%	0.0%	100.0%

Exhibit 12
Variations in Annual Energy Costs
for VAV(FOAF) at Alternative Damper Settings
in Three Climate Locations

HVAC System Type and Climate Location	Annual HVAC Energy Cost Summary			
	Fan $/sf	Cooling $/sf	Heating $/sf	Total $/sf
VAV(FOAF)				
Minneapolis, MN	0.19	0.49	0.10	0.79
Washington, DC	0.17	0.52	0.05	0.74
Miami, FL	0.18	0.62	0.00	0.81
VAV(FOAF) @ 30 cfm/person				
Minneapolis, MN	0.19	0.51	0.11	0.80
Washington, DC	0.18	0.54	0.05	0.76
Miami, FL	0.18	0.66	0.00	0.84
VAV(FOAF) @ 45 cfm/person				
Minneapolis, MN	0.19	0.53	0.11	0.84
Washington, DC	0.18	0.57	0.05	0.80
Miami, FL	0.18	0.72	0.00	0.90



Building: Office A
Location: Minneapolis, MN
Systems: VAV w/ Enthalpy Economizer
OA Control: COA
Design OA Flow: 20 cfm/person
Exhibit 13
Seasonal Variations
in Outdoor Air Fractions for
VAV (COA) with Enthalpy Economizer
Outdoor Air Fraction (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
-20
-10
0
10
20
30
40
50
60
70
80
90
100
Outdoor Air Temperature, (deg F)

Exhibit 14
Outdoor Air Settings for VAV(FOAF) Seasonal Reset Strategy
In Three Climates

	OA Setting				
Season	cfm/person	%OA	Minneapolis, MN	Washington, DC	Miami, FL
Winter	30-40	28-30	Nov-Mar	Dec-Feb	N/A
Spring	70-120	100	Apr-May	Mar-May	Jan-Feb
Summer	10-20	12-14	Jun-Aug	Jun-Sep	Mar-Oct
Fall	70-120	100	Sep-Oct	Oct-Nov	Nov-Dec

Exhibit 15
Variations in Annual Energy Use
for VAV(FOAF) Using a 4 Season Reset Strategy

HVAC System Type and Climate Location	Annual HVAC Energy Use Summary							
	Fan		Cooling		Heating		Total	
	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf
VAV(FOAF)								
Minneapolis, MN	0.19	9.8	0.49	20.0	0.10	20.9	0.79	50.6
Washington, DC	0.17	8.7	0.52	21.0	0.05	9.8	0.74	39.5
Miami, FL	0.18	9.3	0.62	28.5	0.00	0.5	0.81	38.3
VAV(FOAF) w/Reset								
Minneapolis, MN	0.19	9.8	0.58	18.6	0.11	22.5	0.88	50.9
Washington, DC	0.17	8.6	0.52	19.7	0.05	10.1	0.74	38.4
Miami, FL	0.18	9.2	0.70	29.2	0.00	0.6	0.88	39.0

Exhibit 16
OA Flow Rates for VAV(FOAF)
with 4 Season Reset in Three Climate Locations

HVAC System Type and Location	Outdoor Air Flow Rates Achieved (cfm per person)				
	<= 5	**6-10**	**11-15**	**16-19**	**>= 20**
VAV(FOAF)					
Minneapolis, MN	0.0%	42.0%	56.3%	1.7%	0.0%
Washington, DC	0.0%	16.6%	78.1%	5.3%	0.0%
Miami, FL	0.0%	0.0%	42.5%	57.5%	0.0%
VAV(FOAF) w/Reset					
Minneapolis, MN	0.0%	0.0%	25.1%	8.5%	66.4%
Washington, DC	0.0%	0.0%	30.6%	4.6%	64.7%
Miami, FL	0.0%	0.0%	28.8%	39.3%	31.9%

Exhibit 17
Variations in Annual Energy Use
for VAV(FOAF) w/Economizers
and OA Reset for 20 cfm/person at 90°F

HVAC System Type and Climate Location	Annual HVAC Energy Use Summary							
	Fan		Cooling		Heating		Total	
	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf	$/sf	kbtu/sf
VAV(FOAF) $Econ_T$								
Minneapolis, MN	0.19	9.7	0.42	14.2	0.11	21.8	0.71	45.7
Washington, DC	0.17	8.6	0.46	16.4	0.05	10.4	0.68	35.5
Miami, FL	0.18	9.3	0.61	27.9	0.00	0.5	0.80	37.8
VAV(FOAF) $Econ_T$ w/OA Reset								
Minneapolis, MN	0.19	9.7	0.44	14.5	0.11	22.4	0.74	46.6
Washington, DC	0.17	8.6	0.48	16.8	0.05	10.6	0.71	36.1
Miami, FL	0.18	9.2	0.65	28.7	0.00	0.6	0.83	38.5
VAV(FOAF) $Econ_E$								
Minneapolis, MN	0.19	9.7	0.41	13.8	0.11	21.8	0.71	45.3
Washington, DC	0.17	8.6	0.45	15.8	0.05	10.4	0.68	34.9
Miami, FL	0.18	9.3	0.61	27.6	0.00	0.5	0.79	37.4
VAV(FOAF) $Econ_E$ w/OA Reset								
Minneapolis, MN	0.19	9.7	0.43	14.1	0.11	22.4	0.73	46.3
Washington, DC	0.17	8.6	0.48	16.2	0.05	10.6	0.70	35.5
Miami, FL	0.18	9.3	0.65	28.7	0.00	0.5	0.84	38.6

Exhibit 18
Variations in OA Flow Rates
for VAV(FOAF) w/Economizers
and OA Reset for 20 cfm/person at 90°F

HVAC System Type and Location	Outdoor Air Flow Rates Achieved (cfm per person)				
	<= 5	**6-10**	**11-15**	**16-19**	**>= 20**
VAV(FOAF) $Econ_T$					
Minneapolis, MN	0.0%	0.0%	32.5%	0.0%	67.4%
Washington, DC	0.0%	0.1%	48.6%	0.5%	50.8%
Miami, FL	0.0%	0.0%	62.3%	31.9%	5.8%
VAV(FOAF) $Econ_T$ w/OA Reset					
Minneapolis, MN	0.0%	0.0%	0.0%	11.6%	88.4%
Washington, DC	0.0%	0.0%	0.0%	13.9%	86.1%
Miami, FL	0.0%	0.0%	0.0%	10.4%	89.6%
VAV(FOAF) $Econ_E$					
Minneapolis, MN	0.0%	0.0%	18.9%	0.0%	81.1%
Washington, DC	0.0%	0.0%	28.1%	0.5%	71.4%
Miami, FL	0.0%	0.0%	48.2%	29.7%	22.1%
VAV(FOAF) $Econ_E$ w/OA Reset					
Minneapolis, MN	0.0%	0.0%	0.0%	5.6%	94.4%
Washington, DC	0.0%	0.0%	0.0%	4.6%	95.4%
Miami, FL	0.0%	0.0%	0.0%	5.3%	94.7%

Exhibit 19
Variations in Annual Energy Costs
for Various Utility Pricing Schemes
in Washington, DC

HVAC System Type	Annual HVAC Energy Cost Summary				
	Base $/sf	Low Gas/ High Electric $/sf	High Gas/ Low Electric $/sf	High Demand $/sf	Low Demand $/sf
CV (FOAF)	0.86	1.07	0.65	1.03	0.69
CV (FOAF) $Econ_T$	0.85	1.02	0.68	1.02	0.68
CV (FOAF) $Econ_E$	0.84	1.01	0.68	1.01	0.67
VAV(FOAF)	0.74	0.89	0.59	0.89	0.59
VAV(FOAF) $Econ_T$	0.68	0.81	0.56	0.83	0.53
VAV(FOAF) $Econ_E$	0.68	0.79	0.56	0.82	0.53
VAV(COA)	0.74	0.89	0.60	0.90	0.59
VAV(COA) $Econ_T$	0.70	0.82	0.57	0.85	0.54
VAV(COA) $Econ_E$	0.69	0.81	0.57	0.85	0.54
VAV(FOAF) @ 30 cfm OA/per	0.76	0.91	0.61	0.92	0.60
@ 45 cfm OA/per	0.80	0.95	0.65	0.98	0.62
@ 2 Season Fixed	0.73	0.87	0.58	0.88	0.58
@ 4 Season Fixed	0.74	0.88	0.60	0.90	0.58
VAV(FOAF) $Econ_T$ @ 30 cfm OA/per	0.71	0.83	0.59	0.87	0.55
@ 45 cfm OA/per	0.75	0.88	0.63	0.93	0.58
@ 2 Season Fixed	0.68	0.81	0.56	0.83	0.53

Exhibit 20
Variations in Annual Energy Costs
for Various Utility Pricing Schemes
in Miami, FL

HVAC System Type	Annual HVAC Energy Cost Summary				
	Base $/sf	Low Gas/ High Electric $/sf	High Gas/ Low Electric $/sf	High Demand $/sf	Low Demand $/sf
CV (FOAF)	1.02	1.30	0.74	1.20	0.84
CV (FOAF) $Econ_T$	1.01	1.29	0.74	1.19	0.84
CV (FOAF) $Econ_E$	1.01	1.28	0.74	1.19	0.83
VAV(FOAF)	0.81	1.02	0.60	0.96	0.65
VAV(FOAF) $Econ_T$	0.80	1.00	0.59	0.95	0.65
VAV(FOAF) $Econ_E$	0.79	1.00	0.59	0.95	0.64
VAV(COA)	0.83	1.04	0.62	0.99	0.67
VAV(COA) $Econ_T$	0.83	1.04	0.62	0.99	0.66
VAV(COA) $Econ_E$	0.82	1.03	0.61	0.98	0.66
VAV(FOAF) @ 30 cfm OA/per	0.84	1.05	0.63	1.00	0.67
@ 45 cfm OA/per	0.90	1.12	0.68	1.08	0.71
@ 2 Season Fixed	0.80	1.01	0.59	0.95	0.65
@ 4 Season Fixed	0.88	1.09	0.67	1.06	0.69
VAV(FOAF) $Econ_T$ @ 30 cfm OA/per	0.83	1.04	0.62	0.99	0.67
@ 45 cfm OA/per	0.89	1.11	0.67	1.07	0.71
@ 2 Season Fixed	0.79	1.00	0.59	0.94	0.64

Exhibit 21
Variations in Annual Energy Costs for Various Utility Pricing Schemes in Minneapolis, MN

HVAC System Type	Annual HVAC Energy Cost Summary				
	Base $/sf	Low Gas/ High Electric $/sf	High Gas/ Low Electric $/sf	High Demand $/sf	Low Demand $/sf
CV (FOAF)	0.88	1.08	0.69	1.05	0.72
CV (FOAF) $Econ_T$	0.87	1.02	0.72	1.04	0.71
CV (FOAF) $Econ_E$	0.87	1.01	0.72	1.03	0.70
VAV(FOAF)	0.79	0.92	0.65	0.93	0.64
VAV(FOAF) $Econ_T$	0.71	0.81	0.62	0.86	0.57
VAV(FOAF) $Econ_E$	0.71	0.80	0.61	0.85	0.56
VAV(COA)	0.78	0.91	0.66	0.93	0.63
VAV(COA) $Econ_T$	0.73	0.83	0.63	0.88	0.58
VAV(COA) $Econ_E$	0.72	0.82	0.63	0.88	0.57
VAV(FOAF) @ 30 cfm OA/per	0.80	0.93	0.67	0.96	0.65
@ 45 cfm OA/per	0.84	0.96	0.71	1.00	0.67
@ 2 Season Fixed	0.77	0.89	0.64	0.91	0.62
@ 4 Season Fixed	0.88	1.00	0.76	1.07	0.68
VAV(FOAF) $Econ_T$ @ 30 cfm OA/per	0.74	0.84	0.64	0.89	0.58
@ 45 cfm OA/per	0.78	0.88	0.68	0.94	0.61
@ 2 Season Fixed	0.71	0.81	0.61	0.86	0.57

Exhibit 22
Change in Annual Energy Costs
for Various Utility Pricing Schemes
in Washington, DC

HVAC System Type	Change in Annual HVAC Energy Cost from Base				
	Base $/sf	Low Gas/ High Electric %	High Gas/ Low Electric %	High Demand %	Low Demand %
CV (FOAF)	0.86	24.5%	-24.5%	19.8%	-19.8%
CV (FOAF) $Econ_T$	0.85	19.8%	-19.8%	20.1%	-20.1%
CV (FOAF) $Econ_E$	0.84	19.6%	-19.6%	20.3%	-20.3%
VAV(FOAF)	0.74	20.2%	-20.2%	20.3%	-20.3%
VAV(FOAF) $Econ_T$	0.68	18.0%	-18.0%	21.9%	-21.9%
VAV(FOAF) $Econ_E$	0.68	17.7%	-17.7%	22.1%	-22.1%
VAV(COA)	0.74	19.6%	-19.6%	20.9%	-20.9%
VAV(COA) $Econ_T$	0.70	17.8%	-17.8%	22.3%	-22.3%
VAV(COA) $Econ_E$	0.69	17.5%	-17.5%	22.5%	-22.5%
VAV(FOAF)					
@ 30 cfm OA/per	0.76	19.5%	-19.5%	21.1%	-21.1%
@ 45 cfm OA/per	0.80	18.6%	-18.6%	22.1%	-22.1%
@ 2 Season Fixed	0.73	19.7%	-19.7%	20.6%	-20.6%
@ 4 Season Fixed	0.74	19.2%	-19.2%	21.2%	-21.2%
VAV(FOAF) $Econ_T$					
@ 30 cfm OA/per	0.71	17.5%	-17.5%	22.5%	-22.5%
@ 45 cfm OA/per	0.75	17.0%	-17.0%	23.3%	-23.3%
@ 2 Season Fixed	0.68	17.9%	-17.9%	21.9%	-21.9%

Exhibit 23
Change in Annual Energy Costs
for Various Utility Pricing Schemes
in Miami, FL

HVAC System Type	Change in Annual HVAC Energy Cost from Base				
	Base	Low Gas/ High Electric	High Gas/ Low Electric	High Demand	Low Demand
	$/sf	%	%	%	%
CV (FOAF)	1.02	27.6%	-27.6%	17.5%	-17.5%
CV (FOAF) $Econ_T$	1.01	27.2%	-27.2%	17.6%	-17.6%
CV (FOAF) $Econ_E$	1.01	27.1%	-27.1%	17.7%	-17.7%
VAV(FOAF)	0.81	25.9%	-25.9%	19.1%	-19.1%
VAV(FOAF) $Econ_T$	0.80	25.9%	-25.9%	19.1%	-19.1%
VAV(FOAF) $Econ_E$	0.79	25.8%	-25.8%	19.3%	-19.3%
VAV(COA)	0.83	25.6%	-25.6%	19.5%	-19.5%
VAV(COA) $Econ_T$	0.83	25.5%	-25.5%	19.6%	-19.6%
VAV(COA) $Econ_E$	0.82	25.4%	-25.4%	19.7%	-19.7%
VAV(FOAF) @ 30 cfm OA/per	0.84	25.4%	-25.4%	19.7%	-19.7%
@ 45 cfm OA/per	0.90	24.6%	-24.6%	20.5%	-20.5%
@ 2 Season Fixed	0.80	26.1%	-26.1%	18.9%	-18.9%
@ 4 Season Fixed	0.88	24.2%	-24.2%	21.0%	-21.0%
VAV(FOAF) $Econ_T$ @ 30 cfm OA/per	0.83	25.4%	-25.4%	19.7%	-19.7%
@ 45 cfm OA/per	0.89	24.6%	-24.6%	20.5%	-20.5%
@ 2 Season Fixed	0.79	26.0%	-26.0%	19.0%	-19.0%

Exhibit 24
Change in Annual Energy Costs
for Various Utility Pricing Schemes
in Minneapolis, MN

HVAC System Type	Change in Annual HVAC Energy Cost from Base				
	Base $/sf	Low Gas/ High Electric %	High Gas/ Low Electric %	High Demand %	Low Demand %
CV (FOAF)	0.88	22.4%	-22.4%	19.0%	-19.0%
CV (FOAF) $Econ_T$	0.87	17.2%	-17.2%	19.3%	-19.3%
CV (FOAF) $Econ_E$	0.87	17.0%	-17.0%	19.4%	-19.4%
VAV(FOAF)	0.79	16.8%	-16.8%	18.5%	-18.5%
VAV(FOAF) $Econ_T$	0.71	13.8%	-13.8%	20.3%	-20.3%
VAV(FOAF) $Econ_E$	0.71	13.6%	-13.6%	20.4%	-20.4%
VAV(COA)	0.78	16.0%	-16.0%	19.3%	-19.3%
VAV(COA) $Econ_T$	0.73	13.6%	-13.6%	20.7%	-20.7%
VAV(COA) $Econ_E$	0.72	13.4%	-13.4%	20.8%	-20.8%
VAV(FOAF) @ 30 cfm OA/per	0.80	16.1%	-16.1%	19.1%	-19.1%
@ 45 cfm OA/per	0.84	15.2%	-15.2%	19.9%	-19.9%
@ 2 Season Fixed	0.77	16.3%	-16.3%	18.9%	-18.9%
@ 4 Season Fixed	0.88	13.9%	-13.9%	22.2%	-22.2%
VAV(FOAF) $Econ_T$ @ 30 cfm OA/per	0.74	13.4%	-13.4%	20.7%	-20.7%
@ 45 cfm OA/per	0.78	13.0%	-13.0%	21.2%	-21.2%
@ 2 Season Fixed	0.71	13.9%	-13.9%	20.3%	-20.3%