UBC Energy Audit: Laboratory Ventilation and Fume Hoods

Voytek Gretka

University of British Columbia

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Prepared by: Voytek Gretka

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1. Executive Summary

This study focuses on estimating the potential energy savings regarding general laboratory ventilation with special emphasis on fume hood ventilation practices. The initial scope of the study aimed to audit all of the laboratory space on UBC's Point Grey campus. It is well established that a fume hood uses as much energy as three houses; since there are approximately 1000 fume hoods on campus, this represents a significant fraction of campus energy use and therefore provided the motivation for the audit.

The focus of the study was to investigate measures in which energy could be saved by identifying unnecessarily over-ventilated laboratories. Traditionally, it was assumed that hazardous chemicals used in laboratories (carcinogens, etc.) presented an elevated health risk that should be addressed via increased ventilation. Conventional wisdom has recently been scrutinized by scientific studies proving that in fact the improvement in air quality is negligible past a certain threshold of Air Changes per Hour (ACH). Likewise, increased fume hood ventilation rates may cause turbulent eddies and disrupt the ideal air containment strategy within the hood which may decrease worker safety.

The following are four specific measures that were evaluated:

(1) Decreased Air Change Rates (Unoccupied Night Setback with Manual Occupancy Override)
(2) Low-Flow Fume Hood Retrofit
(3) Reduce Constant Air Volume (CAV) Fume Hood Face Velocity to 90fpm
(4) Implement Variable Air Volume (VAV) Fume Hood Alarms

These measures were evaluated where applicable in the following buildings:

- Chemical and Biological Engineering Building (CHBE)
- Advanced Materials Processing and Engineering Laboratory (AMPEL) – Brimacombe Building
- Earth and Ocean Sciences – Main (EOSM)
- Chemistry Centre, D-Block (CHEM D)

The potential reduction of fume hood face velocity was also extrapolated to the entire campus for a general assessment of how much energy could be saved. Table 9 in Section 4.3 neatly summarizes the important parameters for each energy-savings measure. Energy cost savings were estimated using a rate that included the cost of heating, cooling, and mechanically moving a cubic foot per minute (CFM) of air per annum. Based on current energy and carbon tax costs, the rate used was $2.69/(CFM·yr).

The study concluded that nearly all projects are financially viable with the exception of low-flow fume hood retrofits that have a capital cost too high to be able to regain in energy savings in a reasonable amount of time. In that case specifically, the low cost of energy is prohibitive in the project undertaking.

2. Introduction

2.1. Motivation

Laboratory facilities are on average four to five times more energy intensive per unit floor area than similarly sized commercial space (Woolliams et al., 2005; Bell et al., 2003). Buildings at UBC with a high concentration of laboratory space account for approximately 30% of conditioned floor space, while consuming approximately 50% of total electrical energy and 60% of total thermal energy (Sieb, 2009). Laboratory floor space itself consumes up to 10 times as much energy as other space on campus. This can be attributed to energy intensive laboratory equipment and high ventilation rates required for reasons of safety, for example fume hoods and ultra-low temperature freezers. In addition, some of this process equipment creates a significant heat load that increases room temperatures uncomfortably if not ventilated adequately. Conventional heating, ventilation and air-conditioning (HVAC) systems are therefore required to meet the increased demand of air circulation according to safety protocol and to maintain thermal comfort. At the same time, lab users and managers lack the financial incentive to conserve energy since the institution receives lumped electricity and natural gas bills.

Novel laboratory HVAC techniques developed over the last few decades suggest that modernization of ventilation strategies in older buildings can be economically attractive, especially with the rising costs of energy and increasing global awareness with respect to greenhouse gases and climate change. UBC has over 2 million square feet of laboratory space including over 1,000 fume hoods; therefore the pursuit of laboratory energy efficiency is energetically and economically worthwhile since it represents a large percentage of campus energy use.

2.2. Objectives

UBC Campus Sustainability has committed the time and resources to conduct an audit of all laboratory space on campus. The research project aims to quantify all laboratory space energy consumption as it relates to air change rates and fume hoods. The quantitative information will be used to recommend energy saving retrofits or replacements to the current system. Subsequently a business case for the various options will be presented and their likeliness of implementation will be evaluated. The results of the project will also be available in the SEEDS program.

2.3. Background: Sustainability at UBC

UBC's Climate Action Plan has set aggressive greenhouse gas emission reduction targets, part of UBC's commitment to sustainability leadership. The Climate Action Plan stipulates that by 2015 greenhouse gas emissions shall be reduced 33% below 2007 levels.

The Climate Action Plan addresses emissions in the following categories:

- Campus Development and Infrastructure
- Energy Supply and Management
- Fleets and Fuel Use
- Procurement & Business Travel
- Transportation
- Food

Energy used for heating, cooling, lighting and plug loads in UBC buildings represents 96% of campus greenhouse gas emissions. Since there are over 50 laboratory buildings on campus there is a clear opportunity to significantly reduce greenhouse gas emissions by optimizing energy efficiency in this sector.

2.4. Literature Review

2.4.1. General Laboratory HVAC

Laboratory comfort is controlled based on a fixed temperature set point. In practice, heat gain in the laboratory due to equipment (refrigerators, hot-plates, exothermic chemical reactions, etc.) is often the dominating variable in HVAC performance, where higher ventilation rates are required to exhaust excess heat.

Elevated air exchange rates are also crucial for the safety of lab users considering that many toxic, noxious, and/or carcinogenic agents are regularly used in this environment. Laboratory and fume hood exhaust cannot be recycled back into the building as is sometimes done with office and classroom air. A general agreement exists that higher air changes per hour (ACH) will translate into a shorter residence time for airborne contaminants originating from spills either on the floor or on the laboratory bench (Klein et al., 2009; Klein et al., 2010; Whicker et al., 2002). To that end, professional safety agencies and scientific literature have produced ventilation guidelines which recommend that most labs should have air exchange rates between 4 and 12 ACH (some of these are summarized in Table 1). However, this rule of thumb is only a suggestion since many variables in laboratories affect ventilation requirements and air flow patterns including equipment siting, HVAC systems configuration, occupancy, equipment heat gain, and the nature of the hazardous substances. This list is not exhaustive.

Source	Recommended Ventilation Rate (ACH)	Year
National Research Council (NRC): Prudent Practices	6-12	1995
National Fire Protection Association (NFPA) 45	≥8 (occupied), 4 (unoccupied)	2004
American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Handbook	6-10 (occupied)	2004
Occupational Safety and Health Administration (OSHA)	4-12	1996
National Institute of Health (NIH)	6	2003
Labs for the 21st Century: Best Practice Guide. Metrics and Benchmarks for Energy Efficiency in Laboratories	6 (occupied), 4 (unoccupied)	2007
Klein et al.	6-8	2009

Source	Recommended Ventilation Rate (ACH)	Year
Bell	8 (occupied), 6 (unoccupied)	2009
UBC Technical Guidelines Division 15 Section 15003	≥10	2010

Table 1 Recommended laboratory ventilation rates from various sources

Several recent investigations probing the energy efficiency of laboratories show a general consensus that a plethora of opportunities exist for their optimization – and that energy savings translate to financial savings accordingly. A benchmarking study of energy efficiency of a number of similar-type laboratories across the United States indicated that there is as much as an eight-fold variation in energy intensity (Mills et al., 2007). The major opportunities for HVAC-related energy savings are summarized by Mills (2009):

- installing high-efficiency fume hoods
- installing high-efficiency laboratory equipment
- avoiding over-ventilation of the space unnecessarily based on occupancy, type of lab, etc.
- minimizing pressure drop in ventilation ductwork by virtue of intelligent HVAC and building design, i.e. consolidating exhausts using manifolds
- recovering the thermal energy of laboratory exhaust (heat exchangers)
- eliminating simultaneous heating and cooling
- appropriately sizing HVAC systems to match load demand, i.e. minimizing overdesign

2.4.2. Fume Hoods

The purpose of a laboratory fume hood is to facilitate the undertaking of dangerous and/or hazardous chemical or biological processes while exhausting dangerous fumes or particles away from the user. A schematic of a fume hood is illustrated in Figure 1 outlining its general structure and mechanism of operation. From an energy perspective a fume hood is analogous to an open window in a home on a winter day with a fan exhausting warm air from the inside, while the home furnace needs to take on extra duty to maintain the interior comfort of residents. In this context, a typical fume hood operating year round can consume more energy than three homes in an average United States climate (Mills et al., 2005).

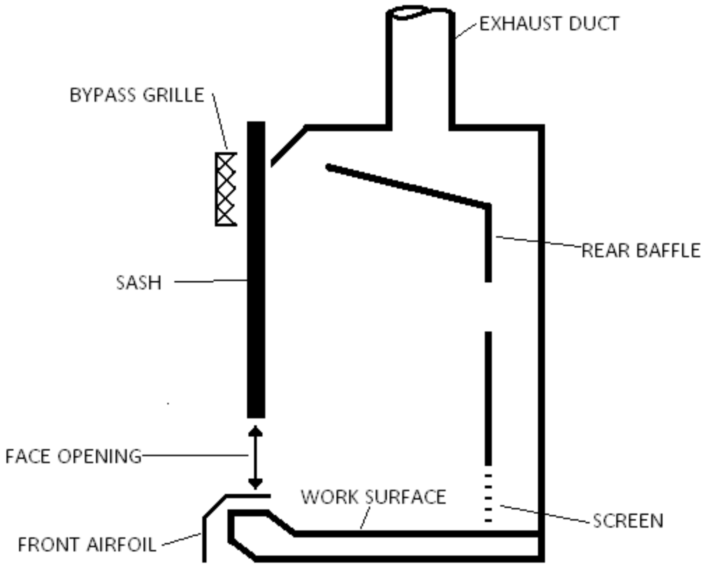

Figure 1 General side-profile schematic of a laboratory fume hood.

Generally fume hoods fall into two main categories: those of constant air volume (CAV) and variable air volume (VAV). As the name suggests, CAV systems draw a constant volume of air regardless of the area of the face opening (dictated by the sash height) via a bypass grille located typically above the working area. In contrast, VAV fume hoods do not have a bypass grille but rather employ a sash height sensor and adjust the exhaust flow rate accordingly by means of electronic control in order to maintain a theoretically constant face velocity. The energy consumption is therefore proportional to sash height, and along with offering an increased level of safety as a result of optimal containment, VAV fume hoods have been hailed as the current state of the art in fume hood design and practice. Behavioural attitudes instilled in lab users can represent a substantial energy savings potential if sash heights are kept at a minimum when the fume hood is not in immediate use. In fact, behavioural campaigns have reported significant energy decreases in academic institutions such as Harvard University and the University of Toronto, and UBC is currently in the process of launching its own pilot campaign.

UBC's fume hood policy is summarized in the Technical Guidelines as follows:

- Division 11 Section 11610 specifies that fume hoods shall be variable air volume (VAV) type.
- Division 11 Section 11610 specifies that fume hoods *shall conform to Part 30 Laboratories, of the Occupational Health and Safety (OHS) Regulation under the inspection jurisdiction of WorkSafeBC*.
- WorkSafeBC's OHS Regulation Part 30.8 Laboratory fume hoods, specifies that a fume hood must: *provide average face velocities of 0.4 m/s (80 fpm) to 0.6 m/s (120 fpm) across the operational face opening*

Since VAV fume hood technology is relatively new (first installed at UBC in 2004), the proportion of VAV fume hoods in core UBC labs is only about 15%. An overwhelming majority (>85%) at UBC are CAV fume hoods thus the general focus of this investigation is to evaluate the best method of optimizing energy efficiency in laboratories with this older technology, which likely represents a larger savings opportunity.

Interestingly, all UBC fume hoods designed prior to 2010 were required to meet a 100-150 fpm face velocity criteria. Conventional wisdom believed that increased face velocities would provide a safer work environment for the lab user by drawing away more hazardous material in the air. Over time research has shown that increasing face velocities to a certain point increases turbulent air flow within the fume hood, and may actually diminish worker safety due to eddies that disrupt the containment strategy (Bell, 2009). This implies that the first and easiest measure to achieve savings could be as simple as reducing face velocities to the minimum acceptable level of 80 fpm.

Research in fume hood design has recently led to the innovation of high-efficiency or low-flow fume hoods, called the "Berkeley Hood" after the Lawrence Berkeley National Laboratory where it was developed. Figure 2 shows the arrangement of this technology which is based on room air being introduced across the face of the hood opening, in essence creating an air wall containment strategy. In keeping with safety as the primary concern, recent literature suggests that high efficiency fume hoods are able to provide an equal or better level of containment while saving up to 75% of the energy consumption depending on the geographical location (Bell et al., 2003; Mills et al., 2004). The Berkeley Hood is also a simpler and therefore less expensive design than VAV fume hood, and ensures savings regardless of operator experience and behavior since it is a constant volume design. In addition the lower fan power offers robust peak-power savings that are unavailable with VAV fume hoods.

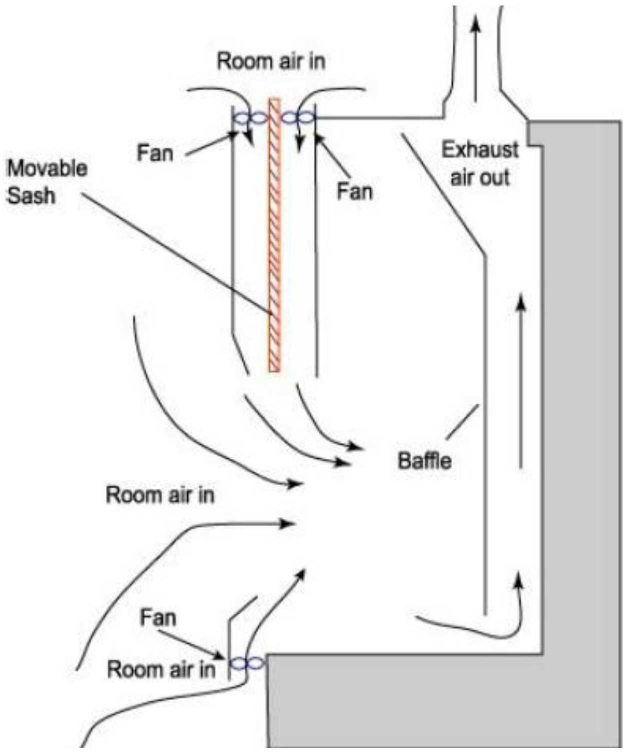

Figure 2 Schematic of the Berkeley Fume Hood; alternative names: Low-Flow Fume Hood, High Efficiency Fume Hood. (Bell et al., 2003)

New technological developments in fume hood design and operation are proving to be successful in real-world implementation. Though each design has its benefits and drawbacks, they are markedly more energy efficient than their early CAV predecessors.

3. Methodology

3.1. Data collection

3.1.1. Databases

Various sources at UBC provided the following data:

- Rooms in each building that are classified as laboratory space
- Floor area of every room in every building
- Fume hood data from Risk Management Services (RMS), including:
  - Type of fume hood (CAV, VAV)
  - Fume hood face opening dimensions
  - Average face velocity across operational face opening
  - Usage (carcinogenic, radioisotope, perchloric acid)
  - Maximum achievable sash height

Using these data, a master list of all laboratory space on campus was compiled as a starting point to provide a scope for the energy audit.

3.1.2. Mechanical Drawings

The campus electronic document management portal (Laserfiche) was able to provide a breadth of information regarding building HVAC design. The documents provide detailed information regarding air handling units (AHUs), exhaust fans, motors, pumps, ducting, pipes, and other mechanical equipment associated with the normal operation of the building.

Mechanical maintenance manuals were included for each building at the time of commissioning or re-commissioning following major renovations. Each fume hood, supply grille, and exhaust grille must therefore be measured in order to verify that specified flow rates by the mechanical contractor are reflected in operating conditions and that actual air change rates are being met in reality. This data was available from balancing reports and was used to calculate supply and exhaust rates for every room.

3.1.3. Room Visits

There were too many (>1200) laboratory rooms to visit in person due to time constraints, especially considering that some had restricted access due to personnel safety and would therefore require a formal training process or accompaniment in order to gain access. It was therefore deemed sufficient to perform a 'spot check' of each building to gather key pieces of information and it was assumed that HVAC configurations would be relatively consistent within the same building.

Photos and information from the room visit were collected to facilitate a better conceptual 'real world' understanding of the building's HVAC systems. Sizes and locations of supply and exhaust grilles were observed. Where achievable, a balometer (Alnor APM 150) was used to measure actual flows in supply grilles in order to evaluate the accuracy of balancing report data (Appendix 6.3). General fume hood features and practices were recorded such as the presence of an on/off switch, whether the storage cabinet underneath the fume hood is vented directly to the fume hood, and whether the fume hood is being used for chemical storage. In addition the ceiling heights were recorded using a laser distance measure (Ryobi Tek4).

3.2. Calculations

3.2.1. Rationale

A common measure of air flow in the industry is cubic feet per minute (CFM). Especially in demand side energy conservation, HVAC costs are reported in units of $/CFM/yr. In other words, this unit captures the cost associated with conditioning outside air (heating and cooling) as well as air movement (fan energy) over the course of the entire year. The cost varies with local climate and energy prices – for example, a general rule of thumb in California is to use between $3.50 and $5.00/CFM/yr when estimating energy costs; however, British Columbia's low energy prices and mild summer temperatures result in a much lower cost of air conditioning which is reflected in a lower total cost. Calculations are listed in the following sections. All HVAC energy and cost savings measures henceforth were based on CFM abatement for simplicity of calculations.

3.2.2. Constants and Assumptions

In order to reasonably estimate cost and energy savings, constants were compiled from various sources. The parameters used in the calculations are listed in Table 2 below, while sample calculations follow in the next section. The basis for the calculations was derived from the TSI Application Note LC – 120 entitled "Energy Savings Estimate – Constant Volume vs. Variable Air Volume Fume Hoods".

Constant	Value	Units	Source
Electricity Price	0.0449	$ / kWh	2010/2011 UBC Utility rate for core buildings
Steam Price	9.07	$ / GJ	2010/2011 UBC Utility rate for core buildings
Supply Steam Enthalpy (includes combustion losses)	1.055	GJ / klb	UBC Energy Manager (usable energy produced by steam at 165psi)
Carbon Offset Price	25	$ / tonne CO_2e	Current cost of offsets purchased from Pacific Carbon Trust
Electricity Emission Factor	25	tonnes CO_2e / GWh	Methodology for Reporting BC Public Sector Greenhouse Gas Emissions v1.0, February 2011

Constant	Value	Units	Source
Steam Emission Factor (includes combustion losses)	65.33	kg CO_2e / klb	Derived from Methodology for Reporting BC Public Sector Greenhouse Gas Emissions
Suggested Ventilation Rate (Occupied Condition)	8	ACH	New UBC laboratory construction best practice; NFPA; Bell, 2009
Suggested Ventilation Rate (Unoccupied Condition)	4	ACH	OSHA; NFPA; Labs21
Daily Occupancy Hours	10	hrs	Personal communication with lab managers and lab users
Daily Vacancy Hours	14	hrs	Personal communication with lab managers and lab users
Heating Degree Days (HDD), Vancouver (below 18°C)	2926.5	°C·day/yr	Canada's National Climate Archive, Environment Canada: http://climate.weatheroffice.gc.ca/
Heating Degree Days (HDD), Vancouver (above 18°C)	44.2	°C·day/yr	Canada's National Climate Archive, Environment Canada: http://climate.weatheroffice.gc.ca/
Air Density	0.075	lb / ft^3	TSI Application Note LC – 120
Air Heat Capacity	0.24	BTU / (°F·lb)	TSI Application Note LC – 120
Refrigeration COP (typical)	1		Personal communications with UBC Building Operations staff
Fluid Moving Energy	.00175	hp / CFM	TSI Application Note LC – 120
Distribution Losses	25	%	

Table 2 Parameters used in energy and cost estimates

3.2.3. Energy

3.2.3.1. Steam Heating Energy

$$E_{HEATING} = 2926.5\left(\frac{°C \cdot day}{yr}\right)\cdot\frac{1.8°F}{°C}\cdot\frac{0.24BTU}{°F \cdot lb}\cdot\frac{0.075lb}{ft^3}\cdot\frac{1GJ}{947817.1BTU}\cdot\frac{24hr}{day}\cdot\frac{60min}{hr} = 0.14\frac{GJ}{CFM \cdot yr}$$

$$E_{HEATING} = 0.14\frac{GJ}{CFM \cdot yr}\cdot\frac{277.78kWh}{GJ} = 40.02\frac{kWh}{CFM \cdot yr}$$

$$E_{HEATING} = \frac{0.14\frac{GJ}{CFM \cdot yr}\cdot\frac{1000lbs}{1.055GJ}}{75\%} = 182.06\frac{lbs}{CFM \cdot yr}$$

3.2.3.2. Electric Cooling Energy

$$E_{COOLING} = 44.2\left(\frac{°C \cdot day}{yr}\right)\cdot\frac{1.8°F}{°C}\cdot\frac{0.24BTU}{°F \cdot lb}\cdot\frac{0.075lb}{ft^3}\cdot\frac{kWh}{3412BTU}\cdot\frac{24hr}{day}\cdot\frac{60min}{hr} = 0.60\frac{kWh}{CFM \cdot yr}$$

3.2.3.3. Fluid-Moving Electric Energy

$$E_{MOVING} = \frac{0.746kW}{hp}\cdot\frac{0.00175hp}{CFM}\cdot\frac{24hr}{day}\cdot\frac{365day}{yr} = 11.43\frac{kWh}{CFM \cdot yr}$$

3.2.4. Greenhouse Gas Emissions

3.2.4.1. Steam Heating GHG Emissions

$$EMI_{HEATING} = 182.06\frac{lbs}{CFM \cdot yr}\cdot\frac{65.33kg\ CO_2e}{1000\ lb}\cdot\frac{1tonne}{1000kg} = 1.59\times10^{-2}\frac{tCO_2e}{CFM \cdot yr}$$

3.2.4.2. Electric Cooling GHG Emissions

$$EMI_{COOLING} = 0.60\frac{kWh}{CFM \cdot yr}\cdot\frac{1GWh}{10^6kWh}\cdot\frac{25tCO_2e}{GWh} = 1.51\times10^{-5}\frac{tCO_2e}{CFM \cdot yr}$$

3.2.4.3. Fluid-Moving GHG Emissions

$$EMI_{COOLING} = 11.43\frac{kWh}{CFM \cdot yr}\cdot\frac{1GWh}{10^6kWh}\cdot\frac{25tCO_2e}{GWh} = 2.86\times10^{-4}\frac{tCO_2e}{CFM \cdot yr}$$

3.2.4.4. Total GHG Emissions (Conditioning and Fuel)

$$EMI_{TOTAL} = 1.59 \times 10^{-2} \frac{tCO_2e}{CFM \cdot yr} + 1.51 \times 10^{-5} \frac{tCO_2e}{CFM \cdot yr} + 2.86 \times 10^{-4} \frac{tCO_2e}{CFM \cdot yr} = 1.62 \times 10^{-2} \frac{tCO_2e}{CFM \cdot yr}$$

3.2.5. Costs of Conditioning

3.2.5.1. Steam Heating Fuel Cost

$$COST_{HEATING\ FUEL} = 182.06 \frac{lbs}{CFM \cdot yr} \cdot \frac{1klb}{1000lb} \cdot \frac{1.055GJ}{klb} \cdot \frac{\$9.07}{GJ} = \frac{\$1.74}{CFM \cdot yr}$$

3.2.5.2. Electric Cooling Fuel Cost

$$COST_{COOLING\ FUEL} = 0.60 \frac{kWh}{CFM \cdot yr} \cdot \frac{\$0.0449}{kWh} = \frac{\$0.03}{CFM \cdot yr}$$

3.2.5.3. Fluid-Moving Fuel Cost

$$COST_{MOVING\ FUEL} = 11.43 \frac{kWh}{CFM \cdot yr} \cdot \frac{\$0.0449}{kWh} = \frac{\$0.51}{CFM \cdot yr}$$

3.2.5.4. Steam Heating Carbon Offset Cost

$$COST_{HEATING\ OFFSET} = 1.59 \times 10^{-2} \frac{tCO_2e}{CFM \cdot yr} \cdot \frac{\$25}{tCO_2e} = \frac{\$0.40}{CFM \cdot yr}$$

3.2.5.5. Electric Cooling Carbon Offset Cost

$$COST_{COOLING\ OFFSET} = 1.51 \times 10^{-5} \frac{tCO_2e}{CFM \cdot yr} \cdot \frac{\$25}{tCO_2e} = \frac{\$0.00}{CFM \cdot yr}$$

3.2.5.6. Fluid-Moving Carbon Offset Cost

$$COST_{MOVING\ OFFSET} = 2.86 \times 10^{-4} \frac{tCO_2e}{CFM \cdot yr} \cdot \frac{\$25}{tCO_2e} = \frac{\$0.01}{CFM \cdot yr}$$

3.2.5.7. TOTAL Cost (Conditioning, Fuel, and Offsets)

$$COST_{TOTAL} = \frac{\$1.74}{CFM \cdot yr} + \frac{\$0.03}{CFM \cdot yr} + \frac{\$0.51}{CFM \cdot yr} + \frac{\$0.40}{CFM \cdot yr} + \frac{\$0.00}{CFM \cdot yr} + \frac{\$0.01}{CFM \cdot yr} = \frac{\$2.69}{CFM \cdot yr}$$

3.2.6. Air Change Rates

Laboratory exhaust rates are typically slightly larger than the supply rate. Such a design ensures the room operates under negative pressure drawing air from offices and/or hallways, as opposed to the reverse condition where hazardous fumes and/or particles could infiltrate non-laboratory space. However, this is not always the case especially situations where infiltration of contaminated hallway air is undesirable, for example in clean-rooms or laboratories where microorganism manipulation are prevalent. In order to calculate the air change rate in either of these cases, the greater of supply rate or exhaust rate Q is divided by room volume V.

$$\dot{r}(ACH) = \frac{\dot{Q}(L/s)}{V(m^3)} \times \left(\frac{1m^3}{1000L}\right) \times \left(\frac{3600s}{hr}\right)$$

3.2.7. Room Configurations

Generally there are five types of rooms with respect to supply/exhaust air strategy in combination with fume hood arrangement. Table 3 below outlines the layout and gives a brief lay description of typical operation.

Case	Control Strategy (CAV or VAV)	General Exhaust Present	Fume Hood(s) Present	Description
A	CAV	YES	YES	Room air exhausts at a constant rate through both a general exhaust grille as well as a fume hood. Both exhaust ducts are sometimes combined into one exit stream (fan). Air supply, general exhaust, and fume hood exhaust are set at the time of air balancing and do not change. Room air change rates may be dominated by fume hood flows; general exhaust could be deleted if room design can support that.
B	CAV	NO	YES	All exhaust is routed through fume hood operational face opening and/or bypass grille depending on the sash position. Air supply and fume hood exhaust are set at the time of air balancing and do not change. Room air change rates are dominated by fume hood flows.
C	CAV	YES	NO	Any CAV building that has laboratories without fume hoods. Air supply and general exhaust are set at the time of air balancing and do not change.

Case	Control Strategy (CAV or VAV)	General Exhaust Present	Fume Hood(s) Present	Description
D	VAV	YES	YES	Room air exhausts through general exhaust grille as well as through VAV fume hoods. Fume hoods have sash position sensors which maintain constant face velocity across their operational face opening. Dynamic equilibrium is achieved by modulating both general and fume hood exhausts proportionally with air supply rates to maintain static negative room pressure.
E	VAV	NO	YES	All exhaust is routed through fume hood operational face opening. VAV fume hoods draw a flow rate proportional to the sash position in order to maintain constant face velocity. Sash position sensors modulate exhaust duct pressure to achieve this condition, and proportionally adjust supply air flow to maintain static negative room pressure. Fume hoods draw a minimum non-zero flow due to their minimum sash position by virtue of a sash stop (typically at 2”) or via a sash bypass that opens to a minimum flow only when the sash is at 0”.
F	VAV	YES	NO	Any VAV building that has laboratories without fume hoods. Air supply and exhaust rate is modulated between different setpoints based on certain criteria: for example, occupancy or time of day.

Table 3 General HVAC categories for UBC laboratory buildings. See Appendix 6.4 for a summary of room type areas by building.

3.2.8. Energy-Saving Measures (CFM Savings)

3.2.8.1. Selection of Measures

Four energy savings measures were analyzed in more rigorous mathematical detail according to the feasibility of performing reasonably accurate calculations and likeliness of implementation with regards to the building types. Additionally, these measures could be implemented in many of the UBC laboratory buildings therefore would have the greatest overall impact on energy savings:

- CAV - Decreased air change rates (night setback with manual override)
- CAV - Low-flow FH retrofit
- CAV - Reduction of FH face velocity to 90fpm
- VAV - Implement VAV FH sash alarms

Other potential energy savings measures are discussed qualitatively in the Discussion and Conclusions section of the report. The scope of the project and time restrictions did not allow for a thorough analysis of measures other than the ones listed above.

3.2.8.2. Measure 1: Decreased Air Change Rates (Night Setback with Manual Override)

Existing air change rates were used as a baseline to determine the CFM that could be abated if air change rates were decreased to 8 ACH during the day (occupied for 10 hours) and 4 ACH during the night (unoccupied for 14 hours) for 5 days per week. The unoccupied rate was assumed for the 2 weekend days per week.

$$\dot{Q}_{saved,occupied}(L/s) = (\dot{r}_{existing,occupied} - 8)ACH \times V(m^3) \times \frac{1000L}{m^3} \times \frac{1hr}{3600s}$$

$$\dot{Q}_{saved,unoccupied}(L/s) = (\dot{r}_{existing,unoccupied} - 4)ACH \times V(m^3) \times \frac{1000L}{m^3} \times \frac{1hr}{3600s}$$

$$CFM_{saved} = \left\{\left[\dot{Q}_{saved,occupied}(L/s) \times \frac{10hrs}{day} + \dot{Q}_{saved,unoccupied}(L/s) \times \frac{14hrs}{day}\right] \times \frac{5days}{wk} + \dot{Q}_{saved,unoccupied}(L/s) \times \frac{24hrs}{day} \times \frac{2days}{wk}\right\} \times \frac{52wks}{yr} \times \frac{1yr}{8760hrs} \times \frac{2.1189CFM}{(L/s)}$$

The sum represents all rooms within the building that were eligible for the air change decrease. Fume hood dominated rooms have a minimum flow equal to the sum of all the fume hood exhaust flows and the reduction was calculated as such. In these cases 4 ACH or even 8 ACH were sometimes unachievable; however, the reduction to minimum exhaust flow was still a savings opportunity that was accounted for.

3.2.8.3. Measure 2: Low-Flow FH Retrofit

Typically a 40-50% flow reduction can be expected with these kits according to the supplier. The savings calculation is relatively straightforward: the flow through all CAV fume hoods in the building was abated by 50% and annualized. This assumption enables a decision to be made based on the maximum possible savings achievable.

3.2.8.4. Measure 3: Reduce CAV FH Face Velocity to 90fpm

The recorded velocities from RMS annual fume hood testing were used as a baseline for these calculations. Velocities were taken by RMS with the sash at the maximum safe operating height of 0.38 m. After performing the following calculation for each CAV fume hood, the sum was taken for all fume hoods in the building:

$$CFM_{saved,CAV} = \left[v_{existing}(fpm) - 90fpm\right] \times 0.38m \times sash\ width\ (m) \times 10.76391\frac{ft^2}{m^2}$$

3.2.8.5. Measure 4: Implement VAV Fume Hood Alarms

VAV fume hood energy use is proportional to sash height since face velocity is maintained at a constant rate by virtue of an electronic sensor and controller. However, user negligence often results in open sashes at night when labs are unoccupied. Since the VAV infrastructure is already installed it is worth investigating the feasibility of this measure.

A spot check of VAV fume hood sash heights in four campus buildings yielded an average of 7 inches (0.18m) open sash and the fully closed position is 0m. The unoccupied condition is again assumed to be 14 hours per day. RMS face velocity measurements ($v_{existing}$) theoretically hold true regardless of sash position, since VAV fume hoods maintain a constant face velocity.

$$CFM_{saved} = \left[(0.18m - 0.00m) \times sash\ width\ (m) \times 10.76391\frac{ft^2}{m^2} \times v_{existing}(fpm)\right] \times \left(\frac{14hrs}{d} \times \frac{5d}{wk} + \frac{24hrs}{d} \times \frac{2d}{wk}\right) \times \frac{52wk}{yr} \times \frac{1yr}{8760hrs}$$

3.2.9. Project Costs

Approximate cost estimates are listed in Table 4. Approximations were based on literature searches and discussions with manufacturers and suppliers.

Material / Task	Estimate	Units	Source
FH Containment Testing, Full ASHRAE 110 (price for testing single hood)	870	$ / FH	Environmental Monitoring Services Ltd.
FH Containment Testing, Full ASHRAE 110 (price per hood if testing 50 hoods)	700	$ / FH	Environmental Monitoring Services Ltd.
Air Balancing	300	$ / FH or $ / room	KD Engineering / Western Mechanical Services (WMS)
Low-Flow FH Retrofit Kit	8700	$ / FH	PSA Laboratory Furniture
Low-Flow FH Installation	2700	$ / FH	UC Davis
Variable Frequency Drive (VFD)	500	$ / unit	Drives Warehouse (http://www.driveswarehouse.com)
Retrofit Air Valve to 2-Position	3000	$ / valve	Olympic Controls
Mechanical / Controls Contractor Overhead	25	%	
UBC Project Services Overhead	5	%	UBC Project Services
Engineering Contingency	10	%	
Discount Rate	5.75	%	Cost of Finance

Table 4 Approximate costs for estimating project capital

3.2.9.1. Measure 1: Decreased Air Change Rates (Night Setback with Manual Override)

A sample calculation for CHBE follows:

Item	Estimate	Units	Quantity	Subtotal ($)
Retrofit Air Valve to 2-Position	3000	$ / valve	97	291,000
Air Balancing	300	$ / room	36	10,800
Engineering Contingency	10	%		30,180
SUBTOTAL				**331,980**
Taxes	12	%		39,838
Mechanical / Controls Contractor Overhead	25	%		82,995
UBC Project Services Overhead	5	%		16,599
TOTAL				**471,412**

Table 5 Breakdown of cost estimates for Measure 1 in CHBE

3.2.9.2. Measure 2: Low-Flow FH Retrofit

A sample calculation for BRIM follows:

Item	Estimate	Units	Quantity	Subtotal ($)
FH Containment Testing, Full ASHRAE 110	700	$ / FH	18	12,600
Air Balancing	300	$ / FH or $ / room	18	5,400
Low-Flow FH Retrofit Kit	8700	$ / FH	18	156,600
Low-Flow FH Installation	2700	$ / FH	18	48,600
Engineering Contingency	10	%		22,320
SUBTOTAL				**245,520**
Taxes	12	%		29,462
Mechanical / Controls Contractor Overhead	25	%		61,380
UBC Project Services Overhead	5	%		12,276
TOTAL				**348,638**

Table 6 Breakdown of cost estimates for Measure 2 in BRIM

3.2.9.3. Measure 3: Reduce FH Face Velocity to 90fpm

A sample calculation for EOSM follows:

Item	Estimate	Units	Quantity	Subtotal ($)
Air Balancing	300	$ / FH or $ / room	27	8,100
Engineering Contingency	10	%		2,700
SUBTOTAL				**29,700**
Taxes	12	%		3,564
Mechanical / Controls Contractor Overhead	25	%		7,425
UBC Project Services Overhead	5	%		1,485
TOTAL				**42,174**

Table 7 Breakdown of cost estimates for Measure 3 in EOSM

3.2.9.4. Measure 4: Implement VAV Fume Hood Alarms

A sample calculation for CHEM D follows:

Item	Estimate	Units	Quantity	Subtotal ($)
Reprogramming controls	500	$ / FH	50	25,000
Engineering Contingency	10	%		2,500
SUBTOTAL				**27,500**
Taxes	12	%		3,300
Mechanical / Controls Contractor Overhead	25	%		6,875
UBC Project Services Overhead	5	%		1,375
TOTAL				**39,050**

Table 8 Breakdown of cost estimates for Measure 4 in CHEM D

3.2.10. Simple Payback

$$SPB(yrs) = \frac{Project\ Cost\ (\$)}{Annual\ Cost\ Savings\ (^{\$}/_{yr})}$$

3.2.11. Net Present Value (NPV)

The discount rate is assumed to be the rate of finance, which is currently 5.75%. The lifetime of the project is assumed to be 15 years.

$$NPV(\$) = \sum_{i=0}^{15} \frac{Annual\ Cost\ Savings(\$) - Annual\ Costs(\$)}{(1 + 0.0575)^i}$$

3.3. Scope and Exclusions

Four of the buildings were analyzed in detail to provide a representative outlook on what could be achieved in other buildings:

- Chemical and Biological Engineering Building (CHBE)
- Chemistry Centre – D Block (CHEM D)
- Earth and Ocean Sciences – Main (EOSM)
- Advanced Materials Processing and Engineering Laboratories – Brimacombe Building (AMPEL, BRIM)

Due to the short timeline of the project it was decided some buildings would be left out of the project scope entirely. The following buildings accounted for a total of only 23 laboratory rooms and 6 fume hoods among them:

- Aquatic Ecosystems Research Laboratories
- Neville Scarfe
- Fred Kaiser
- MacLeod
- Museum of Anthropology
- Botany Annex
- Institute for Computing, Information and Cognitive Systems / Computer Science (ICICS/CS)
- Aquatic Centre
- Wood Products Laboratory
- Osborne Unit 2

Since the focus of some of this initiative was to demonstrate the magnitude of energy savings achievable with various energy savings measures, the additional savings in these buildings can be considered negligible. The next step following this report would involve selecting an appropriate pilot building to demonstrate the energy savings measures, and thus would not involve the above exclusions.

4. Results

4.1. Building Overview and Descriptions

4.1.1. Case A – Chemical and Biological Engineering Building (CHBE)

CHBE is a relatively new building completed in 2005. The main tower has 6 stories, with all the laboratories located on the 4^{th}, 5^{th}, and 6^{th} floors. All of the 4^{th} floor laboratory space is an undergraduate laboratory that is vacant in the summer months. Two other wings make up the CHBE complex: the Clean Energy Research Centre (CERC) and an additional wing on the east end of the building. The CERC wing contains a high head lab (HHL), while the east wing includes offices and machine shops. The CERC HHL is supplied primarily by return air from the main tower. The main tower has an exhaust manifold with three HPE fans with bypass valves, while the CERC lab has two centrifugal exhaust fans. There are 2 AHUs that supply the main tower and both have VFDs installed, while two different AHUs supply the workshops on the east wing. Lab rooms have 12ft ceilings and CAV fume hoods in addition to a general exhaust. VAV boxes are installed in all fume hood and general exhausts; however they are drawing a constant air volume at present.

Figure 3 Exterior profile of the CHBE showing the 6^{th} floor and roof of the main tower. Exhaust stacks from the three wings are visible from left to right – one stack from the east wing, three HPE stacks from the main tower (connected to a sizeable exhaust manifold at their base), and three stacks from the CERC wing. The two chillers are visible between the two sets of triple-stacks.

A tremendous opportunity exists to make the CHBE building more energy-efficient since it already has some of the mechanical and electronic infrastructure that is needed to make some of the intended retrofits. For example, the VAV boxes are connected to the internal DDC but the vast majority of them have constant setpoints regardless of the occupancy of the laboratory. In fact the only laboratory control strategy is to maintain temperature setpoint by marginally adjusting supply and exhaust air rates.

4.1.2. Case A – Advanced Materials Processing and Engineering Laboratory – Brimacombe Building (AMPEL, BRIM)

Although the AMPEL building is relatively new, it was constructed with numerous dedicated exhaust stacks as shown in Figure 4. An opportunity exists to manifold laboratory exhausts and install HPE fans. Lab room air has daytime (occupied) and night-time (unoccupied) settings with local (room-level) manual overrides. Fume hoods are conventional CAV bypass with dedicated exhaust stacks. The west wing of the building is a HHL with dedicated supply air and exhaust fans. General exhaust fans have VFDs installed.

Figure 4 Exterior / roof level of the AMPEL building. Each fume hood has a dedicated stack with an additional 13 general exhaust stacks (~50 stacks total).

4.1.3. Case B – Earth and Ocean Sciences – Main (EOSM)

EOSM was originally constructed with 20 dedicated fume hood exhausts in 1971. There are 2 HPE fans presently connected to an exhaust manifold serving all the conventional fume hoods (17) as per the renovation completed in 2005. These exhaust fans operate on an alternating schedule such that only one fan is operating at any given time. Recertification of these fume hoods ensured a face velocity of 150 fpm at maximum sash height. Two perchloric acid hoods and one radioisotope hood remain with dedicated exhaust fans. There are 9 AHUs serving all the laboratories; supply air diffusers have a low-profile 'hidden' design between ceiling tiles. At the time of balancing, bypass damper was open 29%. All fume hoods are CAV, and some are drawing air through their bypass valves because their sashes are locked shut for the summer semester in teaching laboratories. No general exhaust exists – all laboratory air exhausts through fume hoods. The building is designed with detachable walls that can be rearranged to make rooms of virtually any size according to demand.

Figure 5 Exterior / roof level view of the EOSM building. Exhaust manifold is connected to two HPE fans, the tops of which are visible on the concrete enclosure at roof level.

4.1.4. Case E - Chemistry Centre, D Block (CHEM D)

CHEM D is one of the original campus buildings constructed in 1925. Laboratories can be found on all 4 floors; however, 43 of 45 operational fume hoods are situated on the fourth floor. Ceilings are very high (5.3m) on the 4^{th} level and could definitely be lowered; however, the skylights would need to be augmented to allow this modification.

It has recently undergone a VAV fume hood upgrade as well as general laboratory renovation (2007). Rooms with fume hoods do not have a general exhaust. Supply air is regulated between fixed minimum and maximum set-points to maintain a static room pressure. There are a total of 4 AHUs with VFDs and 4 HPE fans with VFDs serving all laboratory space. The HPE fans are connected to an exhaust manifold.

Figure 6 Rear view of CHEM D showing exhaust manifold and 4 HPE fans on the roof. The height of the 4^{th} level ceiling is visibly taller than the lower levels.

4.2. Extrapolation of Measures to Entire Campus

4.2.1. Measure 1: Decreased Air Change Rates (Night Setback with Manual Override)

An approximation of this measure was extended to all CAV rooms without fume hoods (in 25 buildings), while estimating that current air change rates are in the range of 10 to 20 ACH. Only the energy savings are presented due to the uncertainty of estimating costs for retrofitting buildings of various ages with two-position valves and timed controllers. In the summary table, the savings are presented for the more conservative assumption that existing ventilation rates are 10 ACH.

4.2.2. Measure 3: Reduce FH Face Velocity to 90fpm

This measure was extrapolated to all CAV fume hoods (in 26 buildings), assuming that only 80% of the total reductions will be achievable due to fume-hood dominated instances.

4.3. Summary of Energy-Saving Measures for Selected Buildings

Table 9 below lists the measures that were applicable to each building along with project costs, annual savings, and simple payback period.

Building	Measure #	Annual Cost Savings ($/yr)	Capital Cost ($)	SPB (yrs)	15-yr NPV ($)	Annual Conditioned Air Abated (CFM/yr)	Electricity Saved (MWh/yr)	Steam Saved (lbs/yr)	GHG Saved (tCO_2e / yr)
CHBE	1	100,491	471,412	4.7	652,802	37,406	450	6,810,128	604
CHBE	2	45,081	716,646	15.9	-12,971	16,781	202	3,055,094	271
CHBE	3	39,469	57,794	1.5	333,501	14,692	177	2,674,780	237
EOSM	2	28,818	522,958	18.1	-47,550	10,727	129	1,952,941	173
EOSM	3	53,109	42,174	0.8	470,302	19,769	238	3,599,144	319
BRIM	1	186,204	13,589	0.1	1,730,188	69,311	834	12,618,764	1,120
BRIM	2	22,030	348,638	15.8	-5,393	8,200	99	1,492,915	133
BRIM	3	23,663	14,839	0.6	211,932	8,808	106	1,603,576	142
CHEM D	4	45,027	39,050	0.9	396,732	16,760	202	3,051,391	271
All CAV rooms without FHs	1	649,690	N/A	N/A	N/A	241,833	2,911	44,028,475	3,908
All CAV rooms with FHs	3	420,863	1,032,482	2.5	3,304,143	156,657	1,886	28,521,202	2,532

Table 9 Summary of project costs and potential savings

4.4. General Observations

While the safety of lab users is paramount, some lab users circumvent safety regulations for various reasons. Though there is no reasonable excuse for compromising safety, it appears that forgetfulness and disorganized lab etiquettes play a major role. Some of the questionable lab practices that were observed are listed below:

- Supply grilles have been taped or air has been redirected by forcing it in a certain direction, away from a working space where users have deemed the climate too drafty and/or too cold/hot. This changes the dynamics of the air circulation patterns in the room and could compromise dispersion.
- General exhaust grilles have been retrofitted with aftermarket ducting acting as a snorkel routed to a local experimental set-up. This essentially eliminates the general exhaust from serving that region of the room, again disrupting the designed dispersion patterns.
- Chemical storage cabinets with dedicated exhaust vents should be incorporated directly into exhaust ducting via a snorkel device or otherwise situated in a dedicated chemical storage room. These storage cabinets are often ventilating naturally to the general lab room space (Figure 7) which dramatically affects room air quality and therefore energy use.
- Equipment and/or chemicals have cluttered the fume hood work area to the point that items are located right up against the sash. For proper containment all objects should be at least 6" back from the face of the sash otherwise the designed flow pattern is disrupted and could result in leaks.
- Air/gas/vacuum lines routed from inside the fume hood across the face opening to serve other equipment in the lab room. Sash height cannot be lowered past these tubes.
- Bypass grilles on CAV fume hoods have been taped shut, presumably to increase flow through the operational face opening. Containment is compromised due to turbulent vortices forming that may in fact force air towards the user.
- Fume hoods have been used solely for storage of chemicals (no user occupancy or experiment in progress) both with open and with closed caps.
- Home-made snorkels (plastic tubing) at lab benches have been routed through the bypass grille of CAV fume hoods.

Figure 7 Chemical storage cabinets like these are regularly found in laboratories; however, during the audit only (A) BIOS-S had dedicated ventilation ducts that connect to the HVAC system directly – (B) and (C) represent all other cabinets observed that vented naturally to the ambient laboratory room air.

In graduate laboratories the high student turnover rate and age of the lab contribute to a steady accumulation of equipment and chemicals which are overcrowding work areas and fume hoods, so that fume hoods end up being used for storage. During the audit approximately 32 out of a total of 130 fume hoods (~25%) were found to be storing chemicals when unoccupied by the user. Fume hoods are often left open when unoccupied and while experiments are in progress.

5. Discussion and Conclusions

Effort has been taken to provide the most accurate results for future decision making. It should be noted that the accuracy of the results are only as accurate as the underlying data as well as the assumptions. For a pre-feasibility study, however, the project costs and payback periods provide a good idea of which projects should be preferentially explored.

Since much of the data is calculated based on a conditioned air price of $2.69/CFM/yr, it was reviewed with consultants and UBC mechanical engineers for consistency. The fact that it is a lumped parameter that is heavily dependent on local climate implies that it changes even with variations in annual climates where a particular year may be much different than a historical average year. Laboratories in particular have a high heat load which means that the 18°C balance point for estimating CDD may well be underrepresenting the amount of cooling that is necessary; some labs need cooling even in the winter for this reason. Furthermore, the GHG intensity of BC Hydro's electricity can be argued to be substantially higher than the quoted 25 tCO_2/GWh. Recent amendments to the BC Energy Plan in re-defining energy self-sufficiency will mean that more energy will be imported from carbon-intensive sources; considering all such imports, GHG intensity could be as high as 82 tCO_2/GWh (Hanova, 2007). The amount of energy imported to the BC grid needs to be closely monitored in the near future as it could have a sizable effect on the economic feasibly of energy savings measures in this study.

There are many energy saving opportunities available in UBC laboratories which could make sense from an economic point of view. Savings measures not explored in this report that could be investigated in the future include:

- Replacement of fume hoods with ductless fume cabinets
- Installation of heat recovery unit on exhaust i.e. enthalpy wheels
- Occupancy sensor implementation for:
  - General lab room supply/exhaust
  - VAV fume hood reduction of face velocity (as in Figure 9)
  - VAV fume hood automatic sash closure mechanism
- Active chemical monitoring with real time ventilation: flow adjustment based on contaminant levels
- Increase stack heights, thereby reducing the necessary fan speed (and energy) for adequate dispersion
- Decrease of room volume by virtue of lowering ceilings that are unnecessarily tall
- Consolidating dedicated laboratory exhausts and fans to a common exhaust manifold

The general exhaust can in theory be eliminated from rooms with fume hoods in order to decrease the air change rates. One major consideration when planning such a project is how it will affect the airflow dynamics within the room: all room contaminants would then exhaust across the fume hood user's breathing/working zone. The effects of such a ventilation scheme on human health has not been studied in any great detail therefore more data needs to be collected before proceeding in this direction. Moreover, health risks inherently involve values of the individual which means that populations are not homogeneous in their degree of vulnerability to risks such as exposure to contaminants (Fischhoff, 2011).

Reducing face velocities to 90 fpm is the most economically viable project of the options studied. Paybacks ranged from 0.6 to 1.5 years for the buildings studied in detail (Table 9). A rough extrapolation to the rest of the campus buildings with CAV fume hoods yielded a SPB of only 2.5 years. Considering the annual savings were estimated to be $420,000 with a 15-year NPV of roughly $3.3M this project is well worth pursuing in greater detail, especially since estimates were based on largely conservative assumptions. Associated greenhouse gas reductions are approximately 5% of the campus carbon footprint.

While it was challenging to estimate the project costs involved in retrofitting lab rooms without fume hoods to two-position valves, an order of magnitude estimate for energy savings was feasible. An existing ventilation rate range of 10-20 ACH on average was assumed for all rooms, which yielded approximately $0.6-1.4M in savings. This result is quite appreciable and warrants further investigation as well. The reduction in greenhouse gas emissions amounts to more than 6% of the campus total, even for the more conservative assumption of existing ventilation rates of 10 ACH.

The two measures were not extrapolated to all buildings in tandem, since it is likely that implementing both reductions simultaneously would result in ventilation rates below the minimum permissible air change rates for the space. While determining the savings of Measure 1 and 3 simultaneously was too complex for the current study, this could be investigated further in detailed building audits.

The use of occupancy sensors is limited to a specific laboratory room layout displayed in BIOS-W and BIOS-S. There are little alcove rooms that branch off the main laboratory space that serve only to house fume hoods (Figure 9). Essentially there is no reason for lab personnel to enter this alcove room unless they specifically need to use the fume hood. This strategy makes little sense in the CHEM D+E buildings where fume hoods are arranged next to each other, with their sashes facing high traffic areas.

Figure 9 (A) Image of a state-of-the-art VAV fume hood in BIOS-W. Notable features include the motion sensor for room lighting (top), fume hood occupancy sensor (centre, above bypass grille), and controller (right, with red LED display). (B) Close-up view of controller showing 100fpm face velocity at standard operation (occupied condition). Standby operation typically reduces the face velocity to 60-80fpm (varies) when the fume hood is unoccupied. Flow alarm sounds when sash is raised above safe level such that complete containment is not guaranteed.

The price of LFFH retrofit kits ($8700) as well as the installation labor cost ($2700) inflates the payback period so much that the project is not economically viable. This technology is popular in places like California climate where the price of CFM is twice that of BC's. However, the retrofit should still be considered on an individual installation basis where fume hoods are failing containment tests due to lack of static exhaust pressure (fans are already running at maximum capacity).

Figure 10 View showing the underside of VAV fume hood airfoils in (A) CHEM E and (B) CHEM D. This gap essentially maintains a minimum air flow in the event that the sash is completely flush (shut) with the airfoil.

The reduction in air change rates recommended in this report is based on representative laboratories. Each space is unique in design and therefore requires customized solutions; factors such as occupancy and the nature of the laboratory chemicals alter ambient conditions in different ways. A more accurate analytical method of probing the efficacy of the ventilation strategy is to employ computational fluid dynamics (CFD) programs. This is a very time consuming process – not to mention that again it is a theoretical representation. The ultimate level of accuracy needs to be empirical; a pilot of the ventilation system where an optical marker such as smoke, fog, or bubbles are used to visualize air currents and identify potential dead zones or turbulence. In cases where air change rates are below 10 ACH as proposed in this report, this type of testing may be necessary.

An appreciable component of potential energy savings is based on user behaviours, as observed with fume hoods being used for chemical storage, and with the failure to shut the sash on VAV fume hoods. In McKenzie-Mohr's *Fostering Sustainable Behavior*, there are a series of steps proposed that encourage users to make more sustainably-oriented decisions. This strategy is known as 'community based social marketing' and is summarized in the list below:

- Select behaviours to be addressed
- Identify barriers and benefits
- Develop strategies: commitment, social norms, social diffusion, prompts, communication, incentives, convenience, etc.
- Execute pilot tests
- Broad scale implementation and evaluation

UBC is currently in the process of launching a program addressing the VAV fume hood sash closure in a pilot building.

Since the turn of the 21st century the advancement of electronics/robotics has been appreciable. What the future holds for optimizing laboratory energy efficiency can be predicted based on market penetration of VAV fume hoods and novel sensing technologies like occupancy sensors, effectively automating the entire laboratory for a truly 'worry-free' energy savings. Indeed newly built laboratories at research institutions worldwide have employed these measures and are saving energy and operating costs in the process.

Furthermore, this may indicate that perhaps it is time for researchers to rethink the way chemical or biological processes are carried out altogether. Automated process control in precision experiments or radio-synthesis is well established and rarely requires user intervention. With the correct combination of equipment and computer hardware and software, it is possible to design R&D labs with immaculate control and efficiency for all chemical and biological processes contained within fume hoods (Bernlind, 2009). Such a system design would obviate the need for fume hood sashes to be open for more than a few seconds at a time, potentially reducing energy use by a substantial margin. Not all fume hoods would qualify for such a strategy since some experiments need to be performed manually for the purpose of learning exercises. It is impossible to predict how the future will unfold with respect to volatility of energy prices and new codes and regulations therefore such a drastic change to automating fume hoods may not yet be on the horizon.

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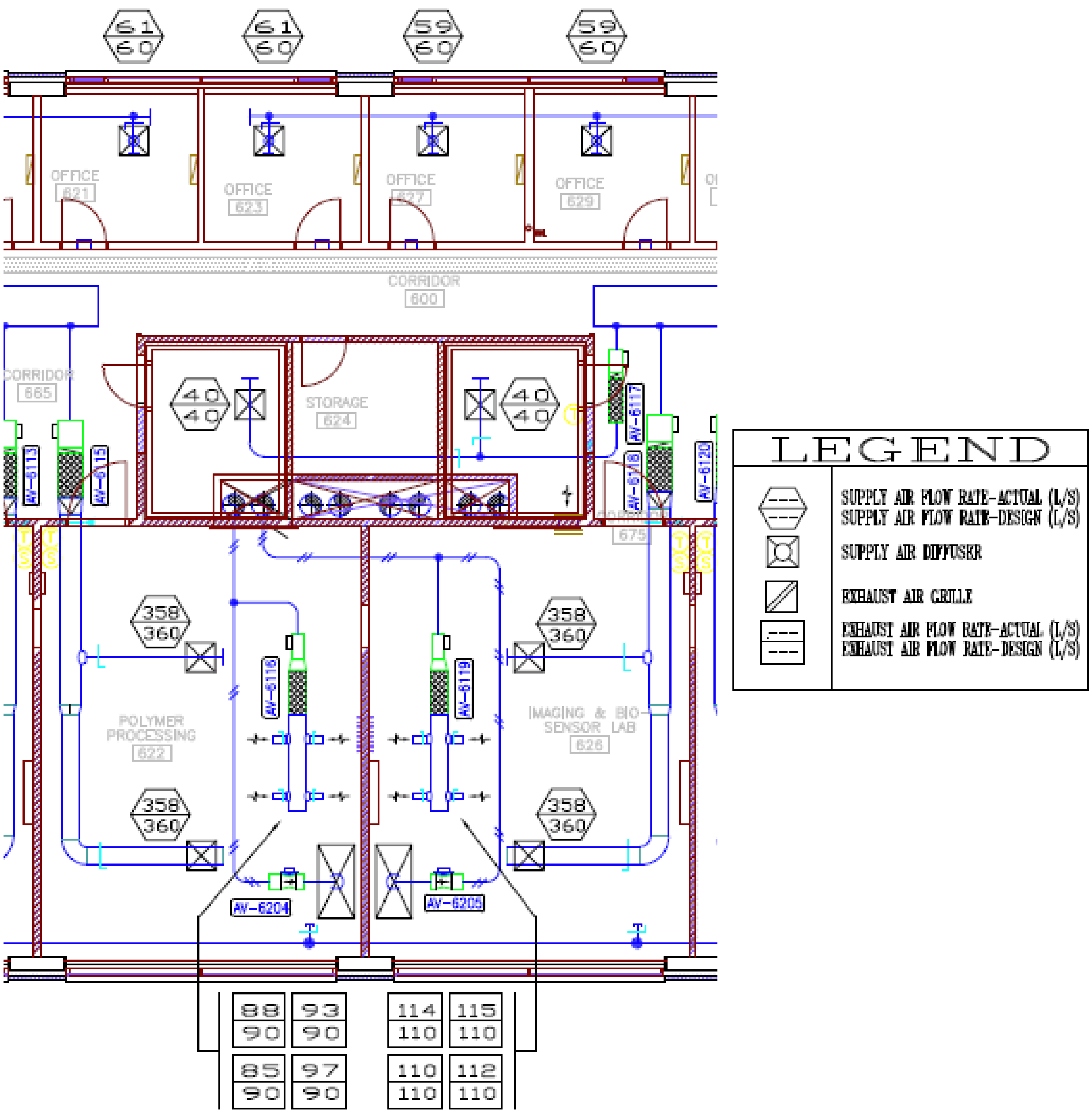
8. Appendix

8.1. Sample of a Balancing Diagram (CHBE)



8.2. List of Abbreviations

ACH – air changes per hour
AHU – air handling unit
CAV – constant air volume
CDD – cooling degree days
CERC – Clean Energy Research Centre
CFD – computational fluid dynamics
CFM – cubic feet per minute
DDC – direct digital control
GHG – greenhouse gas
HDD – heating degree days
HHL – high-head lab
HPE – high plume exhaust
HVAC – heating, ventilation, & air conditioning
NPV – net present value
RMS – Risk Management Services (UBC)
SPB – simple payback
VAV – variable air volume
VFD – variable frequency drive

8.3. Summary of Balometer Measurements

A balometer (Alnor APM 150) was used to measure actual flows in several supply grilles in order to assess the accuracy of balancing report data. On average, the deviation between the balometer measurement and the balancing report was 4.6%. Most of the balometer measurements were higher than the balancing report. Using the flow measurements from the balancing reports can be assumed to be reasonably accurate.

Building	Room	Flow Measurement with Balometer (L/s)	Flow Measurement in Balancing Report (L/s)	±% Difference
Chemical and Biological Engineering (CHBE)	502	296	285	3.9
	502	301	285	5.6
	508	324	347	-6.6
	518	341	322	5.9
	518	327	322	1.6
Michael Smith Laboratories (MSL)	368	112	107	4.5
	368	108	103	4.5
	371	80	77	4.4

8.4. Building Room Type Summary

Floor areas of each room type in each building are reported below. See Table 3 for detailed descriptions of room types. Biological Sciences Building is omitted due to ongoing renovations. Hebb Building is excluded as it does not have any exhaust strategy.

Total area of room type (m^2)						
ROOM TYPE	A	B	C	D	E	F
Control Strategy:	CAV	CAV	CAV	VAV	VAV	VAV
General Exhaust Present:	YES	NO	YES	YES	NO	YES
Fume Hoods Present:	YES	YES	NO	YES	YES	NO
Beaty Biodiversity Research Centre	285		223			
Biomedical Research Centre	577		990			
AMPEL-Brimacombe	868		1,223			
CEME Laboratories	530		1,858			
Chemistry A Block	2,467		849			
Chemistry B Block		2,077	573			
Chemistry C Block		1,197	41			
Chemistry D Block					1,159	225
Chemistry E Block					617	401
Chemical and Biological Engineering	2,169		424			
Coal and Mineral Processing Centre	315		356			
DH Copp		2,346	418			
George Cunningham		941				
Earthquake Engineering Facility			273			
Earth & Ocean Sciences Main		1,380	53			
Food Nutrition and Health		688	289			
Frank Forward		755	1,060			
Forest Sciences Centre	1,290		1,330			
Hennings	98		2,430			
Douglas T. Kenny	114		170			
Lower Mall Research Station	532		784			
Library Processing Centre	265		90			
Life Sciences Centre				8,404		1,285

Total area of room type (m^2)						
ROOM TYPE	**A**	**B**	**C**	**D**	**E**	**F**
Control Strategy:	CAV	CAV	CAV	VAV	VAV	VAV
General Exhaust Present:	YES	NO	YES	YES	NO	YES
Fume Hoods Present:	YES	YES	NO	YES	YES	NO
HR MacMillan		897	1,209			
JB Macdonald	519		179			
Medical Block C		596	356			
Michael Smith Laboratories				431		2,186
Networks of Centres of Excellence	810		346			
Pulp and Paper Centre	565		407			
Wesbrook Building		683	1,914			
TOTALS	**11,404**	**11,560**	**17,845**	**8,835**	**1,776**	**4,097**