Energy Use and Savings Potential for Laboratory Fume Hoods

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Abstract

Fume hoods are critical energy end-use devices, typically relied upon as the primary source of ventilation in laboratory-type facilities while providing for safe conditions in areas where experiments are being conducted, Fume hoods create large amounts of airflow, which drives the overall HVAC sizing and energy requirements of the buildings in which they are located. For standard two-meter (six-foot) hoods, per-hood energy costs range from $4,600 for moderate climates such as Los Angeles, USA to $9,300/year for extreme cooling climates such as Singapore. With an estimated 750,000 hoods in use in the U.S., the aggregate energy use and savings potential is significant. We estimate the annual operating cost of U.S. fume hoods at approximately $4.2 billion, with a corresponding peak electrical demand of 5,100 megawatts. There are various strategies for saving energy, each with its limitations. With emerging technologies, per-hood savings of 50 percent to 75 percent can be safely and cost-effectively achieved while addressing the limitations of existing strategies.

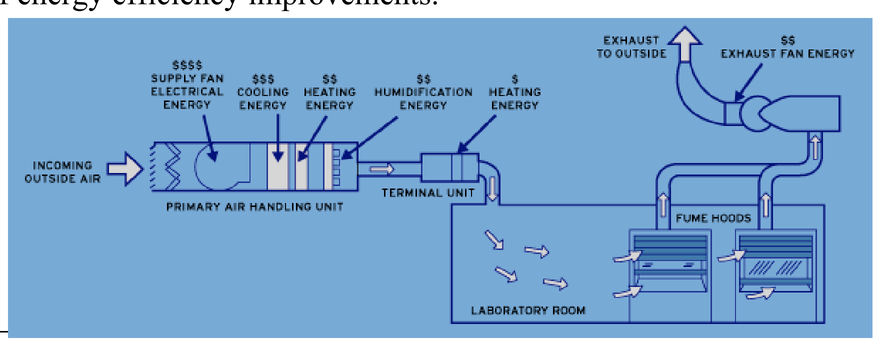
Introduction

Efforts to improve energy efficiency must attend to a host of "non-energy" considerations, primarily safety. In many cases, non-energy benefits can provide an additional impetus for technology innovation beyond the value of direct energy savings (Mills and Rosenfeld 1996; Pye and McKane 1999; Worrell et al. 2003). This is certainly the case with laboratory fume hoods.

Fume hoods are box-like structures, often mounted at tabletop level with a movable window-like front called a sash. Fume hoods capture, contain, and exhaust airborne hazardous materials, which are drawn out of the hood by fans through a port at the top of the hood. Laboratory fume hoods are ubiquitous in pharmaceutical and biotechnology facilities, industrial shops, medical testing labs, private research labs, and academic settings. Their fundamental design has gone largely unchanged for the past 60 years (Saunders 1993).

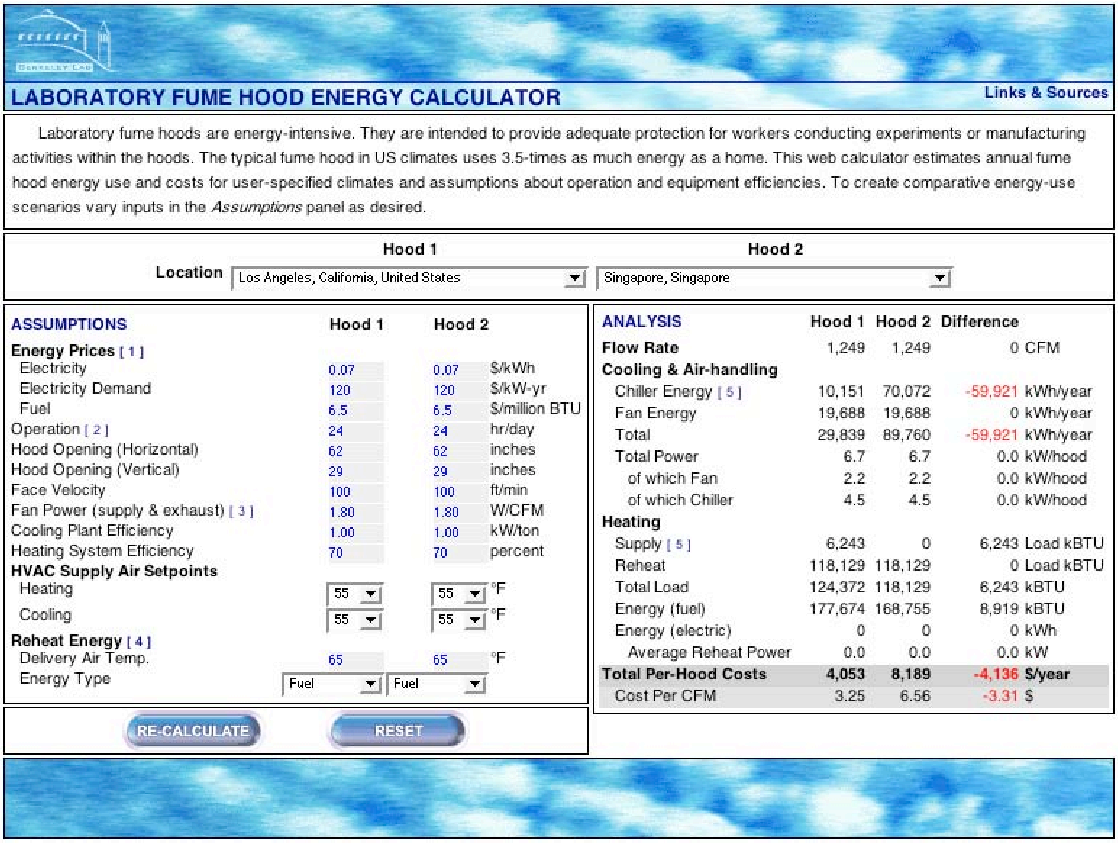
As depicted in Figure 1, overall fume hood energy use is the product of a number of support systems, including: supply and exhaust fans, space-cooling energy, space-heating energy, and (in some cases) humidification or de-humidification and terminal reheat. We developed an engineering model (Figure 2) to perform baseline analysis and test the per-hood and national impacts of energy efficiency improvements.[1]

Figure 1. Typical fume hood cross-section, application and relation to HVAC system (TekAir 2003).



[1] An on-line calculator based on our methodology may be found at http://fumehoodcalculator.lbl.gov

Figure 2. Web-based fume hood energy use model.



Highlighting the "systems nature" of fume hood design and application, hoods require large amounts of airflow that tend to drive the size, and first cost of central heating, ventilating and air-conditioning (HVAC) systems in buildings where hoods are located. As a result, fume hoods are a major factor in making typical laboratories four- to five-times more energy intensive than typical commercial buildings (Bell et al. 2002). A fume hood consumes 3.5-times more energy than an average house. With 0.5 to 1.5 million hoods in use in the U.S. ("central" estimate 750,000), aggregate energy use and savings potential is significant. As will be described below, the annual operating cost of U.S. fume hoods is $4.2 billion with corresponding electricity use of 26 TWh, peak electrical demand of 5,100 megawatts, and 204 Petajoules (193 TBTU) of heating fuel.

Further amplifying the need to improve fume hood design, recent research shows that increasing the amount and rate of airflow (and, consequently, energy use) does not tend to improve containment. Instead, errant eddy currents and vortexes can be induced around hood users as airflows around workers and into the hood, reducing containment effectiveness and compromising safety (Bell et al. 2002).

Baseline Energy Use and Analysis of Potential Savings

We have modeled the energy use and potential savings on a per-hood basis across a variety of weather locations around the globe. Total energy costs are more sensitive to the cooling load. Our calculations account for the heating, cooling, and movement of air through the fume hood, and the associated prices of electricity, peak electricity demand, and fuel. Depending on climate, estimated costs range from $100 to $325/m^3-minute ($3 to $11/cfm).

We assume the hood has a 2-meter (6-foot) nominal opening (this is a common size), and HVAC plant efficiencies of 1 kW/ton (cooling) and 70 percent (heating). Overall fan power (supply plus exhaust) is estimated at 64 W/m3-min (1.8 W/cfm) (Weale et al. 2002). For regional analyses, we use factors from Kjelgaard (2001) to determine the space-conditioning loads, and identical energy prices for each location to allow the influences of climate to present themselves in the results. As an illustration of the importance of local climate variations, in the case of California annual energy costs vary by approximately $1000/hood-year depending on local climate. Results over a range of climates around the globe are shown in Figures 3 through 5. Facility cooling is typically the dominant load.

Figure 3. Assumes fuel used for heating and electricity for cooling. Engineering and economic assumptions described in captions to Figures 4 and 5.

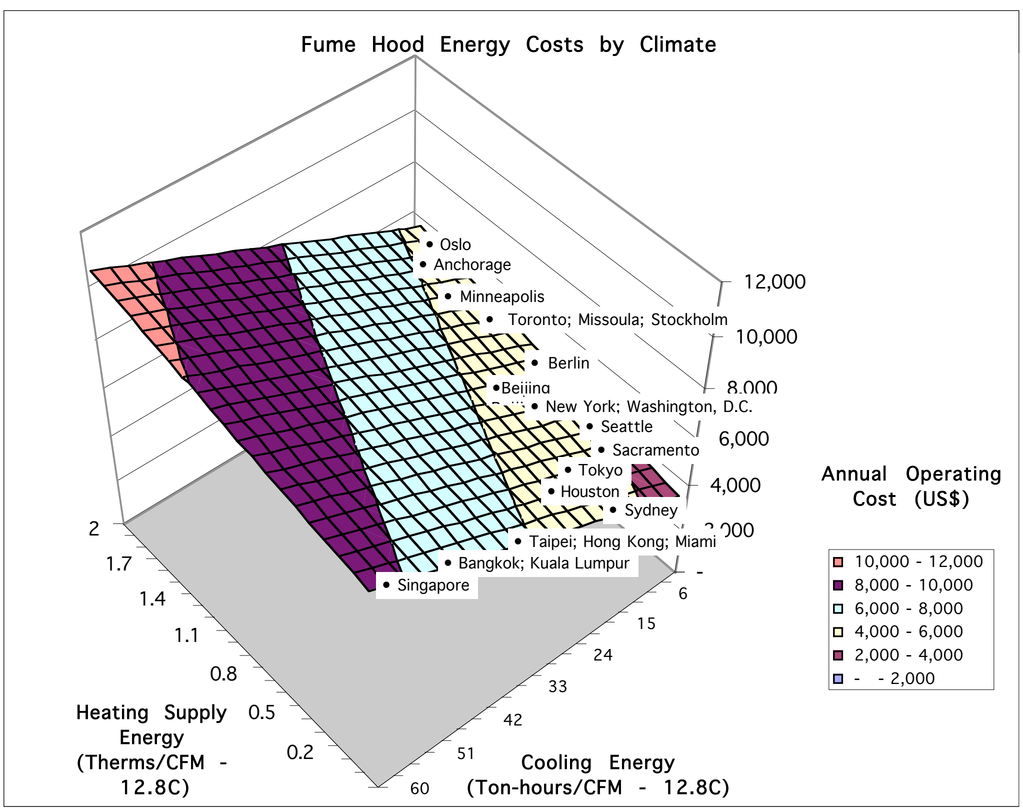


Figure 4. Assumes a 2-meter nominal hood opening, 30.5 meters/minute face velocity, fuel reheat, 24-hour operation per ANSI standards, weather data from [7], cooling plant efficiency 1.0 kW/ton, ventilation system efficiency of 1.8 W/CFM per [8], and reheat results in a load of 3,525 MJ/m^3-minute-year (94,608 BTU/CFM-year). Electricity counted at 3.6 MJ/kWh.

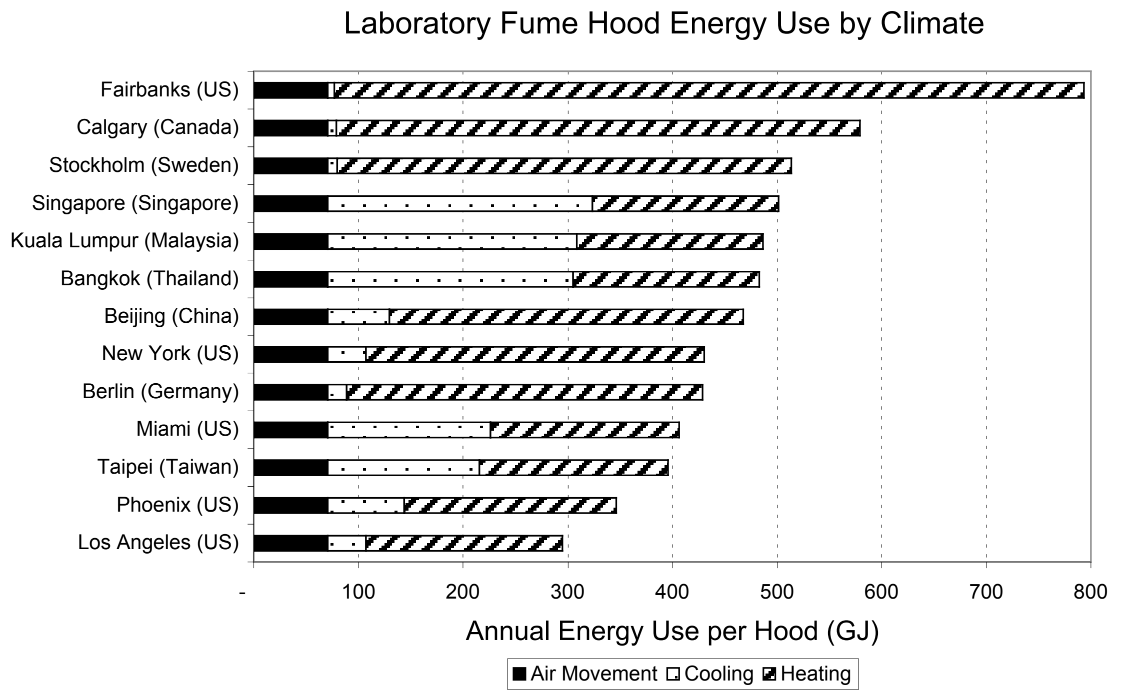
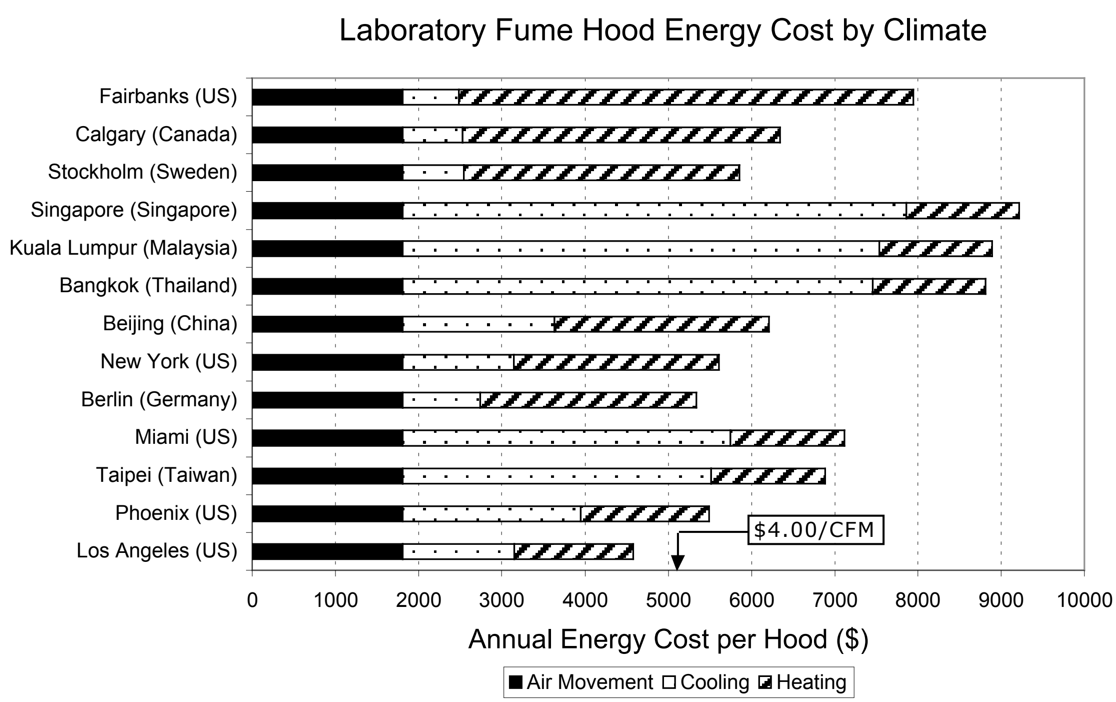


Figure 5. Variability in fume hood energy costs by location (normalized to an average U.S. commercial electricity price of \$0.0786/kWh, \$120/peak kW, and a heating fuel price \$7.62/GJ). (USDOE 2003). Note different ranking from Figure 4, due to relative weights of electricity and fuel.



It is important to note that laboratory ventilation is based on 100-percent outside air; thus all air exhausted by a fume hood has to be made up with unconditioned outside air. Due to safety considerations and standards, fume hoods typically operate continuously.[2] Many labs use "reheat." Typically, the outdoor air is initially cooled to 12.7 C (55 degrees F) or lower and then reheated at each zone to the required temperature to maintain the laboratory's set point temperature. Unfortunately, it is possible for only one laboratory zone to actually need maximum cooling. If the outside air is cooler than the supply air set-point, no cooling is required. However, for example, the outside air can be a "perfect" 18.3 C (65 degrees F). In this situation, it is first cooled at the central air handlers and then re-heated back to 65 degrees F at many zones. The perverse result of this reheat practice is that in many labs the dominant cooling load is the boiler and the dominant heating load is imposed by the chiller. As a result, labs in climates with zero or negligible heating load still use appreciable heating energy. Labs can be designed much better than this, but many are worse than the assumptions used in our calculations. Under the average conditions we specify, reheat results in a load of 3,525 MJ/m^3-minute-year (94,608 BTU/cfm-year). Reheat is typically performed with heating fuel. Electric reheat is not widespread, but incurs a large energy penalty where used (e.g. nearly twice the fume hood's direct fan energy use in Seattle, Washington in the U.S.).

Approximately 150,000 laboratories populate the United States, with 500,000 to 1,500,000 fume hoods installed.[3] The only formally published estimate indicates that there were more than one million units in 1989 (Monsen 1989). Our calculations assume a perhaps conservative "central value" of 750,000. In our analysis of potential savings, we also assume an ultimate market penetration in the US of 75 percent for efficient hood alternatives. Field tests have validated the energy performance of one such design—the "Berkeley Hood--while maintaining or even improving safety containment (Bell et al. 2002).

Field trials of the Berkeley Hood have demonstrated containment with flows down to 34 percent of full flow (Bell et al. 2002), and equal or superior containment performance in comparison to standard hoods (Tschudi et al. 2004a,b). As a conservatism (compared to the field trial results), we assume a 50 percent flow reduction (note that the theoretical fan savings is a cubed function, which means that a 50 percent reduction in flow would result in over an 80 percent savings in fan power). Due to wide variability in local conditions and conventions, we have not included humidity control and exhaust "scrubbing"—used in some hoods—which would increase the total energy savings.

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[2] Per ANSI Standard for Laboratory Ventilation: 5.3.2.11 Continuous Operation. Exhaust systems shall operate continuously to provide adequate ventilation for any hood at any time it is in use and to prevent backflow of air into the laboratory when the following conditions are present: (1) Chemicals are present in any hood (opened or unopened), (2) Exhaust system operation is required to maintain minimum ventilation rates and room pressure control, and (3) There are powered devices connected to the manifold. Powered devices include, but are not limited to: biological safety cabinets, in-line scrubbers, motorized dampers, and booster fans.

[3] This range is based in part on interviews of industry experts conducted on behalf of the US Environmental Protection Agency's Labs21 Program

The per-hood and macro-level energy use and savings potential for the US and California are summarized in Table 1. Fume hood energy use will vary with climate, and the associated space conditioning loads. Based on the aforementioned assumptions, the aggregate U.S. energy savings potential is significant, at approximately $1.6 billion annually, comprised of 9.8 TWh of cooling and fan energy, 77 Petajoules (72 TBTU) of heating fuel, and peak electrical demand of 1,900 megawatts.

Table 1. Fume hood energy use and savings potential.*

	United States*	California
PER-HOOD VALUES		
Electricity Use (kWh/year)	34,871	29,326
Peak electricity demand (kW)	6.74	6.74
Fuel use (GJ/year)	272	223
Annual energy cost per hood ($)		
Total	5,624	6,031
$/CFM	4.50	4.83
MACRO-SCALE BASELINE ENERGY USE		
Number of Hoods	750,000	85,000
Total Electricity (GWh/year)	26,153	2,493
Total Peak Power (MW)	5,057	573
Total Natural Gas (10^{15}J, PJ/year)	204	19
Total Energy Cost ($ Million/year)	4,218	513
MACRO-SCALE ENERGY SAVINGS		
Per-hood energy savings**	50%	50%
Maximum potential market penetration	75%	75%
Electricity ($M/year)	771	112
Demand ($M/year)	228	26
Natural Gas ($M/year)	583	54
Total Energy Savings ($ Million/year)	1,582	192
Total Electricity Savings (GWh/year)	9,808	935
Total Peak Power savings (MW)	1,896	215
Total Heating Fuel Savings (10^{15}J, PJ)	77	7

* Engineering assumptions shown in caption to Figure 3. US average weather conditions modeled as average of Los Angeles, Chicago, Miami, and New York. Average commercial-sector energy prices (2003): US average $0.0786/kWh; California $0.12/kWh. Gas $8.04/MBTU in both cases.

** Estimate is conservative given that R&D goal is to reduce air flow by 75% and theoretical fan savings is a cubed function (a 50% reduction in flow would result in over an 80% savings in fan HP). This conservatism balances existing use of VAV hoods, and the potential that fume hood exhaust may drop below general lab exhaust requirements.

Currently Available Energy-Efficient Systems Face Limitations

In the past, five design strategies have been employed to reduce fume hood energy use. These strategies can result in energy and peak-power savings, and have varying degrees of efficacy in ensuring safe operating conditions.

1. Using "auxiliary" (outside) air to reduce energy required by a central HVAC system that conditions the air ultimately exhausted by the hood.

This strategy, referred to as an auxiliary-air hood, introduces tempered outdoor air near the face of the hood just above the worker. Unconditioned or tempered air introduced by auxiliary-air hood systems causes uncomfortable conditions for workers during periods of summer and winter temperature or humidity extremes. The auxiliary airflow can also interfere, in various ways, with experiments performed inside the hood. More importantly, turbulence, caused by inflowing auxiliary air at the hood opening, increases the potential for pollutants to spill from the hood towards the worker (Coggan 1997). Moreover, auxiliary air hoods only save energy used for conditioning general laboratory air (not for the hood itself). This is the case because the total exhaust flow rate is unchanged. Fan energy consumption attributed to the hood is not reduced. Our estimates indicate that as much as 65 percent of hood electricity is attributable to the fans (moving air) with the balance attributable to conditioning the air being exhausted by the hood. This strategy has fallen out of general use over the past two decades.

2. Employing dampers and adjusting fan speed to reduce exhaust airflow through the hood as the sash is closed. This variable air volume (VAV) approach maintains a constant face velocity, enhancing the hood's ability to contain fumes.

This strategy uses dampers, variable speed drives (VSDs), and sophisticated controls to modulate the hood and in the supply and exhaust air streams. These components communicate with direct digital controls (DDC) to provide a variable air volume (VAV) fume hood system. A VAV fume hood system establishes a constant face velocity. VAV improves safety, compared to standard hoods, which experience variable face velocity as the face opening is adjusted. Additional controls maintain a constant pressure differential between the laboratory and adjacent spaces. These components and controls add significantly to the system's first cost and complexity and require diligent users. Each hood user must close the sash properly to ensure that the system achieves its full energy savings potential. Also, when sizing air distribution and conditioning equipment, many designers assume worst-case conditions—all sashes fully open—requiring larger ducts, fans, and central plants than would be the case if some sashes are assumed to be partly closed.[4] This strategy enjoys significant market share.

[4] Based on the assumption that not all hoods are used simultaneously in a VAV fume hood system, applying a "hood diversity factor" in calculating the building's make-up air has also been suggested as an HVAC energy-saving measure (Moyer and Dungan 1987; Varley 1993).

3. Restricting sash openings by preventing the sash from being fully opened, or using horizontal-sliding sashes that cover part of the hood entryway even when in the "open" position.

This strategy restricts a hood's face opening while maintaining a constant airflow. The face opening is restricted by "stops" limiting vertical sash movement or by using a horizontal-sliding sash system that blocks part of the entrance, even when fully "open." Stops or sashes are routinely defeated (removed) by users to facilitate "set-up" of experiments. During set-up, the face velocity is lowered, often significantly, and containment reduced. Users often do not like the sash opening restrictions, so it is common to observe hoods under normal use with their stops bypassed or the horizontal sashes removed. In these cases, the air velocity may drop below specified levels and compromise safety. When used properly, the partially closed sashes help protect the user.

4. Automated designs that promote a vortex in the top of the fume hood, which is maintained by "sensing" whether it is collapsing, and adjusting movable panels in the top of the hood accordingly.

This strategy has been effectively applied to fume hood design, although it is not widely accepted or understood by laboratory designers. This hood design incorporates, according to the manufacturer, a "bi-stable vortex" to enhance its containment performance. This strategy has helped focus the industry attention on the potential to enhance energy and containment performance.

5. Low velocity hoods.

Creating low-velocity hoods involves aerodynamic enhancements to improve containment efficiency to allow reduced air flow and reduced air flow when the lab is unoccupied.

New Approaches to Containment, Safety, and Energy Savings

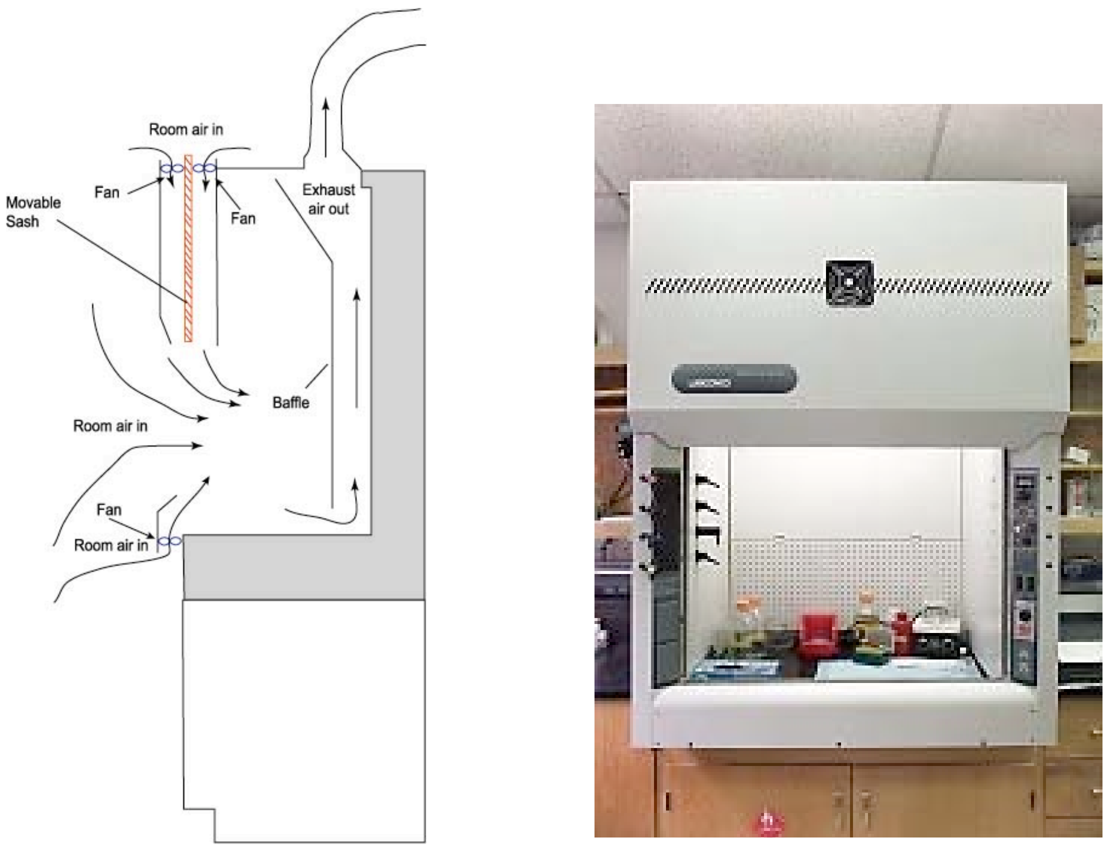
Conventional hoods (and the above-mentioned energy efficiency strategies) rely on pulling supply air from the general laboratory space around the worker and research apparatus that may be located in the hood.

One new strategy for managing fume hood airflow, the "Berkeley Hood" technique, supplies air in front of the operator, while drawing only 20 to 40 percent of the air from around the operator.[5] The Berkeley Hood uses a "push-pull" displacement airflow approach to contain fumes and move air through a hood (Figure 6). Displacement air "push" is introduced with supply vents near the top and bottom of the hood's sash

[5] This generic concept was first tested in the "air vest" technology, invented at LBNL for use with large paint spray hoods (Gadgil et al. 1992) The vest supplies air in front of the operator of the hood, which creates a positive pressure field that prevents development of a wake, therefore ensuring clean air to the operator's breathing zone. Feustel mapped this concept to the problem of fume hoods. For more information, see http://ateam.lbl.gov/hightech/fumehood/fhood.html

opening. Displacement air "pull" is provided by simultaneously exhausting air from the back and top of the hood. The low-velocity supply airflows create an "air divider" between an operator and a hood's contents that separates and distributes airflow at the sash opening (unlike an air curtain approach that uses high-velocity airflow). When the face of a hood is protected by an airflow condition with low-turbulence intensity, the need to exhaust large amounts of air from the hood is largely reduced. The air divider technology contains fumes simply, protects the operator, and delivers dramatic cost reductions in a facility's construction and operation.

Figure 6. Cross section and front view of push-pull fume hood technology ("Berkeley Hood"), plus prototype being field-tested at U.C. San Francisco Medical School (Bell et al. 2002).



Even temporary mixing between air in the face of the fume hood and room air, which could result from pressure fluctuations in the laboratory, will keep contaminants contained within the hood. As a result, far lower exhaust rates are necessary in order to contain pollutants and remain virtually unaffected by adjusting the opening.

The Berkeley Hood must not be confused with the auxiliary air approach. There are fundamental and material differences, stemming from the fact that the Berkeley Hood does not utilize outside air, and that air is introduced from within the sash in a highly controlled fashion with far lower turbulence (and thus lower risk of contaminant spillage) than occurs with auxiliary hoods. In auxiliary-air hoods, turbulent airflows coming from above the worker in auxiliary-air systems increase mixing of incoming fresh air and contaminated air within a hood's workspace.

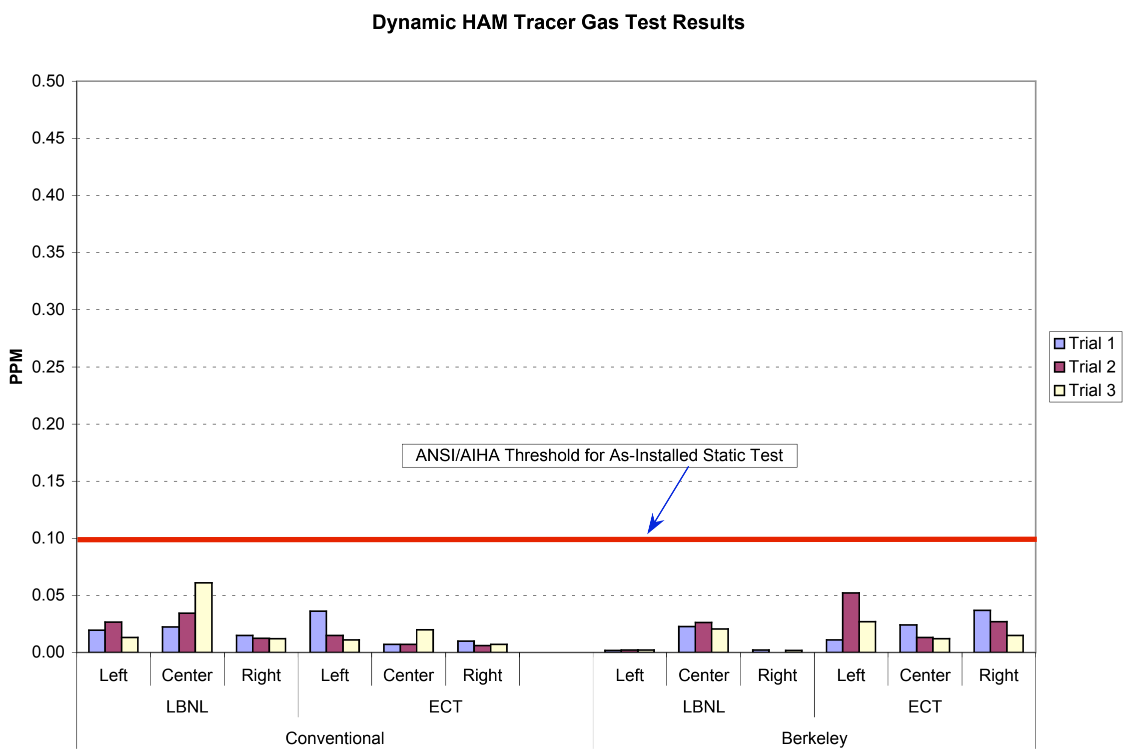
An added attraction of the Berkeley Hood is that its incremental cost is expected to be less than that of VAV systems. Savings from downsized heating, ventilating, and air conditioning systems and less complicated controls would be realized.

Hood Performance Can be Improved Without Compromising Safety

Lawrence Berkeley National Laboratory has developed a standardized dynamic "human-as-mannequin" (HAM) test protocol for laboratory fume hoods (Tschudi et al. 2004b). The test emulates real-world conditions with human movements that help test the hood's ability to contain pollutants within the hood.

Independent HAM tests (funded by the California Energy Commission's PIER program) summarized in Figure 7 show that the Berkeley Hood performs as well as a conventional hood, and well below the threshold for containment safety.

Figure 7. Berkeley Hood contains pollutants (tracer gas) as well as standard hood. The tests were conducted side-by-side on hoods built by the same manufacturer, in the same room, at the same



time.

The test facility, constructed at LBNL, consists of two side-by-side six-foot hoods (one conventional hood operating at approximately 100 fpm face velocity, and one "Berkeley Hood" operating at approximately half the exhaust flow rate). For purposes of equivalency it was agreed (as stated in the protocol) that under HAM testing the Berkeley hood was to contain equal or better than the conventional hood, or no higher than 0.10 ppm SF6 (the ANSI/AIHA Z9.5 as-installed static test threshold). Both hoods were tested and passed the standard static tracer gas test thus assuring that the "bar," based on a conventional hood, was high (higher than many hoods only meeting the Cal/OSHA face velocity requirement).

Both the Berkeley Hood and the conventional hood performed very well, showing that the Berkeley Hood, with its superior design offers equal worker protection even with half the air volume.

The formal HAM test results are an average of nine tests for each hood (three sets of left, center, and right position tests). Note that despite the dynamic nature of the tests, the average leakage rate was substantially below the ANSI/AHIA as-installed (AI) threshold. Leakage as high as 0.10 ppm would be considered good (as that is the allowable AI leakage under a static test). In fact, not only did the hoods perform well on average, but none of the nine individual tests exceeded the threshold.

The University of California has subsequently used the HAM protocol to test 25 conventional hoods and found that most had containment problems with the sash fully open. The one exception was the Berkeley Hood. All hoods performed well at below the CAL-OSHA requirement of 100 feet per minute face velocity.

Barriers to Improving Performance and Energy Savings

There are material hurdles to widespread adoption of new approaches to fume hood design. The problems reside in various standards and regulations and standards that stipulate absolute airflow rates, rather than direct metrics of containment.

A commonly accepted face velocity air flow value of 30.5 meters per minute (100 feet/minute, fpm) is widely applied. While this value has limited technical merit, its simplicity and pervasiveness presents the most significant barrier to widespread adoption of methods that result in lower airflow rates (even if safety is not compromised). The ASHRAE Standard 110-1995 is the most used test method for evaluating a fume hood's containment performance in North America. This method recommends three types of tests but does not stipulate *performance* values to be attained by a fume hood. ASTM sets performance thresholds when using the ASHRAE test. Hoods using the above-mentioned push-pull technique provide containment of tracer gas and smoke per the ASTM/ASHRAE test but have an "equivalent" face velocity of approximately 9.1 to 15.2 meters per minute (30 to 50 fpm) (with the internal supply fans off). The actual velocity is much less as most of the air is introduced at the face.

In California, CAL/OSHA also requires a 30.5 meter per minute (100 fpm) face velocity for a laboratory fume hood (non-carcinogen), limiting the use of the push-pull approach in that State as well as other high-performance hoods that reduce face velocity.

Other similar barriers can be found in other standards. For example, the U.S. Environmental Protection Agency promulgates a standard used in their procurement procedures but is also adopted for use by others. The requirement for 30.5 meter-per-minute (100 fpm) face velocity is deeply ingrained throughout the industry and is a major market barrier to high-performance hoods.

Conclusions and Research Needs

Laboratory fume hoods are important energy end-use devices, with considerable untapped savings potential. However, existing approaches for improving performance and saving energy in fume hoods can be complicated and costly to implement, and may not address worker safety issues inherent in traditional fume hood design. Innovation can overcome these problems, but is hampered by various barriers stemming from existing fume hood testing/rating procedures, entrenched industry practices, and ambiguous and often contradictory guidance on safe levels of airflow.

Promising improvements to hood designs—largely unchanged for many decades—have been identified. It is unfortunate (and ironic) that existing safety codes both impede improvements in energy efficiency as well as safety. Efforts are underway to remedy this situation.

Acknowledgments

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