LABORATORIES FOR THE 21ST CENTURY: BEST PRACTICE GUIDE

MINIMIZING REHEAT ENERGY USE IN LABORATORIES

Introduction

HVAC systems that are designed without properly accounting for equipment load variation across laboratory spaces in a facility can significantly increase simultaneous heating and cooling, particularly for systems that use zone reheat for temperature control. This best practice guide describes the problem of simultaneous heating and cooling resulting from load variations, and presents several technological and design process strategies to minimize it.

This guide is one in a series created by the Laboratories for the 21st century ("Labs21") program, a joint program of the U.S. Environmental Protection Agency and U.S. Department of Energy. Geared towards architects, engineers, and facilities managers, these guides provide information about technologies and practices to use in designing, constructing, and operating safe, sustainable, high-performance laboratories.

Load Variation in Laboratories

Load variation across different laboratory spaces exacerbates the problem of simultaneous heating and cooling, particularly for systems that use zone reheat for temperature control. A measurement study conducted in two laboratory buildings at the University of California, Davis (UC Davis), provides some insight into the extent of load variation across laboratory spaces in a typical university laboratory building. In each building, measurements were made for several laboratory spaces, representing the range of different uses within that building. Clamp-on meters were used to take continuous measurements of equipment electrical loads for each lab space. Each measurement period was typically about two weeks long. The measurements were taken when the labs were nominally fully occupied and used.

Figure 1 shows the range of 15-min-interval power for various laboratory spaces in the UC Davis laboratory building. Consider peak loads: The peak for most spaces is under 6 W/sf; a few are between 6 and 10 W/sf; and one space is high-intensity, at about 17 W/sf. This is a fairly common situation, in which one or two labs have very high equipment loads compared to the others. The problem arises when all these labs are served by a single air-handling unit with zone reheat coils for temperature control (a widely used HVAC strategy). The high-intensity labs then drive the supply air temperatures and flows to handle their high equipment loads, and, as a result, all the other labs have to use reheat to maintain desired temperatures. This issue usually does not come up during design, because designers assume a uniform equipment load intensity for all laboratory spaces served by an air handler and assume no variation between those spaces. Energy simulations conducted during the design phase that reflect this assumption will not show the increased reheat energy use that is due to load variation.

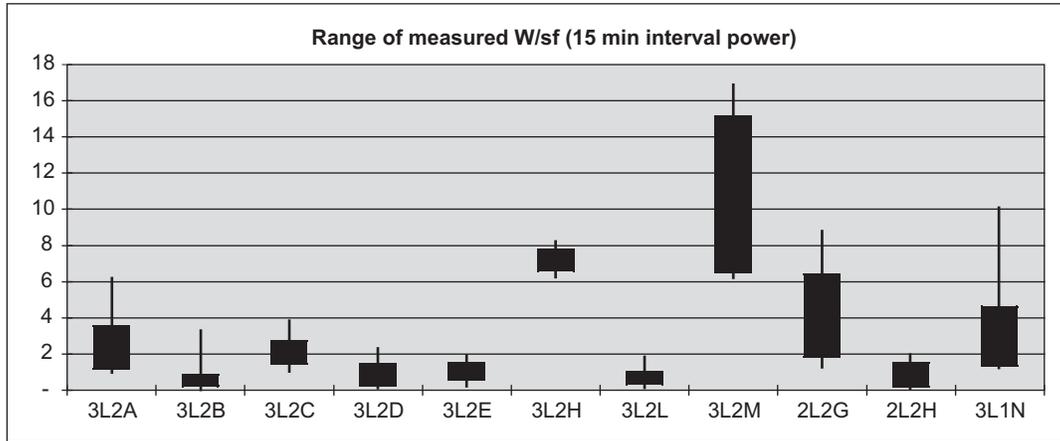Figure 1 also shows that there is significant variation across time within each laboratory. For example, for the

Figure 1. Range of measured 15-min-interval power for various laboratory spaces in a building at UC Davis. The upper and lower ends of the lines represent maximum and minimum, respectively. The upper and lower ends of the boxes represent 99th and 1st percentiles of the measurements, respectively.

first space, 3L2A, the maximum is just over 6 W/sf, and the minimum is just over 1 W/sf. The 99th percentile is at about 3.5 W/sf; i.e., for only 1% of the time does the load in this space exceed 3.5 W/sf, even though the peak is almost double that amount. The wide range within each laboratory suggests that even if peak load variations across labs are accounted for in sizing airflows to these spaces, the variations within each space across time would still provide adequate cause for simultaneous heating and cooling.

Impact of Load Variation on Energy Use

To analyze the increase in reheat energy use arising from equipment load variation, several parametric energy simulations were conducted using the DOE-2.2 energy simulation tool. The simulation model consisted of a set of five laboratory spaces served by a single air-handling unit (Figure 2). To eliminate envelope-related load variations across these spaces, the boundary conditions of all the spaces were assumed to be adiabatic. The lighting and occupancy load profiles in all the spaces were identical.

Each parametric case consisted of two simulations:

- Simulation with load variation: One zone has a "high-intensity" equipment load profile, while the remaining zones have a "typical" load profile.

- Simulation with uniform loads: All zones have the same uniform equipment load profile, which represents an area-weighted average of the "high-intensity" and "typical" load profiles.

These profiles are indicated in Figure 3. The total building equipment load in any given hour is identical for both simulations, as are all other parameters. Thus, energy impacts of load variation can be isolated and analyzed.

The base-case model has a VAV system with hot-water reheat, a water-cooled chiller plant, and a natural gas boiler. HVAC component and system efficiencies were set to be consistent with good practice. None of the HVAC component and system parameters were varied in the parametric simulations. The minimum outdoor air ventilation rate for these spaces was set at 1 cfm/sf.

Figure 2. Simulation model used to analyze the energy impact of load variation. Boundary conditions for all zones were set to be adiabatic to eliminate envelope-related variations in loads for each zone. Zone 3 is about 12.5% of the total area.
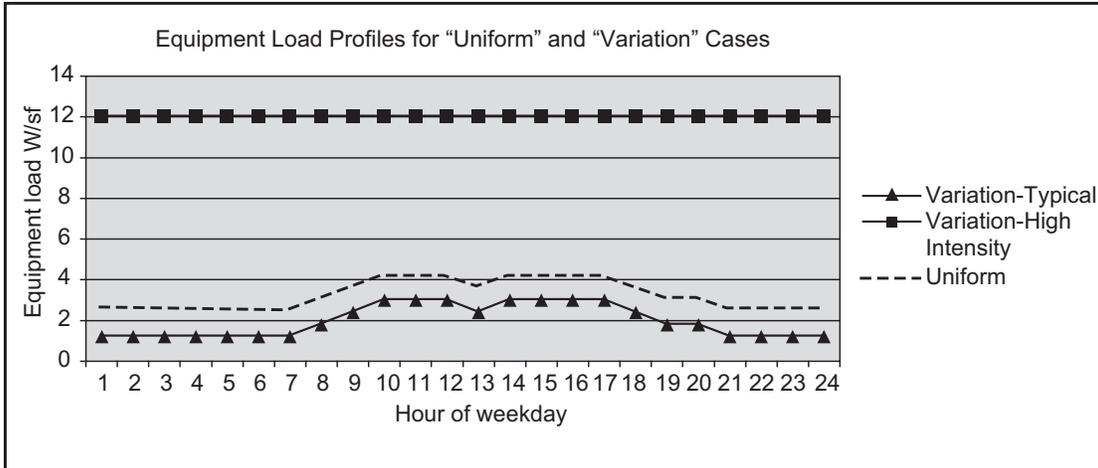
Equipment Load Profiles for "Uniform" and "Variation" Cases

Figure 3. Equipment load profiles used for simulation with load variation and simulation with uniform loads. "Variation-High Intensity" and "Variation-Typical" represent high-intensity and typical space load profiles in the simulation with load variation. "Uniform" represents the area-weighted load profile in all spaces for the simulation with uniform loads. (The total equipment loads for the building in each simulation are identical.)

Figure 4 shows the base-case source energy use intensity in three different climates in the U.S. The increase in total source energy intensity resulting from load variation ranges from 10% in San Francisco to 14% in Atlanta. An analysis of the simulation results showed that the bulk of this increase is due to additional heating. The increase in heating energy use by zone reheat coils was 48% in Washington, DC; 50% in San Francisco; and 68% in Atlanta.

The increase in reheat energy due to load variation depends on the minimum ventilation rate. Higher ventilation rates will increase the total energy use; however, as ventilation rates increase, the heating and cooling requirements are less "internal load-driven" and more "ventilation-driven," thereby reducing the impact due to load variation. Figure 5 shows that if the ventilation rate were doubled to 2 cfm/sf, the percentage increase would be 7% (vs. 11% for 1 cfm/sf). At 3 cfm/sf, the impact of load variation on reheat energy use is minimal.

Another factor that affects the increase in reheat energy is the extent of the differential between the loads in the high-intensity space and the other spaces. In the base case, the high intensity load was 12 W/sf, while the peak of the typical load profile was about 3 W/sf. If the differential is reduced, the amount of increase in reheat energy use will correspondingly reduce. To explore this effect, a parametric analysis was done with the high-intensity load halved to 6 W/sf. The results for two different climates are shown in Figure 6. In San Francisco, the increase drops from 10% to 7%, while in Washington, DC, it drops from 11% to 6%.
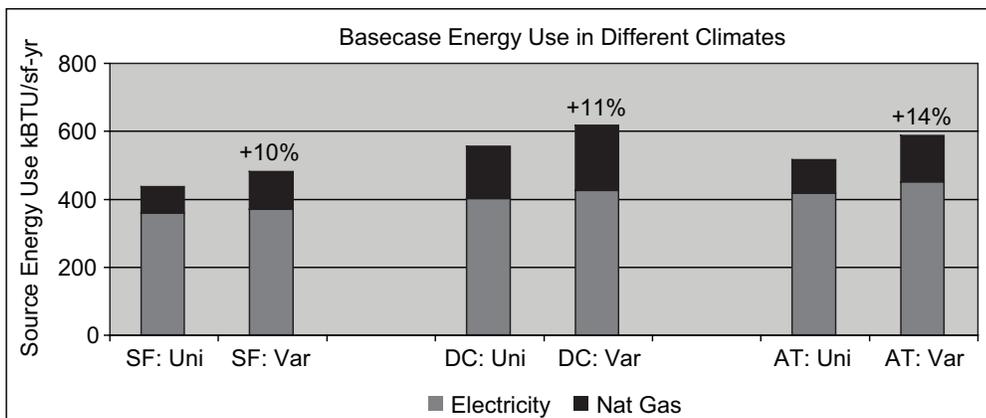
Basecase Energy Use in Different Climates

Figure 4. Base-case source energy use intensity in three different U.S. climates. (SF: San Francisco; DC: Washington, DC; AT: Atlanta; "Uni": uniform load simulation; "Var": simulation with load variation). The percentages are the increase in total source energy relative to the "Uni" for each case.

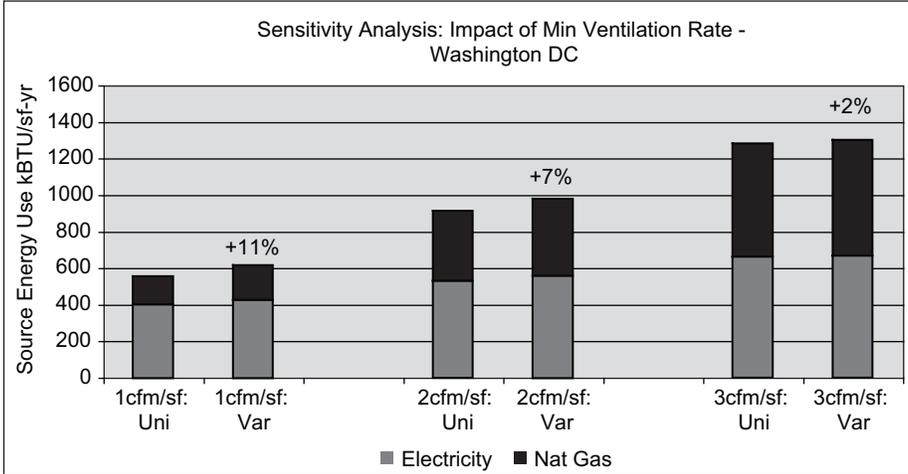Sensitivity Analysis: Impact of Min Ventilation Rate - Washington DC

Figure 5. Sensitivity analysis of source energy use intensities for different ventilation rates ("Uni": uniform load simulation; "Var": simulation with load variation). All results are for Washington, DC, climate.

In summary, the sensitivity analysis shows that the relative (%) increase in reheat energy due to load variation will (a) decrease with higher minimum ventilation rates and (b) decrease with smaller load differentials.

Note that in all the cases the simulation models assume that the HVAC controls are working as intended. However, experience from re-commissioning laboratories indicates that HVAC controls often deviate from design intent, and that consequently the energy use resulting from simultaneous heating and cooling can increase dramatically.

Strategies to Minimize Reheat

As the simulation analysis shows, equipment load variation in laboratories can increase energy use in laboratories that have systems with reheat. The magnitude of this increase varies with location, ventilation rate, and

degree of variation. We will now look at strategies for minimizing reheat.

1. Carefully assess equipment loads, and use profiles during design.

The first step in minimizing reheat energy use is to properly assess it during the design process. Often, HVAC designers assume uniform loads across the labs and do not account for the variation that inevitably occurs. Energy simulations used during design should model the reheat energy use caused by load variation. The simulations should model actual load in each zone instead of an average.

The Labs21 Modeling Guidelines [Labs21 2004], which are designed to be used in conjunction with the ASHRAE 90.1 standard [ASHRAE 2001], specify a standardized approach to incorporating load variation into the

Figure 6. Sensitivity analysis of degree of load differential between high-intensity and typical zone ("Uni": uniform load simulation; "Var": simulation with load variation). 12W refers to base case of 12 W/sf in high-intensity zone. 6W refers to alternative with 6 W/sf in high-intensity zone. (SF: San Francisco; DC: Washington, DC).

Sensitivity Analysis: Impact of High-zone Load Differential
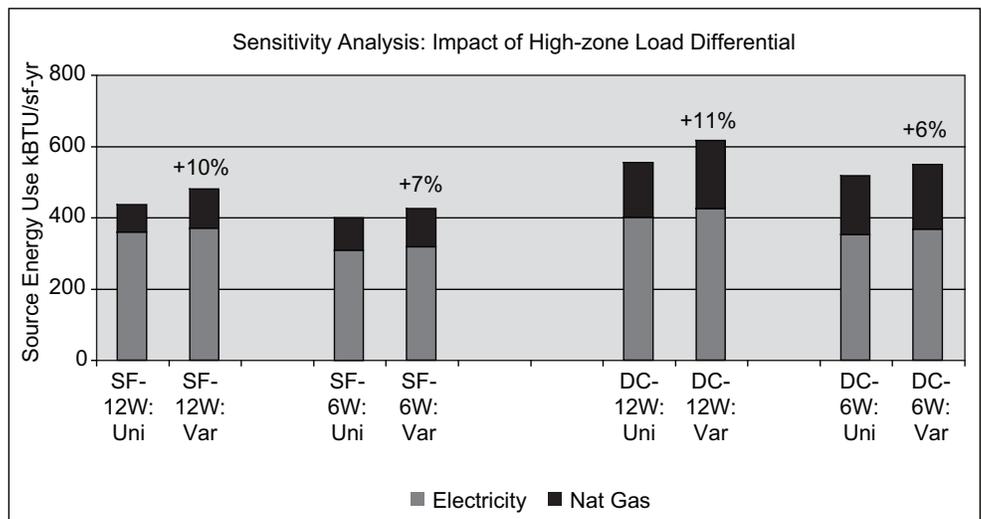
simulation models used for compliance and benchmarking.
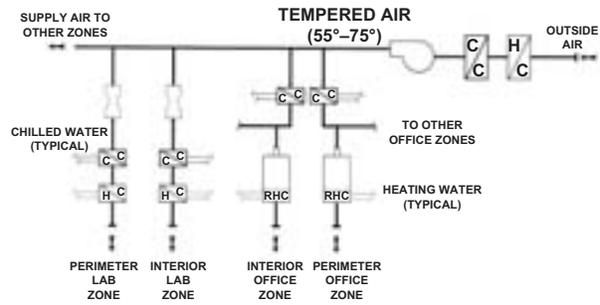
2. Consider alternative HVAC systems.

There are several different HVAC system alternatives that can mitigate reheat energy use, as shown in Figure 7 [Morehead 2003]. They all involve separating the thermal and ventilation systems, as follows:

- Dual-duct with terminal heating (DDTH): This system consists of two separate variable volume supply air streams: one with tempered air, and one with cold air. Labs that require more cooling will draw more air from the cold air stream while others will draw primarily from the tempered air stream.

- Zone cooling and heating coils (ZC): This system has a single tempered supply air stream, with the primary cooling and heating provided by zone heating and cooling coils. The temperature of the tempered air stream will be adjusted to minimize or eliminate the requirement for any zone reheat. This system has been installed in two laboratory buildings at Lawrence Berkeley National Laboratory (LBNL).
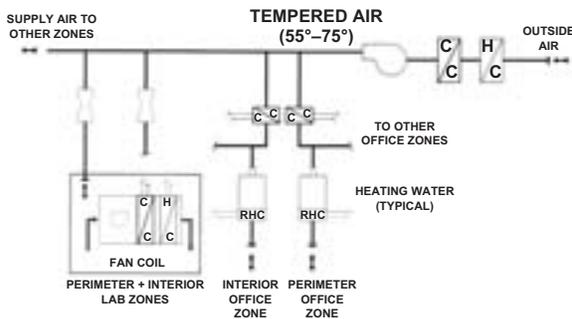
- Ventilation air with local fan coils (FC): This is similar in principle to the zone cooling and heating coils. The difference is that the heating and cooling occurs with fan coil units rather than coils directly in the ventilation air stream. Note that implementing a fan coil in a space may require coordination with and education of local authorities if there are any prohibitions in the local codes on air re-circulation in a laboratory space. A properly implemented fan-coil system will not mix air between any zones and will have no impact on space pressurization and ventilation rates. While it does not violate the intent of most code regulations, this approach may be unfamiliar and may require educating and gaining the approval of inspectors. This system was a key energy efficiency feature of the Koshland Integrated Natural Science Center at Haverford College. During the summer, no heat is used by the system (the heating supply is shut off); it is therefore a system that literally does not use any reheat. For more information on this building, see the Labs21 case study [Labs21 04].

- Ventilation air with radiant cooling (RC): This system also has a tempered supply air stream for ventilation.
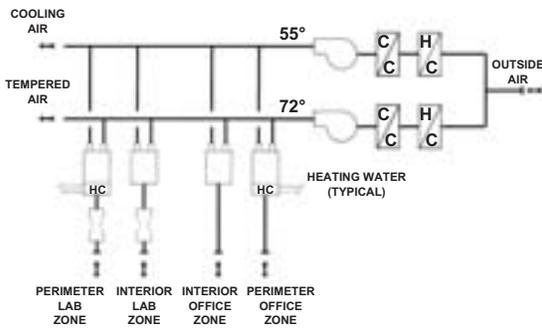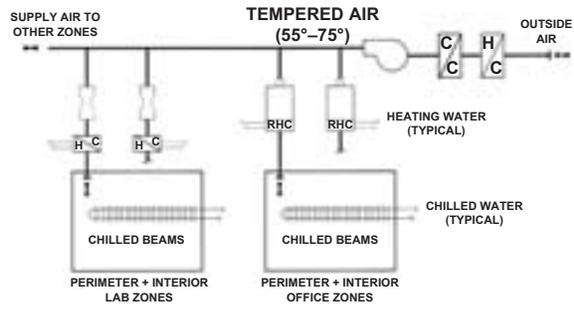

DUAL TEMPERATURE SUPPLY AIR WITH TERMINAL HEATING

ZONE COOLING & HEATING COILS

VENTILATION AIR WITH LOCAL FAN COILS

VENTILATION AIR WITH CHILLED BEAMS

Figure 7. Alternative HVAC systems that minimize reheat energy use caused by load variation between zones.

Space cooling is provided by radiant panels or chilled beams. Space heating is provided by zone heating coils located in the supply air stream. The major concern with radiant cooling is avoiding condensation by ensuring that the wet bulb temperatures are below dew point. This requires robust and reliable sensors and controls. Chilled beams have been applied in laboratories in Europe (Figure 8) and are beginning to be applied in the US as well. Chilled beams are especially being considered in retrofit applications as a way to provide additional cooling capacity in labs that are already running at maximum airflow capacity.

Note that these alternatives do not necessarily imply constant volume air supply. They may still require variable air supply to account for variable volume fume hoods or variable general ventilation requirements.

These systems may have a higher construction cost than the conventional VAV system with reheat. A study by Davis Langdon compared the HVAC construction costs for a base-case VAV reheat with four alternatives: 55° dual duct system, 45° dual duct system, fan coil system, and a radiant panel system. The cost analysis was done on a 150,000-sf prototypical laboratory space located in the San Francisco region, based on summer 2005 cost data. Figure 9 summarizes the key findings:

- The HVAC system construction cost for the base-case VAV system is $72/sf. The costs for the alternative systems are $78/sf for 55° dual-duct, $73/sf for 45° dual-duct, $69/sf for fan coils, and $84/sf for radiant panels.

- The dual-duct system is cost-competitive with the VAV system if it is designed for 45° supply air. A dual-duct system configured for 55° supply air results in increased cost for air handling equipment and air distribution.

- The fan coil system costs less than the VAV. The cost increases for the piping, and fan coils are offset by larger cost decreases in air distribution and controls.

- Although the radiant cooling system results in reduced cost for air handling equipment and air distribution, this saving is outweighed by the cost of the radiant panels.

For other locations in the United States, the cost differences between these systems is quite sensitive to the relative price differences between system components. Equipment costs do not have significant geographic variation, but the wet and dry distribution systems can vary considerably. Thus, in very low-cost areas, the equipment-intensive options would become relatively more expensive (particularly systems such as radiant panels, which are unfamiliar to HVAC installers in most areas).

Integrated design can minimize construction cost premiums, as in the case of the Haverford College laboratory building, which uses ventilation air with energy recovery and local fan coils. The size of the heating and cooling plant was reduced by almost 60%; the supply air ductwork was substantially reduced, and the control system is much simpler than required by a traditional VAV system. As a result, the final construction costs for this facility were less than 90% of comparable facilities in the area [Bartholomew 2004].

All other things being equal, these alternative systems will typically use less energy than conventional VAV with reheat in laboratory applications, because they minimize simultaneous heating and cooling. Some of these systems are also inherently more efficient because they use water as a cooling medium rather than air.
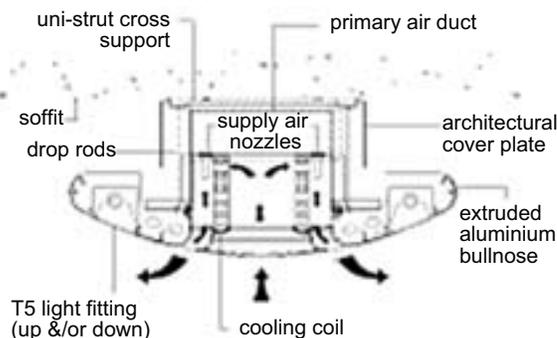

Figure 8. Chilled beams have been installed in laboratories in Europe and are beginning to be applied in the U.S. as well. Source: TroxUSA
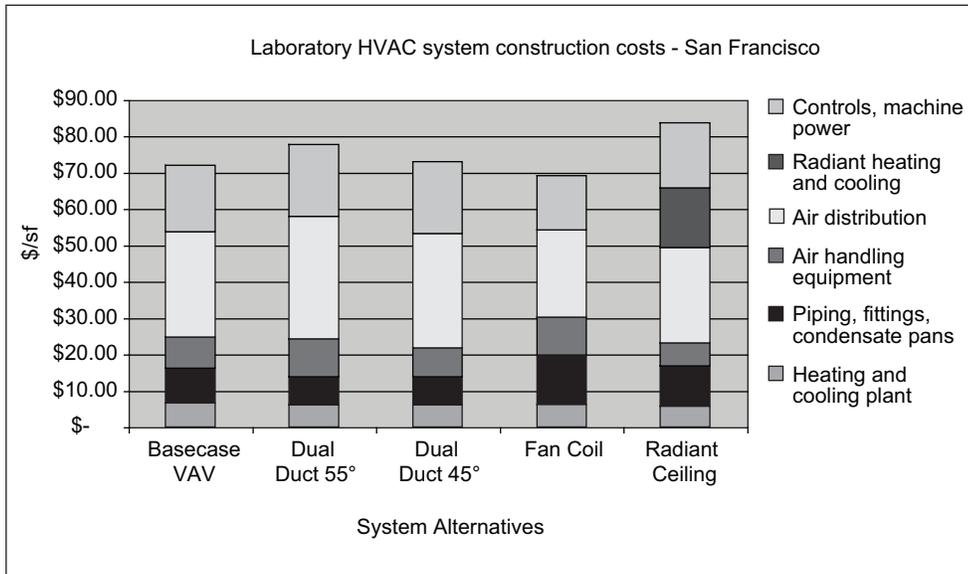
Figure 9. HVAC cost comparison for a 150,000 sf prototypical laboratory space located in the San Francisco region, based on summer 2005 cost data. Data source: Davis Langdon.

It is important to note that the above discussion has focused on reheat due to internal load variation. However, in many parts of the U.S., there is also significant reheat energy use due to dehumidification requirements. The system alternatives discussed above should additionally incorporate technologies, such as energy recovery wheels or wrap-around heat-pipe coils around the cooling coils, to significantly reduce or eliminate reheat energy use needed for dehumidification.

These four alternatives should also be evaluated in terms of flexibility, maintenance, and other performance parameters. Some key points to be noted include the following:

- The ZC and FC systems are inherently modular and provide more flexibility in adding cooling capacity to the space.

- The ZC, FC, and RC systems require less space for ducts in load-driven labs, since the ducts are only for ventilation air, not thermal conditioning.

- The ZC and FC systems have distributed condensate drain pans, which need to be properly maintained and serviced. RC systems have to be carefully controlled to avoid condensation within the space.

- All these systems may have higher maintenance requirements than single-duct reheat systems, due to the greater number of components distributed throughout the building.

- The lack of familiarity of owners with these systems may be a barrier. This will require additional effort by designers to convince the owner of the benefits of these systems. Low engineering fees can also be a barrier. These higher-performance systems may require more engineering skill and time.

3. Continuous commissioning.

Finally, it is important to note that good operations and maintenance practices can help to minimize energy use in all the system types described above. HVAC controls often deviate from design intent, which can lead to an increase in the energy use due to simultaneous heating and cooling. Continuous commissioning and diagnostics can help to identify zones with excessive reheat, and to adjust system control and operation accordingly. A forthcoming Labs21 best practice guide will cover this topic in more detail.

Conclusion

Equipment load measurements from various laboratories show significant load variation between spaces. This variation can increase energy use in laboratories that have systems with reheat. A simulation analysis showed that the magnitude of this increase varies with location, ventilation rate, and degree of variation. When designing a laboratory HVAC system, it is important to consider load variation in order to better evaluate the energy efficiency of alternative HVAC systems vis-à-vis simultaneous heating and cooling. There are several alternative system types that can minimize or even eliminate the use of reheat energy, including dual-duct-dual-fan systems, fan coil systems, zone cooling and heating coils, and radiant cooling. Continuous commissioning is also an important tool in minimizing simultaneous heating and cooling.

References

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Labs21 [2004]. "Marian E. Koshland Integrated Natural Science Center," published by Laboratories for the 21st Century Program. Available at: http://www.labs21century.gov/toolkit/case_studies.htm

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Acknowledgments

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