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The Berkeley Hood: Development and Commercialization of an Innovative High-Performance Laboratory Fume Hood

Progress Report and Research Status: 1995–2001

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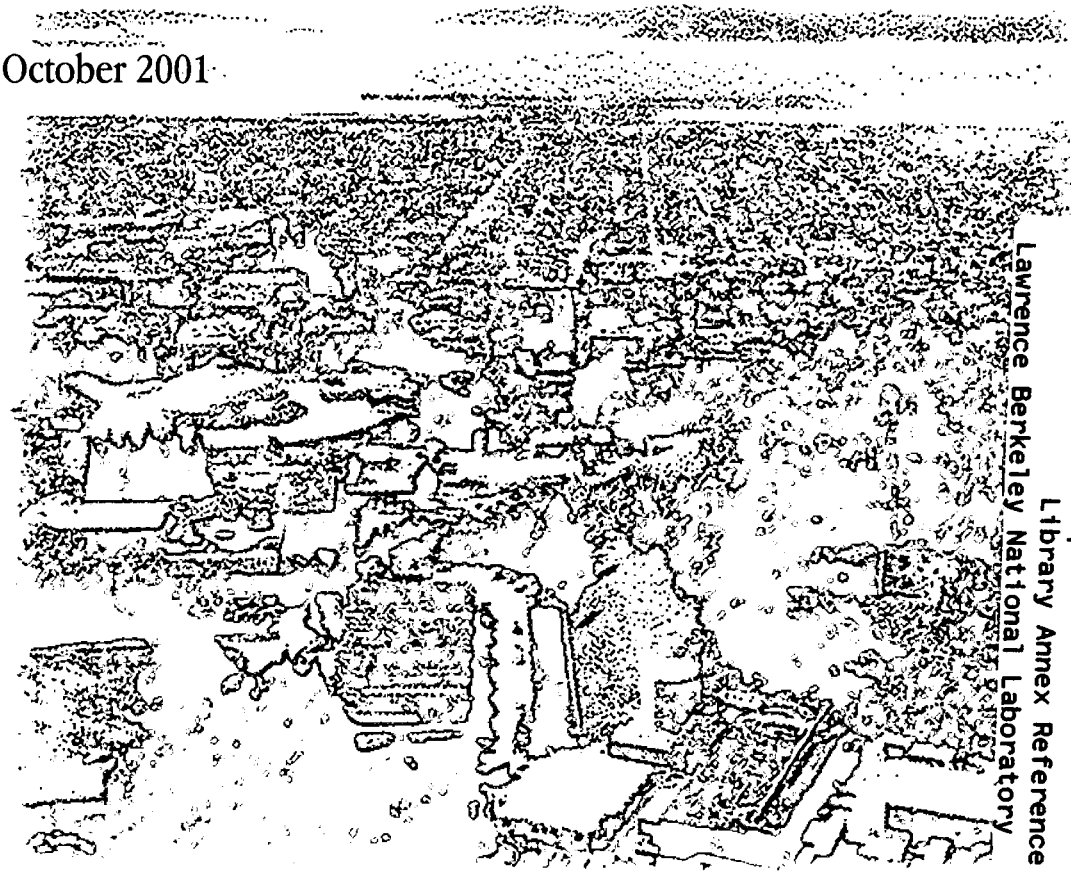
Environmental Energy Technologies Division

October 2001



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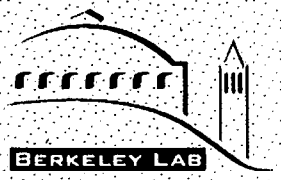

The Berkeley Hood

Development and Commercialization of an Innovative High-Performance Laboratory Fume Hood

Progress Report and Research Status: 1995–2001

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SYNOPSIS

Fume hoods have long been used to protect workers from breathing harmful gases and particles, and are ubiquitous in pharmaceutical and biotechnology facilities, industrial shops, medical testing labs, university research labs, and high school chemistry labs. Fume hoods are box-like structures, often mounted at tabletop level with a movable window-like front called a sash. They capture, contain and exhaust hazardous fumes, drawn out of the hood by fans through a port at the top of the hood.

Highlighting the "systems nature" of the fume hood design, high amounts of air flow tend to drive sizing (first cost) and energy use of central heating, ventilating and air-conditioning systems in the buildings where hoods are located.

As a result, fume hoods are a major factor in making a typical laboratory four- to five-times more energy intensive than a typical commercial building. A typical hood consumes more energy than an average house. With 0.5 to 1.0 million hoods in use in the U.S., aggregate energy use and savings potential is significant. The annual operating cost of U.S. fume hoods ranges from $1 to $2 billion, with a corresponding peak electrical demand of 2,300 to 4,600 megawatts.

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

Existing approaches for saving energy in hoods are complicated and costly to implement, and do not address the worker safety issues inherent in the traditional fume hood design. Innovation is hampered by various barriers stemming from existing fume hood testing/rating procedures, entrenched rules of thumb, and ambiguous and often contradictory guidance on safe levels of airflow.

To address the shortcomings of existing approaches and to promote innovation in the marketplace, Lawrence Berkeley National Laboratory has developed and patented a promising new technology—The Berkeley Hood—which uses a "push-pull" approach to contain fumes and move air. Small supply fans located at the top and bottom of the hood's face, push air into the hood and into the user's breathing zone, setting up an "air divider" at the hood opening. Consequently, the exhaust fan can be operated at a much lower flow rate. Because less air is flowing through the hood, the building's environmental conditioning system can be downsized, saving both energy and initial construction costs—offsetting the potential added cost of the Berkeley Hood.

This report describes the technology development behind the Berkeley Hood, field trials demonstrating pollutant containment down to 34% of full flow, current R&D needs, and technology transfer work underway to continue moving the hood towards commercialization. Based on conservative assumptions, we have identified a preliminary U.S. electricity savings potential for the Berkeley Hood of $240 to $480 million annually, a number that would rise with the inclusion of space-heating fuel.

EXECUTIVE SUMMARY

Laboratory Fume Hoods—Critical But Costly

Fume hoods have long been used to protect workers from breathing harmful gases and particles by capturing hazardous airborne materials created in laboratories, manufacturing facilities, and other settings (Fig ES-1). These box-like structures offer users protection with a movable, window-like front "face" called a sash. Fans draw fumes out of the tops of the hoods. With as many as 1 million hoods in use in the U.S., aggregate energy use and savings potential is significant.

Figure ES-1. Standard laboratory hood in use.

Conventional fume hoods rely solely on pulling air through the hood's open sash from the laboratory, around the worker, and through the hood workspace.

The generally accepted "face velocity" is around 100 feet per minute, depending on hazard level. Interestingly, recent research shows that increasing face velocity (and, consequently, air volume and energy use) does not tend to improve containment. Instead, errant eddy currents and vortexes are induced around hood users as air flows into the hood, reducing containment effectiveness and compromising worker safety (Figure ES-2).

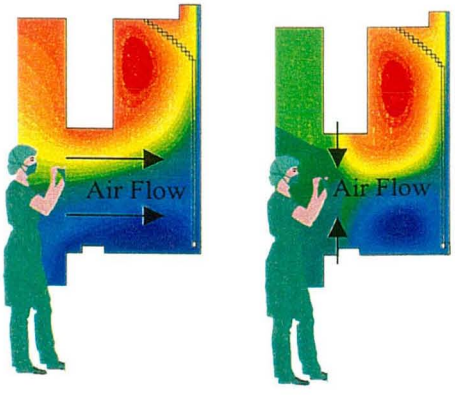


Figure ES-2. CFD Modeling. Standard fume hood (left) and Berkeley Hood (right), with smaller vortices (red and blue circular areas) and the air divider isolating interior and exterior air flows.

Fume hoods typically exhaust large volumes of air at great expense. Furthermore, the energy to filter, move, cool or heat, and in some cases scrub (clean) this air is one of the largest loads in most facilities and tends to drive the sizing (first cost) and energy use of the central heating, ventilating and air-conditioning systems in the buildings in which the hoods are located. Fume hoods are a major factor in making a typical laboratory four- to five-times more energy intensive than a typical commercial building. A six-foot-wide hood exhausting 1200 cubic feet per minute, 24 hours per day, consumes more energy than an average house.

The most common energy-efficient modifications to traditional fume hoods are based on use of outside air (auxiliary air) or variable air volume (VAV) control techniques. While these approaches can save energy, they are complicated and costly to implement and operate, and do not address the worker safety issues inherent in the traditional fume hood design.

Innovation is hampered by various barriers stemming from existing fume hood testing/rating procedures, entrenched rules of thumb, and ambiguous and contradictory guidance on safe levels of airflow. These conditions make this technology area ripe for public interest research and development aimed at introducing innovative alternatives to current practice.

Containment Innovation

To address the shortcomings of existing approaches and to promote innovation in the marketplace, Lawrence Berkeley National Laboratory has developed, and patented, a promising new technology—The Berkeley Hood—that reduces the hood's airflow requirements by up to 70% while enhancing worker safety by supplying most of the exhaust air in front of the hood's operator.

The LBNL containment technology uses a "push-pull" displacement airflow approach to contain fumes and move air through a hood (Figure ES-3). Displacement air "push" is introduced with supply vents near the top and bottom of a hood's sash opening. Displacement air "pull" is provided by simultaneously exhausting air from the back and top of the hood. These low-velocity 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 air flow with low turbulent intensity, the need to exhaust large amounts of air from the hood is largely reduced. The air divider technology is simple, protects the operator, and delivers dramatic cost reductions in a facility's construction and operation.

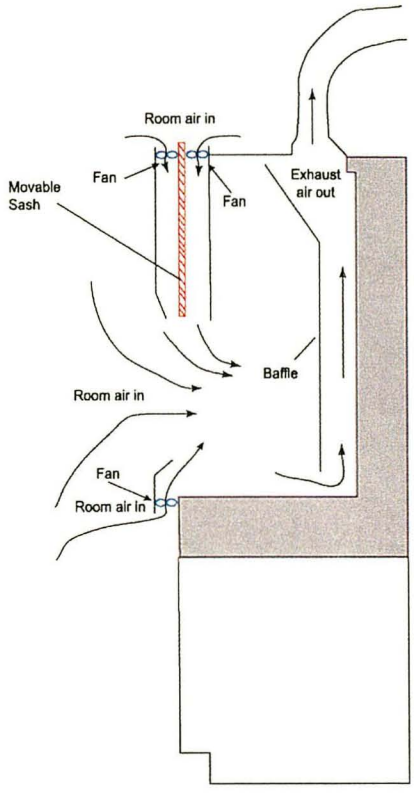


Figure ES-3 Schematic of the high-performance Berkeley Hood; sectional view shows airflow patterns.

The Berkeley Hood attains greater containment and exhaust efficiency, resulting in an effective and energy-efficient solution (Figure ES-4).

The project also addressed hood lighting systems, designing new components that cut lighting energy nearly in half while improving lighting quality.

The research project team has developed several "alpha" prototypes of the Berkeley Hood for laboratory applications (see Fig ES-5). LBNL is collaborating with various industrial partners to refine and apply the technology in research laboratories and in microelectronics applications.

Figure ES-4. High-performance Berkeley Hood, showing full pollutant containment.

An added attraction of the Berkeley Hood is that it is expected to be less expensive than VAV fume hood systems. Savings from downsized heating, ventilating, and air conditioning systems would, in most cases, will offset any first-cost premium of the Berkeley Hood.

Field Trials Validate Performance

A series of field trials have increased our understanding of operability of the Berkeley Hood under actual working conditions in functioning laboratories.

At UC San Francisco, the Berkeley Hood has performed quite well (while the existing standard hood failed all tests) and in some cases exceeded expectations (Table ES-1), containing test smoke and tracer gas under all conditions down to 34% of full flow.

Table ES-1. Siemens Control test results for Labconco unit at UC San Francisco.

Test Type		*Air Flow % of "normal"*[1]	*Containment? yes/no*
Local ventilation	Smoke tube	50%	Yes
Tracer gas	ASHRAE 110	50%	Yes
Tracer gas	Sash movement	50%	Yes
Tracer gas	Safety margin check	40%	Yes
Tracer gas	Safety margin check	34%	Begin spilling

[1] "Normal" being the equivalent of 100 fpm face velocity.

Tests at Montana State University found that when tested per ASHRAE's Standard 110-1995 protocol, the prototype hood contained smoke and operated at significantly less than 0.10 ppm leakage (Table ES-2) a maximum level recommended by the American Council of Governmental Industrial Hygienists (ACGIH).

Table ES-2. Fisher-Hamilton's test results for unit installed at Montana State University.

Test	*Stand. ASHRAE 110*	*Manne-quin Height (inches)*	*Sash Height (inches)*	*SF_6 Release Rate (liters per minute)*	*Tracer Gas Ejector Test Position & Resulting SF_6 Concentrations in The Hood*			*Worst-case Hood Rating (target <0.10 ppm)*
					Left (ppm SF_6)	*Center (ppm SF_6)*	*Right (ppm SF_6)*	*(ppm SF_6)*
1	Yes	26	25	4	< 0.01	<0.01	<0.01	<0.01
2	No	18	25	4	<0.01	<0.01	<0.01	<0.01
3	No	18	31	4	0.05	0.04	0.01	0.05

Widespread Benefits

When cutting airflow by up to 70 percent in standard laboratory fume hood installations, we estimate that California laboratories could save 360-720 Gigawatt-hours (GWh) annually, and 0.1-0.2 GW of electrical peak generating capacity. This energy savings equates to about $30-$60 million per year, or $1,000/year/hood, with higher savings likely in most other U.S. climates. Nationwide, total annual savings are estimated to be $240-480 million,[2] corresponding to 2,100-4,200 GWh annual electricity production and 0.6-1.2 GW of peak electrical capacity.

Beyond the ventilation reduction and associated energy savings, the Berkeley Hood offers design features that deliver a range of benefits:

Figure ES-5. Labconco alpha prototype Berkeley Hood.

[2] These estimates predate the energy crisis of 2001, at which time prevailing energy prices were three to four times higher in some areas than those used in this analysis ($0.08/kWh for electricity and $120/kW demand charges).

- Simpler design than state-of-the-art variable air volume (VAV) fume hood systems offers more certain energy savings, coupled with easier and less expensive installations and maintenance.
- Constant volume operation ensures energy savings are independent of operator interface.
- Improved containment reduces dangerous airflow patterns, eddy currents, and vortexes.
- Clean room air flowing, into the operator's breathing zone reduces potential hazard from fumes.

In new construction projects, designers specifying the Berkeley Hood can achieve savings in energy, construction, and maintenance costs. While the Berkeley Hood itself is expected to have a direct first-cost premium over a current standard hood, this cost can be offset with first-cost savings from smaller (right-sized) ducts, fans, and central plants, as well as simpler control systems, offering lower overall first cost than standard or VAV hood systems.

In retrofit projects, Berkeley Hood users can receive critical HVAC system benefits beyond energy savings. Many laboratories are "starved" for air as their need for hoods has grown over the years. As a result, low supply or exhaust airflows cause inadequate exhaust, in some cases, potentially leading to contaminant spills from the hood. Since increasing supply airflow is very costly in most cases, many laboratories cannot add new hoods. By replacing existing hoods with Berkeley Hoods, users can increase the number of hoods or improve exhaust performance, or both. The final result is improved worker productivity, enhanced safety, and lower energy bills.

Project Timeline

Table ES-3 summarizes highlights of the Berkeley Hood project through June 2001.

Table ES-3. Berkeley Hood development timeline.

1995-98	• LBNL research scientist Helmut Feustel, develops concepts of a Berkeley Hood design
1998	• California Institute for Energy Efficiency funds fume hood research as part of a broad high-tech buildings research program • Market analysis conducted • Industrial partner identified • Patent application filed
1999	• Project funding from: US DOE (research) and Montana State (field demonstration) • CFD analysis completed • Containment achieved with "alpha" prototype • Testing and evaluation per ASHRAE 110 begin
2000	• Additional industrial partners join research efforts • Scale-up to larger hoods begins • Patent issued in July 2000; applied for additional patents • PG&E funds field demonstration project • Hood débuts at LABS for the 21st Century in San Francisco • Montana State Univ. demo unit installed September 2000 • PG&E demo unit installed Nov. 2000 at Univ. of Calif. SF
2001 (through June)	• SDG&E funds demonstration project • CEC funds field demonstration analysis • Licensing proposal request distributed to partners and industry • LBNL joins ASHRAE 100 committee • LBNL joins CAL/OSHA hood advisory committee • Three industry experts brought to LBNL for independent evaluation and consultation • Extension of refinements to air supply distribution • Licensing request for proposal (RFQ) request distributed to industrial partners and industry; none of the RFQ responses were satisfactory; no license agreement resulted; the technology continues to be available for licensing.

Key Accomplishments

The following summarizes key project accomplishments:

- Developed the high-performance design concept.
- Obtained a patent for the basic concept (U.S. Patent # 6,089,970), with additional patents pending.
- Identified hood design and exhaust system characteristics.
- Conducted computational fluid dynamic (CFD) analysis to speed design optimization.
- Fabricated and tested design alternatives to optimize system performance.
- Demonstrated capture and containment following the ASHRAE Standard 110-1995 test, with 70-percent flow reduction compared to standard systems.
- Completed schlieren visualization testing to confirm capture and containment.
- Designed alternate lighting systems that reduce lighting energy use by 47 percent, improve lighting quality and reliability while reducing maintenance.
- Established partnerships with laboratory hood and controls manufacturers to develop and test alpha units.
- Signed intellectual property agreement for product development in the microelectronics field.
- Verified performance goals through field tests.
- Developed project website and other outreach activities.

Project Supporters

Funding has been provided by the following organizations to address various aspects of the hood's development and testing:

- *U.S. Department of Energy...* Multi-year funding for hood development and to develop intellectual property.
- *California Energy Commission...* Expected to provide funding for demonstration project evaluations and to determine future research needs. Will be funding three to four demos for commercial/industrial sector in FY2002.

- *California Institute for Energy Efficiency (CIEE)...* 1998-1999 for technology development and technology transfer.
- *Montana State University...* 1999/2000 funding for one field test and market transformation activities. First field demonstration site.
- *Pacific Gas and Electric Company...* 2000 funding for one field test and market transformation activities.
- *San Diego Gas and Electric Company, through San Diego State University ...* 2001 funding for one field test and market transformation activities. Providing site for second California demonstration of Berkeley Hood.

The following organizations provided in-kind support:

- *Labconco...* Provided a fume hood superstructure for modification and use in prototype development. Built two prototypes for demonstration installations and field testing.
- *ATMI...* LBNL has partnered with ATMI to develop the Berkeley Hood technology for the microelectronics industry (e.g. wet benches, and equipment cabinets). Entered into an "option to license" agreement for the air divider technology in the microelectronics industry. Developed their own adaptation of the technique for "wet benches" used in semiconductor manufacturing.
- *Fisher-Hamilton...* Provided a six-foot hood for prototype development for larger hoods. Built a four-foot fume hood for field testing.
- *Fisher-Nickel/PG&E Food Service Technology Center (FSTC)...* Collaborated by sharing ideas and methods to visualize air flow in hoods. Used FSTC schlieren device to study Berkeley Hood airflow patterns. LBNL presented at conferences sponsored by FSTC to demonstrate airflow visualization techniques.
- *Phoenix Controls/Newmatic Engineering...* Phoenix engineers evaluated hood's performance with standard ASHRAE 110 protocol and additional challenges, e.g., "walk-by" challenge. Phoenix Controls will provide control package and monitoring interface at SDSU demo site with installation by Newmatic Engineering.
- *Siemens Building Technologies and Controls...* Provided monitoring and control equipment and expertise for one field test.
- *US Filter/Johnson Screens...* Provided protective grill for lower plenum supply at reduced cost; worked with LBNL to design and fabricate special grill; estimated production pricing.
- *University of California at San Francisco...* Provided site and funded installation for first California demonstration of Berkeley Hood.

The following organizations served as consultants to the project:

- *Earl Walls Associates...* Will test and evaluate demo installation at SDSU.
- *Exposure Control Technologies...* Provided expert review and evaluation of Berkeley Hood at LBNL.
- Knutson Ventilation... Provided expert review and evaluation of Berkeley Hood at LBNL.
- *Marina Medical Mechanical...* Mechanical contractor that installed the Berkeley Hood at UCSF Medical Center in San Francisco.
- *SafeLab Corporation...* Provided expert review and evaluation of Berkeley Hood at LBNL.
- *Technology Performance Group...* Technical consultant to ATMI during development of semiconductor wet bench system.

Report Overview

This report summarizes the Berkeley Hood project since its inception, focusing on recent achievements. The remainder of this report is divided into the following sections:

- *Background...* describing historic development of hood technologies and design criteria
- *Issues and Opportunities...* giving an overview that demonstrates the importance of changing the market to adopt Berkeley Hoods
- Project Activities and Accomplishments... summarizing the work completed
- *Future Activities...* describing research and development needs as well as upcoming field tests and prototype fume hoods
- *Appendices...* providing additional details on selected subjects

The project web site (http://ateam.lbl.gov/hightech/fumehood/fhood.html) includes additional project information, including detailed supporting documents, videos demonstrating containment, and current/upcoming project activities.

BACKGROUND

Historical Laboratory Fume Hood Development

The earliest fume hoods were used over open fires inside buildings, e.g. at smith's forges. They provided containment with thermal updrafts in tall chimneys, which resulted from rising air made buoyant by the fire. During the Industrial Revolution, the gas-burning rings used to increased drafts were replaced by mechanical fans. The next major improvements were the introduction of a five-sided "box" with an operable sash that protected workers by varying the opening size. Later, a baffle system was added at the back of the box. The baffle helped to exhaust air from the hood's working surface area as well as from the top canopy area (Saunders 1993).

In the 1940s, the Atomic Energy Commission asked the Harvard School of Public Health to develop equipment for improving hood operation and safety. As a result, the School improved fume hood entrances to streamline air flow patterns. The advent of High Efficiency Particulate Arrestors (HEPA) filters also resulted from this work. One industry source notes that, despite the claims of hood manufacturers, the basic hood design has changed little over the past 60 years(Saunders 1993).

In today's world, laboratory fume hoods are widely used in laboratories and other "high-tech" facilities such as cleanrooms. Varying estimates place the existing stock of fume hoods between 0.5 and 1.5 million. Fume hoods protect operators from breathing harmful fumes by capturing, containing, and exhausting hazardous airborne material created in laboratory experiments or industrial processes. These box-like structures, often mounted at tabletop level, offer users protection with a movable sash that varies the opening size. Exhaust fans draw fumes out the top of each hood by inducing airflow through the front opening, or face, of the fume hood.

Hood airflow face velocity through the sash was originally considered adequate at 50 feet-per-minute (fpm, or 0.25 meters per second – m/s). However, this value increased over time to 150 fpm (0.75 m/s)to "improve" hood safety. Only when a research project, sponsored by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), produced a procedure for establishing fume hood performance were face velocities reduced to the range of 60–100 fpm (0.3–0.5 m/s) (Caplan and Knutson 1978a). This research—based on new information relevant to worker safety–formed the basis of ASHRAE Standard 110-1985, a standardized method for evaluating laboratory fume hood performance.

Design Criteria and Conditions for Conventional Laboratory Fume Hoods

General

A conventional fume hood contains hazards by maintaining inward-directed airflow through the face of the hood. The "open face" of a hood corresponds to the area

below the sash at the front of the hood through which air enters (ASHRAE 1995). The size of the open face is variable with the position of the movable sash.

For safe fume hood operation, effective air circulation throughout the laboratory is essential. However, a fundamental goal of energy engineers is to reduce the amount of exhaust air to the lowest safe level because conditioning of make-up air is very energy intensive, in addition to the direct fan energy that can be saved. LBNL's Laboratory Design Guide (Bell et al. 1996) states that surprisingly few codes stipulate the actual amount of exhaust for laboratory-type facilities.

For laboratories that routinely use hazardous material, the "rule of thumb" of 10 to 12 outside air changes per hour (ACH) is typically used. Bell et al. (1996) recommend an exhaust air flow rate of 1 cfm/ft^2 of laboratory floor area (17 m^3/h per m^2) for occupancy classifications through "H-7."[3] Therefore, for a "B" occupancy laboratory with a ceiling height of 10 ft (3.05m), 1 cfm/ft^2 provides six air changes per hour (6 ACH). Often, hoods are the primary exhaust in a laboratory. For example, a fume hood with a face opening of 5 ft by 2.5 ft (1.52 m by 0.76 m) and a face velocity of 100 fpm (0.5 m/s) exhausts 1,250 cfm (2,080 m^3/h), which would provide sufficient exhaust for a laboratory space of 1,250 ft^2 (116 m^2).

Face Velocity

Recommendations for face velocity range from 75 fpm (0.37 m/s) for materials of low toxicity (Class C: TLV > 500 ppm) to 130 fpm (0.65 m/s) for extremely toxic or hazardous materials (Class A: TLV < 10 ppm) (Cooper 1994). Industrial hygienists generally require minimum face velocities of 100 fpm (0.5 m/s) for hoods with open sashes.

However, as shown above, face velocity recommendations have changed over time. In the 1970s, recommendations for face velocity moved from 50 fpm (0.25 m/s) to 150 fpm (0.75 m/s) and higher. Face velocities higher than 125 fpm (0.63 m/s) can create significant turbulence inside and outside the hood, causing fumes to spill into the laboratory (Monsen 1989). The literature reveals there is little relationship between face velocity and containment level (Hitchings 1996; Hitchings and Maupins 1997; Caplan and Knutson 1977; Saunders 1993); many factors are responsible for the effectiveness of a fume hood.

Other Influences On Containment

In addition to the hood design, the position of the worker has a significant influence on air flow patterns in the hood, and particularly in the face of the hood. Air flow around a person's body standing in front of a hood creates a region of low pressure downstream of the person. This region, which is deficient in air movement (aka "momentum"), is called the wake. A human body disturbs the directed air flow in the face of the hood and can cause contaminants to spill (ACGIH1995).

[3] Group H occupancies include buildings or structures, or portions thereof, that involve the manufacturing, processing, generation or storage of materials that constitute a high fire, explosion, or health hazard.

A hood's overall "box leakage factor" (sash leakage and box leakage) correlates strongly with turbulence intensity. The National Institutes of Health (NIH 1996) and Caplan and Knutson (1978) found that sash leakage is dependent on laboratory air flow patterns. Turbulent fluctuation of air velocity generated outside of the hood in the room can be carried into the hood. This situation can result in spillage from the hood, despite high design face velocities.

Therefore, a hood's performance is affected by its location with respect to doors, supply air outlets, and areas with foot traffic. Saunders (1993) shows that even the highest proposed hood face velocity is smaller than the air velocities created by door openings [175 to 450 fpm (0.83 to 2.25 m/s)] or people passing the hood [260 to 450 fpm (1.30 to 2.25 m/s)]. Even supply air diffusers can create air velocities in the vicinity of the hood that are higher than the hood's face velocity.

A hood's position in relation to other hoods influences its performance. The National Institutes of Health's study (1996) suggests placing fume hoods on the same wall at least 4 ft (1.22 m) apart, preferably in corners. Hoods on opposite walls perform well, but, according NIH's findings, best performance is achieved when fume hoods are installed on perpendicular walls. In any case, maximizing the distance between two hoods on the one hand and the supply air grille on the other hand provides the best performance. For more details about laboratory design, see Bell et al. (1996).

Construction Details Of Conventional Fume Hoods

The size of a fume hood is described in terms of its outside dimensions. The width of the interior work chamber is found by subtracting the thickness of the two sidewalls from the total width. Therefore, a 6 ft (1.83 m) fume hood with side walls of about 6 inches (0.15 m) each has an interior work chamber width of 5 ft (1.52 m). The sidewalls have considerable width because they contain mechanical and electrical services. Typical hoods have aerodynamically-shaped sidewalls.

The most important aerodynamic design feature of a standard fume hood is an entrance airfoil. This airfoil helps prevent formation of turbulent airflow at the front edge of the hood's working area. The depth of the work space depends on the design of the hood's air foil and the back baffle (Saunders 1993). This leaves a work area that is approximately 21 inches (0.53 m) deep. The dimensions of the work space within the fume hood should be determined by the worker's needs. Using a hood that is larger than needed triggers unnecessary initial costs, energy, and other operating costs (Cooper 1994). However, deeper hoods offer superior containment. In sum, overall hood depth, including the thickness of an outside shell, varies from 32 to 37 inches (0.81 to 0.94 m).

Air flow in an optimum hood design "sweeps" the work area without forming vortexes (Figure 1) inside the hood. Uncontrolled vortexes within a hood can cause spillage of contaminants into the laboratory. Typical locations for a vortex to form are: (1) above the open sash, which spills through the hood's face and (2) near the work surface. If room air flow patterns of sufficient velocity create cross drafts in front of the hood, air flow into the hood can be disturbed enough to cause a dangerous reversal of flow.

Movable sashes offer greater safety than a full open-faced hood. A lowered sash offers the operator "a quick place to hide" in the event of a mishap.

Sashes are available in vertical or horizontal arrangements. A vertical sash can provide an open face area of 100 percent. Typically, a vertical sash is framed and moves up and down in tracks in the hood's wall. Horizontal sashes move from side to side and limit the open area Therefore, the fume hood is rarely, if ever, in a fully open position unless the operator removes a sash permanently.

Combining a vertical sash and a horizontal sash can provide user flexibility (allowing a full opening during set-up) and can save significant energy. However, in actual laboratory conditions, many operators feel horizontal sash arrangements to be cumbersome and limit their flexibility to work.

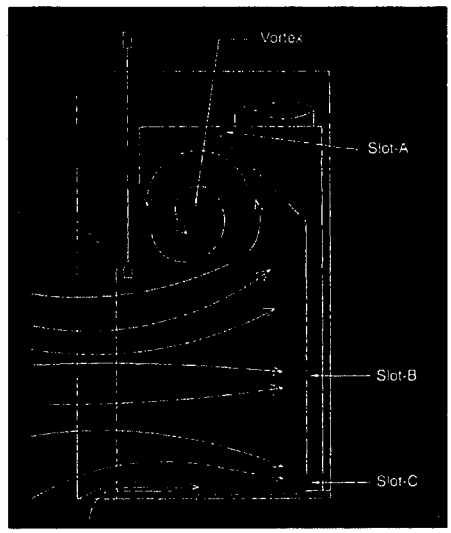


Figure 1. Air flow pattern inside a standard fume hood (Saunders 1993).

ISSUES AND OPPORTUNITIES

Current Technology

Standard Designs Dictate High Exhaust Rates

Standard fume hood design (Figure 2) is based on air flows of 100 feet per minute and the assumption that the sash is fully open. Therefore a hood with a standard 5-foot by 2.5-foot opening requires an exhaust rate of 1250 cubic-feet-per-minute.

Figure 2. Standard laboratory hood in use.

As previously described, and contrary to common expectations, increasing the face velocity does not improve containment. Instead, errant eddy currents and vortexes are induced around hood users as air flows into the hood, reducing containment effectiveness.

Laboratory fume hoods are operated 24 hours/day. Since many laboratories have multiple hoods, they typically dictate a lab's overall required airflow and thus the entire facility's supply and exhaust system capacity (and thus cost). The result is larger fans, chillers, boilers and ducts compared to systems having less exhaust. Consequently, fume hoods are a major factor in making a typical laboratory four- to five-times more energy intensive than a typical commercial space.

Currently Available Energy-Efficient Systems Face Limitations

In the past, four design strategies have been used to reduce fume hood energy use.[4] These include:

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

[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). For safety reasons, we do not suggest switching off hoods.

- 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.

- Automated designs that promote a vortex in the top of the fume hood, and maintained by "sensing" whether it is collapsing, or not, and adjusting movable panels in the top of the hood accordingly.

The first design strategy, referred to as an auxiliary-air hood, introduces outdoor air near the face of the hood just above the worker. Un-conditioned 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 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; Feustel et al. 2001). Moreover, auxiliary air hoods only save energy used for conditioning general laboratory air. This is the case because total exhaust flow rate is unchanged. Fan energy consumption is not reduced and may even be increased by the necessity of an auxiliary supply fan. Our estimates indicate that as much as 65 percent of hood energy is attributable to the fans (moving air) with the balance attributable to conditioning the air (see Table 1).

The second strategy requires 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. This VAV system provides a fume hood with a constant face velocity. VAV improves safety, compared to standard hoods, which experience variable face velocity. Also, a constant pressure differential is maintained 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 operate the sash properly to ensure that the system achieves the 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 were assumed to be partly closed.

A third strategy restricts a hood's face opening while maintaining air flow velocity. The face opening is restricted by limiting vertical sash movement with "stops" or using a horizontal sash system that blocks part of the entrance even when fully open. Generally, the stops or sashes are 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 these restrictions, so it is not uncommon to see hoods under normal use with their stops bypassed or the horizontal sashes removed. In these cases, the air velocity drops below specified levels and compromises safety.

A fourth strategy has been effectively applied to fume hood design though it is not entirely accepted or understood by laboratory designers. This hood design incorporates, according to the manufacturer, a "bi-stable vortex" to enhance its containment performance. The design promotes a vortex in the top of the fume hood, and maintains this vortex by "sensing" whether it is collapsing, or not, and adjusts movable panels in the top of the hood accordingly. This design is controversial, at best, and, at worst, is subject to a variety of control input and output reliability concerns.

Opportunity For Improvement

A New Approach to Containment and Safety – The Berkeley Hood

Conventional hoods (and the above-mentioned efficiency techniques) rely on pulling supply air from the general laboratory space around the worker and through research apparatus that may be located in the hood. Safety performance is susceptible to everyday activities in the lab, movement of people, opening and closing of doors, central air supply fluctuations, etc. Past efforts have not looked at the potential for re-conceptualizing and redesigning the hood to maintain or improve worker safety with lower air flows.

A new strategy for managing fume hood energy, the Berkeley Hood technique supplies air *in front* of the operator, while drawing only about 10-30% of the air from around the operator.[5] As a result, far lower flow-rates are necessary in order to contain pollutants and flow-rates remain virtually unaffected by adjustments to the sash opening. This supplied air creates a "protective layer" of fresh air free of contaminants. 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.

The Berkeley Hood uses a "push-pull" displacement airflow approach to contain fumes and move air through a hood. Displacement air "push" is introduced with supply vents near the top and bottom of the hood's sash opening. Displacement air "pull" is provided by simultaneously exhausting air from the back and top of the hood. These low-velocity 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 air flow with low turbulent 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.

[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.

The Berkeley Hood must not be incorrectly 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. This is in contrast to the beneficial layer of clean air provided in the opening of the Berkeley Hood. 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 installation 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 installations would also be realized.

The Berkeley Hood project also included hood lighting systems. Newly designed components cut lighting energy nearly in half while improving control, quality and reliability.

Initial Groundwork

LBNL developed basic concepts for a high-performance laboratory fume hood during 1995–1998 (Feustel et al. 2001).[6] This early work included a number of activities, including:

- Establishing proof of concept by fabricating and testing hood mock-ups.
- Conducting simple, two-dimensional computational fluid dynamic (CFD) analysis to determine airflow patterns in standard hood configurations.
- Presenting preliminary results to industry groups and soliciting funding support.
- Publishing preliminary findings.
- Collaborating with other staff personnel and submitted patent application.

Market Analysis

The project team conducted a preliminary market analysis to identify market size, potential energy savings (Table 1), and potential market impact.

[6] Dr. Feustel left LBNL in January 1999. At that time, LBNL's Environmental Energy Technologies Division (EETD) transferred the project to its Applications Team, with Dale Sartor, P.E. as Principal Investigator and Geoffrey C. Bell, P.E. as Project Head. Dr. Feustel remains a consultant to the project.

The results suggest the following:

- Approximately 150,000 laboratories populate the United States
- We estimate that between 500,000 and 1,000,000 fume hoods are installed in the United States. While we have seen estimates as high as 1.5 million, we have conservatively chosen a narrower range for the purposes of estimating energy savings.
- Each new hood will save about 2.3 kW and 8.5 MWh/year (based on mild California weather conditions; savings will be greater in other climates).
- Approximately 50 percent of all existing hoods could be replaced with the Berkeley Hood, with total annual U.S. electricity savings of 2,100 to 4,200 GWh and 0.6 to 1.2 GW. Inclusion of space-heating (largely non-electric) would increase the total energy savings.

Further work is required to refine the engineering assumptions as well as the data on stock characteristics. Existing estimates of hood populations vary widely. The energy performance and savings potential of fume hoods is highly dependent on regional weather conditions, baseline HVAC system efficiencies, and market penetration of substitute technologies.

Table 1. Analysis of fume hood national electricity savings potential.

Assumptions	
Average hood flow rate	1,250 cubic feet per minute (cfm)
US hoods	500,000 to 1,000,000
California hoods	85,000 to 170,000
Maximum replacement potential	50% of all existing units
Air flow supply & exhaust system fan energy	1 W/cfm (much higher at margin in retrofit)
Chiller plant energy	1 kW/ton
Cooling peak delta T	30 degrees F
Average cooling delta T	20% of peak (i.e., 6 degrees F)
Cost per kWh	$0.08
Cost per kW	$120/year
Per-hood savings	50% (75% for hood, but assumes minimum general lab exhaust overrides)
Calculations	
Cooling peak tons/hood	3.44 (1250 cfm * 1.08 BTU/h/ft ^{3}/minute/degree F * 30 degrees delta-T / 12,000 BTU/hour/degree F)
Cooling peak kW/hood	3.44
Air flow kW/hood	1.25
Total peak kW/hood	4.69
Cooling kWh/hood	6,023 (8760 hrs * 3.44 kW/hood * 2 0%)
Air flow kWh/hood	10,950 (8760 hrs * 1.25 airflow kW/hood)
Total kWh/hood	16,973
US energy use, peak demand, and annual cost	8.5-17 TWh / 2.3-4.6 GW / $1-2 billion
Calif. energy use, peak demand, and annual cost	1.4-2.8 TWh / 0.4 -0.8 GW / $0.2-0.4 billion
Annual savings kW/hood	2.34 ($281)
Annual savings kWh/hood	8,486 ($679)
Total annual savings/hood	$960
California peak power savings	0.1 to 0.2 GW
Annual California electricity savings	360 to 720 GWh
U.S peak power savings	0.6 to 1.2 GW
Annual U.S electricity savings	2,100 to 4,200 GWh
Annual cost savings ($M) – CA / US	$41 - $82M / $240 - $480M

Notes: Approximately 150,000 laboratories populate the United States, with 500,000 to 1,000,000 total fume hoods installed. This range is based in part on interviews of industry experts conducted on behalf of the Labs21 project, and excludes an "outlier" estimate of 1.5 million. The only formally published estimate indicated that there were more than 1 million units in 1989 (Monsen 1989). Conservatively we estimate that each new hood will reduce peak electrical load about 2.3 kW and save 8.5 MWh/year. Further, we estimate that 50% of all existing hoods could be replaced with the Berkeley Hood (technical potential virtually 100%), with total annual U.S. electricity savings of 2,100-4,200 GWh and 0.6-1.2 GW. Note that our cost estimates (based on electricity prices of $0.08/kWh and $120/kW demand charges) predate the energy crisis of 2001, at which time prevailing energy prices were three to four times higher in some areas than those used in this analysis. Note: engineering analysis reflects California weather conditions. Usage (and savings) will be higher in many other regions, and if space heating and reheat (largely non-electric) are included.

Institutional Barriers

In conjunction with identifying design improvements and market opportunities, the project team identified market barriers to adopting the new hood technology (Vogel 1999). Their research uncovered numerous hurdles to widespread adoption, including:

- The ASHRAE Standard 110-1995 is the most widely used test method for evaluating a hood's containment performance. This method recommends three types of tests but does not recommend performance values that need to be attained by a fume hood. Aside from the ASHRAE method, the most commonly used indicator of hood capture and containment is hood face velocity. A commonly accepted value of 100 feet/minute (fpm) is widely applied. While this value has limited technical merit, it presents the most significant barrier to widespread adoption of the Berkeley Hood. Hoods using LBNL's low-flow technique provide containment of tracer gas and smoke per the other ASHRAE 110 tests but have an "equivalent" face velocity of approximately 30 to 50 FPM. The actual velocity is actually much less as most of the air is introduced at the face rather than pulled from outside the hood.

- In California, CAL/OSHA requires 100 fpm face velocity for a laboratory fume hood (non-carcinogen) to be in compliance, limiting the use of the Berkeley Hood in California and potentially in other States that follow California's lead.

- Other similar barriers can be found in a variety of standards. For example, the EPA promulgates a test standard that is used in their own procurement but is also adopted for use by others. The requirement for 100 fpm face velocity is deeply ingrained through this industry and will be a major market barrier to this new technology.

Research Efforts Expand

Based on early findings and successes, the project team developed a research plan with a comprehensive approach for developing the Berkeley Hood. The project worked with the California Institute for Energy Efficiency (CIEE) to verify the performance of the technique. The hood's ability to contain hazardous fumes was checked by an outside consultant by performing tests per a standardized protocol (ASHRAE 110, described below). This rudimentary prototype passed the containment tests, proving the merit of the technique (Feustel et al. 2001). CIEE funding was augmented with support from the DOE and Montana State University (MSU). This support, and the test results, encouraged Labconco to provide "in-kind" support by donating a four-foot-wide hood to the project. This combined support allowed research to expand significantly. The project subsequently increased research with new, innovative airflow visualization methods. Fisher-Hamilton also became interested in the project and provided support at several levels), including providing a six-foot-wide hood for scaling-up the technique for application in the next larger size hood more typically used in laboratories. Further field demonstrations have

been conducted. A greater understanding of the technique was gained from this research, new intellectual property was identified, and the hood design refined. In parallel with technology development, LBNL is participating in critical codes and standards activities being conducted by ASHRAE and CAL/OSHA.

PROJECT ACTIVITIES AND ACCOMPLISHMENTS

This section summarizes project activities and accomplishments, with the information split into three categories: (1) project administration planning; (2) technology development; and (3) market development.

Project Administration

The Berkeley Hood project is a multi-year, multi-phase research and technology development project effort. It has been widely supported, by public and private organizations alike, and has leveraged expertise within a number of groups within LBNL.

Project Supporters

Initial work was supported by general funds in LBNL's Environmental Energy Technologies Division. In 1998, the California Institute for Energy Efficiency (CIEE) began funding the hood research as part of a multi-year, multi-phase research project in LBNL's high-tech building area. The early scoping research on the topic was also performed by LBNL (Mills et al. 1996). Additionally, the U.S. Department of Energy (DOE) and Montana State University funded basic research and prototype development from 1999 through 2001. A full list of project sponsors and in-kind contributions is provided in the Executive Summary.

Project Plan Established

Project activities increased in 1999 with the additional sponsorship noted above. The team developed an extensive work plan to develop the technology, establishing key goals. To adequately structure these goals, 26 work elements were identified. From these work elements, the team then created the following eleven Tasks:

1) Analyze Air Flow And Containment
2) Characterize Screen Air Flow
3) Design Supply-Air Plenums
4) Design Rear Baffle System
5) Construct, Install, And Startup A Prototype Hood
6) Ensure Hood Operational Safety
7) Perform Hood Tests
8) Secure Patent

9) Transform Regulatory Barriers

10) Implement Hood Demonstration Program

11) Develop Outreach Activities

Preliminary Measures

The identified tasks included numerous aspects that needed to be handled before experimentation with the Berkeley Hood could begin, including:

- Secure a research space
- Ensure Labconco fume hood superstructure delivery
- Purchase hand tools
- Install fume hood (detail below)
- Modify standard fume hood(detail below)
- Design supply air systems(detail below)
- Install special low-flow components(detail below)
- Review ASHRAE 110 test procedure
- Purchase tracer gas ejector for ASHRAE test
- Arrange testing of hood with Indoor Air Environment Department
- Determine instrumentation needs
- Identify alternative modes for airflow analyses
- Purchase Helium Bubble Generator
- Hire summer student help

Project Team

The project team leveraged expertise throughout LBNL's Environmental Energy Technologies Division (EETD). A team of student researchers greatly aided their efforts, particularly in fabricating and testing alternative hood features.

Summer Student Contributions

Soliciting candidates from The U.S. Department of Energy's Energy Research Laboratory Undergraduate Fellowship (ERULF) and Community College Initiative

(CIC) Student Mentor Programs, LBNL hires students from various engineering disciplines from universities around the nation and abroad.

Once on board, the students face a steep learning-curve to become familiar with laboratory fume hood technologies and to work productively in LBNL's environment. Each researches fume hood technology and analyzes data. The students have made significant accomplishments in developing components and features for the prototype hood (Chan 1999; Fox 2000; Griffin 1999, Roberts 1999; Vogel 1999).

LBNL's experience with the DOE program was quite positive and the project was decidedly enriched by each student's commitment to their task. Keys to their successful involvement included the following:

- Feeling a common sense of purpose
- Sharing information and problems at regular meetings
- Knowing that their input was relevant
- Seeing tangible and demonstrable results
- Having involvement at all levels of the process, including hood demonstrations to outside professionals

Technology Development

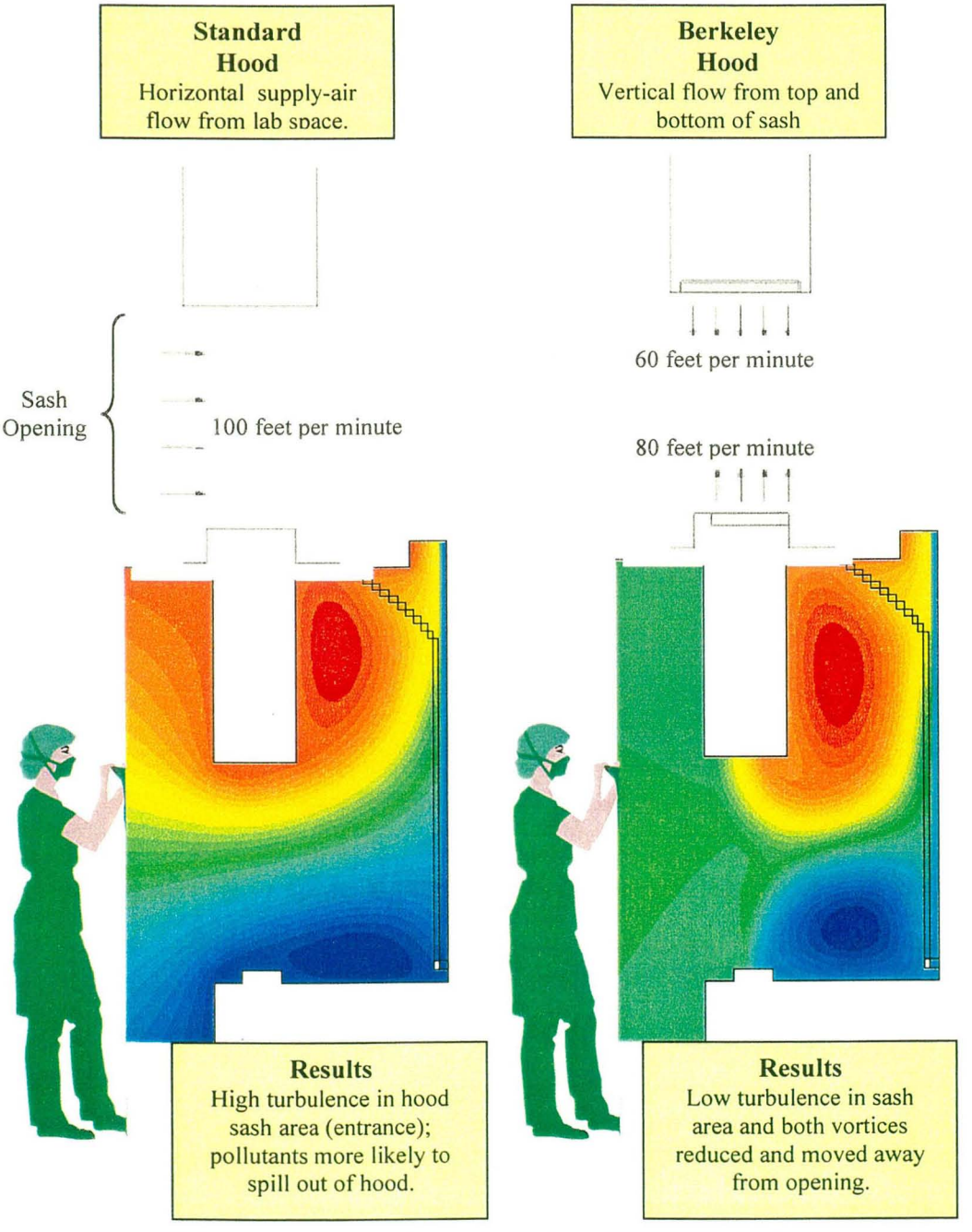
Analyze Air Flow and Containment

Use Computational Fluid Dynamic (CFD) Modeling

LBNL researchers conducted over 30 Fluent™ Computational Fluid Dynamic (CFD) runs to model airflow through the hood. Examples comparing the Berkeley Hood to a standard hood are shown in Figure 3. The series of simulations studied numerous airflow arrangements and criteria, including:

- Total supply volume versus total exhaust; Total exhaust only
- Volume of each of four supply inputs
- Eliminating one or two supply air inputs
- Relative intensity of air flow vectors and streamline boundaries
- Flow from the room into the hood
- Induced vortexes inside of the hood
- Flow near and through back baffle slots

Figure 3. Computed fluid dynamics (CFD) air-flow simulations. In these simulations, color contours show streamlines; flow rates are higher where the distance between streamlines is small. In the standard hood (left), all airflow exhausted is drawn through the sash opening. The Berkeley Hood (right), introduces 70 percent of total exhaust flow vertically at the sash in front of the operator with low-turbulence intensity. Consequently, the Berkeley Hood can be operated at 75% less air flow than the standard hood. Closed loops indicate zones of recirculating air (blue – clockwise; red – counterclockwise) and potential contaminant spill. The recirculating loops have been eliminated in subsequent design improvements to the Berkeley Hood.



Researchers completed modeling on both a generic design and an actual fume hood superstructure. Initial CFD runs were computed prior to LBNL obtaining an actual fume hood superstructure from our industrial partner. Therefore, geometric relationships were generalized with respect to sash size, interior dimensions, back-baffle arrangement, etc. These runs varied air flow quantities for all three supply plenums and overall exhaust quantity.

Our first industrial partner, Labconco, provided a fume hood superstructure and its dimensions were transferred into the CFD model. We included an advanced shape for the lower, inside plenum surface. It is curved with a constant radius; however, the model uses a simple combination of a vertical and horizontal surface to approximate the curved surface.

Observations and interpretations of the CFD modeling yielded the following critical findings:

- All four supply air inputs (two upper plenums and a vertical and horizontal surface of the lower plenum) are necessary;
- Total supply air through the sash grilles should not exceed 80% of total exhaust volume;
- Horizontal flow from lower plenum supply was not producing the expected results;
- A strong vortex in the bottom of the hood at the working surface was being generated. This vortex spun horizontally such that air in its lowest portion was directed towards the hood's sash. Inside this vortex was a zone of "no flow," a situation both undesirable and potentially dangerous; and
- Another strong vortex was also being generated in the top of the hood near the sash (this is the most typical region to spill and fail on standard hood designs). This vortex spun horizontally so that air in its upper portion was directed towards the hood's sash. Inside this vortex was a zone of "no flow," a situation both undesirable and potentially dangerous.

Analyze Interior Vortex

The potentially dangerous interior vortexes, noted in the CFD runs and shown in Figure 3, are also found in standard hood configurations. To eliminate, or reduce, induced vortices generated in the bottom and top of the fume hood, approximately twenty back baffle arrangements were modeled. From the CFD runs, it was observed that the back baffle has a strong role in forming the upper and lower vortices. However, none of the back-baffle arrangements modeled eliminated these vortices. To confirm results predicted by the CFD models, various back baffle configurations were built and checked by empirical observation. The CFD model results were validated.

Although the CFD computer runs by themselves did not lead directly to a design that fully contained the flow or eliminated the vortices, the models were helpful in

increasing the team's understanding of airflow problems within the hood. The results were ultimately positive, and the CFD runs helped achieve a physical solution to eliminating the vortices.

Examine Airflows

In addition to CFD analysis, the team applied several other types of flow visualization techniques to qualitatively understand airflow into and through the prototype hood. The techniques included the following:

- Smoke; small volume - Very stable "point source" smoke can be provided with smoke "sticks" using titanium tetrachloride. These sticks were used after any design change or rearrangement to quickly determine how air was moving within the hood.

- Smoke; large volume - Theatrical smoke machines generate large quantities using superheated glycols. Smoke was released inside the hood and into each supply fan inlet to observe supply plenum effect.

- Bubbles - A device using helium gas to blow bubbles with a specially formulated detergent was used. The resultant bubbles are neutrally buoyant and provide a unique method to observe all types of air flow in the hood's interior.

- Schlieren Effect – We employed a schlieren flow analysis methods to visualize air at different densities. The team borrowed a schlieren visualization unit from PG&E's Food Service Technology Center, which enabled us to record very small amounts of smoke moving through the hood. Observations were performed, varying one of several variables at a time, and a digital archive of the results was established. Funding limitations have hindered further analysis of the schlieren results which could lead to hood design improvements.

Evaluate Performance Envelope

A range of empirical test runs were completed on the prototype hood to establish an operational envelope. These runs are part of establishing the hood's performance under varying operation regimes. Parameters varied during these empirical test runs included total exhaust volume and individual supply fan volumes. Safe levels of containment were verified with tests per ASHRAE 110 standards. Significantly more work is required to establish this operational envelope under a variety of "real-world" conditions.

Characterize Screen Air-Flow

Background

A laminar supply-air flow is desirable. It was known that a mesh screen placed across an airflow (e.g. in a fume hood) will have an evening effect, distributing both the velocity and pressure across the screen. However, this effect had not been quantified

and the effect of differing mesh geometry was unknown. It was desired to understand the relationship between airflow velocity, the pressure behind the screen and the free hole area of the screen. We concluded that pressure is proportional to the velocity for a given free hole area, and inversely proportional to free hole area for a given velocity. Screens with less free hole area also maintain laminar flow on exit for a greater distance. Testing addressed two issues: (1) the relationship between air flow velocity and pressure, and (2) the distance laminar flow exists after leaving the plenum.

The tests were performed on a test apparatus constructed from acrylic tubing. This transparent construction allowed easy observation of flow patterns within the device. It consisted of an orifice-plate for flow measurement, an axial flow fan, several sections of honeycomb for flow straightening, and the screen holder (Figure 4). Measurements were taken from two pressure taps situated at either end inside the orifice plate and screen holder.

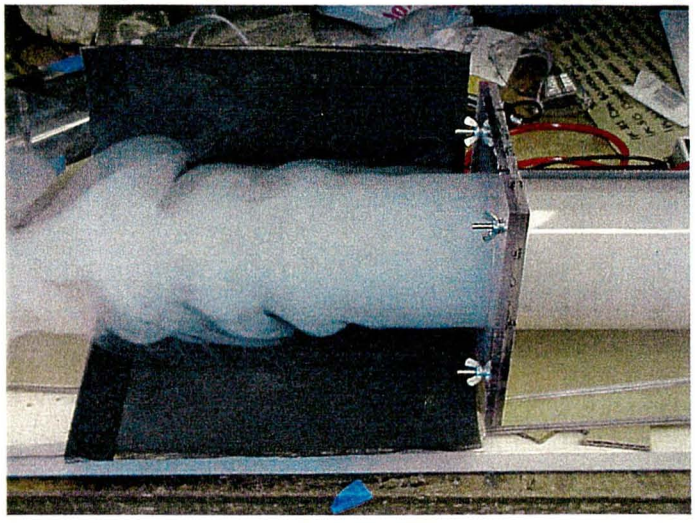


Figure 4. Screen test rig.

Before it could be used for experiments, the test apparatus was calibrated to obtain a relationship between the orifice pressure and the flow velocity since a pressure meter is more convenient than an anemometer. The pressure meter can provide time averaged results, whereas the anemometer gives instantaneous (and often wildly fluctuating) results. To calibrate the apparatus, a series of velocity/pressure readings were taken and graphed, obtaining a fitted curve and equation.

The curves and equations were obtained by regression analysis, fitting the points to a power law relation ($y=ax^b$). They generally fit the test results quite well. Some insignificant deviation is evident on certain screen runs. Qualitatively it is possible to conclude that increasing the free hole area of a screen decreases the back pressure. This is consistent for all screens tested.

First Set of Tests

Once the testing was calibrated, it was possible to run the actual tests on the screens. Each screen in turn was placed between the two front plates and measurements were taken at the orifice plate and just behind the screen for the fan's entire velocity range. In addition to taking the numerical measurements, smoke was blown through the system and its exit behavior observed.

Second Set of Tests

The second set of tests involved measuring the laminar distance of the flow upon exit—a difficult process since room air currents could easily disturb the flow and cause inexact results. Although the flow results were too erratic to attempt to draw any mathematical relation, clearly, a smaller free hole area causes the flow to remain laminar for a greater distance. It is unknown how this length will scale for different exit geometries, and since the length is quite small (less than 3"), it is unlikely this property will have relevance on a larger scale.

Photos of the laminar flow after existing a screen illustrate a series of vortices developing at the edges of the flow (Figure 4). Although the vortices were unclear in the two-dimensional images, they appear to mimic a Karman Vortex Street[7] in three dimensions. These vortices seem to be the mechanism by which the flow disperses and spreads out.

A numerical relation was obtained for screen pressure, velocity, and free hole area that confirmed the expected results. The relation between free hole area and laminar distance was a new discovery and raises many questions about the geometric exit effects. Additionally, comparing the test results with and without the screen clearly demonstrates that a screen causes the flow to remain collimated for a much greater distance before it disperses.

Since each fume hood application has unique needs for a screen, this experiment provides a method of determining required fan capacity when using screens (Roberts 1999).

Design Supply Air Plenums

Overview

Ideally, air flowing out of all supply plenums should be of equal velocity over its entire surface. Further, this air flow should remain laminar for the greatest distance possible into the hood to help move air and fumes towards the hood's outlet. In designing the plenums the researchers sought to achieve uniform air velocity across the entire plenum surface. Further, they sought to have laminar air flow for the greatest distance possible into the hood to help move air and fumes towards the hood's outlet. To improve viewing of the air flow in the bench-test unit the team constructed the plenums from clear plastic (Figure 5). For construction simplicity the plenums have a rectangular cross-sectional area. Time constraints prevented the team from investigating the impact of round, pipe-style plenums and vertical plenums near the sash tracks.

[7] This is the term a fluid dynamics boundary theory. The phenomenon is observed when flow is initiated around a cylinder. The process is initiated when "vorticies break away alternately from the cylinder an move downstream..." "The arrangement of these vorticies in the wake is called a Karman vortex street" (Shames 1962).

Fabricate Supply Air Plenum

The prototype hood superstructure was closely examined for "available real estate" that could contain the supply plenums. There are three supply air plenums are used in the Berkeley Hood: Front, Top, and Bottom (or lower).

- The Front Plenum, above the operator in front of the sash, was the simplest to design and construct because space was readily available.

- The Top Plenum, inside the sash above the operator at the top, presented design challenges. The Labconco superstructure incorporates a cross brace located were the top plenum needs to be installed. Therefore, it was necessary to relocate this cross brace prior to installing the top plenum.

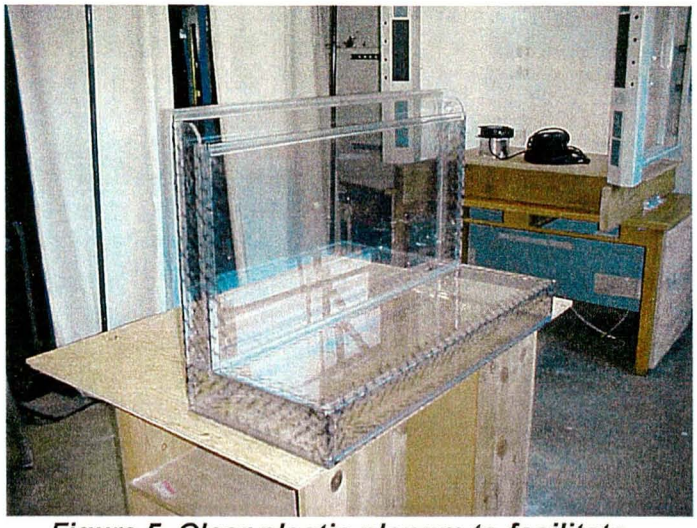


Figure 5. Clear plastic plenum to facilitate visual tests

- The Bottom (or Lower) Plenum, at the work-surface leading edge, across the bottom of the hood, continues to require design refinements. In this part of a hood, many design elements are competing for space. Hoods are typically mounted on cabinets. The presence and access to these cabinets limits the size of a lower supply plenum greatly. In addition, fan size, type, and location are also major design considerations. In order to eliminate the recirculation area, which prevents proper floor sweeping in the hood, we redesigned the lower supply air outlet using wire mesh to achieve multi-directional distribution of the supply (i.e. through a ninety-degree angle from vertical to horizontal at the level of the hood floor).

Select Supply Fans

Appropriate fans are available from standard catalog lists provided by equipment suppliers. Fan types used initially were axial flow units with a maximum volume of 240 CFM. These fans are inexpensive and consume very small amounts of electricity. The fans were oversized to account for a performance losses from a "critical orifice" being installed on each configuration to measure air flow. The critical orifice provides a convenient method to accurately determine the quantity of air being provided. All supply fans are variable speed controlled with a nearly infinite turn-down ratio. Centrifugal fans were also studied.

Fan Location

An axial supply fan's rotating blades tend to spin, or "swirl", air it is flowing. Swirling air causes erratic flow out of a plenum. Correctly locating a fan in a plenum correctly mitigates swirl caused by an axial fan. Numerous approaches were tried to eliminate swirl, and other flow problems, caused by this type of supply fan. A costly but effective approach uses aluminum honeycomb material as a "straightener" to defeat swirl. Alternatively, when a fan can be located a sufficient distance from the plenum's outlet, swirl can be eliminated by forcing a fan's airflow through one ninety-degree turn.

Airflow Profiles

We evaluated air flow distribution from each supply plenum's outlet surface. The airflow velocity profile emerging from the bottom plenum was particularly uneven. Certain areas of the outflow surface tended to have much higher velocities than others due to the close proximity of the supply fan. Most importantly, an area of reverse flow was noted in the outlet surface nearest the supply fan. In this case, air was actually flowing into the plenum instead of outwards. Regions of very high velocity behind the outlet surface, combined with other construction features, caused a "shadowing" effect. This effect caused an area of low pressure which resulted in air flowing back into the supply plenum.

Plenum Screens

Each supply air plenum concept developed incorporated various screen configurations to help equalize pressure distribution and thus, velocity distribution. Many different screen surface shapes were studied including various curves and combinations of curves and flat surfaces (Roberts 1999). Promising shapes were used in the plenums. A great amount was learned about "steering" airflow with screens. For instance, air can be distributed (turned) through an arc of nearly 180 degrees out of one outlet surface. Screen mesh and wire size, along with "free hole area" are important parameters in applying screens in supply plenums. To date, screens used in the Berkeley Hood have small pressure drops, in the range of 1 to 3 Pascal. Screen mesh, wire size, and free-hole area are important parameters to investigate. Much remains to be learned about the complex interactions between the screens and air flow patterns necessary to optimize the design.

Screens used to even out and turn air flow are easily damaged and dented. Therefore for impact protection, a grill was added to cover the bottom plenum screen. The grill design was a combined effort between LBNL and an industrial partner, U.S. Filter/Johnson Screens. These grills are a latticework of elliptical rods and heavy-gauge wire with a triangular cross section. Depending upon assembly, the triangular wire can have a flat side or an angle pointing into the hood. Airflow characteristics of the two grill-types were studied. More laminar and higher velocity air flow results from a grill with its "points out", i.e., into the hood's interior (rather than with a side of a triangle towards the hood's interior). We have been advised by U.S. Filter/Johnson Screens that the grill can be made out of plastic in addition to the "304-grade" stainless steel units used in our prototype development.

Interior Plenum Baffles

Air flow distribution was equalized across the plenum exit by using interior baffles, and other techniques. Various baffle arrangements helped even out air distribution but did not solve the problem completely. The velocity profile emerging from the bottom plenum was very uneven, tending to be very concentrated in the center. To alleviate this a baffle was placed across the entire width of the box to force the airflow horizontally from the fan, rather than flowing directly into the opening.

Additional Experiments

Other experiments were carried out using additional foils placed at the front and top of the baffle to try to redirect the flow more horizontally. The velocity across a modified bottom plenum opening was measured to determine the exact profile and regions of reverse flow. The resulting velocities were very erratic. Further research is required (Chan 1999).

Design Rear Baffle System

Study Rear Baffle Design

After studying CFD modeling results, a direction for improving the rear baffle design was not evident. As a new approach, time was spent with simple construction materials, primarily cardboard and tape, looking for the best baffle system to move air through and out of the hood.

After testing many configurations, a baffle system was constructed that virtually eliminated unwanted vortices. The baffle system reduced the upper vortex to a small, insignificant roll that did not leak out into the breathing zone. It also did not impede air flowing out the top of the hood. The bottom turbulence was virtually eliminated and "floor sweep" was satisfactory. The hood sidewalls were also swept well as air moved through the hood. This configuration included two new design features:

1. An angled baffle surface that connects inside the hood near the top of the opened sash and is sloped towards the exhaust outlet port (opposite conventional design strategy).

2. A rear baffle that is a continuous surface up to the top of the hood with a perforated section only in the lower portion that is no taller than the hood's sash opening.

Evaluate Exhaust Port and Outlet Design

After studying the new sloped interior surface and perforated lower baffle, the connection between the hood and its exhaust duct was noted to be an important geometric feature that needed refinement. We decided to discard the conventional round or small rectangular connection to the exhaust system. The new connection was elongated to be as wide as the hood's width, approximately 36 inches for a nominal four-foot wide hood, narrowed in depth to five inches. This created an exhaust port 36 inches by 5 inches. Additional airflow enhancement was achieved by

extending the sloped baffle surface, noted above, into the new elongated exhaust port, thus eliminating all turns and obstructions that would impede air exiting the hood.

In sum, the new baffle system and outlet port virtually eliminated vortexes inside the hood. Air flowing out of the upper cavity of the hood is quickly evacuated into the laboratory's exhaust ductwork. Observed patterns of air flowing out of the fume hood have improved significantly. Research continues on perforation size, density, and distribution in the baffle's lower portion.

Install, Modify, and Startup Prototype Hood

Prototype Hood Installation

Installing the Berkeley Hood superstructure required coordination beyond a normal hood installation. Several construction trades and interface with laboratory supply providers, metal shop, duct fabrication shop, and purchasing department was necessary. Highlights of the installation process included:

- Clear and arrange laboratory space
- Mount hood and seismically brace
- Determine exhaust duct routing for lowest cost
- Size exhaust fan and ductwork
- Select exhaust and supply fans
- Complete ductwork installation
- Upgrade electrical service
- Mount control rheostats for exhaust and supply fans
- Calibrate exhaust air flow through hood
- Mount helium tank for bubble generator
- Verify compressed air source
- Upgrade and install computer for data retrieval and storage
- Document all phases with digital photos

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Modify Prototype

Once installed, the hood required extensive modification because of the customized and experimental nature of the project. The Labconco fume hood superstructure was highly customized to allow observation of airflow within the hood and to accommodate installation of supply air systems and controls (Figure 6) that are fundamental to the low-flow technique. The necessary tasks included:

- Remove standard Labconco airfoils and upper cross bracing
- Reposition and re-install main internal cross bracing
- Install clear plastic side-wall for interior observations
- Design and build supply air plenums
- Mount supply air fans
- Calibrate supply air flows
- Monitor and analyze fan settings
- Establish stable operation by coordinating all fans speeds
- Verify containment visually
- Catalog vortexes inside hood
- Modify back baffle installation to allow experimental adjustments

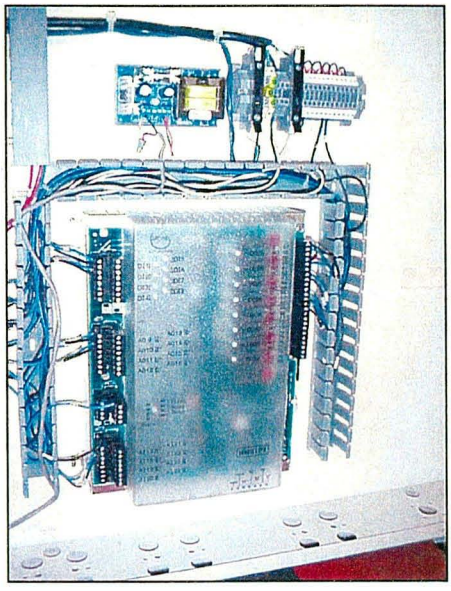

Figure 6. Berkeley Hood controls.

Prototype Hood Startup

The team took special care to calibrate air flows and to install accurate measurement equipment. The first prototype hood, incorporating a Labconco superstructure, became operational on 25 June 1999 and testing began shortly thereafter.

A second prototype hood, using a Fisher-Hamilton (F-H) superstructure, became operational in January 2000. This unit was a four-foot-wide hood that became the basis for producing a field test unit for Montana State University (MSU) by F-H. In May 2000, F-H provided a six-foot-wide superstructure for modification by the LBNL team. Within two months, the technique was scaled up to accommodate the wider hood and the six-foot unit became operational in July 2000.

Perform Hood Tests

Study Safety and Containment Requirements

There is a certain level of confusion among industry professionals in applying fume hood safety standards, containment methods, and recommendations by "the authority having jurisdiction." Regulating authorities that have the "force of law" rarely agree on testing standards and regulating practices for fume hoods. Even experts can not always resolve conflicting recommendations and information provided by testing companies.

According to Uniform Building Code and Uniform Mechanical Code regulatory guidelines, laboratory fume hoods are primary environmental safety devices. Consequently, testing is necessary to ensure that fume hoods provide containment, which in turn means that workers are protected. The ASHRAE Guideline ANSI/ASHRAE 110- 1995, *Method of Testing Performance of Laboratory Fume Hoods* is the foremost protocol used to perform laboratory fume tests. Additionally, to ensure safety, it is necessary to test each fume hood's efficacy on a continuing basis.

Perform ASHRAE 110 Tests

Test Preparations

Since the ASHRAE 110 Guideline is the most widely accepted method of testing fume hoods, a significant effort was made to prepare for conducting multiple ASHRAE-110 tests at LBNL. Initial steps included:

- Discussing with outside consultants to learn more about prior testing procedures on the original Berkeley Hood prototype.
- Contacting various companies concerning sulfur hexafluoride (SF_6) detectors, in an attempt to determine our best option for obtaining a detector.
- Collaborating with other LBNL staff members to complete the testing process.
- Pressure-testing the hood, ductwork, and plenums. Sealed all leaks possible with weather stripping and/or caulk.
- Preparing apparatus for testing—mounting brackets, mannequin height adjustments, velocity meter calibration, laboratory instrument placement representing real-world obstacles to airflow and containment.
- Participating in actual test runs and reducing data to leakage metrics.

110 Test Basics

The ASHRAE-110 Method of Performance for Laboratory Fume Hoods is an elaborate, three-part test that involves face velocity testing, flow visualization, and a tracer gas test. These three main tests are outlined below:

Upgrade Lighting

LBNL's Lighting Systems Research Group developed an improved lighting system for the Berkeley Hood (Figure 8). They performed a thorough evaluation of a standard hood's lighting system to provide a design baseline. Next, the Berkeley Hood's interior geometry modifications were studied and incorporated into an upgraded lighting system. Standard lighting system of two T-12 lamps and magnetic ballasts was discarded. The new lighting system uses a single T-5 lamp, an electronic ballast, and specially made asymmetric parabolic reflector. Lighting quality and efficacy is improved while energy use is reduced from 66 watts to 36 watts, i.e. 47 percent. Additional benefits include increased reliability and safety, reduced maintenance thanks to longer lamp life, and more uniform illumination (Figure 9) across the work area (Mitchell et al. 1999).

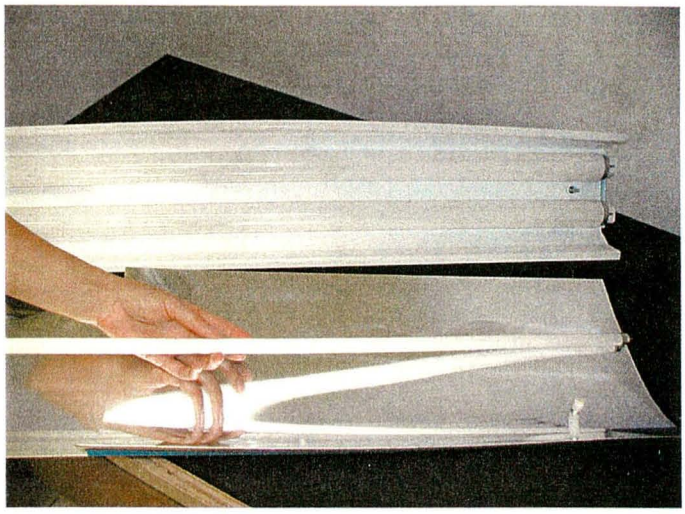

Figure 8. Standard hood lamp and fixture (top) and energy-efficient lamp with reflector (below).

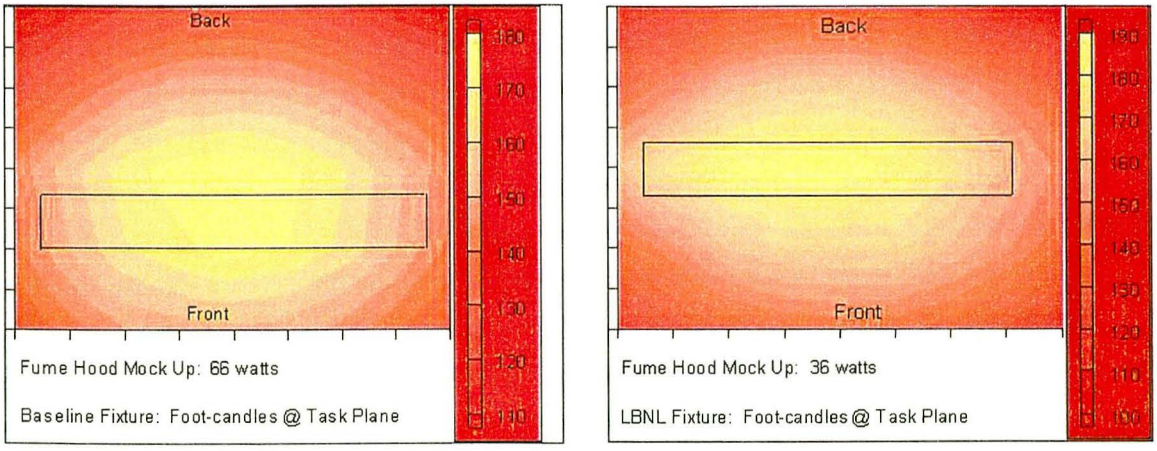

Figure 9. Iso-lux plots at work plane: standard fume hood lighting and Berkeley Hood. The resulting pattern of illumination is more uniform (less of a range in light levels, measured in footcandles) and more well-centered over the work area.

Perform Hood Tests

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110 Test Basics

The ASHRAE-110 Method of Performance for Laboratory Fume Hoods is an elaborate, three-part test that involves face velocity testing, flow visualization, and a tracer gas test. These three main tests are outlined below:

- Face Velocity is a measure of the average velocity at which air is drawn through the face to the hood exhaust. It has been the cause of debates among standards committees. Regulating bodies do not agree on a specific number. For the most part, the accepted face velocity measure falls within 80 – 100 fpm. Some laboratories have accepted face velocities as low as 60 or 50 fpm (Ruys 1990). Despite their relatively low value in judging containment, face velocity tests are performed most often thanks to their low cost.

- Flow visualization tests can be performed with various smoke-generating substances (Figures 10 and 11). Theatrical smoke, superheated glycol, smoke "sticks", titanium tetrachloride, and dry ice, solid-phase CO_2, are examples of smoke sources. A qualitative understanding of containment is gained from conducting smoke tests. A rating system has been devised for "poor to good" patterns of smoke (Smith 2001). However, these tests are only used as indicators of containment. When satisfactory results are observed, they should be followed by tracer gas testing.

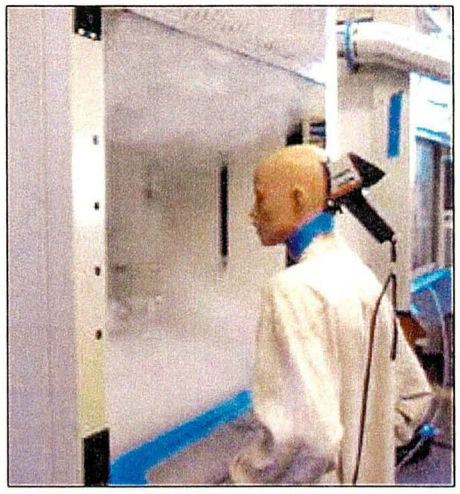

Figure 10. Berkeley Hood, showing patented air-divider supply effect.

- Tracer gas testing is the most reliable method for determining a fume hood's containment performance. The gas most typically used is sulfur hexafluoride, or SF_6.[8] This gas flows into a fume hood being tested through a specially constructed "ejector" (Figure 12). The ASHRAE 110 guideline includes engineering drawings to fabricate this ejector. SF_6 flow rate is set at four liters per minute. The ejector is placed in different positions (center, left, and right) in the hood. A mannequin is placed in front of the hood being tested to simulate an operator. An inlet port to a detector device is placed at the "breathing

Figure 11. Berkeley Hood, showing full containment.

[8] Gases are more likely to spill from a hood than are particulates. Thus, by inference, hoods passing this test will also adequately eliminate particles from the hood chamber.

(the nose) of the mannequin. Tracer gas is allowed to flow for five minutes and spillage levels are recorded by the detector. Ratings can be provided for a hood at three levels of installation:

- *"As manufactured"*—initial test of performance in a highly controlled/idealized setting commonly at the manufacturer's facility.
- *"As installed"*—testing is completed in the actual, fully operating facility, potentially more difficult conditions than the manufacturers' facility.
- *"As used"*—testing is performed by adding a hood operator's experimental equipment, a.k.a., "clutter", to the "as installed" hood, making the test conditions even more difficult.

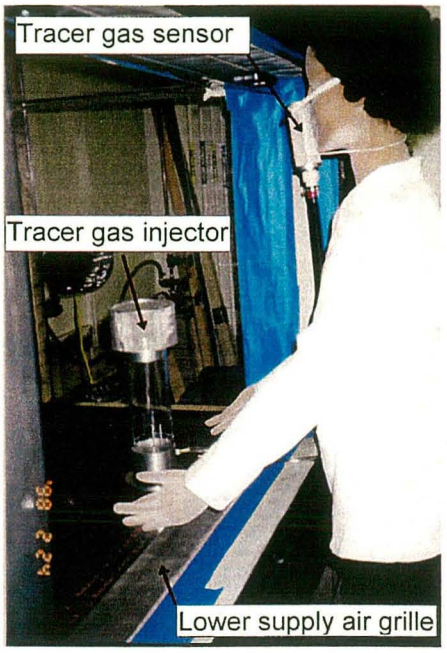

Figure 12. Setup for tracer gas test, with injector and mannequin in "right" position.

110 Test Limitations

The ASHRAE 110 procedure is a performance test method and does not constitute a performance specification. It is analogous to a method of chemical analysis, which prescribes how to analyze for a chemical constituent but, not how much of the substance should be present. Another analogy would be a method for measuring airflow; it prescribes how the flow should be measured, not how much volume it should be.

ASHRAE 110 is a series of static tests; it only approximates the actual dynamic conditions of humans using a hood. For instance, the mannequin remains static throughout the entire testing procedure. At present, the mannequin's height is at one level. It has been demonstrated that as the mannequin's height is lowered, passing the 110 test may become more difficult. This is because a leak in the hood's lower level may not to drift to the breathing zone (which is set at 26 inches [66 cm]above the work surface) of a 5'7" [170 cm] mannequin.

Industry Issues

Once identified, limitations of the ASHRAE 110 method were discussed within LBNL. Communications with industry experts did not provide definitive resolutions. Though similar concerns are shared, no consensus has yet developed. However, developments in safety and containment evaluations and protocols are continuing.

Conducting a full ASHRAE 110 procedure is both time-consuming and expensive. Facility operators typically perform the 110 test only one time (if at all), at start-up, and conduct an annual face-velocity test thereafter. Testing requires complicated equipment such as purpose-built tracer gas ejectors, electron capture instrumentation, and mannequins (we found these to be surprisingly expensive). Highly trained technicians are required to operate the test apparatus and to evaluate a hood's performance.

LBNL is actively participating in the ASHRAE 110 committee to improve this test standard.

Summary of ASHRAE 110 Test Results

After conducting the extensive research and prototype development described above, the project team demonstrated that the Berkeley Hood achieved containment levels equivalent to the majority of fume hoods "as manufactured," at exhaust flow reductions of 50–70 percent. Although no codes or standards provide performance criteria that categorically state a hood is "safe," the Berkeley Hood meets the ASHRAE Standard 110 Test with a containment rating of no greater than 4-AI-0.1 (4 liters/minute of SF_6, As-Installed, 0.1 ppm), suggested by ANSI/AIHA Z9.5-1992, *American National Standard for Laboratory Ventilation*. The hood achieved a leakage rate of only 0.01–0.02 ppm, far below the 0.1 ppm recommended maximum level noted by the American Council of Governmental Industrial Hygienists (ACGIH).

Market Development

Patent Activities

Securing rights to intellectual property (IP) developed from technological improvements realized during research is very important. Interfacing with the U.S. Patents and Trademarks Office (PTO) was accomplished with help from an outside law firm.

Review Patents

LBNL staff and summer students performed a literature search for patent application features. Some work in this area was performed by our industrial partner but a more extensive effort was required. To the best of our knowledge, all patents relative to laboratory chemical/biological fume hoods were identified (Vogel 1999).

Complete Patent Application

The project team worked closely with LBNL's patent attorney and the U.S. Patents and Trademarks Office (PTO). A patent application is comprised of two main parts: the specifications and the claims of the invention. Typically, after a patent application has been filed, the PTO will respond with an "office action". In the first office action, most of LBNL's original patent application was rejected in both the specification and

claims sections. While not unexpected, it was necessary to extensively re-evaluate the claims made in the original application.

The basis for rejection was on prior illustrations in previous patents. Each of the patents cited had relative similarities to the Berkeley Hood; however, in each case, there were important differences that distinguished our high-performance, air divider fume hood approach from other design concepts. The Berkeley Hood has a unique design that uses already-conditioned laboratory air. The hood's auxiliary fans direct the laboratory air through fan vents and over the work surface in a unique push-pull ventilation system.

Ensure Patents for Future Research

Protection of Intellectual Property (IP) is important to future licensing agreements and to maintain industry interest in the low-flow technique. An understanding of a correct procedure to include any new achievements was researched and implemented.

Significant performance enhancements and containment improvements were achieved during calendar year 1999. It was resolved that these achievements warranted filing additional clarifications and claims as a "continuation-in-part" to the original patent prior to the PTO issuing an "original" or "base" patent describing the technology.

Patent Timeline

The following summarizes patent-related activities.

- April 1998—Submitted base patent application
- July 1999—U.S. Patent Office (PTO) issued its first "office action," rejecting LBNL's specification and set of claims.
- August 4, 1999— meeting with consulting patent attorney to discussed how to restructure the specification and claims for a second Office Action review.
- October 1999—LBNL resubmitted to the PTO. A revised, narrowed specification and a clarified set of claims was written and resubmitted. Particular revision information clearly states that LBNL's technique uses laboratory air that has already been conditioned and directs this air through supply fan vents over the hood's interior work surface in a unique push-pull ventilation system. Further, it accomplishes this with "low turbulence intensity." The technique also allows a significant decrease in energy use to achieve containment while maintaining, if not improving, operator safety.
- February 10, 2000—PTO "allows" the patent by accepting the revised application.
- May 1999 to Feb 2000—Throughout this time period significant improvements were made to the original hood configuration. It was resolved that these achievements warranted filing additional clarifications and claims

as a "continuation-in-part" (CIP) to the original patent. This CIP needed to be filed prior to the PTO issuing an "original" or "base" patent describing the technology.

- May 2000—LBNL files "continuation in part," establishing patent rights to two hood design improvements identified since the initial patent application; design improvements include: (1) supply plenum size, position, and shape, and (2) interior baffle arrangements, perforations, and slot exhaust port.

- July 19, 2000—PTO issues patent #6,089,970 to LBNL for "Energy efficient laboratory fume hood."

- March 13, 2001—The "Continuation in Part" to the patent issued in July 2000 was rejected by the PTO in an Office Action. A response by LBNL's patent attorney was filed in May 01 stating our reasoning to allow the claims.

Transforming Regulatory Barriers

Background

As explained above, the ASHRAE 110 guideline is a performance test method and does not constitute a safety rating. Therefore, organizations that issue standards and recommendations may supplement ASHRAE 110 by providing "target values" for tests results. These values are intended to indicate a hood's relative performance between safe and unsafe.

Two evaluation procedures in ASHRAE 110 are quantifiable and can be assigned target values to indicate a "safely" operating fume hood. They are the face velocity test, in feet per minute (FPM), and the tracer gas containment test, in parts per million (PPM) leak of SF_6 tracer gas when ejected at a particular rate inside the hood. Acceptable values for these tests are provided by various standards organizations.

Identify Implementation Barriers

Uniform building, mechanical, and electrical codes; state and federal OSHA regulations; and Fire and Safety regulations (specifically NFPA) were studied with respect to laboratory "fume" hood installations. When adopted by local jurisdictions, these codes and regulations "carry the force of law." Many regulations make reference to certain industry standards and guidelines. Potential barriers to using the Berkeley Hood were noted in these existing protocols and "standard" design guidelines (especially ASHRAE and ACGIH) (Vogel 1999; Fox 2000).

Nearly all fume hood designs are tested by their manufacturers per the ASHRAE 110 Guideline. However, it is a very comprehensive test that can be time-consuming and expensive. To minimize testing cost and complexity, a facility typically performs only part of the ASHRAE 110 hood protocol, specifically face velocity tests. These face velocity tests are normally the sole basis that a facility uses to indicate a hood's containment performance. Further entrenching face velocity as the only test for examining an installed hood is recurring (usually annual) testing. Most organizations

can only afford to administer an annual face velocity test, thinking this is an adequate test for determining hood containment. (In many cases, a hood that passes a face-velocity test fails this tracer-gas test.)

Since ASHRAE 110 does not specifically stipulate what face velocity (in FPM) is "safe", it is left up to "the authority having jurisdiction" to decide a face velocity that will provide operator safety. Most standards recommend an average face velocity "target value" of 100 FPM. Unlike standard fume hoods, the Berkeley Hood containment method decouples face velocity from safety performance. Consequently, recommendations of 100 FPM face velocity present the most significant implementation barrier to using the Berkeley Hood.

Transforming Testing Barriers

Developing methods to overcome institutionalized design practices will facilitate application of the Berkeley Hood. A series of recommendations to nullify real and perceived barriers to using the Berkeley Hood are being compiled based on the hood's advanced containment approach. Consequently, a new test protocol is being researched that verifies any hood's performance, without measuring face velocity.

Crafting a new, widely-accepted test protocol will be a difficult process. Most testing programs conducted by a facility's Environmental, Health, and Safety (EH&S) group, rely upon face velocity measurements to indicate a hood's ability to contain hazards. These tests are performed on a regular basis, and therefore, a new test must be simple to conduct and repeatable. An SF_6 tracer gas test provides far more direct and compelling evidence that containment is being achieved, however, its high cost has precluded wide adoption.

For instance, Cal-OSHA relies solely on an average face velocity of 100 FPM to indicate a "safely" operating hood. The current Berkeley Hood configuration has a equivalent face velocity of around 30 FPM. Upon hearing this, most dismiss the Berkeley Hood as being unsafe, yet it has passed flow visualization and tracer gas tests that are far superior for determining containment and safety.

Face Velocity Questioned

Reliance on face velocity testing as the sole method to assure a worker that their hood is containing fumes has been called into question in the past few years. A brief overview of the results of some studies follow:

- A recent study by Dale Hitchings (1996), an industry consultant, noted that 59% of the hoods passed face velocity criteria. However, only 13% of those same hoods met tracer gas standards set by industry.

- Another report shows that 30%–50% of hoods leaking excessive levels of contaminants still pass the traditional face velocity tests (Hitchings and Maupins 1997). These failure rates have been confirmed by other fume hood testing experts (Knutson 2001; Smith 2001).

- In another study, an investigator found that in a properly designed laboratory, fume hoods with face velocities as low as 50 fpm provided "...protection factors..." 2,200 times greater than hoods with face velocities of 150 fpm. (Caplan and Knutson 1977).

- Another set of tests indicated that with the exception of one particular type of hood operation, there was no difference in hood containment with face velocities between 59 and 138 fpm. (Ivany et al. 1989).

- At some laboratories, 60 or 50 fpm has been accepted (Saunders 1993).

Participate on Standards Committees

At present, surrogate measurements that do not directly measure a hood's ability to contain hazardous fumes, vapors, or substances hold sway in determining efficacy by most testing "standards" cited by standards committees. Participation on various standards committees can help garner acceptance of the Berkeley Hood's high-performance air divider technique. Fundamental arguments regarding safety and containment capabilities of laboratory-type hoods need to be presented to committee members.

ASHRAE Activities

The ASHRAE Guideline ANSI/ASHRAE 110- 1995, *Method of Testing Performance of Laboratory Fume Hoods* is revised on a ten-year cycle. The next revision is due to be published in the year 2005. ASHRAE announced the formation of the committee (June 2000) to revise the guideline, with LBNL staff among the members.

The LBNL project team has offered to work in four specific areas of interest that will be eventually addressed by the full committee including:

- Specialty hoods
- Ejector design and flow rate
- Effect of turbulence intensity
- ASHRAE vs. other standards

CAL/OSHA Activities

CAL/OSHA was petitioned by private industry to amend their stance on requiring all hoods (except for those working with 13 known carcinogens) to have 100 FPM face velocity. In response, CAL/OSHA convened an advisory committee to the Standards Board to review and recommend changes proposed to their standard 5154.1 *Ventilation Requirements for Laboratory-Type Hood Operations.* LBNL was invited to join this advisory committee.

LBNL staff are coordinating a subcommittee that is developing a "compliance specification" that is "performance based." The specification is an attempt to build a so-called "performance-based" standard while the existing standard can be

considered a "prescriptive-based" standard. The approach is predicated upon acceptance of an "either, or" compliance doctrine, i.e., of a prescriptive or a performance hood evaluation methodology, by the whole committee.

The proposed, "alternate" standard is intended to be used only if the "authority having jurisdiction" decides not to use the existing CAL/OSHA standard which only requires a face velocity test. The committee struggled with stipulating a "floor" face velocity. This struggle goes to the heart of the matter; Can CAL/OSHA establish a standard that helps workers be "safe" and not be prejudicial against some fume hood technologies?

Review Alternative Test Methods

LBNL's project team contacted several industrial hygienists, EH&S personnel, and other experts in the fields of fume hood testing and certification to help develop methods or recommendations for testing the Berkeley Hood. Many potential hood test procedures and methods were identified. The new hood tests were compared and evaluated. Empirical evaluations need to be conducted (Griffin 1999) *User Tracer Gas Test*—a variation of the ASHRAE 110-tracer gas test using a human subject instead of a mannequin. As in the original test procedure, all facets of the ASHRAE-110 tests are followed. This user tracer gas test was performed with a human subject standing in front of a hood making consistent, prescribed movements, such as extending both arms into the hood and pulling them back out in one motion every 30 seconds (Altemose et al. 1998).

- *Air Monitoring Test*—a very simple test, but may require several days to collect useful data. In this method a user wears an air-monitoring device in the breathing zone while working in the hood and the test staff evaluates contamination levels at various velocities.

- *In-Use Testing Procedure*—similar to the User Tracer Gas Test but using other vapors and detectors while hood operators conduct normal hood activities. SF_6 was used in the original study, but other vapors and detectors could be used. It was designed to assess fume hood performance during normal work activities. Escape of the "challenge" gas is measured in the operator's breathing zone by a direct reading instrument (Ivany and DiBerardinus 1989)

- *Dioctylphthalate (DOP) Test*—DOP is a part of the NSF 49 test for Biological Safety Cabinets (BSCs) used to stimulate particles of less than 3 microns in size. In BSCs, this test is performed to determine the integrity of supply and exhaust HEPA filters, filter housing, and filter mounting frames while the cabinet is operated at the nominal set point velocities. An aerosol in the form of generated particulates of dioctylphthalate (DOP) is required for leak-testing HEPA filters and their seals. A recent research study (Joao et al. 1997) suggests that a more quantitative approach, using the NSF 49 procedure, might lead to a better understanding of fume hood limitations. Exposure evaluation and potentials to not only the fume hood worker, but those sharing the laboratory as well. The test proceeds in the following manner: A DOP

aerosol generator operated at 20 psi is connected to a metal canister 7 inches in diameter. The canister's open top is covered with 1-inch-thick open-cell foam to allow a relatively even discharge of aerosol in the geometric center of the fume hood work zone, approximating an aerosol emitting from a large beaker in the hood where the outer edge of the vessel was 10 inches behind the sash. DOP is released at 150 L/min. An aerosol photometer is employed to detect aerosol escape from the face of the hood. At the fume hood's face opening, the photometer probe is passed from left to right across the plane of the face, one inch in front of the opening in 1-inch-wide rows from top to bottom and readings are recorded. At the face opening a concentration reference point is recorded 4 inches deep in the work zone in the center of the face opening.

- *NIOSH Method 1500*—a test using special air sampling pumps (e.g. SKC Model, Gillian, MSA Personnel Pump), a human subject, and NIOSH Method 1300 equipment. This is an expensive alternative to other methods noted here.

- *Photo Ionization Detector (PID) Test*—PIDs monitor the concentration of toxic gas. These units have many applications in industry, at utility companies, and by fire fighters. Additionally, environmental consultants use PIDs to detect small traces of toxic gas, monitor hazardous waste, inspect leaking underground storage tanks, and monitor personnel exposure.

- *CO_2 Test*—a simple test where a palm-sized CO_2 packet is placed inside the fume hood. As the CO_2 is emitted, an air monitoring device or wand is used to capture and record the amount of spillage. This test is ideal in terms of expense, time, and portability. This makes the test seem a very promising choice. However, the drawback to using CO_2 is the chance of producing erroneous values due to human CO_2 production and normal "background" fluctuations.

Implement Hood Field Test Program

Experiences and lessons learned from the LBNL's field test program described below have already led to refinements in the hood's design and improved understanding of its operational envelope. An important first step in the field test program was to establish working partnerships with companies that have experience and industrial resources to assist research efforts.

Establish Industrial Partnerships

Partnerships have been established with research organizations, commercial hood manufacturers, and control companies. Industrial partners have built "alpha" prototype Berkeley Hoods used in the field tests. The most current design information is transmitted to our partners on a regular basis.

Early Associations

A close association with Pacific Gas and Electric Company's Food Services Technology Center (FSTC) was formed early in the development process. This Center studies and evaluates commercial kitchen devices, including those that use exhaust hoods to remove waste heat and fumes. There is a great amount of similarity in the goals of a kitchen exhaust hood and a laboratory fume hood to remove unwanted air. A flow-visualization tool used at the FSTC, called a schlieren device (noted above in Task 1), was borrowed by LBNL for testing our Berkeley Hood. A set up of the complex schlieren tool was completed at LBNL. We performed extensive evaluations of the Berkeley Hood, produced videos of test runs, and archived videos of the schlieren work on CD-roms.

Labconco became our first industrial partner. In May 1999, Labconco shipped a standard fume hood superstructure to LBNL. It was modified to become our first operational prototype. Containment was achieved in June 1999. Research and modifications continued until December 1999 when the design was provisionally "frozen." An evaluation commenced to determine the hood's performance envelope and to establish its operational safety testing until June 2000.

Labconco provided industrial "muscle" to build the alpha generation of Berkeley Hood. This prototype was assembled in August 2000 and delivered to PG&E's Pacific Energy Center the first week of September. At the Center, the hood was made operational and displayed for the *Laboratories for the 21st Century* conference attendees.

Significant Support

Additional support from other industrial partners has provided significant insights and improvements to building a viable Berkeley Hood. These companies include: Siemens Controls, U.S. Filter/Johnson Screens, Technical Safety Services Company, ATMI, and Fisher-Hamilton. The field test sites themselves have made significant contributions. For example, UCSF contracted for and funded mechanical and electrical system upgrades to accommodate the field test hood. See Executive Summary for a complete list of our industrial partners.

Perform Field Tests

Field tests of an alpha-generation of the Berkeley Hood are ongoing. These trials have increased our understanding of operability of the Berkeley Hood under actual working conditions in functioning laboratories.

Trial Sites

Tests are in progress at two sites—the first, sponsored by NIST at Montana State University and the second, sponsored by PG&E at UC San Francisco. These first trial sites were picked partially because campus personnel are highly regarded and have professional Environmental, Health, and Safety (EH&S) and facilities staff to assist with implementing the test. A third alpha hood (provided by Labconco) is scheduled to be installed at our newest field test site at San Diego State University. Funding for this test is provided by San Diego Gas and Electric Company.

Field Test at Montana State University

In 1998, Montana State University (MSU) established plans to build an environmentally friendly "green" laboratory facility. The building was to incorporate state-of-the-art mechanical and electrical systems to provide occupants with a high-quality environment with low energy-use requirements. MSU staff researched cutting-edge technologies and discovered the Berkeley Hood. MSU funded LBNL's development and field test efforts. LBNL worked with their hood supplier, Fisher-Hamilton (F-H), to develop a field test unit for the site (Figure 13). LBNL researchers developed a prototype hood from a F-H superstructure, which was installed at LBNL's test lab in late 1999. LBNL then:

- completed extensive modifications of standard F-H fume hood for field test of in February 2000.
- modified the design further to accommodate new requests by F-H and passed the ASHRAE 110 test, performed by F-H personnel
- shipped field test unit to arrive at F-H by end of March 2000.
- attended additional testing at fume hood's facility by independent testing company in August 2000.
- installed newly fabricated unit at MSU in September 2000.

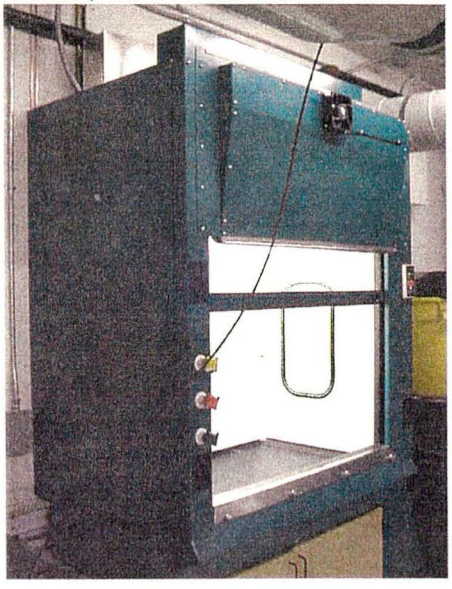

Figure 13. Fisher-Hamilton alpha prototype Berkeley Hood.

Table 2 summarizes Fisher-Hamilton's test results. They found that when tested per ASHRAE's Standard 110-1995 protocol, the prototype hood contained smoke and operated at significantly less than 0.10 ppm leakage; a maximum level recommended by the American Council of Governmental Industrial Hygienists (ACGIH).

Table 2. Fisher-Hamilton's test results at Montana State University.

Test	Stand. ASHRAE 110	Manne-quin Height (inches)	Sash Height (inches)	SF_6 Release Rate (liters per minute)	Tracer Gas Ejector Test Position & Resulting SF_6 Concentrations in The Hood			Worst-case Hood Rating (target <0.10 ppm)
					Left (ppm SF_6)	Center (ppm SF_6)	Right (ppm SF_6)	(ppm SF_6)
1	Yes	26	25	4	< 0.01	<0.01	<0.01	<0.01
2	No	18	25	4	<0.01	<0.01	<0.01	<0.01
3	No	18	31	4	0.05	0.04	0.01	0.05

Field Test at UC San Francisco

With support from PG&E, a field test Project was initiated in March 2000. The project staff identified a field site at UC San Francisco's Medical Radiology Center in a pathology laboratory building. We began evaluating the site and potential installation challenges. Fabrication and installation work began in late April and lasted until October 2000.

A kick-off meeting with UCSF personnel, our industrial partners, Labconco, Siemens Controls and UCSF's mechanical contractor, Marina Mechanical, was held at UCSF on 1 August 2000. On the same day, a baseline ASHRAE 110 test of an existing fume hood was performed in the Pathology Lab. The existing hood failed the ASHRAE 110 protocol according to CAL/OSHA Standard 5154.1 and recommendations per ANSI Z9.5 in its normal operating mode.

The Berkeley Hood became operational on 17 November 2000 (Figure 14). ASHRAE 110 testing by LBNL and Siemens Controls was performed on 5 December 2000. Flow deficiency was noted in lower plenum, although the hood passed all ASHRAE 110 requirements. Evaluations and modifications were completed prior to Christmas 2000.

Figure 14. Labconco alpha prototype Berkeley Hood at UC San Francisco.

The installation includes several novel features, including:

- A special Siemens control package that included alarms on the supply fans.
- An interface with the building exhaust fans to alert hood users if the fans failed.
- A purge feature with an override button that forces hood operation at full flow if the user encounters a spill or evidence that the hood is not containing the effluent.

Modified and auxiliary ASHRAE 110 tests were also conducted, simulating "as-used" operating conditions. The current version of the Berkeley Hood has performed quite well and, in some cases, exceeded expectations (Table 3). The hood contained the test smoke and tracer gas under all conditions down to 34% of full flow. The hood will be operated at 50 percent of normal flow to provide the operator with a margin of safety.

Table 3. Siemens Control test results for Labconco unit at UC San Francisco.

Test Type		*Air Flow % of "normal"[9]*	*Containment? yes/no*
Local ventilation	Smoke tube	50%	Yes
Tracer gas	ASHRAE 110	50%	Yes
Tracer gas	Sash movement	50%	Yes
Tracer gas	Safety margin check	40%	Yes
Tracer gas	Safety margin check	34%	Begin spilling

Field Test at San Diego State University

During the summer of FY 2001, three nationally recognized experts in the field of fume hood testing and commissioning visited LBNL. Extensive tests were performed on a prototype Berkeley hood provided by Labconco. Each expert prepared recommendations to improve the air-divider technique's performance. Appropriate modifications were then made to the field demonstration unit. Improvements included altering the amount of air flow inside of the hood "behind" the sash, increasing effectiveness of airflow "sweeping" the work surface inside the hood, and addressing "lazy and reverse flow" inside the hood under certain situations. Some of these improvements resulted from employing newly-styled ejector designs being developed by two of the consultants. The hood was subsequently delivered to San Diego State University to serve as the third field test unit.

[9] "Normal" being the equivalent of 100 fpm face velocity.

Develop Outreach Activities

Create Laboratory Hood Brochure

The project team developed a four-page informational brochure in the summer of 2000 that gives a clear overview of the Berkeley Hood (LBNL 2001) Using color photos and graphics, the brochure introduces readers to laboratory hood use, demonstrates the energy impacts of hoods in a laboratory environment, gives a brief technical overview of the high-performance, air-divider approach, and describes the hood's benefits. The brochure has been widely distributed in both paper and electronic formats. A lengthy review process ensured that the brochure suits a wide audience.

Deploy Project Web Site

In 2000, the project team developed a Web site (http://ateam.lbl.gov/fhood.html), which includes a range of content, including a project overview, brochure, video clips demonstrating prototype hood operation, and a market analysis. The project team frequently updates the site with new information. Links to other LBNL resources and other relevant energy information sites is included.

PG&E FSTC Demonstrations

In March 2000 LBNL demonstrated a neutrally-buoyant bubble generator at the annual conference sponsored by PG&E's Food Service Technology Center (FSTC) in San Ramon, California. The team also delivered a presentation on the Berkeley Hood at the Flow Visualization Conference sponsored by FSTC on June 30, 2000 at the Pacific Energy Center in San Francisco. The team continues to pursue ongoing collaboration efforts with the FSTC.

Prototype Presentations

Numerous presentations and demonstrations have been performed at LBNL of the Berkeley Hood for organizations including: Pacific Gas & Electric (PG&E), Southern California Gas Company (SOCALGAS), San Diego Gas and Electric Co. (SDG&E), Southern California Edison (SCE), The U.S Department of Energy, California Energy Commission, Northwest Energy Efficiency Alliance, San Diego State University, UC Santa Cruz, UC Santa Barbara, GPR Planners, San Francisco Chronicle, Siemens Controls, Phoenix Controls, Technology Performance Group, and many others.

EPA/DOE Labs21 Conferences

The project team presented an overview of the Berkeley Hood Project to the 1999 Labs 21 Conference attendees in Boston and at the following year's conference in San Francisco on September 7, 2000. The team demonstrated the hood at a reception held at during the 2000 conference. The demonstration, held at the Pacific Energy Cen ter, was well attended by at least 75 laboratory professionals.

Publicity

A number of organizations have recognized the Berkeley Hood's importance and potential impact and have publicized it or otherwise recognized it. These include:

- *UniSci* – Daily University Science News; 18 Jan 2000; news article.
- *Laboratory Network.com*; News and Analysis web site, 25 Jan. 2000; article.
- *The Alchemist*, trade organization's web site, 27 Jan. 2000; news article.
- *The Daily Californian*, Sci-Tech section, 14 February 2000; newspaper and web article.
- Daily University Science News, January 18, 2000
- *E-Source Tech News* Vol. 1 Issue 1, 18 February 2000; article.
- Advanced Manufacturing Technology Alert, 18 Feb. 2000; news article.
- *DOE This Month*, March 2000; article.
- ATMI's advertisement in *Cleanrooms*, Vol. 14, No. 3, a trade journal, March 2000.
- Patent Announcement in *Cleanrooms*, Vol. 14, No. 10, October 2000.
- *San Francisco Chronicle*, article on the front page of the Business Section, Sunday, 28 January 2001.

ONGOING AND FUTURE ACTIVITIES

Although the Berkeley Hood is well on its way to commercialization, numerous hurdles remain before facility owners or designers can easily integrate this technology into their projects. This section summarizes a number of essential activities, grouped according to their status within the project's overall research plan.

Ongoing activity is currently funded by several sources (e.g. DOE, CEC< PG&E, and SDSU/SDG&E), much of which is specifically targeted for field tests and demonstrations. Much of the ongoing technology development and some of the market development (e.g. working with ASHRAE AND CAL/OSHA) are multi-year activities and require ongoing funding. Therefore, work listed under "Ongoing or Funded Activity" should not be considered to be sufficiently funded to attain completion. Significant additional resources will be required to complete these tasks.

Technology Development

Safety Testing And Monitoring Techniques

Work currently in progress

- Develop in-house capability to perform ASHRAE tests with various, competing SF_6 detection devices.
- Work on ASHRAE and CAL/OSHA committees to improve test standards.

Ongoing or Funded Activity

- Continue tests to define operational envelope and user interface.
- Continue development of monitoring methods to ensure proper hood operation; include total flow sensor (flow device or static pressure sensor).
- Begin development of low-cost performance test(s) procedure(s) to validate hood performance (comparable to face velocity tests now performed on traditional hoods).
- Evaluate "as used" (AU) test modes with "clutter" in hood and operators present; consider disturbances caused by an experiment's setup, e.g., power cords into hood, and by particular experiments, e.g., pipette procedures; consider applying NIH test protocol.
- Begin non-standard testing including arm movements, walk-up, and walk-by.
- Study interface with laboratory control and monitoring systems.

Prototype Development, Including Larger Hoods

Work currently in progress

- Optimize supply surface geometry to "sweep" interior hood surfaces including obstruction by hands.
- Evaluate containment of liquid spills on fume hood work surface by lower supply plenum.

Ongoing or Funded Activity

- Begin development of larger hoods: six- and to sixteen-foot versions.
- Advanced study of back baffle design to more effectively gather and move fumes out of hood.
- Implement enhanced design features including vertical supply plenums.
- Optimize supply fans by; type, size, efficiency, quantity, noise, control, durability, placement.
- Refine main hood outlet exhaust connection to maximize fume extraction.
- Review space requirements of experimental set-ups that could be performed in a typical hood that a Berkeley Hood may constrain.
- Develop additional foils at the front and top of the baffle to redirect the flow more horizontally.
- Optimize lower baffle perforation size, density, and distribution.
- Analyze complex interactions between the screens and air flow patterns necessary to optimize the design.
- Study optional construction materials for alternates to stainless steel screens and grills.
- Integrate sensor-based controls that slow fan speed when hood sash is closed, is unused, or airflows outside hood are sufficiently non-turbulent.

Failure Modes

Work currently in progress

- Study failure modes for "lazy smoke" (slow-moving, randomly-moving) removal at work surface and along side walls.

Ongoing or Funded Activity

- Investigate residence time of smoke and helium bubbles to help understand points of tracer gas concentration and potential explosive hazard.
- Begin testing prototype under various failure conditions to define operational envelope, e.g., minimum and maximum flows, supply/exhaust flow ratio, flow imbalances.
- Investigate operating envelope by studying and comparing schlieren videos already produced.
- Evaluate impact of laboratory exhaust failure and possible control/response modes.
- Study hood operation in manifolded exhaust systems and with other types of hoods in same system.

Computational Fluid Dynamics (CFD) Modeling

Work currently in progress

- Develop a 3-D CFD model of the hood situated in a laboratory space.
- Create a CFD model that contains a "functioning" SF_6 ejector with an "operator" present; vary breathing-zone height.

Ongoing or Funded Activity

- Utilize CFD models to optimize hood features including: shape and location of supply air outlets, internal duct and plenum design (to minimize turbulence intensity and pressure drop), and back-baffle design.
- Study other laboratory-space influences on hood, e.g., temperature of conditioned supply air to lab.
- Evaluate intake air flow patterns induced by each plenum's supply fan and potential impacts on containment.
- Evaluate fan volumetric changes with CFD model including failures and spills.
- Study Lower Explosive Limits (LELs) inside hood using CFD.
- Interface with outside consultants that have already performed CFD fume hood studies.

Laboratory HVAC System Integration

Work currently in progress

NONE

Ongoing or Funded Activity

- Evaluate impacts and challenges of supply diffusers, doorways, pathways, other hoods, general exhaust.
- Examine room pressure control requirements.
- Assess supply and exhaust system effects introduced by sash movement and individual hood failures.
- Study and develop a "systems approach" to using and commissioning Berkeley Hoods in lab buildings; possibly combine with CFD modeling.
- Study interaction of laboratory HVAC operation on a Berkeley Hood, especially when connected to manifolded fume-hood-exhaust systems.
- Study effect of conventional hoods on operation of low-flow type in same lab.
- Perform side-by-side test challenges of a conventional hood and a Berkeley Hood to determine each type's relative containment ability.
- Evaluate EMCS interface and remote information needs.

Hood Lighting

Work currently in progress

NONE

Ongoing or Funded Activity

- Refine T-5 lighting system and demonstrate efficacy.
- Develop prototype arrangement and field test.
- Establish industrial partnerships and technology transfer.

Retrofit Kit

Work currently in progress

NONE

Ongoing or Funded Activity

- Explore developing a method to retrofit existing hoods with air divider technique.
- Investigate retrofit option (kit) to convert existing conventional fume hoods to energy-efficient Berkeley Hoods, perhaps for the most popular manufacturers and models.

Intellectual Property

Work currently in progress

- Respond, as necessary, to pending patent claims.

Ongoing or Funded Activity

- Identify new technology refinements that could lead to new patents and licensing opportunities.

Reporting

Work currently in progress

- Produce comprehensive technical report.

Ongoing or Funded Activity

- Produce annual progress reports.

Market Development

Impact Analyses and Business Case

Work currently in progress

NONE

Ongoing or Funded Activity

- Study existing laboratory building stock and existing fume hood installations to determine potential market penetration of the Berkeley Hood.
- Evaluate hood savings potential regionally and nationally.
- Develop models for performing life-cycle cost analyses.
- Create business case and marketing strategy for Berkeley Hood.

Industry Partnerships

Work currently in progress

- Issue Request for Proposal (RFP) for licensing low-flow hood technology
- Work with Labconco in fabricating 6-foot prototype.
- Work with Phoenix Controls in design and fabrication of monitoring and control systems for San Diego State University demonstration project.

Ongoing or Funded Activity

- Select industrial partners for licensing and negotiate licensing agreements.
- Notify potential licensee(s).
- Negotiate license agreement.
- Select licensee as industrial partner(s).
- Develop additional applications for the containment technology (e.g. for wet benches).
- Continue interface with PG&E Food Service Technology Center for containment techniques, and capture and flow visualization methods.

Design Practices

Work currently in progress

NONE

Ongoing or Funded Activity

- Define and analyze the optimum Berkeley Hood design.
- Determine "best practices" for Berkeley Hood installations and operation.

Field Test and Demonstrations

Work currently in progress

- Continue testing and refinements of hood design utilizing feedback from field tests.

Ongoing or Funded Activity

- Increase number of field tests.
- Seek location for additional field tests including commercial sites.
- Continue testing and refinements of hood design utilizing feedback from field tests.

Outreach Activities

Work currently in progress

- Continued technology transfer through website, trade media, presentations at conferences, and interactions with industry.

- Transfer technology through publications in professional and popular journals.

Ongoing or Funded Activity

- Develop relationships with EH&S and CIH professionals and organizations.
- Submit invention for awards, e.g., Discover magazine and R&D 100.

Codes and Standards

Work currently in progress

- Work on ASHRAE committee to develop new hood test standard, e.g., study ejector design under various flow rates.
- Participate on CAL/OSHA committee to develop new hood test evaluations for certification.

Ongoing or Funded Activity

- Identify other standards committees, such as EPA and NIH, to develop new hood test standards and certifications.

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