Tackling the Giants: Applying Smart Labs Principles to Constant Air Volume Lab Buildings

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ABSTRACT

Laboratories typically consume 3 to 10 times more energy than similarly sized commercial buildings, and as much as 50% of that energy is wasted by inefficient and poorly operating fume hoods and ventilation systems. One challenge faced by older laboratory buildings is the heating, ventilation, and air-conditioning systems serving many of these buildings. The older systems are usually constant air volume (CAV) systems that maintain constant ventilation rates that cause excess airflow and inefficient energy use. Variable air volume systems can be more efficient systems with sensors to detect the need for a change in volumetric flow rate; however; renovation of ventilation systems can create disruption to ongoing research and operations along with considerable up-front costs. When a Smart Labs program is implemented, an organization has a systems-based management approach that yields a high-performing laboratory building.

As decarbonization continues as a priority for sites, buildings with CAV systems are difficult to address. This work centers around practical guidance for improving lab buildings with CAV. In conjunction with industry input on top technology solutions and best practices, recommendations will include performing a laboratory ventilation risk assessment in conjunction with robust retro-commissioning work, which is a crucial step in the Smart Lab process. By applying Smart Labs principles, the aging laboratory building stock of 153,343 (Lawrence Berkeley National Laboratory [LBNL] 2017), comprising roughly 500,000 lab spaces in the United States, can be brought to safe and high-performance operations.

Introduction

Laboratories play crucial roles in research and innovation, supporting the successes of scientific activities across multiple sectors; however, laboratory buildings are complex, costly, and challenging to operate. It is well-established that laboratories typically consume significantly more energy that commercial buildings with a substantial portion being wasted by inefficient fume hoods and ventilation systems. A fume hood, along with other ventilation systems in the laboratory, can consume up to 3.5 times more energy than an average house (Mills and Sartor 2006).

To address this challenge of wasteful lab energy consumption and create more efficient laboratory buildings, many organizations are adopting best practices recommended in the Federal Energy Management Program’s Smart Labs initiative. The system-based management approach aims to improve health and safety, reduce energy consumptions, and lower operating costs. However, a significant obstacle faced by older laboratory buildings is their outdated heating, ventilation, and air-conditioning (HVAC) systems.

Constant air volume (CAV) systems deliver constant ventilation rates throughout the space, which results in excessive airflow and inefficient energy use. It is estimated that 70,500 laboratories nationwide still obtain CAV systems (U.S. Energy Information Administration [EIA] 2012). Variable air volume (VAV) systems can work to solve the issues related to excess energy consumption and interior air quality from CAV systems. VAV systems work by placing an actuatable damper inside the supply and exhaust duct systems. When sensors detect the need for a change in volumetric flow rates, a control signal will be sent to modulate the damper to adjust the airflow rate to meet the comfort and ventilation needs of the space. While implementation of VAV systems proves to be more efficient CAV systems, the conversion from CAV to VAV involves a significant construction cost and can be disruptive to laboratory operations.

Due to the high energy use of CAV systems, meeting decarbonization use in facilities can be difficult. Following phases in the Smart Labs process provides laboratory users and managers with a step-by-step approach to achieve energy efficiency goals. A laboratory ventilation risk assessment (LVRA) is a crucial step in the Smart Labs process for addressing current ventilation needs in your facilities. Developing minimum ventilation requirements for each lab space provides a baseline for ongoing retrofitting and commissioning. Some opportunities in CAV upgrades can include energy recovery mechanisms and conversions to VAV systems. Applying Smart Labs principles in laboratories aims to support new or ongoing projects in upgrading outdated building stock into safe, efficient, high-performance facilities, thereby benefiting ongoing innovative research and scientific advancements.

The High-Performance Laboratory HVAC System

The safety of occupants in the working environment is paramount, especially in high ventilation performance areas such as laboratories. Smart Lab principles, such as HVAC effectiveness and occupant safety, are implemented in high-performance labs. HVAC systems provide the right amount of conditioned air to the right place at the right time to meet occupant safety and thermal comfort requirements. The design incorporates several features. To start with, the conditioned 100% outdoor ventilation air from a dedicated outdoor air system entering the lab space comes through diffusers. Diffusers should be located away from exposure control devices (ECDs), and supply air should sweep across the lab without creating excessive air currents that could compromise containments by ECDs, such as fume hoods and snorkels (Figure 1). Laminar or radial flow type air diffusers that provide low-velocity air should be used in laboratories instead of a mixing type of air diffuser that is typically used in offices.

Airflow patterns play an important role in understanding and determining air velocities, air temperatures, thermal comfort of occupants, and indoor air qualities. Airflow patterns and flow path of contaminants can depend on several interrelated factors, including supply airflow rate and air changes per hour (ACH), which vary with each laboratory type. Adopting the practices to optimize the flow path of supply to exhaust air improves ventilation effectiveness, leading to safe, energy-efficient laboratories.

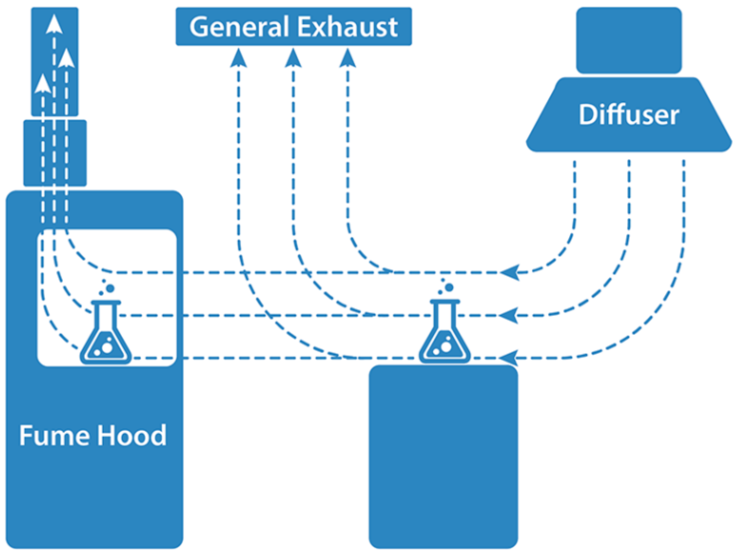

Figure 1. Air sweeping across the lab and exhausted out through general exhaust or fume hood (Van Geet, Reilly, and Fulton 2020)

Demand control ventilation uses real-time information provided by occupancy and/or air quality sensors to vary ventilation rates directly, meeting the space and occupant needs at a given time. This ventilation demand-based approach employs a VAV system control as opposed to a constant air-ventilation rate. Real-time measurements of actual indoor environmental quality vary air change rates from minimums as low as 2 or 4 ACH up to purge values of 8 to even 16 ACH. Demand control ventilation systems go beyond ensuring safe environmental conditions for occupants by improving energy efficiency, preventing excess ventilation when contaminants are not present. Like any techniques related to VAV systems, stakeholders must weigh the benefits and costs to determine whether the improved laboratory performance is worth the complexity and costs. A study conducted by University of California Irvine found that an installed demand-controlled ventilation system was estimated at $125,00 with included potential annual services costs. The team at University of California Irvine found that the total annualized savings was around $22,000 with a simple payback of 5.8 years, and the system provided substantive energy reduction of nearly 39% (Bell, Mathew, and Van Geet 2010).

ECDs, such as fume hoods, are crucial for containing hazardous chemicals in a laboratory environment. Fume hoods are defined as “a safety device specifically designed to carry undesirable effluence away from laboratory personnel and out of the building, when connected to a properly designed laboratory system,” according to the Scientific Equipment and Furniture Association (ASHRAE 2015). The relationship between these devices and ventilation systems determines temperature control, dilution, and chemical isolation. Other than fume hoods, other ECDs include:

- Biological safety cabinets
- Ventilated balance enclosures
- Slot hood
- Canopy hood and dedicated equipment exhaust
- Snorkels and spot exhausts.

The paramount objective in fume hoods is safety for the researcher; however, energy consumption should be considered a vital part of operations. Energy efficiency measures should be integrated into the operation and maintenance of these devices.

To maintain a safe lab environment, ventilation design typically trends toward high-flow exhaust systems, which then must be matched by the supply system. Low-pressure-drop design in a laboratory's ventilation system offers potential savings up to 65%, greatly lowering energy costs over the life of the HVAC system (Weale et al. 2020). Pressure drop should be addressed throughout the system, both on the supply and exhaust sides. Establishing a system pressure requirement, equipment selection, and proper layout of supply and exhaust ductwork can greatly reduce pressure drops and act as important components for ventilation systems. Best practices include limiting turns in the ductwork and making ducts as large as possible while still being cost-effective to install. Low-pressure-drop design should be addressed on both the supply and exhaust side.

Background of the Laboratory Building Stock

The frequency of CAV systems in commercial buildings, including laboratories, is significant due to their historical use and age of building stock in the United States. CAV systems have been used since the introduction of air-conditioning, while VAV control systems gained popularity in the 1960s (Aktacir, Büyükalaca, and Yılmaz 2006). Given that nearly half of all commercial building stock in the United States was constructed before 1980 (EIA 2012), it is reasonable to assume that most of these buildings operate under a CAV system if there is an HVAC system present. With an estimated 153,343 laboratory buildings in the United States (LBNL 2017), it can be inferred that approximately 50% are CAV laboratories.

Most of the energy consumed by building service systems is attributed to HVAC, domestic hot water, lighting, and appliances. Among these, HVAC systems alone represent nearly half of the overall energy consumption in commercial buildings, including laboratories (Cao, Dai, and Liu 2016). With a larger emphasis on energy efficiency best practices, the inefficiencies associated with CAV systems have come under scrutiny. This scrutiny prompts consideration for upgrades or retrofits to more efficient systems like VAV. From various investigations, energy savings from 12% to 22% can be achieved by transitioning systems away from CAV (Kalaiselvam et al. 2006). However, CAV systems are often a simple design as well as low first cost (Gao et al. 2018). Life cycle cost analyses have been performed to determine the initial and operating costs to evaluate economic feasibility of CAV and VAV systems. In most cases, it was found that net present worth of VAV systems is lower than that of CAV systems at the end of the lifetime. The payback periods of implementing a VAV system ranges from 4 to more than10 years (Aktacir et al. 2006). However, implementing VAV systems may disrupt current research and innovations.

Laboratory-specific environments where precise air-quality and temperature control are essential for research and operations tend to have high energy use. Initiatives such as the Smart Labs program can work to addresses energy efficiency issues in labs. As noted in the introduction, there are approximately 70,500 laboratory buildings operating with CAV systems. Rather than whole-system replacement, retrofitting of CAV systems for improved energy efficiency presents an effective and pragmatic approach to achieving efficient laboratories.

The Smart Labs Approach

The Smart Labs program is a systematic process to support laboratory owners and operators in managing high-performance laboratory buildings. The Smart Labs Toolkit summarizes each phase of the Smart Labs process while providing resources, videos, tools, and case studies to support Smart Labs program implementation. The toolkit was developed by several contributors and includes results of best practices and lessons learned from the Better Buildings Smart Labs Accelerator. The approach incorporates planning, assessment, optimization, and management phases to encourage cost-effective, safe, efficient, and sustainable laboratories. Each distinct phase includes specific tasks and resources proven to provide high-performance labs, increase engagement with key stakeholders, and enhance benefits for the organization. The four phases of the process are highlighted below:

1. **Plan**
   - To kickstart the Smart Labs program, it is essential to initiate a coordinated team effort involving facilities management and environmental, health, and safety staff.
   - Defined program goals based on benchmarked data and analysis of current spaces are essential for designing and operating an efficient and safe laboratory.
   - A charter or roadmap document will help pave the way for engagement and joint decision-making to outline the plan moving forward.
2. **Assess**
   - The targeted changes in the building must undergo assessment by key stakeholders in ventilation, energy, water, and resilience usage.
   - Conducting an LVRA is a foundational Smart Labs principle that helps gather ventilation system data and establish a consumption baseline for ventilation rates and airflow controls via control banding process.
   - Based on the conducted assessments, appropriate measures for improving performance are determined, and a scope of work is defined for the next phase.
3. **Optimize**
   - Execute the scope of work proposed in the Assess phase through appropriated funds or applicable financing mechanisms per the organization's mechanisms. Project funding can be available through external sources such as energy saving performance contracts and utility incentives.
   - Implementing improvement measures to optimize operations and establish new baselines promotes continuous enhancement and efficiency in building performance.
   - Commissioning or retro-commissioning supports reviewing the building's systems and ensuring that systems are working as designed and in application.
   - The adoption of a building management plan then documents how to direct future operations and manage laboratory systems.
4. **Manage**
   - The Smart Labs team should establish ongoing benchmarking and analytics to maintain high-performance laboratories.
   - Developing a Smart Labs management plan consists of several components to coordinate the management of systems throughout lab facilities.
   - Change management procedures should be updated frequently to ensure added, updated, or altered laboratory needs.

Organizations spend up to millions of dollars designing and constructing laboratories with specialized workspaces. Laboratory scientific discovery, guided by Smart Lab principles, often plays a crucial role in advancing institutions and can frequently serve as the primary driver of reputation, growth, and profitability. Some key components highlighted in the Smart Labs process are proper design and operation of building systems, including airflow controls, ventilation, and best practice implementations.

The Role of the LVRA in the Modern Lab

The LVRA is a method to systematically evaluate risks associated with lab operations, involving collaboration between facility and research staff, environmental, health, and safety professionals, and industrial hygienists. The demand for ventilation establishes the current airflow requirements that can be used to design systems or compare how the systems are currently operating. Quantifying demand for ventilation enables evaluation of the potential for flow reduction and energy conservation.

Labs should follow the ANSI/ASSP Z9.5-2022 standard, which "establishes minimum requirements and best practices for laboratory ventilation systems," such as the components of the LVRA. This standard includes conducting site walk-throughs to establish baseline metrics of an LVRA by gathering data on hazards, procedures, and ECDs, and categorizing risks using control bands. Data should be collected and recorded separately for ECDs and laboratory environment based on the following assessment categories such as type of hazards and procedures, generation characteristics of each hazard, quantity of materials used or generated, frequency and duration of hazard generation, and containment by ECDs.

The LVRA process utilizes risk control bands (RCBs) to facilitate categorization of risk for laboratory spaces, fume hoods, and other ECDs. RCB categories provide a range for assignation of risk from negligible risk of exposure to airborne hazards generated during laboratory scale procedures. Ventilated ECDs and spaces with higher RCB ratings require higher volumes of airflow, whereas devices and spaces assigned lower RCB ratings require less air to meet the functional requirements of the ECDs and lab occupants. The LVRA RCB score then corresponds to the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) *Classification of Laboratory Ventilation Design Levels* (ASHRAE 2018) to further understand ventilation design requirements.

The minimum amount of airflow in a lab is often defined in ACH. Typical specifications for ACH ranged from 4 to 12 for all labs on a campus, while various codes and standards will recommend different values. The Z9.5-2022 standard requires that each lab's ACH be established independently based on risk, potentially assessed from an LVRA, to account for wide diversity in airflow requirements among different labs.

Documenting, recording, and managing airflow specifications is a critical component of a laboratory ventilation management plan . Changes to airflows for laboratories or ventilated ECDs resulting from changes in demand (i.e., physical changes or changes to processes conducted in the labs or devices) must be reflected in the laboratory ventilation management plan documentation to share current conditions.

Working With the Aging CAV Laboratory Stock

Older lab CAV HVAC systems lack terminal airflow control devices, or valves. The ventilation rate in a laboratory CAV system must maintain the highest rate that could occur, such as when all the fume hood sashes are fully open or the highest equipment heat load is entering the laboratory space and needing to be removed by ventilation air. Because CAV systems must provide constant airflow for design conditions, they provide excess airflow at all other times and therefore excess energy usage. The supply air temperature in a CAV system must be set to cool the highest heat load space. All other spaces will need extra energy to reheat the air, such as using hot water or steam reheat coils within the space. The system can be multizone or dual duct. CAV buildings often incorporate pneumatic controls, which were once a prevalent component of commercial building control systems. Even today, approximately 20%–30% of commercial buildings still rely on these systems (Auvil 2024). However, despite their continued use, pneumatic controls suffer from limitations due to their reliance on compressed air, resulting in reduced controllability and slower response times, which contribute to system inefficiencies. Additionally, older air handlers often feature high coil velocities, necessitating the use of drift eliminators and sound attenuators. Over time, coils can become clogged with dirt buildup on both the air and water sides.

When assessing CAV laboratory buildings, an optimal strategy involves undertaking a comprehensive renovation aligning with principles from the Smart Labs process aimed at transitioning to VAV systems. As noted, the adoption of VAV systems, in general, holds the promise of achieving substantial energy savings, potentially up to 22% compared to conventional CAV systems (Kalaiselvam et al. 2006). Although an optimal strategy, it is important to recognize that the conversion process involves significant expenses. This includes installing laboratory-specific VAV valves in both supply and exhaust air systems, upgrading controls to match the new system, and making essential modifications to fume hoods. These factors collectively contribute to the potential need for an overhaul of the entire ventilation system. The complexity of the renovation is further exacerbated by the intricacies of existing infrastructure within the building. Moreover, the ongoing research operations introduce an additional challenging dynamic—disruption of regular staff activities, which makes the feasibility of the conversion process a consideration in specific cases.

Opportunities in CAV Buildings for Smart Labs Upgrades

When looking at opportunities for Smart Labs in CAV buildings, the opportunities are in maintenance, an LVRA, occupancy-based control, minimizing reheat by decoupling ventilation rate from thermal conditioning rate for thermally driving labs, optimizing ECDs' energy recovery, preparing for a conversion, and combining a risk assessment with commissioning, all of which benefit from scientist engagement.

General Maintenance

Maintaining CAV systems involves ensuring proper functioning of various components, including coils, reheat and preheat valves, and dampers. Regularly cleaning coils helps maintain airflow and heat transfer efficiency. Checking and repairing any bypasses in the reheat and preheat valves prevents unintended steam or hot water flow, while ensuring proper operation of face and bypass dampers on steam preheat coils helps regulate air temperature. Following these steps can help ensure efficient and smooth operation of your CAV HVAC system. It is important to consult the specific maintenance instructions provided by the system's manufacturer for a comprehensive overview.

LVRA To Lower Air Change Rates of the Entire Building

As previously discussed, the “assess” phase in the Smart Lab process encompasses principles to implement the LVRA approach, assessing risks based on the hazards present in the space. This approach remains applicable. In a building with CAV, the LVRA will determine the lowest safe ventilation rate for each laboratory space. Once the appropriate ventilation rate is determined, the entire supply and exhaust systems will need to be rebalanced to the new ventilation rate.

The LVRA may also determine that a lower ventilation rate is acceptable when laboratory spaces are unoccupied. If all the laboratory space served by the same supply and exhaust air systems can be turned down (as determined by the LVRA for each lab space), then the entire supply and exhaust air systems to those lab spaces can be turned down when unoccupied. For example, if all the lab spaces can be turned down from 6 ACH when occupied to 4 ACH when unoccupied, then the supply and exhaust systems could be turned down by one-third. A variable speed drive would be required on the supply and the exhaust fans to accomplish this turndown. Occupancy-based controls would be required to implement a turndown of ventilation rates.

If a lab space ventilation rate is driven by ECDs, then the size, type, and quantity of ECDs should be scrutinized. The most common ECD is a fume hood. If a smaller fume hood meets the research needs, then a smaller hood can be installed, reducing the required airflow rate. High-performance fume hoods can provide containment at lower ventilation flow rates than old fume hoods. The lowest face velocity that provides adequate containment can be determined by conducting an ASHRAE 110 test of the installed fume hood and the flow rate can be set based on the test. Limiting the sash opening using sash stops can limit the required flow rate. The quantity of ECDs should also be scrutinized; if an ECD is not needed, it should be hibernated (safely turned off) or removed.

Minimizing Reheat

Many lab designers overestimate the actual plug load and resulting heat load that occurs in laboratories. If the assumed heat load drives the ventilation rate it should be scrutinized by measuring the plug load of similar equipment and basing the heat load on actual measurements. If the heat load is still driving the ventilation rate in a space, then auxiliary cool such as fan coils, chilled beams or heat pumps should be considered for the high heat load laboratories instead of overventilation and the resulting reheat.

Energy Recovery

The capture of energy from exhaust air presents an opportunity through energy recovery, which is especially important in a CAV system because the amount of exhaust air is large and constant. While not applicable in all circumstances, energy recovery can be easier to retrofit and may have an attractive payback depending on energy costs.

For retrofitting existing systems, runaround loops (Figure 2) are a practical option and do not require adjoining supply and exhaust.

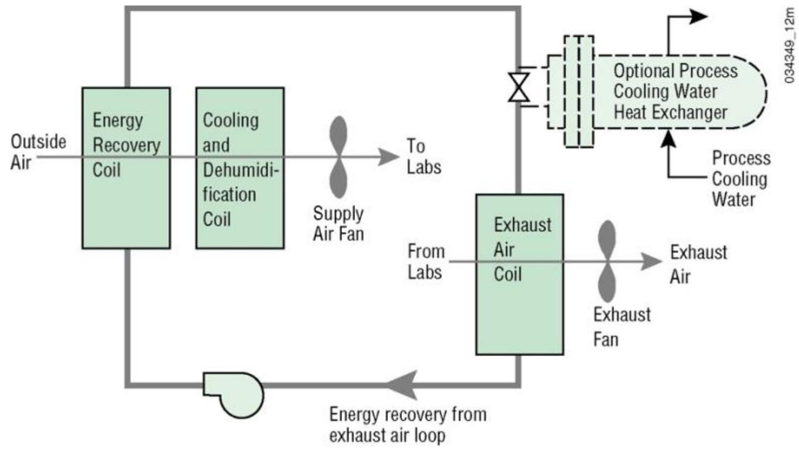

Figure 2. Runaround energy recovery loop with dehumidification (NREL 2012)

Prepare for Conversion to VAV

The ideal approach to CAV buildings is to add new VAV air values and reheat coils as areas are renovated. This phased approach limits the one-time expense but requires a phased shutdown of labs. When major lab renovations are taking place for maintenance or research reasons, this is the optimal opportunity for the retrofit and optimization of labs. Then, when the building is approaching mostly VAV air valves, the plan for a system renovation can take place to finalize VAV building controls.

Risk Assessment with Robust Monitoring-Based Commissioning Effort

Monitoring-based commissioning (MBCx) efforts maintain and continuously improve building performance over time through fault detection and diagnostics, energy information systems, and building automation system trend logs by identifying and implementing low-cost operational improvement measures (LBNL 2017). When the LVRA is completed in conjunction with MBCx, the overall airflow rate can be reduced in most labs, which in turn saves both fan and thermal energy. An additional benefit is that these tools often find other operational improvements.

Scientist Engagement

Collaboration among different lab stakeholders, such as occupants, researchers, managers, and environmental health and safety professionals, can indirectly contribute to reducing energy consumption and mitigating hazards in research facilities. Sharing decarbonization and efficiency goals to researchers in the laboratory can lead to behavioral changes to implement energy-saving practices, resulting in energy savings over time. While implementing modern and efficient technologies in laboratories can lead to reduction in energy consumption, effective energy conservation and energy-efficient solutions will likely draw on a better understanding of the social systems and human behaviors that shape energy consumption (Kaplowitz et al. 2012).

Engaging scientists and occupants in hazard identifications and mitigation efforts can lead to safer laboratory practices. Identifying proper storage and handling of chemicals and the risks associated with the hazards can reduce energy efficiency in the space while adhering to safety protocols. Establishing this information early in the Smart Labs process can assist in completing LVRAs and continuing to monitor and manage the hazards in the space. Occupant comfort and safety is of utmost importance while research is present. Discussing comfort levels with scientists can lead to adjustments in HVAC settings that optimize energy use while maintaining a comfortable environment. By fostering relationships in research facilities among multiple stakeholder groups, energy-saving and hazard-reduction efforts can create a sustainable and safe environment.

Case Study: NREL's Solar Energy Research Facility

The NREL Solar Energy Research Facility (SERF) began operation in 1993. The SERF (Figure 3) has 30,000 square feet of 100% outdoor air-ventilation laboratory space, housing research in advanced material synthesis and photovoltaics (NREL 2024). The HVAC system is a pneumatically controlled CAV with CAV venturi valves with a minimum air pressure drop of 0.6 inches of water column. Because of the addition of exposure control devices such as fume hoods and ventilated enclosures, the HVAC system is operating at 100% capacity because ventilation flow rate must be based on all ECDs being open at the same time. NREL would like to install additional ECDs but lacks the necessary funding, which limits research. The CAV system also wastes a significant amount of energy.

Figure 3. SERF lab at NREL in Golden, Colorado. *Source:* Werner Slocum/NREL 2020

The SERF laboratory spaces have undergone extensive modification in the past 30 years. NREL would like to convert the HVAC system at SERF from a CAV system to a VAV system to allow additional ventilated research equipment installation and save energy. In preparation for a full system conversion to VAV, NREL has been installing VAV valves on new or modified ventilated research equipment when lab modifications have occurred. The new VAV valves are set to CAV mode until funding can be obtained to change the entire system to VAV. Changing the VAV valves from CAV mode to VAV mode is a control programing change that would also require the installation of sensors such as sash position sensors on fume hoods. The supply and exhaust fan systems already have variable speed drives, so the entire HVAC system is "VAV ready," which will minimize disruption and cost for future conversion to a VAV system when funding is obtained for the full conversion.

Conclusion

As large energy consumers, labs have a corresponding opportunity to save energy and, in turn, improve safety and performance of operations. VAV systems represent a modern and efficient HVAC solution that can address ventilation challenges present in CAV systems commonly found in labs. While the opportunities are limited in CAV laboratory buildings, building owners must tackle these labs to align with and achieve the organization's energy management goals, including the implementation of a Smart Labs program.

Buildings with CAV systems may be difficult to retrofit for proper energy efficiency standards. However, by adhering to best practices, labs can improve ventilation rates based on LVRAs, minimize reheat, and optimize HVAC components like ECDs, diffusers, and low-pressure-drop designs. This commitment to Smart Labs principles ensures heightened effectiveness in ventilation and safety across laboratories settings.

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