ASHRAE TECHNOLOGY AWARD CASE STUDIES

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Displacement Ventilation Key to Lab Renovation

The Materials Research Laboratory at the University of Illinois at Urbana-Champaign.

BY MICHAEL MCDERMOTT, MEMBER ASHRAE



The Materials Research Laboratory (MRL) fosters cuttingedge interdisciplinary research, including condensed matter physics, materials chemistry, and materials science. A phased \$15 million HVAC renovation replaced all major systems serving the fully occupied, 123,000 ft² (11,427 m²) building ($121/ft^2$, or $1.313/m^2$).

Five major and eight smaller air-handling units (AHUs) were replaced with two central, dualpath (outside and return air), lowvelocity AHUs. Sixty lab exhaust fans were replaced with three high-plume exhaust fans, operating with a dedicated outside air system (DOAS) with heat-pipe heat recovery. Air distribution was changed from high-velocity, dual-duct constant volume to low-velocity displacement ventilation, variable-air-volume systems. Passive chilled beams with convective, low-velocity air movement were used in labs with high sensible loads, and low-mass radiant cooling panels were used in electron microscope labs.

A cleanroom renovation created a 4,000 ft² (372 m²) ISO 7 lab for student development and manufacturing of silicon-waferintegrated circuit boards. An electron microscope lab renovation created a 500 ft² (47 m²) ISO 8 lab suite, which featured non-metallic ductwork/piping and ultralow-velocity displacement ventilation, coupled with high-mass radiant cooling panels for precise space temperature control.

Energy Efficiency

AHUs were selected to operate at low velocity across coils and filters

Michael McDermott, is a project manager at Grumman/ Butkus Associates, Evanston, III. (250 to 350 fpm or 1.27 to 1.78 m/s) to reduce pressure loss, greatly reducing fan power draw versus the traditional 500 fpm (2.54 m/s) face velocity.

Preheating/precooling of outside air is provided using a refrigerant-coil heat-recovery system that recovers energy from the lab exhaust with passive refrigerant coils. Heat recovery is located in the DOAS rather than the mixed airstream, to maximize heat transfer between the two airstreams and to eliminate pressure drop during economizer-mode operation.

Displacement ventilation was an important aspect of the HVAC system design to lower supply air rates in sensible load dominated labs while improving the IAQ for lab occupants. Fresh conditioned

Building at a Glance Materials Research Laboratory

Location: Urbana, III.

Owner: Univeristy of Illinois at Urbana-Champaign

Principal Use: Education facility, research laboratory

Gross Square Feet: 123,000

Substantial Completion/Occupancy: The building was fully occupied throughout. December 2018 was the official completion date.

Occupancy: 34 staff, 15 faculty, 52 researchers (graduate students, postdoctoral associates, and visitors)

supply air is supplied from strategically located low velocity overhead diffusers in the lab working lanes away from fume hoods and heat generating process equipment. Heat generated at process equipment creates thermal plumes or convection currents caused by buoyancy forces that cause local air to warm and rise above the heating source into the unoccupied zone. When sensible load is displaced to the upper zone of the space a reduced amount of supply air is then required to meet the occupied space load.

Load calculations were performed using "System Performance Evaluation and Design Guidelines for Displacement Ventilation," by Qingyan Chen and Leon Glicksman (ASHRAE Research Project 949, in cooperation with TC 5.3, Room Air Distribution, and TC 4.10, Indoor Environment Modeling). This resulted in a significant reduction in required supply air, from 206,085 to 140,290 cfm (97 261 to 66 210 L/s), using a 65°F (18.3°C) supply-air temperature at 50°F (10°C) dew point.

Instead of working as a stand-alone system, the displacement ventilation system was coupled with convective chilled beams and low-mass radiant panels in labs with high sensible loads to move cooling capacity from air to water. The lab supply air capacity was limited by the exhaust air duct riser infrastructure, which remained throughout the building. The new design reduced supply air to accommodate the lab makeup and air-changeper-hour safety requirements and added convective cooling (chilled beams) to meet the calculated space-cooling load. Lower supply capacity at the diffusers means lower pressure drop, smaller fans, and less energy consumption. Fan horsepower reductions can be attributed to a reduction in air movement.

The existing HVAC system was dual-duct constant-volume, which was inefficient compared with the lab's new, ASHRAE/IES Standard 90.1-2016 energy code-compliant VAV system. The occupied minimum air change rates per hour (ach) for labs were reduced from the original design range of 11 to 43 ach, down to 6 ach (consistent with current University of Illinois at Urbana-Champaign lab safety standards).

Savings were achieved with demand-based control



of exhaust fans. The system monitors contaminants within the exhaust plenum and compares the measurements with predetermined thresholds. If threshold levels are exceeded, the fan system is triggered, providing higher stack velocity. When sensors indicate "clean" conditions, stack velocity and fan-power consumption are reduced to a predetermined value that yields a lower dilution level, but is sufficient for the majority of chemicals used in the building.

The new DOAS and lab exhaust system fixed unwanted negative building pressurization that had previously been caused by insufficient makeup air. Previously, makeup air was being pulled into the facility through its window/wall envelope, truck dock doors, and fire doors. The new system was designed to actively control the makeup air entering the building and to use heat-pipe heat recovery to precool and preheat all incoming makeup air.

Pressure-independent control valves were installed at cooling coils to stabilize system flow, improve comfort, and reduce energy consumption.

Impact of mechanical improvements on the building was significant, with a total reduction in site energy use index (EUI) of 202 kBtu/ft²/yr (2294 MJ/m²/yr).

Indoor Air Quality (IAQ) and Thermal Comfort

Previously, the building systems recirculated lab general exhaust to AHUs serving other areas. Today's environmental, health, and safety (EHS) standards do not allow recirculation of exhaust air from labs with fume hoods. The new design directs all wet-lab lab exhaust to the lab exhaust system.

Displacement ventilation yields superior IAQ, achieved with exhausting contaminated air from the room, providing clean-to-dirty airflow.

Displacement ventilation with warmer dehumidified supply air (61°F at 48°F dew point [16.1°C at 8.9°C dew point]), coupled with convective chilled beams, minimizes air draft on scientists, which improves occupant thermal comfort and productivity.

Dual-path air-handling units decouple the ventilation makeup air (OA deck) from space thermal control (RA deck), allowing precise control of the building humidity at 50°F (10°C) dew point (70°F [21.1°C] and 50% RH), and outside air to meet makeup air requirements, as well as those laid out in ASHRAE Standards 62 and 55.

New high-plume dilution fans are strategically located away from outside air intakes and are used to extract and dilute lab, process, and fume-hood effluent air. Because of the nozzle design, the diluted effluent is displaced high into the atmosphere at a constantly high discharge velocity. As a result, highplume fans have greater exhaust dilution, higher discharge velocity, greater exhaust mass, and a greater plume height than conventional blowers and fans, improving building and campus IAQ. The stack height plus momentum of airflow are designed to be adequate to discharge air above the turbulent zone around the building, preventing recirculation of contaminated air into intake air openings.

Pressure-independent chilled-water control valves installed at cooling coils in the distribution system stabilize system flow and improve IAQ by more precisely controlling AHU discharge air temperature and building humidity.

Previously, many labs in the building were pressurized incorrectly, displaying positive pressure with respect to adjacent corridors. Air distribution systems that serve chemical laboratories should minimize transfer of odor and airborne contamination. The new design maintains appropriate relative air



New exhaust fans.

pressurization via volumetric airflow tracking, maintaining labs at a negative pressure for "dirty operations" (to keep what is in, in) and positive for "clean operations" (to keep what is out, out).

Existing lab supply air diffusers were located too close to fume hoods and delivered air at high velocities, creating turbulence. Supply air diffusers should be located and oriented so supply air is introduced to the lab without causing turbulence at or near the face of any fume hoods or other sensitive equipment. The new design provides displacement diffusers (sized at 40 fpm [0.2 m/s]) over work areas for dilution ventilation; diffusers were installed away from fume hoods.

Innovation

One of the primary challenges was replacing all AHUs in a penthouse mechanical room packed full of equipment while the building remained occupied. Thus, new AHUs were installed outside the existing penthouse. The lower roof, the location of the old cooling tower, was structurally reinforced to support the new DOAS, and the area was ultimately closed in to create a new, indoor mechanical space. The upperroof of the penthouse was structurally reinforced as required, and the new laboratory exhaust fans were installed there. Once the units were secured in place, the main exhaust and supply ductwork were run across the roofs, down to the DOAS, and into the building. The new main exhaust header was installed with capped terminators, where each fan would eventually be tied.





The AHUs were fully operational before successive, existing AHUs were demolished and switched over, minimizing shutdowns. The air distribution throughout the building was then renovated to meet the owner's phasing requirements, with local shutdowns done in three- to five-room groupings, while the remainder of the building remained fully operational.

Low-velocity supply air diffusers in labs were located such that airflow was introduced into the lab without creating turbulence around any fume hood or other equipment that is sensitive to air currents.

Demand-based control of exhaust fans used sensors to monitor contaminants within an exhaust plenum. Measurements were compared with predetermined thresholds, and higher stack velocity was triggered if the predetermined contaminant levels were exceeded.

Passive technologies of displacement ventilation, coupled with convective and radiant cooling, shifted cooling capacity from an all-air system to a waterbased system, when possible.

A new process water system (60°F [15.6°C] supply

water temperature) was used to serve convective chilled beams, while converting all lab processequipment cooling from domestic water (once through to drain) to a closed-loop process water system, with a plate and frame heat exchanger served by plant chilled water. By the end of construction period Year 3, this strategy resulted in a 44% reduction of annual building domestic water use vs. the baseline (from 38,013 kgal to 21,349 kgal [143,894,858 L to 80,814,756 L]). Newly available data from 2019 indicate even more dramatic results (usage of only 4,810 kgal [18,207,831 L], or an 87.35% reduction versus the baseline).

Operations and Maintenance (O&M)

The existing AHUs were in poor condition and well past their service life expectancy, and the mechanical room layout impeded the maintenance staff. The new design includes equipment consolidation, along with replacements. Fewer pieces of equipment, and new layouts and service corridors, will make future maintenance easier.

The existing lab hood exhaust fans were also in



poor condition and well beyond their service life expectancy. The prior fume exhaust air configuration allowed discharge into workers' breathing zones and at velocities below 1,000 fpm [5 m/s]. In the new design, fume hoods, chemical storage cabinets, and so on are served by one manifolded exhaust system with N + 1 redundancy, facilitating safe and efficient maintenance. Each exhaust fan was sized, configured, and controlled so full system design capacity can be maintained when any one fan fails or is taken out of service. Isolation dampers were provided to allow each fan to be taken out of service for maintenance, repair, or replacement, while the exhaust system remains in operation at full capacity.

Preheating/precooling of outside air via a refrigerant coil heat recovery system has low maintenance requirements; it is a passive system with minimal moving parts.

Cost-Effectiveness

The new, single-duct VAV design reuses existing dual-duct air distribution (converted to all cold deck

operation). The original supply air and associated ductwork was sized at 4,000 to 5,000 fpm (20 to 25 m/s). When the supply air was reduced and the hot and cold deck ductwork connected to be served by a single-duct VAV system, air velocities were reduced to 1,500 to 2,000 fpm (7.6 to 10.2 m/s). This created significant fan energy savings, while allowing costeffective reuse of most of the high-pressure supply ductwork.

The original supply air total of 206,000 cfm (97 221 L/s) was reduced to 150,000 cfm (70 792 L/s). This reduction was supported by detailed load analysis and made possible by consolidation of AHUs, reduced lab air change rates, and use of passive chilled beams and low-velocity displacement ventilation.

The consolidation of AHUs and lab exhaust fans reduced initial, operational, and maintenance costs.

Baseline water and energy expenditure was \$1,577,493, annually. Through the project, five major AHUs and eight smaller ones were replaced and consolidated with two central, dual-path (outside and return air), low-velocity AHUs. Sixty lab exhaust

TABLE 1 Energy savings, baseline vs. 2018 (fully occupied).

Year	Electricity		Chilled Water		Steam		Water		Sewer		Total Annual Utility
	\$	kWh	\$	MMBTu	\$	Klbs	\$	Kgal	\$	Kgal	(Or Savings)
Baseline Consumption	\$355,081	3,980,725	\$415,817	23,933	\$546,700	28,220	\$142,697	38,013	\$117,198	38,013	\$1,577,493
Actual Savings, 2018 (fully occupied)	\$27,094 (7.63%)	291,960 (7.33%)	\$148,459 (35.70%)	8,213 (34.32%)	\$276,226 (50.53%)	13,107 (46.45%)	\$68,181 (47.78%)	16,664 (43.84%)	\$54,400 (46.42%)	16,664 (43.42%)	\$574,350 (36.41%)

fans were replaced with three high-plume fans with dedicated outside air systems and heat-pipe heat recovery. As shown in Table 1, by 2018, the new systems were saving \$574,350 a year, a reduction in utility costs of 36.41%. (Even more recent data, from

TABLE 2 Energy savings (Btu), baseline vs. 2018 (fully occupied).

Year	Electricity (MMBtu)	Chilled Water (MMBtu)	Steam (MMBtu)	Total MMBtu (Or Savings)
Baseline Consumption	13,586	23,933	33,864	71,383
Actual Savings, 2018 (fully occupied)	996 (7.33%)	8,213 (34.32%)	15,728 (46.45%)	24,938 (34.94%) 1997

2019, indicated an annual savings of \$723,999, or 45.9%, versus the baseline.)

Environmental Impact

Environmental impact will result from energy and water savings. The actual annual savings (Table 1), as measured in 2018, was 291,960 kWh of electricity (7.3% reduction); 8213 MMBtu (8.7 billion kJ) of chilled water (34.32% reduction); 13,107 klb (16 570 887.9 MJ) of steam (46% reduction); and 16,664 kgal (63.8 kL) of water/sewer (43% reduction). A Btu savings calculation appears in Table 2.

Newly available data for 2019 indicated 3.91% of electricity savings versus the baseline; 29.16% chilled-water savings; 52.71% of steam savings; and 87.35% of water/sewer savings.

The lab building site energy use intensity (EUI, Table 3) was reduced from 580 kBtu/ft²/yr (6587 MJ/ m^{2}/yr) to 378 kBtu/ft²/yr (4293 MJ/m²/yr), which equated to a 35% reduction in site energy.

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TABLE 3 Energy savings (EUI), baseline vs. 2018 (fully occupied).

ol-	Year	EUI KBtu/ft ² /yr		
s	Baseline	580	SV G/ BA	
5,	2018 (Fully Occupied)	378	TABLE COURTE	

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