# LABORATORY SPACE PRESSURIZATION CONTROL SYSTEMS

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## INTRODUCTION:

Maintaining the proper differential pressure in laboratory spaces is one of the most challenging tasks facing the laboratory environmental control engineer. Some of the items which need to be addressed when designing a space pressurization control system are:

- Hazard Assessment
- Constant-volume vs. VAV Systems
- Differential Pressure vs. Differential Volume Systems
- Negative vs. Positive Pressure Requirements
- Control Signal to Noise Ratio
- Control Stability and Speed of Response
- Failure Mode Analysis
- Building Construction impact on space pressure control
- Duct Leakage impact on space pressure control

Laboratories and clean rooms may require that a differential pressure be maintained between them and the adjoining spaces. This requirement may come from code considerations or from the operational requirements of the space. For example, NFPA-45 states that *"laboratory work units and laboratory work areas in which hazardous chemicals are being used shall be maintained at an air pressure that is negative relative to the corridors or adjacent non-laboratory areas.."* [1] This is to prevent the migration of

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fire, smoke and chemical releases from the laboratory space. Labs containing radiation hazards or biohazards may also be required by different agencies to maintain a negative pressure to contain these hazards. Clean Rooms , on the other hand, are normally operated at a positive static pressure to prevent infiltration of particulates. Even if your building codes and regulatory agencies do not require pressurization you may wish to include this feature in your facility anyway for the reasons described above.

## CONTROL STRATEGIES:

The desired result of all space pressurization control systems is to control the infiltration into or the exfiltration out of a space. Space pressurization control strategies can be divided into two major categories: *passive* and *active*.

For constant-volume laboratories a *passive* method involves simply balancing the system so that the desired space pressurization is achieved. This method has serious limitations which should be considered carefully before choosing to design a constant-volume system with *passive* space pressurization "control." This type of system will work *only* if: 1) all fume hoods remain on and at constant speed or volume at all times, 2) no exhaust sources (i.e. hoods) are added or removed, 3) the offsets are large enough to mask changes in exhaust and supply system performance caused by filter loading, etc., 4) the system is tested and balanced frequently to design conditions, and 5) the system is adequately maintained. If you cannot guarantee (or even desire) all these restrictions then this design approach is inappropriate for your application.

An *active* method for use in a constant-volume laboratory involves the utilization of pressure-independent, constant-volume control devices in the exhaust and supply ducts to actively and dynamically adjust the flowrates to keep them constant and decoupled from system static pressure fluctuations.

VAV labs require active methods to control space pressure due to the continuously changing exhaust volume from the fume hoods and other exhaust sources. Active VAV space differential pressure control methods may be subdivided into two types: pure differential pressure measurement/control (ÆP) and differential volume or *flow-tracking* (ÆV).

## **DIFFERENTIAL PRESSURE SYSTEMS:**

The ÆP method of space static pressure control is relatively straightforward and a schematic of it is shown in Fig. 1. In this method, the differential pressure is controlled with a differential pressure sensor and a controller and the supply air volume is simply a function of the ÆP, the setpoint, and the PID constants $\alpha$ and $\beta$. Another similar method of static pressure control utilizes the Bernoulli principle which states that a pressure gradient will accelerate a fluid to a velocity proportional to the square root of the pressure differential. These *pseudo-ÆP* systems utilizes an air velocity probe mounted in a tube inserted into a hole in the wall between the controlled space and the reference space. The differential pressure will induce air to flow through the tube and the velocity of the air is sensed by the velocity probe. A controller then varies the supply air volume to the laboratory to maintain a velocity pressure setpoint.

## **FLOW-TRACKING SYSTEMS:**

The ÆV method of space pressurization control utilizes analog or digital electronic controls to measure the real-time variables and solve the dynamic air balance equation. A typical ÆV system is shown in Fig. 2. The exhaust volume is either measured after convergence into a manifold or the individual sources are measured and summed as shown. The supply volume is then controlled (tracked) to achieve the *offset*. The offset is the desired infiltration or exfiltration in CFM. A negative offset will reduce the supply volume below the exhaust volume and will result in a negative space pressure. A positive offset will increase the supply volume above the exhaust volume and will result in a positive space pressure. Although the equation in Fig. 2 implies that the offset is a constant, in practice, it is a variable. As the volume sensors drift in accuracy, the actual offset will change. It is necessary to choose an offset that is large enough to compensate for tight vs. loose envelope construction, duct leakage, and the accuracy of the flow measuring devices. You should choose an offset using Equation 1.

$$Offset_{design} = 2\,\varepsilon\,S\,F_{max} \qquad \textbf{Equation 1.}$$

Where:

$\varepsilon$ = instrument error in % full scale or % of reading

S = safety factor: depends on tightness of envelope, amount of unmeasured duct leakage and degree of laboratory hazard present; recommended range: 0.5 - 2.0

$F_{max}$ = design maximum exhaust or supply flowrate, whichever is greater

This will assure (if the safety factor is greater than 1) that under worst case conditions you still have some actual offset in the desired direction of flow. For example, in a negatively pressurized lab, the exhaust flow rate will be higher than the supply flow rate, so the $F_{max}$ is the maximum exhaust volume. If $F_{max}$ is 5000 CFM, $\varepsilon$ is 5% (0.05), and S is 110% (1.1) then the $Offset_{design}$ = (2)(.05)(1.1)(5000) = 550 CFM. Therefore, the worst case scenario would be a system where the exhaust volume reading is 5% below actual, and the supply volume reading is 5% above actual, giving a total airflow error of +500 CFM. If the design offset is -550 CFM then the *actual* offset will be -50

CFM. Normally, airflow errors are random and will tend to cancel. In large labs with multiple flow measuring instruments, you would expect the total error to be less than the maximum cited in the example. If this is the case, and there is minimum duct leakage, the laboratory envelope is very tight, and the laboratory hazard is low, then a safety factor less than 1 may be appropriate. In any case, verification of actual operating ÆP's and tuning of lab offsets should be done at a predetermined frequency based on the level of hazard in the laboratory. A maximum of six months between offset calibrations is recommended.

## HYBRID SYSTEMS:

In laboratories containing extremely toxic or infectious agents such as Biosafety Level 3 or 4 laboratories, it may be prudent to utilize *both* a ÆP and a ÆV system to assure that an adequate differential pressure is maintained at all times. The most common way of doing this is to design a basic ÆV system as previously described, and add a ÆP sensor and controller which is used to reset the ÆV system offset. Here, the long time delays required to produce an accurate average do not affect the speed of response of the system. The ÆP system can dynamically calculate an appropriate offset. As the characteristics of the room change, such as duct leakage and envelope tightness, the offset will change (it usually grows) to maintain the desired laboratory space pressure. Once the offset has grown to a predetermined value it may be necessary to recalibrate flow measuring instruments, seal ductwork, or seal bypasses in the laboratory envelope to bring the system back into specification. Monitoring the offset in a hybrid system of this type is a good way to monitor the integrity of the total duct/control/envelope system.

**STABILITY vs. SPEED OF RESPONSE:**

ÆP and pseudo-ÆP control schemes have certain characteristics which the designer/owner needs to be aware of. A reasonable pressure differential to maintain using normal construction techniques is approximately 0.01" water gauge (w.g.) To put this into perspective, 0.01" w.g. = 0.00036 PSI. This is an *extremely* small pressure differential (signal) to measure and providing adequate calibration for the instrument is also difficult. The fluctuations (noise) in this signal, which are caused by the opening and closing of doors, people traffic, elevators, stack effects and atmospheric disturbances like wind, are on the order of 0.1" w.g. This represents a signal to noise ratio of approximately 1:10.

Imagine trying to determine the level of a lake to within an inch when the waves are a foot high. To do so, it would be necessary to average out the wave crests and troughs. It can be done, but it takes time. If you want great accuracy you have to average over a long period of time. If you need to respond quickly to the signal then you can't be as accurate. Accuracy and speed or response are in direct conflict. For true stability in a ÆP system, the response time is usually measured in minutes. Therefore, many of these systems and instruments sacrifice stability for speed and can oscillate about the setpoint for quite some time before settling down to stable control. Unfortunately, this settling down period is often greater than the frequency of upsets and the controlled device may oscillate all day long until everyone goes home.

pseudo-ÆP systems which measure the air velocity are somewhat faster and more stable because the velocity signals and noise are proportional to the square root of the differential pressure. This improves the signal to noise ratio to approximately 1:3. This simple change in the measured variable improves the system performance by a factor of three. However, the noise is *still* about three times as large as the signal and you still may wait as long as 60 seconds for marginally stable output after an upset in the space pressure. The performance of this type of equipment varies from manufacturer to manufacturer and care should be exercised when selecting them for your facility.

Another undesirable characteristic of both of these pressure measuring devices is that the measured variables (pressure or velocity) totally disappear when the laboratory door is opened. Some controllers have the ability to freeze the output for a predetermined time delay to compensate for this. However, if the door is left open long enough, the pressure control system will start to shut down the supply volume in order to bring the space back to a negative setpoint. When this occurs, the air from the hallway flows into the open laboratory to replace the exhaust air and the hallway pressure may drop. Other lab pressure controls which use this hallway as a pressure reference may also start to close down the supply air to their labs thereby creating a cascade effect. As more air is drawn into the affected labs from the hallway, the pressure will continue to drop even more. As you can imagine, this can cause serious building pressure problems. However, for facilities not requiring critical room pressure control and where the effects of settling time and stability are not an issue from a hazard assessment standpoint and where the HVAC system and architectural designs can minimize the cascade failure effect mentioned above, this control system may be used with some success.

In comparison, the signals measured using airflow stations by ÆV systems are on the order of 1000 feet per minute and the noise is on the order of 100 feet per minute resulting in a signal to noise ratio of approximately 10:1. This allows much more accurate, stable, and rapid response to changing inputs characteristic of a VAV laboratory. All airflow measuring devices are not created equal, however. There are types which employ arrays of hot wire anemometers. These are very accurate and have a relatively wide turndown but are sensitive to buildup of particulates and corrosives on the sensors which affects their response time and reliability. Averaging pitot-tube arrays have a similar problem with buildup plugging the sensing ports and causing non-averaging response. They are also extremely inaccurate at low velocities due to the exponential nature of the velocity pressure signal. A velocity sensing technology which has been used for years to measure liquids is now being applied to airflow stations. It is called *vortex shedding*, and is showing up in some newer laboratory pressure control systems. There is some debate over the theoretical accuracy of these devices at large turndowns due to reynolds numbers, but field testing will prove if these devices can be effective in ÆV control systems.

**OTHER DESIGN CONSIDERATIONS:**

Construction techniques can also influence the performance and effectiveness of space pressurization controls. Loose construction makes it difficult to establish an effective differential pressure in the space and large offsets are necessary to compensate. When large offsets are used, pulling large amounts of secondary air in from adjoining spaces, temperature and humidity control problems may result. Plugging all the holes and bypasses in the laboratory envelope during the renovation or construction process may be required to eliminate this problem.

Duct leakage may also effect the accuracy and performance of ÆV systems. Air leaking out of or into the duct system between the flow measurement device and the laboratory envelope can result in significant error. In constant pressure systems this error may be relatively constant, but if the system static pressure floats then the error will float also. The author recommends that supply and exhaust ductwork be specified and leak tested to allow a maximum of 0.5% leakage. This is easily achievable by most contractors with some practice and guidance in duct sealing and construction techniques. Using welded and/or flanged and gasketed duct construction can make it virtually leak-free. Placing flow measuring devices close to the wall penetration in a tight section of duct is recommended because it minimizes errors by reducing the duct length where leakage effects the flow measurement. Assuming that the flow measuring device is located *inside* the laboratory envelope, leakage which occurs upstream of the exhaust flow measuring device and downstream of the supply flow measuring station has already been measured and should not effect the error.

**COST COMPARISONS:**

The ÆP and pseudo-ÆP systems, due to their simplicity will typically cost less than a ÆV system for the same laboratory. How much less depends upon the size and complexity of the laboratory ventilation system and the type of fume hood controls. As the number of measured and controlled devices increases so will the differential cost. If exhaust and supply volumes are measured at only one position each, the cost differential will decrease. However, if you have chosen VAV fume hood controls and general exhaust controls that have flow measurement capability built into each, then only a supply air flow measuring device and controller are needed to complete the system. In this case the cost of the two systems may be negligible. It is difficult to divorce the cost of the space pressure controls from the cost of the fume hood controls since they are often integrated.

**FAILURE MODES AND SYMPTOMS:**

The easiest way to assure proper space pressurization control system operation is to monitor it with sensitive equipment which has been properly calibrated and to provide alarms to alert personnel when conditions are outside specifications. A simple qualitative measure of space pressurization control system effectiveness is smell. If you can smell the chemicals which are used in the laboratory when you are in the corridor this *may* be an indication that your space pressurization controls are ineffective. It may also mean that contaminated air from the laboratory is be reingested back into the building air supply due to inadequate stack design. In the case of a clean space, excessive particulate counts may indicate a space pressure problem causing infiltration. Another simple experiment which can be done quickly and easily is the foot-in-the-door test. Open the lab door and place your foot in the doorway next to the jamb and allow the door to close against it. Next, feel the airflow through this opening with your hand, or use a smoke tube to determine its direction. It's not quantitative, but it will sure tell you if your positive when you should be negative (or visa versa) or if there is an excessive pressure differential. If either of these are detected then a more quantitative approach should be used to diagnose the magnitude and cause of the problem.

During the design of the laboratory environmental control system, a careful analysis of the failure modes of each component and the effect of a failure on the operation of the system should be undertaken. There are many methods to do this, most of which are beyond the scope of this article. One of the more popular methods is called a *fault tree*. This method may be used on entire systems, subsystems, and individual components. For example, if attempting to do a fault tree analysis on a room pressure control system, choose the component you wish to analyze such as a through-the-wall velocity sensor. List this at the top of the tree. Next consider all of its failure modes and list them underneath. Next, for the most serious failure modes consider all the affects on controlled components and other coupled and decoupled systems and list them underneath that mode. Repeat this process until all the paths are complete. It may be necessary to do all the branches of the tree to discover which paths represent the worst scenarios. When all the failure modes of all the components, subsystems and systems have been completed, you can make some strategic design modifications to eliminate or ameliorate the most serious scenarios by installing more reliable components in key locations or installing redundant controls or systems to provide backup and thus truncate the tree.

## HAZARD ASSESSMENT: MAKING THE PRUDENT CHOICE

Before choosing a space pressure control system, the design team should assess the hazards present in the laboratory and choose a system which is appropriate given its failure modes, the level of hazard and the level of risk that the owner is willing to accept. *Chapter 14: Laboratories* of the 1991 ASHRAE Applications Handbook is currently undergoing a re-write for the 1995 volume. The first section if this chapter is entitled "Risk Assessment." During a discussion of this topic by the Handbook Subcommittee of TC9.10 Laboratory Systems, it was decided that the words "risk assessment" and "risk analysis" were often mixed up and misinterpreted. Furthermore, the work "risk" has certain legal definitions associated with it. The general opinion of the committee was that risk analysis, if interpreted literally, involves the assimilation of hundreds of pieces of design and hazard information and the calculation of the probable frequency of accidents and the probable results of those accidents using experience and/or actuarial data. The committee felt that most mechanical engineers were not qualified to perform an analysis of this type and that it should be undertaken by the owner who is probably more familiar with the specific hazards and processes in their laboratory than the laboratory designer could ever be. The designer should, of course, participate in the exercise to supply data about the facility and systems design and their impact on the risk of operating the facility, including the space pressurization systems. The title of the handbook section has now been changed to “Hazard Assessment” since the discussion of “risk” was considered to be beyond the scope of the chapter (and this article).

## CONCLUSION:

There are many types of space pressurization control systems, methods and equipment to choose from. You can make your decision based on instinct, vendor data, your own experience, objective testing, or by seeking advice from a laboratory consultant. The instinct and vendor data methods involve more risk than some are comfortable with. User experience is the least risky option, but only if you have the experience with the equipment. Objective testing provides excellent results but is expensive and time consuming. Seeking advice from a laboratory design consultant will cost less than objective testing and much less than replacement of equipment which does not meet owner specifications. However, the equipment is only one piece of a complex puzzle. The design of the laboratory envelope, its layout, and the supply and exhaust systems all interact in an intricate fashion. An experienced laboratory consultant can also lead you around the pitfalls, help avoid common problems and show you how *all* the aspects of the facility affect its performance and help assure that the laboratory facility operates as safely and efficiently as possible.

## REFERENCES:

[1]NFPA Standard Code No. 45, *Fire Protection for Laboratories Using Chemicals,* National Fire Protection Association (NFPA), Quincy, MA, 1986.