The use of feedback in lab energy conservation: fume hoods at MIT

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Received 18 June 2009
Revised 14 September 2009
Accepted 10 February 2010

Abstract

Purpose – The purpose of this paper is to report on the results of an Massachusetts Institute of Technology Chemistry Department campaign to reduce energy consumption in chemical fume hoods. Hood use feedback to lab users is a crucial component of this campaign.

Design/methodology/approach – Sash position sensor data on variable air volume fume hoods are remotely collected. A 15 minutes average fume hood sash positions for each laboratory are recorded. Data are compiled monthly and a report with average sash position over time and relative frequency of hood position are delivered to the principal investigators of the labs.

Findings – Average sash height is lowered by 26 percent (from 16.3 ± 0.85 percent open to 12.1 ± 0.39 percent open) throughout the department, saving an estimated $41,000/year. Sash position during inactive periods is lowered from 9 to 6 percent open. Half of all department savings occurred in four (of 25) labs. Energy savings are substantially less than original expectations because most installed fume hoods use combination sashes. Labs with vertical sashes use the most energy, and see the most savings from the intervention.

Practical implications – Monthly feedback is an effective tool for encouraging better hood use behavior. Potential savings from even large behavior changes can be limited if existing equipment is relatively efficient, so conservation programs should be tailored to the existing conditions.

Originality/value – The present analysis provides data on the impact of a program in a relatively efficient setting compared to other fume hood conservation reports. The results have cautionary value for designers of similar programs. A breakdown of a laboratory building utility use is also provided.

Keywords Feedback, Energy conservation, Laboratory testing

Paper type Research paper

1. Introduction

Energy use and greenhouse gas emissions are becoming increasingly important. Massachusetts Institute of Technology (MIT) shares this concern and has made a commitment to "walk the talk" and implement conservation and efficiency programs on its campus. One aspect of this campaign is examining MIT's laboratory energy consumption. Laboratory spaces consume about five times more energy per square foot than ordinary office space (Mills and Sartor, 2005a), and on the MIT campus eight of the ten buildings with the highest energy consumption per square foot are at least 30 percent research lab space (Facilities, 2008). Laboratory space must have a high rate of air exchange for safety purposes. Occupational Safety and Health Administration recommends four to 12 air exchanges per hour (ACH) in lab spaces (Deluga, 2000), although the merits of this criterion are debated (Woolliams *et al.*, 2005). MIT uses six ACH as its design standard. This high air exchange rate requires fuel for air

International Journal of Sustainability
in Higher Education
Vol. 11 No. 3, 2010
pp. 217-235

1467-6370
DOI 10.1108/14676371011058523

conditioning (both heating and cooling) and electricity for fans, and accounts for over 60 percent of the energy consumption in lab buildings (Weale *et al.*, 2002).

One significant contributor to laboratory air exchange is fume hoods. Fume hoods are one of the most common pieces of personal protection equipment in laboratories that handle volatile chemicals, such as acids and solvents, or biological agents. Hoods provide an alternative to self-contained breathing apparatus (SCBA) for performing bench chemistry with volatile substances. Fume hoods are an essential piece of equipment in a chemistry teaching environment, as they create a flexible work space where more than one person can safely observe and work with chemicals. SCBA requires professional training to use, is expensive, is not conducive to collaborative work, and provides less physical protection (e.g. splash protection) from reactive components.

A hood works by drawing air from the laboratory space through an opening between a bench-top and a moveable sash. The air passes over the chemicals and is drawn up through a plenum into the ventilation ductwork and out of the building (Figure 1). The flow of air over the chemicals prevents vapors from escaping into the laboratory

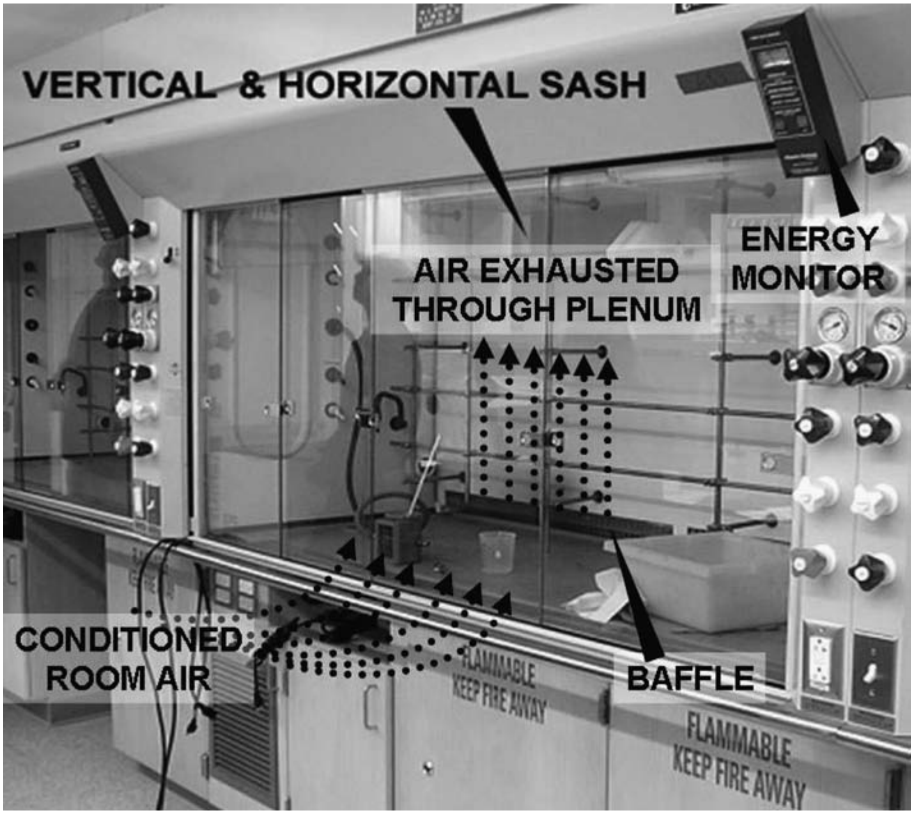


Figure 1.
MIT Chemistry Department combination sash fume hood

Notes: Room air passes through the sash and is exhausted through a baffle into a plenum and outside; the glass panels slide only horizontally, but are enclosed in a frame that has vertical motion; note the energy monitor, which indicates the energy required to achieve the face velocity environment, allowing workers to safely handle dangerous materials without wearing SCBA.

Fume hoods are considered to have a large energy draw. Fume hoods use high power fans to pull air through the hood, leading to a substantial electric load (Weale *et al.*, 2002). Moreover, all the air is drawn from conditioned laboratory space air, so makeup air must be conditioned to replace this draw. This is a substantial energy loss, especially in cold or humid climates. The most efficient MIT Chemistry Department fume hoods, for instance, vent air at up to 850 cubic feet per minute (CFM). Makeup air in Boston requires around 0.31 mmBTU per CFM per year of continuous air flow (mmBTU/CFM year). Therefore, this single fume hood has the potential to vent 266 mmBTU of energy. This is the annual energy consumption of roughly 2.5 average single family homes in the USA. Fume hoods are often cited as using the energy of 3.5 homes (Mills and Sartor, 2005b; Brewer *et al.*, 2003; Woolliams *et al.*, 2005), and some go on to suggest the 75,000 fume hoods in the US cost upwards of $3 billion/year to run (Woolliams *et al.*, 2005).

Laboratory building operation and fume hood design may substantially reduce potential savings. Many new hoods use technology that is more efficient than venting air at the maximum flow rate all the time. Moreover, much of the air that passes through fume hoods contributes to general laboratory ventilation and would have to be moved regardless of the presence of the fume hood. The difference between the required air exchange rate for the lab space and the rate with the fume hood is the real energy use of the hood. This should be much less than the energy of 3.5 homes and, although unlikely, it may be as little as zero in some spaces (as in the case of a single hood in a large room). New laboratory buildings use heat recovery technologies that use heat from exhaust air to preheat makeup air further reducing energy requirements.

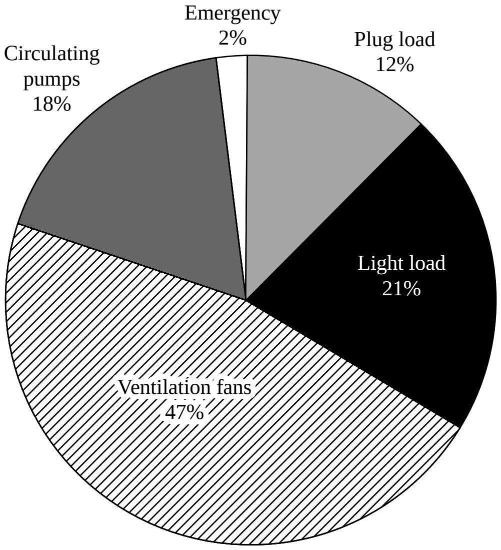
This report analyzes the use of fume hoods in laboratories of the Chemistry Department at MIT. The impact of those hoods on building energy use was determined. The Chemistry Department, in cooperation with the Environmental Programs Office, Department of Facilities and the MIT Energy Initiative engaged in a concerted campaign to reduce energy consumption through their variable air volume (VAV) hoods. Hood use feedback to lab users was a key component of this campaign. The effect of that campaign on user behavior and building energy use is considered.

1.1 History of fume hood conservation efforts at MIT

The MIT Chemistry Department is home to almost 30 faculty members, 250 graduate students, and 100 undergraduate majors. About 100 post-doctoral researchers also use the department facilities. The home of the MIT Chemistry Department is Building 18, which houses department offices and about two-third of the department's laboratories. The building opened in 1969, but complete renovation was finished in 2003. A key component of the renovation was an increase in the density of fume hood space from five to seven linear feet per researcher. There were constraints on the capacity of the ventilation system, so an efficient fume hood design was required from both an energy economics standpoint and the air supply constraints. A heat recovery system was not installed during the renovation due to concerns about the potential chemical corrosion of heat transfer elements within the available heat recovery systems at the time.

Interest in behavior-related fume hood energy conservation on campus began to build in 2006. An undergraduate thesis examined the electric load of Building 18 in detail after observing the lights were on essentially 24 hours a day. However, it was shown that heating, ventilation and air conditioning (HVAC), not lighting, is responsible for the largest fraction of total building energy use (Amanti, 2006). Figure 2 shows a breakdown of electricity use in Building 18. Fume hoods are responsible for a large fraction of this HVAC load, although a significant portion of this load is the fixed minimum air flow through the hoods. Amanti made the first assessment of hood use by walking through labs at night and manually counting the number of open and closed fume hood sashes. This analysis indicated about half the fume hoods were open, on average (i.e. an average sash height of 50 percent). An energy assessment based on the assumption of perfect sash closing at night indicated that the energy savings potential in Building 18 was around 17 percent of the annual energy budget, or a total utility savings of $350,000. The magnitude of the potential savings prompted the behavior change campaign, but it was eventually determined to be a substantial (2-3 ×) overestimate of potential savings. The source of the discrepancy is discussed later in Section 3.3.

Amanti's thesis supervisor was startled by the potential savings and passed the information on to the Dean of the School of Science and the Chemistry Department Head. Action on the problem began soon after. The School of Science, Chemistry Department, and Department of Facilities began maintenance work and calibration of sash position sensors in the summer of 2006. Repair and calibration of face velocity for all the fume hoods in the department began that fall. The Chemistry Department worked with Andover Controls, the building operations contractor, to arrange for sash sensor position data to be grouped by the principal investigator (PI) responsible for each fume hood and sent to the Chemistry Department's Environment, Health, and Safety (EHS) Coordinator automatically beginning in November 2006.



7.2 million kWh total

Note: The light load was found to be the previously unassigned electricity use in the 480 V circuit
Source: Revised from Amanti (2006)

Figure 2.
Electricity use breakdown for Building 18

The first fume hood behavior intervention occurred mid-November 2006, when the Chemistry Department's EHS Coordinator[1] reinforced the importance of closing fume hood sashes at the regularly scheduled EHS laboratory representative[2] meeting. The presentation covered the reasons for shutting the sash (cost savings, benefit to the environment, personal safety), a description of how fume hoods work and how energy is consumed, the dangers of improper fume hood use, and the magnitude of the potential energy savings. These savings are startling – up to $400/inch of hood opening per year in the widest hoods in the Chemistry Department (and $80/in/year for the hoods in Building 18). Representatives were encouraged to respond after the presentation and after discussion with their labs. This message was reinforced by an e-mail from the department head to the faculty, ensuring the entire department was familiar with the program. The "shut-the-sash" message has since been integrated into the Chemistry Department's EHS training sessions that are required for all new graduate students.

The second intervention was the release of fume hood use data to the faculty PI in charge of each lab. The first datasets were distributed by the department EHS coordinator to the Chemistry faculty in early August 2007. These data were then distributed to other members of the lab at the faculty PI's discretion.

1.2 Overview of fume hood technology

There is a wide variety of fume hood types, and a number of strategies for minimizing their energy use (Deluga, 2000; Kolkebeck, 2006). Fume hoods can have vertical (up and down), horizontal (side to side) sash movement, or a combination sash with both. Fume hoods can also either move a constant air volume (CAV) in a period of time or a VAV. The CAV hood operates at maximum air exchange at all times, regardless of sash position (Deluga, 2000). This increases the face velocity as the sash is closed. CAV bypass hoods have vents at the top of the hood to keep the face velocity more constant. A two-position hood reduces air flow when the sash is effectively closed, but otherwise operates at maximum air exchange like an ordinary CAV hood.

VAV hoods use sensors to calculate the pressure differential necessary to maintain a constant face velocity. Air volume may be adjusted using a closed- or open-loop control. Closed-loop control uses a small air speed sensor embedded in the hood to measure the face velocity and adjust dampers to change the air volume accordingly. Open-loop control hoods use sash position sensors to calculate the necessary air volume. Air valves are used to control the flow of air between the hood and the exhaust network. Either open- or closed-loop design drops the air flow through the hood substantially. The hood usually operates at minimum air exchange, if workers properly close the hood when it is not in use.

VAV hoods are considered much more energy efficient than CAV hoods, but this is not necessarily true. CAV designs are well suited to large laboratory spaces with few fume hoods. The ventilation through the CAV hood can be subtracted from the general laboratory ventilation, keeping the overall energy use to a minimum (Kolkebeck, 2006). Low-flow CAV hoods can be used to achieve this in smaller spaces (Mills and Sartor, 2005a). Small labs with a high density of fume hoods (the vast majority of labs at MIT) benefit from VAV designs, since even the minimum air volume through CAV hoods far exceeds the minimum requirements in small spaces. For instance, a single 650 CFM CAV fume hood can produce six ACH in a space of 6,500 ft^2 (a room $25' \times 25' \times 10.4'$), which is two times larger than any lab space in the Chemistry Department (Facilities, 2008).

It is necessary to have good user behavior with VAV hoods to achieve low energy use, since all additional opening adds to the room ventilation load. Automated sash closing systems are not always a viable alternative to proper use of fume hoods. Retrofitting these systems can be nearly as expensive as purchasing new VAV fume hoods and they do not work with all hood designs.

1.3 Fume hoods in the Chemistry Department

The Thermo Fisher Hamilton SafeAire Concept fume hood was selected after a thorough test of alternatives as the only fume hood to be installed during Building 18 renovation. The Concept hood is a 72 × 28.5 inch combination sash, VAV hood with an open-loop control system. The renovated building features 200 of these hoods. The hood sash has two sets of two horizontal sliding panels in a frame that can be lifted vertically (Figure 1). It is almost always used as a double horizontal sash hood rather than raised vertically. This effectively blocks at least half the face of the hood at all times.

Building 18 contains 201 of the 253 fume hoods under the control of the Chemistry Department (there is one CAV hood in the sub-basement of the building). The 52 fume hoods in other buildings (56, six, and two) are mostly traditional vertical single-sash designs. All these hoods have a vertical face dimension between 27 and 31 inch, but the horizontal face dimension varies from 40 to 114 inch. The average maximum air volume through these hoods is close to 1,345 CFM. Face velocity at a maximum safe opening is determined by the EHS Office during periodic inspections, so the total air flow through hoods in the department can be calculated.

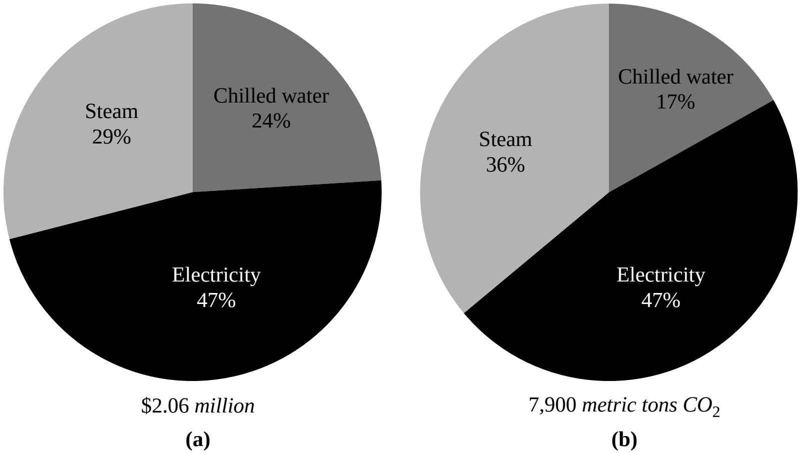
Air volume through all VAV hoods in the department is modulated by a Venturi-type air valve by Phoenix Controls. A nominal face velocity of 100 ft/min is maintained. Data from sash position sensors on each fume hood are sent to a central processor that controls laboratory-scale and building-level exhaust. This real-time data were not stored prior to the work described in this report. Andover Controls wrote software to automatically collect and redistribute the 15 minutes average sash position by laboratory from this central database after the start of this program.

1.4 Chemistry Department energy use

The overall utility use for the department is difficult to assess because MIT charges a flat overhead rate and does not bill each laboratory separately. However, the sole occupant of Building 18 is the Chemistry Department, so inferences about the energy intensity of chemistry can be made by examining that building's energy use. Utility cost and estimated carbon emissions from Building 18 are shown in Figure 3. FY 2007 (July 2006-June 2007) utility use amounted to over $2 million, most of which was electricity. Electricity also accounted for the majority of CO_2 emissions. Building 18 was responsible for approximately 7,900 metric tons of CO_2 and the consumption of 117,000 mmBTU of energy in FY 2007.

2. Experimental method

A wide body of literature has indicated that providing feedback to consumers about their energy use often leads to a reduction in use (Peterson *et al.*, 2007). Feedback is most effective when the feedback is as close to the time of action as possible, for instance warning lights or interactive prompts. However, this was not practical with the resources available for this experiment. A more appropriate analog to the present



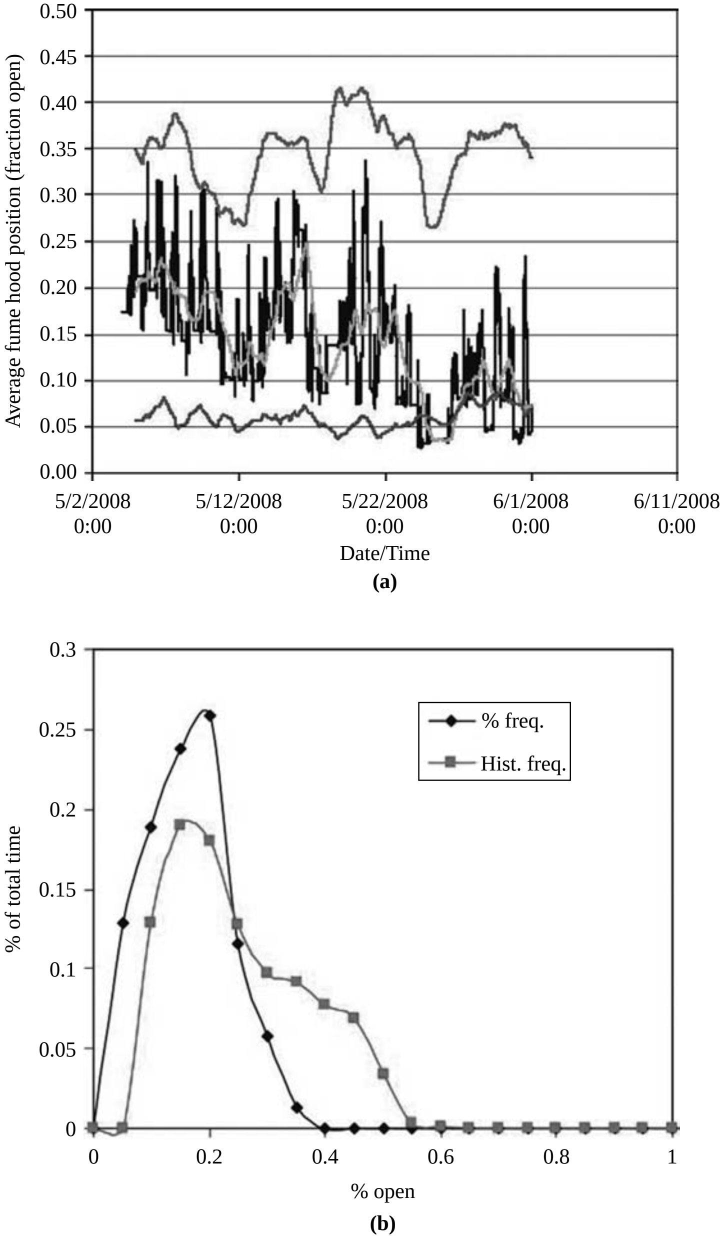
Notes: (a) Cost: \$2.06 million; (b) emission: 7,900 metric tons CO_2; CHW, steam, and electricity cost more than \$2 million and was responsible for 7,900 metric tons of CO_2 emissions

Figure 3.
Utility use in Building 18 in 2007

feedback study is a monthly utility bill. Many studies of the effectiveness of electricity bills in promoting conservation have been performed, including several reviews (Egan, 2001; Collins *et al.*, 1985). Savings of 3-21 percent have been reported, with higher frequency and fidelity (e.g. including a graph of electricity use over time instead of just a use and cost number) associated with higher energy savings (Collins *et al.*, 1985). Wilhite and Ling (1995) reported that even bimonthly feedback was associated with a 10 percent reduction in electricity use compared to an annual bill.

The design of the feedback is particularly important. Well-designed feedback should clearly state all important data in a way that users can relate to their actions, such as the amount of electricity required to run a fan rather than just the monthly household electricity use (Kempton and Layne, 1994). The ideal feedback should be presented in a form that is important to the user (such as a bill), has clear representations of the person's use, and makes meaningful comparisons to his peers (Wilhite and Ling, 1995). A monthly feedback-based program was developed to encourage better fume hood use in the MIT Chemistry Department. Use charts based on sash position sensor data were provided to fume hood users in this study, and the effect on hood use and building energy were monitored.

The design of the feedback mechanism in this study is shown in Figure 4. The Chemistry Department contains 25 laboratories (a laboratory was defined as the space supervised by a single PI). A single sheet with two charts was provided to each laboratory PI once a month (Figure 4). The top chart showed four plots – the 15 minutes average sash position for that laboratory and a 24-hour averaging of that position data, as well as the 24-hour average sash position for the lab with the highest average sash position and the lab with the lowest. Labs with less than five hoods were excluded from consideration as the highest or lowest user in the department, leaving 16 labs for comparison. All labs received the feedback, but labs with few hoods typically showed hood use below the low bound. The bottom chart provided a frequency



Notes: (a) Fifteen minute average use, with a 24-hour moving average for this lab, the highest use lab, and lowest use lab in the department; (b) histogram comparing current use to the use during the pre-feedback period. No additional information was provided, although the EHS coordinator would comment on the lab performance in the e-mail with this sheet

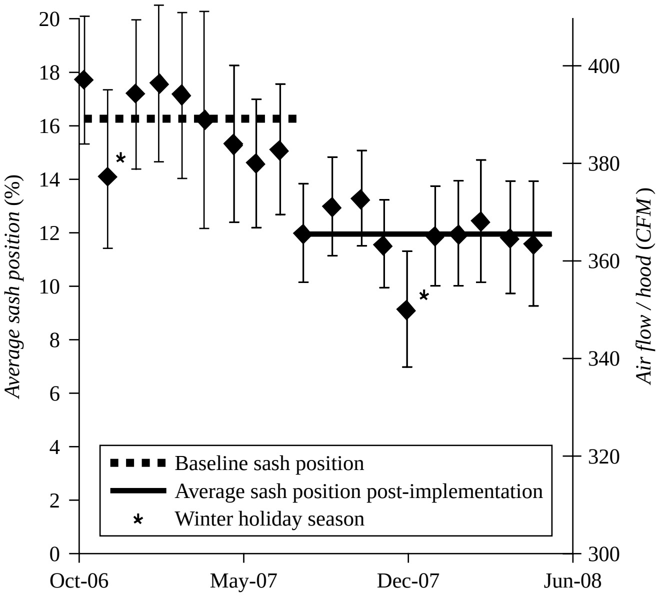
Figure 4.
Example of feedback delivered to PI's of labs

histogram of hood use. Two curves were plotted: the hood use prior during the baseline period (November 2006-June 2007) and their hood use during this month. The 15-minute average sash positions were binned in 5 percent intervals to generate the frequency histogram.

The social context for the delivery of this feedback device should be considered. As a result of a US Environmental Protection Agency regulatory enforcement action against MIT in 1999, MIT implemented a substantial overhaul of its programs to manage hazardous waste on campus. MIT created one of the nation's most sophisticated environmental management and training systems at a university, managed by the EHS Office. The fume hood data feedback deployed in this experiment was delivered using this environmental management system. The department-level EHS coordinator first emphasized the importance of closing fume hoods during annual training of lab-level EHS representatives (graduate students and research staff within each lab make up these representatives) in November 2006. Feedback was delivered to each PI by the EHS coordinator. Concern about whether the PIs were forwarding the feedback led to the addition of EHS representatives to the feedback mailing list in early 2008.

3. Intervention results and energy implications

The effectiveness of the feedback mechanism was judged in terms of its impact on user behavior and in terms of building energy savings. Significant impacts were found in both cases. Figure 5 shows a modest reduction in sash position in May 2007, potentially resulting from the Amanti report and subsequent conversations occurring within



Note: Feedback began at the beginning of August 2007 and resulted in a 26 percent drop in average position, from 16.3 to 12.1 percent open, or 23 CFM/hood

Figure 5. Average sash position for the Chemistry Department, by month

the department. More significantly, after sash position monitoring feedback began in August 2007, the average sash height was lowered by 26 percent (from 16.3 ± 0.85 percent open to 12.1 ± 0.39 percent open) as shown in Figure 5. Ninety-five percent confidence intervals for the points are indicated. This reduced the flow through each fume hood by approximately 23 CFM. The gains in Building 18 were slightly smaller (a 22 percent reduction from 13.9 ± 0.94 percent to 10.8 ± 0.46 percent open). Estimated net savings are $24,000/year in energy in Building 18, and $41,500/year throughout the entire department. The program averted approximately 93 tons of CO_2 in Building 18 and 160 tons of CO_2 department wide.

3.1 Analysis of behavior change from feedback

Examination of average sash position reveals patterns in hood use. The 15-minute average sash position data for each lab reveals more details of user behavior. Figure 6 shows data from example labs for the third week of January in 2007 (before the feedback intervention) and in 2008 (after feedback). The figure shows the expected pattern of behavior. Fume hood use peaks during the day and the average sash position varies as hoods positions change with use. The average position remains flat at night. The time the average position is constant was determined by taking a moving standard deviation over a two-hour interval. This indicated labs are active (at least one hood moving) on average 14 hours/day, although this is highly variable. Figure 6 shows that only Sunday has an appreciable drop in hood use and increase in inactive time.

The overall impact of the feedback intervention in August 2007 is evident in the monthly aggregate sash position data (Figure 5). The average difference in sash position before and after August 2007 is 23 CFM, excluding two one-month dips in the average sash position in December 2006 and 2007. These dips are likely a drop in fume hood use during the holiday season. This shows that even before the feedback was implemented users were opening and closing the fume hoods. A study at Duke University found that almost all hoods were left open all the time before their intervention (Brewer *et al.*, 2003).

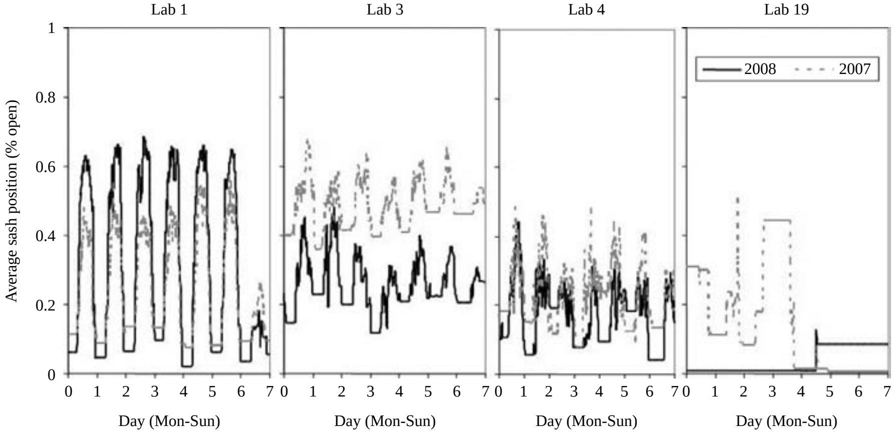


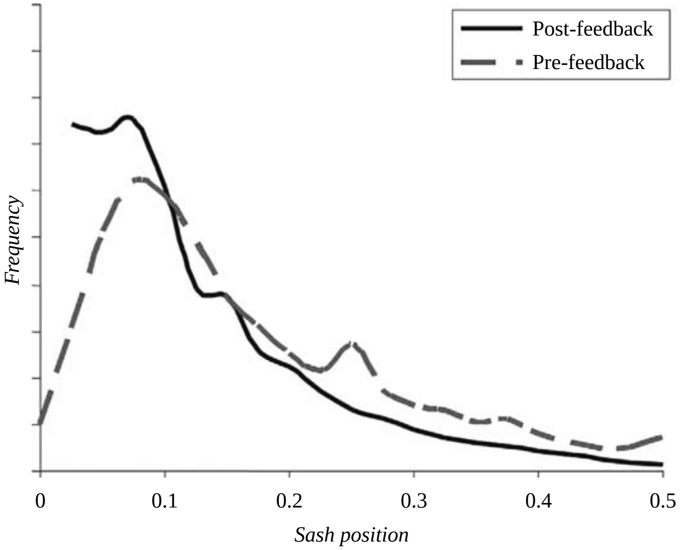
Figure 6.
Plots of 15 minutes average sash position from several example labs for the third week of January 2007 and 2008

Notes: The sash position when the lab is inactive drops in all cases by at least 4 percent and up to 25 percent; the overall average sash position also in general dropped, with Lab 1 the exception; this group has very intensive use of its fume hoods

The reason may be the Duke hoods have two positions, and users in general did not close hoods enough to cause the hood to go into the low-flow position. The proportional VAV hoods in Chemistry respond to any change in sash position.

The average sash position frequency distribution (Figure 7) illustrates the overall effectiveness of the feedback mechanism. The distributions before and after implementation are both bimodal. The peak at higher sash positions (corresponding to the average in-use sash position) is almost 15 percent lower after feedback. The most common closed position is still around 10 percent, but the hoods are closed much more often after implementation. Moreover, there is little drop off as the sash position approaches zero, meaning these positions are used relatively frequently compared to before implementation. The average sash position was less than 7.5 percent (that is, an equivalent vertical sash position of less than 1.35 inch) for only 5.5 hours (0.3 percent) out of the two months considered in 2007, as opposed to 432 hours (30 percent) in the same period in 2008.

There is evidence from these data that sash height was lowered as the result of both onetime action and attempts to modify long-term behavior in actively used hoods, as will be illustrated below. Figure 8 shows the contribution to total program savings from each lab. Lab numbers were assigned in this report based on the frequency of use, from Lab 1 (for a lab with 118 hours/week of fume hood use) to Lab 20 (a lab that averaged only 6.6 hours of use/week). All three of the least utilized labs achieved at least 10 percent reduction in actual sash opening, including a 25 percent reduction (to an average 4 percent open) in the least utilized lab. These results are consistent with a onetime closing of hoods. Fifty percent of the total program savings, however, comes from four labs.



Notes: Fume hoods were almost never completely shut prior to feedback; after feedback, the department average position drops below 7.5 percent open almost 30 percent of the time; also note the shift in the peak open sash position from around 25 percent to less than 15 percent

Figure 7.
Histogram of department-wide average sash position before and after feedback

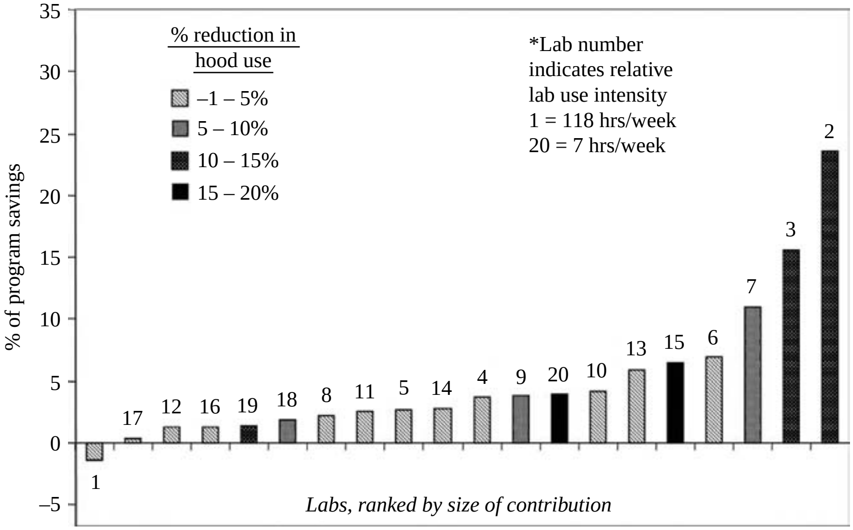


Figure 8.
Labs, sorted by contribution to total program savings

Notes: Total savings is the product of average sash position and number of hoods; only one lab did not contribute to savings, and that group is shutting sashes better at night, but using the hoods more intensely than before the intervention; the top four contributors account for more than half of the total savings

These labs are some of the most active in chemistry, averaging over 16 hours of use per day (the department average is 14 hours), and each has at least 13 hoods. The drop in use in labs with a high intensity of fume hood use indicates the program has been successful in changing user behavior.

3.1.1 Discussion of example labs. Examination of the Lab 3 use patterns (Figure 6) indicates the importance of the type of fume hood when considering the results of hood conservation programs. This lab has been one of the most active in the department, averaging 116 hours of activity per week. Lab 3 also consistently has some of the highest average fume hood positions in the department – they were the high use group seven of the 11 months tested. The baseline behavior in 2007 is very poor. The night sash position rarely drops below 40 percent open, with daytime peaks around 60 percent open. The peak-to-valley height in 2008 is nearly the same – about 30 percent. However, their nighttime average position is much lower – less than 20 percent open. The departmental average sash position dropped 5 percent before and after implementation. Lab 3, on the other hand, lowered their sashes almost 20 percent immediately after the feedback began (it is beginning to climb again). A drop in nighttime sash position is observed in nearly all the labs, but other labs have almost all been able to reduce their nighttime sash position below 10 percent open, while Lab 3 has remained almost two times higher.

The observations of both large changes in use after the intervention and relatively high air flow even after the intervention can be explained by the difference in fume hood type in this lab. The maximum air volume through Building 18 hoods was determined with a vertical sash opening of 18 inch, rather than the full 28.5 inch height. However, hoods are almost always used as horizontal sash hoods. Only 50 percent of the face is accessible in this configuration, as there are two sets of two panels that can be adjusted-essentially, two horizontal sashes. This leads to an air volume equal to about 70 percent of the rated air flow when the horizontal panels are stacked. Thus, the maximum sash position in Building 18 is realistically 70 percent, rather than 100 percent. Moreover, the presence of two sets of sliding sashes encourages proper hood use. Four panels must be moved to fully open a combination sash, while only one is moved to open a vertical sash.

Lab 3 is not in Building 18; that lab instead has 13 vertical sash fume hoods. This makes improvement more difficult, despite a strong effort to conserve. The discrepancy between large, substantially unrecognized improvements and poor, repeatedly publicized performance ultimately led to a number of discussions between the lab EHS representative and the department EHS coordinator. The group improved four times more than the overall average drop in sash position so the lab representative could not believe the sashes were still so high. The sensors were repeatedly checked at the request of the lab rep, and they were correct. The lack of horizontal panels on this lab's hoods handicaps the group's performance.

This incident illustrates the importance of ensuring the equality of the operational environment when comparing behavior. Many behavior change campaigns use relative measures to compare groups. This feedback mechanism presented absolute data, and although it was effective at motivating behavior change it also antagonized a group that did proportionally well. At the same time, the presence of a single sash both increases the hood use and magnifies any changes, so Lab 3 has an environmental advantage over other groups if a relative measure is employed. A fair fume hood closing competition between combination sash groups and single sash groups is difficult to implement.

Another interesting group is Lab 1, which has had a small negative contribution to overall savings (Figure 8). However, the group has improved their nighttime average sash position by almost 5 percent, from 11 percent to a very low 6 percent (Figure 6). The group simply is working more this year, averaging two hours more a week (up past 118 hours of activity a week) with a 2 percent higher average sash position. Again, the group cannot be blamed for their relatively high average sash position (they were the high use group three of the four months Lab 3 was not). Details of their behavior indicate very good compliance with the sash closing campaign. This group illustrates time series changes in environment leading to a metric for comparison becoming unreliable. In this case, average sash position is a poor tracer of behavior change over a couple years. Rather, the average night sash position has become the accurate measure of the campaigns effectiveness. This could change in the future if, for instance, a new group of students works later at night.

3.2 Energy, cost, and CO_2 emissions savings estimates

The impact of the fume hood program was estimated from the change in air flow through hoods. Air flow was calculated from the average sash position and designed maximum and minimum air flow. This feedback resulted savings of 23 CFM/hood or 5,860 CFM department wide. About 60 percent of this savings occurred in Building 18, where the Chemistry Department is the sole occupant. The averted airflow in Building 18 equals about 920 mmBTU/year of thermal energy. Fan electric energy was determined using a facilities estimate based on an 8 inch water pressure drop across the building envelope and equals 44,400 kWh/year of savings. This is a savings of about 1.1 percent of the total building energy use.

The cost and carbon intensity of air exchange are more difficult to determine as MIT uses cogeneration to produce electricity, steam and chilled water (CHW). Carbon intensities and costs of utility products were determined through examination of production and cost reports. The results of this analysis are summarized in Table I. Thermal conditioning has an estimated cost of \$5.14/CFM, and total air exchange costs \$7.09/CFM including fan load. Carbon dioxide emissions are estimated based on the above assumptions to be 45 lbs/CFM for thermal load, and 60 lbs/CFM including fan load.

The total intervention savings are \$17,600 in steam and CHW and \$6,700 in electricity in Building 18, averting a total of 93 metric tons of CO_2. This is about 1.2 percent of the total emissions from Building 18 in 2007. The 5,860 CFM averted department-wide corresponds to \$41,500 (\$30,100 thermal, \$11,400 electric) and 160 metric tons of CO_2. This was achieved with approximately \$12,000 in initial investment, and minimal continuing cost.

3.3 Potential further savings

Fume hoods are responsible for a large energy load, but about 75 percent of that is the minimum energy flow through the hoods that is required for general lab ventilation. Fume hoods could account for 40 percent of the heating load if they were left completely open, but the average sash position is closer to 12 percent open. Current variable fume hood use in Building 18 is estimated at 16,900 CFM; this is the amount of CFM that can be averted if the fume hoods in Building 18 are fully closed all the time. This air exchange is therefore equivalent to \$99,000, or 460 metric tons CO_2. This air exchange is about one-third of the \$350,000 estimated possible savings originally mentioned by Amanti. The discrepancy occurred because the initial survey assumed a two-position style hood, rather than a true VAV, and used manual counting of hoods rather than electronic monitoring. However, even close examination indicates fume hoods are a significant energy draw, accounting for about 4.1 percent of total carbon emissions and total energy expenditures. This is a significant single area for concern when examining total building energy consumption. Overhead lighting is responsible for about 10.6 percent of all emissions, and all plug load in the building accounts for just 5.8 percent of building emissions. The minimum air exchange requirement for this laboratory building accounts for about 53 percent of the energy use, and is the single largest component of energy consumption. Reductions in this baseline air exchange may be a valuable source of energy savings, as suggested by Woolliams *et al.* (2005). Occupancy sensors integrated into ventilation systems also address this large source of energy use.

The potential exists for still further savings in fume hood use. Labs are inactive an average ten hours/day, and fume hoods average 6 percent open during this period. Shutting sashes completely would save an additional 2740 CFM

Table I.
Energy, cost, and carbon intensity of utility products and conditioned air

	Steam (per klb)	CHW (per ton h)	Electric (per kWh)	Thermal (per CFM)	Total (per CFM)
Energy (BTU)	10^6	12,000	3,413	269,000	313,000
CO_2 (lbs)	184	1.52	1.16	44.7	59.8
Cost (\$)	18.1	0.26	0.15	5.14	7.09
Per CFM	0.188	6.74	12.97		

(13.6 CFM/hood, or $13,800). That is almost as much energy as was saved from the program so far. It is clear that closing hoods at night leads to lower averages during the day as well (the average total savings was actually slightly higher than the average nighttime savings). An additional $47,000/year in savings can be achieved in Building 18 if 6 percent further reduction in average sash height is achievable.

The examination of lab-level activity, as opposed to hood-level data, may dramatically overestimate the time any one particular hood is in use. 14 hours/day of use is assumed based on the department average for time that labs have hood activity, but other studies have indicated this may be as little as two to six hours/day (Brewer *et al.*, 2003; Woolliams *et al.*, 2005). This could mean nearly the entire $99,000 of variable fume hood use could be averted with perfect fume hood use.

The large estimated savings observed here and elsewhere (Emig, 2006; Brewer *et al.*, 2003) are based on averted airflow. Actual savings require averted utilities, and this requires that the building operates as expected. No observed change in utility use was observed in the Duke study (Brewer *et al.*, 2003). A detailed examination of building utility use as a function of sash position was performed and will be presented elsewhere (Wesolowski and Olivetti, 2010). Variable fume hood use was determined to have a small but measurable impact on utility use. The effect was comparable to the estimates derived here based on sash sensor data. However, it was difficult to deduce the effect of the behavior change campaign from a background of a building undergoing many efficiency upgrades, such as fixing ventilation ductwork. About three times more energy was saved over the course of this study than would be expected based on sash position alone.

4. Implications for conservation programs

The feedback-based intervention pursued in the MIT Chemistry Department can be compared to other recent fume hood conservation campaigns. Duke (Brewer *et al.*, 2003), Harvard (Emig, 2006; Woolliams *et al.*, 2005), and University of California (UC)-Irvine (Kao, 2007) have all recently completed studies of hood conservation programs. Comparison between these reports is difficult because the type of hood and use environment varies widely. The following analysis attempts to generate a fair comparison of the results of these studies by normalizing them to a model fume hood (VAV, vertical sash, 100 ft/min face velocity, 300 CFM minimum flow, 62 × 29 inch face). The results in Table II indicate that all interventions demonstrated a significant improvement from baseline behavior. However, some sites used manual accounting to determine sash position, which was found to be very unreliable at MIT.

The type of fume hood in place has a substantial impact on the effectiveness of a fume hood conservation campaign. The MIT feedback-based program at first appears less effective than others, especially when the total reduction in variable air flow is examined. However, fume hood use behavior in Building 18 was substantially better before the intervention than any of the other schools thanks to an investment in highly efficient combination sash designs. The building actually used less air per hood before the intervention than any of the other universities after their intervention.

Feedback in Lab 3 is more directly comparable to Harvard because that lab has vertical sash hoods. Feedback in this lab has comparable effectiveness to the Harvard lab competition. The relatively high savings at Duke were substantially due to having inefficient two-position designs; their baseline behavior was essentially no hoods closed, so the 29 percent savings is equivalent to 29 percent of hoods being closed.

Table II.
Comparison of fume hood conservation programs at several universities

Site	Hood type, sash	Intervention	Actual savings/hood (CFM)	Est. savings for model hood (CFM)	Original model sash height (inch)	Percentage drop from baseline	Percentage of total variable flow
MIT – Building 18	VAV, combination	Feedback	17	39	3.8	22	3
MIT – Lab 3	VAV, vertical	Feedback	178	150	12.2	29	12
Harvard (Emig, 2006)	VAV, vertical	Energy competition	230	200	15.3	55	16
UC-Irvine (Kao, 2007)	VAV, vertical	Competition and stickers	47	47	7.0	16	4
Duke (Brewer *et al.*, 2003)	Two-position	Training and stickers	75	320	26.2	29	26

Feedback generated a comparable amount of sash closing, as fume hoods in MIT Chemistry are closed (average vertical sash position <1.35 inch open) approximately 30 percent of the time following feedback vs 0.3 percent prior to the feedback intervention.

The Duke and Harvard programs featured stickers, as well as other community-based social marketing techniques, to encourage better hood use. The impact of small prompts alone is probably small. No additional savings were seen after hood stickers were added at Harvard. Other studies indicate small prompts are ineffective. A campus study of revolving door use showed no impact from the replacement of existing 4×5 inch stickers with new prompts the same size (Wesolowski *et al.*, 2010). Similarly, Austin *et al.* (1993) observed low rates of recycling with similarly sized prompts on bins. Both of these studies saw a substantial response to the installation of large ($>11 \times 17$ inch) signs. For example, revolving door use rates increased nearly 40 percent. However, all prompts are subject to user habituation (Benway, 1998), so the long-term effectiveness of any static prompt is limited. It is also impractical to put large prompts on fume hoods.

Studies of feedback on conservation have continually supported the need for proximal and immediate feedback for effectiveness. Electric bills with use data, for instance, have a larger impact the more often the bill is presented (Egan, 2001), and dorm electricity competitions with high-resolution feedback have more success (Peterson *et al.*, 2007). The fume hood program had results comparable to daily feedback on electric use, or similar to more intensive programs such as energy competitions.

The success of the feedback program, much like the success of sticker-oriented campaigns, may come from accessing other social cues with the intervention. The importance of social cues in dictating behavior is well described in literature (Egan, 2001; Emig, 2006; Griskevicius *et al.*, 2008). The successful Harvard energy competition and Duke one-on-one training both employed social marketing techniques. The fume hood campaign at MIT used many aspects of social marketing without ever explicitly designing them into the study. The project had the support of faculty, especially the department head. This central figure conveys some authority, which dramatically enhances the rate of adoption of a new practice (Griskevicius *et al.*, 2008). The dissemination of reports through the existing and respected EHS management system structure also contributes to the credibility and authority of the feedback mechanism. More importantly, the requirements of the existing EHS management system structure mean that an EHS representative familiar with the fume hood intervention program is present in each laboratory. Their actions can contribute strongly to forming the laboratory cultural norms because of their connection to a respected authority (the EHS administration). Moreover, they can close rarely used hoods themselves.

5. Conclusion

Feedback, through the distribution of monthly use reports to lab users, was found to be a highly effective method for reducing fume hood sash position. Average sash height was lowered by 26 percent (from 16.3 ± 0.85 percent open to 12.1 ± 0.39 percent open) throughout the Chemistry Department at MIT, saving $41,500/year throughout the entire department. The program averted approximately 93 tons of CO_2 in Building 18 and 160 tons of CO_2 department wide. Savings were achieved with approximately $12,000 in initial investment, and minimal continuing cost. The presence of less efficient vertical sash hoods in the Chemistry Department outside of the main Department building, Building 18, amplified the effectiveness of the intervention in these labs.

The feedback intervention was a successful conservation campaign in that it achieved a substantial change in user behavior. Fume hoods were closed only 0.3 percent of the time during two months considered in 2007, as opposed to 30 percent in the same period in 2008. Sash height was lowered as the result of both one time action and behavior change. The least utilized lab achieved a 25 percent reduction to an average 4 percent open, likely from closing their only fume hood. Fifty percent of the total program savings, however, came from four labs. These labs each have at least 13 fume hoods and are active in excess of 16 hours/day, indicating that the feedback mechanism is effective with groups that use fume hoods regularly.

Comparisons between this work and other fume hood campaigns show that comparable changes in user behavior can be effected by feedback or social marketing techniques like an energy competition. However, the dramatic savings in averted air flow reported elsewhere were not realized in Building 18 because the site selected had fume hoods that were inherently efficient (allowing only 70 percent of the face to be opened in normal operation) and conducive to good user behavior (a double sash design). The type of hood strongly affects how users interact with the hood and the resulting air flow, and should be considered when deciding how to pursue a conservation program.

Notes

1. The EHS Coordinator is an employee of a particular department who provides day-to-day [0]implementation and oversight of EHS programs, trainings and regulatory requirements.
2. The EHS Representative is a student member of the lab who reports to and assists the faculty or staff PI/Supervisor and staff EHS coordinator in identifying and addressing EHS issues.

References

Amanti, S. (2006), "Potential energy savings on the MIT campus", BSc thesis, Department of Mechanical Engineering, MIT, Cambridge, MA.

Austin, J., Hatfield, D., Grindle, A. and Bailey, J. (1993), "Increasing recycling in office environments: the effects of specific informative cues", *Journal of Applied Behavior Analysis*, Vol. 26 No. 2, pp. 247-53.

Benway, J. (1998), "Banner blindness: the irony of attention grabbing on the world wide web", *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting, Chicago, IL*, pp. 463-7.

Brewer, B., Harris, A. and Thomann, W. (2003), "Evaluation of the benefits of best management practices used to conserve energy in laboratories", paper presented at Laboratories for the 21st century, Colorado.

Collins, N., Berry, L., Braid, R., Jones, D. and Kerley, C. (1985), *Past Efforts and Future Directions for Evaluating State Energy Conservation Programs*, Oak Ridge National Lab, Oak Ridge, TN.

Deluga, G.F. (2000), "Achieving maximum laboratory ventilation effectiveness at lowest cost", *Chemical Health and Safety*, Vol. 7 No. 2, pp. 37-40.

Egan, C. (2001), "The application of social science to energy conservation: realizations, models, and findings", paper presented at American Council for an Energy-Efficient Economy, Washington, DC.

Emig, J. (2006), "Shut the sash behavior change programs in labs at Harvard", paper presented at Laboratories for the 21st century, San Antonio, TX.

Facilities (2008), "MIT space accounting", available at: www.floorplans.mit.edu (accessed July 2009).

Griskevicius, V., Cialdini, R. and Goldstein, N. (2008), "Social norms: an underestimated and underemployed lever for managing climate change", *International Journal of Sustainability Communication*, Vol. 3, pp. 5-13.

Kao, S. (2007), "Inter-building fumehood competition", *The Green U @ UC-Irvine*, Vol. 3 No. 3, p. 3.

Kempton, W. and Layne, L.L. (1994), "The consumer's energy analysis environment", *Energy Policy*, Vol. 22 No. 10, pp. 857-66.

Kolkebeck, K. (2006), "Getting the most from critical airflow (VAV) control systems", available at: www.labs21.lbl.gov (accessed July 2009).

Mills, E. and Sartor, D. (2005a), "Energy use and savings potential for laboratory fume hoods", *Energy*, Vol. 30 No. 10, pp. 1859-64.

Mills, E. and Sartor, D. (2005b), "Laboratory fume hood energy calculator", available at: www.fumehoodcalculator.lbl.gov (accessed July 2009).

Peterson, J., Shunturov, V., Janda, K., Platt, G. and Weinberger, K. (2007), "Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives", *International Journal of Sustainability in Higher Education*, Vol. 8 No. 1, pp. 16-33.

Weale, J., Rumsey, P., Sartor, D. and Lock, L. (2002), "Laboratory low-pressure drop design", *ASHRAE Journal*, Vol. 44, pp. 38-42.

Wesolowski, D. and Olivetti, E. (2010), "Measurements of the effect of fumehood use on building energy consumption", *Energy* (in press).

Wesolowski, D., Sukkasi, S., Lee, O. and Cullum, B. (2010), "Modifying habits towards sustainability: a study of revolving door use", *Environment & Behavior* (in press).

Wilhite, H. and Ling, R. (1995), "Measured energy savings from a more informative energy bill", *Energy and Buildings*, Vol. 22 No. 2, pp. 145-55.

Woolliams, J., Lloyd, M. and Spengler, J. (2005), "The case for sustainable laboratories: first steps at Harvard University", *International Journal of Sustainability in Higher Education*, Vol. 6 No. 4, pp. 363-82.

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