California Energy Commission
Public Interest Energy Research Program

LBNL No. 52571
HPCBS # E5P2.1T1d

HPCBS

High Performance Commercial Building Systems

Functional Testing Guide for Air Handling Systems: From the Fundamentals to the Field

Element 5—Integrated Commissioning and Diagnostics
Project 2.1 Commissioning and Monitoring for New Construction

Developed by:

David Sellers, Hannah Friedman, Tudi Haasl
Portland Energy Conservation, Inc.
1400 SW 5th Avenue, Suite 700
Portland, OR 97201

Norman Bourassa and Mary Ann Piette
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720

May 2003

Table of Contents: Functional Testing Guide

Acknowledgements

This work has been supported by:

- The California Energy Commission's (CEC) , Public Interest Energy Research Program, under Contract No. 400-99-012.
- The Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Building Technologies Program of the U.S. Department of Energy (DOE) under Contract No. DE-AC03-76SF00098.

Special thanks to Martha Brook (CEC) and David Hansen (DOE). Ken Gillespie of Pacific Gas and Electric Company led the development of the Commissioning Test Protocol Library, to which the Functional Testing Guide is linked. Appreciation is extended to Marti Frank of PECI for her assistance.

Technical review was provided by the following experts:

Gretchen Coleman, P.E., Engineering Economics, Inc. (EEI)

Jay Santos, P.E., Facility Dynamics Engineering

Karl Stum, P.E., CH2M HILL

Treasa Sweek, P.E., CTG Energetics, Inc.

DISCLAIMER

Chapter 1: How to Use the Functional Testing Guide

1.1. Overview

The ***Functional Testing Guide for Air Handlers: From the Fundamentals to the Field*** (Functional Testing Guide) provides both a practical understanding of the fundamentals of air handling systems and field tips for functional testing. The Functional Testing Guide also reviews the energy and performance implications of common problems and provides links to test procedures.

The Functional Testing Guide allows easy access to the many functional tests collected in the *Commissioning Test Protocol Library* (CTPL) developed by Pacific Gas & Electric Company. The CTPL is the largest existing collection of functional test procedures, including many non-copyrighted test procedures that can be customized to suit individual system configurations. Since the test procedures in the CTPL do not include detailed explanations, the Functional Testing Guide explains the "how" and "why" behind the functional tests in the CTPL. Understanding the reasoning behind test procedures and how to interpret and act upon the results is essential for successful testing.

Together, the Functional Testing Guide and the CTPL will help commissioning providers standardize their functional testing procedures and improve quality control, two issues which continue to burden the commissioning industry. The Functional Testing Guide also covers design issues as a basis for design review and to help identify solutions for failed functional tests. The information in the Functional Testing Guide will help commissioning providers:

- Understand how to test from a systems perspective
- Identify common problems and the root causes of these problems
- Customize test procedures to meet the needs of their specific projects
- Understand why a specific test sequence is being executed
- Understand the possible outcomes and necessary precautions for the test sequence
- Understand the costs and benefits of the test sequences

Commissioning providers are the primary audience for the Functional Testing Guide and the CTPL. The commissioning providers using the Functional Testing Guide should already be familiar with the commissioning process, HVAC fundamentals, and the building construction process and industry.

1.2. Chapter Summaries

Chapter 2: Functional Testing Basics The first chapter of the Functional Testing Guide covers the general functional testing concepts that underlie all subsequent chapters. Basic concepts that are given only minor treatment during later chapters are covered in detail here. This chapter includes an introduction to the system approach - a fundamental way of looking at the components of an HVAC system as a whole. Other topics include the testing hierarchy, training, verification checks, useful tools, components of a functional test procedure, precautions, and test preparations.

Chapters 3 – 18: Air Handler Components These chapters cover the functional testing of each component of an air handler, from the outdoor air intake section to the exhaust air discharge point. Regardless of the system configuration, the functional testing associated with a component is similar. For example, a preheat coil in a variable volume system performs the same function as it would in a constant volume system. The following components are included:

- Outdoor air intake (Chapter 3)
- Fan casing (Chapter 4)
- Economizer and mixed air (Chapter 5)
- Filtration (Chapter 6)
- Preheat (Chapter 7)
- Cooling (Chapter 8)
- Humidification (Chapter 9)
- Reheat (Chapter 10)
- Warm-up (Chapter 11)
- Fans and drives (Chapter 12)
- Distribution (Chapter 13)
- Terminal equipment (Chapter 14)
- Return, relief and exhaust (Chapter 15)
- Scrubbers (Chapter 16)
- Management and control of smoke and fire (Chapter 17)
- Integrated operation and control (Chapter 18)

These chapters will help commissioning providers, building operators, and designers identify and solve problems on paper during design and in the field. Each chapter contains links to relevant test procedures from the CTPL and other additional test procedures, which give commissioning providers easy access to all publicly available tests. The tests from each chapter can be combined and customized to suit specific system configurations.

Although each chapter covers a different component of the air handling system, they all follow the same format:

- **Table of Contents** The table of contents allows the user to quickly assess the chapter's content and jump to topics of interest.
- **Theory and Applications** This section provides general insight and theory regarding the typical applications of the component or system.
- **Functional Testing Benefits** The benefits associated with testing the component are described, including energy and resource savings, reliability issues, and indoor environmental quality.
- **Functional Testing Field Tips** Practical, field-tested functional testing information includes:

  Purpose of the Test

  2 Instrumentation Required

  3 Test Conditions

  4 Time Required to Test

  5 Acceptance Criteria

  6 Potential Problems and Cautions

- **Design Issues Overview** This insightful look at how the design parameters affect the outcome of functional testing also supports the design review process. Currently, this overview has been completed for following components: Cooling (Chapter 8), Humidification (Chapter 9), Reheat (Chapter 10), Warm-up (Chapter 11), Fans and Drives (Chapter 12), Distribution (Chapter 13).

- **Typical Problems** Important problems normally uncovered during testing or design review are highlighted. Currently, this section has been completed for the following components: Preheat (Chapter 7), Cooling (Chapter 8), Reheat (Chapter 10), Warm-up (Chapter 11), Fans and Drives (Chapter 12).
- **Non-Copyrighted Tests** Hyperlinks provide access to the CTPL test procedures and, in some cases, additional test procedures created for the Functional Testing Guide. The tests can be edited to serve a specific project or as the basis for development of a new test procedure. The structure of the Functional Testing Guide allows the user to extract tests from the applicable component chapters to develop a comprehensive procedure for a real air handling system. The Functional Testing Guide is a work in progress, and future versions will contain additional test procedures to supplement those currently available in the Functional Testing Guide and the CTPL.
- **Supplemental Information** Supplemental information describes the fundamental concepts behind the component under discussion. The extent to which this information has been developed will vary from chapter to chapter. *Chapter 5: Economizer and Mixed Air* and *Chapter 13: Distribution* include a more complete presentation of supplemental information.

Appendices The Functional Testing Guide features three Appendices.

- **Appendix A Overview of the Commissioning Test Protocol Library** provides direct links to all publicly available test procedures available in the library. While links to each of these procedures have been included in the appropriate FT Guide chapters, the links are provided in one place as Appendix A for convenience.
- **Appendix B Resources** provides a list of resources that can be useful for further reference.
- **Appendix C Calculations** is the main component of the cost-benefit analysis for the Functional Testing Guide. Currently, the calculations for fan energy savings associated with static pressure reduction have been fully developed and serve as a model for additional calculations. Spreadsheets associated with these calculations are provided to help streamline their use.

1.3. Getting Around the Guide

While the Functional Testing Guide contains a large amount of information in each chapter, this information can be easily accessed using four features: the table of contents, the web toolbar, hyperlinks, and the FTG Document Access Panel. The Functional Testing Guide is intended to be used electronically with these navigation features, rather than printing out the entire document. As needed, individual functional tests and chapters can be printed for ease of use.

The navigation features within the Functional Testing Guide were carefully designed to allow users to easily find topics of interest and edit 40 different non-copyrighted tests for use on their own projects. Users can access the functional tests through hyperlinks embedded in each chapter or through a control panel designed for the Functional Testing Guide.

1.3.1. Using the Table of Contents

The table of contents for the Functional Testing Guide is titled, "TableofContents_FTG.doc". It provides links to each of the seventeen chapters. Clicking on the chapter title opens the chapter as a separate document. Within each chapter, you will find another table of contents. The chapter's table of contents contains links to each section of the chapter, figures, tables, and equations.

1.3.2. Web Toolbar Navigation

The easiest way to navigate through the Functional Testing Guide is to use each chapter's Table of Contents, along with the "back" button on the Web Toolbar. Figure 1.1 below identifies the back button, a left-facing blue arrow. The back button allows you to return to your previous location in the document, much as the back button on your web browser returns you to the previous web page.

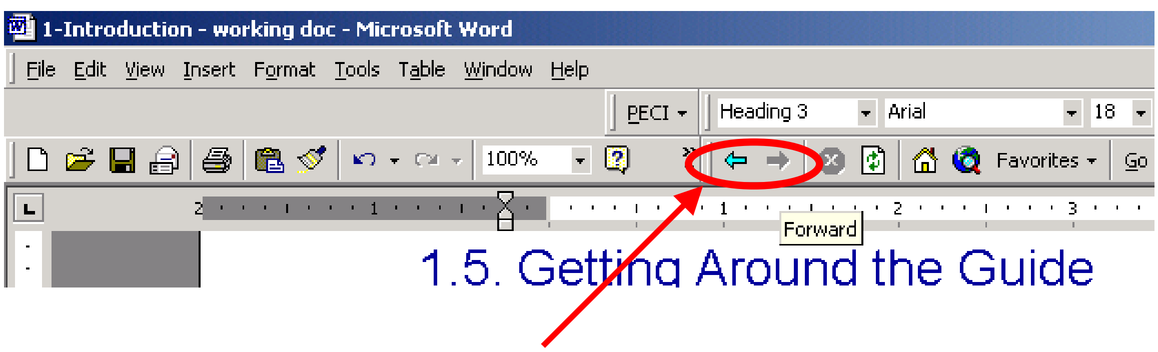


Figure 1.1 Identifying the Web Toolbar Navigation Arrows

If the back button is not currently showing in your toolbar, you can add it by following these steps:

Go to the ***Tools*** menu, click on ***Customize***…

2 In the ***Toolbars*** tab, check '**Web**' to add this toolbar.

3 The Web toolbar will show up at the top of your screen, including the navigation arrows

Try using the back button in the following exercise:

- Begin with the Introduction document.
- Click on the link to the Table of Contents for the Functional Testing Guide for Air Handling Systems (TableofContents_FTG.doc)
- Click on any chapter within the Table of Contents – for each chapter, you'll see a table of contents for that chapter
- Click on any topic in the chapter's Table of Contents and it will take you to that section
- To get back to the chapter's Table of Contents, click the back button.
- To get back to the Functional Testing Guide's table of contents, click the back button again.

You will also notice that the "forward" button (a right-facing blue arrow) appears after you use the back button. The forward button has a similar navigational effect – it returns you to the previous location in the document. The back button and forward button will help you explore the chapters of the Functional Testing Guide and still get you back to the primary navigation point – the Table of Contents.

1.3.3. Hyperlinks

Hyperlinks embedded throughout the Functional Testing Guide can be used to quickly access information. Clicking on a hyperlink will take you directly to the topic of interest. In the Functional Testing Guide, the hyperlinks are formatted in two ways, with examples from Chapter 5 shown below:

- **Blue Text With Underline:**

Example: Poor mixing causes numerous operational problems, which are discussed in Section 5.4 Typical Problems.

- **Blue Button:**

Link to Check List EconEval

Link to a checklist that helps assess the susceptibility of a new or existing economizer to operating problems. Includes evaluation criteria, links back to the Guide and directs the user to appropriate follow-up actions.

There are two types of Blue Button links. There are static hyperlinks to a document and there are macro links that open a testing form or CTPL reference document. When clicking on a macro button, there is an additional message prompt that confirms the user's desire to open the document.

The macro code has been designed for extensible user linking. If the user finds documents in the CTPL database that they want linked to the Functional Testing Guide, the documents can be added with the simple addition of a correctly formatted bookmark. Please contact the Functional Testing Guide authors for help. Additionally, custom tests or verification checks created by the user can be added to the FTG Document Access Panel through the same bookmark process.

Also remember that each line in the main Table of Contents document as well as in each chapter's Table of Contents has an embedded hyperlink.

1.3.4. FTG Document Access Panel

The FTG Document Access Panel is launched with a button at the top of the Functional Testing Guide's Table of Contents document (Figure 1.2). Note, this button will not appear until the Functional Testing Guide has been installed by closing all FTG chapter documents and then opening "FTG_Install.doc" to execute the installation macros. Before attempting installation, make sure your MS Word setup is configured for a Medium security level. This is done by opening any MS Word document, open the "Tools|Macro|Security…" drop menu, select Medium and click OK. Close MS Word. MS Word will now notify the user of the presence of document macros and provide an option to enable or disable their operation. The Functional Testing Guide requires that macros be enabled.

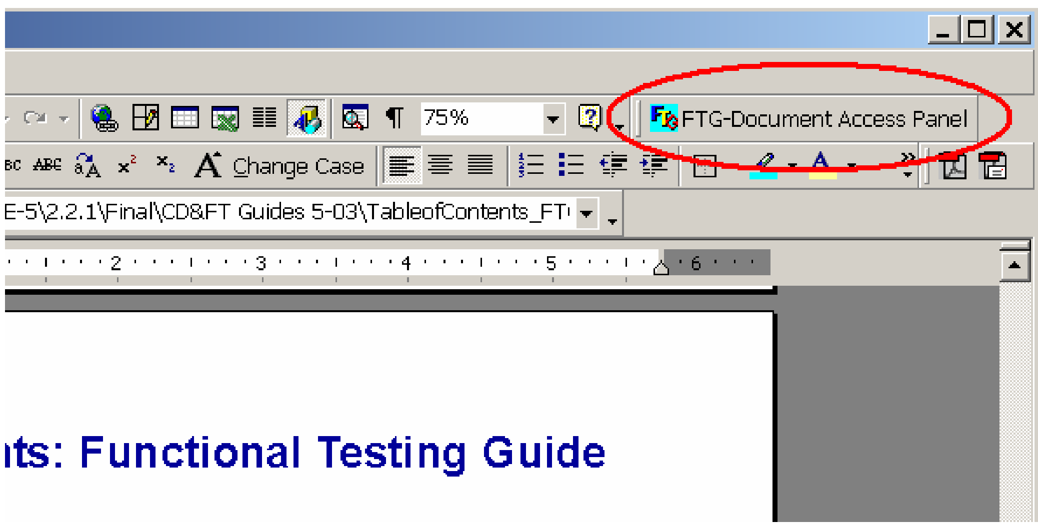


Figure 1.2 Functional Testing Guide Document Access Panel Button

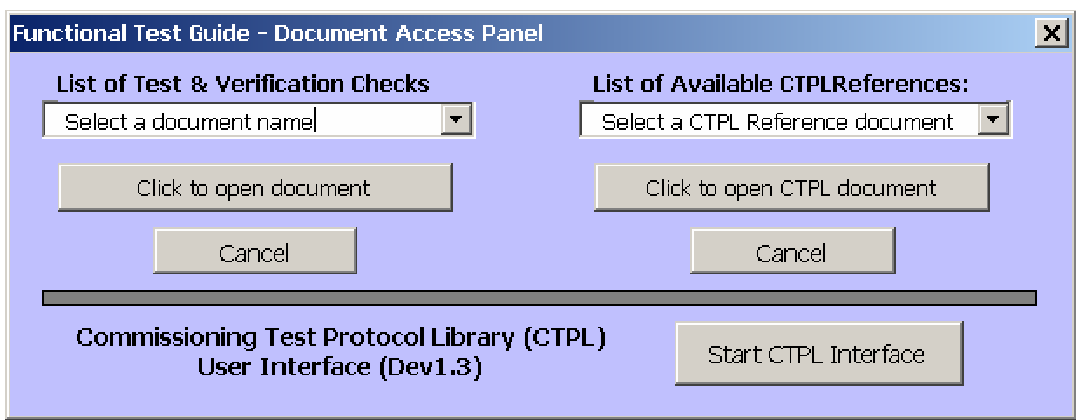


Figure 1.3 Functional Testing Guide Document Access Panel

The Functional Testing Guide Document Access Panel (Figure 1.3) will help you find tests and verification checks as well as open the CTPL itself. These functions are described below.

Click to open document: This drop-down menu allows you to directly access all test procedures and checklists created for the Functional Testing Guide. (Note: When initiated within the tool bar of a Functional Testing Guide Chapter, it will display the only the links in that chapter.)

2 **Click to open CTPL document:** This drop-down menu allows direct access to all the publicly available tests in the CTPL. The functional tests in the Commissioning Test Protocol Library include specific procedures or test protocols that are referenced throughout the Functional Testing Guide. You will find hyperlinks to applicable tests within each chapter of the Functional Testing Guide. A master list of CTPL tests is also included in Appendix A. (Note: When initiated within the tool bar of a Functional Testing Guide Chapter, it will display the only the links in that chapter.)

The automation features in the Functional Testing Guide allow the user to open and edit the CTPL procedures and save their modifications in a project folder. This feature allows utilization of the CTPL to create both job-specific tests and edited templates for future use.

3 **Start the CTPL:** Clicking this button starts the Microsoft Access application and the Commissioning Test Protocol Library (CTPL) database. Here, you can search through reviews of both copyrighted and non-copyrighted test procedures and manuals. The non-copyrighted test procedures can be accessed from the CTPL as well. Appendix A contains more information on the CTPL and its background.

1.4. The Commissioning Process

Figure 1.4 illustrates the general steps in the commissioning process and how the Functional Testing Guide fits into that process. The commissioning process for HVAC systems is detailed in ASHRAE Guideline 1 1996 – The HVAC Commissioning Process.

The Functional Testing Guide supports the development of verification checks, while focusing on supporting the functional test writing and the functional testing process. The verification checks and functional tests developed for the commissioning process will ideally form the basis for an ongoing or continuous commissioning process that is a part of the building’s operating standard for its useful life.

This flow chart illustrates the steps in the commissioning process. Shaded steps are the areas targeted by the information in the Functional Testing Guide for Air Handling Systems.

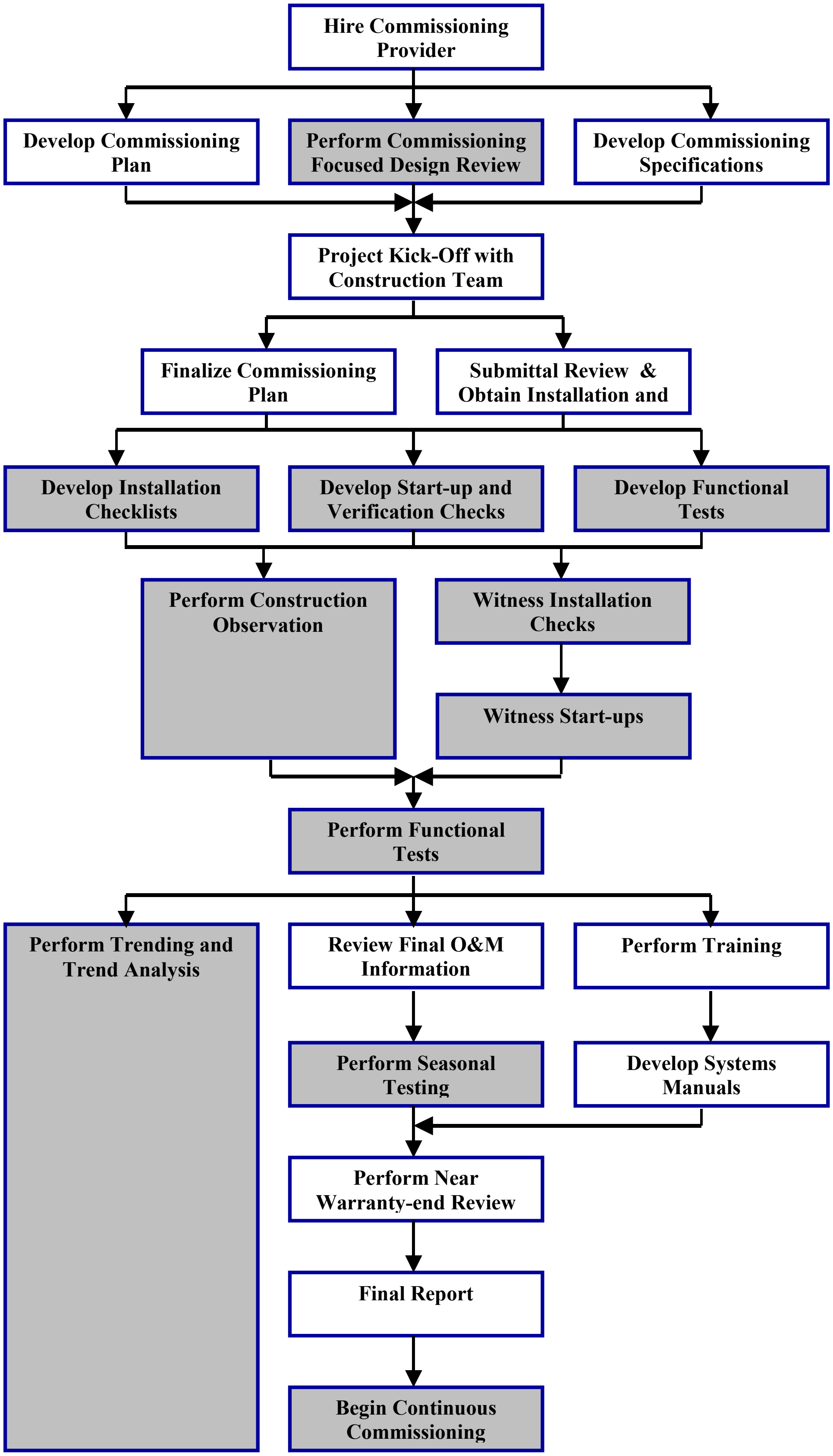


Figure 1.4 The Commissioning Process

1.5. Non-Copyrighted Test Procedures in the CTPL

An important function of the Functional Testing Guide is to make the CTPL test procedures easily accessible. These tests cover a wide range of equipment and system types, and should be used and modified as necessary by commissioning providers. The non-copyrighted protocols in the CTPL are linked to each chapter of the Functional Testing Guide as they apply to the subsection in that chapter. In addition, each procedure can be opened as a separate Word document by clicking on the CTPL ID# in *Appendix A: Overview of the Commissioning Test Protocol Library*. The CTPL includes an evaluation, summary, and bibliographical information for each test reviewed. To access these materials, browse the CTPL Reviewed Protocols and jump to the specified ID#.

The list below summarizes all sources of publicly available test procedures in the CTPL.

Kaplan, Mike. Multnomah County, Oregon Document Review. Publisher: Multnomah County, Oregon.

Summary: These protocols cover all aspects of HVAC and Lighting commissioning tasks for county projects. The author indicates that these standardized procedures fit no real case exactly and that it is critical that the user of these forms (or any standard form) take the time to tailor them to the case at hand.

Seattle City Light, Building Commissioning Assistance Handbook. Various Authors.

Summary: Seattle City Light, an electric utility in Seattle WA, has developed a commissioning-related guideline entitled "Building Commissioning Assistance Handbook", which supports the city's building code requirements and the utilities energy efficiency program. These protocols are a more recent version of Kaplan's Multnomah County protocols. The Building Commissioning Assistance Handbook can also be accessed online at: http://www.ci.seattle.wa.us/light/conserve/business/bdgcoma/cv6_bcam.htm

USDOE/FEMP/PECI Version 2.05 Commissioning Tests, PECI. 1998. Publisher: U.S. Department of Energy and PECI, Portland, Oregon.

Summary: This collection of protocols contains multiple pre-functional checklists, functional test forms, and instructions.

Each of the pre-functional checklists contains the following sections:

1. Submittal / Approvals
2. Requested documentation submitted
3. Model verification
4. Physical Installation Checks
5. Operational Checks
6. Sensor and Actuator Calibration

Each of the functional test forms contains the following sections:

1. Participants
2. Test Prerequisites
3. Sampling and Additional Testing

4. Sensor Calibration Checks
5. Device Calibration Checks
6. Verification of Misc. Pre-functional Checks
7. Testing Procedures and Record

The publicly available documents are intended to provide contractors and the commissioning provider with examples of a format that may be used, and an indication of the rigor of the required pre-functional examinations, functional testing, and documentation for various equipment types. The functional test procedures include details on the expected system response to each step.

Malek, Bill & Caluwe, Bryan. Comprehensive Commissioning Services Guideline. Consultant; Pacific Gas & Electric Co. Rev.0, May 1995, Section 6, 274 pages (never officially published).

Summary: This document details a utility design assist/build program to promote the installation of energy efficient technologies in existing commercial buildings. It details the process and duties of the participants. It includes program requirements and documentation, inspection, verification and functional performance checklists and design and O&M issues. This document has never been officially published and only one complete hardcopy copy is known to exist.

Gillespie, Kenneth. A General Commissioning Acceptance Procedure for DDC Systems. Pacific Gas & Electric Co. Publishing source: Commissioning Test Protocol Library Developmental Release 1.3., November 2001.

Summary: PG&E has developed a general commissioning procedure for direct digital control (DDC) systems. The procedure was developed with the assistance of PG&E's Commissioning Test Protocol Library's Templates and user input as part of a Library upgrade project.

The procedure includes definitions and terminology; a general description of method(s); required information and conditions for initiating a check or test; recommendations for applying general protocols specific applications; uniform method(s) including identification of test equipment and measurement points for performing such checks or tests; identification of requirements for acceptance; and references and bibliography. The protocols included are not intended to be used "as is" on a specific project, but are to be used as guides for developing project specific protocols that aid the user in verifying that a DDC system has been installed as specified and performs as intended. Specific verification check and functional test forms are provided as well as examples.

Chapter 2: Functional Testing Basics

Figures

2.1. Introduction

The Functional Testing Basics chapter provides general guidelines for performing the functional tests discussed for the systems and subsystems in Chapters 3-18. This section is not focused on any particular system type or configuration.

Chapter 2 begins the Functional Testing Guide for Air Handlers. This chapter explores functional testing concepts and practices that will be nearly universally applicable to any test process, regardless of the component or configuration of the system. After gaining an understanding of these subjects, the reader will be able to move about through Chapters 2 through 18 as necessary to learn what they need to know for specific projects.

Each of the chapters 2 through 18 contain both educational information as well as actual testing routines that can be developed and customized for a given project. The chapter topics were selected to reflect the key components associated with air handling systems and are presented in the general order in which the components would be encountered as you moved through an air handling system from the intake to the exhaust. It would be unusual for one air handling system to contain all of the components included as chapter topics, and many systems will contain only a few of the components covered. Most users will focus on the chapters that cover topics that relate to the subsystem they are currently involved with.

2.2. Understanding the Fundamentals

To be truly successful in the commissioning arena, it is essential to understand the background behind how the system will respond to a test as well as what could be causing the observed responses.

To help commissioning providers gain this knowledge, the Functional Test Guide focuses on the fundamentals behind testing. Functional tests are supplemented with information that will allow the commissioning provider to improve their ability to find and correct deficiencies in a cost effective way. Additionally, understanding the physical principles behind the HVAC process under test will be helpful in developing a test procedure that truly verifies the process.

One of the primary purposes behind commissioning a system is to ensure that it functions according to its design intent. If it doesn't, the commissioning provider often identifies the problem that is preventing intended operation. Since we are dealing with machines assembled by humans in a real world (usually under a lot of stress), it is a near certainty that there will be some problems identified by the commissioning process, even on the most well designed, well-implemented project.

If you (as the commissioning provider) have identified a deficiency, then you probably will need to become proactive in correcting it. When a problem has been identified, it is fairly common that the test process is questioned. In other words, the system did not have a problem, it was the test routine that had a problem. If the test is well understood, and you are not just performing steps in a process, then you will gain the following benefits:

- **Confidence that the test was done correctly and the observed deficiency is real.** Without this confidence, you may be intimidated into doing extra work. This additional work would be in reaction to an accusation by the responsible party that the problem does not exist.
- **An understanding of how the test result could be wrong.** Knowing what you don't know is extremely important. This perspective can be helpful when troubleshooting a problem with the other people involved in correcting it.

- **The ability to discuss the facts.** Handing out a trend graph that shows a picture of the deficiency can focus the discussion on the problem, instead of the people. The problem is with a machine, not another person or organization.
- **An expanded knowledge base from which to draw.** In the modern construction process, resolving commissioning problems is a lot like a tennis match. No matter how good you are, every time you hit the ball over the net, there is a chance that it will come back your way and you will have to deal with it again. The bigger your knowledge base is, the higher the likelihood that you'll be able to easily and quickly "return the serve".

> "You can lead a horse to water but you can't make him think."
>
> -Hospital Facility Director commenting on the actions of a mechanical contractor who was core drilling holes over live 480 volt distribution gear with the buss bars exposed

Sometimes, having a complete understanding of the issues is still not enough and the consequences of the less enlightened actions of other parties will still need to be dealt with. The more you understand about the fundamentals associated with the systems, the better prepared you will be to deal with commissioning issues. Providing an understanding of the fundamentals behind air handling systems and how these fundamentals relate to functional testing is a goal of the educational component of the Functional Test Guide.

In some cases, one of the problems that must be faced is that we, as commissioning practitioners probably aren't aware of what we don't know. This problem is especially true when we are dealing with new technology for the first time or with a technology in a unusual application. For example, in moderate climates like San Francisco, coil freezing and freezestat problems are relatively rare. However, if one travels East towards the Sierra Nevada in California, these issues are quite common. Someone who has spent most of their career working along the coast may approach the problem of designing, starting up and commissioning their first system in the mountains in a manner similar to what they might use in the San Francisco Bay area, with frozen coils as a result.

> **"Any sufficiently advanced technology is indistinguishable from magic."**
> -A.C. Clark

While simple in concept, HVAC systems are actually complex applications of technology and physical principles that must function in a dynamic environment to meet the changing requirements of the loads and occupants they serve. The sheer volume of this Guide (including the Design Guide and Functional Test Guide) can be thought of as a statement of one of the current problems in the HVAC industry. We assemble prototypical systems that rely on sophisticated equipment and complex events to function properly, yet we expect these systems to work flawlessly with few modifications when they are first started up.

2.3. The System Concept

The information and testing procedures covered in the guide are viewed from a system perspective rather than a component perspective. This is especially critical for functional testing and the overall success of the system. The performance of the system is dependent on four areas of interaction:

- The individual components in the system.
- The components with each other as a system.
- The system with other systems in the building.
- The building with the ambient environment.

Successful performance is only achieved when these interactions occur in a harmonious fashion in the real world-operating environment. For instance, all of the components associated with the operation of a preheat coil may check out satisfactorily when tested for sequencing logic (i.e. when the control system thinks it's moving the preheat control valve, the valve is actually moving and moving in the correct direction), proper action, and correct arrangement. These pre-functional verifications must be correct for the functional test to be successful.

The goal of the functional test is to look at what happens to this properly installed preheat coil when it is called upon to operate as a part of a complete system. A properly written functional test may uncover the fact that the preheat coil controls properly during a steady-state operating mode, but experiences problems at start-up, when the coil must deal with flow variations and other shifting parameters. Instability in the system flow control loop may cascade into instability in the preheat coil control loop. The system needs to be tested and adjusted so that the components can respond to changing conditions and restabilize without excessive oscillation or damage to the equipment while maintaining tolerable conditions. The functional test's ultimate goal is to identify and correct these system level problems. Thus the guide will take a systems perspective.

2.3.1. The System Diagram

Two important tools to supporting the use of the system concept in the commissioning process are the system diagram and system sequence of operations. The system diagram is a drawing that shows the entire system under consideration in schematic format, not just portions of the system. The system diagram should not be confused with the system schematics and riser diagrams often found on construction documents. While the schematics and riser diagrams included in most construction drawings are useful tools and often are good starting points for developing a system diagram, they often lack important features and/or only show a portion of the system and its components. To gain a better understanding of these differences, Figure 2.1 with Figure 2.2. Both figures are drawings of the same system, but Figure 2.1is the schematic that was presented on the contract drawings and Figure 2.2 is the system diagram, which was developed from this information as well as other information in the contract documents.

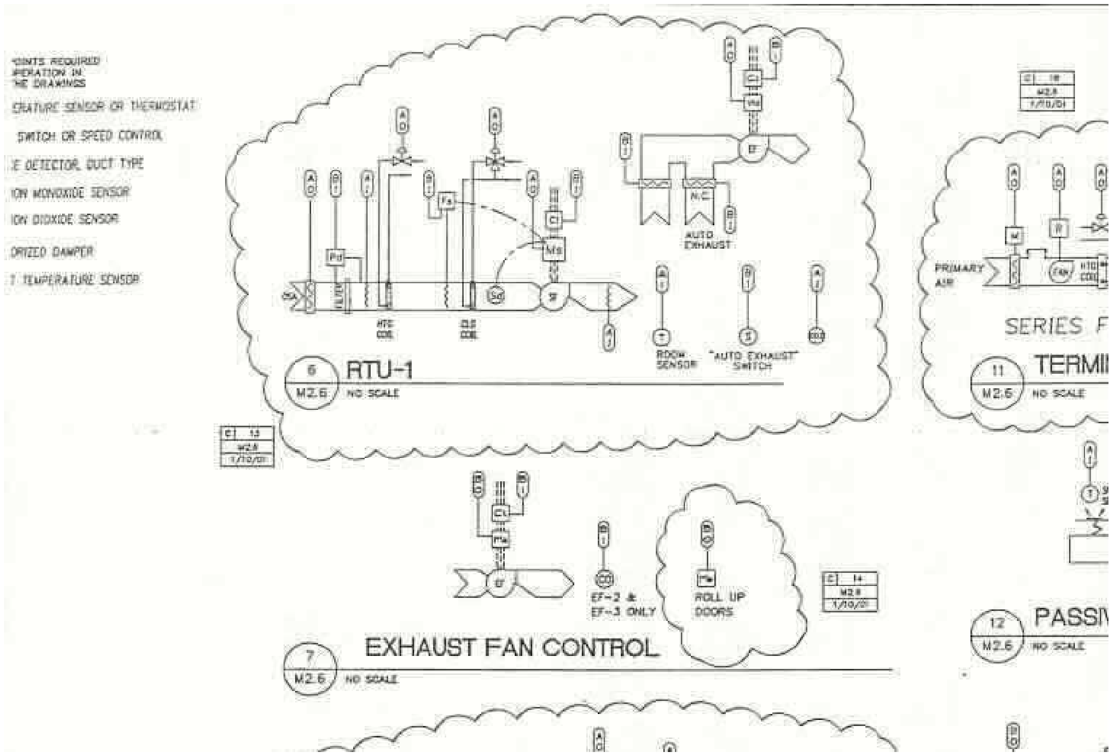


Figure 2.1 System schematic from the mechanical drawings

Notice how Figure 2.2 shows the complete system associated with the air handling equipment, not just the equipment itself. This allows the user to see the entire process and visualize the potential interactions without having to flip between multiple documents. A well-developed air handling system diagram will include the following features:

- The system will be depicted in a logical arrangement but not necessarily a physical arrangement. Relatively passive elements, like elbows, are simply not shown so that the system flow path can be shown in orderly, non-contorted manner.
- The complete air flow path, from point of entry in the building to point of exit is depicted along with all significant system components such as dampers, coils, filters, and fans. Terminal and zone control equipment is shown to the extent necessary to allow a complete understanding of the operation of the system. For simple systems or systems with widely varying terminal equipment arrangements, this may mean that every zone is shown. For more complex systems or systems where one zone may be a typical representation of several other zones, only a typical zone of each type is shown.
- Equipment operating parameters are indicated including flow ratings, horsepower ratings and other pertinent operating data.
- Final control elements that can affect the system operating parameters are shown. In most cases, it is also advantageous to show any sensors associated with the system on this diagram.

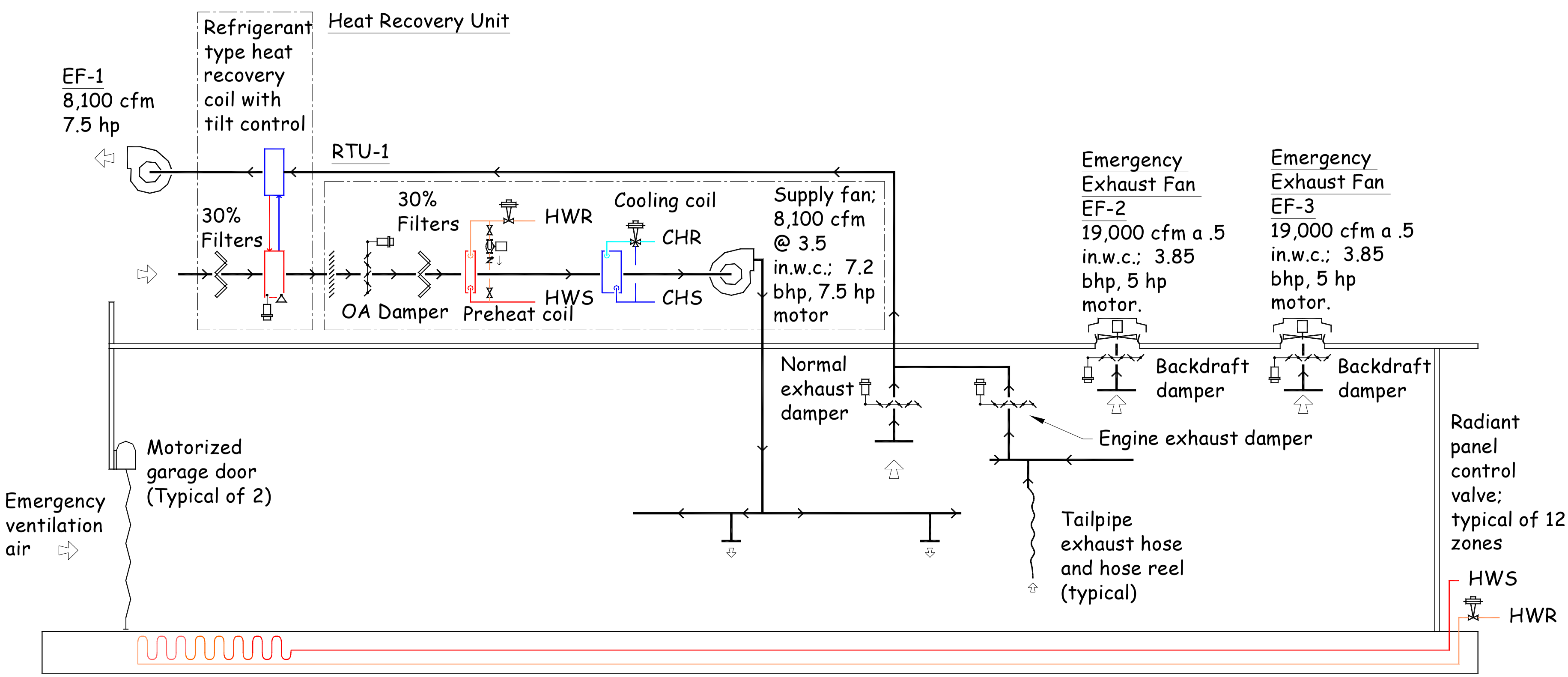


Figure 2.2 Full system diagram for the air handler in Figure 2.1.

On projects where a system diagram does not exist, developing one is a good first step in any commissioning process. When retro-commissioning, the development will familiarize the developer with the system. For new construction projects, the commissioning provider should work with the design team to make the system schematics into system diagrams. This process aids in understanding and documenting the operation of the system. Once completed, the system diagram can serve as the schematic on the contract drawings, an illustration in the System Manual, and as the graphic for the system in the DDC operator's terminal.

2.3.2. Detailed Sequence of Operations

A detailed system sequence of operation or system narrative goes hand in hand with the system diagram in documenting the overall operation of the system. Many times, the sequence provided on the contract drawings and duplicated in the specification provides a good overview of how the system is intended to perform, but fails to address critical details which can make or break the success of the installed system. Consider the following fairly common air handling unit sequence of operation:

> *The control system shall modulate the economizer dampers, heating valve and cooling valve in sequence as required to maintain the discharge set point of the system. The discharge set point shall be reset from 55°F to 70°F as the outdoor air temperature varies from 80°F to 0°F.*

While on the surface, this statement appears to reasonably state the system requirements, there are many details missing. The missing details must be addressed for the sequence to function efficiently in a real-world operating environment. A fully developed version of this sequence is included in 2.17 Supplemental Information.

There are several commissioning related benefits associated with developing a detailed sequence of operations. The most obvious is that the sequence provides a good description of how the system is intended to work under all operating conditions. Working with the design team to develop such a sequence allows the commissioning provider to clearly document the design intent of the system. The detailed sequence is essential for a systems manual and serves as a firm basis for the control system programming. In retro-commissioning applications, taking the time to develop this sort of information based on existing project documents, reviewing program codes, and observing system performance via functional testing and trending provides excellent documentation of how the system is currently functioning.

If the design and construction team do not address the details prior to development of the control program, then most of these details will be addressed in response to a start-up or operational problem; a reactive and potentially costly approach. Scenarios include:

- The problem will be caught and corrected by an experienced controls programmer but will not be documented in the project construction documents.
- The problem will be caught by an experienced controls programmer but will not be corrected without a change-order from the Owner. If the Owner does not issue the change order, then the sequence will be programmed incorrectly.
- A less experienced programmer who won't recognize the problem will program the sequence as written.
- The commissioning provider will catch the problem during functional testing. Correction may require a change order.

- If the functional testing plan does not identify the problem, then the problem will most likely show up as an operational issue.

The bottom line is that creating a detailed system-oriented sequence of operation is important for a successful commissioning process. This sequence will provide a firm basis for functional testing, the systems manual, and a re-commissioning plan, all of which are important parts of the commissioning process.

2.4. Testing Hierarchy

There is a fairly specific order of testing associated with the functional testing process. Generally, testing should proceed from the support system level, to the component level, to the subsystem level, to the system level. In most cases, tests at the support system level and component level can occur concurrently. For example, the electrical contractor can verify the power distribution equipment associated with an air handling unit while the mechanical contractor is testing the coils and terminal equipment, and the control contractor is verifying sensor wiring and calibration. Simultaneous testing is also possible at the subsystem level as long as the various subsystems are not interdependent for the process under test.

For a typical air handling system, the general order of testing might be as follows:

Verify, start-up, and test the supporting utility systems such as the power distribution system, chilled water system, and steam system.

While the supporting utility systems are being tested, verify connections and calibration for the various control elements and safety interlocks associated with the system.

Verify, start-up and test the individual components directly served by the supporting utility systems like the cooling and heating coils and terminal equipment.

Test the integrity of any safety systems to the extent possible without operating the fan. These tests give the test team a measure of confidence that the system will be protected when the fan and its drive are started up. For example, a meter might be connected across the contacts on the system's discharge static pressure limit switch and the set point changed so that it is above the ambient pressure to verify that the contacts change state and that the switch must be manually reset. As another example, the permissive interlock circuit should be verified to ensure that the outdoor air dampers are open on a 100% outdoor air unit prior to start-up. The functionality of the dampers and the limit switches and their settings should be verified prior to actually allowing the interlock to start the fans.

Verify, start-up, and test the supply fan, return fan and exhaust fans. Note that there may be a specific order in which the fans should be started to minimize over or under pressurization or maintain necessary flow relationships. One hundred percent outdoor air systems may require the simultaneous start-up of the supply and exhaust fans or temporary limits on the capacity capabilities of the fans to prevent pressurization problems when they first start.

Immediately complete testing the safety systems so that they will protect the system for the remainder of the test sequence.

Test control functions associated with individual system components like the mixed air low limit controller the discharge static pressure control.

Test integrated control functions where multiple components must function together. The discharge temperature control sequence is a common example because maintaining set point will require the stable, repeatable interaction of a cooling coil, heating coil, and economizer sequenced using one loop or as cascading control loops.

Test the system for totally integrated operation. Functions such of these involve the interaction of multiple independent components that control process variables that impact the inputs to the control loops associated with other process variables. Instability in one loop can quickly cascade into instability in other loops, and these instabilities may exist only under specific operating conditions. These tests include power failure response with restart and recovery, or testing the interactions of the building static pressure control system with the economizer cycle and the fan capacity control system. A system that was stable in all tested operating modes during a fall start-up may become unstable during colder weather when the effects of economizer damper non-linearity become more pronounced. These instabilities can have far reaching impacts on the performance of the building as can be seen from the example in *Chapter 18: Integrated Operation and Control*, Figure 18.1.

2.5. Documentation

Documentation is an important part of any commissioning process. Having the documents listed below on hand for the functional testing process will be helpful for creating and performing the tests.

2.5.1. As Built Submittals And Shop Drawings

These documents will provide valuable information regarding the characteristics of the equipment installed on the project. If the commissioning provider has been involved in the shop drawing review process, then this information should already be available to them in their project files. If not, then copies should be obtained from the appropriate contractor(s) prior to developing functional tests.

Ideally, the machinery characteristics depicted on the shop drawings will be identical to the specified characteristics in the contract documents. However, substitutions made by the contractor during the buy-out process often result in machinery being provided that is similar to what was specified, but not identical. In a perfect world, the design team will have reviewed these differences. But occasionally equipment is approved or installed without approval and does not meet the specified performance requirements; thus, any effort to functionally test the equipment to prove that it meets the specified levels of performance will be unproductive. Pointing out a problem of this sort after the equipment has been purchased and installed will result in some heated discussions. Issues of this type must be resolved prior to functional testing since efforts aimed at proving unachievable performance will need to be repeated once the deficiency is corrected.

The bottom line is that it is highly desirable for the commissioning provider to be included in the shop drawing review process. When shop drawings are approved, a design shifts from concepts that exist as lines on paper and words in specifications to three-dimensional, bolted-in-place reality. And, while there may be some costs associated with modifications during the shop drawing review process, these costs will be far less than those associated with modifying it after it has been fabricated or installed. For example, a commissioning provider reviewing an air handling unit shop drawing might notice that there is no access section provided between the preheat and cooling coil, which makes cleaning coils and installing temperature control elements between the coils virtually impossible. Once the lines and words become physical walls, ducts, pipes and machinery, it may be nearly impossible to resolve the problem in a satisfactory, cost effective manner.

The benefits of time spent by the commissioning provider in reviewing shop drawings and submittals include:

The commissioning provider becomes familiar with the machinery that they will be testing.

The commissioning provider identifies commissioning and operations and maintenance issues for correction at a point in time where the costs associated with correction will be minimal.

An independent "second set of eyes" reviews the proposed equipment selections in light of the project's design intent and specification requirements.

While the commissioning provider is not directly responsible for ensuring that the specified machinery and levels of performance are furnished and installed, they have a vested interest in this process since a successful test is unlikely unless the machinery is capable of the intended performance.

2.5.2. Installation Inspection Report Forms

In most cases, installation inspection report forms are generated by the commissioning provider and are a part of the project documentation package associated with the commissioning process.

Documentation of verification checks can be accomplished by a variety of methods including:

- Collecting a signed certification letter or other verification from the responsible party.
- Having the responsible party sign the functional test procedure.
- Informal verification by the executor of the functional test.

Having this information readily available during the functional testing process can provide a handy reference if problems are encountered or questions arise regarding the systems readiness for testing.

2.5.3. Performance Sheets

Performance sheets are often generated by the commissioning provider but can also be standard forms provided by the manufacturer. The general intent is to provide a convenient place to document key system performance parameters during the start-up process. Examples of the information documented include motor voltages and amperage, component pressure drop, system temperatures and other physical parameters related to the system. Many times, the functional testing process will involve documenting these parameters as a system responds to a test process and then comparing them to the base case documented at start-up in the equipment performance sheets.

2.5.4. Installation and O&M Manuals

The equipment installation and operation and maintenance manuals are essential for reference while developing and performing a functional test. Often these manuals contain specific information and requirements that should either be verified prior to start-up or verified by functional testing. This information is also an important part of the documentation package generated by the commissioning process and will be a key component of any systems manual developed by the commissioning team.

Unless otherwise directed, the equipment suppliers will furnish the equipment installation and O&M manuals with their product when it is shipped. There are several potential problems with this approach.

- Often the information provided in this manner becomes part of the colorful paper that is seen blowing around the construction site when the field staff, intent on moving the machinery from the shipping trailer into the building, set the documentation aside and then forget to recover it after they complete the equipment setting operation.
- To develop good installation checklists, start-up plans, and functional testing plans, it is essential that the commissioning provider and construction team have access to this information prior to the arrival of the machinery.

Requesting that the suppliers provide the manuals immediately upon approval of the shop drawings can usually circumvent these problems. In most instances, obtaining the information at this point in the process is not a problem but may require some persistence on the part of the commissioning provider and contractors since it is not the normal sequence of events. Many manufacturers will be happy to provide the information earlier in the process because it allows them to satisfy one of their contractual obligations at a point in time when they are focused on the project rather than responding to a request for information that was provided but subsequently lost when the equipment arrived on site. Furnishing the information directly to the commissioning provider and contractor ensures that the information is going to the people who are directly responsible for including it in the construction documentation package.

2.5.5. Balance Information

In most instances, the balancing contractor will need to have substantially completed their balancing efforts prior to the final phases of functional testing of the air handling system. Assuming they have used proper techniques, the information they have gained in their efforts will be a good indicator of the system's baseline performance and readiness for final testing.[1] Reviewing the balance information prior to the final steps in the functional testing process because can provide insights into how the system is going to respond to tests. In some cases, the information in the balance report may result in a decision to delay final testing until a deficiency documented by the balancing process is corrected.

2.5.6. Operating Sequence

Having a good operating sequence is a critical component for developing a good functional test plan and a good system narrative for the projects system's manual. If such a narrative does not exist, it is often in the commissioning provider's best interest to work with or push the design team towards developing one. If the details of the operating sequence are not anticipated and addressed by the design process, then "mother nature" will bring them up for resolution in the field. As a result, the problems will be addressed reactively, rather than being addressed proactively by parties with a detailed understanding of the design intent.

---

[1] Typically, it will take several weeks or even months for the balancing agency to assemble the field data into a final report. However, the raw data and field forms contain all of the information required by the commissioning provider and should be available immediately after the balancing work. It may be desirable to include language in the balancing contractors specification section or scope of work that directs them to make the raw data available to the commissioning team prior to publication of the final report to avoid contractual disputes in the field that could delay the commissioning process.

2.5.7. As Found and As Left Conditions

Most people recognize the need to document the results of the functional tests as they move through the testing process. What is sometimes overlooked is to document the "as found" and "as left" conditions; the system state immediately prior to and after the test process.

The "as found" information can be critical to recovering from a problem encountered in a test because it usually represents a stable system state that can be achieved by the current system configuration, even if it is not the final state required by the design intent. If problems are uncovered by the functional test, returning the system to the as found state will allow the loads it serves to be maintained while a solution to the issue is developed. Documenting "as found" conditions typically involves noting flow rates, pressures, temperatures, and other system operating parameters as well as the set points, tuning parameters, valve and damper positions, and other inputs that create them. As a general rule, if you move something, or change a setting, note the original position or value before making the change.

Documenting the "as left" information serves several purposes. It formally records the operating state that the system was left in after testing. For a successful test sequence, this record documents successfully achieving design intent. If you are returning the system to the state it was in prior to the test, this documentation provides a good crosscheck against the "as found" information to verify that parameters are returned to the previous state. For additional discussion of "as left" conditions, refer to Section 2.14 - Returning to Normal.

2.6. Training

Training is an important component of the commissioning process. A well designed training plan supported by the operations and maintenance manuals, a systems manual, and videotapes of the training sessions will help ensure that the building is operated efficiently and according to the design intent. Training and documentation also help ensure that the benefits associated with the commissioning process persist for the life of the building and its systems.

2.6.1. When to Start

Traditionally, the commissioning process includes formal training for the operating staff after functional testing. At this point in time, most of the items required to complete a thorough, formal training process will be in place:

- The systems will be fully operational and available to demonstrate operation.
- The operating staff will be hired.
- Much of the as-built information will be available.
- Operations and maintenance manuals will be available.
- A draft of the systems manual including the system narratives and design intent will be available.

While not required, initiating training earlier in the commissioning process is desirable. Including the operating staff in the construction observation, start-up and functional testing processes can provide invaluable training that is difficult to duplicate in a formal training setting. Early involvement allows the operating staff to observe the fabrication of the systems and building and observe many things that will be concealed when the building is complete. Participating during start-up and testing provides first-hand insight into the operating fundamentals of the systems and equipment, as well as the design intent. This involvement will also expose operators to the nuances of the system operation and the resolution of any difficulties produced by these issues. When operating the building, these experiences will help operators respond more efficiently to unusual situations that occur. In addition, exposure to the functional testing process will give them hands-on training in some of the test sequences that they will use as part of a continuous commissioning program or to troubleshoot operational issues that arise over the life of the building.

As a commissioning provider, you can encourage the Owner to hire some of their operating staff early in the project to allow them to reap the benefits of being involved in the construction and start-up of the building and its systems.

2.6.2. Supplemental Information

Most training processes rely heavily on resources provided by the manufacturers and suppliers of the various systems installed in the building. Much of this information focuses on the specific model or product line installed on the project and assumes that the fundamental knowledge behind the product is well understood by the trainees. While an experienced operating staff may understand the fundamentals, some staff members may be new to the field or may not have received adequate training in the past. Thus, there may be significant benefits to be gained in supplementing the standard training information provided by the manufacturers with information and training regarding fundamentals.

Generally, there will be two avenues open to you as the commissioning provider if you which to supplement the standard training in this manner.

Supplemental Information from the Manufacturer: The first avenue involves contacting the various manufacturers associated with the project and asking them to furnish training materials that deal with the fundamentals behind their products. Most manufacturers offer this type of information, which can often be downloaded from their web site.

It may also be desirable to request that the manufacturers supplement their product specific training with some training in the fundamentals behind their equipment. This requirement can be included in the training portion of the commissioning specifications.

A Short-Term Course Yields Long-Term Benefits: In an effort to ensure that a new heat recovery system would be operated properly, the Facilities Director initiated training sessions in which the project's design and start-up team discussed the theory behind the system, how the system was configured and programmed, how it was to be operated, potential operating problems, and how to solve these problems. The classes were held towards the end of the construction cycle and included time in the equipment rooms examining the equipment that had been discussed earlier in the training room. As a result of the classes, the operating staff were familiar with the system when it was brought on line and were an extremely valuable commissioning resource. In the long term, the facility's Owner was the big winner because the proper operation of the new system coupled by the overall diligence of the operating staff with regard to performance and efficiency allowed the facility square-footage to be increased by 94% while the energy consumption increased by only 17%.

Supplemental Information from the Commissioning Provider: The second avenue involves the commissioning provider providing supplemental training to fill in the gaps not covered by the manufacturers. For example, providing some training in psychrometrics in layman's terms can provide significant benefit for all parties as illustrated in the story in the side bar. The educational information contained in this guide can also be used as a resource for training. The electronic format will allow the user to cut and paste the information to target specific training requirements.

At first glance, providing this supplemental training and information may appear to be an overwhelming task. However, once the package is developed, most commissioning providers will find that they can easily adapt it to specific projects and offer it to their clients as a value added feature for little cost. Providing this information promotes good client relationships, solid operating practice, and persistence of the enhanced performance and efficiency.

2.6.3. Control System Training

Building control systems can be complex and operating them properly is essential for building efficiency and performance intended by the project's design. Because of this complexity, the training associated with control systems deserves special consideration. As a commissioning provider, you may want to include some of the following features in the training program associated with your project's control system.

- **Provide supplemental training on control theory and technology:** Before dealing with the specifics of any given control system, it is important that the operating staff have a firm grasp of control fundamentals, the sensing and actuation technologies, and the control algorithms and tuning practices.
- **Provide a phased training approach:** To fully understand the operation of a control system, a large amount of information must be learned; attempting to learn it all at once can be overwhelming. It can be useful to develop a training plan that spreads the control system training over a period of time, beginning before start-up and ending near the end of the warranty year. Typical phases are as listed below:

  Provide training in fundamentals prior to the start-up. This will allow the trainees to relate the fundamentals they are learning to the fundamental system components like sensors and actuators as they see them installed.

  Provide training on the fundamentals of the specific control system that will be used on the project including the controllers, system architecture, and operator interface. The staff will become familiar with how the system is configured and basic operator interface functions during start-up.

  Prior to the integrated functional testing of the various building systems, provide training on the specific operating sequences. This will allow the operating staff to become familiar with the operating strategy the interface to the control system while participating in the functional testing.

  Six to nine months into the warranty period, provide a training session with the control contractor devoted to answering operating staff questions and concerns. This gives the operating staff time to become familiar with the control system and discover their weak points, as well as uncover day-to-day problems with the control system.

  Obviously, if the operating staff is not on board early in the construction process, then it will be necessary to modify this training format to accommodate the actual hiring schedule. And, smaller buildings with less complex systems and/or a less sophisticated operating staff may not require training of the depth and breadth described above. In any event, spreading the control system training out over a series of classes that move from the basic to the complex will provide advantages that can not be achieved in a concentrated training agenda. The proposed training schedule also offers the advantages to the commissioning provider in that it will provide them with a "refresher course" on the intended operation of the control system to be commissioned.

- **Provide factory training for key operating personnel:** One of the best ways to ensure that a projects control system and the features it contains are understood and utilized to the fullest extent possible is to send key operating personnel to the factory training course associated with the control system. Most factory training classes are taught by experts on the system who will immerse the students in 3 to 5 days of detailed instruction and experimentation with the hardware and software. While somewhat expensive when compared to the more normal training approach, there can be significant benefit to all parties when the operating staff has been provided with factory training early in the start-up process.

  The Owner benefits the most because the trainee will understand the control system in detail. This will provide them with the capability to operate the building to its peak of performance and efficiency and will also allow them to serve as a "second set of eyes" to monitor the work of the control contractor during construction and subsequent upgrade and repair work. It may also eliminate the need to have the control contractor perform some routine service functions since the trainee will be familiar with many of the necessary procedures and can perform them in house.

  The commissioning provider will benefit because the trainee will be a valuable resource during the commissioning process. The trainee will tend to become a participant in the process rather than an observer, which will make them a better operator and bring added value to the commissioning process.

  The trainee will gain knowledge and experience and may be more motivated to operate the building efficiently and participate in the commissioning process. This, in turn, will further expand their knowledge base.

  The contractor will benefit because the trainee will fully understand their system and will have been exposed to its features and benefits.

2.6.4. Factory Training

Control systems are only one of the areas where factory training can yield significant benefits. Owners of large buildings or complexes may benefit from sending some of their key personnel to factory schools for some of the major components like air handling systems, chillers, pumps, and steam specialties. Even though the specific lessons learned will apply to the equipment of one manufacturer, the general knowledge gained can be transferred to similar equipment from other manufacturers. Although the costs for the training may be quite high, the benefits will often outweigh the costs in terms of operating savings and avoided costs. Many times, the knowledge gained will prevent an operating error that could have resulted in costs that exceed the value of the training by many times over.

2.7. Verification Checks

Verification checks are an important prerequisite to functional testing. In the field, verification checks are often referring to as pre-start checks, start-up checks, or pre-functional tests. Regardless of the specific terminology used, these items consist of necessary checks prior to activating a system or immediately subsequent to its activation to ensure that it is safe to operate and ready for the more rigorous processes associated with a functional test. Typical examples of this type of check include:

- Verifying piping and wiring connections
- Verifying calibration and sensor locations.
- Verifying safety settings.
- Flushing and static pressure testing of piping systems.
- Verifying belt tension.
- Verifying electrical parameters like voltage and amperage.
- Verifying pressure and flow ranges for utility and support systems.

This section describes different ways in which verification checks are handled by commissioning providers, including delegating to contractors and factory testing.; And how this relates to system readiness. And ends with checklist.

2.7.1. Verification Checks Development

Most of these verification checks are specific to the make and model of the equipment and are usually well addressed by the manufacturer's installation and start-up documentation. Thus, most commissioning practitioners simply rely on the manufacturers information for these checks, supplemented by insights gained in the project team's past experience. It is not unusual for the commissioning provider to delegate the responsibility for developing the necessary verification checks to the contractors and their suppliers, providing only editorial input and coordination to the process followed up by spot checks to ensure documented compliance with the requirements. The development of verification checks depends on a variety of factors including the contractual arrangements with the installing contractor and the commissioning provider, the type of systems and equipment associated with the project, the complexity of the system, and the level of rigor required.

Each chapter of the Guide will direct the user to test procedures in the CTPL that may include verification checks appropriate to the chapter's topic. Many of the functional tests in the CTPL include verification checks in their list of prerequisites. The CTPL also contains some separate documents for verification checks, as summarized in *Appendix A Overview of the Commissioning Test Protocol Library*.

The information and test procedures in the Functional Test Guide assume that the necessary pre-functional verifications are addressed by the equipment manufacturers or by tests in the CTPL. The Functional Test Guide only discusses critical or unique pre-start or start-up considerations when the checks will have a significant impact on the functional testing, represent areas that are not well covered by typical manufacturer checklists or verification checks currently available in the CTPL. The Verification Checks checklist provided in Section 2.7.2 can be appended with requirements listed in the CTPL verification checks, or the test writer's own verification checks.

Seismic restraint is one area that is not well addressed by the verification checks included in the CTPL. Section 2.17 Supplemental Information contains information to be used as a starting point for commissioning providers charged with seismic verification.

2.7.2. Verification Checks Checklist

The following generic checklist has been developed to aid in documenting the completion of the verification checks. It is arranged to allow the test executor to check off the requirement after collecting a certification letter from the various parties responsible for the major subsystems. A dated signature is used to document completion of individual items not related to any particular subsystem. This form could be used “as is” or tailored by the user to meet the needs of their project and process via editing.

Verification Checks Checklist

Link to Verification Checks Checklist

2.7.3. Factory Inspections and Tests

For larger facilities and/or facilities with specialized air handling needs, it is not unusual for the air handling system to be a custom fabricated unit to meet the specific project needs. For this class of equipment, it is often desirable an Owner’s representative, a design engineer’s representative, the commissioning provider, and a mechanical contractor’s representative to inspect the unit at the factory prior to shipment. Factory testing large or highly customized air handling systems provides the following advantages:

- **Factory testing can be witnessed by the parties with the highest level of interest in the outcome.** Factory tests for air handling equipment typically include leakage testing, capacity testing, variable speed drive testing, and verification checks for factory-installed controls. By witnessing the verification testing of critical performance parameters, the designer, Owner, and contractor can feel confident that the special performance features that were purchased have been provided. The air handling unit manufacturer also has a vested interest in this test approach because it allows them to document that the unit as shipped met the project specifications and limits their liability for defects that may show up in the field due to improper shipping, handling, or installation. The factory often provides a better test setting than the construction site since special instrumentation required is readily available.
- **Design, operation and maintenance features can be verified prior to the unit’s shipment and corrections can be made at the factory.** Even with a detailed specification and submittal review process, misinterpretations can occur. Occasionally a special feature does not work out as anticipated. Detecting these problems in the factory allows them to be corrected in a controlled environment by people intimately familiar with the required fabrication processes. Most equipment manufacturers will have a vested interest in this approach because they avoid the costs associated with sending a skilled craftsman out to the field to correct a deficiency not caught by their own quality control process.

In some instances, limited field-testing will be required to re-verify some of the factory test items. This is especially true for larger units that must be disassembled for shipment. The responsibility for correcting problems that show up in these re-tests usually falls to the contractor, not the equipment supplier. If the unit was not factory tested, the lines of responsibility for correcting problems uncovered in the field can become controversial, especially if the problems are not immediately discovered.

2.7.4. Factory Supervision, Assembly, and Start-up

Some components associated with air handling systems, like variable speed drives for example, may require factory assembly and start-up or factory supervision of the parties performing the work on the unit after it arrives at the project site. This requirement may be invoked by the Owner or the designer as a quality assurance process, or it may be a requirement of the manufacturer. In any case, there are several commissioning issues related to this work that should be considered.

The start-up plan needs to coordinate these requirements into the start-up schedule. In addition, good planning and coordination will ensure that all prerequisites required by the factory for their work are in place and verified prior to their arrival. If the factory representatives travel to reach the project site and the equipment is not ready, then they will be unable to perform their work in a timely manner and the entire project start-up may be delayed. In addition, the factory may seek reimbursement for their costs associated with travel to and from the site as well as lost time if they arrive and cannot perform the intended work.

As can be seen from the story in the sidebar, the involvement of a factory service technician in the reassembly process does not guarantee that something will not be misinterpreted or go unnoticed. Include time and steps in the start-up procedure to have a "second set of eyes" inspect and verify critical items can be desirable and provide redundancy.

For some machines, there may be requirements associated with a proper and safe start-up that may be less obvious to someone who is not intimately familiar with the equipment. In fact, this is one reason for including a factory start-up requirement in the project specifications or manufacturers start-up requirements.

Assembly instructions that are thrown away yield a field joint that's blown away: Occasionally major problems can occur even with a factory-supervised start-up of an air handling system. Such was the case for large, custom make-up air handling unit. The size of the unit required that it be fabricated with flanged shipping joints to allow it to be disassembled after construction at the factory into modules that could be shipped by truck to the project site. The reassembly instructions required that a factory-furnished gasket be installed on the flanges and the bolts that were removed from the joint at the factory be reinstalled. When the bolts were removed at the factory, they were placed in a bag that was then tied to one of the bolt holes on the flange. Unfortunately, the reassembly instructions were not followed and the field joints were instead assembled with self-drilling screws. This arrangement provided little clamping force at the flange since the thread engagement occurred only in the gasket. The section was held in place by gravity and friction between the unit base and supporting structure. This condition went undetected, despite a factory-supervised start-up, but became alarmingly obvious when an air hammer event triggered by a power surge and an interlock failure blew the unit apart at the seam.

In addition to pre-start and start-up checks, some components may require adjustment or inspection during the initial hours of operation. In some cases, someone with special training, typically the factory service representative, must make these adjustments. Some of these procedures may be critical to preventing damage to the machinery during the initial run cycle and subsequent testing and operation. Examples include:

- Re-tensioning of belts after their initial run-in period.
- Oil changes for oil lubricated bearings or gear boxes after the initial run-in period.
- Blade security checks for the locking bolts on axial fan adjustable pitch fan blades after the initial run-in period.

It may be necessary to adjust the start-up schedule and functional testing plan to accommodate requirements of this type.

2.7.5. System Readiness

The start-up and testing of air handling equipment is usually dependent on several other systems in the building being operational. Typically, these include:

- Electrical Distribution System
- Cooling or Refrigeration System
- Heating System
- Control and Safety Systems
- Graphical User Interface
- Trending and Data Logging Systems
- Life Safety Systems

Successful testing of the air handling system will require that these related and supporting systems be online, tested, and functional, so that the testing of the air handling equipment will not be adversely impacted by deficiencies in its supporting utility systems. However, on projects with fast paced schedules and multiple construction phases, full commissioning of the utility systems is often not possible. For instance, it may be necessary to start up and commission an air handling system in an office building during the fall months in order to meet a December occupancy deadline. This start-up could occur without functional refrigeration systems since the economizer cycles could provide the necessary cooling during the winter months. However, proceeding in this manner has risks, as discussed in the side bar. With phased installation of equipment,

Unseasonable Weather, Unusable Space: By pushing occupancy ahead of the start up of its refrigeration equipment, an office building located in the Midwest was caught off guard by a mid- winter heat wave. The mechanical systems consisted of large, field assembled air handling units served by field erected direct expansion refrigeration systems. Occupancy was targeted for the end of December, and the mechanical design was not completed and approved until early the preceding spring. In order to work with shipping schedules and the need to coordinate major erection work for both the air handling systems and the refrigeration systems, the design-build team elected to build up the refrigeration systems during the winter, after the building was occupied. The air handling systems and large ductwork could be assembled, started up and tested in time for occupancy. This plan seemed to be going well until the February heat wave arrived. Without operable windows, indoor temperatures rapidly soared as the outdoor temperatures climbed to 80°F. The tenants had to send their employees home causing them significant losses in productivity and creating leasing problems for the Owner.

it is important to keep several things in mind:

- Any phased commissioning process that requires starting up and operating a system prior to construction and commissioning of one or more of its supporting utility systems places the project at greater risk for problems. The team should recognize that they are increasing their exposure and fully evaluate the potential outcomes.
- If an air handling system is started up and placed in operation prior to the completion of one of its supporting subsystems, then it will typically be necessary to repeat a portion of the air handling system's functional test after the start-up and commissioning of the untested subsystem is complete. Retesting will add time and cost to the commissioning process and will often create a disruption in service. These items need to be anticipated and accounted for in the commissioning plan and budget.
- Some portions of the air handling system's functional test plan may be skipped or deferred at the time of initial start-up due to the phased installation approach. When these portions are deferred, the door is opened for simply never performing that part of the test for a variety of reasons including oversight, difficulties scheduling an appropriate test window for an operational system, and difficulties in reconvening the test team. If these test steps are permanently deferred, then any operating deficiencies will either persist in an undetected state, often wasting energy or other resources, or manifest themselves as an operational issue.

In addition to coordinating air handling system testing with the testing and start-up of its supporting utility and subsystems, there may be specific procedures from the manufacturer that must be followed during the initial hours of operation if the functional integrity of the air handling equipment is to be ensured. Finally, the test plan will typically have a hierarchical structure, as discussed in Section 2.4 Testing Hierarchy. The successful testing of the entire system will be dependent on the successful completion of subsystem testing, which, in turn, will be dependent on the successful testing of the individual components. The following sections will discuss these topics in greater detail.

2.7.5.1. Electrical Distribution System Readiness

Prior to starting up and functionally testing the air handling equipment, all components of the electrical distribution system required for the operation of the air handling system need to be verified, started up, and tested to the extent necessary to support the safe operation of the air handling equipment. This testing should include all primary and secondary distribution and supply equipment, including the control system.

At first glance, this may seem obvious because the electrical motors that power the air handling system simply won't work without voltage supplied to their terminals. However, just because voltage is available to the motor's terminals does not necessarily mean the electrical system is ready to support the sustained operation of the motor. In general, the following items should be complete:

- Programming and manufacturer's start-up procedures for the motor starters and variable speed drives
- Motor overloads should be selected and set to match the requirements of the motors
- All wiring connections should have been checked for security and proper connection points.
- Phase rotation should have been checked and adjusted as required to assure the proper direction of rotation for the air handling system motors.

2.7.5.2. Cooling/Refrigeration System Readiness

The cooling and refrigeration systems associated with the air handler to be functionally tested needs to allow the system to meet the cooling and dehumidification requirements mechanically if it cannot meet the requirements using outdoor air. Operating the air handling system without mechanical refrigeration when it is required can result in loss of environmental control and may result in damage to the system and building envelope.

The cooling and refrigeration system readiness deserves careful consideration well in advance of the air handling system start-up because addressing and resolving issues can be time consuming. For instance, on a fast-paced construction project, it is not unusual for the start-up team to begin operating and functionally testing the refrigeration equipment prior to insulation of the distribution-piping network. This method allows the refrigeration equipment to be commissioned so that the air handling commissioning can begin. If the refrigeration equipment commissioning occurs during the summer months when ambient humidity levels are high, then condensation will occur on the distribution piping. The condensation can cause the following problems:

- **Water damage to the building envelope and finishes due to condensation dripping off of the uninsulated piping** This damage can lead to other delays and contractual problems because the damaged finishes need to be repaired prior to acceptance by the Owner at the contractor's cost.
- **Building structural degradation or indoor air quality problems** Uninsulated lines may be located out of sight in vertical shafts or insulated walls. The condensation that occurs on the lines may be light enough that it can be absorbed by the surrounding building finishes without causing water damage. Or, the visible indication of the condensation problem may be remote enough to evade detection. The accumulated moisture can corrode building structural elements and piping, leading to future maintenance problems. If insulation and building materials located in the immediate vicinity of the piping absorb this moisture, they will provide an ideal environment for the growth of mold and mildew.
- **Damage to the pipe insulation itself if the insulation is installed over the wet lines** Water that is trapped inside the insulation, and its vapor seals, corrodes insulated piping and equipment. If the integrity of the vapor seals is not good, then water will migrate from the humid ambient environment through the exposed, non-vapor sealed insulation surfaces. This moisture will condense in the insulation and lead to corroded piping and the ultimate failure of the insulation system. In a hot and humid environment, it is not uncommon to find the insulation on a chilled water line to be totally saturated 15 to 20 feet upstream of an exposed, non-vapor sealed insulation surface.
- **Scheduling problems** Once the cooling systems are started up and operational, there is considerable pressure on the project team to keep them operational to allow the air handling systems they support to be started up and tested. Shutting down the system to allow the piping to dry off so that it can be properly insulated is undesirable, which paves the way for the problems associated with installing insulation over wet piping.

If condensation issues are brought up for discussion early in the project, they are often dismissed as minor annoyances that probably will not occur if schedule is maintained. However, if these issues become field problems, the pressure to complete the building on time can make it nearly impossible to resolve them in a satisfactory manner. Thus, it is probably better to raise the issue early and "plant the seed" for discussion at a later date.

2.7.5.3. Heating System Readiness

Readiness requirements associated with the central heating equipment are similar to those discussed in the preceding paragraph for the cooling and refrigeration systems. If there is a heating load on the air handling system, then the heating system and its associated fuel supply system needs to be verified, started up, and tested to the extent necessary to support the safe operation of the air handling equipment. Operating an air handling unit without a functional heat source when the freezing is possible can cause significant damage to the unit. During functional testing, systems with reheat need a functional heating supply to maintain comfort conditions in the occupied zone, even if the heating system operation would not be required by the current seasonal conditions.

The coordinated start-up of the heating system relative to the start-up of the air handling systems it serves is an issue that needs to be considered early on in the planning process.

2.7.5.4. Control and Safety Systems Readiness

A fully functional and robust control system is critical for the successful functional testing of the air handling equipment. The control hardware directly related to the system to be tested must be fully commissioned prior to the functional testing of the air handling system. At a minimum, the necessary programming and physical hardware that allows the air handling system to execute its full control sequence must be in place, calibrated, and verified (actuators stroked, point to point wiring checked, etc.). In some cases, the communications network may also be required.

Many functional testing procedures involve pushing the systems to their design and operational limits which, to some extent, places the system at risk. For example, testing the mixed air low limit software on an economizer equipped system may involve lowering the discharge temperature set point below the mixed air low limit set point and observing the results on a cold day. Ideally in this situation, the mixed air low limit software should take over and prevent the temperature in the mixed air plenum from dropping to the point where the freezestat trips. But, if there is a problem with the software, then this test sequence will place the system at risk for damage due to the introduction of freezing air. Since the freezestat is intended to protect the system from this occurrence, it is important that the freezestat is fully tested and known to be operating satisfactorily prior to performing the functional test on the mixed air low limit software.

As a general rule, hardware safeties and interlocks that prevent damage to the equipment, system or building in the event of a failure must be commissioned and fully functional prior to performing the functional testing of the system they serve. Examples of this type of safety include freezestats, permissive start circuits, pressure relief doors, and duct static pressure safety switches. The installation of these components is discussed in the Control System Design Guide Chapter 3, Section 3.4.1.

As with the other prerequisites, coordinating the commissioning of the control system with the overall commissioning of the air handling system deserves some advanced planning supplemented by careful monitoring during the construction process. Control contractors (and commissioning providers) often find themselves in a tough situation because the completion of their work is highly dependent on the completion of the work of the other parties involved in the construction process (see the discussion in the Control System Design Guide, Section 2.2.2 The Contractor's Requirements and Challenges). The commissioning provider needs to carefully monitor the progress of the control work in relationship to the other work on the project, the proposed schedule, and the time available prior to functional testing. If there is significant delay in work required for the control and commissioning work to proceed, there should be reasonable delay in the completion date for the control system and commissioning work. If not, then the issue needs to be brought to the attention of the project team for resolution as soon as possible.

As was the case for the other subsystems, the details of these requirements associated with commissioning the control system are beyond the scope of this guide. But, due to the crucial nature of the control system to successful air handling system operation, control-related topics are included in just about every chapter of the Guide.

2.7.5.5. Graphical User Interface Readiness

Functional control system graphics are desirable, but may not be necessary to accomplish the functional test. If the system graphics are available, they can aid in observing the functional test progress and results. In addition, the features associated with the graphics can be functionally tested at the same time as the air handling system

If the system graphics are not available for the functional test, a separate functional test will need to be executed to verify these graphic features at a later date. The following graphic capabilities should be verified but may not affect functional testing of the air handling system:

Graphic response to alarms.

Graphic nesting; i.e. the ability to get to a related graphic by a direct link from a current graphic.

Graphic dynamics and response time to real data.

The test writer will need to determine the level of graphic functionality required for the air handling system functional test.

2.7.5.6. Trending and Data Logging System Readiness

Trending capabilities for air handling unit functional testing is desirable but may not be necessary. System trending can provide valuable documentation and a second set of eyes and hands during a functional test. However, it is possible to structure tests or use data loggers in a manner that makes the trending capabilities unnecessary for functional testing.

In addition to start-up, trends are required for ongoing operation, warranty phase commissioning, and continuous commissioning functions. Thus it is imperative that the commissioning provider spends some time during the design phase commissioning process to ensure that the automation system structure and performance characteristics specified will support the required trending functions for the project. This is discussed in greater detail in 2.16.1 Laying the Groundwork. This design phase work should be supplemented by functional testing to ensure that the targeted trend capability goals have been achieved in the field.

If the trending capabilities will be used for the functional testing of the air handling system, then the functional testing of the trending system will need to occur prior to that of the air handling system. On the other hand, if the trending and monitoring requirements for the air handling unit will be handled in other ways (i.e., data loggers), then the functional testing of the trending capability can be deferred until after air handling unit testing.

The following items may need to be verified, but may not affect functional testing of the air handling system:

Point lists for continuous trending.

System response times under fully implemented trending.

Trend data archiving.

The test writer will need to determine the level of trending functionality required for the air handling system functional test they are writing and modify the prerequisites list appropriately.

2.7.5.7. Life Safety System Readiness

Many air handling systems provide life safety functions in a coordinated effort with the Fire Alarm and/or Smoke Control System. If the operation of these systems must be integrated with the operation of the air handling system, then these systems must be available, verified, and fully functional to allow the integrated operation with the air handling system to proceed.

Integrating the operation of the life safety systems with the operation of the air handling system can be a complex task involving the coordination and interaction of just about every trade involved in the project. (See *Chapter 17: Management and Control of Smoke and Fire* for additional discussion on this topic.) A commissioning provider can bring significant value to the project as well by making sure the commissioning plan coordinates the start-up and commissioning of these functions and allows sufficient time for the process to occur prior to the functional testing of the air handling system.

2.8. Warranties

Warranty statements are an important part of the turnover package provided by the contractor to the Owner at the completion of the project and are typically a part of the commissioning documentation. However, there are commissioning related issues associated with warranties that go far beyond the simple terms and conditions contained in the various warranty statements. The beginning of the warranty period often coincides with the point of beneficial use - the point in time where the Owner is receiving benefit from the building and systems. At this point, the responsibility for their operation and maintenance transfers from the contractor to the Owner. The warranty period is often the point when the contractor receives the final payment on the project. Since the commissioning provider may be placed in the middle of all of these events, the following issues are worthy of consideration.

- The commissioning provider should understand the basis for the component and system warranties to ensure that the testing sequences that will be used will not violate any of the warranty requirements. Often, it is desirable to have the proposed test processes reviewed by the contractors and suppliers to obtain their buy-in and avoid warranty problems down the line.
- The warranty requirements are typically located in the project contract documents. These requirements are typically found in a variety of places including the Architect's Division 1 requirements, the mechanical spec general conditions, the specification sections dealing with the component(s) in question, and the actual contract, like the *AIA General Terms and Conditions of Contract*. Occasionally, the language in these different locations is contradictory. Resolving conflicts prior to the beginning of the warranty period is beneficial to all parties. Any contradictory statements can dilute the effectiveness of the warranty protection. The commissioning provider can serve their own interests as well as the Owner's by reviewing the warranty requirements as a part of their project familiarization process and proactively pursuing the resolution of any conflicts prior to the beginning of any warranty period.
- The warranty provided by the contractor is often based on warranties provided by the various subcontractors and equipment suppliers. In most cases, the warranty provided by the manufacturer of a particular piece of equipment will begin with the start-up of the

equipment. However, the intent of most contractor warranties provided for the Owner is that the warranty period begins when the Owner begins receiving beneficial use of the equipment, systems, and building. Usually the start dates of the warranties for the various components and the start date of the warranty to the Owner are not the same. For example, a fan may need to be started up and tested well in advance of the air handler functional testing and the Owner will generally not receive beneficial use of the system until functional testing is nearly complete. There are several issues related to these differences in warranty start date.

Since the contractor is generally obligated to provide a warranty on all of the components, systems and equipment for which they are responsible starting with the date of beneficial use, they will be forced to assume some risk for the failure of various components whose warranty started prior to that date. Usually, this means that they will carry an allowance in the project budget tailored to cover their perception of that financial risk. Contractors who find themselves faced with a warranty claim near the end of their contractual warranty period may need to pay for the repairs as opposed to turning to the supplier of the equipment that failed. As a commissioning provider assisting a client in dealing with a warranty claim, it is good to keep these situations in mind.

Temporary operation of equipment and systems can blur the point in time when the contractor's warranty is deemed to start. (The technical details of temporary operation are covered in Section 2.9.) For example, consider a project where the contractor is running behind schedule and asks the Owner if they can run the incomplete air handling systems to provide temporary cooling and dehumidification so that the drywall work can proceed more quickly. Is the Owner receiving beneficial use of the systems since their operation is allowing the contractor to complete the project on schedule? Is the contractor receiving beneficial use because they were contractually obligated to complete on schedule anyway and the Owner is just being a "nice guy" by letting them use the building systems rather than bring in temporary equipment of their own? Does the warranty of the incomplete portions of the systems begin with the temporary operation date, or does it start at the point in time when the subsystems are complete? It's hard to say what the right answers are to these issues, but they can become a "hot buttons" at the time of contract closeout or when a problem shows up late in the warranty year. Since the commissioning provider is often involved with the project through the warranty year and may be performing end of warranty period testing, it is in their best interest to proactively establish a starting point for the warranty period that is agreeable to all parties.

Phased construction projects where some areas become occupied prior to the completion of other areas are also instances that blur the point in time when the contractor's warranty is deemed to start. In many cases, phased warranties are provided for these projects. For the protection of all parties involved, the lines of distinction associated with the phased warranties need to be clearly defined. The commissioning provider may want to be proactive in establishing the warranty plan.

Given the nature of DDC control systems and the fact that the control contractor is usually "caught between a rock and a hard place" at the end of the construction cycle, it is not uncommon for significant control work to be completed after the substantial completion of the building and air handling equipment. Generally, the owner is receiving beneficial use of the system and the warranty period is initiated. The control system warranty may be short-changed if there was a significant difference between the times that the air handling system was placed in service and when the details of the control system were completed. The commissioning provider is in a good position to advocate for the owner that the full warranty benefit is realized.

- Beneficial use of the building, the commencement of the warranty period, and final payment to the contractor are often related to successful completion of the functional testing process. This is a double-edged sword that gives commissioning providers a great deal of power but also sets them up to be a "bad guys" if there are problems. Significant percentages of the contract value (typically 5-10%) are often retained until beneficial use is achieved. Usually, this retention represents all of the contractors profit on the project plus some of the overhead expense. This retention is often used as a financial lever to help persuade an otherwise unmotivated contractor to complete their work and correct any outstanding problems identified by the functional testing process. But it can also place extreme financial pressure on the contractor that can make a bad situation worse. Commissioning providers involved with the Owner and design team in negotiating solutions to problems identified during functional testing may want to keep this in mind. Most problems have a variety of satisfactory solutions, some of which may be more palatable than others to a contractor under financial pressure.

The commissioning provider needs to be aware of these warranty issues since some portion of the commissioning work will occur during the warranty period. Any tests or other commissioning processes should be structured in a manner that does not jeopardize the warranty protection provided by the contractor, and the warranty start date should be clearly understood by all involved parties.

2.9. Temporary Operation

Many times the general contractor will ask the MEP trades to run their equipment to provide temporary heating, cooling or ventilation to allow work to proceed on the project when environmental conditions would otherwise preclude it. The design team, owner, and commissioning provider should be involved in this decision especially if it has not been addressed by the project specifications and other contract documents.

From the owner's standpoint, the contractor may be operating the equipment for his own benefit, not the owner's and the proper maintenance and care of the equipment will be considered the contractor's responsibility during this time. In addition, the owner may want to be sure that the warranty starts from the time that the equipment is accepted, not the time the contractor starts it, even though the equipment supplier may considers the warranty period to start when the equipment starts. The owner may also be concerned with both the local code officials and insurance underwriters. In most cases, these entities will only allow systems to be operated in a temporary state if the building, equipment, and its occupants are protected.

From the designer's standpoint, the operation of the systems needs to be accomplished in a manner that does not damage or contaminate them. The following list summarizes a minimum level of completion for temporary operation:

- The control and safety system must be complete enough to safely run the unit. Usually this means that freeze and static pressure safeties need to be in place, motor overloads need to be set, and some sort of basic temperature and fan volume control sequence needs to be in place.
- If cooling is to be provided, the lines serving the unit and all the accessories and specialties will need to be complete, tested, insulated and vapor sealed.
- If the temporary heating source is steam or high temperature hot water, then that piping system must also be tested and enough insulation will need to be in place to prevent the

tradesmen working on the project from accidentally being burned if they brush up against the piping.

- Temporary filters will need to be in place to prevent contamination of the duct system by construction dust. It is important to note that the nature of this dust may require filtration levels or efficiencies that are higher than what will be required by the normal operation of the system. Additional temporary filters may also be required to protect return ducts at their termination points.

Missed Dust Leads to Misdiagnosis: On one medical office building project, the contractor started up the air handling systems to provide temporary heat and ventilation so that the drywall work could proceed on schedule. Despite being advised by both the Owner and the project engineer of the need to maintain proper filtration in the units to prevent the fine dry-wall dust from contaminating the duct systems, the contractor failed to monitor and change the filters on a regular basis. As a result, the filters collapsed and allowed unfiltered air to be circulated in the duct system for several days. The Owner did not discover this problem until the radiology suite that was served by the unit started experiencing difficulties with false indications on their X-rays. The false indications were traced to air-borne drywall dust from the contaminated duct systems. The spots caused by the dust could have lead to a misdiagnosis with significant litigation liabilities. As a result, there were significant remedial costs to the contractor to clean up the ducts and pay for the loss of facility use during the interim period.

The designer also will be concerned about the loads that temporary operation will place on the system and any central utility systems serving it. These loads could actually exceed those that the unit would see in normal operation. For instance, a system designed for a 30% minimum outdoor air rate may not be able to meet the heating load when it is operated at 100% outdoor air in the middle of the winter to remove construction fumes. In addition, the heating coil piping configurations and control sequences used by the 30% outdoor air system (the normal operating mode) may be unsafe for use at 100% outdoor air without some modification.

From the commissioning providers standpoint, temporary operation will just about always require that the functional testing occur in two phases instead of as one test at the point when the construction of the system is complete. This can have a significant impact on the commissioning budget, plan and schedule.

Another commissioning impact associated with temporary operation relates to the hierarchy of the testing and start-up process (see Section 2.4 for more details)**.** Subsystems must be complete and ready to run prior to the temporary start-up of the system they serve. Sometimes, in the contractors rush to complete the subsystems, they forget about the need to test. For example, the insulator is applying insulation to the projects piping systems in an effort to prepare them for the temporary start-up, but the systems have not been pressure tested, you may want to meet with everyone to review the difficulties associated with locating a leak when pressure testing an insulated piping system. Remind everyone that there will be a pressure test and clarify who will bear the cost of any repairs, including damage to the work of other trades. Discussing what ***might*** happen is easier than a disagreement about what ***did*** happen.

At the opposite end of the spectrum, if you discover that the chilled water system is about to be placed in operation for testing or temporary cooling but the insulation work is not complete, you may want to take steps to ensure that the construction team has a plan for:

- Drying the condensation from the piping and equipment prior to insulating them.
- Providing moisture and condensation protection under the uninsulated lines for the work of the tradesmen that are installing ceilings, wall coverings, and floor coverings.

Regardless of the specifics of the temporary operating requirements, prior to releasing the system for temporary operation, the commissioning provider will want to verify that all pre-start and start-up checks have been performed satisfactorily, and that enough of the control and safety system is in place to allow the unit to operate without endangering itself or the occupants of the spaces it serves.

2.10. Elements of a Functional Test

Based on current best practice, a functional test should include all of the following components:

- Test name
- General documentation of the building, system, actual test conditions, personnel involved, time, date, etc
- Conditions under which the test is to be performed
- Test duration
- Data to be gathered
- Instrumentation methodology and locations
- Data acquisition requirements including tolerances, number of samples, etc
- Results to be obtained, including some method of documentation and any analytical calculations required
- Measurable acceptance criteria
- Precautions associated with executing the procedure
- Description of the test procedure steps in the order they are to be performed including:

    The prerequisites required to be ready to perform the test.

    The steps necessary to prepare for the test.

    The actual steps in the test process.

    The steps necessary to return the system to normal operating status.

    Instruction regarding information that needs to be documented and a place to record this information.

In actual practice, some of the components may be addressed informally through meetings and field discussions.

2.11. Basic Tools, Instrumentation, and Equipment

Many of the functional tests in the CTPL contain a list of the tools, instruments, and equipment necessary to perform the test. In addition, the Functional Testing Field Tips table in each chapter of the Functional Test Guide lists the instruments and tools typically required to perform the tests associated with the topic of discussion in the chapter. The tools in the following list are basic tools that you will probably need in the course of commissioning a project, regardless of the testing to be performed. They are broken into two categories: essential and desirable. The tools in the essential list are strongly recommended for any basic tool set for commissioning work. The tools listed as desirable would make good additions to the essential tool set as funding becomes available.

These lists are just starting points and are by no means comprehensive. The longer you work as a commissioning provider, the more you will find that your tool and equipment set grows and adjusts to accommodate your personal needs and preferences. In any case, having your own tools and equipment offers advantages over borrowing the things that you need from others working on the project site.

You can make sure that you have what you need when you need it.

You will have direct knowledge of the accuracy, capabilities, and limitations of your instruments. This knowledge can be important in evaluating the information you gather.

You will have with you what you consider to be the right tools for the job.

Essential Tools, Instrumentation, and Equipment

- **Hand tools:** A good set of hand tools includes an assortment of wrenches, screwdrivers, pliers, wire cutters, wire strippers, channel locks, punches, hammers and other common hand tools. These tools are especially useful in a retro-commissioning environment where it is unlikely that there will be tradesmen available with the tools that you need.
- **Flashlights:** Having both a large flashlight and a mini flashlight is essential. The mini flashlight will serve for most purposes, but the larger light can be useful for inspections above ceiling spaces or other areas.
- **Clipboard:** Having a clipboard is important to provide a portable writing surface as well as a way to hold on to notes and test procedures. For a little extra money, you can get one with a storage compartment that provides a convenient way to carry some of your other equipment around on the site with you (Figure 2.3).

Figure 2.3 Storage type clipboard

- **Safety Equipment:** Hard hats, safety glasses, ear protectors, and steel-toe shoes are generally good ideas on construction sites and around machinery and may be mandatory at some locations.
- **Calculator or Slide Rule:** Having a small pocket calculator available makes quick field estimates easy to accomplish. Having a slide rule means you can do the same thing without batteries.
- **Psychrometric Chart, Tables, and Other References:** Access to a psychrometric chart makes analyzing an HVAC process easier to accomplish in the field. Having some

pocket hand books and frequently used tables can also be useful for helping you solve problems in the field as they occur. Useful references might include:

- The ASHRAE Pocket Handbook and similar handbooks by other professional organizations
- Steam tables
- Refrigerant tables
- A list with frequently used equations, formulas and units conversion factors
- Tables of pressure loss factors for common duct and pipe fittings
- Small scale floor plans of the building you are working in

Laminating these papers will make them more durable in the field and will also allow you to draw and erase using a wax pen or crayon.

- **Multi Tool:** A folding multiple tool device, like a Leatherman or a Gerber Tool, can come in handy in the field. Just remember to take it off your belt and put it in your checked luggage before going through airport security on your way home.
- **Camera:** Documenting existing conditions and problems with a camera can be a real time saver and memory jogger. Digital cameras have the advantage of providing an instantaneous picture that can inserted in reports and e-mail. Some commissioning providers use a digital camera plugged into a laptop logged into the Internet to witness pressure tests or observe operating conditions from a remote location.
- **Indelible Markers:** Several "write on anything" markers in different colors can be useful for marking sensor locations on pipes and ducts. Soap stones and white grease pencils are useful for making sensing port locations on black iron pipe.
- **Jeweler's Screw Drivers:** A set of small screw drivers with different blade styles and sizes can be useful for working on control system components for calibration and other adjustments as well as working with small terminal strips.
- **Drill and Drill Bits, Hole Plugs:** A rechargeable, portable electric drill is useful in the field to make holes in ducts for measuring air flows and temperatures. Hole plugs in the form of rubber stoppers or sheet metal caps seal your test ports when you are done. (Figure 2.4)
- **Duct Tape and Silicon Sealant:** Both of these products can be handy for temporarily sealing test openings created in a duct system or for repairing the vapor barrier on insulation when it is broken by a test port penetration. They need to be used with caution in some process environments however. The off-gassing from the silicon sealant can create quality control problems for some clean room processes.

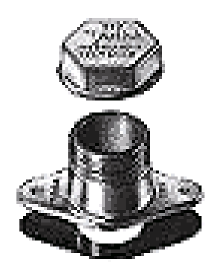


Figure 2.4 Duct Test Port

(Image courtesy of the Vent Fabrics web site)

- **Tape Measure and 6 Foot Folding Ruler:** Having at least one of these measuring tools is nearly mandatory. Having one of each can be handy for taking measurements in different situations.
- **Electrical Meters:** Having a small portable multimeter and an amprobe available can allow valuable troubleshooting information to be readily obtained. In inexpensive pocket multimeter has the advantage of portability. However, a larger, higher precision meter can be useful for cross checking calibration and input signals on control systems.
- **Lab Grade Thermometers:** Electronic thermometers win the contest in terms of ease of use, durability, and cost, but it's hard to argue with a lab grade fluid in glass thermometer. There are no batteries to fail and no calibration adjustments to make. Thermometers for several common temperature ranges can be useful for providing a baseline for a relative calibration test or troubleshooting. Pairs of thermometers in common ranges can provide a good way to document temperature changes across heat transfer elements. Mercury thermometers were the original instruments of choice in this category, but with the growing concern over hazardous waste, thermometers using other liquids are becoming popular because if they break, they do not pose a contamination problem. If you purchase these devices, it's a good idea to make some carrying cases for them out of PVC pipe large enough to accommodate the thermometer encased in a layer of bubble wrap.
- **Sling Psychrometer:** While somewhat harder to use than an electronic hygrometer, a sling psychrometer will provide a reliable measure of wet bulb temperature. The instrument uses mercury thermometers so there is never a need to change batteries or calibrate. Be careful not to swing it into a wall or equipment housing. For tight quarters, units are available with a battery-powered fan.

Figure 2.5 Lab grade thermometers

Note the 2/10 degree scaling marks. (Image courtesy of the Fisher Scientific web site)

- **Inclined Manometers:** A set of inclined manometers and several different sized pitot tubes allow a variety of pressure and flow readings to be taken for a relatively low first cost. At least two meters should be obtained, one in the 0 to 1/4 inch water column range for low pressure readings and another in the 0 to 10" water column range for higher pressures. This is one instance where the advantages of the electronic versions of these instruments might outweigh the advantage of the inclined manometer measurement with no power supply required. However, the inclined manometers will usually cost significantly less than the electronic meter and offer a good compromise between price, flexibility, ease of use, and accuracy. The meter set should be supplemented with several static and pitot static probes. The probes come in a variety of lengths to allow ducts of all sizes to be traversed. The typical diameter is 1/4", but short, flexible, smaller diameter probes are also available. These probes are useful where pressure relationships must be verified by sliding the probe under a door threshold or through the crack between the door and the jamb.

- **Precision Pressure Gauges:** A set of high accuracy pressure gauges will be useful for measuring coil and valve pressure drops as well as performing pump tests. This is another area where the electronic version may provide better accuracy and flexibility, but at a cost premium. A set of two or three precision gauges may be more viable as an initial investment.
- **Backpack:** A backpack is a convenient way to carry all of this equipment around. It allows you to keep both hands free yet have everything you need close at hand.
- **Pocket Tape Recorder:** A small portable dictation type tape recorder can be a convenient way to gather nameplate data in the field or record observations. It also is a convenient way to take meeting minutes (be sure to tell everyone you are doing it first). A voice activated feature is especially convenient since it allows you to simply clip the mike to your shirt collar, slip the recorder in your pocket and make comments or document data as needed.
- **Anemometer:** A rotating vane anemometer can be a convenient way to estimate low velocity air flows. Rough estimates of unit flow rates and minimum outdoor air flow rates can be obtained by taking velocity readings across filter banks or intake louvers with this device. The readings may not be exact, but they will be better than a guess. (Figure 2.6).

Figure 2.6 Portable anemometers

(Images courtesy of the PG&E Energy Center)

- **Tachometer:** The speed at which shafts rotate can be a key indicator of performance. There are a variety of tachometer options available such as mechanical tachometers, digital tachometers, and strobes that allow the shaft speed to be measured without actually being in contact with the shaft. The strobe tachometer is generally the most expensive option, but it also is the most flexible and safest approach. When working with a strobe tachometer, it is important to remember that the strobe will freeze the shaft motion at the fundamental speed (the speed that you want to measure) as well as at its harmonics (even multiples of the speed you want to measure).

Figure 2.7 Tachometers

The instrument on the left must be in contact with the rotating shaft to measure rpm. The strobe on the right can be used for non-contact measurement by "freezing" the motion of the rotating element.

Taking shaft speed measurements will involve working in close proximity to rotating machinery and extreme caution should be exercised when taking these readings. Make sure that you do not have any items which could become entangled with the shaft and pull you into the machine. If possible, take shaft speed readings through the openings provided with the belt and shaft guards in place. If the motor and shaft are mounted internal to the fan casing, you need to be aware that if someone opens the access door to the unit while it is operating, there can be considerable wind pressure generated which can throw you off balance.

- **Dataloggers:** Even though most current technology buildings are equipped with DDC systems that allow trending of the data required to commission the system, having several data loggers available with a variety of input sensors to supplement this capability can often be useful for the following reasons:

Figure 2.8 Data loggers

A wide variety of data logging equipment is available in the current market at modest cost. Capabilities range from small, dedicated purpose units like the loggers pictured to the left to multiple channel, programmable loggers like the unit pictured on the right.

Proper commissioning or troubleshooting of some systems may require a sensing point that was not included with the DDC package. Using a datalogger available to pick up this information is often the quickest, least costly way to obtain the data.

Retro-commissioning applications in older buildings may involve working with non-DDC controlled systems. For these situations, portable dataloggers provide an economically feasible approach to obtaining trend data.

Most commercial DDC systems are restricted to a trending rate of 1 sample per minute or more. This is suitable for many applications, but can be a limitation for a identifying problems in some processes. Many dataloggers are capable of sampling at frequencies of once per second or more.

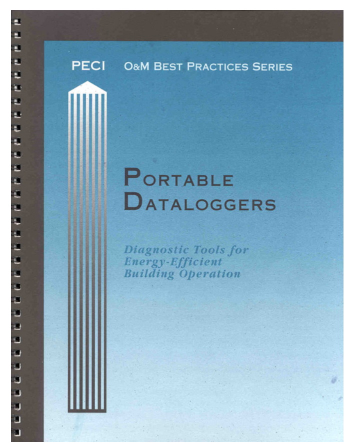


Figure 2.9 Portable Datalogger Guide

This guide on portable dataloggers, along with other manuals outlining O&M best practices can be downloaded free of charge from www.peci.org/om/index.html

The capability to log four temperatures, one or two amperages, and status of motors and lighting will allow a commissioning provider to address most of the common problems encountered in the field when the need exists to supplement existing DDC equipment or troubleshoot an isolated problem. Humidity and low and high range pressure logging capability can also be useful. In situations where multiple systems and parameters must be monitored, significantly more datalogging capacity will be required if there is not a DDC system available. If the commissioning provider does not have the datalogging capacity necessary, they can lease dataloggers and input sensors or purchase the additional dataloggers.

Most investments in current technology data logging will pay for themselves quickly in improved diagnostic capability, reduced trouble shooting labor, and more accurate energy savings projections.

Desirable Tools, Instrumentation, and Equipment

- **Shortridge or Other Electronic Air Data Multimeter:** An electronic pressure measurement meter like the meters used by most balancing firms is an expensive but highly useful tool. Most meters of this type can measure pressures in the thousandths of an inch water column range accurately, and thus can detect and measure low velocity pressures and air flow rates. Typically, they have a variety of ranges and often will perform the calculation to convert a velocity pressure to velocity, allowing direct readings of velocity to be taken. They also can be purchased with a memory feature that allows multiple readings to be taken, stored and averaged allowing a pitot tube traverse to be made easily by one person.

Figure 2.10 Air Data Multimeter

(Image courtesy of the Shortridge Company)

- **Radios:** For large projects or for tests requiring coordinating multiple parties at different locations, a set or even several sets of radios are invaluable. Generally, the more expensive radios are worth the extra money in terms of range and flexibility, especially inside buildings and on large projects where numerous people are using radios to communicate.
- **Personal Organizers:** Personal organizers, like the Palm Pilot™, can be quite useful for commissioning providers and others working out in the field. At a minimum, having a ready reference for schedules, appointments and contacts can be useful. There are also numerous engineering applications available that can make life easier including units conversion programs and psychrometric programs.
- **Electronic Thermometer:** Electronic thermometers are a rugged and easy approach to field temperature measurements. The accuracy will probably not be as good as a good lab grade thermometer, and this reduced accuracy should be kept in mind when taking readings. Many of these devices use thermocouples for inputs and the accuracy can easily be ±2° or more degrees. Accuracy will not matter for differential readings taken with the same meter or relative calibration work, but it may be significant in instances where absolute accuracy is important.
- **Electronic Hygrometer:** Electronic hygrometers offer a more rugged, faster way to take humidity measurements compared to a sling psychrometer. However, these devices may not offer the accuracy of a good sling psychrometer with matched liquid filled thermometers. Special

Figure 2.11 Electronic Hygrometer and Electronic Pressure Gauge

(Images courtesy of Omega Engineering and the PG&E Pacific) Energy Center) equipment is often required to perform accurate calibrations of electronic hygrometers.

- **Electronic Pressure Gauge:** Electronic pressure gauges often offer a more versatile approach to multiple range pressure measurements, but usually at a cost premium compared to precision bourdon tube type gauges. The electronic version most likely offers better accuracy than the mechanical version.

- **Dataloggers:** As indicated previously, expanding your stock of dataloggers is desirable. Adding datalogging capacity or the ability to log different data sources will improve your ability to diagnose and correct problems in a timely fashion.

- **Signal generators, and Field Calibrators:** In most instances, the calibration of sensors will be the responsibility of other parties. However, in a retro-commissioning or troubleshooting environment and in situations where calibrations need to be crosschecked, field calibrators can be a useful tool. In addition, having this type of calibration equipment will allow a true, multipoint calibration to be performed in the field.

  Multi-function units frequently allow one instrument to simulate a variety of fairly standard functions, as shown in the upper left in Figure 2.12. Dedicated instruments, like the RTD calibrator shown in the upper right in Figure 2.12 may offer better precision or the ability to simulate many different variations of a particular device.

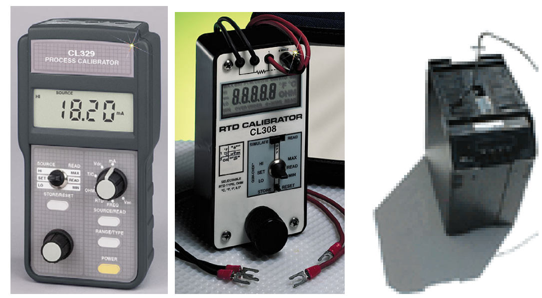


Figure 2.12 Field Calibration Equipment

A multiple function calibrator is shown in the upper left, a RTD calibrator in upper right, and a constant temperature dry bath at the bottom. (Images courtesy of Omega Engineering and the PG&E Pacific Energy Center)

  When using field calibrators and simulators, there is one important point to remember. Unless the simulator is simulating the measured parameter in a manner that subjects the entire sensing system to the simulation, then calibration to the simulated signal is only calibrating a portion of the system. For example, if a 4-20 ma field calibrator is installed in place of a duct mounted RTD with transmitter and the readings at the controller are adjusted based on the signals from the calibrator, then the calibration assumes that the information provided by the transmitter/RTD assembly is accurate. To improve upon this situation, an RTD simulator could be installed on the transmitter in place of the RTD. Now, adjustments made include any inaccuracies placed in the input by the transmitter. But, the process still assumes that the RTD is providing accurate information to the transmitter. Immersing the transmitter in a bath that subjects it to the required calibration temperatures (Figure 2.12 right picture) calibrates the entire system. Of course, the calibration will only be as good as the reference standard used to determine the bath temperature.

- **Portable Folding Ladder:** Having your own ladder will usually pay for itself in the long run because it can take a surprising amount of time to locate, borrow, and return a ladder on a construction site or in an existing facility.

- **Portable Folding Table And Chair:** As a commissioning provider, you will find that you are working with manuals, drawings, binders, laptop computers, and other equipment on a frequent basis. Having a portable folding table and chair will allow you to quickly set up a temporary work area on a project site and get organized.

All tools should be used safely and with consideration for the labor practices at the job site. Work rules and trade practices can vary by location. You probably have found that at some sites there is a lot more latitude regarding how "hands on" you can be. These rules can also change when the project transitions from being owned by the contractor to being owned by the Owner. Finally, corporate safety plans and practices may restrict the amount of hands-on work that can be accomplished by someone who is not an employee of the company. For your own sake and the sake of safety and labor relations, always check on the rules and practices that are in effect on a site before diving into working on a machine with your tools.

2.12. General Precautions and Preparations

As you prepare to perform a functional test, there are several precautions and preparations that need to be considered to protect personnel and equipment. Precautions for the industrial building environment have been included in Section 2.17 Supplemental Information.

These discussions do not represent a comprehensive list of issues and safety concerns associated with working around machinery and performing functional testing. Thus, PIER, LBNL, and PECI assume no responsibility for how they are applied beyond the teaching purposes of this guide. It is up to the commissioning practitioner to assess each project for its own specific risks and liabilities and to plan their testing process and site visit protocols accordingly.

Personnel safety will continue to be discussed throughout this guide. Sometimes, you won't realize that a certain procedure has risk until you actually start performing it. If you can't do something safely or are not comfortable with an evolving situation, then stop and reevaluate. You may need to develop a better approach or may need to be assisted by someone with more experience in a particular area prior to proceeding.

Working safely on a commercial construction site is usually a matter of complying with the existing safety requirements, including a hard hat and eye protection, and steering clear of hazardous work areas. As a commissioning provider on larger projects, you may be contractually obligated to attend a safety training session prior to being allowed to work on the site. In addition, you may be required to attend regular project safety meetings. It is important to assess this requirement when you are preparing your bid or proposal for the commissioning work and budget for it accordingly.

Working safely on an industrial site can be more complicated than a typical commercial construction site. For information on industrial personnel safety practices, refer to Section 2.17 Supplemental Information.

Equipment safety is an underlying theme in many commissioning test plans. By their nature, some of the functional tests that you will perform will place the systems at risk. One of the major goals of this guide it to help commissioning providers assess specific test situations and understand:

Risks to the system in normal operation.

Safety measures to adequately protect the system from those risks.

Tests that ensure that safety measures function properly.

Generally, this information is presented in the *Functional Testing Benefits* table in each chapter under *Other Benefits* and the *Functional Testing Field Tips* table in each chapter under *Precautions*. The test writer should evaluate this information with other project specific information, and then develop their test plan accordingly. When exposing a system to a potential risk through a functional test, structure the test to minimize that risk and be ready to respond if a problem does occur. The key question is what level of risk is appropriate for the benefit gained.

For example, one of the most difficult things for a large HVAC system to do is to simply come online and stabilize.[2] The start can be a simple scheduled start or it can be a recovery from a power failure or fire alarm. The start-up event places a step change into the system that impacts most of its control loops and can ripple out to the supporting utility systems. If there is instability in any one of the loops, a restart is one of the situations under which this instability will likely show up. If the system has not been tuned to dampen these upsets, then they can quickly escalate out of hand. On large systems, the pressure and flow surges associated with a restart can trip safety systems and ultimately can become destructive if left unchecked. So, for some large systems, a restart from a shutdown places the system at risk for a failure. As a result, you might consider a simple test to shut down the system, perhaps under near design climate conditions, and then restart it. Is this test worth the potential risk of disruption of service or potential damage? In almost all situations the answer will be "yes" for the following reasons:

In a real operating environment, most systems will have to deal with a restart, even if they are intended to run 24 hours per day, 7 days per week. At some point in time, there will be a power failure, a fire alarm, or an equipment failure that will knock the system off-line. If you don't do the test, then "mother nature" will, probably in the middle of an ice storm with record low temperatures on Christmas Eve. At that point, any failure will be unanticipated and there will be limited resources available to deal with it.

2 If problems are discovered, you and the test team will be there to observe the response, use the information to formulate a solution, and abort the test before any damage occurs. In addition, since the test was a scheduled event, any problems or failures will be less of a surprise to the test team and the building occupants.

All tests may not be worth the risk. For example, verifying that the system's pressure relief doors will blow open by forcing the discharge smoke damper to slam closed has the potential for causing more problems than the benefit of such a direct test would provide. If the pressure relief doors did work flawlessly, then you would have absolute assurance of their functionality in a real event. On the other hand, if a problem occurred and the doors failed to function properly, then considerable damage could occur including rupturing of the air handling unit casing or duct system and distortion of the smoke dampers due to air hammer effects. As a result, you might choose a less rigorous test approach that provided nearly the same degree of certainty of the damper functionality. One option might be to use a duct testing machine and a specially fabricated test boot to subject only the door to its rated release pressure and verify that it opens. Another might be to use a spring scale to exert the force that correlates to the doors release pressure on the door and verify that it opens.

The preceding example shows that commissioning providers need to carefully evaluate all aspects of a system's test requirements and match the needs of the system with the limits of time, budget, risk, and benefit. Items to consider when developing and executing the test procedures include:

- **Risk:** What level of testing rigor is appropriate for the risk? How dangerous will the test be and how dangerous will the system be if not tested for a particular situation?

  Contractually, it is important that the Owner and/or contractor approve of the testing plan. A well-designed test will not put a system at risk in any manner that it would not normally encounter at some point in its operating life. However, tests are often targeted

[2] Field experience indicates that many systems are kept in operation round the clock simply because of the problems associated with restarting them if they are shut down.

at verifying the stability of the system and the performance of interlocks and failure functions, which can put the system at risk. Since it is the Owner's or the Contractor's system, they need to formally acknowledge and accept those risks.

In understanding the risks imposed on the system by the test, the commissioning provider should understand the problems that could occur in the event that the system fails the test. If the risks of damage to the system are high, it may be good to have a plan of action in place for different scenarios. The plan should include:

A specific decision point that when reached will result in the test being aborted without question.

2 **A plan of action** that will be used to shut down the test including specific assignments for responsibilities and actions associated with the test shut down.

3 **A recovery plan** if the premature shut down of the test places the system in a mode that will cause significant disruption at the loads or pose other operational problems.

- **Degree Of Certainty Required:** How much assurance do you need that the outcome predicted by the test will be the actual outcome in the real time operating environment? Life safety functions typically require a high degree of certainty and are generally tested rigorously via a code enforced testing regime. Efficiency functions, while economically important, have more tolerance for failure. Problems that do occur can typically be identified by alarms, utility monitoring and continuous commissioning processes and corrected without performing tests process that might subject the system to damage. Testing processes for efficiency functions should prove that the process should work and then supplement the testing with trending to verify the process.
- **Clear Understanding of the Limits of the System and Test:** The test writer and the technicians performing the test should have a clear understanding of the limits of the system and the test. It is highly desirable to document this information somewhere in the test procedure for ready reference. Building occupants should also be informed of any tests that may affect their environmental conditions. Laboratory, process, and health care environments are particularly intolerant of unannounced environmental swings.
- **Chain of Command:** Frequently, contractual requirements, labor regulations, work rules, and Owner operating protocols may dictate that someone other than the commissioning provider actually run the test. In these situations, the commissioning provider becomes more of a planner, consultant, and observer of the test. It is essential that the commissioning provider clearly communicate the test procedure to whomever will be running the test. This person needs to understands the test and be committed to performing it. If they do not agree with the plan, then it is usually better to negotiate to a test plan that is satisfactory to them rather than attempting a test that they disagree with.
- **Dry Run:** For complex tests or tests with critical failure modes, rehearsing the test steps, including what will happen if something goes wrong, can go a long way towards verifying the understanding of the test process among the team members. In addition, this process often will uncover weak points in the test plan, allowing the plan to be modified and improved.

Obviously, not every test will require a high level of planning and consideration. The commissioning provider should assess which tests merit this level of effort and then plan the testing accordingly.

2.13. Observing Tests

An important part of the functional testing process is observation. The test procedure initiates an input to the system, and the commissioning provider and test team observe, react to, and document the result. Even if this sounds simple, some issues may cause misinterpretation.

- **What Really Happens vs. What You Expected to Happen:** In a well-planned test sequence, the commissioning team will initiate the test having anticipated and planned for as many of the potential test outcomes as possible. This allows the team to quickly respond to any problems that occur as discussed in the preceding section. However, it is possible to trick yourself into to seeing what you wanted to see instead of what really happened. Often, there are only subtle differences between the two, but the differences can be the line between a system performing as intended and a system that is wasting energy.

- **Repetitive Test Sequences:** Many test sequences are repetitive in nature. For example, the testing used for zone controllers on a project may be nearly identical from zone to zone. When performing repetitive test, it is not difficult to miss an obvious problem because you have been lulled in to complacency by numerous successes on the preceding test cycles. In addition, be careful not to confuse the data from one test with the data from another. Working with a team member is one way to combat these sorts of problems if the project economics can sustain it. Switching tasks between team members as you work through the test cycles also helps.

> **Comprehending the Situation:** Early in the space shuttle program, Barbara Walters was interviewing John Young and Bob Crippen, the astronauts who would be the test pilots for the first flight of the space shuttle Columbia (not the first manned flight, the first flight). In the course of the interview, she asked them if they would be nervous. After a slight pause, John Young, a veteran of flight test and the Gemini and Apollo programs and commander for the mission looked at her and said something like 'If you are piloting an untested vehicle on its first test flight and that vehicle contains more propellant than was ever placed on a launch pad before and the vehicle was assembled by the low bidder, and you aren't a little nervous, then you don't fully comprehend the situation[3].'

- **Checklists and Test Procedures as Guides:** Many experienced commissioning providers say that the benefits of a formal checklist or test procedure are realized more during its development cycle than when it is actually used. To develop the checklist or procedure, the test writer must assess the system and consider all of the factors. In doing so, they develop an intimate understanding of the system and how they expect it to work. This understanding can be a greater benefit than the documented procedure. In fact, once experienced commissioning providers are in the field, many use the checklist as a guide and a way to document results, but frequently deviate from the exact process outlined due to the dynamic nature of the field environment.

  However, it is important to understand that deviating from a well-planned procedure is not a casual decision, especially for a large system undergoing a complex test or a test with a high element of risk. In these situations, if you think there is a need to deviate

[3] Paraphrased.

from your plan due to a change in the field or an unanticipated result in the test, then you may want to stop the test to re-evaluate and document your new plan.

- **Anticipating the Unexpected:** Many times, the only real problems during functional testing are the ones you didn't think of as possible prior to their occurrence. Once they occur, they often seem blatantly or even painfully obvious.

The bottom line is that when we as commissioning providers set out to functionally test the HVAC systems that are built in the modern construction environment, we are testing complex assemblies of interactive components. These systems are designed and assembled by teams of people with conflicting priorities and interests under intense budget and time constraints, often based on specifications and plans that are lacking in detail and contradictory. When considering all of that, if we don't expect a few problems, then perhaps, as John Young said in the story in the side bar, we don't fully comprehend the situation.

2.14. Returning To Normal

The final step in any functional test should be the return of the system under test to a normal and safe operating state. It is important to allow some time in your schedule to remain on site and around the system you have been testing after the test is completed.

It can take some time, perhaps even an hour or more, for a system and its supporting utility systems to return to a stable operating state following test sequence, especially if the test sequence involved a lot of upsets and/or the systems and subsystems are large and have a lot of inertia. If something does go wrong immediately after the test or immediately after you have made an adjustment to a system, then your knowledge of the system, the test results and process, and the changes made will be invaluable aids in solving the problem or stabilizing the system.

The bottom line is to simply be courteous to the people who must operate and work in the building. Let them know when you arrive, what you are going to do, and when you finish. Hang around to make sure that the results of your effort are truly having the desired effect. If it turns out that there is a problem, you will have a client who appreciates your responsible attitude and courtesy.

2.15. Getting To Team-based Solutions

You probably don't need to worry to much about the your engineering on that project. You're experienced and the design is solid. Focus your attention on dealing with the people. They're the ones who will make or break it for you and they're a lot more complicated than a variable flow chilled water system.

-Principle engineer discussing a project with his project engineer

Frequently, the most difficult problems for commissioning professionals are not the engineering challenges we are presented with by the systems we test. Rather, they are the challenges associated with the "people issues". Resolving conflicts in order to arrive at a team-based solution takes skill and experience. The following list of basic rules for conflict resolution can help you get to team-based solutions with greater ease.

- Identify the problem (state it clearly and get agreement)
- Focus on the problem, finding the root cause, and getting to the solution
- Attack the problem, not the person or people involved

- Listen with an open mind to everyone involved (keep from jumping to conclusions or becoming accusatory)
- Use respectful language through out the process (no blaming or put-downs)

Beyond the basic rules, commissioning professionals should consider the following tips:

- Be fair and honest. Most people are ultimately interested in a fair and equitable solution to a problem. They may not like it, and it may take a while to get them to accept it, especially if it will place them under financial pressures. However, in most cases, the individuals involved want to deliver a satisfactory product.
- Work to find common ground. Many problems in a construction project are integration issues and are not the fault of any one person or group. In some cases, unanticipated issues require brainstorming a creative solution.
- Trust physics. It's difficult to get angry and emotional when the problem comes down to an equation.

For the building and its systems to work, everyone involved has to want them to work and have some measure of dedication to the process. Commissioning professionals are hired to take a holistic view of the project, which puts them in a good position to nurture that attitude. In doing so, the commissioning process can foster everyone's success.

2.16. Trend Analysis as a Functional Testing Tool

Data collection and analysis has always been an integral part of any commissioning process. But modern electronics have increased the sampling frequency, accuracy and presentation of the data by several orders of magnitude over the more traditional approaches (see Figure 2.13). Experienced retro-commissioning providers, facilities engineers, and operators all know that most buildings will "tell you" where their problems are if you spend a little time looking at what is going on. The data handling capabilities of modern data loggers and DDC systems provide a powerful tool for taking a detailed look at how a building is operating in a variety of test situations:

Figure 2.13 Data Logging Advances over the Years

A good operator with a clipboard and a pocket full of gauges was the original data logging and trending system. This approach still provides a cost effective, reliable way to document operating parameters in some situations. But, recent technology advances take this function to a whole new level in terms of sampling rate, accuracy and data presentation.

- The trending software and data loggers can be used to create a running record of the system performance during a functional test sequence. This will allow the test team to go back and review what happened if there are questions or if things were happening so quickly they could not absorb everything that was going on. The data sets also provide a record of the test results and a baseline of comparison for future testing efforts.
- The trend data collected after functional testing provides an ongoing record of system performance. Setting the system up to archive the data essentially places the building in a perpetual functional test mode where Mother Nature writes a new test sequence every couple of days. The information documented can be invaluable to commissioning providers and facilities personnel as they work with the building during its first operating season to fine-tune its systems to the real world environment. Continuing the process after the first year provides a good foundation and baseline for an ongoing commissioning process and measurement and verification programs.
- Many times, trending can be used to streamline the functional testing process on a project with a tight budget or tight schedule or in situations where equipment-shipping delays conspire with a firm occupancy date to erode away the original window targeted for functional testing. The information gleaned from trend data analysis can be used to focus functional testing efforts on the systems and problems that will yield the most benefit for the effort expended. Issues not immediately addressed can be placed on a list of projects and optimization opportunities to be pursued by the facilities staff as part of an ongoing continuous commissioning process.

2.16.1. Laying the Groundwork

Most current projects come with a powerful built-in data logging capability in the form of the DDC control system. But, to take full advantage of this capability, it is important to start planning for it during the design and construction phases of the project, as described below.

- **Specify and configure the points list to provide the data necessary for commissioning, operation, and maintenance:** Typically, points are required beyond those associated with simply controlling the systems.
- **Specify and configure the controllers for trending:** Typically this involves addressing memory requirements, establishing sampling rates, defining file structures and file transfer protocols and dealing with general data handling and accuracy issues.
- **Include data logger requirements in the commissioning proposal and scope of work:** Even with a DDC system, data loggers may be required to supplement the information available from the it due to point limitations or because you suspect you will need to sample some processes faster than the proposed control system is capable of performing the task.
- **Specify and configure the control system network for trending:** The DDC system architecture needs to be configured to support the data handling required for trend analysis with out adversely impacting system performance for day-to-day operations. Just because a DDC system can execute the control sequence specified for a project does not automatically mean it can handle the high sampling rates and large data sets associated with trend analysis.
- **Specify and configure the operator work station for trending:** The operator work station needs to be configured to work in harmony with the trending requirements. This includes specifying the data storage capacity and the programming necessary to properly retrieve and archive the data both for the commissioning process as well as the ongoing operation and maintenance processes.

In the context of the project scope and budget, setting the DDC system up to accommodate trending will be highly cost effective and may not even impact the budget in a measurable manner. Sensors, controllers, a work station, and some sort of network infrastructure will be required. During the design, make sure that these features can handle the trending requirements so those infrastructure dollars are spent wisely. If you have to go into an existing system that was not properly configured and make the changes necessary to support trending, it can become quite expensive because you often must abandon some of the existing investment in infrastructure and replace it with new equipment. The differences in equipment first cost are probably not that great; the expense comes from having to make the investment in material and labor twice.

These topics are all discussed in greater detail in Chapter 2 and Chapter 3 of the Control System Design Guide as well as in some of the resources included with this document. Being proactive during the design and construction phases of the project to ensure that these issues are addressed will yield significant long term benefits to you as the commissioning provider as well as the facilities engineers and operators who will deal with the building and systems long after your work is complete.

2.16.2. Defining the Data Set

One of the most important discussions you will have as a commissioning provider with regard to trending is to define the points you want to trend and how often do you want to sample them. Since you often don't really know what you are looking for in a diagnostic and troubleshooting environment, the list of points can become quite extensive. It will also be influenced by the nature of the machinery and configuration of the systems. As a result, the specifics for any given situation will probably vary from location to location and system to system. Requirements may also change as you progress through the diagnostic process. Issues to consider as you formulate your requirements include:

- **Points to be trended**

  All physical points; i.e. all points that are real inputs or outputs from the controllers: The interactive nature of HVAC systems will often cause the reaction of one output to ripple through the other inputs and outputs associated with the system. If you aren't watching all of the possibilities, you may misdiagnose a problem because you misinterpret the information that is available. Usually, the real problems are the things we didn't think of.

  All set points: Set point changes can also ripple out through a system, triggering other problems or potentially being misdiagnosed as a problem that does not exist. The discharge temperature may have taken a jump because a valve failed closed or because it was commanded to a higher value.

  Utility consumption data such as gas usage, electricity usage, and water usage: Monitoring this information is an important step in making Owners and operators aware of the resource impacts of their buildings. In addition, energy utilization patterns can often be a clue regarding system performance problems. See Appendix B: Resources for a paper that describes how this information can be used as a commissioning and operation guide (*Using Utility Bills and Average Daily Energy Consumption to Target Commissioning Efforts and Track Building Performance)*.

- **Sampling time:**

  Analog data, including set points that are automatically reset by other parameters, need to be sampled very frequently. If you don't sample the data set faster than any potential disturbance, you may be fooled by aliasing. Once you have analyzed the system for a while and know that there are not any rapid disturbances, the sample time can be increased to minimize network traffic and the need for archiving data.

Most current technology systems have a limit on sampling speed somewhere around once per minute. If you suspect disturbances are occurring with a cycle time of 3 or 4 minutes or less, then you may want to supplement the EMCS with data loggers capable of sampling rates in second (vs. minutes) for your initial analysis work.

Binary data and manually adjustable set points can be sampled based on change of value as long as the data is recorded with a time/date stamp. This will allow it to be viewed simultaneously with the once per minute analog data and significantly reduces the number of samples that must be stored.

A trend request based on these parameters can be quite significant involving tens or hundreds of points and thousands of samples. When making a request like this, you need be cognizant of the fact that if the system has not been designed with trending in mind, then these requirements may be unrealistic and could degrade the performance of the system to the point of being useless. Thus, you may want to initiate your request with a discussion of the capabilities of the system that will be performing the task lest you find pipe wrenches or change orders hefted your way by annoyed operators and control technicians. Based on the discussion, you may decide to temper you requirements to avoid over-burdening the system and/or the Owner's pocket book. This can be accomplished in a variety of ways including:

- **Focus on one system:** Focusing on the detailed performance of one system at a time may be a more manageable arrangement for the DDC system and your work schedule. But, keep the potential for system interactions in mind. You may want to look at additional points from other systems concurrently with the focus system, even if you can't trend all of them.
- **Reduce the sampling rate subsequent to your initial analysis:** If your initial data set reveals that aliasing is not a concern, then you can reduce the sampling rate to a level that is appropriate for the conditions you are observing. During training, you may want to suggest that the operators occasionally increase the sampling rate to catch problems introduced by changes in the operating cycle or process. For example, a system that is perfectly stable when using chilled water as a source of cooling may become unstable when the economizer cycle must function especially at low ambient temperatures when economizer damper sizing becomes critical.
- **Don't archive trend data:** Many of the system problems associated with high sample rates are related to the network traffic imposed on the system as it archives the trend data from the controller to the hard drive on the host. Configuring the controllers to bump the oldest data with the newest data when memory fills up rather than archiving it can eliminate most of this network traffic. Of course, this will limit the historical information available to you for analysis, especially if most of the controller memory has been used for program functions. In these situations, you may need to adjust your work plan and budget to allow you to spend more time on site so you can use the data while it exists.

2.16.3. Using the Data Set

One of the biggest advantages of trend data is that it allows you to use graphics to paint a picture of what is going on, and when dealing with data sets, a picture is often worth ten thousand words. Tools that allow data visualization and analysis, both manually and automatically, are constantly evolving and emerging. The resources listed in Appendix B: Resources discuss several of them. Many of the control system suppliers and data logger manufacturers can furnish software modules and packages that allow the data from their system to be viewed and manipulated. Lacking any of these options, most systems can be set up to export data into a delimited file which can then be analyzed using standard spreadsheet software.

Regardless of the analysis technique employed, trend data can be a valuable aid in the functional testing process. For example:

- Combining information from multiple data sets on the same graph can be a convenient way to assess performance and identify inconsistencies. For instance it may be desirable to overlay outdoor air condition data from the National Weather Service on a plot of economizer performance to allow the integrated performance of the process to be evaluated.
- Unstable control loops become immediately apparent in a graphical presentation of the data. Don't forget about scale factors though. An out of control duct static pressure swinging half an inch w.c. around set point may "disappear" when plotted on the same axis as discharge temperature with the axis scale set at 0-100.
- Plotting the same data set different ways may reveal new information or make different trends easier to see. The plots in both graphs in Figure 2.14 are from the same economizer data set. But the plot on the left is a time series plot, useful for verifying sequencing, looking at relationships between triggering conditions and their responses, and looking for instability. The plot on the right is a scatter plot of temperature differences in the system, which reveal general performance information about the economizer like how well it maintains minimum outdoor air flow and how well it changes over.
- Trending may give you some insight into conditions you observed during construction that caused you concern. For instance, you may have seen something that caused you to wonder about how well calibrated some of the sensors actually were. Looking at a trend of what happened during a warm-up cycle when the system operated with full recirculation (no outdoor air) and all warm-up was provided by the zone reheat coils may provide a clue. One would expect all of the temperature sensors in the air stream ahead of the reheat coils to read the same or nearly the same value. If they don't, then maybe the calibration effort needs to be re-evaluated.

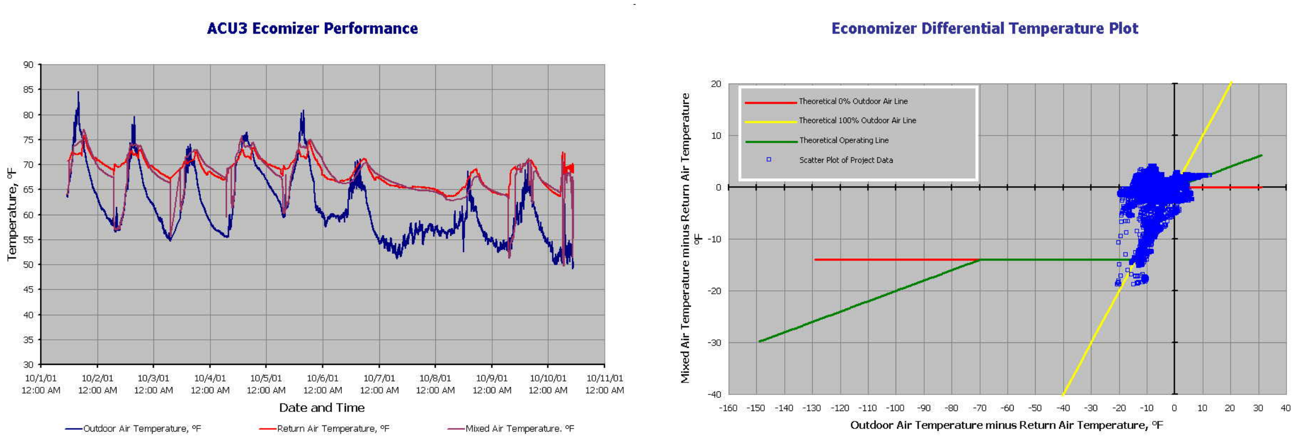


Figure 2.14 Different Ways to View the Same Data Set

- Trending may help you target additional functional testing based on the performance of the system to date, thereby averting future operating problems or energy waste. For instance, if you started up your project in the summer, you may be concerned about what will happen during extreme winter conditions when the sizing of the economizer dampers and performance of the economizer cycle becomes critical. Pulling some trend data and looking at it during the swing season may tell you what to anticipate. If the system starts with minimal instability on a cool fall morning and transitions from economizer cooling to mechanical cooling and back smoothly as the daily outdoor air temperature swings from the 40º's F to the 70º's F, then you probably can have some confidence in the system's ability to handle extremely cold weather. On the other hand, if you saw a lot of instability in these transitional conditions, you may decide that some additional focused functional is in order[4] before the weather outside becomes subfreezing and the instability you are observing leads to freezestat trips, coil failures, and operator frustration.

2.17. Supplemental Information

Supplemental information regarding the following topics has been developed to provide necessary background information for functional testing.

- Air Handler Example Sequence of Operation (referenced in Section 2.3.2)
- Seismic Restraint Issues (reference in Section 2.6.1)
- Industrial Personnel Safety (referenced in Section 2.12)

Chapter 2
Supplemental
Information

[4] For example, you may focus more effort on loop tuning or perform a mixed air plenum temperature traverse.

Chapter 3: Outdoor Air Intake

3.1. Theory and Applications

The outdoor air intake is the portion of the system that brings outdoor air from the exterior of the building to the air handling unit location. For some systems, such as packaged rooftop equipment, this section is simply a screen and an outdoor air damper incorporated into the unit housing. For other systems with mechanical rooms deep inside a building, the outdoor air intake can be more extensive, including:

- Louvers
- Outdoor air dampers
- Fire dampers, smoke dampers, or combination fire and smoke dampers
- Ductwork and related accessories

For small systems or packaged air handling units, there is usually little functional testing required for the outdoor air intake section. However, if the system is large, complex, or capable of generating significant static pressures, then functional testing may be required. Some of the tests may focus on verification of the performance of individual components such as acoustical louvers or smoke and fire dampers. Other tests may ensure that the individual components work in harmony with the rest of the air handling system. For instance, verification of the interlocks associated with the intake damper or an operable intake louver on a large, 100% outdoor air system can be crucial to prevent duct implosion if the intake damper or louver failed to open during start up.

Louvers are typically found in HVAC systems at the point where air enters and exits the air handling equipment. In the outdoor air intake section, louvers generally have fixed blades, but operable louvers are installed when the system does not include outdoor air dampers. While louvers are often thought of as relatively insignificant and passive elements in the system, they perform critical functions and, when located in a moving air stream, have a dynamic impact on the performance of the system, especially operable louvers.

Louvers typically provide one or more of the following functions:

- **Contaminant Protection** The louver blades themselves and any screening provided behind the blades acts as the first stage of very rough filtration for the air handling equipment. Some manufacturers have developed designs that will filter out sand and dust in the 140-200 micron size (a human hair is about 100 microns in diameter).
- **Visual Screening** Louvers can screen equipment such as cooling towers or rooftop air handlers from view when they are located on the exterior of a building. Typically, this function is achieved by a combination of blade orientation (vertical or horizontal) and blade design.
- **Vandal Protection** Louvers located in accessible areas are sometimes designed to be vandal proof. These louvers can include special vandal resistant hardware, security bars, and blade designs aimed at preventing penetration of the louver by foreign objects.
- **Acoustical Protection** - Occasionally, the equipment located on the system side of a louver can have a noise signature that would be objectionable on the exterior of the building without acoustic treatment. Vane-axial fans are one example of equipment that may have acoustical problems. Some louver designs utilize blades constructed and arranged to decrease sound transmission.

An important louver parameter that is common to many of the louver performance specifications is louver free area. The free area of a louver is the area actually available for the passage of air. This should not be confused with louver face area, which is the overall cross sectional area of the louver perpendicular to the direction of airflow. The referenced Air Movement and Control Association (AMCA) standards indicate how free area can be calculated based on dimensions taken from the louver. Some manufacturers state performance data in terms of free area velocity while others state performance in terms of face area velocity, so it is important to determine which velocity is being used when documenting louver performance criteria.

As indicated previously, one of the primary functions of a louver is to minimize the entry of water into an air handling system. In addition to being designed to resist penetration by water and channel water away from the interior of the system, louvers must be applied properly to achieve success in this area. As a general rule, face velocities should be 700 fpm or less to prevent water induction. It is also important to understand that a louver that is designed and tested to AMCA standards may still allow some water penetration. The test associated with the AMCA standard is designed to define the "point of beginning water penetration"; i.e. the louver face velocity at which water begins to make its way through the louver. This provides a consistent basis for comparison of different louver designs, but does not provide quantitative data on how much water can be expected to penetrate a louver under actual service conditions. For instance, the AMCA standard does not address driving rain, and real rainfall rates can exceed test standards. The design of the intake compartment should assume some rain penetration will occur, so the use moisture tolerant materials and including drainage is advisable.

The moisture droplets associated with heavy fog can penetrate louvers even when they have been properly sized and selected to minimize rain penetration. This moisture often becomes trapped in the first filter section in the system and can cause problems there unless the filters are selected and installed to minimize this complication. Systems that handle 100% outdoor air are particularly prone to this problem.

Additional information regarding louvers can be obtained a number of publications, which are referenced in *Appendix B: Resources*.

3.2. Non-Copyrighted Tests

3.2.1. Outdoor Intake Verification Checks

This test is not part of the CTPL database. PECI created the test to cover a level of instructional detail not currently found in the CTPL.

Outdoor Air Intake Verification Checks

Link to verification checklists for the outdoor air intake section.

3.2.2. Rain Penetration Test

The rain penetration test is not part of the CTPL database. PECI created the test to cover a level of instructional detail not currently found in the CTPL. This test provides additional educational information to supplement the test protocol, including a discussion of benefits and field tips.

Rain Penetration Functional Test

Link to supporting information on how and why to perform the rain penetration functional test, as well as the test form itself.

3.2.3. Tests for Future Development

Several functional tests for outdoor air intake have been identified for future development, and may be included in later versions of the Guide.

Outdoor Intake Tests for Future Development

Link to a list of tests related to the outdoor air intake section that have not yet been developed.

Chapter 3: Tests for Future Development

Outdoor Air Intake Tests for Future Development

Sand Penetration Functional Test

Some manufacturers have developed specialized louvers designed to remove sand and dust in the 140 - 200 micron range as a first step in the air handling filtration process. While unusual, the functionality of these louvers can be critical for preventing rapid loading and clogging of pre-filter systems. If these louvers were to fail to function as intended, then system could see high filter pressure drops and high filter consumption rates. Thus, some sort of functional testing to verify that the design intent is being achieved may be warranted.

Typically, these louvers are tested to ASHRAE Standard 52-76 (superceded by ASHRAE 512-99). However, as with rain penetration tests, duplication of the test set-up in the field may be difficult and most likely, impractical. However, a passive functional test similar to the rain penetration test would allow the performance of the louvers to be qualitatively verified. Development of this test could be modeled on the rain penetration test presented in the previous section.

Louver Pressure Drop Functional Test

Sight Proof Louver Functional Test

Vandal Proof/Security Louver Functional Test

Acoustical Louver Functional Test

Operable Louver Actuator Stroke Functional Test

This test provides a template for a variety of options that allow the settings of pressure relief doors to be verified while minimizing the risk to the air handling system.

Chapter 4: Fan Casing

Figures

4.1. Theory and Application

4.1.1. Construction

On a project with large packaged rooftop units, a young commissioning provider aggravated the project's experienced lead electrician by insisting that they open the 480 volt electrical compartment to verify the security of the wiring connections prior to energizing the unit for start-up. When they opened the compartment, gallons of water spilled out because the gasket on the top part of the service panel allowed rainwater from a week of thunderstorms to enter and accumulate in the compartment. This situation convinced the electrician that checklists might not be such a bad thing after all.

Fan casing requirements for an air handling system can vary from none for a simple ventilation system supplied by a thru-the-wall prop fan and exhausted by a small utility fan to extremely sophisticated for a custom roof mounted air handling package that includes service corridors and all of the related heating boilers, water chillers pumps, piping and electrical equipment necessary for operation.

Casing configurations and quality can vary over a wide range. At the low cost, less sophisticated end of the spectrum, the casings provided with packaged equipment are generally weather resistant, easily shipped, and easily installed. At the upper end of the spectrum, fully customized air handling packages are available from a variety of manufacturers. Typical configurations are available for standard equipment rooms or a custom approach can be fabricated to enhance maintenance and durability with features like insulated double wall construction, walk-in man doors, internal lighting and convenience outlets, and all aluminum construction. Top of the line custom packaged units may also include factory installed controls, wiring, pumps, boilers, chillers and other processes, which only need to connected to a source of electricity and fuel to function.

The modular packaged equipment offered by many of the major manufacturers provides a good compromise between the two ends of the spectrum. Designers can pick and choose from a wide array of standard building blocks to assemble a unit that meets their specific project needs. Many features like double wall construction, factory wired controls, variable speed drives, and internal lighting and convenience outlets are available as standard options in these product lines.

Regardless of the quality level, one of the important features that should be included in a double wall construction system is providing a thermal break in the channel and framing system that used to assemble the sections. Without this break, there can be significant condensation problems for units installed in unconditioned areas. The thermal losses associated with this are not nearly as significant as the potential for water damage and moisture related IAQ problems that can be caused by the condensation. This is a good item to include in a design phase commissioning review of the project documents.

4.1.2. Shipping and assembly

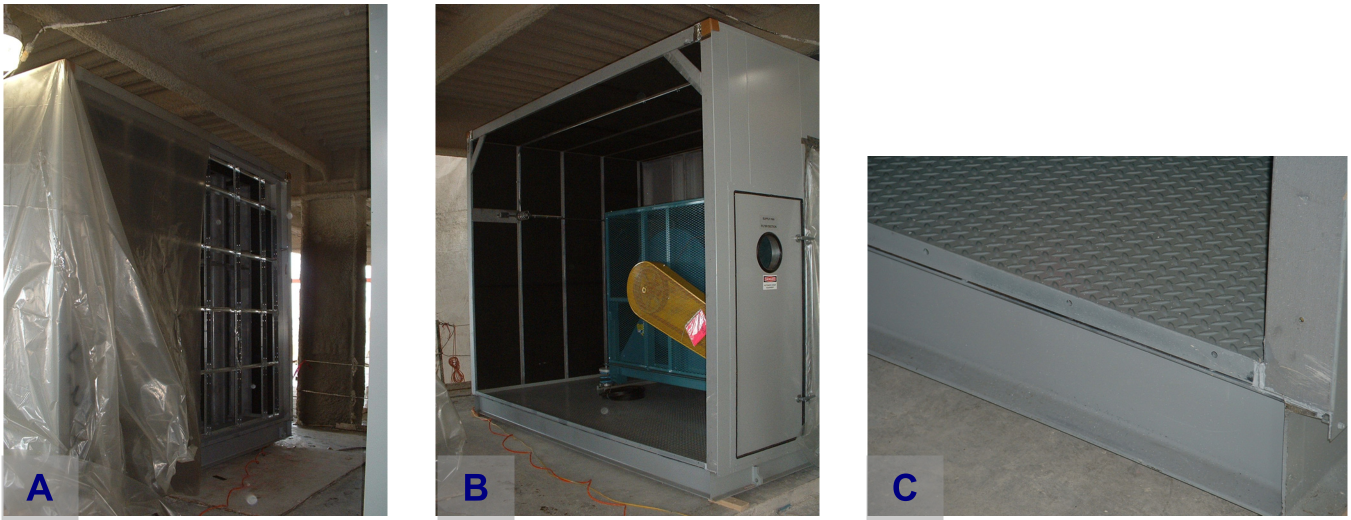
For most product lines, shipping limitations will typically result in larger air handling units being shipped in several pieces. In most instances, the units are assembled at the factory to ensure that everything lines up, then disassembled and shipped. While performing construction observation, it is often wise for the commissioning team to spot-check the field assembly process during the following steps:

- **Move the sections into place** This is an obvious first step, but is not without its potential pitfalls. Many of the sections in a large air handling unit can look similar, especially to the teams rigging them into place whose expertise lies in moving heavy machinery rather than in air handling system design. Mislabeling at the factory or confusion in the field can lead to sections being assembled in the wrong order, sections from different units being assembled together, and units being installed at the wrong location. If any of these problems occur, it will only get worse as final connections are made and other equipment is moved into place. Catching this type of problem early can save everyone a lot of trouble.
- **Prepare joints for assembly** Usually this step consists of applying a gasket or caulk to the mating surfaces of the joint. After final alignment, the mating surfaces are pulled together. If a heavy section is being pulled up to mate with a light section, there may be a tendency for the light section to move, which can deform the connection between the light section and the module it is connected to at the other end (see Figure 4.1). This problem leads to misalignment with openings in the building structure arranged to allow utility and duct system connections to the unit.

Figure 4.1 Casing Joint Damage

The joint between these two sections was damaged during assembly. The threaded rod between the lifting lugs was used to pull the joint back together again.

- **Install the mechanical connectors** After the modules are in their final locations, they can be physically connected to each other. Usually this involves installing bolts through flanges around the perimeter of the unit. The exact requirements will vary with the manufacturer and the configuration of the unit, but there will usually be a bolted connection on at least one if not all sides.
- **Install and joint covers** Most manufacturers provide sheet metal covers that are caulked and then fastened into place over the field joints. These covers can be critical to maintaining the joints integrity and preventing moisture penetration into the insulation for units that are located outdoors or in unconditioned environments. The roof joint is particularly important in this regard. Inverted U caps are often employed over standing flanges for this location. Some high-end manufacturers install a continuous rubber membrane type roof after the sections are assembled on units located outdoors. In this particular situation, the integrity of the roof joints can be important in terms of preventing air leakage from blowing the roofing material off of the unit. Thus, it may be desirable to perform any casing leakage tests prior to installing the membrane roof, so leaks can be detected and repaired before they have a chance to cause a problem with the roofing system.



A and B - The two sections that are to be joined.
C and D - The flanged joint on the bottom of the unit before and after bolt-up. Note the evidence of caulk after assembly (inside the red circle).
E - Side and top joints at the flange location. This unit only had a bolted flange on the bottom. The sides and top were caulked but had no other fasteners other than the external joint covers and inverted U channel on the roof. Note the diagonal corner brace at the top of the unit (inside red circle).
F - The completed joint with joint covers in place.

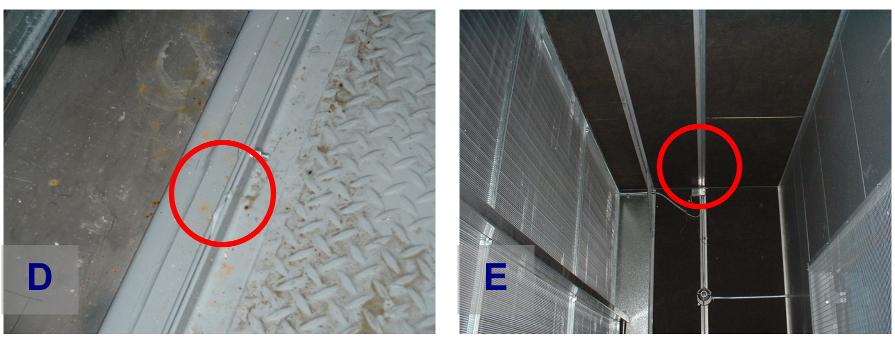


Figure 4.2 Typical Air Handling Unit Field Assembly

Ideally, it is best to witness this process as it occurs, but in most cases, assembly problems can be detected after the process. For example:

- **Empty holes** Empty bolt holes are evidence of missing bolts. While it is possible that there are holes that were not intended for mechanical fasteners at a field joint, it is unlikely.
- **Extruded caulk** Extruded caulk can show that efforts have been made to properly seal (Figure 4.2) as well as point to missing fasteners (Figure 4.3)
- **Nuts and bolts** The type of fastener installed in a flange can also be an indicator of a problem. Most (but not necessarily all) flanged joints are designed to be used with bolts. A zip screw installed in a hole in a flange that was intended for a bolt can be a recipe for disaster waiting to happen.

Figure 4.3 Extruded Caulk Points to Missing Bolts

If the units are going to be sitting on site or in a storage yard for a while before being placed into operation, it is important to periodically inspect them. Items to check for include:

Figure 4.4 Field Damage

- **General condition** Look for evidence of damage while in storage like broken windows. Catching problems such as the broken windows shown in Figure 4.4 as soon as they occur will speed resolution, prevent them from becoming an obstruction to start-up, and prevent other problems such as water accumulation.
- **Moisture accumulation and condensation** The temperature and humidity changes that can occur in non-operating units stored outdoors and other uncontrolled environments during construction can cause condensation internally, even if the units are properly covered and protected. This condensation can cause corrosion on the components and could lead to mold and mildew growth. If this occurs, it may actually be necessary for the contractor to temporarily remove covers and tarps that are protecting the unit to allow it to air out.
- **Bearing care** Bearings that sit in one position without rotating for a long period of time coupled with a moist environment can develop a form of corrosion called false brinnelling as a result of metal to metal contact between the race and roller that occurs as the lubricant is gradually squeezed from between the two surfaces by the weight of the inactive shaft and its related assembly. Thus, it is often a good idea to manually rotate inactive shafts on occasion to spread out the lubricant and maintain a film on all bearing surfaces.

4.1.3. Location

In addition to being a large energy consumer, the fan and its related air handling unit casing represent a significant assembly of raw materials. In contrast to some HVAC machinery (a chiller for instance), air handling units are relatively simple machines with few moving parts or complex assemblies. Equipment location is an important consideration in light of the longevity of the air handler. Units located outdoors will deteriorate at a faster rate than those located indoors.

Equipment longevity can also be ensured by configuring the air handling unit assembly in a manner that promotes ongoing maintenance and provides enough flexibility to allow the system to meet the changing needs of the building over time. A long-lived unit optimizes the use of the resources, which is more sustainable than replacing the entire assembly. Commissioning providers are in an ideal position to help ensure that the system is configured and installed in a manner that will provide for good O&M and adaptability. Many of these issues are best addressed during design phase commissioning and supplemented by follow-up during field inspections over the course of the construction project.

4.2. Commissioning the Fan Casing

The following tables outline the benefits and background information associated with testing fan casings. These tests can be used in a retro-commissioning process to define and correct existing operational issues. The tables are linked to related information throughout the Guide. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

4.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. Verifying casing integrity will ensure that leakage and thermal losses are minimized. 2. Ensuring that operation and service considerations are taken into account during design and construction of the air handling unit will help ensure the persistence of the efficient operation of the unit.
Other Benefits	1. Monitoring operation and service considerations during design and construction will allow maintenance to be accomplished effectively and minimize ongoing maintenance costs. 2. Monitoring the handling and status of the air handling unit casing during storage and construction will minimize the potential for failures and IAQ problems over the life of the system.

4.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	1. To ensure that the conditions that the fan casing are subjected to during storage and assembly are designed to prevent damage and conditions that could result in IAQ problems. 2. To ensure the thermal and structural integrity of the casing.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard toolkit listed in *Chapter 2: Functional Testing Basics*: 1. A duct leakage testing machine to test the leakage rate from the air handling unit casing. This is often available from the sheet metal contractor, but may require certification if it has not be certified recently. It is also possible to field erect a test rig using a small variable speed utility fan equipped with appropriate duct connections that allow it to be installed on one of the air handling unit's access doors and provide for accurate flow measurement. 2. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. 3. The structural integrity test involves pressurizing the air handling unit casing to specific levels and then measuring deflections. The duct leakage test rig can provide pressurization. Vernier calipers or other

	precision measuring equipment will be required to measure the casing deflections for comparison to design values.
Test Conditions	Tests to verify design parameters for the enclosure can be performed after the assembly of the air handling unit but prior to its start-up.
Time Required to Test	The time required to test can be several hours to a day for a team to verify casing leakage and structural integrity.
Acceptance Criteria	Casing leakage and deflection test results should meet or exceed the project specification requirements.
Potential Problems and Cautions	1. Applicable cautions as outlined in *Chapter 2: Introduction to Functional Testing* should be observed. 2. Casing leakage and structural integrity tests will subject the assembly to design static pressure values. Caution should be used when applying and removing these pressures to prevent damage due to sudden changes or assembly errors. 3. Caution should be exercised when opening and closing access doors on pressurized casings to prevent injury via a door slamming on the person using it. Caution should also be exercised to ensure that test personnel do not become trapped inside the unit by the pressure differentials

4.3. Non-Copyrighted Tests

Several functional tests for fan casings have been identified for future development, and may be included in later versions of the Guide.

Fan Casing Tests for Future Development

Chapter 4: System Configurations

Figures

4.1. Introduction

Many different air handling system configurations may be tested using the procedures in the Functional Testing Guide. For each of the twelve system configurations presented, the following information is provided:

- **Description of function**
- **Points list**
- **Appropriate applications**
- **Energy conservation control strategies**

The points lists are intended to be used by designers and commissioning providers as starting points for their own points lists. In a future Design Guide revision, system diagrams may also be provided (similar to Figure 5.1) for each configuration as links to AutoCAD drawings that can be used by designers and commissioning providers as starting points for their own system diagrams.

Users may encounter a system that does not match any of the configurations shown in this chapter. Such a system will likely be a variation on one of the basic systems, and the user should be able to adapt the information to their specific application.

System Variations

The system configurations begin with a single zone constant volume 100% outside air configuration. All subsequent configurations are recirculating systems with economizers. Systems that use 100% outdoor air are possible in almost all of the configurations discussed in this chapter, but we focus on recirculation systems because they are more typically found in office applications. Although the points list for 100% outside air systems may be somewhat simpler, designers should remember that freeze protection and humidity control become even more critical in air handlers that use 100% outside air.

A number of the air handling systems presented in this chapter must reheat the supply air to offset perimeter loads. Alternatively, any of these systems could use hydronic heat for the perimeter loads instead of the ducts, dampers, and controls associated with an all-air reheat system. Using hydronic perimeter heating can often be more easily implemented and controlled than reheating air. Perimeter hydronic heating also has the potential to be more comfortable than warm air due to radiant heating effects. As a result, space temperatures tend to run lower for equivalent comfort, and less reheat is required. Eliminating the reheat element pressure drop also saves fan energy, but this may be balanced by the pump energy of the heating water system.

The systems configurations in this chapter may require a return or relief fan if they recirculate air, however, the addition of these fans does not affect the system configuration. The pressure drops associated with the return and relief paths determine if the fans are required to avoid over-pressurizing the occupied zone due to the restriction created by the return and relief system. Additional discussion of this topic can be found in *Chapter 20 Return, Relief and Exhaust*. The examples below will assume the return or relief fans are required in order to demonstrate their impact on the point lists.

Static Pressure Safety Points, Limit Switches, and Permissive Interlocks

Static pressure safety points and limit switches have more to do with the outdoor air and life safety requirements associated with a system than the HVAC process it provides. The following three systems are examples of how the system size and configuration can affect the safety points installed:

- A 100% outdoor air constant volume system rated for capacities in excess of 15,000 cfm and equipped with a fan capable of developing significant static pressures. There would typically be an inlet damper that closed when the system was not operating to isolate it from the external environment. In turn, these dampers may cause the designer to consider some combination of limit switches, static pressure safety switches and permissive interlocks to prevent the fan from starting with the dampers closed and damaging the fan casing or duct system.
- The above 100% outdoor air system that is rated for less than 15,000 cfm would most likely not require smoke isolation dampers. However, the designer still may apply safeties to protect the inlet system and fan casing from problems associated with the failure of the inlet damper to open.
- For an economizer system rated for less than 15,000 cfm with return ducts and a return damper, the designer may rightly deem the system safe to operate without any static pressure related interlocks or safety systems.

In short, the safety point functions will tend to be independent of the HVAC process associated with the system. Since the point lists associated with this chapter are related to the HVAC process, they will not reflect every safety point associated with smoke isolation or 100% outdoor air configurations. To illustrate these concepts, the Single Duct, Single Zone, Constant Volume System point list includes the points associated with protecting the intake system and fan casing from excessive negative pressures due to a failure of the inlet damper. The Single Duct Variable Volume Reheat System has been configured to reflect a system with smoke isolation requirements and the associated safety interlocks.

4.2. System Descriptions and Points Lists

For each system configuration described in this chapter, there is a corresponding points list that can be used as a starting point for creating your own points lists. Information for the control contractor regarding application of the points can be found in the footnotes of the Points List Spreadsheet. The last column in the spreadsheet, *Design Guide Supplementary Notes*, contains a more detailed explanation of point application specifically for designers and commissioning providers. At the end of each system description in this section, the points list is compared to a previous list. Within the Points List Spreadsheet, these differences are listed in **bold** type. Table 4.1 gives an overview of the points lists provided in the link below:

Points List Spreadsheet

Link to an Excel spreadsheet of the points lists indicated in Table 5.1 below.

Points List Explanations

Link to a document that contains the Points List Explanation notes referenced in the last column of the Points List Spreadsheet.

Table 4.1 Points List Overview

System Configuration	Tab in Excel Spreadsheet	System Reference
Constant Volume, Single Zone, 100% Outside Air	CV SZ	
Constant Volume, Single Zone with Economizer and Return Fan	CV SZ econo & return	
Constant Volume with Reheat	CV Reheat	
Constant Volume with Bypass Variable Volume	Bypass VAV	
Variable Air Volume with Reheat	VAV Reheat	
Hybrid Constant and Variable Volume Systems	None	VAV with reheat
Constant Volume Multizone	CV MZ	
Variable Volume Multizone	VAV MZ	
Texas Multizone	Texas MZ	
Three Deck Multizone	3Deck MZ	
Dual Duct Constant Volume	DD CV	
Dual Duct Variable Volume	DD VAV	
Dual Duct Dual Conduit	None	Building envelope loads system: VAV; Internal loads system: Constant Volume Reheat
Low Temperature Air	None	VAV with reheat
Natural Ventilation	None	No mechanical cooling for pure natural ventilation, various applications for mixed mode systems.

4.2.1. Single Duct, Constant Volume, Single Zone

Figure 4.1 illustrates a typical single duct, constant volume, single zone air handling system. This air handling system is probably one of simplest configurations possible since there is no terminal control equipment. Most residential air handling systems are of this configuration. In a sophisticated application, the system can still have some complex components. The preheat coil in the figure can see large quantities of subfreezing air, requiring that special design steps be taken to prevent it from freezing. The constant volume pumped coil approach shown is one of many solutions to this particular design issue. Depending on the capacity of the system and the use of an economizer, the return/exhaust/relief fan may not be necessary.

More information regarding this particular system configuration can be found in:*2000 ASHRAE Handbook, Heating, Ventilating, and Air Conditioning Systems and Equipment*, Chapter 2, American Society of Heating Refrigerating and Air Conditioning Engineers, 1791 Tullie Circle, N.E., Atlanta Georgia 30329, 404-636-8400, www.ashrae.org.

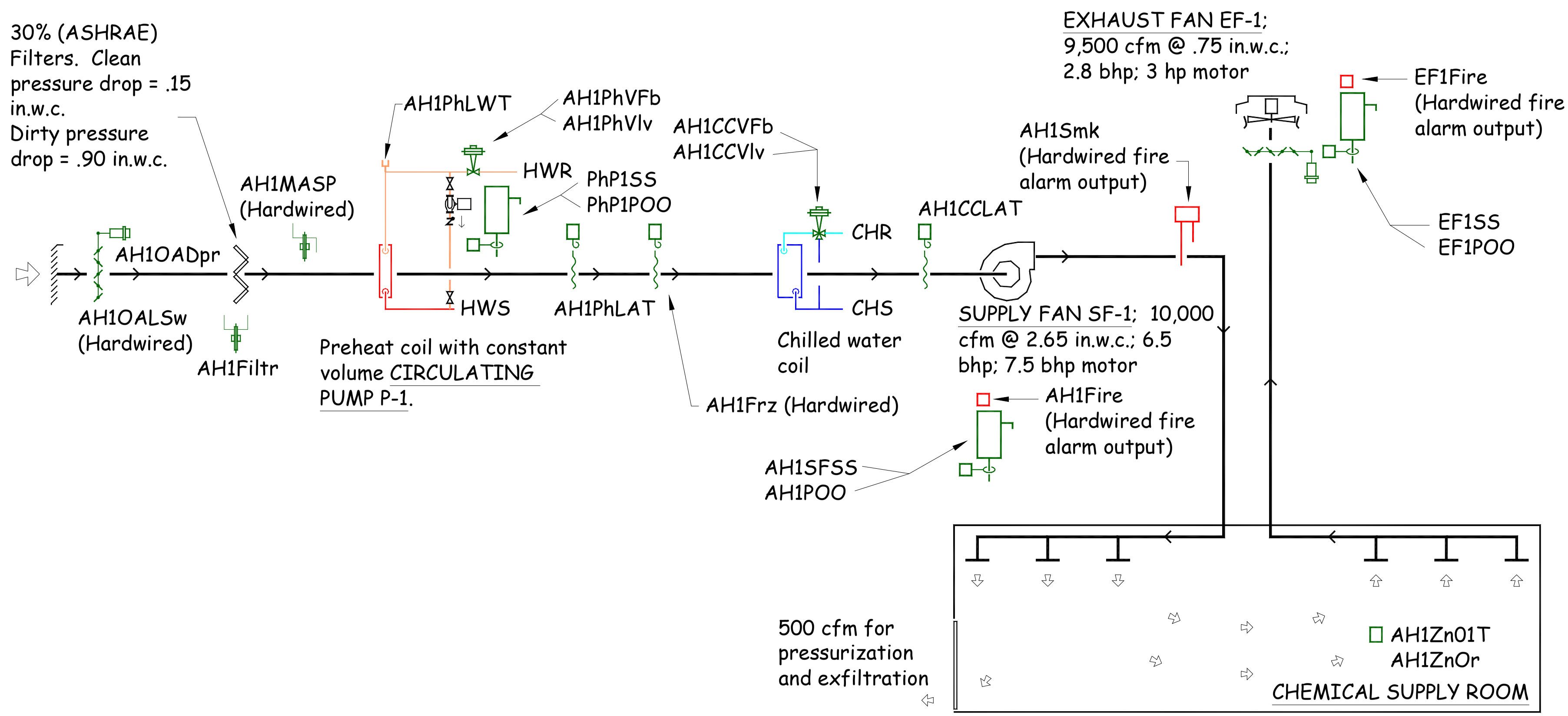


Figure 4.1 Typical Single Duct, Constant Volume, Single Zone Air Handling System

Single Duct, Constant Volume, Single Zone with Economizer

With an economizer, the single zone constant volume system requires the following additional points:

- Return air temperature
- Mixed air temperature
- Return air damper command and damper feedback (proof of operation)
- Relief air damper command and damper feedback (proof of operation)
- Relief air control point (outdoor/return damper signal or building static pressure signal) For constant volume systems, having the relief air dampers track with the economizer dampers will usually work reasonably well unless the building is excessively leaky. For additional information on this topic see the related discussions in *Chapter 9: Economizer and Mixed Air*.
- Minimum outdoor air damper command and feedback (if applicable)
- Zone CO_2 Level (if applicable)
- Manual override capability for the unoccupied cycle. The owner may desire a simple way for the zone occupants to override the operating schedule regardless of whether or not a facility operator is on site. Refer to Section 3.4.2 Manual Override for details regarding how to implement this function.

Single Duct, Constant Volume, Single Zone with Return or Relief Fan

For systems with a return or relief fan, the single zone constant volume system can include the following additional points:

- Return/relief fan start/stop command and feedback
- Return/relief fan hours of operation
- Smoke detector and/or fire alarm interlocks will be required for the return or relief fans in most instances
- Return/relief fan capacity control command and feedback. In the event that the relief dampers are not controlled by the same signal as the economizer, the return fan will need capacity control.

4.2.2. Single Duct, Constant Volume, Reheat

A typical single duct, constant volume air handling system with reheat delivers a fixed volume of cool supply air to multiple zones and reheats this air as demanded by the thermostat in each zone. The supply air temperature is set low enough to meet the zone with the highest demand for cooling. Terminal equipment at each zone consists of a set of steam, hot water, or electric reheat coils controlled by the zone thermostat. Constant volume with reheat provides comfort control for zones with unequal loads and is often used for applications with close temperature and/or humidity tolerances. In some instances, recovered energy can be utilized for reheat to minimize the energy intensity of the process.

The energy intensity associated with this process can be reduced by setting the minimum outside air flow appropriately for all zones. Constant volume reheat systems tend to require reheat for all zones if the minimum outside air flow has been set too high.

Energy can also be minimized by incorporating a strategy to reset the system supply temperature based on the cooling demand of the zone with the highest load. In a properly operating resetting routine, the zones at or equal to the maximum demand for cooling will be the only zones that are not being reheated. To make sure that air temperature is reset as high as possible during cooling mode, compare reheat valve positions. At least one reheat valve should be nearly closed. Values of 95 to 98% closed are common when using this routine. If the discharge temperature was reset until a valve was fully closed, then there would be no way of knowing if the zones in that state were satisfied or actually starting to overheat and required additional capacity through lower supply temperatures. The bottom line is that this approach minimizes the energy burden associated with a constant volume reheat system by keeping at least one zone on the verge of running out of cooling capacity.

Even with the reset strategy, the reheat process results in high energy use. Supply air temperatures in the system are generally set based on the sensible heat ratio in the space and the associated humidity control requirements. Air volumes are then determined based on this supply air temperature and the design load in the space. Since the spaces seldom see the full design load, any excess capacity must be used up in the reheat process to avoid overcooling the zone. There are several energy implications to this reheat process.

- The cooling plant provides cooling that is reheated, in addition to the cooling that is required to meet the load in the space. Thus, the cooling plant tends to run at a constant load factor even though the load is varying.
- The fans must deliver a constant volume of air based on the design load condition at a temperature based on dehumidification requirements in the space on a design day.
- The heating plant, including boilers, pumps, and any other related equipment must run any time the reheat air handling system is operating if temperature control is to be maintained. This is true even in the summer, because reheat energy is required to prevent the zones from overcooling.
- In the winter months, for reheat zones that serve perimeter areas, the supply air must be reheated to make up for the initial cooling of the air and then heated further to meet the any heating loads.

In an efficient constant volume reheat system, the supply air temperature should be reset based on the maximum demand for cooling, but during moderate cooling loads, a raised supply air temperature could result in problems with humidity control. Therefore, the reset schedule needs to include an upper limit. A lower limit is also desirable to prevent an errant zone or inappropriate operator command from lowering the set point beyond what is necessary to properly dehumidify the air.

If the system under consideration is a true constant volume reheat system, then the distribution system pressure or flow requirements for different zones to will not usually vary.[1] As a result, the zone control system requires no flow regulation and simply consists of a thermostat and the reheat valve. The most cost effective way to provide this function is usually with a stand-alone pneumatic, electric, or electronic thermostat. However, installing a DDC controller to perform the zone control functions can have benefits that often justify the added costs. Benefits of DDC control include:

---

[1] This should be very carefully considered during the design process. Installing unnecessary constant volume regulators adds an on going energy burden to the system due to their static pressure requirement. It also adds complexity and first cost due to the flow regulation and control requirement associated with it. This added complexity will ripple out into the operating life of the building as a higher maintenance cost.

- Zone valve position and temperature data become available from a central location. This provides the following benefits that are useful for commissioning and ongoing operations.

  Faster response to comfort problems.

  Mitigation of comfort problems in critical areas before they become issues by using alarm settings.

  Documentation of performance for quality control purposes or to demonstrate compliance with specified zone temperature requirements through trending functions.

- Many current technology DDC terminal unit controllers have the capacity beyond what is required for basic control functions. These spare points can be used to provide energy conservation and improved performance in the following ways:

  Monitoring of the reheat coil discharge air temperature for commissioning and diagnostic purposes. For example, an alarm can be generated if the reheat valve is commanded fully closed but there is still a temperature rise across the reheat coil due to a leaking valve.[2]

  For systems serving zones with radically different operating schedules, a spare output can be used to control two position dampers in the branch ducts serving the different areas to shut down the air flow when the zone is unoccupied. This function is similar to a two-position VAV system. To be effective, this feature needs to be combined with at least one of the following measures to prevent the flow eliminated in one area from simply moving to other zones.

  - A variable speed drive at the supply fan controlled to maintain a constant pressure at some point in the duct system. This is usually the most cost effective approach because it maximizes the fan energy savings at a minimum of cost.

  - If the fan can tolerate being pushed up its curve, installing constant volume regulators on the zones will allow them to control flow as well as temperature. This usually is more costly than installing a variable speed drive unless there are only a few zones. In addition, the ongoing maintenance of the flow control loops adds complexity to the system.

Single Duct, Constant Volume with Reheat - Additional Points compared to Single Duct, Constant Volume, Single Zone System with economizer and return fan:

- Reheat valve command and feedback
- Discharge air temperature per reheat valve
- Alternate configuration (points not included in example points list below): Zone flow control to allow flow to portions of the areas served by the system to be shut down when they are unoccupied while other areas remain in operation. Usually, this feature requires some form of capacity control at the air-handling unit, or some sort of volume regulation at the zones as discussed previously. These requirements add some points in addition to the point controlling the shut down damper.

---

[2] Measuring the temperature across the reheat coil is not as simple as it sounds, so judicious application to the larger zones may be more viable than application to all zones. To be effective, the initial and ongoing commissioning process needs to perform a relative calibration between these sensors and the main discharge air sensor to ensure that an indication of a temperature rise is truly a temperature rise and not a false indication due to sensor calibration accuracy issues. In addition, duct temperature rise needs to be accounted for in some manner. And if the discharge sensor is located ahead of the fan, the fan heat also needs to be accounted for.

4.2.3. Single Duct, Constant Volume, Bypass VAV

The single duct constant volume with terminal unit bypass is a slight variation on the constant volume reheat system. Instead of terminal reheat coils, the constant supply flow is varied to meet the cooling load in the space by diverting some of the air directly to the return plenum or duct, thus bypassing the space. Injecting supply air directly into the plenum can pressurize the plenum and cause the return air to flow back into the space. For this reason, the return plenum in bypass systems must be kept at a lower pressure than the occupied space. Return fans may be necessary to attain this low plenum pressure. Constant volume bypass VAV systems can be more energy efficient in cooling and heating modes than constant volume reheat systems since the bypass air reduces the return air temperature during cooling mode and increases the return air temperature during heating mode. As a result, the cooling or heating at the air handler is reduced. However, since a constant volume of air is moved through the space, fan energy is not saved compared to a conventional VAV system, which can often be much more significant than the heating or cooling energy.

The terminal equipment applied with this system can be very similar or identical to the terminal equipment associated with a conventional VAV system and can include reheat capability. For additional information on these terminals refer to Section 4.2.4 Single Duct VAV with Reheat. The point requirements for VAV terminals applied in the bypass VAV system configuration will be similar to those described in Section 4.2.4.

Single Duct, Constant Volume, Bypass Variable Air Volume - Additional or replacement points compared to Single Duct, Constant Volume Reheat System:

- Return plenum pressure differential to zone pressure. Several sensors may be required if the plenum is subdivided by smoke or fire separations due to the pressure drops created by flow through the transfer ducts.
- Bypass air damper command and feedback. Some systems use a common bypass damper, while others bypass at the zone level with the same actuator that controls the terminal damper. To check against bypassing too much air, in cooling and heating modes, at least one bypass damper should always be fully closed. Otherwise the discharge air temperature set point could be increased (for cooling) or reduced (for heating).

Since the zones in this application are variable air volume zones, each zone requires all of the points associated with variable air volume operation.

- The least point-intensive approach to VAV systems is to provide pressure-dependent VAV operation. These terminal units will require damper and reheat control (may need reheat in addition to the bypass during minimum flow) and a space temperature sensor as an input.
- Pressure independent control requires the same points as pressure-independent control plus a flow input from a flow-measuring element on the terminal unit intake.

4.2.4. Single Duct VAV and VAV with Reheat

The single duct variable air volume (VAV) system controls temperature by varying the supply air flow rate to each zone. Air flow is varied by modulating dampers at the terminal units, or VAV boxes. Variable volume systems are more energy efficient than constant volume systems, especially when loads vary across zones. Since each zone is supplied with the minimum amount of flow necessary for cooling or ventilation, the total airflow demanded is greatly reduced compared to constant volume systems. A fan capacity control mechanism[3] reduces the supply air flow and saves energy.

If perimeter heating loads are addressed by an independent perimeter heating system, like finned tube radiation, fan coil units, or radiant slabs, then it is often possible to achieve temperature control simply by varying air flow. In situations where the perimeter heating loads must be served from the VAV system, or where the ventilation requirements (and thus, the terminal unit minimum flow settings) are high, it will probably be necessary to provide reheat coils on many of the terminal units and operate the reheat system all year. Zones with less demand for cooling limit the flow through their VAV boxes, then reheat the supply air if the minimum flow exceeds space cooling demand. The reheat process in a VAV system adds energy, but it is far less significant than the reheat associated with a constant volume system. Using recovered energy from the refrigeration system condenser circuit to serve the reheat requirements in the summer can mitigate this energy burden to some extent.[4]

New VAV boxes are commonly pressure independent, with a flow sensor at the inlet of the box that regulates the zone airflow based on the zone temperature. Pressure dependent boxes, an older VAV technology, operate without this flow sensor. Instead of controlling the damper based on the measured air flow, the damper in a pressure dependent VAV box modulates based directly on the zone temperature. In this case, the flow varies with duct static pressure and is more difficult to control. In all cases, the terminal units are set up to provide some minimum flow level required for ventilation purposes, even if the airflow is not needed to serve the load during lightly loaded conditions. For pressure dependent systems, minimum flow is achieved simply by a limit on the minimum damper position. For pressure independent systems, a minimum flow set point must be met.

Instead of changing the supply air temperature (the only temperature control mechanism for the constant volume system), the variable volume system maintains a fixed supply temperature for similar outdoor air conditions. Although the VAV system does not need to change supply air temperature, for energy savings and comfort control, the supply air temperature can be reset based on ambient conditions or some other indicator. When supply temperature reset is used, the supply temperature is decreased in the summer to meet high cooling and humidity loads and increased in the winter to match the lower cooling loads and reduce reheat energy.

However, supply temperature reset needs to be applied with caution on VAV systems since it can counteract the variable flow operation, resulting in reduced fan energy savings and often

---

[3] Typically, the fan capacity is controlled using a variable frequency drive, inlet guide vanes, variable blade pitch, or discharge dampers. All of these approaches will save the fan energy associated with the flow reduction, although some strategies save more energy than others. For smaller systems with low peaks on their fan curves, the complexity associated with these fan capacity control approaches may not be warranted when compared to simply allowing the VAV terminals push the fan operating point up the curve. Pushing the fan operating point up its curve is also the process provided by a discharge damper, the least desirable of the capacity control mechanisms due to the low fan energy savings potential and the impact the damper can have on the fan's performance due to system effect.

[4] Sellers, David and Tom Stewart, "Making Energy Intensive HVAC Processes More Sustainable via Low Temperature Heat Recovery", Proceedings of ACEEE 2002.

nearly constant volume operation. Increasing the supply temperature setpoint so that the fan does not reduce speed is undesirable since the fan energy savings usually outweigh the heating and cooling energy savings achieved by the temperature reset.

Heating can be accomplished through hot water, steam, or electric reheat coils (with or without a fan-powered VAV box), or by circulating warm return plenum air using fan-powered or induction VAV boxes. In some situations where the loads served have high internal gains and the ventilation requirements are relatively low, reheat is not necessary during the summer months if some discharge temperature reset is provided. In these situations, reheat can be accomplished by using the perimeter heating system during the winter, spring, and fall months. Eliminating the reheat coils and the piping network and controls associated with them has the following benefits:

- Reduced first costs and operating costs
- Reduced potential for energy waste via unnecessary reheat due to inappropriate settings or valve leakage.
- Parasitic losses associated with operating the reheat system during warm weather are eliminated.
- Fan energy is saved since the reheat coil pressure drop has been eliminated from the system.

More information regarding this particular system configuration can be found in:

ASHRAE Systems and Equipment Handbook, 2000, p. 2.10.

Single Duct Variable Volume with Reheat - Additional Points compared to Single Duct, Constant Volume System with Reheat:

- Supply and return/relief fans motor speed command and feedback (compare for VFD diagnostics)
- Drive selector switch status
- VAV box flow
- VAV box discharge air temperature

4.2.5. Hybrid Constant and Variable Volume Systems

In large systems or systems that have undergone renovation, it is not unusual to find a combination of constant volume and variable volume zones in a single air handler. Health care, laboratory, and process applications are particularly prone to this configuration. In general, the central system portion of these air handling arrangements will look schematically identical to a VAV system with similar point and control requirements. The zone portion of the systems will appear to be schematically identical to the VAV zones with the constant volume feature achieved by operating the VAV terminals at a fixed volume. Usually the fixed volume is accomplished by setting the maximum and minimum flow settings of the VAV box to the same value, but it can also be accomplished using mechanical flow regulators that have no external control connections.

Regulating the constant volume flow is necessary to ensure that the flow and pressure variations created in the system by the operation of the VAV terminals do not cause flow variations in the constant volume areas. Without the flow regulation, the flow variations produced in the constant volume zones will tend to be above design flow since the system was probably balanced for design flow at maximum capacity. As the VAV terminals reduce flow, excess flow would occur at the constant volume zones. These flow variations can cause several problems.

- The excess flows in the constant volume zones lead to even greater reheat loads (and the related parasitic loads) than would be seen if the constant volume flow was regulated, thus energy is wasted.
- The excess flows reflect fan energy that could be saved if the constant volume flows were regulated, thus energy is wasted.
- The excess flows in the constant volume zones can create pressure relationship problems between the constant volume zones and their surroundings. Without regulation on the constant volume zones, pressure relationship problems can be difficult to control and diagnose since they vary with the operation of the VAV terminals. Even with regulation on the constant volume loads, there can be pressure relationship problems that occur as the VAV terminals in surrounding areas operate. However, regulating the constant volume zones minimizes this potential. Additionally, if the flow regulation is provided with DDC technology, then the potential exists to write control algorithms that modify the constant volume parameters based on the current state of the air handling system as a field solution to a pressure control problem that may occur down the road.

Point requirements for these systems will be similar to those associated with the single duct VAV and single duct VAV reheat systems, as described in Section 4.2.4 Single Duct VAV with Reheat.

4.2.6. Constant Volume and Variable Volume Multizone

Overview

The traditional multizone includes separate ducts for the heating coils and cooling coils, traditionally called the hot deck and cold deck, respectively. The discharge of the air handler is divided into a number of zones via a zone damper assembly. For each zone, the full cold deck, the full hot deck, or a mixture of the two airstreams can be supplied - as the cold deck damper closes, the hot deck damper opens. The dampers modulate to provide a supply air temperature that adequately serves each zone's heating or cooling load. The air is distributed by a single dedicated duct to each zone.

Multizone systems are often served by packaged air handlers that supply only up to sixteen zones, but these systems are cost-effective compared to built-up air handling systems. The traditional two-deck multizone cools and heats air that is supplied to a single zone, which is a reheat function that is not allowed by many energy codes. This issue is addressed by the three-deck multizone discussed in Section 4.2.8.[5] Although traditional multizones do have some reheat, multizones (without precooling coils) do not cool all of the supply air, since some of the supply air is diverted to the heating coils. As a result, multizone systems are more thermally efficient than constant volume reheat systems, which cool all of the supply air before reheating it as necessary. However, multizone systems are not as flexible as constant

---

[5] An interesting and unusual variation on this approach has been observed where a chilled-hot water coil was installed in the traditional cold deck position, and the hot deck was simply a bypass of the cold deck. When outdoor conditions were not suitable for cooling, the chilled-hot water coil was served with chilled water and the temperature control function was achieved by mixing air discharged from the cooling coil with air that bypassed it. In this mode, the bypass air was very near the return temperature since the system was recirculating and only bringing in the minimum outdoor air required for ventilation. When outdoor conditions were suitable for economizer cooling, the chilled-hot water coil was served with low temperature hot water, the action of the thermostats was reversed and the traditional cold deck became the hot deck and the bypass deck became the cold deck, served by economizer cooling.

volume reheat systems for future reconfigurations since the zone configuration is based on the air handling unit configuration at the zone control dampers.

Multizone systems can be a low first-cost method of serving different loads in a number of zones and have the advantage of placing all of the zone equipment at the air handling unit location (except for the Texas Multizone, discussed in Section 4.2.7 Texas Multizone). This configuration lends itself to applications with a limited number of multiple zones where the zone requirements and configurations are unlikely to change over time.

The constant volume multizone supplies multiple zones with different loads using a constant volume fan. In most instances, this is accomplished with a single fan, but there are designs that utilize a fan for each deck for energy conservation purposes. In many ways, these designs are schematically similar to double duct systems.

The energy efficiency of a multizone system can be improved by adding a variable volume feature. The zone dampers can be delinked with independent actuators for the hot and cold deck dampers associated with each zone. The zones are then controlled to modulate the cold deck damper to a minimum position that will guarantee the required ventilation flow prior to opening the hot deck dampers. If the flow at the minimum cold deck position results in the space being overcooled, then the hot deck damper is allowed to modulate open as required to maintain temperature.

Installing and Commissioning Multizone Systems

Through the process of mixing hot and cold air streams at the air handler for each zone, thermal efficiency is lost due to significant heat transfer between the hot and cold decks at the air handler and leakage through the deck dampers. Over time, damper linkages must be well maintained to minimize this leakage. For larger building areas, extensive ductwork is required to supply air to remote spaces. Duct leakage along this distance should be minimized, since the leakage wastes energy and may result in uncomfortable conditions as remote zones are supplied a reduced amount of air.

Since the entering condition to both decks of the multizone is the mixed air condition for recirculating systems or the preheat coil leaving condition for 100% outdoor air systems, coordinating the economizer control or preheat control with the hot and cold deck control is important from an energy efficiency and performance standpoint. For a recirculating system operating on an economizer cycle, the depressed mixed air temperature (relative to the return air temperature) places an extra heating load on the system for any air that serves the hot deck, compared to serving the hot deck directly with return air. Thus, maintaining an economizer set point that is as warm as possible, perhaps based on the cooling demand, will minimize the reheat penalty at the hot deck.

Multizone units with high percentages of outdoor air which are located in humid environments often use a precool coil upstream of the hot and cold decks. Without a cooling coil upstream of the hot deck, all air passing through the hot deck to the zones will be at a specific humidity determined by the mix point for the return air and outdoor air. For a 100% outdoor air system or a system in economizing mode, the hot deck can be 100% outdoor air. Integrating the economizer cycle with the operation of the cold deck capacity control needs to be used with caution since the air going out to the loads through the hot deck may not pass through a cooling coil and thus may not be dehumidified. Similarly, on a 100% outdoor air multizone unit, the preheat function should be coordinated with the control of the cold deck so that the preheat coil does not heat air any higher than the requirement of the cold deck.

Deck temperature reset routines targeted at maximizing the cold deck temperature and minimizing the hot deck temperature can be particularly important for multizone units from an energy conservation standpoint for several reasons:

- These routines will minimize the heating energy in the hot deck and cooling energy in the cold deck.
- The closer the deck temperatures are, the lower the thermal losses will be from the air from a zone at full cold deck flowing past the fully closed, but warm hot deck damper blades as the air passes through the zone dampers. Similar effects will be minimized on zones demanding full hot deck.
- The thermal losses through the hot deck casing will be minimized.

For multizone systems serving internal zones, it may be possible to reset the hot deck temperature as low as the return temperature since there is no need to heat the internal zones. Multizone units serving perimeter zones can also use return air in the hot deck once the outdoor conditions rise to the point where the zone is experiencing a net heat gain. In most buildings, this occurs somewhere between 60 and 70°F outdoor air temperature unless there are extensive areas of glass. Perimeter zones that have an independent perimeter heating system can also use this approach to hot deck reset.

In order to have a reasonable control response, the pressure drop through the hot deck and cold deck needs to be nearly identical. This is often accomplished by using a smaller coil in the hot deck section since the hot deck coil will typically be shallower than the cold deck coil and will never be wet. Some systems also have a baffle plate in series with the coil to tune this pressure drop relationship. These arrangements can produce high static pressure losses that translate to a constant fan energy penalty.

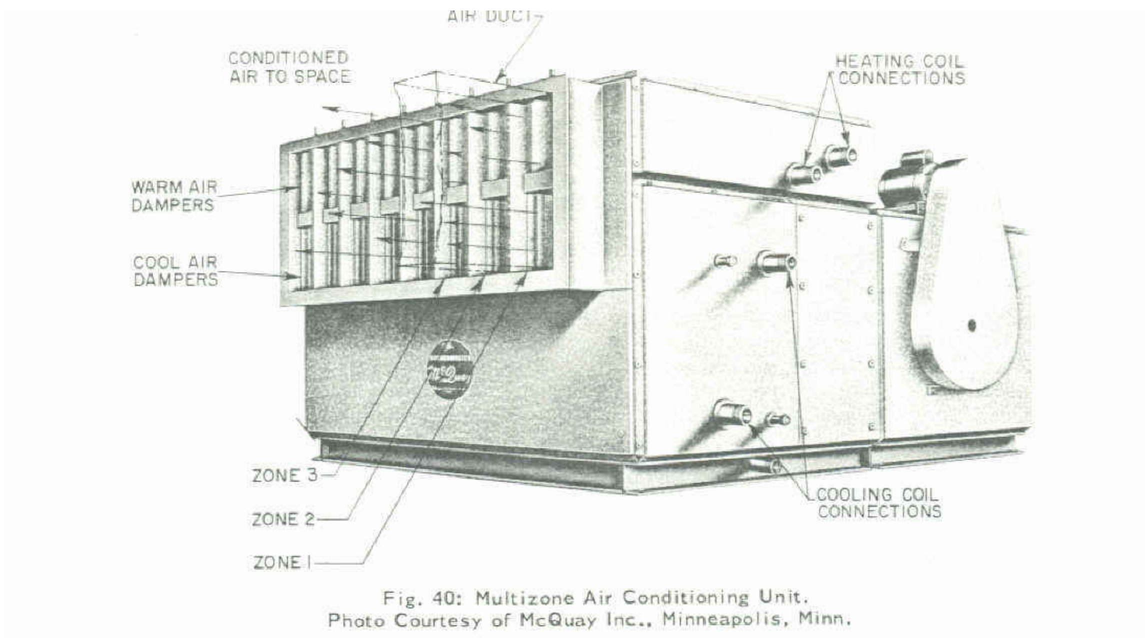


Figure 4.2 Multizone Unit

Constant volume multizone - Additional or replacement points compared to Single Duct, Constant Volume, Single Zone System with Economizer and Return Fan:

- Preheat coil leaving air temperature is the hot deck temperature
- Preheat coil leaving water temperature is the hot deck coil leaving water temperature
- Cooling coil leaving air temperature is the cold deck temperature
- A unit with a high percentage of outdoor air may require a preheat coil and/or a precool coil ahead of the fan. (Add a preheat leaving air temperature sensor, valve command, and feedback and/or a precool leaving air temperature sensor, valve command, and feedback) These configurations are not included in the points list below.
- Mixing damper position command and feedback for each zone
- Zone temperature feed back (to zone dampers)

Variable Volume Multizone - Additional or replacement points compared to Constant Volume Multizone

- For each zone, a hot deck damper command and feedback independent from a cold deck damper command and feedback

4.2.7. Texas Multizone

The Texas multizone, designed to serve hot and humid climates, is a modification of the traditional two deck multizone unit. In hot and humid climates, the cold deck air typically must be overcooled for adequate dehumidification. Return air (typically called the neutral deck) is used instead of an actual hot deck to provide some reheat for each zone. The use of return air as the first stage of reheat saves energy compared to the traditional multizone configuration. Additional heating is provided by independent reheat coils in the individual zone ducts, often at a location near the zone they serve. The zone reheat valve is modulated open after the zone dampers are in the full return air position. Placing the reheat coils in the individual zone ducts saves energy by ensuring that only the air for the zone with a heating demand that cannot be met by the return air will use additional reheat.

Since there is not heating coil in the hot deck, all air flow resistance required for creating an equivalent pressure drop through the hot deck compared to the cold deck is provided by a baffle plate.

Additional or replacement points compared to Constant volume multizone:

- Hot deck temperature is replaced by mixed air temperature
- Perimeter zone reheat valve command and feedback
- Leaving air temperature from zone reheat coil. Use for commissioning and troubleshooting.

4.2.8. Three Deck Multizone

The three deck multizone adds a neutral deck (mixed air) between the cold deck and hot deck. Through the zone damper configuration, cold deck and hot deck air are not allowed to mix. The neutral deck air is mixed with the cold deck or hot deck air to meet the space requirements. In this way, there is no reheat energy used. Full neutral deck air can also be supplied for low heating loads. Like the Texas multizone, using return air for reheat is a heat recovery function, which makes this strategy more energy efficient than the traditional multizone.

The neutral mixed air condition can be much different than neutral return air, especially if the unit requires a high outside air percentage and is located in a hot and humid climate. In these cases, the humidity of the neutral and hot decks may be too high to meet space conditions. The cold deck can be overcooled to reduce its humidity further, or the outdoor air can be pre-cooled to reduce the latent load of the mixture of outside and return air that supplies the hot, neutral, and cold decks. In this way, the neutral deck can be used to temper the cold deck air to meet the space condition required at each zone without increasing humidity to inappropriate levels. This precooling configuration adds a reheat function to the three-deck multizone if the hot deck is utilized during times that pre-cooling occurs.

Three deck multizone - Additional or replacement points compared to Constant volume multizone

- Mixing damper position for each zone (one damper linkage for three decks)
- Neutral deck temperature

4.2.9. Dual Duct Constant Volume and Variable Volume

Overview

Dual duct systems consist of a hot supply air duct and a cold supply air duct that run throughout the building to each terminal unit. This configuration is similar to a multizone, except mixing does not occur at the air handler, but at a mixing box at each zone location. Dual duct constant volume systems maintain a constant volume of air to each zone terminal unit, and vary space temperature by changing the fraction of hot and cold air that is mixed. Since the hot and cold decks may have different static pressures, controls must be used to maintain a constant flow through each terminal unit. The temperature of the hot deck can be reset higher in the winter and lower in the summer to save reheat energy. If heating loads are low enough and the system has two fans, return air can be utilized in the hot deck instead of the heating coils. Similar to traditional constant volume multizone systems, dual duct constant volume systems lose thermal efficiency due to the cooling and reheating process that occurs to maintain space temperature. Dual duct constant volume systems are an improvement over constant volume reheat systems since not all air passes through both the cooling and heating coils, thus some reheat energy is saved.

Dual duct variable volume systems are more efficient than dual duct constant volume systems because the cold deck and hot deck airflow can be modulated at each zone based on the zone thermostat. As a result, fan power and reheat are reduced, since the volume of air to the space can be reduced to a minimum before the hot deck air is introduced.

Both constant volume and variable volume systems can utilize a single fan for both the hot and cold ducts or two fans, one for each duct. When a single fan serves both ducts, the mixed air (mix of return and minimum outdoor air for ventilation) is sent through both the heating and cooling coils. Thus, the ventilation air can lead to increased hot deck reheat energy compared to full return air, and the single fan configuration may not be conducive to economizer use. With separate hot deck and cold deck fans, the hot deck can draw from the return airflow directly, while the cold deck can draw from the outside air as necessary for economizing. The thermal energy savings can make up for the potential increase in fan power from the two fans.

Installing and Commissioning Dual Duct Systems

In this section, the challenges in installing and commissioning dual duct systems for energy efficient operation are discussed.

In order to use the hot deck for only reheat and avoid sizing the hot deck for perimeter loads, most dual duct systems have reheat coils at the perimeter zones to handle the envelope losses. In the dual fan case, the minimum flow for ventilation must come from the cold deck since the hot deck is pure return air. In this way, for zones with heating loads, the reheat is similar to a VAV or constant volume reheat system.

The dual duct system has nearly twice as much sheet metal as you would for other approaches since you end up running two ducts, each one of which must be sized for more than 50% of the air flow, and generally end up being the same size. Even if the ducts were sized for 50% air flow each, there would still be more metal used in the duct system at an equivalent friction rate due to perimeter vs. cross-section issues. (For instance, two 12 x 12 ducts have 8 feet of perimeter and can not carry as much air as one 12 x 24 duct, which has 6 feet of perimeter.)

All of this extra ductwork creates congestion in the ceiling cavity. When tapping the ducts for a terminal unit, one duct will cross the other; i.e. if you connect on the cold deck side, then the hot deck connection has to cross over or under the cold deck to get to the terminal unit. A solution to this problem is to put the supply ducts up high and the terminals down low and tap the bottom of the duct. However, most buildings do not have enough ceiling space to do this.

From a control standpoint, the dual duct system is more complex, especially with the dual fan. For instance, you have one return fan that has to track with two VFD supply fans. In addition, the hot deck fan must never move more air than the return fan; otherwise, it will pull mixed air into the hot deck portion of the system. Designing the controls to make the system work under all operating modes is not easy.

At the terminal unit, similar control problems can exist. Two dampers must be controlled for correct minimum and maximum air flow and space temperature. Dual duct systems can waste energy when hot and cold deck dampers at each zone do not fully seal, creating a false load and unnecessary heating or cooling. Commissioning and maintaining the damper close-off positions on possibly hundreds of dual duct terminal units can be a difficult task.

Single Fan Dual Duct Constant Volume: Additional or replacement points compared to Constant Volume Multizone system

- Mixing damper command (at the zone instead of at the air handler)
- For any terminal units with supplemental perimeter heating with reheat coils, similar to constant volume reheat system (not shown in points list)

Dual Fan Dual Duct Constant Volume: Additional or replacement points compared to Single Fan Dual Duct Constant Volume

- Start/stop command output and proof of operation input for both hot deck and cold deck fans.

Dual duct variable volume: Additional or replacement points compared to Variable Volume Multizone system

- Motor speed command and feedback (compare for VFD diagnostics)
- VAV box flow
- VAV box discharge air temperature

4.2.10. Dual Duct, Dual Conduit

Overview

The dual duct, dual conduit system is a subtle variation of the dual duct dual fan approach that provides supply air for building envelope loads separately from internal loads with two separate supply conduits (supply ducts). The hot deck in a dual duct, dual fan system may use mixed air or full return air, and therefore is not decoupled from the outside air. The dual duct, dual conduit configuration creates a separate system that can be tailored to the needs of the perimeter loads, which will be a heating load part of the year. The second system can be tailored to the needs of the interior, which will generally have a year round cooling load. These systems have frequently been high velocity systems that used induction units[6] for the terminal devices and served high-rise buildings.

Since the perimeter load condition varies with the season, the temperature of the supply air for the envelope loads usually is varied based on ambient conditions. In many applications, independent perimeter systems are provided for each face of the building. This configuration allows the supply air temperature for each face to be tailored to the current load conditions. For instance, a building with a lot of glass on a sunny winter day may actually require cooling on the perimeter on the South face for a portion of the day, but require heating on the perimeter on the North face at the same time. In some arrangements, the perimeter terminal equipment can be an all-air system. In other arrangements, the perimeter terminals consist of reheat coils or chilled-hot water coils. Systems with chilled-hot water coils could be operated in many modes including:

- Supply cold air to the terminals with chilled water in the coils for supplemental sensible cooling on peak days
- Supply cold air to the terminals with hot water in the coils for operation more along the lines of a constant volume reheat system for days when some zones, but not all zones might require some heat while others were a net cooling load.
- Supply warm air to the terminals with hot water to the coils for peak heating loads.

Many times, the hot water system supply temperature is operated on a reset schedule based on outdoor ambient conditions.

The supply air system that serves internal cooling loads and ventilation loads for dual conduit system is cool year-round since, in theory, an internal space will never see a net energy loss if it is surrounded on all sides by conditioned spaces. In the past, induction terminals that mimic current technology VAV and VAV reheat systems served the interior zones. Many of

[6] Induction units are discussed in more detail in *Chapter 19: Terminal Equipment*.

the older versions of this system have been converted to current technology VAV and VAV reheat systems to reduce the operating static requirements.

In a variation on this system, one conduit or duct system is heating-only, utilizing return air and a heating coil while the other is capable of cooling and handles the conditioning of the ventilation air. In this configuration, the envelope and the internal zones that require reheat terminate in a dual duct mixing box and the system tends to operate like a dual duct system.

Installing and Commissioning Dual Duct, Dual Conduit Systems

There are some operational and commissioning issues that are unique to dual conduit systems. Terminal units that were equipped with chilled water coils typically had a small drip pan that was intended to collect any minor condensation that occurred when chilled water was in the coil. Generally, these pans were not piped to drain (hence the name drip pan vs. drain pan). While in theory this is reasonable, since the ambient air dew point should have been reduced by the central system, infiltration through the envelope on the perimeter can cause locally high dew points resulting in condensation problems that overwhelm the drip pans and cause water damage. This problem is most prevalent in older high-rises with leaky envelopes located in humid environments. It can be especially pronounced if the building is operated on a schedule and pressurization is not maintained overnight. When this occurs, the stack effect or other phenomenon that can make the building negative, like a continuously operating exhaust fan with no positive make-up air source, fills the building with humid air during the shutdown period. Then, when the systems are restarted, they must deal with a dehumidification load, and, if chilled water is introduced into the perimeter system coils, the dehumidification occurs there, often with disastrous results in terms of water damage. This usually terminates any efforts at operating the building on a schedule, much to the detriment of its energy efficiency.

This problem usually can be mitigated in the following manner. If not all of the central systems are shut down and the cooling plant remains in operation, then the systems that stay on line will hold the dew point of the building at the intended level, eliminating the start-up dehumidification load and associated condensation problems. In most cases, the systems can be operated in a pure recirculation mode (no minimum outdoor air) to conserve energy. However, introducing some outdoor air will help pressurize the building and may prove beneficial in terms of avoiding localized condensation at start-up due to localize infiltration of the envelope.

From an energy approach, this method of unoccupied operation will use more energy than simply shutting everything down because it requires operating enough air handling capacity to adequately circulate some air through most of the building in some manner. But this can often be accomplished by running only a few of the systems because the real issue is controlling the vapor pressure in the building, not the temperature, and the water vapor will migrate to the area of lower vapor pressure even if there is no active air flow forcing it in that direction. It also requires operating the cooling plant at a low load condition. But, experience has shown that operating in this manner will prevent the water damage problems if the systems that remain on line are carefully selected. And since the energy used to keep these systems running with the chiller plant at low load is often less than the pull down load that occurs if the building fills with humid air during the off cycle.[7] Thus, as an alternative to not shutting anything down during hot and humid weather, it offers an attractive method to achieve some of the fan energy savings available via scheduled operation without risking

[7] When the building fills with humid air, the moisture content of the moisture absorbing materials in the building increases. To bring the building back under control, all of this moisture needs to be pulled back out of the materials and shows up as a part of the pull down load, just like the thermal energy that ends up being stored in the building elements when they are allowed to warm-up over night.

damage to the building finishes and the subsequent termination of any scheduled operation. Savings can still be significant since fan energy is a major constituent of the overall energy consumption pattern of many buildings, often several times the consumption of the cooling plant.

Building envelope loads system: Single duct VAV

Internal loads system: Constant volume with reheat

4.2.11. Low Temperature Air

Low temperature air systems have the opportunity to reduce costs – both annual operating costs and first costs. The principle behind this system is that by supplying air between 45°F and 48°F instead of the typical 55°F supply air, the volume of air supplied can be greatly reduced. Low temperature systems can reduce supply air volume by 30%-40%. The fan energy savings and other benefits must be weighed against any increases in energy and other drawbacks to decide if a low temperature air system is appropriate for a given application.

The reduction in air flow requirements translates into a number of related benefits:

- **Reduced fan power** A smaller fan motor can be selected, and/or the VFD will have greater turn down. It also may be possible to eliminate the return fan. Lower fan horsepower also reduces fan heat in the supply air stream.
- **Smaller air handlers** Smaller duct sizes and reduced coil face area will decrease the footprint of the air handler. The area needed for vertical air shafts is also reduced.
- **Smaller ductwork** In cramped spaces above the ceiling, smaller ductwork makes installation easier. The space savings from smaller ductwork can also lead to shorter floor-to-floor height.
- **Smaller terminal units** Smaller terminal units are cheaper and save space above the ceiling.

Lower supply air temperatures result in lower room relative humidity, which has the following benefits:

- **Indoor air quality** Less potential for growth of mildew and mold due to the reduction of condensation. To achieve this, the building envelope needs to have low infiltration. Slightly positive pressurization is an effective way to achieve this; rather than humid air infiltrating, dry air exfiltrates.
- **Longevity** Building materials and finishes are likely to last longer with reduced humidity.
- **Raise space temperature setpoint** Lower humidity allows a higher temperature setpoint for equivalent comfort. To avoid dumping cold air on occupants, low temperature air systems typically use high-aspiration diffusers that increase room air mixing and diffuser throw. Fan-powered VAV terminal units can also be used to improve mixing with constant fan operation during occupied hours.

While the overall system often saves energy, a number of aspects of the low temperature air system reduce this total savings. Designers should be aware of the following energy increases in their calculations of system energy consumption:

- **Chilled water system efficiency** Low temperature air systems rely on low flow (high delta T) chilled water systems, which tend to increase energy chiller energy slightly. Producing colder water (leaving chilled water temperatures of 42°F to 38°F) can reduce chiller efficiency by 6%-10%. Efficiency can be improved by selecting a chiller precisely for the desired chilled water temperature. To further optimize the chillers, the actual load profile must be used to optimize the chiller part-load efficiency. This actual load can be difficult to predict during design. If actual loads are variable, there may be a mismatch between the load profile that the chillers have been optimized for and the load profile that the chillers will actually see.

- **Cooling energy** With a low temperature air system, significant dehumidification occurs that is not necessary to meet a typical space design condition. The lower humidity levels mean larger cooling loads for an equivalent zone temperature setpoint. Less air is being conditioned to this lower humidity, so the fan energy savings can offset or partially offset this increased cooling and dehumidification energy.

- **Reheat** Compared to a traditional 55°F supply air system, the low temperature system will cause zone reheat to increase if the minimum air for ventilation has greater cooling capacity than the load in the space requires; zones reheat 41°F air rather than 55°F air. Resetting the amount of ventilation air based on actual ventilation requirements can minimize the reheat loads, although this strategy requires a means of sensing and controlling outdoor air flow and a method of detecting occupancy (typically CO_2 sensors). These items add complexity to the system and must be well maintained for persistence of savings.

  Even if the spaces do not run at minimum flow with reheat in the summer months due to the loads on them, they will run at minimum flow in the heating mode. If chilled water was not being used for cooling in any of these zones, then the supply air temperature could be raised to avoid excess reheat. Raising the supply temperature may be difficult because different zones will transition into the heating mode at different times depending on their exposure and loading.

- **Economizer cooling hours** Using low temperature supply air means that the chillers have to run until the outdoor air temperature is below 41°F instead of 55°F. In moderate climates, this difference can translate into thousands of hours per year of additional chiller plant operation.

- **Condensation** In moderate climates, buildings do not typically need to be kept pressurized or dehumidified overnight[8]. In these moderate climates, the outside air dew point can be greater than the low temperature system supply air temperature. If the building is shut down overnight or over the weekend, the stack effect and the difference between the vapor pressure inside and outside can fill the building with outside air. Since this outside air has a higher dew point temperature than the supply air temperature, condensation problems can occur during start-up. The cold supply air can cool the diffusers and other objects below the dew point of the outside air that infiltrated into the building, with resulting condensation damage and indoor air quality problems. Operable windows also represent a path for outside air to enter the building and cause condensation problems upon start-up.

[8] In hot and humid climates, the building must be kept dehumidified and slightly pressurized during all hours of the cooling season to guard against condensation problems.

4.2.12. Natural Ventilation Cycle

The systems previously described consist of mechanical equipment for heating, cooling, and ventilation for commercial buildings. Buildings can also be designed to provide comfortable thermal conditions without using air handling equipment, or only using the equipment for part of the year. Natural ventilation is a low-energy approach to fully meet ventilation requirements and fully or partially meet cooling requirements. Airflow in a natural ventilation cycle may rely on the stack effect, operable windows, wind pressure, wind driven ventilators, or other pressure effects. When the outdoor air is cooler than the air in the building, the stack effect causes warm air inside the building to rise and exit at the top levels and colder, more dense outdoor air to enter at the lower level. The neutral plane can be raised to the top of the building by creating a venturi as the air exits the top floor. Natural ventilation is a site-specific way to bring in outside air for cooling and ventilation without using mechanical energy.

If the natural ventilation cycle cannot meet cooling requirements, an air handler can take over. When natural ventilation and mechanical ventilation systems are implemented together, it is often referred to as a *mixed mode* system. Due to their highly customized nature, natural ventilation and mixed mode strategies are not specifically covered in this Guide, but commissioning the components of these systems, such as dampers and actuators, are covered. Thus, a commissioning practitioner faced with a project that includes such a system should be able to develop a test plan by assembling the necessary components from the information presented.

Chapter 4: Tests for Future Development

Fan Casing Tests for Future Development

4.1. Verification checks

4.1.1. Section bolt-up

4.1.2. Damper reinforcement

4.1.3. Roof

4.1.4. Door swings

4.1.5. Seismic considerations

4.1.6. Housekeeping pads

4.1.7. Rails

4.1.8. Roof curbs

4.2. Functional Tests

4.2.1. Air Handling Unit Casing Leakage Test

4.2.2. Air Handling Unit Casing Structural Integrity Test

Chapter 5: Economizer and Mixed Air

Figures

5.1. Theory and Applications

Outdoor air that comes into a building generally falls into three categories:

- Air that is brought in for ventilation/indoor air quality and make up air.
- Air that is brought in by the economizer cycle to meet cooling loads.
- Air that is brought in to pressurize the building and control infiltration.

The economizer and mixing section includes the outdoor air dampers, return air dampers, and mixing box as shown in Figure 5.1. These components provide an important energy conservation function by allowing the system to mix return air with outdoor air to minimize mechanical cooling and heating.

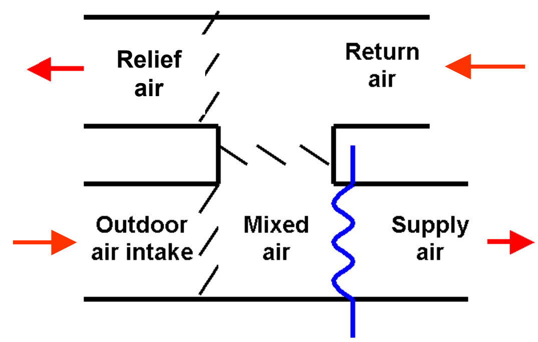


Figure 5.1 Air-side economizer

The design, performance, and operation of the economizer cycle are directly related to the overall make-up and exhaust flow pattern for the system. Therefore, it is necessary to consider the economizer cycle in the context of the requirements for minimum outdoor airflow and exhaust airflow. The minimum outside air is intended to provide ventilation to ensure satisfactory indoor air quality (IAQ) and make up for any exhaust that is taken from the space by process functions like a lab exhaust hood. The minimum outdoor air requirement often includes an additional component to provide for building pressurization.

The economizer cycle operates if there is a cooling load and the outdoor air temperatures are low enough. Extra outside air is brought in instead of running refrigeration equipment to cool the mix of return air and minimum outdoor air.

If outdoor air was simply introduced into the building without regard for how it would be removed, then there would be a tendency for the supply fan system to pressurize the building. Eventually, the pressure in the building would become so high that the doors would be blown open or the flow of outdoor air into the building would be restricted. While these problems seem obvious, they are often not addressed by the design documents or are misinterpreted in the field, resulting in commissioning and operational problems. Problems with bringing in outdoor air fall into the following categories:

- Pressure relationship problems between various spaces in the building.
- Building pressurization problems.
- Temperature control problems when operating in the economizer mode.

The additional outdoor air that is brought in by the economizer cycle for temperature control purposes is generally removed from the building by some sort of relief system. Relief systems are discussed in 5.1.3 Building Pressure Control.

Despite the significant energy savings that can be achieved by proper application of economizers, many economizer sections never achieve their design intent in the real world operating environment. Thus, proper functional testing and adjustment of the economizer and mixed air section is essential to achieving design intent, efficient operation, and good indoor air quality. Common economizer problems are presented in Section 5.4.

While simple in concept, the successful operation of an economizer is dependent upon the dynamic interaction of a variety of components, all of which must be properly designed, installed, and adjusted. The information in this chapter promotes successful economizer systems by providing technical information about the process and its components as well as information about functional testing.

The following subsections give more detail on the three main functions of the economizer and mixed air section operation:

1. **Minimum Outdoor Air**
2. **Economizer Free Cooling**
3. **Building Pressure Control and Return Air Heat Recovery**

5.1.1. Minimum Outdoor Air

As stated previously, minimum outdoor airflow must be introduced in most air handling systems to ensure good IAQ and to pressurize the building. In general, this flow rate should match or exceed the amount of exhaust taken from the area served by the system unless the area served is required to operate at a negative pressure relationship relative to the surrounding areas. Building pressure control functions are discussed further in Section 5.1.3

For energy efficiency, the system must be set up to only ventilate as necessary for the real occupant load and only supply air as cool as necessary for the worst case cooling requirement. The flow required to meet the actual load is often below the design minimum flow setting when the minimum flow rate is based on an overestimation of the number of occupants. With excess ventilation air, the air handling system serves an unnecessary heating load during cold outside conditions and an unnecessary cooling load during hot and humid conditions.

The following approaches can be used to provide minimum outside airflow, sometimes with varying degrees of success:

- **Provide a Limit Signal for Minimum Outdoor Air:** In this arrangement, the minimum outdoor airflow is often neglected or is set based on a percentage of the output signal to the outdoor air damper. For instance, if the system is designed for 20% minimum outdoor air, then a minimum position signal equal to 20% of the actuator span is sent to the economizer dampers. This method assumes a linear relationship between actuator stroke and airflow, which is often a bad assumption, especially if the dampers are oversized. The two most likely problems are:

  The minimum flow may be much higher than required because of the non-linear relationship between flow and damper stroke. Review the damper sizing curves depicted in Figure 5.10, Section 5.6.1.2. A high minimum flow wastes energy due to treating excessive quantities of outdoor air.

  The minimum flow is not positively set (the amount of outside air is not regulated). Older or lower quality dampers may still provide 5-10% minimum outdoor air when they are closed due to leakage, but newer, low leakage dampers may not be counted on to provide this air. Without adequate minimum outdoor airflow, the building can experience indoor air quality problems (IAQ) and/or problems with pressure relationships.

  The limit signal approach can work for constant volume systems where the economizer dampers have been properly sized and the pressure relationships tend to remain fixed. The approach may not provide the required flow under all operating conditions in systems where the pressure and flow relationships vary with load, like a VAV system. As the load decreases, less outdoor air may be brought into the system as the VAV system turns down, depending on the pressure in the mixed air plenum. If the load change is not proportional to the occupancy change, then inadequate minimum outside air may result from the VAV system turn down. In any case, it is critical that the system be set up to provide the required minimum outdoor air flow rate and then maintained in a manner that ensures this. The commissioning process can pay a key role by:

  Functionally testing and coordinating with the balancer at start-up to ensure proper minimum outdoor air flow rates and building pressure relationships.

  Training the operating staff to help them understand the initial settings and ensure their persistence.

  Document the initial settings as well as the procedure used to obtain them, thereby further ensuring their persistence.

- **Provide an Independent Non-Regulated Minimum Outdoor Air Damper:** This approach is an improvement over a limit signal because an independent damper dedicated to the minimum outdoor air function can provide more reliable outside air regulation. Typically the damper is interlocked to open when the unit is in operation and in an occupied cycle and closed when the unit is shut down.

  Achieving the desired flow rate involves an effort on the part of the start-up team to measure and adjust the system to meet the design requirements. Sometimes, an independent manual balancing damper is provided in series with the automatic minimum outdoor air damper so that it can be used to set the flow while the automatic damper provides the on/off function. In other instances, the required flow is achieved by adjusting the automatic damper's crank radius or limiting its travel so that it only opens to the point required to deliver the design minimum outdoor air flow.

  Because this method does not measure and regulate for a specific flow rate it is still subject to the same problems as the first approach on systems where the pressure and flow relationships vary with the load. As with the first case, a good commissioning process is a key step in achieving and maintaining design operation.

- **Provide an Independent Regulated Minimum Outdoor Air Damper** This approach adds flow measurement and control to the independent non-regulated minimum outdoor air approach discussed previously. In some applications, a dedicated minimum outdoor air fan is also provided. When properly implemented and commissioned, this design provides one of the most effective ways to:

  Ensure that the required minimum outdoor air flow rate is delivered under all operating conditions.

  Allow the minimum outdoor air flow rate to be adjusted to match current occupancy levels.

  The minimum outdoor air set point can be a fixed value set for the design minimum flow rate or can be a variable based on occupancy, CO_2 level or some other parameter. The commissioning issues are similar to the previous options discussed, but have the added complication of a flow control loop. The commissioning provider should take steps to ensure that the control loop is properly set up and tuned and that the input signal it is receiving accurately represents the actual flow rate. These checks often require attention during the design and construction phase to the inlet conditions at the flow sensor to ensure a good velocity profile.

- **Provide an Independent Make Up Air Handling System** This system treats all of the make-up air and supplies it to recirculating air handling systems. This approach is frequently seen in systems like clean rooms where pressure relationships and cleanliness requirements make an airside economizer cycle difficult and/or cost prohibitive (due to filtration requirements) to implement. The commissioning issues are the same as previously discussed; the outdoor air flow needs to be set correctly, and, if the recirculating system operates with variable flows and pressures, then it may be necessary to regulate the make-up air connection.

During commissioning, it may be desirable to determine the outside air percentage to make sure minimum damper position is correctly set. In addition, the commissioning provider may want to predict the mixed air temperature that should occur with a known outside air percentage. The predicted temperature can be compared to the measured average mixed air temperature. Significant deviations from the prediction may indicate that the system minimum outdoor air flow is improperly set.

When the supply, return, and outdoor air temperatures are known Equation 9-1 can be used to calculate outside air percentage or the mixed air temperature. This equation assumes that perfect mixing occurs; i.e. the temperature or moisture content of the mixed air stream will be the same regardless of where they are measured in the air stream. This approach works best when there are significant differences between the outdoor air temperature and the return temperature. Accurate measurement of the temperature is critical. Using the same temperature sensor to measure all temperatures will help eliminate temperature sensor calibration errors. Several mixed air temperature readings may need to be taken and averaged to accurately reflect the true mixed air temperature.

$$\%_{\text{ Outside air}} = \frac{T_{MixedAir} - T_{ReturnAir}}{T_{OutsideAir} - T_{ReturnAir}}$$

Equation 5.1

Ultimately, the control of minimum outside air needs to be integrated with the economizer functions. This integration is most critical during extreme weather conditions when the system is not operating on an economizer cycle. At other times, the extra outdoor air brought in by the economizer cycle usually mitigates any IAQ issues and provides more than enough air for building pressurization requirements.

5.1.2. Economizer Free Cooling

The primary design intent behind most economizer systems is to provide free cooling any time the outdoor temperature is below the required system supply temperature. The economizer cycle will also reduce the mechanical cooling load when the outdoor temperature is higher than the required supply temperature but the outdoor air enthalpy (or total heat content) is less than the enthalpy of the return air. They key is to minimize energy – a task that relies on accurate control system and component operation.

The outdoor air damper modulates from minimum position, when the full cooling load can be met by the minimum outside air volume, to the 100% outdoor air position as the outdoor air temperature approaches the required supply air temperature. When outdoor air temperature (or enthalpy) is greater than the return air (or enthalpy), the outdoor air damper should revert back to the minimum setting for ventilation.

Figure 5.2 illustrates the operating curves for an economizer section serving a system with 75°F return air when operating at a 55°F supply air set point and a 65°F set point. The curves are based on the conservation of mass and energy relationships.

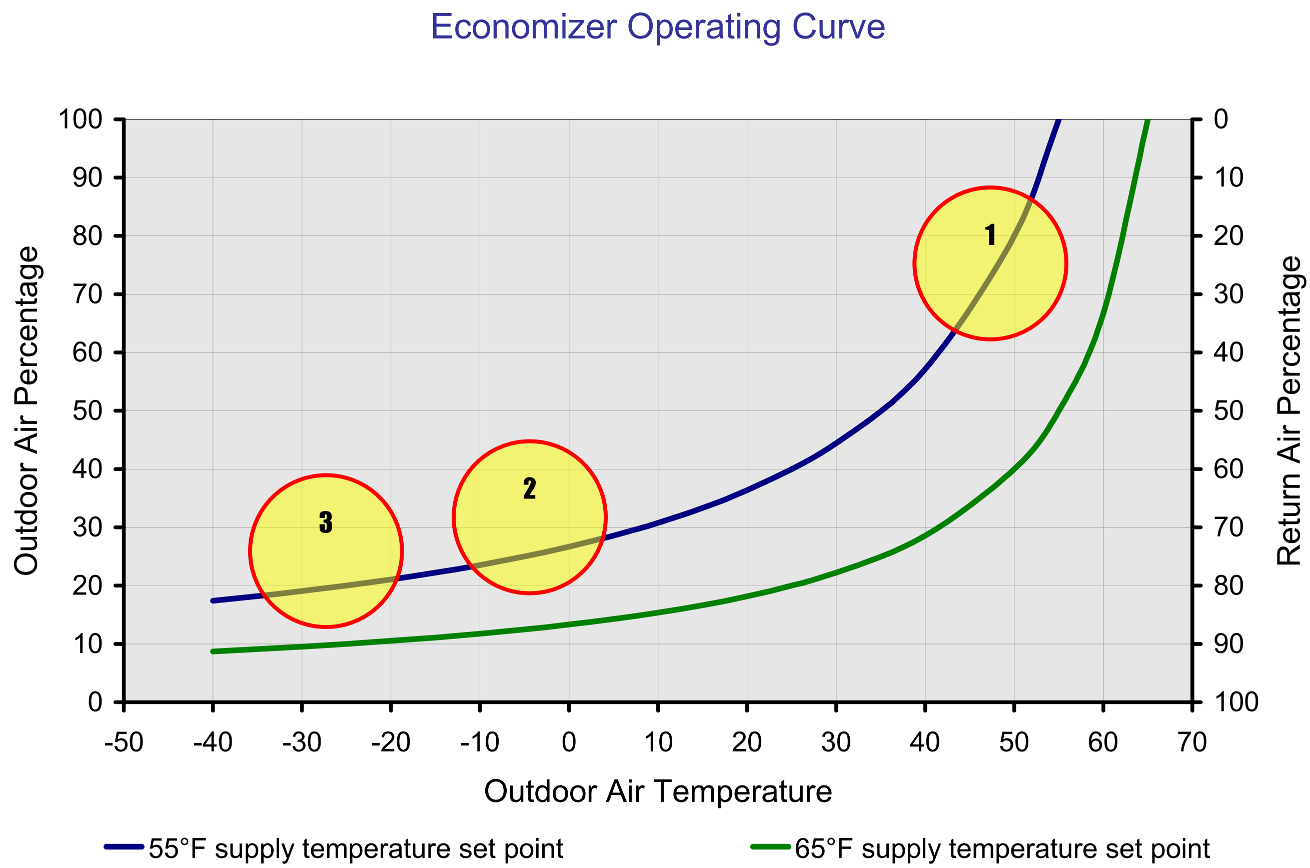


Figure 5.2 Economizer Operating Curves (75°F Return Air)

Figure 5.2 conveys two important points:

The economizer operating curve is non-linear. A 10°F outdoor air temperature change at low temperatures only requires a 4% change in the amount of outdoor air brought in to maintain the set point (Circle 2). At higher outdoor temperatures, the same change in temperature requires a requires a 23% change in the amount of outdoor air brought in to maintain set point (Circle 1).

At low outdoor air temperatures, a change in outdoor air temperature requires a much smaller change in the percentage of outdoor air brought in to maintain set point compared to higher outdoor air temperatures. This introduces a non-linearity into the control loop that can make the loop more difficult to tune. A loop that was tuned and stable when it is cold outside may become unstable (hunting or oscillations) when the outdoor air temperatures warm up or visa-versa. This instability can cascade into other control loops in the system. These issues are discussed further in 5.4 Typical Problems.

Typical office environment minimum outdoor air percentages will not require preheat until it is fairly cold outside. Air handling systems serving office environments typically operate with an outdoor air percentage in the range of 10-30% and discharge temperatures in the 55-65°F range. The operating curves in Figure 5.2 show that it must be quite cold before the desired mixed air set point cannot be achieved by mixing outdoor air with return air. For instance, on a system with a 20% minimum outdoor air requirement and a 55°F discharge set point, it will be approximately 28°F below zero before the mix of minimum outdoor air and return air will result in a temperature below 55°F (Circle 3). This implies that most systems should not use preheat until the outdoor temperatures are extremely cold if everything is functioning properly.

For an air-side economizer system to function well, it must mix the supply and return air streams effectively. Often economizer sections cannot mix the air streams in their designed configuration. In some cases, there can be a 50° - 60°F temperature difference between the warmest and coldest point in the mixed air plenum. Poor mixing causes numerous operational problems, which are discussed in Section 5.4.2.

5.1.3. Building Pressure Control and Return Air Heat Recovery

The temperature control function of operating the outdoor air and return air dampers in an economizer cycle generally results in the need for building pressure control to allow the extra outdoor air that was brought into the building for cooling purposes to exit the building. Additionally, the minimum outdoor air requirement often includes an additional component to provide for building pressurization. In most cases, operating a building at a positive pressure relationship relative to the outdoors is desirable with benefits that include:

- **Improved occupant comfort due to reduced drafts and infiltration** Pressurizing the building tends to cause air to exfiltrate through the leaks and openings in the building envelope rather than infiltrate through them. Occupants in perimeter spaces will be more comfortable if conditioned air from inside the building moves past them to exit the building rather than having unconditioned air from the exterior of the building move past them into the building.
- **Avoided IAQ and condensation problems** Pressurizing the building ensures that outside air does not infiltrate into the building, and all air entering the building is positively conditioned. During the summer, the potential for condensation in the building envelope is minimized since all of the air inside the building is brought in through the air handling system and has been cooled and dehumidified. If hot, humid air is allowed to infiltrate through the building envelope, then it is likely that moisture will condense when it comes in contact with air or surfaces inside the building that have been cooled below its dew point. At a minimum, this can cause damage to finishes and materials. Frequently this situation will lead to mold growth and IAQ problems.
- **Recovered heat from the return air** Pressurizing the building results in reduced perimeter heating loads because instead of infiltrating air at the perimeter, the air is exfiltrated at the perimeter. This exfiltrated air has been heated by the internal gains in the building either at the mixed air plenum where return air and outdoor air are blended or via the heat gains in the space as the supply air warms up to the space temperature. In most cases, any cold air infiltration load on the perimeter system is compensated using energy from a boiler system. Reduced return fan energy consumption results because the return fan moves less air back to the relief damper location. Through experience with retro-commissioning projects, fan energy use has been reduced as much as 20% to 40%.

  Recovering energy from the return air stream is limited when the outdoor air quantities are great enough and/or the outdoor temperatures low enough that preheating the mixed air is necessary to achieve the required supply temperature. However, in many parts of the country, these are extreme conditions, not the norm.

The desired level of building pressurization will be accomplished via one of the following methods:

Barometric Dampers This is generally the simplest approach to controlling building pressurizations and works well if the building is reasonably tight, not geometrically complex or tall enough that chimney effect becomes a factor, and if the path from the occupied space to the relief damper location does not have much pressure drop at design flow. The dampers generally consist of blades and a frame that are mounted and pivoted in such a way as to allow gravity to close the damper and small, positive building pressures to open the damper. Some dampers are counter balanced and can be adjusted to control at specific pressures.

Modulating Relief System using the Same Signal as the Outdoor Air and Return Air Dampers This approach is a common way to control building pressure, especially on older systems. The approach works well for constant volume systems. It also can provide reasonable performance for VAV systems serving relatively small non-geometrically complex low-rise buildings. However, problems can occur because the signal controlling the relief dampers (a pressure control function) is also the same signal as the one controlling the economizer dampers (a temperature control function). As a result, building pressure control problems can be aggravated in high rise buildings, leaky buildings, and buildings with relief fans (as compared to return fans) serving VAV systems. Consider what happens to the partially occupied building in the following example on a 55°F overcast day.

The building's air handling system is VAV with an economizer cycle equipped with relief fans. The relief fans and dampers are controlled by the same signal that is used by the economizer cycle to control the outdoor air and return air dampers to maintain a 55°F discharge temperature. On this particular day, since the outdoor air temperature is equal to the required discharge temperature, the economizer cycle opens the outdoor air dampers and relief dampers to 100% and the closes return dampers. The relief fans are being commanded to run at full speed. But, since there is no solar load and the internal gains are low due to the low occupancy level, the VAV function of the air handling system is meeting the supply flow requirements by operating the supply fan at 50% of its design flow rate. As a result, there is a serious mismatch between the air being brought into the building through the wide open outside air dampers by the supply fan running at 50% capacity and the air being removed from the building through the wide open relief dampers by the relief fans running at 100% capacity. In this particular case, the difference was so significant that most people attempting to enter the building could not open the entry doors due to the forces placed on them by the severe negative pressure difference relative to atmosphere.

Modulating Damper System Controlled by Some Other Signal such as Building Static Pressure This approach solves the problem described in the example above. The relief dampers (and relief fans if the system is configured that way) are operated based on building static pressure instead of by the economizer signal. As a result, the system only begins to relieve air when the building becomes slightly positive. Only as much air is relieved via the relief system as necessary to maintain the slight positive pressure relationship in the building relative to atmosphere.

This approach is especially beneficial in older, leaky buildings, large complex buildings and high rises regardless of the HVAC system type. In these situations, the chimney effect and other factors can become significant influences on the pressure relationship between the inside and outside of the building. By controlling the relief damper off building static pressure, problems with significant positive or negative pressure from the economizer mode can be avoided.

For systems equipped with return fans, the relief system is usually downstream of the return fan location. On systems not equipped with return fans, there may be relief fans if the pressure drop through the relief system with the economizer on 100% outdoor air is greater than the desired positive pressure in the building.

5.2. Commissioning the Economizer and Mixed Air Section

In new construction processes, economizer and mixed air section commissioning tests are targeted at ensuring that the economizer, minimum outside air, and building pressurization meet the project's design intent, both on their own and in integrated operation with the rest of the air handling system. These tests can be used in a retro-commissioning process to define and correct existing operational issues.

In general, test requirements should be tailored to the needs of the systems and the project. To aid in evaluating these criteria for a project, the functional tests in the guide have two tables associated with them:

Section 5.2.1 Functional Testing Benefits lists the potential energy and resource savings that can be attributed to commissioning the economizer and mixed air section.

Section 5.2.2 Functional Testing Field Tips includes information about the time and conditions required to conduct the test, precautions, instrumentation requirements, and acceptance criteria. This information can be weighed against the benefits to guide the user in determining if the test is appropriate for the project and system under consideration.

5.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	An operating economizer can save significant cooling energy compared to operating mechanical refrigeration (Section 5.1.2). Exactly how much energy will vary with climate and building operating hours. Exact calculations require computer modeling. Approximate solutions can be arrived at by using programs such as EZSim® to simulate a virtual building with and without an economizer. Spreadsheets can also be used to develop approximate solutions based on bin weather data and estimated loads at low ambient temperatures. However, it is reasonable to assume that if an economizer has been provided by the design then the effort necessary to make it work is justified. If there are problems with the economizer that require major capital outlays to correct, then additional evaluation regarding the value of the economizer cycle vs. mechanical refrigeration may be necessary. For example, a system that would not function in economizer mode because the relief air was directly recirculated into the outdoor air duct may require some quantification of costs and benefits to prove that it is cost effective to correct the problem.
Other Benefits	Properly adjusted economizer cycles can help control building pressure relationships (Section 5.1.3). This control can make the building more comfortable and can save energy by converting perimeter infiltration loads to exfiltration loads handled by the heat gains in the space. Since an economizer cycle will bring in outdoor air beyond what is required

	for ventilation purposes, it will tend to improve building IAQ. If the economizer process is not properly integrated with other building control functions, it can cause condensation and pressurization problems that degrade IAQ.

5.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	The purpose of functionally testing an economizer cycle is to verify that the process and its related functions perform satisfactorily under all building operating conditions to provide free cooling using outdoor air quantities beyond ventilation requirements. The economizer cycle typically will involve verification of: Operating control (Section 5.5.1) Limit controls (Section 5.5.3) Operational interlocks (Section 5.5.2) Safety interlocks (Section 5.5.4) Ambient Condition Interlocks (Section 5.5.6) Alarms (Sections 5.5.7) Once the economizer functions have been verified, it will be necessary to verify the integrated performance of the economizer with other control processes like the minimum outside air (Section 5.1.1) and building pressure control (Section 5.1.3).
Instrumentation Required	Instrumentation requirements will vary with the specific test sequence selected. In general, having the following instruments available while testing an economizer process will be beneficial. ■ Temperature measurement instrumentation. ■ Sling psychrometer and psychrometric chart. ■ Digital camera. ■ Tape measure or folding ruler. ■ Pneumatic pressure gauge and gradual switch baumanometer to allow pneumatic actuators to be stroked independently from the control system. ■ Air pressure gauge capable of measuring very low air pressures and differential pressures in the range of 0.01 to 0.25 inches w.c. An inclined manometer or magnehelic gauge is typical of this type of instrument. ■ Airflow measuring device capable of measuring very low velocities in the range of 50 to 1,000 fpm. A Shortridge airflow multimeter is ideal for this and also provides a low pressure and temperature measurement capability. Rotating vane anemometers represent a less costly approach. ■ Multipoint data logger with several temperature probes can be very helpful if there is not a building automation system with trending capabilities available.

Test Conditions	Ideally, an economizer cycle should be tested several times during the year to allow its functionality to be confirmed under different seasonal conditions. This is because the dynamics of an operating economizer will vary with the seasonal conditions and loads, and because failure to function properly under different seasonal conditions can often lead to energy waste and IAQ problems. If time or budget do not allow for several test cycles, then it is best to test the economizer under extreme winter and extreme summertime conditions. If only one test sequence can be performed, then it should be performed under extreme winter conditions. Extreme winter conditions typically are the times when most of the problems encountered with economizers become apparent as operational issues. Failure of important control cycles and interlocks to function properly, such as ambient condition interlocks and minimum outdoor air regulation typically are easiest to detect under seasonal extremes. If undetected, these failures will result in significant energy waste that is often masked by other processes in the air handling system.
Time Required to Test	The time required to test an economizer cycle will vary with the complexity of the system and the level of rigor, but will be fairly significant. At a minimum, 2 to 4 labor hours will be required to verify interlocks and integrated function for the small, simple, packaged systems often provided with small tonnage rooftop equipment if the functions are only going to be tested one time at start-up. At the high end, 3 to 5 labor days can be required over the course of the first year of operation if the economizer-equipped systems are large and complex and can interact with other systems in the building, and if the economizer performance is to be evaluated under a variety of seasonal conditions.
Acceptance Criteria	The performance of an economizer under test is acceptable if it meets the design intent of the cycle. Typically, it will include some or all of the following components. ■ The control process is robust and provides reliable free cooling when conditions are appropriate under all building and system operating modes and under all climate conditions, including seasonal extremes outside the statistical design envelope. ■ The functionality of the cycle is integrated with other building processes and systems including building pressurization requirements, zone pressurization requirements, minimum outdoor air requirements, normal and emergency operating modes, and scheduled operation. ■ Interlocks return the economizer dampers to safe and efficient positions when the air handling system is shut down. ■ Interlocks disable the economizer cycle when it no longer provides energy savings benefit. The set points of these interlocks are appropriate for the loads served and the local environmental conditions. ■ Interlocks protect the air handling system and building areas served by the economizer from damage in the event of a failure of the control process or a component of the system. These interlocks include low temperature cut-outs, high and low static pressure cut-outs, pressure relief doors, and limit switches. ■ Alarms are provided to alert the operating staff to economizer operating

	conditions that could lead to energy waste and/or the failure or unscheduled shut down of the air handling system served by the economizer.
Potential Problems and Cautions	Like most functional testing process, economizer test procedures generally force the system to operate at the extremes of its design and performance envelope during portions of the test cycle. When everything is working properly, systems operating at these extremes generally will be exposed to the greatest risk of failure, energy waste or other undesirable outcomes. Thus, the testing team needs to have evaluated the system for the test to be performed. Many of these issues are covered in *Chapter 2: Functional Testing Basics*. Specific areas of concern for economizer testing include: ■ Safety interlocks such as the low temperature cut-out and the mixed air plenum low static pressure cut-out and permissive interlock functions should be verified early in the test sequence to protect the system from problems caused by test of the operational control and interlock systems. ■ If testing occurs in extreme weather, then it would be desirable to know that the heating and cooling/dehumidification functions associated with the system were minimally functional. This will help to protect the system and building from temperature and humidity extremes and their related freezing, overheating, or condensation potential if problems occur with control of the economizer while under test.

5.3. Non-Copyrighted Tests

Not every test contained in this chapter will apply to every system. The configuration or operating environment of the system may not justify the time, effort and expense of some tests. For example, the integrity of the mixing and the operation of the freezestat may not be important (or even required) on a 5,000 cfm packaged rooftop unit equipped with a factory economizer, direct expansion cooling, and a gas furnace located in a mild climate like San Francisco. In contrast, the same size unit, equipped with a field-erected economizer and located in Minneapolis, may require that attention be paid to the mixing functions of the economizer and the performance of the freezestat if equipment damage and nuisance freezestat trips are to be avoided.

5.3.1. CTPL Functional Tests

The Commissioning Test Protocol Library contains the following tests focused specifically on testing economizers. These tests are generally for systems with building automation systems (BAS), but the tests can be modified to fit different systems.

Economizer Procedure (PG&E)

Link to "General Commissioning Procedure For Economizers" as prepared for the Pacific Gas & Electric Company, Customer Energy Management Non-Residential New Construction Program.

Economizer Procedure (PECI)

Link to "Functional Performance Test: Air-Side Economizer" as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, PECI. 1998.

5.3.2. Economizer Evaluation Checklist

It is important for the commissioning agent to follow through on these items as the project moves from design into construction by reviewing shop drawings and verifying proper installations during site inspections. In the end, these efforts will be rewarded by a system with fewer commissioning issues to address at start-up and during the first year of operation.

Items to watch for include:

- Make sure someone is taking responsibility for sizing the dampers. Sizing can either be done by the designer on the actual contract documents or through assignment to the controls contractor. If damper sizing is assigned to the controls contractor, then the commissioning agent should review the sizing calculations and other details included in the control submittals. Additional discussion about damper sizing can be found in Section 5.4.1.1 Damper Oversizing and in the Supplemental Information in Section 5.6.1.2 Damper Sizing.
- When necessary, be sure that a mixed-air, low-limit cycle is included in the control sequence. Additional information on this sequence and its benefits can be found in Section 5.5.3 Limit Control.
- Be sure the design provides sufficient distance for the air to mix between the mixing dampers and the first coil in the air handling system. Be sure that the design reflects an economizer damper configuration that promotes mixing both by the arrangement of the dampers relative to each other as well as by the way the dampers rotate to close. Ideally, the designer should detail the required arrangement on the construction documents. However, if the engineering time or budget does not support this, then the details can be delegated to the control contractor. When delegated, the contract documents should require that the control contractor include the necessary detailing as a part of the controls submittal package and the commissioning agent should review this information. These issues are discussed in Section 5.4.2.
- Make sure the documents reflect installing the mixed air sensors and freezestats in a manner that fully covers the mixed air plenum and allows the mixed air sensor to accurately reflect the conditions that the freezestat will see. This may require multiple sensors for larger systems. Running the sensing elements for the mixed air sensor and freezestat together helps to ensure consistent system performance by subjecting these two related sensors to identical conditions. The support system detailed for the sensors should ensure that they are only affected by the air stream conditions, not frame or coil radiant effects.
- Make sure the documents detail the installation of actuation systems in a manner that assures linear or near linear relationships between actuator stroke and blade rotation (and thus flow if the dampers are sized). Additional information regarding this topic can be found in Figure 5.16 in *Section 5.6.2.5*.
- Make sure that the designer has considered the impact of flow reductions in VAV systems on damper performance at part load. Damper performance and linearity are velocity dependent, as is discussed in Section 5.4.1.2. The problem is much easier to address at the design phase when the necessary adjustments are made on paper.

The checklist that is linked to the button below uses some rules of thumb and quick evaluation techniques to help evaluate a new or existing system and determine if the system is likely to have economizer-related operating problems.

Link to Check List EconEval	**Link to a checklist that helps assess the susceptibility of a new or existing economizer to operating problems. Includes evaluation criteria, links back to the Guide and directs the user to appropriate follow-up actions.**

The checklist summarizes many of the concepts presented in detail in this chapter in a form that is usable as a field tool. There are several ways that this checklist can be used:

- **As a design review tool** The checklist can be used during the design phase to evaluate the economizer design information shown on the plans. Issues identified can be targeted for further review and evaluation by the design team.
- **As a field tool for new construction** The checklist can be used in new construction during the construction observation phase to allow the installation to be evaluated as it is installed. Problems identified can be flagged and resolved prior to start-up and the functional test sequence can be structured to ensure successful resolution.
- **As a field tool for retro-commissioning** The checklist can be used during the initial assessment phase of the project to help identify potential problem areas with energy conservation and performance improvement potential. The results can be used to target functional tests and identify solutions.

5.3.3. Economizer and Mixed Air Tests for Future Development

Several functional tests for fan casings have been identified for future development, and may be included in later versions of the Guide.

Economizer and Mixed Air Tests for Future Development	**Link to a list of tests related to the economizer and mixed air section that have not yet been developed.**

5.4. Typical Problems

The following typical problems with economizer and mixed air operation are described briefly in this section. When each problem is described, references are provided to educational information contained in the remainder of this chapter and in Section 5.6 Supplemental Information.

- Control Loop Instability
- Poor Mixing
- Excess Minimum Outside Air
- Terminating the Economizer Cycle
- Setting Damper Interlocks
- Nuisance Freezestat Trips
- Coil Freeze-ups

5.4.1. Control Loop Instability

With regards to economizer operation, two system characteristics can lead to discharge air temperature control loop instability: outdoor and return air damper oversizing and operation at a high turn down ratio.

5.4.1.1. Damper Oversizing

Dampers that are oversized or not properly actuated can cause control linearity and mixing problems. If the damper is oversized, the air may be moving too slow through the damper to result in a significant pressure drop. Damper pressure drop relative to the system pressure drop has a major impact on achieving a linear relationship between damper flow rate and damper stroke. Refer to Figure 5.10 in Section 5.6.1.2 for a damper characteristic curve (% flow vs. % damper stroke) and discussion about how to achieve good damper performance. The linkage arrangement used to connect the actuators to the dampers can also have an impact on achieving this linear relationship. Without a linear relationship between flow and damper stroke, the economizer cycle is difficult to control – instability in the economizer cycle can cascade into other control loops.

Where independent loops are used to control each heat transfer element, instability in the economizer loop causes an unstable input to the control loop for the next heat transfer element. If the economizer control loop starts to hunt, it will introduce pressure variations into the air handling system. In variable volume systems, these pressure variations can cascade into the fan capacity control loop and cause it to become unstable. In turn, fan control instability can result in unstable supply static pressure at the inlet to the terminal unit, which can trigger instability in the terminal equipment flow regulation control loops. The bottom line is that a hunting system can waste energy due to simultaneous heating and cooling, wear out valve and actuator seals and other mechanical components, and create operational and comfort control problems.

5.4.1.2. High Turn Down Ratio

VAV systems can pose particularly challenging economizer control problems if the system must operate at a high turn-down ratio. VAV systems provide a wide variation in flow rate -

it is not uncommon for systems with the ability to shut off flow to an unoccupied zone to see a flow variation of 10:1 or more (design flow vs. flow with one tenant area occupied at low load). The linearity of the dampers as well as the mixing performance are related to velocity of the air through the damper. The reduced flow rates in VAV systems at part load translate into reduced damper velocities. Specifically, at 50% flow, the damper velocities are 50% of design flow, and the pressure drop across the damper is 25% of the design value. This reduced pressure drop can cause a significant decay in the linearity of flow through the damper vs. damper stroke. A VAV system with reasonable damper flow vs. stroke linearity at higher load conditions can become less linear at low load, resulting in poor control. An oversized damper exacerbates the problem, since even at design flow, the velocity is lower than desired.

When economizers fail to perform reliably at high turn down ratios, the solutions typically involve either preventing the system from turning down as much or giving up on the economizer and running mechanical cooling in its place. These solutions can be energy intensive and have some operational problems of their own at the central plant. But, many times, they are the only viable solutions for an existing system, especially if the system doesn't spend a lot of time running at the low turn-down ratio.

To address high turn-down ratios on larger systems with multi-section dampers, each damper section of the multi-section outdoor air, return air and relief air dampers is equipped with an independent actuator.[1] The output signal to each damper assembly is split so that half of the sections are controlled by one output and the other half are controlled by the other. The control logic is arranged to disable and force closed half of the damper sections in each assembly when the system reaches 50% turn-down. This will reduce the available damper area by 50%, which increases the velocities at low loads. As a result, the damper pressure drops increase and the flow linearity at low load improves. In addition, the higher velocities also promote mixing. This solution is easier to implement in a new design rather than as a retrofit, but retrofits can be feasible if the existing dampers are multi-sectioned.

5.4.2. Poor Mixing

The configuration of the mixing plenum and the damper sections play important roles in ensuring the outdoor air and return air streams are thoroughly *mixed* by the economizer process. Economizers with poor mixing can have excessively stratified air streams. The problems occur partly because the momentum and turbulence that promote mixing drop off significantly as the velocities in the mixing box and through the dampers drop.

In one instance in a retro-commissioning environment, performing the temperature traverse test revealed a temperature difference of 60°F across the plenum with nearly the subfreezing outdoor air temperature in one layer at the bottom of the plenum and nearly the return air temperature in a layer at the top. The freezestat element was located in a manner that did not expose it to the layer that was subfreezing. The averaging sensor controlling the economizer was doing what it was designed to do (averaging the temperature across its element) and indicated a mixed condition of 53°F. As a result the economizer control loop thought it was doing a fine job, the freezestat sensed that nothing was wrong, and the coil froze several of the bottom rows where the subfreezing air in the bottom layer contacted it. VAV systems require special attention in this regard as is discussed in Section 5.4.1.2 High Turn Down Ratio and Section 5.5.1 Operating Control.

---

[1] This has some other advantages since it is often better to have a small actuator on each section rather than a large actuator with a jackshaft running multiple sections to ensure that the dampers achieve their leakage rating.

Occasionally, poor mixing conditions can have far reaching and unexpected implications. Figure 5.3 is an example of a particularly interesting problem related to vertical stratification that was set up by a bad mixing arrangement and carried itself through the DWDI fan to the discharge duct. For a significant distance down the discharge duct, zones on one side were hot and zones on the other side were cold.

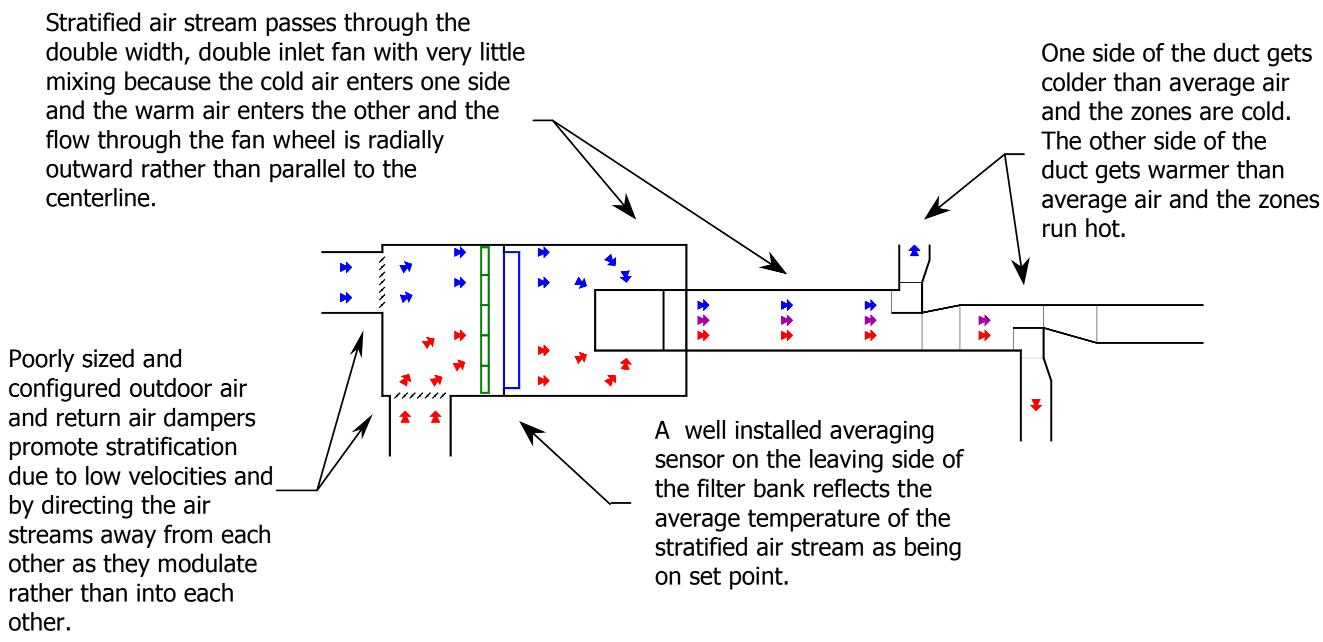


Figure 5.3 Mixed Air Stratification Carried Through a DWDI Fan

Additionally, a high turn down ratio can cause a system that exhibits good mixing characteristics at design flow rates to degrade to poor control at low flow rates. Variable air volume systems are particularly prone to this issue.

Problems that result from poor mixing:

- Turn down capabilities are defeated.
- The economizer function is disabled and the chilled water plant is operated all year to serve the cooling loads.
- Outside air that stays at the bottom of the duct trips the freezestat.
- Systems cannot cool spaces during winter months because the mixed air controllers have to be set to extremely high temperatures to prevent nuisance freezestat trips.

Identifying a mixing problem:

- Take a temperature traverse of the mixed air plenum in cold weather to better understand the problem. The results of this test can be used to direct the remaining steps in this list.
- Calculate the turn down ratio (see 5.3.2 Economizer Evaluation Checklist). High turn down ratios lead to low velocity through the dampers and poor mixing.

Methods for improving mixing:

- Disable and permanently close some of the damper blades to improve the velocity through the damper. This makes the damper characteristic more linear and gives the air streams momentum to mix.
- Rotate the damper sections so that the damper blades direct the air streams into each other as they close. This creates turbulence and helps to promote the mixing process.
- Add baffles to divert the air stream several times before it reached the coils. This also creates turbulence, which promotes mixing. If the baffles are arranged so that the velocity through them is low (800-1,000 fpm) then significant benefits can be realized without significant additional pressure drop. Applying these techniques to solve a problem is described in Section 5.6.6.

By taking some or all of these steps on problem systems or by focusing attention during design phase commissioning, it is possible to obtain systems that have a 5°F or less temperature variation between the warmest and coldest point in the mixing section, even in extreme winter weather.

5.4.3. Excess Minimum Outside Air

The design minimum outdoor air flow setting at the air handler ensures that adequate outside air is distributed to the building for occupant ventilation and building pressurization. This design outside air flow is often well above the actual flow required, since design flow is routinely based on an overestimation of the number of occupants. With excess ventilation air, the air handling system serves an unnecessary heating load during cold outside conditions and an unnecessary cooling load during hot and humid conditions.

Regulating the outside air flow is a challenge. Placing a limit signal on the outside air dampers may not correctly regulate flow, since this method assumes a linear relationship between actuator stroke and airflow, which is often a bad assumption, especially if the dampers are oversized. Another option is to provide an independent minimum outside air damper that modulates open or closed. This independent damper can also be regulated, which adds flow measurement, control, and sometimes a dedicated minimum outside air fan. An alternative way to bring in outside air is to use a dedicated outside air make-up unit in conjunction with recirculating systems. These issues are discussed in detail in Section 5.1.1 Minimum Outdoor Air.

However, it is not unusual to find office air handling systems using preheat when the outdoor temperatures are over 40°F. There are a variety of reasons for this including:

- Systems do not have a mechanism in place to regulate the minimum outdoor airflow rate regardless of system flow rate.[2]
- Figure 5.4 illustrates the mixed air temperature will be achieved by systems with good mixing operating at different minimum outdoor air percentages as the outdoor air

---

[2] Without such regulation, variations in the system pressure relationships that occur with variations in flow on VAV systems can change the minimum outdoor air percentage as the sensible load changes. This change in minimum outdoor air may not be desirable depending on the relationship between occupancy and sensible loads. If the sensible load is closely coupled to occupancy, then it is desirable to reduce the minimum outdoor air flow rate as the system flow rate drops off, which tends to maintain a constant percentage of minimum outdoor air. Without flow regulation, many systems will tend to maintain a constant minimum outdoor air *flow rate* which increases the minimum outdoor air percentage at low flow. This situation can cause a system to preheat when it is unnecessary.

temperature varies. Notice that Figure 5.2 shows the same information as Figure 5.4 but with different axes.

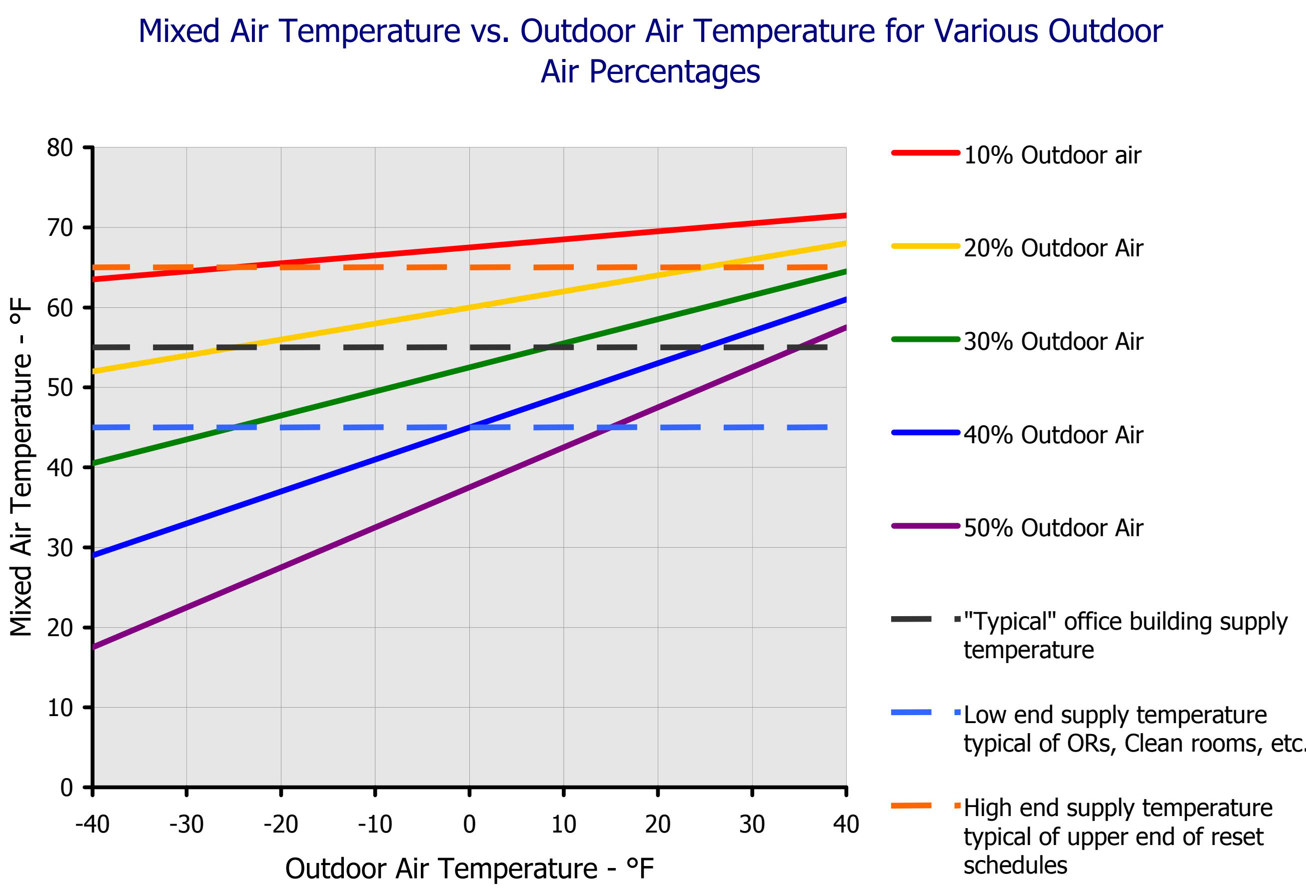


Figure 5.4 Mixed air temperature vs. outdoor air temperature

5.4.4. Terminating the Economizer Cycle

The combination of outdoor temperature and humidity will reach a point where the economizer provides no energy savings benefit. At this point, an interlock disables the economizer and changes the system over to a recirculating mode with minimum outdoor air. There are three main operational interlocks for the economizer cycle:

- **Fixed dry bulb** Compare outside air dry bulb temperature to a fixed setpoint to control the economizer cycle.
- **Differential dry bulb** Compare return air dry bulb temperature to outside air dry bulb temperature to control the economizer cycle.
- **Differential enthalpy** Compare return air enthalpy to outside enthalpy to control the economizer cycle.

These operational interlocks are often incorrectly set, changing over to purely mechanical cooling when the outside air can still provide energy savings. With a fixed dry bulb setting, ASHRAE 90.1 and California's Title 24 require that the setpoint be 75°F in dry climates, 70°F in intermediate climates, and 65°F in humid climates. These setpoints were determined from building energy modeling to minimize energy use. In dry climates, the differential drybulb control may not improve energy savings enough to justify the added cost. Terminating the economizer cycle based on the enthalpy of the outside air provides the maximum amount of free cooling. However, the additional maintenance of the enthalpy sensor must be weighed against the incremental hours of economizer cooling. The improvement in performance of differential enthalpy can be justified for humid climates if the sensors are kept in calibration.

For more details on selecting an outdoor temperature interlock setting or an enthalpy-based interlock setting, refer to Section 5.5.6 Ambient Condition Interlocks. Enthalpy switches and sensors are discussed in Section 5.6.3.3.

5.4.5. Setting Damper Interlocks

The operation of the economizer cycle needs to be interlocked with the operation of the system it serves so that the outdoor air and relief dampers are closed when the system is shut down, thereby preventing problems with unconditioned air entering the building during unoccupied hours. There are a number of issues that often show up as commissioning or operational problems if they are not addressed during design. Interlocks need to operate reliably in all system modes, and on systems with large fans capable of high static pressures, interlocking the return dampers to close when the unit is off for smoke isolation purposes sets the system up for a failure if both the outdoor air and the return dampers fail to open prior to fan operation. These issues are described in detail in Section 5.5.2 Operational Interlocks.

5.4.6. Nuisance Freezestat Trips

Nuisance freezestat trips can be challenging to troubleshoot because they often occur under very specific conditions that are difficult to duplicate or simulate. Furthermore, it is often difficult to restart the system and return to normal operation after the trip. In an extreme case, some systems simply will not run below certain outdoor temperatures due to freezestat trips.

Nuisance freezestat trips can become frustrating to operators, who usually solve the problem by either defeating the scheduling program, preventing the economizer operation and using mechanical cooling, manually cracking the hot water valve open so that there is always enough heating to protect the freezestat, or by jumping out the freezestat. The first three solutions will waste energy. The last solution can lead to a failure of the water coil or coils due to freezing, and in extreme cases can freeze the entire building plumbing system. If the unit operates on a schedule, then the problem will show up during the warranty year and there is some hope that it will be addressed and corrected via the warranty process. However, for systems that operate 24 hours per day, 7 days per week, the problem will most likely occur the first time there is an extended power outage during cold weather. This may not occur for years after the unit is installed. When a nuisance freezestat trip occurs, it is quite likely that a less than optimal solution will be employed in an effort to return the critical system back to operating status.

The commissioning provider can alleviate the likelihood of nuisance freezestat trips through a well-designed inspection and functional testing program focusing on the following areas:

- **Mixed air low limit control** Sometimes it is necessary to use a low limit control strategy for economizers in cold climates. When the economizer is controlled based on the discharge air temperature from the supply fan, employing mixed air low limit control during operation will reduce freezestat trips. If the economizer is controlled off the mixed air temperature, then the mixed air low limit control strategy is not necessary.

  Consider the following scenario. During an extended shut down, the air in the vicinity of the discharge sensor as well as the various components in the unit will tend to stabilize at the temperature of the surroundings, typically 65°F - 75°F range. When the system restarts, the discharge temperature is significantly above set point (usually in the 55°F - 60°F range) and begins to drive the economizer dampers toward the 100% outdoor air position. Since there is some distance between the mixed air plenum and the discharge temperature sensor, and since the air from the mixed air plenum will be warmed up as it cools down the coils, casing, fan housing and other components of the air handling unit, it will take some time for the discharge temperature to drop to match the mixed air temperature. As a result, the unit will tend to drive toward and stay at the 100% outdoor air position until the temperature at the discharge sensor drops toward the discharge temperature set point. However, if the outdoor air temperature is below freezing, the mixed air temperature can drop below the set point of the freezestat. The outside air trips the freezestat, which typically requires a manual reset. In most cases, it will take 5-10 attempts to start the unit before the discharge temperature will catch up with the mixed air temperature fast enough to prevent the problem. In some cases it is impossible to get out of this mode by repeated freezestat resets; the thermal inertia of the system is too great when combined with the dynamics of the intake system, control dampers and control system.

- **Freezestat Location** Sometimes, systems experience nuisance freezestat trips simply because the freezestat element has not been located properly. The purpose of the freezestat is to protect water coils that have not been designed to handle subfreezing air by shutting down the system if the air that reaches them is approaching freezing. The freezestat element should be at a location in the system that is never expected to see air near freezing temperatures under all normal operating conditions.

- **Sensor Calibration** Some freezestat problems to be traced to sensor calibration either directly with the mixed air sensor or freezestat or with the relative calibration of the other sensors in the system with reference to the mixed air sensor or freezestat. If the individual heat transfer elements are controlled by independent control loops and there are relative calibration problems between the control loops, then the loops will tend to fight each other. Any instability in one could cause the other control loops to hunt. If the hunting becomes pronounced enough, a temperature swing may trip the freezestat. The Relative Calibration Test in Chapter 18 can be used to check new and existing systems for problems in this area.

- **Mixing** Poor mixing is also a common cause of nuisance freezestat trips. Section 5.4.2 discusses key system parameters and design features that can help promote good mixing.

- **Transient Condition** Many nuisance freezestat trip problems can be traced to the inability of the system to respond to a transient condition. The most common transient condition is a system start-up. Other transient conditions include:

  Changes in the operating mode of a system from continuous operation to scheduled operation.

  Changes in load profile that increases the turn-down ratio of a VAV system.

Climate extremes at or beyond design which were not encountered in the previous operating life of the system.

Changes in the performance characteristics of one or more of the heat transfer elements due to fouling, component wear, or some other age related factor.

Unanticipated outages in a system that normally operates continuously due to a power outage in extreme weather.

5.4.7. Coil Freeze-ups

The direct cause of coil freezing is typically that the freezestat failed to function and did not provided the intended freeze protection. The indirect cause is a malfunction upstream of the freezestat that caused the coil to be subjected to subfreezing air. These malfunctions include poor mixing, improper damper sizing, and damper actuation problems. Most coil freeze-ups can be attributed to one of four causes:

Coils subjected to subfreezing air by design but were not installed and controlled properly or the protecting mechanism failed. Steam coils that have not specifically been designed to handle subfreezing air can freeze, especially at low steam flow rates. At low steam flow rates, the steam condenses to a liquid at some point early in the tube circuit. It then must flow as condensate (liquid water) to the end of the tube and out of the coil. If the air is subfreezing, the coil is often capable of cooling the condensate to the freezing point before it exits the coil, eventually rupturing the tube. Steam coils that are not designed to handle subfreezing air need to be protected by a freezestat, just like any other water coil.

Coils subjected to subfreezing entering air temperatures by the operation of a life safety control function (intentional or false trip). This failure is discussed in *Chapter 17: Management and Control of Smoke and Fire*, Section 17.4.5 Coil and Water Piping Protection, Condensation Protection.

Coils subjected to subfreezing entering air temperatures due to failure of a preheat system or failure of a control or limit system. Failures in this category usually relate to malfunctions in the economizer system, especially poor mixing and damper oversizing.

There are instances where a coil has frozen and the freezestat never tripped. This can occur for a number of reasons.

- **Freezestat Mechanism Failure** Freezestats can fail within the switching mechanism as well as a failure of the sensing element. For this reason, a functional test that targets the entire mechanism, including the sensor, is a better test than one that targets just the electrical switching mechanism.
- **Freezestat Disabled** If the economizer has not undergone a thorough commissioning process that ensured that the economizer functioned reliably, then the economizer may plague the operators with nuisance problems, particularly, the start-up problems associated with a lack of a mixed air low limit control sequence. In frustration, the operators may have disabled the freezestat. Unfortunately, this approach places the system at risk.
- **Outside air dampers** Failure of the outside air dampers to close when the air handler is not operating can result in cold air entering the system. This situation is not a freezestat failure since a conventional freezestat installation merely shuts down the fan when the freezestat trips. This situation is discussed in Section 5.5.4 Safety Interlocks.

5.5. Economizer Control Strategies

Economizer cycles typically have several different control requirements associated with them including:

- The operating control strategy that governs the cycle in normal operation.
- Interlock strategies designed to terminate the economizer cycle when it no longer provides any useful benefit or the system it serves is not in operation.
- Limit control strategies designed to accommodate transient conditions such as start up or sudden load changes.
- Alarms designed to detect problems.

5.5.1. Operating Control

The operating control of the economizer system is designed to modulate the supply and return dampers to maintain either the mixed air temperature, or in sequence with the heating and cooling coils to maintain the discharge air temperature or zone temperature. In addition to these temperature control related functions, the control of the relief dampers must also be integrated with the operation of the return and outdoor air dampers. Relief dampers need to be controlled in a manner that allows the system to deal with the extra outdoor air brought in by the economizer cycle. This issue is discussed in Section 5.1.3 Building Pressure Control and Return Air Heat Recovery.

In many ways, a start-up is one of the most difficult and complex operational modes for an HVAC system. Every component and control loop in the system is subjected to a significant step change in its input (going from the shut down state to the operating state). These upsets result in the control loops modulating their outputs in an effort to find a stable control point in the new operating mode. The unstable output of one control loop can become an unstable input to the other, causing instability in the second control loop in the cascade.

The following common problems related to operating control are presented in Section 5.4:

- **Control Loop Instability**
- **Excess Minimum Outside Air**
- **Poor Mixing**
- **Terminating the Economizer Cycle**

5.5.2. Operational Interlocks

The operation of the economizer cycle needs to be interlocked with the operation of the system it serves so that the outdoor air and relief dampers are closed when the system is shut down, thereby preventing problems with unconditioned air entering the building during unoccupied hours. However, there are several details that need to be addressed in order to provide the most robust and reliable system. These issues often show up as commissioning or operational problems if they are not addressed during design.

The interlocks that shut down the economizer dampers need to function regardless of the position of any hand-off-auto selector switches at the DDC controller, fan drives or starters. Interlocks that depend on the operation of the DDC system are easy to implement. If the system is being operated manually, either for commissioning purposes, temporary heat purposes or in an emergency, perhaps caused by the failure of the DDC controller, then the interlock function can inadvertently be aborted. In these cases, the system runs without freeze protection.

Interlocks that are based on pressure or current signals need to be set to function reliably at all system operating points. As a basis for the operating interlocks on a system, proof of operation must be determined. Fan motor current or pressure differential across a filter bank, cooling coil, or fan are good indicators, but they need to be set up to provide reliable information in all operating modes.

Differential pressures vary as a function of the square of the flow rate, and motor horsepower (and thus, amperage) varies with the cube of the flow rate. As a result, when a variable volume system unloads, the signals available for differential pressure-based and motor current-based proof of operation inputs can decrease quickly. In order to ensure operation of the economizer and other features that use this information as an interlock, the functional testing process should verify that a reliable signal is provided at design flow as well as at the minimum flow.

Some system differential pressure signals prove fan operation but do not necessarily prove flow. Consider a system where the fan has started but the discharge smoke damper has failed to open for some reason. A proof of operation input from based on fan differential pressure would indicate that the system was running since the fan does not have to move air to generate a pressure difference. A proof of operation input based on coil or filter bank differential pressure would not indicate the system is running since there must be flow to generate a pressure difference across these elements.

Any damper that is used for fire or smoke control functions must be listed for that service. On some larger systems, the outdoor air and return air dampers are selected and controlled to provide code dictated smoke isolation of the air handling equipment from the duct system[3]. These installations are less flexible for field modifications to address economizer problems. In addition, any repairs or component replacements made must be done with components designated and installed in a manner dictated by the manufacturer in order to retain the U.L. rating.

If the return dampers are being used for smoke isolation purposes, then they will need to be interlocked to close rather than open when the unit is shut down. This is contrary to the conventional operating mode for an economizer, which closes the outdoor air and relief dampers and opens the return dampers when the unit is shut down.

[3] See 1999 NFPA 90A paragraph 2-3.9.2 for and example of this requirement. Other codes contain similar language or simply refer to NFPA.

4 Interlocking the return dampers to close when the unit is off for smoke isolation purposes sets large systems up for a failure if both the outdoor air and the return dampers fail to open prior to the fan start. Under a no-flow condition, a fan will generate its rated shut-off static pressure. If the inlet side of the fan is closed off and the outlet is reference to atmosphere via the open but inactive duct system, then the fan will attempt generate its rated static as a negative pressure on its inlet. Many large fans can generate static negative static pressures in this manner that are well above the rating of the intake systems, mixing boxes and air handling unit casings. To prevent damaged to the air handler, there are several measures that can be taken.

- Fabricate the duct and plenums on the intake side of the fan for a pressure class rating in excess of the fan's rated shut-off static pressure. This may be the most viable and trouble-free approach on systems with fans rated for modest static pressures at shut-off.
- Install manual reset type static pressure limit switches and wire them into the safety circuit to shut down and lock out the fan in the event such a condition were to occur. This may not be the best course of action since the switch needs to respond quickly enough to shut down the fan before it can do damage. A large fan wheel can take several minutes to decelerate (spin-down time).
- Install pressure relief doors. These devices are discussed in Section 13.5.3 Air Hammer.
- Install limit switches wired in a permissive interlock circuit so that the fan will only be allowed to start after the dampers are open to the point where no damage to the ductwork and air handler casing can be done. The switches should monitor blade position, not shaft or crank arm position since crank arms and shafts can come loose from the blades they serve. Figure 5.5 illustrates a typical installation of this type of switch.

Figure 5.5 Typical damper limit switch installation

Note that the switch is sensing blade position and that the unistrut mount makes it easy to adjust the switch for the desired trip point.

If limit switches are used for an economizer-equipped air handling unit, then both the return and outdoor air dampers need to have limit switches, and the limit switches need to be wired and adjusted so that if either damper is open sufficiently, then the system will be allowed to start (or remain in operation). If the limit switches were installed only on the return damper, then the system would "think" it had a problem when the economizer drove to the 100% outdoor air position. The start-up and commissioning process needs to include a Permissive Interlock Test to verify that the adjustment of the switches on the different damper assemblies is coordinated and will not inadvertently shut down the system when the economizer is under modulating control or the outdoor or return dampers are closed.

5.5.3. Limit Control

Sometimes it is necessary to use a low limit control strategy for economizers in cold climates. When the economizer is controlled based on the discharge air temperature from the supply fan, employing mixed air low limit control during operation will reduce freezestat trips. If the economizer is controlled off the mixed air temperature, then the mixed air low limit control strategy is not necessary.

A properly employed mixed-air low-limit cycle can prevent freezestat trips and not reduce the performance of the system. A control loop is created based on mixed air temperature that overrides the normal economizer control sequence to prevent the mixed air plenum from dropping below some limit, like 40°F. This limit cycle will hold the mixed air temperature at a safe level until the temperature at the discharge sensor drops toward the discharge temperature set point.

5.5.4. Safety Interlocks

Like operational interlocks, safety interlocks need to be arranged to function regardless of the position of any hand-off-auto or inverter-bypass selector switches associated with the air handling system's fan motors. In many instances, it is also desirable to have them trigger some sort of alarm to bring the problem to the attention of the operators. This section discusses control issues related to two safety interlocks: freezestats and static pressure switches.

5.5.4.1. Freezestat Control Sequences

The most common safety interlock associated with the mixed air section is the low temperature cut-out, typically referred to as the freezestat. Control strategies are discussed below, while freezestat installation details are discussed in Section 5.6.3.2.

There are some situations where a properly installed and functioning freezestat will not protect the coil it is associated with from freezing. In this situation, the outdoor air dampers fail to close or seal completely when the unit shuts down during subfreezing weather. The dampers can fail to close for a variety of reasons including actuator failures, blade and jamb seal failures, linkage failures, operator errors, or binding of the damper blades. If damper failure combines with a pressure difference between the inside and outside of the building, like stack effect in a high rise, or an operating exhaust system with no make-up air, then outdoor air can flow through the open dampers and unit into the building. Since the flow is not directly related to the operation of the fan, a conventional freezestat installation (where the freezestat is wired to shut down the fan when it trips) will afford little protection. There are several approaches that can be used to address this problem.

Arrange a freezestat trip to cause full flow to the heating and cooling coils. In addition to shutting down the air handling unit, the freezestat can be arranged to fully open the valves on the heating and cooling coils and to start the chilled and hot water distribution pumps. These safety interlocks provide several layers of protection. The most obvious is that activating the heating coil will provide heat inside the unit and warm up the subfreezing air stream until the operating staff can respond to the alarm. Moving water through the coils provides a second layer of protection. The thermal energy stored in the piping circuit, even if the water is at ambient building temperatures, will protect the system. If subfreezing air entering the unit persisted long enough, the heat transfer out of the water system to the subfreezing air stream would eventually drop the temperature of the water system to dangerous levels.

Some control sequences vary this approach by commanding the coil valves fully open any time the unit is shut down. While this strategy accomplishes the same intent as the interlock of flow to the coils with the freezestat, there are some operating difficulties associated with it. If there is no air flow through the unit when it is off, then the air and air handler casing in the vicinity of the coil will approach the cooling or heating water temperature. In the case of the heating coil, this slug of very hot air, in addition to the other start-up transient conditions, can make the system difficult to start. Wide-open valves also can put a significant parasitic burden on the heating plant, with energy losses through the air handling unit casing. Problems associated with a cooling coil operated with a wide-open valve when the unit is off are less severe. The lower tube and fin temperatures mean that the coil has a lower apparatus dew point (a measure of its ability to dehumidify). As a result, the air inside the unit casing is cooled and dehumidified more than it would be if the unit were in operation. The open valve wastes energy and can cause condensation and water damage problems, especially for rooftop equipment in hot and humid environments.

Arrange the freezestat to start the return fan when it trips. This approach provides temporary protection for the coils by using the warm air in the building to pressurize the mixing plenum until the operators can respond to the alarm. It is a reasonable temporary measure to prevent frozen coils, but can create problems if it persists long term since the air that the return fan is moving is drawn from elsewhere in the building.[4]

Include a control sequence that uses the hot water coil to hold the air handling unit casing temperature above freezing any time the unit is not operating. In this approach, an independent control loop is set up to modulate the heating valve to hold the mixed air plenum or coil plenum at some safe value, like 40°F - 45°F when the unit is off. With modulating the hot water valve, the system will be easier to start than if the valves were commanded fully open since it will not have a large amount of very hot air that accumulated in the unit while it was off. In addition, heating energy will be saved: heating energy in the form of lower losses due to lower temperatures at the unit casing, and pumping energy (assuming a variable flow system) since the valve will be modulated, probably nearly closed, most of the time rather than wide open. Using a mixed air low limit cycle when the system is not operating also makes a central heating plant easier to control since the wide open valve(s) serving a coil with no air flow represent a short circuit on the hydronic system. The short circuit artificially raises the system return water temperature and creates flow conditions in variable flow systems that look like design load conditions without the corresponding thermal loads. This condition is similar to the overflow problem on a variable flow chilled water system. Modulating the hot water valve to hold the air handler above freezing will also make the start-up swings of the entire system, including the economizer dampers, less pronounced.

Obviously, the best approach to guarding against freezing air entering a unit due to damper failure is to prevent the failure. On new construction projects, the issues that

---

[4] Since the return fan will pressurize the mixing plenum in this operating mode, it is likely that air will be blowing backwards (out) of the intake louver. Since this means air is leaving the building at the intake louver, then air must be entering the building at some other location, probably through leakage around cracks or through other air handling systems. Eventually, this could cause freezing problems at those locations.

cause damper failure are addressed by good field inspection practices followed up by a thorough functional testing plan. Field inspections should target:

- Verification of the blade and jamb seals and general damper construction.
- Verification that the damper assembly is installed in a manner that prevents racking and binding.

Functional testing should target:

- Verification of damper actuator stroke and smooth operation.
- Verification of proper interlocks.
- Verification of any special safeties and cycles incorporated into the system to counteract operating problems like a unit shutdown with the outdoor air dampers stuck open.

In existing systems, the issues typically are related to Operations and Maintenance (O&M) practices that can be addressed by targeting the items listed above as a part of the ongoing O&M program.

5.5.5. Static Pressure Switches

Another common safety associated with the mixed air section is a low limit differential pressure switch (Figure 5.6). This type of interlock is applied to systems where the fan is capable of significant static pressures and a control or damper limit switch interlock failure would make it possible for a fan to attempt to start or remain in operation with both the return and outdoor air dampers closed.[5]

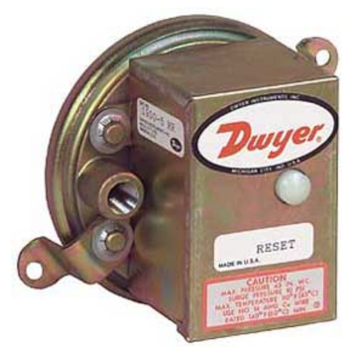


Figure 5.6 Typical static pressure safety switch

(Image courtesy of the Dwyer web site)

Static pressure switches do not provide absolute protection against duct system collapse. The air hammer phenomenon discussed in Section 13.5.3 happens too quickly for this switch to provide protection.

In addition, large centrifugal fans can take some time to spin down to a stop after power is removed due to the inertia of the fan wheel. They continue to generate pressure and flow during this spin down cycle. The setting of this switch needs to be adjusted to shut down the system before the dangerous conditions exist so that the conditions created as the fan spins down do not cause the duct to collapse. It is important to coordinate closing the outdoor air and return dampers with the fan spin down time on systems where both dampers are closed when the fan is off.[6] Otherwise,

[5] Centrifugal fans will generate their rated pressure on their inlet or their outlet or both. If the inlet connection is totally closed off, as would occur if a control failure caused both the outdoor air and return air dampers to close, then the fan will generate its rated no-flow static pressure as a negative pressure on the inlet side since the discharge is essentially referenced to atmospheric pressure via the supply duct system. If this no-flow or shut off static pressure rating exceeds the negative pressure class of the intake duct or the negative pressure rating of the air handling unit casing, the casing or duct could collapse. Note that the positive and negative pressure ratings for any given duct construction is usually not the same. Typically a duct will be capable of withstanding more positive pressure than negative pressure.

[6] While not the standard configuration for most systems, this arrangement will often be found on systems where the return damper provides the smoke isolation function required by NFPA or other building codes and in systems with parallel air handling units where the return damper is used to isolate the off-line system from the ductwork and other operating systems to prevent backflow.

the pressures created as the fan spins down and the dampers stroke closed can cause nuisance trips of this safety device.

5.5.6. Ambient Condition Interlocks

In most locations, the ambient conditions will reach a point where the economizer provides no energy savings benefit. To address this issue, an interlock needs to be provided to disable the economizer and return the system to a recirculating mode with minimum outdoor air. There are two main ways to accomplish this: outdoor temperature based interlocks and enthalpy based interlocks.

5.5.6.1. Outdoor Temperature Based Interlock

Interlocks based on outdoor dry bulb temperature is usually the least complex and least costly to implement. Typically, the economizer cycle is terminated based on some ambient outdoor air temperature, also called the changeover setting. The trick is to select a temperature that will maximize the energy savings obtained from the economizer. The temperature will vary by location depending on the local climate. In dry climates with low mean coincident wet bulb temperatures it is possible to set the changeover setpoint near the design space temperature. However, in a hot and humid climate, this approach can place a significant energy penalty on the air handling system since it will have to do much more dehumidification to cool the outdoor air at or near the design space temperature compared to cooling the return air from the space mixed with the minimum outdoor air requirement.

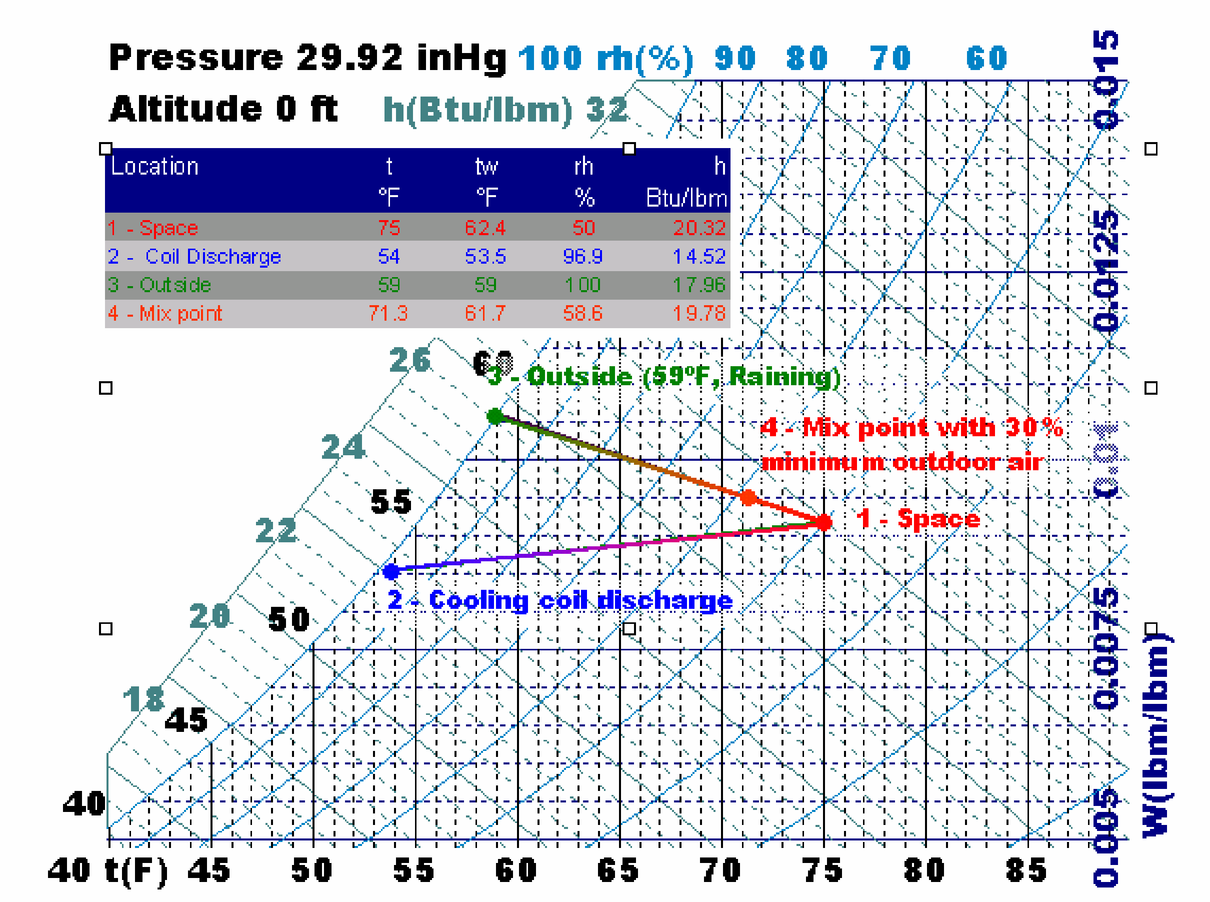


Figure 5.7 Cooling minimum outdoor air vs. 100% outdoor air

Figure 5.7 shows that cooling and dehumidifying 100% outdoor air to 54°F requires 3.44 Btu of energy be removed from every pound of air (17.96 Btu/lb – 14.52 Btu/lb). Cooling the mix of 70% return air and 30% outside air requires that 5.26 Btu/lb be removed (19.78 Btu/lb – 14.52 Btu/lb). Even though the outdoor temperature is above the required supply temperature, the system will use less energy if it remains on the economizer cycle using 100% outdoor air. Mechanical cooling is still necessary, but not as much as would be required if return air were used.

The energy needed to cool the air depends on the temperature and moisture of the incoming air, which must be taken into account when determining a dry-bulb economizer changeover setting. Figure 5.8 illustrates one possible method of determining an energy-efficient dry bulb changeover temperature. The steps are listed below:

A line representing the statistical average of a specific location's climate conditions is plotted on a psychrometric chart. In the example, bin data from the Air Force Engineering Weather Data Manual was plotted using the Mean Coincident Wet Bulb (MCWB) temperature for each dry bulb temperature bin.

2 A second line is plotted that is a constant enthalpy line for the state of the air in the space at its design condition.

3 The economizer change over controller is set for the dry bulb temperature where the two lines intersect.

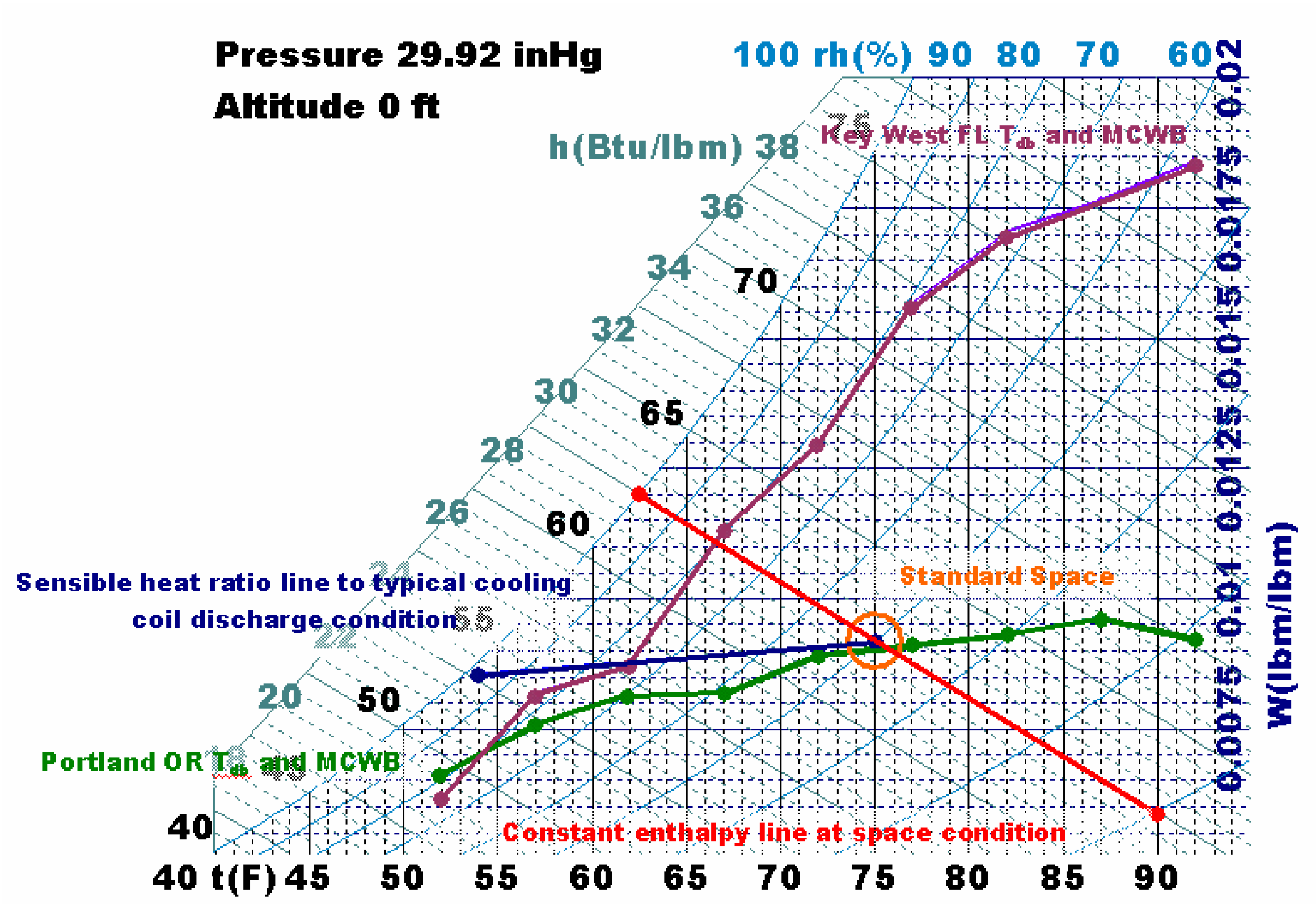


Figure 5.8 Determining temperature-based economizer changeover

From a statistical standpoint, it will take less energy to cool the outdoor air than the return air at the conditions to the left of the intersection for the particular location being analyzed. Conditions to the right will take more cooling energy to cool the outdoor air compared to the return air. Therefore, the dry bulb controller should be set up to shut down the economizer for temperatures above the intersection point and allow it to function for conditions below the intersection point.

As can be seen from Figure 5.8, the exact value for this point can vary significantly from location to location. In the very hot and humid climate of Key West, the change-over point is somewhere in the 66-67°F range. In the mild climate of Portland Oregon, the changeover point is 75-76°F. The lines on this graph were developed from bin weather data in the Air Force Engineering Weather Data Manual but could also be developed from other readily available sources such as NOAA.

It is important to understand that the statistical weather data reports average conditions. The changeover temperature selected by plotting this data on a psychrometric chart will be correct most of the time, but probably not all of the time. However, this method provides more insight and better criteria for the correct changeover set point selection compared to simply shutting down the economizer function when the outdoor temperature is warmer than the required supply temperature or warmer than the space design temperature. When properly applied and then verified by the commissioning process, the optimized set point selection saves energy.

5.5.6.2. Enthalpy Based Interlock

When properly applied, using an enthalpy-based interlock has the advantage of providing an exact solution to determining the changeover point, while the preceding approach provided an approximate solution. Unfortunately, enthalpy is a property that is more difficult to understand and measure than temperature. Several approaches to applying enthalpy-based economizer control can provide reliable performance if they are properly implemented, adjusted, and maintained.

The importance of proper adjustment and maintenance of enthalpy sensors cannot be overemphasized. Verification of operation requires a basic understanding of psychrometrics and access to a sling psychrometer or some other reliable indicator of atmospheric moisture content. Most of the maintenance problems are related to the portions of the equipment that sense humidity and often can be traced to contamination of the sensing element by dust and water or failure due to exposure of the plastics used to the direct or reflect rays of the sun and their associated ultraviolet component. The Enthalpy Change Over functional test included later in this chapter as well as the information in the following paragraphs and in the Sensing Elements section of this chapter are targeted at providing guidance for an enthalpy-based economizer interlock.

There are two main ways to implement an enthalpy based change-over from economizer to non-economizer operation.

- The most common approach simply assumes an enthalpy state of the return air based on design conditions and then allows the economizer to function only if the measured outdoor air enthalpy is less than the assumed return air state. This approach avoids the cost of an enthalpy sensor or switch for the return air and allows the change over decision to be made by one master switch for the building. The approach will provide the desired result as long as the fundamental assumption regarding the constant enthalpy state of the return air is valid. In projects where constant return enthalpy is not a good assumption, a differential enthalpy-based strategy is often employed.
- Differential enthalpy-based economizer change-over cycles require at least one enthalpy switch or sensor in the outdoor air stream for the building or system and another switch or sensor in each air handling system’s return air. The control strategy is arranged to change over from economizer mode to non-economizer mode if the actual measured enthalpy of its return air stream is less than the current outdoor air enthalpy. This approach provides the most precise solution to determining the changeover setting, but it also adds first cost for the sensors and commissioning, as well as a significant ongoing maintenance burden compared to an outdoor temperature-based interlock. Enthalpy sensors tend to require more attention than temperature sensors if they are to remain reliable. This is discussed in greater detail

later in this chapter under *Sensing Elements*. Thus, the decision to use differential enthalpy to optimize energy consumption should be weighed against the added resources required to implement it.

To measure enthalpy, two position switches and enthalpy transmitters. As an alternative, it is possible to use a temperature transmitter and a humidity or dew point transmitter and calculate enthalpy based on ASHRAE psychrometric equations.

5.5.7. Alarms

There are several alarms and smart alarms that can provide benefit for economizer-equipped systems. The minor commissioning costs to verify the alarms are typically small relative to the potential benefits if the alarms are properly applied. The alarm requirements should be identified before the system is programmed, allowing the logic to be developed in conjunction with the rest of the operating software. Alarms to consider include:

- A mixed air low limit alarm set to provide a warning of an impending freezestat trip.
- Low and high alarms on the set point used by the system for the mixed air low limit control as well as the normal mixed air control cycle. These alarms will alert the operating staff to inadvertent changes to these set points that could cause operational problems.

Smart alarms require the development of program logic as opposed to simply entering a value in a point parameter screen. Thus, there can be some cost associated with implementing them. Options to consider include:

- Alarm if the system is not on minimum outdoor air but is using preheat.
- Alarm if the system is using mechanical cooling but is not on maximum outdoor air when the conditions are suitable for using outdoor air.
- Alarm if the outdoor or return air dampers are hunting.

5.6. Supplemental Information

There are many hyperlinks throughout *Chapter 5* that reference supplemental information regarding components of an economizer. In addition to accessing this information by clicking the hyperlinks, the supplemental information document can be accessed using the link below.

Economizer and Mixed Air Supplemental Information

Chapter 5 Economizer Components Supplemental Information

Table of Figures

Most economizer and mixing sections include some or all of the following components.

Dampers to control the flow and mixing of the air streams and regulate minimum outdoor air.

Actuators to power the dampers.

Sensors that provide the inputs to the control loops, interlocks, and safety circuits that control the temperatures, pressures, and flows associated with the economizer process.

Blank-off Plates to adapt dampers that are smaller than the duct.

Air Blenders and Baffle Plates to promote the mixing process.

The following sections will discuss these items in greater detail.

5.6.1 Dampers

5.6.1.1. Damper Selection

Dampers are provided in the mixing section to modulate the outdoor air and return flows as required by the economizer cycle. There are two common blade arrangements used for these control dampers, opposed blade and parallel blade, shown in Figure 5.9.

- The blades of a parallel blade damper remain parallel to each other throughout the rotation cycle. This arrangement allows the damper to direct the air as it moves through them, which can be an advantage in a mixing situation. However, the dampers require a higher pressure drop through them to achieve a linear control characteristic compared to opposed blade dampers.
- Opposed blade dampers have a linkage arrangement that causes pairs of blades to rotate towards each other as the damper actuates. As a result, the air stream experiences very little change in direction as it passes through the damper. When compared to a parallel blade damper with identical dimensions and the same air flow across it, an opposed blade damper will achieve a linear flow characteristic with less pressure drop.

In both arrangements, the damper blades are mounted on a shaft that allows the blades to rotate around their long axis. For multi-blade assemblies, there is typically one blade or shaft that is designed to be the drive blade or shaft to which the actuator is connected. The other blades in the damper are driven by a linkage system from the drive blade. There are typically two arrangements for this linkage system.

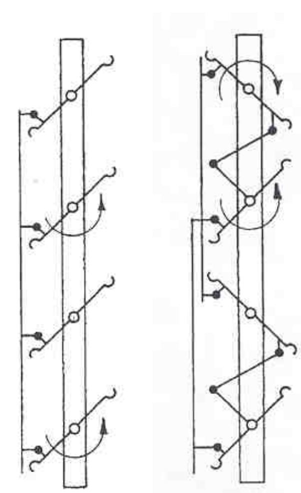


Figure 5.9 Parallel and Opposed Blade Dampers

- The linkage drives the blades by rotating the shaft and is completely concealed in the damper frame. This arrangement keeps the linkage and pivot points out of the air stream, which can be an advantage from a pressure drop standpoint as well as a maintenance stand point if the air stream is dirty. However, if linkage maintenance is required, it is often more difficult due to the concealed location inside the frame.
- The linkage drives the blades through a linkage that extends from blade to blade. In this arrangement, the shafts provide support and a pivot point, but generally do not transmit power from the actuator to the blades. The drive linkage is more accessible in this arrangement, but is

also exposed to the air stream, which can add pressure drop and reduce the life of pivot points if the air stream is dirty.

In addition to the blade-oriented considerations discussed in the preceding paragraphs, the actual configuration of the blade itself should be considered when the damper is selected. There are two general blade designs available in the HVAC market currently.

- **Flat Plate** This configuration is the standard offering of most manufacturers and consists of a flat plate secured to the damper shaft, usually with some sort of bend or break folded to the length of the blade to ensure rigidity.
- **Airfoil** In this configuration, an extruded blade with a streamlined profile is used. An airfoil provides a rigid assembly that is resistant to flutter at high velocities and helps to ensure good blade seal compression. Thus, these dampers are often have a low damper leakage rating. The streamlined shape results in a significantly lower pressure drop as compared to the flat plate design; often by as much as half for identical damper geometries at identical flow rates. This lower pressure drop can be an advantage or a disadvantage depending upon how the damper is applied as will be seen in the next paragraph.

5.6.1.2. Damper Sizing

For most control applications, it is desirable to achieve some sort of linear relationship between damper position and damper flow. For example, the damper should reduce the flow through it by 50% when the damper has rotated 50% closed. To achieve this, it is necessary for the damper to have a significant pressure drop relative to the system that it serves. Figure 5.10 illustrates the damper characteristic curves for a parallel blade damper at a variety of pressure drop ratios (α) where α is the ratio of system pressure drop to damper pressure drop. Opposed blade dampers have similar characteristic curves, but require less pressure drop to achieve the same linear control.

- Ideally, the mechanical designer or controls contractor should have sized the dampers to achieve a nearly linear characteristic. Unfortunately, this step is often neglected and commissioning problems are often the result. Generally, the problems will fall into the following categories: Poor mixing due to lack of velocity of the air streams. This topic is discussed in *Chapter 5,* Section 5.1.2: Economizer Free Cooling.
- Poor controllability due to a non-linear relationship between damper position and flow.[1]

[1] To gain some insight into this, consider two parallel blade dampers, one sized for an $\alpha = 10$ and the other sized for an $\alpha = 200$. By looking at the curves in Figure 5.10, it can be seen that when the first damper is at 20% stroke, the flow through it will be approximately 28% of maximum. While not perfectly linear, this control is much better than the second damper, which at 20% stroke allows nearly 77% of maximum flow. The over-sizing of the damper causes the controller to have to control over a limited portion of its span, making it difficult to achieve tight, stable control.

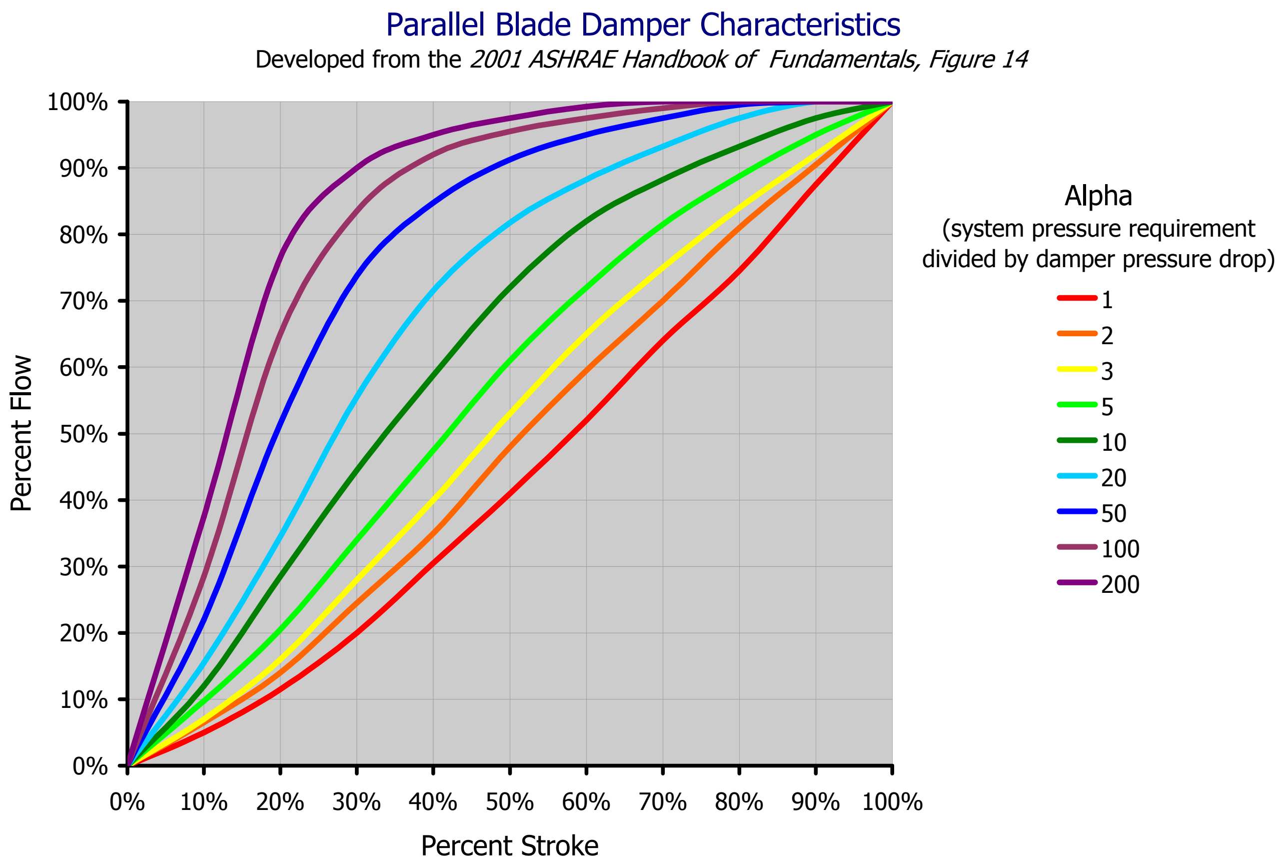


Figure 5.10 Parallel Blade Damper Characteristics

Alpha is the ratio of system pressure drop to damper pressure drop. An alpha of 200 means the damper pressure drop is 1/200 of the pressure drop of the entire system. As seen from the graph, a parallel blade damper needs to have a significant pressure drop across it relative to its system in order for the control to be nearly linear (50% stroke = 50% flow). The curves for opposed blade dampers are similar, but require less pressure drop to achieve the same linearity of control. (Developed from data in the ASHRAE Handbook of Fundamentals)

As a general rule, achieving a linear damper characteristic in most systems will require damper face velocities in the range of 2,000 to 2,500 fpm for flat plate type dampers and 2,500 to 3,000 fpm for airfoil type dampers. Based on this information a commissioning agent can quickly assess a system for potential mixing and economizer control problems by simply dividing the design flow rate by the damper face area. If the result is a velocity outside of the ranges indicated above, the commissioning agent should spend extra time on the testing and tuning of the economizer cycle.

As can be seen from the preceding discussion, the details of damper blade configuration can have a significant impact on the performance of the system the damper is installed in. Other details related to damper design, installation and construction with significant efficiency and/or other operational implications include:

- **Document the details to successfully achieve design intent** An amazing number of commissioning problems occur simply because the dampers are not installed correctly. There have been instances where multi-section parallel blade dampers were assembled with different blade rotations for each section; in other words, the blades in one section were horizontal and rotated downward as they closed, in the next section horizontal but rotating upward as they closed, in the next section the blades were vertical and rotated to the left, etc.. In other instances, it was virtually impossible to maintain actuators and linkages due to the installed configuration of the damper assembly. To avoid this sort of confusion, mixing damper configurations should be detailed in the design, preferably by the designer but as an alternative, by the control contractor, prior to installation. The detail should show configurations, number of sections, blade rotations, actuator locations, actuator linkage arrangements, blank-off panel locations and all other items required to install the dampers as required to achieve the design intent.

- **Provide adequate access** Each control damper (not just fire and smoke dampers) should be provided with an adequately sized access panel (or panels) that is unobstructed by surrounding systems, equipment, and building structure. This panel should be located so that when a technician is working through it, they can reach all damper components that are inside the duct, including linkage, bearings jamb seals and blade seals. (A 12" x 12" access panel in a 72" x 24" duct located 25 feet in the air over a motor control center and 3 feet upstream of the control damper is an access panel in name only.)
- **Vertical blades need to have thrust bearings** Usually, but not always, the manufacturers catch this. Without them, the operation of the damper will wear out the jamb seals very quickly at a minimum. It is also possible that the blades will start to push into the degraded seals as they wear leading to other operation problems.
- **Limit blade length** Blade lengths in excess of 48 inches are undesirable, especially for non-airfoil, non-extruded blades. At high velocities, the longer blades can flutter, and getting good blade seal compression as required to achieve the rated leakage rates can become a problem.
- **Select dampers that securely attach the shaft to the blade** There are a variety of techniques used to secure damper blades to shafts. Approaches vary from set screws to keyed arrangements. As a general rule the more positive connection provided between the damper blade and shaft by a slot and key or hexagonal shaft in a hexagonal hole is highly desirable. Less positive arrangements like set screws can often become loose over time, resulting in loss of damper functionality.

On occasion, the configuration of the air handling unit and the building make it desirable to combine some of the code-dictated fire and smoke isolation damper requirements with the economizer functions. This approach can have several advantages including:

- Reduced cost due to multiple functions being served by one device.
- Reduced energy requirements due to the elimination of one pressure drop generating element from the air stream.
- Reduced space requirements due to the need to only install one device.

As a result, some of the economizer damper assemblies are fire and smoke rated assemblies and the control signals to them must accommodate these functions in addition to the more conventional economizer functions. These applications deserve special attention from the commissioning agent to:

- Ensure that all life safety control functions take precedence over environmental control functions, regardless of operating modes. For example, the smoke control cycle should have priority over the economizer cycle.

- Ensure that all life safety functions are implemented in a manner that does not threaten to harm the air handling system due to excessive positive or negative pressures or air hammer effects. Air hammer is presented in *Chapter 13: Distribution*.
- Ensure that the integrity of the fire and smoke damper assemblies are maintained during the installation and start-up process so that the agency listing of the dampers is not violated.

Additional information regarding fire and smoke dampers can be found in *Chapter 17: Management and Control of Smoke and Fire.*

5.6.2 Actuators

The actuators used for HVAC control dampers generally fall into the following four categories, which are discussed in detail in this section.

- **Piston actuators**
- **Gear train actuators** use an electric motor with reduction gearing to rotate and output shaft that then moves the damper via crank arms on the actuator and damper shaft and an intervening linkage system.
- **Gear train actuators** use an electric motor with reduction gearing arranged to mount with their output shaft concentric with the damper shaft, thereby eliminating a crank arm and linkage system.
- **Linear actuators** use an electric motor with reduction gearing to drive a jack screw which drives a crank arm on the damper shaft directly with out an intervening linkage system.

5.6.2.1. Piston Actuators

Figure 5.11 Typical Pneumatic Piston Actuator and Positioning Relay

(Image courtesy of the Kele Associates web site)

From a mechanical standpoint, piston actuators are generally the simplest, consisting of a housing, a piston and diaphragm, a spring, and a shaft through which force on the piston is transferred to the damper crank arm. They are typically actuated by pneumatic air pressure, with a maximum pressure of 30 psig or less in commercial applications. The spring constant determines the range over which the damper will actually stroke as the actuating pressure varies.

There are variations on the pneumatic actuator concept seen in the commercial HVAC market that are electrically powered. One fairly common design uses a small hydraulic pump to circulate oil from a reservoir to a chamber behind the piston. A variable size orifice controls how quickly this fluid can bleed back into the reservoir from the piston chamber. The orifice size is controlled by the control signal. As the size of the orifice is decreased, pressure builds up in the piston chamber and the piston extends. As the size of the orifice increases, pressure bleeds off and the actuator spring causes the actuator to retract. In another variation developed for remote sites with no control air source, a small self-contained compressor generates air pressure for use by a conventional pneumatic actuator. A fairly rare actuator design that may be seen on older projects uses a wax that has a high thermal coefficient of expansion and a heater. The heater output is varied by the control signal, which causes the wax to expand and move the piston.

Pneumatic piston actuators are often sequenced by selecting spring ranges appropriately so that one actuator strokes fully before the next actuator begins to stroke. However, forces generated by airflow acting on the damper blades in the HVAC system can feed back through the actuator shaft and work against the spring. The forces can shift the spring range significantly and significantly alter the sequencing, which can lead to energy waste.

Figure 5.12 Hydraulic Type Piston Actuator

(Image courtesy of the Kele Associates web site)

For example, if a control system designer wanted to sequence a chilled water valve with the economizer dampers based on discharge temperature, the designer might specify a spring range of 5-8 psig for the economizer dampers with a normally closed outdoor air damper and a normally open return damper. To sequence the chilled water valve properly, they might specify an 8-13 psig range for the valve actuator with a normally closed valve. On paper, the outside air damper would be fully open by the time the signal reached 8 psig. At this point, the chilled water valve would start to open, thus guaranteeing the full utilization of free cooling using the outdoor air prior to using chilled water.[2] However, if the forces on the damper blades shifted the spring range 1 or 2 psig, the chilled water valve might start opening before the outdoor air damper was fully open, thus using chilled water for cooling when it may have been possible to serve the load with outdoor air. To solve this problem, a device called a positive positioner or positioning relay is installed on the actuator.

The positive positioner is a position controller that has its own source of supply air. The device senses the position of the damper shaft with adjustments for start point and span. The positioner applies pressure to the actuator piston in order to get the piston to move as the control signal varies in the specified range. For example, if you wanted to be sure that a damper moved exactly over a 5-8 psig range, then you would install a positioning relay on the damper and set it to have a 5 psig starting point and a 3 psig span. In operation, when the control signal to the positioning relay reached 5 psig, the positioner would begin to apply main air pressure to the actuator piston until it detected shaft motion, even if it took 7 or 8 psig to make the damper start to move. The positioner would then proportionately move the damper shaft in response to an increase in control signal to ensure that the shaft was fully extended by the time the control signal reached 8 psig (the sum of the 5 psig start point plus the 3 psig span value).

[2] This sequence would be typically be overridden when outdoor conditions were no longer suitable for free cooling to return the system to minimum outdoor air.

5.6.2.2. Gear Train Actuators With Crank Arm Drives

These actuators represent older electronic technology in which a small single-phase motor (usually the shaded pole type) is used to drive a crank arm through a gear train. The gear train actuator can interface with a variety of signals including electric floating contact type controllers, variable resistance type controllers, two position signals, and common automation system outputs like 4-20 milliamps, 1-10 vdc or pulse width modulation. The type of interface is usually determined by an interface circuit board in the actuator or an interface module mounted to the actuator. Settings on the circuit boards or independent modules allow these actuators to be sequenced in a manner similar to that described for pneumatic actuators discussed in the piston actuator section. Most models can be equipped with a spring return feature to guarantee a fail-safe position on power failure.

Figure 5.13 Electric Gear Train Actuators

(Image courtesy of the Johnson Controls website)

5.6.2.3. Gear Train Actuators With Shaft Concentric Drives

Figure 5.14 Electric Gear Train Actuator, Shaft Centerline Mounting

(Image courtesy of the Siemens website)

These actuators represent newer technology that developed in response to the widespread use of DDC control systems in the commercial buildings industry. The actuators avoid some of the potential linkage problems associated with piston actuators and gear train actuators driving through crank arms by mounting the actuator directly to the damper shaft, with the output torque applied directly to the shaft. Since the DDC market drove the development of these actuators, they can usually be interfaced directly to common DDC outputs. Sequencing with other actuators is usually accomplished by settings incorporated directly into the actuator. Most of these actuators are offered with spring return options for fail safe positioning on power failure.

Several manufacturers combine the actuator in the same housing as their VAV terminal unit controllers. This tends to make the installation costs lower with less start up problems as compared to systems that require that the VAV unit damper actuator be mounted and wired independently from the controller. But, it can increase the replacement cost when the unit fails since the entire assembly needs to be replaced, not just the failed component.

5.6.2.4. Linear Actuators

These actuators are more common in the industrial market than the commercial market but are sometimes found serving applications such as inlet guide vanes where a lot of actuating power is required. They typically consist of a jackshaft coupled with a motor of some sort and can accept most of the common output signals available from a DDC system.

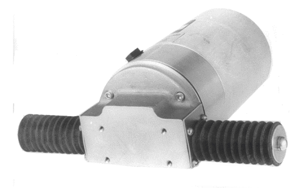


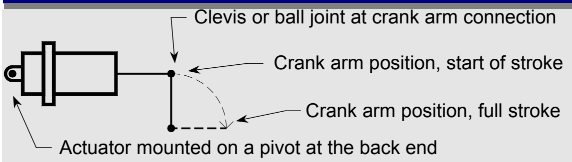
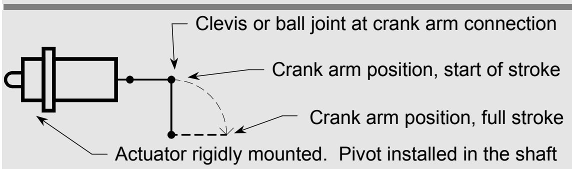
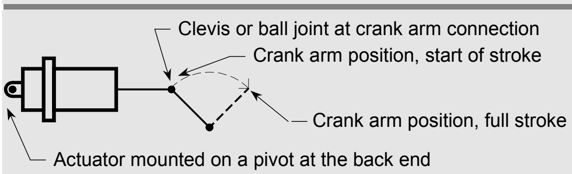
Figure 5.15 Linear Actuator

(Image courtesy of the Tyco website)

5.6.2.5. Installation and Commissioning Issues

Generally, there are several commissioning issues related to installation of damper actuators as follows:

- **Sizing** By reading the fine print on the damper leakage curves, one may discover that the preload torque required to achieve the leakage rate is higher than the torque required for actuation. Actuator selection, sizing, and set-up need to take the pre-load torque into consideration and the commissioning process should include verification that the field installation meets all applicable requirements.
- **Linkage Arrangement** Piston and linear type damper actuators need to be mounted a manner that allows the linear motion of the actuator shaft to be converted to rotation at the damper shaft. Usually this is accomplished via a linkage system that includes crank arms, extensions and swivels. Actuators should be mounted to maximize the linearity between actuator stroke and blade position and also maximize the torque available to the damper from the actuator through the damper stroke. The kinematics associated with the linkage arrangement are often not well understood by the field personnel installing the actuators, thus issues related to this can show up as a commissioning problem. Figure 5.16 illustrates how the relationship between actuator stroke and damper bland position varies for a piston actuator.

Mounting Arrangement	Percent Actuator Stroke at the Indicated Percent Blade Rotation					Maximum Deviation from Linear (Note 1)	Maximum Force Reduction (Note 2)
	0 (0°)	25	50 (45°)	75	100 (90°)		
	0%	32%	62%	85%	100 %	+12%	66% (occurs at full stroke; 100% available at start)
	0%	29%	56%	79%	100 %	+6%	43% (occurs at full stroke; 100% available at start)
	0%	24%	50%	78%	100 %	-1%, +3%	29% (occurs at the start and at full stroke, 100% available at 42%)

Note 1 A + indicates that the percentage of stroke leads the percentage of blade rotation.

Note 2 Only the actuator force applied perpendicular to the crank arm creates rotation and torque.

Figure 5.16: Piston actuator linkage arrangements

Similar considerations apply to linear actuators as well as gear train actuators that drive the damper via a crank arm and linkage. Actuators that concentric to the shaft and drive the damper shaft directly eliminate these issues by virtue of their mounting and drive arrangement.

Multiple section dampers with multiple actuators need to have identical actuators with identical linkage arrangements for all sections to make the characteristic for all of the sections consistent. Consistent damper section installations also make the performance of the entire assembly predictable based on the performance of one section. If the outdoor air damper and the return damper are multi-sectioned dampers controlled by the same signal, then all actuators for both sections should be identical with identical mounting arrangements for the same reason.

- **Actuating Speed and Power** Most electric actuators have operating times that can vary from 30 to over 90 seconds to move through a full stroke. The slow speed is due to the small motors, which must be geared down significantly to deliver the necessary torque required to actuate common HVAC devices. Pneumatic actuators, on the other hand, can have full stroke actuating times that are extremely fast and can deliver tremendous power due to the amplifying effect of air pressure over a large diaphragm area. For instance, a six inch diameter piston damper actuator with 20 psi air acting on it can easily deliver over 500 pounds of force at the shaft, even after compressing the damper spring. These characteristics can be advantages or disadvantages depending on the application.
- **Rapid actuation speeds** are desirable and even necessary if tight, reliable, and stable control is to be achieved on some systems. Usually, this is expensive and difficult to achieve electrically using commonly available technology in the HVAC industry. This item is worthy of review by the commissioning agent in the design phase. During start-up or in a retro-commissioning environment, changing from electric to pneumatic actuation may represent a viable solution to a start-up or operational problem related to system response time.
- **Rapid actuation** can be undesirable in cases where air or water hammer could be the result of a rapidly closing valve or damper.[3] In situations where this is a possibility, the slower actuating times associated with electric actuators may be an advantage.[4] If pneumatic actuators are installed at locations where they could generate air or water hammer, then it may be necessary to slow them down by using restrictors or metering valves in the circuit serving them. The commissioning agent needs to be aware of these issues and requirements and design functional test sequences to ensure that they are properly addressed.
- **Sequencing** As described earlier in this section, proper sequencing of actuators is often essential for efficient system operation, but cannot be solely guaranteed by the specifications and requirements of the contract documents. The functional testing performed during the commissioning process should include verification of proper sequencing under all operating modes. If sensors are installed at the proper locations in the system, trending can be used to allow the commissioning agent and operators to verify the persistence of the original sequencing. “Smart alarms” triggered by conditions that are not logical (a temperature rise across a heating coil that has its valve commanded closed for instance) may also be desirable.

From a historical perspective, pneumatic actuation and control systems where quite common in the commercial buildings industry. In the past decade, the wide acceptance and implementation of DDC control systems coupled with the development of shaft centerline drive type actuators have made electronic/electric actuation system more common in the commercial HVAC market. The electric/electronic actuators often can interface directly with the DDC system where as pneumatic actuators require some sort of signal converter[5]. In addition, pneumatic actuators require a source of clean, dry air. On sites where this is not already available, the use of pneumatic actuation will require that this equipment be installed, operated and maintained. However, if a large operating torque is required and/or quick (less

---

[3] See the *Chapter 13 Distribution* for a discussion of air hammer and its effects.

[4] Note that there still may be a maximum allowable actuation time for life safety related functions like smoke or fire dampers that is dictated by the governing codes.

[5] Some manufacturers have developed devices that combine an electronic to pneumatic signal converter in the same package as a pneumatic positioning relay.

than a minute) actuation speed is necessary, then pneumatic actuation often represents the most cost effective and reliable option.

5.6.3 Sensing Elements

Sensing elements perform critical tasks in ensuring proper economizer operation. The following paragraphs discuss sensing requirements particular to economizers. Refer to the Control System Design Guide, *Chapter 3: Selection and Installation of Control and Monitoring Points* for general information regarding sensors used in air handling systems. Refer to *Chapter 18: Integrated Control Functions* for additional information regarding the interaction of the economizer cycle with other building control cycles.

5.6.3.1. Temperature Sensors

Selection and proper configuration of the temperature sensors used by the economizer cycle can have a very significant impact on its ability to perform as intended. Since even a well-designed mixing plenum can have some temperature stratification over its cross section, selecting and installing a temperature sensing system that averages the temperature across the entire cross section is an important aspect of the overall system design. There are a surprising number of projects encountered by commissioning agents where the first step in solving the economizer operating problems is the replacement of a single point sensor with an averaging sensor. The picture in Figure 5.17 is from one such project. In this instance, the poor sensor configuration coupled with independent heat transfer element control loops was causing the system to do 10°F of unnecessary preheating.

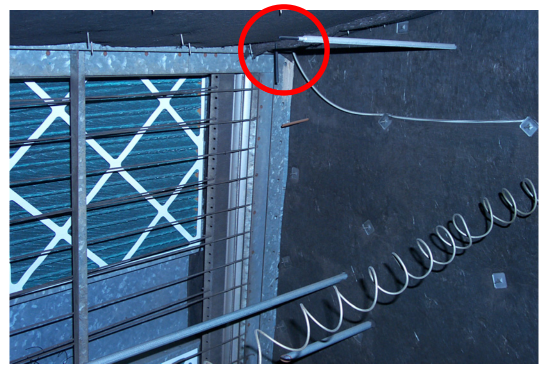


Figure 5.17 Averaging sensor application

The mixed air sensor is in the red circle. The spiraled sensing element is the freezestat. This single point sensor will have a difficult time averaging the temperature in this 6 ft by 10 ft mixing plenum.

Specifying averaging sensors for economizer applications is a good first step, but it does not fully address the issues related to measuring temperatures in a mixed air plenum. The following items should also be considered:

The temperature that will ultimately be achieved by the complete mixing of a stratified air stream is a function of both the temperatures and the mass flow rates of the different temperature layers. The information sensed by averaging temperature elements is purely temperature and is effectively immune from the influences of mass flow rate[6]. If the nominal face velocity over all portions of the averaging element is the same, then the average temperature indicated by the element is probably a reasonable measurement of the temperature that will be achieved in the air stream when it is completely mixed. However, if there are significant differences in the velocity over certain areas of the averaging element, then the average temperature indication sensed by the element may not accurately reflect this final mixed temperature. For example, when mixing a teaspoon of water at 200°F water with a gallon of 100°F, you would not expect the mixed temperature to be 150°F, even though this is the average of the two temperatures being mixed. Similar considerations apply to airstreams in mixing plenums.

- If the true mixed temperature is higher than what the averaging element predicts, there may be comfort control problems since the system will not be delivering air at the required temperature. In some systems, the refrigeration equipment may operate to make up for this difference even though the system could achieve the required set point by using additional outdoor air in the economizer cycle, thereby negating some of the energy benefits of the cycle.
- If the true mixed temperature is lower than the value indicated by the averaging element, then there could be problems with nuisance freezestat trips or coil failures. In some systems, the preheat coil will be activated to warm the air up to the required setting despite the fact that the system could achieve this temperature by using less outside air on the economizer cycle. Again, this wastes energy and negates some of the benefits of the cycle.

Stratification patterns and their associated velocity profiles can change with the operating point of the economizer. As the outdoor air and return air dampers modulate due to changes in set point, return, and outdoor air conditions, the temperature and velocity profile produced at the discharge of the mixed air plenum can change. Systems that mix well under some operating conditions may stratify under other conditions. Other systems may exhibit similar profiles regardless of the operating point. The Temperature Traverse Test and the High Turndown Ratio Test help identify temperature and flow patterns in the mixed air plenum and target solutions to related problems.

Large plenums may require multiple sensors to accurately reflect what is occurring in the plenum. In the Control System Design Guide, Section 3.5.1 Temperature, discusses various approaches that can be used to accomplish average temperature from multiple sensors. The mixed air plenum stratification test included in this chapter can be used to determine the best configuration for the mixed air sensing elements under different operating conditions. It may be necessary to perform this test as part of new construction or retro-commissioning to optimize the configuration of the sensing elements so they provide repeatable, reliable information under all operating modes.

The mounting system used for the averaging elements should allow them to be easily reconfigured during the commissioning process if necessary. It should also support the

[6] Mass flow rate will in fact influence the sensed temperature to some extent in that higher mass flow rates will have better convective heat transfer coefficients between the sensing element and the air stream. Sensing elements in air streams with higher mass flow rates (and thus higher velocities) will generally display a quicker response to a change and a closer approach to the actual air stream temperature. These effects are relatively insignificant in the context of the accuracy of the temperature measurements made in a mixed air plenum. The improved response characteristic associated with the higher flow rates can make the control loop easier to tune because time lags are reduced.

sensing elements in a manner that allows them to accurately reflect the air stream conditions, free from other influences such as heat conduction from coils or other supporting equipment and radiant temperature effects from high temperature heat transfer elements like steam coils. Radiant temperature effects can be felt upstream as well as downstream of a heat transfer element. If you can stand at the mixed air sensor location with the palm of your hand facing a nearby high temperature coil, and can feel the radiant heat from the coil with your hand, then the element is probably being influenced by the coil.

5.6.3.2. Freezestats

Freezestats are limit controls that are installed to protect the coils in an air handling system from being subjected to sub-freezing temperatures. Typically, they are arranged to shut down and lock out the system and a manual reset is required to resume normal operation. Contrary to popular opinion, the long sensing elements that they are provided with are not really averaging elements, even though they are visually similar. The sensing elements on most freezestats will respond to the coldest temperature seen by any one or two foot segment. This is desirable because it only takes a small stream of subfreezing air to freeze and rupture a tube in a coil.

Even though freezestats are not averaging elements, the same considerations outlined previously for the installation of averaging elements apply to the installation of sensors on freezestats. In fact, it is often desirable to string the freezestat element along with the mixed air temperature-averaging element so that they both are subjected to the same conditions. This allows the mixed air sensing element to reliably generate a pre-freezestat trip alarm that can be used to prevent an unscheduled outage. The advent of DDC technology has lead to the development of software-based freezestats. At first glance, this approach appears to offer some advantages in terms of lower installed cost and ease of operation. However, there can be some problems with this approach that can very quickly negate any of its benefits.

Usually the first cost savings is achieved by eliminating a device; i.e. the independent freezestat and its associated wiring to the starter. This means that the mixed air sensing element becomes the input to the freezestat control code and, in a sense, the mixed air sensor ends up trying to protect itself from its own failure.

Since the operation of the freezestat is now dependent on the operation of the DDC controller, a controller failure eliminates the freezestat protection. In some cases, a controller failure will not necessarily shut down the unit, so it is possible for a system to end up on line and operating without the intended protection in place.

Since the freezestat function in this approach is part of the controlling software, it is a part of the automation. Usually, the automated output that starts and stops the fan is wired to the “Auto” position of the “Hand-Off-Auto” selector switch on the fan. If the fan is placed in “Hand”, then the freezestat protection is eliminated from the circuit. An independent device can be wired into the common side of the selector switch so that it provides the necessary level of protection regardless of the selector switch position.

For these reasons, the best approach is to simply not use software based freezestat (or a software based safety of any type for that matter). If the software-based system is employed on a project, it needs to be very carefully designed and commissioned to prevent the types of problems outlined above from occurring.

Most people think of a freezestat as providing protection for systems with water coils and would not consider installing one on a system that is equipped with direct expansion cooling and gas fired furnaces for heating. Generally, this is a reasonable assumption. But there have been instances where the plumbing and sprinkler piping in a building was frozen because such an air handling system remained in operation with an economizer that failed wide open during extreme weather over a weekend. Since there are no water coils to protect in this situation, the freezestat can be installed in the discharge duct where it is relatively immune from the effects of poor mixing and the related problems with nuisance freezestat trips, yet will provide protection against freezing the building plumbing and sprinkler piping.

Repetitive freezestat trips? No problem with the correct tools and equipment!
On one project, the owner wanted their mechanics to be able to rapidly identify a freezestat shutdown of the air handling equipment and demanded that the freezestat be wired into the control circuit only on the auto side of the hand-off-auto selector switch. This would allow the mechanics to quickly place the unit in hand and see if it ran when it was off for some unexplained reason. If it ran, then they knew they had a freezestat trip, the anticipated most likely problem. If the unit didn't run, they would focus their troubleshooting efforts elsewhere. The consultant reluctantly agreed with the owner's demand with the stipulation that the hand position be designed to spring return to the off position to prevent an operator from inadvertently walking away and leaving the system operating in hand with no freezestat protection. During the first winter of operation, the designer was called to the project site to investigate and determine why a coil had been frozen in one of the air handling units equipped with the spring return type switch. When they walked up to the starter, the cause of the problem became immediately obvious. A creative mechanic (who didn't understand the control system) had solved the problem with that pesky selector switch that wouldn't stay in the hand position by clamping the jaws of a crescent wrench to the actuating tab on the selector switch.

5.6.3.3. Enthalpy Switches and Sensors

To perform the enthalpy-based economizer changeover function described in *Chapter 5,* Section 5.5.6.2: Enthalpy Based Interlock, enthalpy switches or transmitters may be used.

Two Position Enthalpy Switches

Figure 5.18 illustrates a typical two-position enthalpy switch. The different scales on the switch correspond to different near-constant enthalpy states. By coordinating the scale selected with the requirements of the project, the switch can be used to provide a relatively low cost enthalpy based economizer change-over signal. The switches need to be mounted in an accessible location that subjects the sensing element to a free-flowing outdoor air stream yet protects the element from exposure to water and direct and reflected sunlight. This location can introduce some operating anomalies into the system due to lack of air flow when the unit is not in operation. For instance, minor air leakage back out of the unit from the building when the unit is off may cause the sensor to "think" the ambient conditions are suitable for cooling in the summer when they are not. When this unit first starts, it may try to operate on the 100% outdoor air cycle until the outdoor air flowing through the intake system can bring the local environment at the switch location into alignment with the actual outdoor conditions. This process usually happens fairly quickly, but it can be misleading to the commissioning agent during testing.

Protecting the enthalpy switch from dust is also desirable, but usually difficult to accomplish because most recirculating systems do not filter the air until after the mixing plenum. For sites with a 100% outdoor air unit, the enthalpy switch can be protected by locating it downstream of the first set of filters but upstream of any heat transfer elements. This enthalpy signal can be used to pilot the other units on the site. For this approach to be successful, the unit where the switch is installed must be one that runs at all times that any of the other units piloted by the signal run. Without air moving across the filters and to the enthalpy switch, the signal from the switch will not necessarily reflect the ambient conditions.

Figure 5.18 Typical two position enthalpy switch

(Image courtesy of the Honeywell web site)

The switch settings correspond to a set of near-constant enthalpy lines on a psychrometric chart. Many of the manufacturers include a small chart with the operating curves as a part of the switch installation literature or they may print the chart on the switch housing. However, in the event that the installation instructions are not available, then it is fairly easy to construct the operating curves from a blank psychrometric chart and the tables included in the catalogs. Figure 5.19 is an example of a chart constructed in this manner. Another option is to go to the internet and download the installation instructions since many manufacturers now provide this information in the form of .PDF files. The following link contains the information for the switch depicted in the curves below; http://hbctechlit.honeywell.com/request.cfm?form=60-2301.

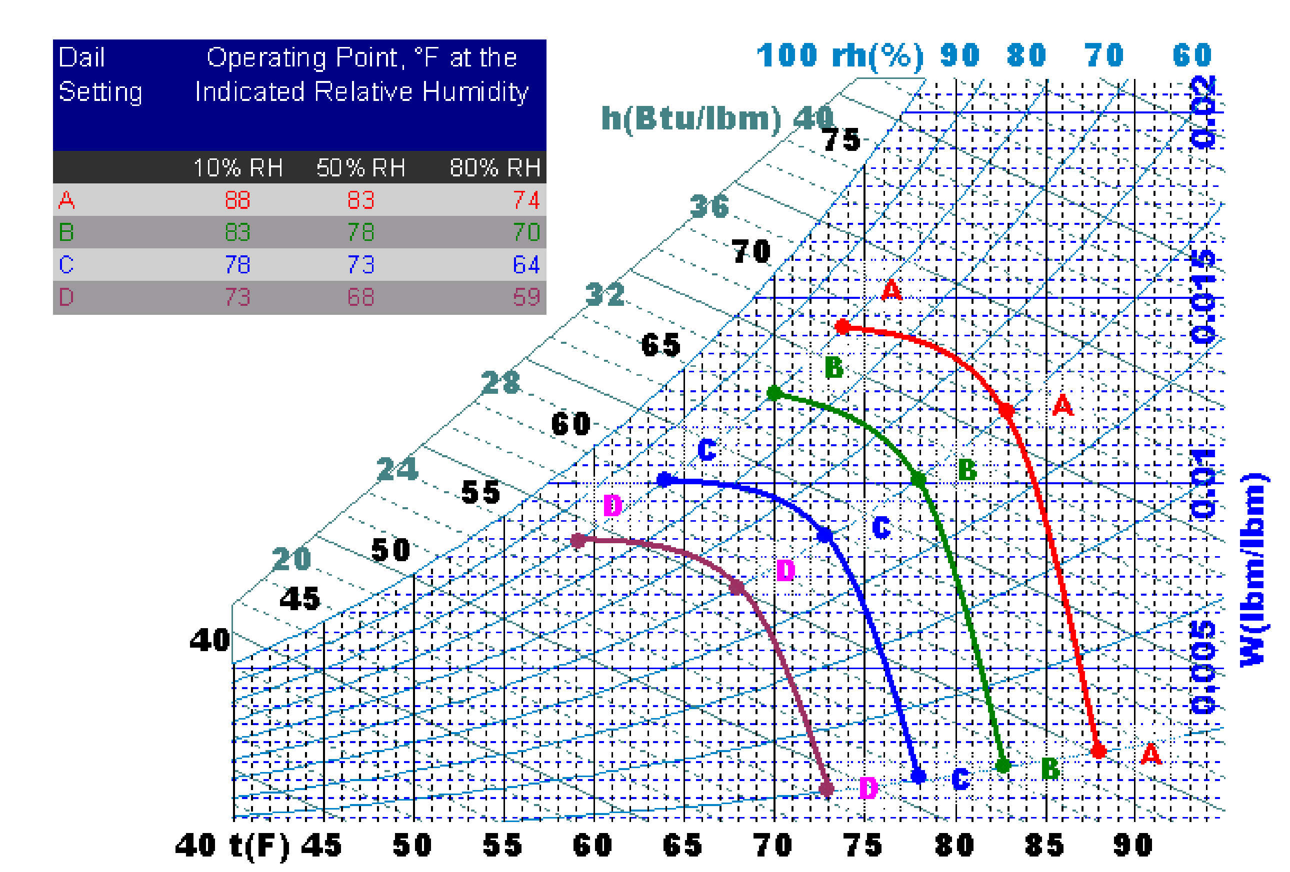


Figure 5.19 Enthalpy switch operating curves for a typical switch

If the installation information with the enthalpy switch operating curves is not available, operating curves can be drawn on a psychrometric chart using the information typically included in the supply catalog. Once you have made the curve for one type of switch, you can just keep a copy with your test equipment. For this set of curves, if the switch was set on scale D, then it would be in economizer mode for any condition left of curve D and out of the economizer mode for any conditions to the right of curve D.

Notice how the operating curves in Figure 5.19 are really not constant enthalpy lines. They parallel the lines reasonably well for the upper portion, but fall away from running parallel, from the 50% point to their lower end. This curvature should be taken into consideration when determining the appropriate switch setting.

Enthalpy Transmitters Figure 5.20 depicts an analog enthalpy transmitter. These units provide an analog output that is directly proportional to enthalpy. They can be wired as an input to the control system and the information they provide can be used for various enthalpy-based control decisions such as enabling or disabling the economizer mode. In general terms, the same mounting and servicing considerations apply to enthalpy transmitters as apply to enthalpy switches, although there are some designs available that are suited for direct or nearly direct exposure to the outdoor environment.

Figure 5.20 Enthalpy transmitters

(Image courtesy of the HyCal web site)

Enthalpy Calculations Today's control systems generally are capable of performing mathematical operations on their variables. This opens the door for calculating enthalpy using psychrometric equations contained in the *ASHRAE Handbook of Fundamentals* or the *ASHRAE Brochure on Psychrometrics*. Both of these documents contain psychrometric equations that can be solved for enthalpy if other parameters are known. Usually, the required inputs include dry bulb temperature, relative humidity or dew point, barometric pressure and elevation. For most applications, assuming a constant elevation and barometric pressure for the site will provide a satisfactory level of accuracy. As a result, the calculation can be reduced to one based on dry bulb temperature and humidity or dew point. For instance, outdoor air temperature and humidity are measured, then outdoor air enthalpy can be calculated and used for enthalpy based economizer interlocks assuming a return air enthalpy. Space or return air temperature and humidity sensors can be used to calculate space or return air enthalpy, and economizer changeover strategies based on differential enthalpy can be implemented.

5.6.4 Pressure Sensors and Switches

Pressure switches are also used in some systems to provide a safety interlock to prevent over or under pressurization of the duct or air handling unit casing in the event of a control failure. This is discussed in greater detail in the *Chapter5*, Section 5.5: Control Strategies.

While pressure sensors are not used directly by the economizer cycle, they are used in some control strategies to modulate the relief air dampers, which relates to the economizer function. This is discussed in greater detail earlier in *Chapter 5, Section* 5.1.3: Building Pressure Control. When this approach is employed, building static pressure is measured and the system is arranged to modulate the relief dampers to maintain a slightly positive pressure in the building.

One of the most important things to remember about measuring building static pressure is that very low differential pressure levels must be measured and controlled, typically less than on tenth of an inch water column. In most cases (but not all as will be discussed later), this pressure needs to be converted to some sort of force for an instrument to detect it and produce a signal as a result of it. The force needs to be great enough to move whatever mechanism is used to generate the signal in response to its variations magnitude. The impact of the mechanism activated by the force on the signal needs to be minimal. Frictional forces, springs, and other mechanical resistances imposed on the force generated by the measured signal in converting it to an output all work against generating a repeatable useable signal. For instance, if the break-away torque for a bearing is 1 foot-pound, then the shaft it serves will not move until the torque applied to it exceeds this value. If the force that was being applied to the shaft in normal use never ran much above this, then the mechanism would be fairly useless in transmitting the input force to the output shaft.

Instruments that measure the low differential pressures associated with building and air handling system static pressures typically use a diaphragm to actuate the signal producing mechanism. The differential pressure is applied across the diaphragm, causing it to deflect. The deflection is then used by a system of levers, pivots and springs or by discrete electronic components to generate an output.

Minor variations in static pressure can cause interesting system problems if detected and processed by the control system. On one project, the minor building pressure changes associated with the employee entrance door opening and closing were driving the fan speed control loop for a 40,000 cfm air handling system into instability during shift changes. When the door opened, the building pressure dropped several hundredths of an inch. The change in building pressure was telegraphed to the supply duct static pressure transmitter, located in a branch duct near a diffuser near the door where it showed up as a change in duct static pressure of several hundreds of an inch (the set point was 0.5 inches w.c.) One or two door operations were not a problem, but when 40 or 50 employees left the building within a 10-15 minute interval, the pressure pulses drove the system into instability for several hours as the fan control system tried to follow them and the inertia of the large DWDI airfoil fan kept it from catching up. Filtering the input so that minor pressure pulses were not processed by the control system solved the problem.

To put this into some practical terms consider a 4-inch diameter diaphragm measuring a signal of one tenth of an inch water column.[7] In this instrument, the force available from the diaphragm (assuming it is a perfect diaphragm with no mechanical losses of its own) to move the signal generating mechanism is less than one tenth of an ounce. A first class letter weighs approximately one ounce. That is not much force to move the levers, pivots and springs associated with this type of mechanism in a repeatable, reliable fashion for years in an environment that can see large temperature swings, dust, moisture, and vibration. Anything that can be done to improve this situation, like providing more force via a larger diaphragm or eliminating moving parts or increasing

[7] Four inches in diameter is a fairly typical size for many of the pneumatic pressure transmitters in the commercial market. One tenth of an inch water column is probably the high end of the control range for building static pressure; i.e. you will control for that pressure or less and need to be able to detect and respond to changes that are at least one order of magnitude smaller (one one-hundredth of an inch water column).

sensitivity to motion via electronics, or using some other approach to measuring pressure will result in an improved signal, a more robust system, and better control and efficiency. Thus a transmitter with a large diaphragm area will tend to be superior to a transmitter with a small diaphragm area, all other things being equal. Transmitters that are based on electronics rather than mechanics and kinematics will tend to be superior to those with many moving parts.

Another important point to remember is that even though the desired result for a building static pressure control system is a positive building pressure, in the real world operating environment, it may be beneficial to be able to detect and indicate both positive and negative pressures. Thus a sensor with a range of -0.1 inches w.c. to +0.1 inches w.c. might be better than a sensor with a range of 0 to +0.1 inches w.c.

Figure 5.21 Pneumatic low differential pressure transmitter and controller

The transmitter on the left serves as an input to the controller on the right. Because this type of controller "receives" its input from an external source rather than a built-in sensor, it is referred to as a "receiver controller" and can be used with a variety of input sensors rather than being segregated to one particular function. (Image courtesy of the Siemens web site)

There are a variety of technologies used to sense pressures in this range for building static pressure applications. Generally, the fall into the following categories:

1. **Pneumatic differential pressure transmitters that sense via a diaphragm and create a force based on the sensed pressure - These transmitters typically use a diaphragm to sense and create a force based on the measured pressure**. Figure 5.21 presents a typical example along with a controller that it would be coupled to. The force generated by the diaphragm in the transmitter is used by a system of linkages, levers, and springs to generate a nominal 3-15 psig pneumatic signal that is proportional to the sensed pressure. This signal is used as an input to a controller that allows it to be compared to a set point and then generates an output. The output is used to modulate a final control element such as an actuator or variable speed drive as required to make the sensed pressure match the set point. In some cases, the pressure sensing function is combined with the control function in one package.
2. **Electronic differential pressure transmitters sense via a diaphragm and create a force based on the sensed pressure** Electronic components use the force to generate a standard electronic output such as 2-10 vdc, 1-5 vdc, or 4-10 ma. The output is proportional to the measured pressure. As in the case of pneumatic transmitters, this signal is then used as an input to a controller that, in turn, generates a control output to modulate the system.

3 Electronic differential pressure transmitters that measure the velocity of a flow stream created by the pressure difference between to pressure zones as an indicator of pressure. If there is a pressure difference between two areas, then there will be flow between the two areas if there is an open flow path between them. This phenomenon is used to advantage by some transmitter technologies to measure pressure difference. Generally, these transmitters consist of a tube with a hot wire anemometer or similar thermal based flow-measuring device located in it.[8] One end of the tube is connected to the location where the desired pressure is to be monitored. The other end is connected to the reference pressure. If there is a difference in pressure between the two ends of the tubes, then air flows through the tubes. This flow is detected and measured by the hot wire anemometer and an output in terms of pressure is generated based on the flow rate. The output is typically a standard electronic output such as 2-10 vdc, 1-5 vdc, or 4-10 ma and this signal is then used as an input to a controller that, in turn, generates a control output to modulate the system. Figure 5.22 illustrates a typical transmitter of this type.

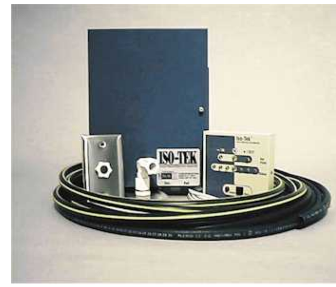


Figure 5.22 Typical flow based pressure sensor

This particular sensor is designed for monitoring hospital isolation room pressure, but the technology can be adapted to other low differential pressure applications. (Image courtesy of the TekAir web site)

The following sections will discuss these approaches in greater detail.

5.6.4.1. Pneumatic Pressure Transmitters

Though less common due to the advent of DDC technology, there are still numerous existing systems that use pneumatic pressure transmitters to provide inputs to pneumatic controllers for building static pressure control. While the systems can be made to function, the resolution and repeatability associated with modern electronic-based transmitters will provide a better solution on new projects, thus a pneumatic based system should not be the system of choice for this application in new construction if at all possible. However, there are often situations where commissioning agents find themselves confronted with making this approach work reliably and repeatedly. In this case, the following issues should be considered and evaluated.

Differential Pressure Measurement Capabilities Unfortunately, many of the transmitters available in the commercial pneumatic product lines are not very well suited for measuring the low pressure differentials typically associated with building static pressure control.

- The available ranges are often two to four times what might be desired.
- The stated accuracy of the transmitter is often a significant percentage of or even equal to the signal that must be measured.
- Diaphragm areas tend to be small and thus the forces produces to actuate the measurement mechanism.

---

[8] Hot wire anemometers and other thermally based flow measuring technologies are very sensitive to low flow rates. They work by measuring the cooling effect of airflow over a heated wire. The amount of cooling is directly related to velocity and thus to flow. By measuring the energy used to heat the wire, the devices can detect and accurately report very low flow rates.

- The measurement mechanisms tend to be mechanical with the associated frictional losses and hysteresis problems.

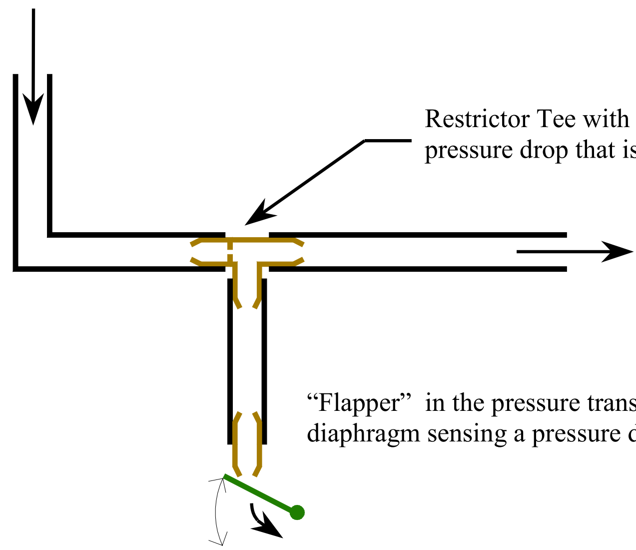


Figure 5.23 One pipe pneumatic transmitter operation

A one pipe transmitter creates its signal by varying the flow of control air through a fixed orifice. The sensing mechanism is arranged to continuously bleed air from the down-stream side of the orifice with the bleed rate controlled by the process variable. As a result, the pressure downstream of the tee will vary with the process variable. The term "one pipe" comes from the fact that the sensing element or transmitter has only one pneumatic line connected to it. A two pipe transmitter has a supply line connected to it as well as a signal line and does not continuously bleed air to generate a signal. Instead, it uses a feedback mechanism to add or remove air from the signal line so that the pressure in the signal line is proportional to the variable sensed.

Signal Transmitting Technology Transmitting the pneumatic signal is further complicated by the fact that most of the commercial grade units use one-pipe technology. This approach is illustrated in Figure 5.23 and is prone to the following problems:

- The tubing between the restrictor tee and the transmitter can become a source of pressure drop that affects the signal from the device but is not accounted for in its calibration. If a long run of tubing is installed between the transmitter and the restrictor tee, the calibration may not match the factory specifications. Most manufacturers state a length of run limitation for their transmitters to address this issue. It is important that this length is the length of the tubing run, which may be different than the distance between the transmitter and the restrictor tee on a plan view of the building.
- Most restrictor tees include a foam filter element to protect the very tiny hole that forms the orifice in the tee from being obstructed with grit. As this filter becomes dirty, it also adds an un-calibrated pressure drop to the system. Most manufacturers recommend changing restrictor tees out annually (or more often) in order to address this issue. However, most building maintenance staffs are unaware of this requirement and may even be unaware of the presence of restrictor tees in the first place. So, when faced with commissioning or re-commissioning an existing system

that uses this technology, a good first step is to perform the restrictor tee replacement recommended in addition to checking calibration of the instruments.

- Most commercial one-pipe transmitters are factory calibrated and cannot be calibrated in the field. (If you decide to try it you will probably wish you hadn't. Barely detectable movements of the zero and span screws can cause output changes of 10% or more.)

All of these issues with pneumatic transmitters can result in an input system that does not provide reliable, repeatable data for use by the control system. Fortunately, there are several options available that can help address these problems.

Install a Process Grade Transmitter Pneumatic pressure transmitters are still available in the product lines of many process control manufacturers. Often, the available ranges are not much better than the ranges available in the commercial product lines, but the overall accuracy can be significantly better (0.5% of full scale vs. 5% of full scale). Some product lines include a device called "draft pressure transmitters" which were originally designed for boiler combustion control systems. These devices can have spans as small as 0.25 inches w.c. with accuracies of 2% of full scale. This is a significant improvement over any of the available commercial products. Generally, these improvements are achieved by using larger diaphragm areas and high precision mechanisms with better bearing systems and lower resistance to movement and hysteresis. In addition, the process grade instruments use two-pipe technology, thereby eliminating all of the problems associated with one pipe technology.

The down side is that the process grade products are much more expensive than the commercial products, often by a factor of 10 or more ($150 vs. $1,500). This cost can often be very easily justified in light of the energy and comfort benefits gained by making a non-functioning system function as intended and the durability and improved service life that can be expected. However, the cost premium can come as quite a shock to an Owner who is unfamiliar with the problem and the requirements of the solution. The other problem with using process grade transmitters is lack of familiarity with the product in the commercial HVAC marketplace. Many times, this can be easily addressed by training, a primary component of the commissioning process. But, in buildings where the operating staff undergoes frequent changes or where the maintenance is handled by a service contract, this lack of familiarity can be a significant issue.

Install an Electronic Sensor and Convert the Signal to Pneumatic for Use by the Pneumatic Controller While slightly cumbersome technically, this approach can provide a significant improvement in the input signal quality to an existing pneumatic control system in some cases. The input signal improvements are accomplished using readily available commercial products, combining a standard low range, high accuracy electronic pressure transmitter with an electronic to pneumatic signal converter. The accuracy, repeatability and hysteresis characteristics of the signal converter are key to achieving good overall accuracy with this approach. A low quality converter can quickly erode away any benefits gained in using an electronic sensor. The most significant disadvantage of this approach is that the existing pneumatic tubing from the transmitter to the controller location must be replaced with wire to accommodate the electronic signal or wiring must be run to the transmitter location to power the transmitter and electronic to pneumatic signal converter.

Replace the Pneumatic Controller and Sensor with an Electronic Controller and Sensor and Convert the Output to a Pneumatic Signal For a relatively modest incremental cost increase over option 2, it is often possible to replace the entire pneumatic control system through the controller with an electronic system using a stand-alone process controller (Figure 5.24). This approach allows all of the advantages typically associated with DDC technology but can be easily interfaced to the existing pneumatic actuation system via a standard, readily available electronic to pneumatic converter. In installations where the existing pneumatic signal is being converted to an electronic signal for interface to a variable speed drive, this approach can actually simplify the system since the controller will most likely be able to interface to the drive without a signal converter. The disadvantage to this approach is that wiring must be installed to replace the pneumatic tubing that provides the input signal in an all-pneumatic system. Once installed, the system will generally provide much better performance and can be readily adapted to DDC technology and controllers if and when the rest of the control system is upgraded.

Figure 5.24 Typical stand-alone process controller

The controller pictured here is typical of the single loop stand alone controllers manufactured by many process control companies. While it may appear somewhat intimidating to the uninitiated, the operation is usually very well documented in the manuals. If you can work a VCR remote, you can probably master one of these devices (Image courtesy of the Partlow web site)

5.6.4.2. Electronic Force Based Differential Pressure Transmitters

In principle, electronic force based transmitters function in a very similar manner to the pneumatic transmitters discussed in the preceding paragraphs. The difference is that the motion of the diaphragm (created by the pressure difference across it) is converted to an electronic signal rather than a pneumatic signal. However electronic components are used to make the signal conversion rather than a mechanical system of levers, pivots and springs. This takes advantage of the inherent sensitivity of electronics and their lack of moving parts to provide a more repeatable signal with higher resolution. Techniques for making generating the electronic signal typically involve using the diaphragm to cause some change in capacitance or resistance with is then amplified and conditioned by an electronic circuit to provide a standard output. It is not unusual for the diaphragm to function as one plate of the capacitor in capacitance-based instruments. In other instruments, strain gauges attached to the diaphragm generate a variable resistance as the diaphragm flexes. There are products where the diaphragm is actually an etched out part of the semiconductor chip upon which the integrated circuit for the sensor is fabricated.

Figure 5.25 Typical force based differential pressure transmitter

These particular transmitters use a capacitance type pressure cell. (Picture courtesy of the Kele web site)

All of these factors combine to create sensors that provide more robust performance as compared to pneumatic products in the same price range. However, even better performance in terms of resolution, can be achieved with the flow based pressure sensors discussed in the next section.

5.6.4.3. Electronic Flow Based Differential Pressure Transmitters

As indicated previously, transmitters in this class indicate a pressure difference based on and input generated from the flow created by that pressure difference. The technology was originally developed to provide monitoring and control for hospital isolation rooms where very low-pressure differentials must be monitored, maintained, and alarmed if infections control requirements are to be met. The technology has also found application in application specific controllers targeted at laboratory fume hood control systems. Both systems can be adapted for use to monitor and control low-level static pressures associated with other HVAC processes such as building static pressure control. These transmitters are generally capable of resolving pressures as slow as one ten-thousandth of an inch water column and can be set up for a full scale range of several hundredths of an inch with an accuracy of ±2% of that range, making them ideal for this application. This performance comes with a bit of a cost penalty relative to the other electronic technologies; typically by a factor of 2 or 3 ($150 - $200 vs. $600-$900). However, in the context of the task to be performed and the benefits in terms of energy and comfort that can be attained by a persistent, successful implementation of the strategy, the benefits almost always outweigh the costs.

5.6.4.4. Transmitter Installation and Sensing Line Considerations

Regardless of how the static pressure signals are measured, the method used to extend the sensing connections from the transmitter to the location sensed as well as the method used to terminate the tubing ends at the sensing location can have significant impacts on the system's ability to perform. The issues to be considered are as follows.

1 **Transmitters are More than Signal Converters** One of the functions that a transmitter performs is to convert a low grade, noise susceptible, non-standard signal such as the resistance or capacitance variation in a differential pressure sensing element to a higher grade, industry standard, noise immune signal such as a 4-20 ma current loop. This function:

- Allows a nearly infinite variety of process sensors to be readily interfaced to a few industry standard inputs.
- Protects the relatively low level (e.g. milivolt, micro-ohm, micro-farad, hundredths of an inch water column) sensor signal from the effects of electrical noise between the sensing location and the input location.
- Allows the signal to be transmitted over large distances without degradation due to wiring resistance.

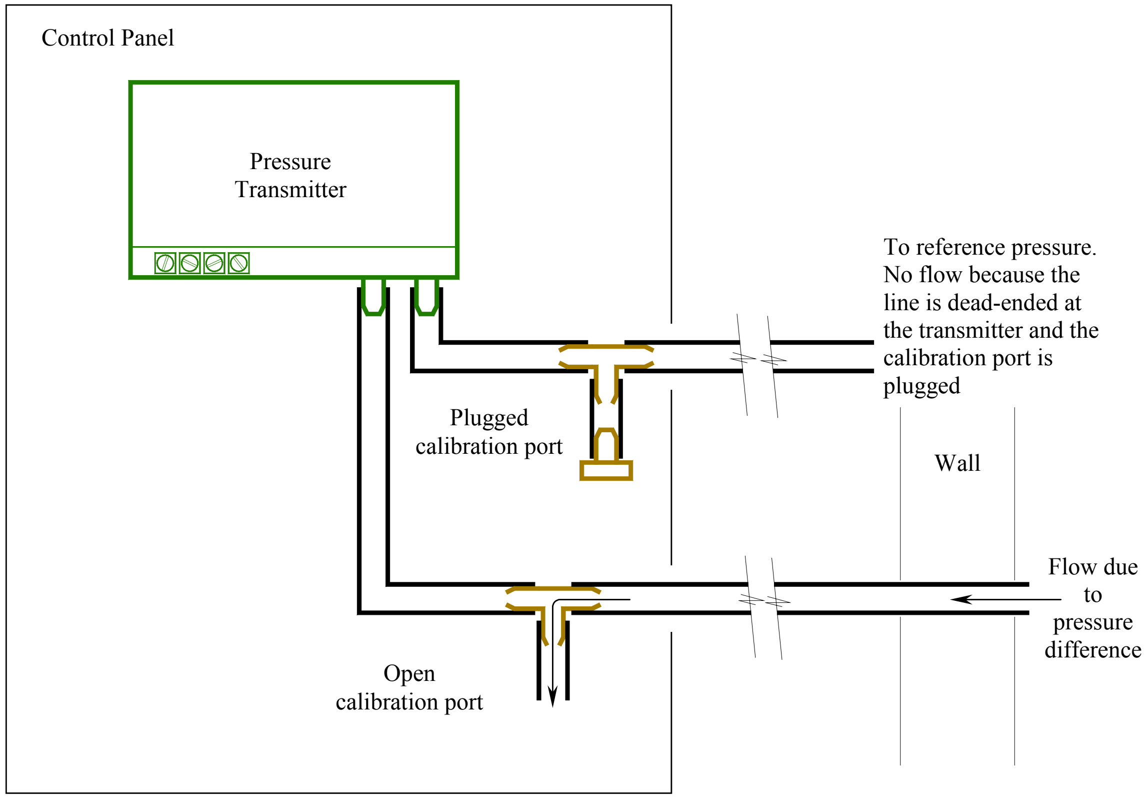


Figure 5.26 Pressure Measurement with an Open Calibration Port

This figure shows the impact of an open calibration port on the input signal measured by a pressure transmitter located at the control panel location instead of at the point where the signal is measured

Many times, pressure transmitters are installed with a plugged tee on their input sensing lines where they connect to the transmitter to allow a separate meter to be connected in parallel with the inputs for calibration purposes. This figure illustrates what happens to the input signal to the transmitter if one of these ports is unintentionally left open in a situation where the transmitter is located at the control panel rather than at the location where the pressure is being measured. At a minimum, the open connection at the equipment room tends to reference the transmitter to that location rather than to the desired point. If there is a significant pressure difference between the two locations, then air will flow through the input tube, creating a false reading due to the pressure drops associated with flow through the tube. While the magnitude of the pressure drop may not be significant in absolute terms, it can be a significant factor when the pressure being measured is only several hundredths of an inch w.c. in the first place. Leaks in the tubing due to nicks or loose fittings can create a similar situation.

It is not uncommon to find transmitters located in the auxiliary panel immediately adjacent to the controller and hundreds of feet from the location of the sensor. While desirable from a maintenance standpoint since all of the transmitters are easily accessed for calibration or replacement when necessary, it defeats some of the most significant benefits of having a transmitter in the first place; to protect the sensor signal from noise and degradation. In the case of the transmitters used for building static pressure monitoring and control, locating the transmitter next to the control panel and extending the tubing to the sensing location means that the very low signals associated with building pressurization (usually no more than ten hundreds of an inch) are sent through hundreds of feet of tubing. At first glance, this distance may not seem like much of an issue, since the tubing does not carry flow (except for a few fractions of a second when there is a pressure change). The pneumatic tubing is dead ended at the transmitter location and therefore is immune to the effects of pressure drop due to flow as a matter of normal operation. However, the pressure drop is not immune to the effect of flow created by leakage due to branch connections that were un-intentionally left open, loose fittings, and nicks introduced during the construction process and subsequent life of the building. Figure 5.26 illustrates the impact of a calibration port that was left open to the equipment room environment. Other unintended openings in the sensing tubing runs can have a similar effect. Even a minor leak can have the effect of neutralizing the signal from the intended location and referencing it to a different pressure condition.

When properly installed and applied, the electronic output signals from pressure transmitters are relatively immune to the effects of distance and the conditions in the spaces they traverse. Thus, the best input system is provided by locating building static pressure sensors (as well as other sensing elements) near the signal they are measuring and allowing them to act as signal transmitters as well as signal converters. Additional information regarding signal transmitters and their impacts on input accuracy can be found in the Control System Design Guide, *Chapter 3 Selection and Installation of Control and Monitoring Points.*

A Single Sensing Tube Connecting the Pressure Sensor Input to Multiple Spaces at Different Pressures does not Provide an Input that is the Average of the Different Space Pressures Often, it is desirable to measure several different building pressures and use the average value as an input or indication of building static pressure. Many times, an effort is made to minimize the cost to accomplish this by installing one static pressure sensor and then connecting its reference ports to multiple spaces. Unfortunately, this results in a situation very similar to what is depicted in Figure 5.26 above. The input created is some function of the different space pressures, but it does not adequately represent the mathematical average. The resulting pressure input is the result of a complex set of flow patterns and relationships set up in the tubing system by the *pressure differences* in the rooms that the tube is connected to and the *pressure drops* through the tubing system due to the flows created by the pressure differences. While it may be possible to make the system perform reasonably well based on this information, the signal is not equivalent to the average pressure or any actual pressure but as a potentially non-linear pressure coefficient that is a function of the various pressures.

Approaches that would provide a true indication of average pressure value include:

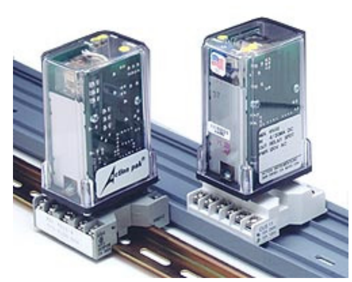


Figure 5.27 Typical math function type signal conditioner

(Image courtesy of the Action Instruments web site)

- Provide a transmitter in each space wired to an individual input and use the system software to average the signals. This approach makes the most information available to the operators and the allows greatest flexibility since the software can be modified to do other things besides average the inputs, like select the highest or lowest if necessary. However, the approach requires an input for each space referenced.
- Provide a transmitter in each space wired to an independent signal-conditioning module that provides an output that is an average of its inputs (See Figure 5.27 for an example). This approach minimizes the number of inputs required but is less flexible because it provides less data and the averaging calculation is fixed in hardware rather than software.

The Technique Used to Terminate the Static Pressure Reference Sensing Lines can Impact the Signal Measurement The ends of the sensing lines used to measure static pressures need to be located and arranged so they are immune to the effects of wind, space air motion, duct air flow, and other velocity pressure influences. A 5-mile per hour breeze has a velocity pressure of 0.01 inches w.c. associated with it. This error could be a significant portion of the value registered by a building static pressure probe.

Figure 5.28 Typical static pressure sensing probes

(Image courtesy of the Tek-Air web site)

A well-designed outdoor air static pressure probe will provide a reference point that is relatively immune to this type of effect if properly located. Location is an important factor because a probe that is located in a low-pressure zone created by the motion of the air around the building will still provide a bad reference and cause operational problems. Finding a good location for a static probe can be tricky and takes some time during the commissioning process. The benefits are usually worth in the effort in terms of more stable system performance.

There are a wide variety of probes manufactured by different companies targeted at measuring different static pressures including outdoor air static, duct static and space static. Figure 5.28 illustrates several designs by one manufacturer. In general, the devices make use of baffles and pulsation dampening chambers to eliminate some of the spurious effects associated with air motion.

Provisions that Filter Out Minor, Random, Static Pressure Variations can Often Provide Significant Performance Improvements Many of the electronic pressure sensing technologies used to measure building static pressure are capable of detecting and reporting very small and rapid pressure changes. This can be both a good thing and a bad thing for the commissioning agent, as can be seen from the previous side bar. Detecting and attempting to respond to the minor variations in building static pressure associated with a door opening every once-in-a-while may not be necessary and could create more problems than it solves. On the other hand, responding to a small but sustained loss of building pressure created by a door that is blocked open for some reason might be highly desirable in terms of controlling building pressure relationships and comfort.

Because the static pressure signals measured in air handling applications are relatively small and easily influenced by other factors such as air motion, they tend to be very “noisy” when viewed in terms of the desired average value. There are a variety of ways to mitigate this signal noise. Implementing one of the following techniques to correct a noisy signal identified in a functional test may yield very significant improvements in the performance of the system.

- Many modern DDC control system can apply a filtering factor directly to any analog input on the system. If available, this approach is probably the easiest to implement.
- If a standard filtering factor is not available, most systems will allow the user to write some software that averages the input based on a moving window of some sort. The output of this calculation can then be used as the actual input to the control or monitoring process.
- Resistor/capacitor and resistor/inductor networks can be wired across the input connections on most system to stabilize a noisy signal. The companies that

manufacture the signal conditioning modules shown in Figure 5.27 also typically manufacture modules that will provide this function as a packaged solution.

- Simply creating a pulsation chamber with a restricted inlet in the input sensing lines to the transmitter can often solve a noisy signal problem[9]. Any pressure change that occurs must first change the pressure in the entire volume of the pulsation chamber before it actually impacts the reading at the transmitter. The restriction in the input prevents minor pulses from affecting the chamber pressure significantly but will allow a sustained pressure change to eventually be reflected in the chamber, and thus, at the input to the transmitter.

5.6.4.5. Flow Sensors

In economizer systems, flow sensors are typically encountered in the minimum outdoor airflow regulation portion of the system. The set points of the loops controlling outdoor air flow may be optimized by a variety of factors including CO_2 level, schedule, occupancy, etc., but the primary control loop is typically based on measuring and controlling for a flow. As a result, verification of flow measurements and flow sensing equipment often must be accomplished as a part of testing the operation and performance of the mixing section of an air handling system.

A general discussion of flow measurement can be found in the Control System Design Guide, *Chapter 3: Selection and Installation of Control and Monitoring Points*. In addition, since many flow measurements are based on velocity pressures, many of the guidelines in the preceding section on static pressure measurement also apply. The following additional points should be considered when commissioning flow measurement systems for minimum outdoor air control.

Obtaining a Uniform Velocity Profile Under All Operating Conditions is Critical to Ensuring Good Control This point is true in any flow measurement application, but is often neglected in the sensing arrangements used for measuring the minimum outdoor air flow into a unit. In addition, the close-coupled configuration of typical intake systems can often make it difficult to find the physical space to meet the typical rules associated with establishing a uniform velocity profile. Finally, the modulating operation of the maximum outdoor air dampers can have a variable impact on the performance of the minimum outdoor air flow sensing and control system depending on the current operating point of the economizer.

Figure 5.29 Packaged outdoor air measurement and control assembly

The round devices on the plenum are air control valves that include an averaging type flow measurement ring as a part of the assembly. (Image courtesy of the Trane web site)

Some manufacturers now offer packaged products that incorporate flow measuring and control elements to accurately measure and control outdoor air flow using technology similar to what is applied on a VAV terminal unit. Figure 5.29 is one example of this type of product.

9 There are commercially available products that perform this function, but one can be easily fabricated in the field from a 6" long piece of 1/2" or 3/4" PVC pipe, a couple of end caps, an in line pneumatic control system restrictor fitting, a barbed fitting. and some 10 minute epoxy. Since the pressures are in terms of inches w.c., the pressure rating of the assembly is not critical. The caps are simply glued to the end of the tube and drilled to accommodate the inline restrictor fitting at one end and the barbed fitting at the other. The fittings are then epoxied in place. The pulsation chamber is then simply installed in the line ahead of the transmitter.

The Pressure Relationships Between the Outside, the Mixing Plenum, and the Return System Play a Critical Role in System Performance The flow through the minimum outdoor air flow control system is driven by the pressure difference that exists between the outdoors and the mixing plenum. On economizer systems, this pressure can vary as a function of the position of the economizer dampers, especially if they have not been sized for linear performance. If the system is a VAV system, then the pressure relationship can also vary with system flow rate. All of these issues need to be considered when selecting and commissioning the flow control system and its sensing elements. If the pressure required to drive the necessary flow through the sensing system is not sufficient, then the system will not be able to achieve the required flow rate, no matter what its nameplate rating is.

When the System is Operating on the Economizer Cycle at a Flow Rate Above its Minimum Outdoor Air Flow Requirement, Then the Operation of the Minimum Outdoor Air Flow Control System May Be Irrelevant Operation of the minimum outdoor air flow measurement and control system is critical for controlling indoor air quality when the system is operating in the minimum outdoor air mode. The system must be arranged and controlled in a manner that prevents it from delivering less than the minimum outdoor airflow requirement. Usually, this occurs during extreme winter and summer weather.

If the system is using significant amounts of outdoor air for an economizer cycle, then the performance of the minimum outdoor air flow control system may not be relevant since the system is bringing in outdoor air in excess of the minimum flow requirements. Thus, the functional testing of this system can often be targeted at ensuring its performance during extreme conditions with little if any attention paid to its performance under the economizer cycle, unless there is some requirement for documenting the minimum outdoor air flow at all times.

5.6.5 Blank-off plates

Most control dampers (like control valves) will be smaller than the duct they are in. Usually, this means that blank-off plates are installed to make up the difference. Two important factors need to be considered with regard to blank-off plates.

- The location and configuration of the blank-off plate/damper assembly needs to promote mixing.
- The pressure loss associated with the reduced damper area relative to the duct need to be taken into account in the sizing of the fan system. Some manufacturers include a factor for this in their pressure drop tables. Others allow the designer to determine the impact through an independent assessment.

Blank-off plates are also used in troubleshooting and retro-commissioning applications to deactivate portions of an existing, oversized damper to improve its performance characteristics. Disconnecting blade linkages to deactivate the blades and then screwing the blades in the closed position can achieve a similar effect. These procedures will be discussed in more detail in the following section.

5.6.6 Air Blenders and Baffle Plates

In a mixing plenum with dampers that has been optimized to promote mixing, there will be some distance required for mixing to occur. As a general rule, there should be at least 3 or 4 feet between the downstream side of the mixing dampers and the location in the unit where complete mixing needs to have occurred (usually the first coil in the unit). There are a variety of ways to accomplish full mixing including:

- Use the space required for filter banks and operator access to provide the necessary distance for mixing. In some instance, the filters can help to promote the mixing process due to the turbulence they create as the air flows through them and because they tend to promote a uniform velocity profile.
- Locate the mixing box some distance from the air handling unit so there is duct work and, ideally, an elbow or two between the outside and return dampers and the components of the air handler.

There are many instances where there simply is not enough space allocated in the mechanical room to provide the distance necessary for good mixing to occur. In these instances, air blenders or baffle plates can provide a mechanism to enhance the mixing of the outside and return air flow in a shorter distance.

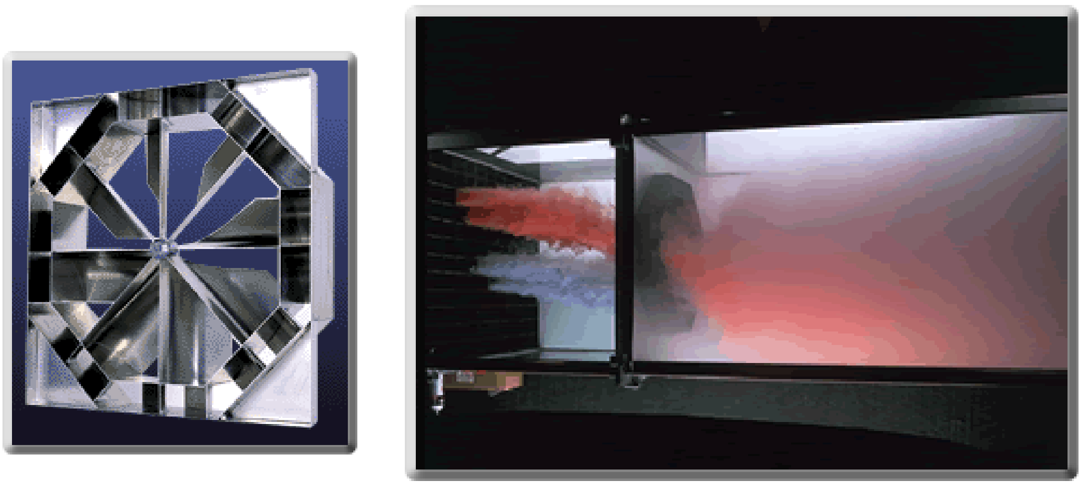


Figure 5.30 Typical Air Blender

The picture to the left is an air blender module. The picture to the right is a similar module under test, demonstrating its ability to mix the two colored air streams. (Pictures courtesy of the Blender Products web site).

Air blenders are manufactured devices that are designed to promote mixing and eliminate stratification in very short distances. A well-designed mixing box with properly sized and arranged dampers and sufficient distance for mixing can often achieve a 3-5°F spread between the warmest and coldest spot in the plenum discharge. For many HVAC applications, this level of mixing will be satisfactory. But if more uniform temperatures are required, or the available space does not provide sufficient distance for mixing, air blenders can be applied to meet or possibly exceed this level of performance. On existing projects with stratification problems, air blenders can be retrofitted into the system as a corrective measure, assuming the system has sufficient static pressure capability to handle the added pressure loss.

On many occasions, commissioning agents, Owners, facilities engineers and other people concerned with system operations find themselves faced with a system that has severe stratification problems that cause nuisance freezestat trips (or worse) without the luxury of time or budget necessary to allow air blenders to be retrofitted into the system. In these situations, baffle plates can offer a low cost, easily improvised, field solution to stratification problems that would otherwise be handled with air blenders. Baffle plates are sheet metal baffles installed downstream of the mixing dampers in an arrangement that will cause the airflow through the unit to change direction and/or induce turbulence. These directional changes can often improve the mixed condition enough to eliminate the problem.

Baffle plates can be solid metal or perforated metal. The solid metal plates rely on directional changes to achieve the desired effect. The perforated metal plates cause some directional changes but also induce mixing due to the jet effect created by the air that passes through the holes in the plate. If sufficient free area is maintained so that the average velocity in the airflow path is below 800-1,000 feet per minute, baffle plates can produce a significant improvement with little increase in pressure drop.

Baffle plates can be especially effective when combined with other improvements like adding a mixed air low limit cycle and improving the performance of oversized mixing dampers by disabling damper blades.

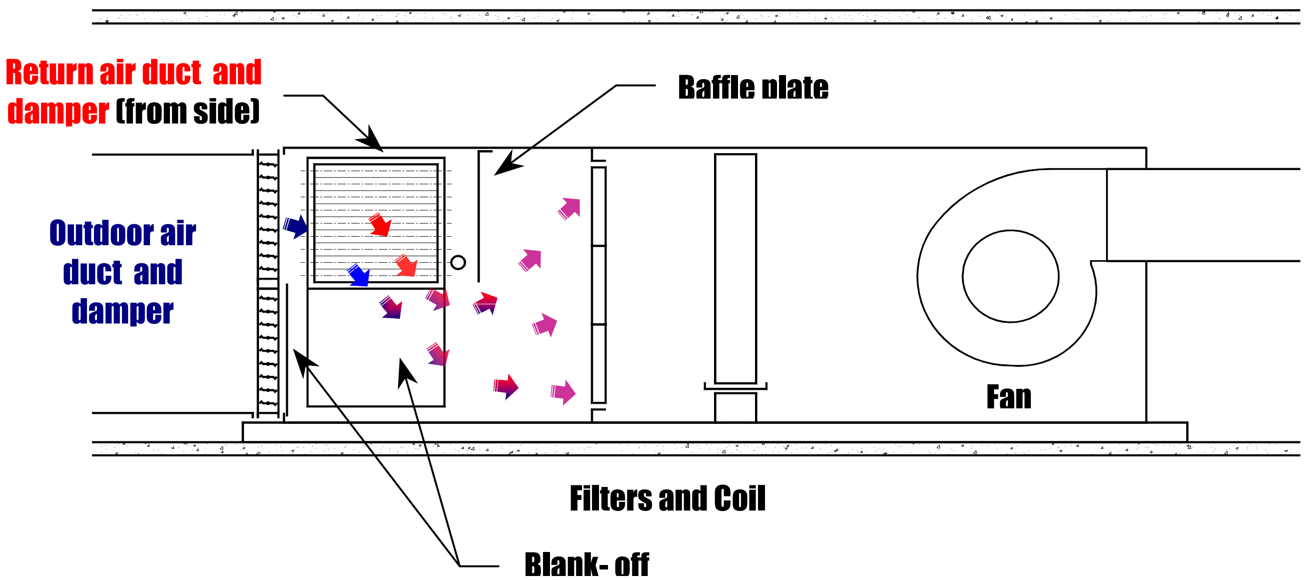


Figure 5.31 Blank-off plates and baffle plates help alleviate a stratification problem

On the VAV unit in Figure 5.31, a stratification problem that was causing nuisance freezestat trips when outdoor air temperatures dropped below the mid 20°'s F was solved by blanking off one of two damper sections on the outdoor air and return air dampers and adding a baffle plate ahead of the filter bank. Blanking off one damper section increased the velocity through the remaining section, improving its linearity and adding momentum to the air stream, which promoted mixing. The baffle plate forced the air to turn and then re-expand at the filter bank, which further improved the mixing. The velocities through the area below the baffle plate were still well below 1,000 fpm, thus little additional pressure drop was added. Increasing the damper velocity through the blank-off plates added some pressure drop, but running the motor into its service factor on design days and changing the filters slightly sooner accommodated this. The VAV system spent very little time at full capacity, thus running into the service factor had minimal impact on the motor life expectancy.

Chapter 5: Tests for Future Development

Economizer and Mixed Air Tests for Future Development

These functional tests will be developed in a future revision of the FT Guide. The descriptions are provided for reference.

Actuator Stroke Test

The purpose of the actuator stroke test is to assess and document the relationship between damper command and damper position. The test can be used to identify and quantify hysteresis and sizing issues associated with the economizer dampers. This test was developed by Lawrence Berkeley National Labs and ultimately will be used to characterize a real time continuous commissioning tool that is under development at the lab. The tool will compare the actual performance of the economizer with the performance predicted from the test and flag operating problems.

Energy and Other Benefits

Benefit	Comments
Energy Efficiency Related Benefits	Performing this test provides a means to document that important parameters affecting the ability to the economizer to perform have been addressed by the design and installation of the damper actuators.
Other Benefits	In combination with proper damper sizing, a linkage system that ensures linearity between the actuator stroke and the damper blade rotation can be critical to achieving a linear control characteristic.

Damper Limit Switch Adjustment Test

This test is targeted at verifying the limit switch settings and adjustments for systems with a permissive interlock that won't allow the fan to run until the return or outdoor air dampers are open sufficiently to prevent plenum and duct pressures that exceed the duct's pressure class rating. It can also be used to verify limit switches on dampers that serve other functions like driving indicator lights on a smoke control or smoke and fire management system.

Fan Spin Down Test

This test is targeted at identifying the time required for a fan wheel to spin down to a point where it will not generate pressures in excess of the duct or air handling unit's pressure rating as it coasts to a stop. The test result provides information for programming time delays and adjusting interlocks on dampers and other functions where the fan need to have coasted to a stop before proceeding. Generally, it will only be needed on large fan systems.

Minimum Outdoor Air Flow Test

This test will be developed for a future revision of the Guide. The description is provided for reference.

This test provides several options for measuring or verifying the minimum outdoor air flow into a system when there is no indication available in the DDC system. Some of the options can be executed using fairly simple instruments like those listed in *Chapter 2*, Section 2.10 Basic Tools, Instrumentation, and Equipment.

Building Pressurization Test

This test uses the outdoor air capabilities of the building air handling equipment to perform a blower door type test and obtain an indication of the building leakage rate. This information can be useful in evaluating infiltration loads, building envelope integrity, and assessing the potential for using building static pressure based control of the relief dampers to combat stack effect and envelope deficiencies.

Outdoor Condition Interlock Test

This test provides a template for guiding the evaluation and verification of the outdoor air temperature based change-over interlocks associated with economizer cycles, including enthalpy based change-over and dry bulb based change over.

Safety Interlock Test

This test provides a template for guiding the verification of safety interlocks typically associated with economizer cycles including freezestats and plenum static pressure switches.

Fan Operation Interlock Test

This test provides a template for verifying the fan interlocks associated with the economizer cycle including returning dampers to save positions, closing control valves where appropriate, and low ambient temperature interlocks associated with the how water valve.

Permissive Interlocks Test

This test provides a template for verifying permissive interlock systems where the fan operation is allowed only after dampers have been proven to be sufficiently open to allow fan operation with out generating static pressures in excess of what the plenums and duct systems on the project are designed to handle. It is usually used as a follow up test to the Damper Limit Switch Adjustment Test listed previously in this section.

Temperature Traverse Test

This test is used to evaluate the mixing effectiveness of the economizer dampers and/or any air blenders associated with the system. It can be used as an evaluation tool for economizers where there may be some question regarding the mixing effectiveness due to other indicators like dampers that appear to be oversized or poor results from the Actuator Stroke Test, the High Turndown Ratio Test, or Flow Linearity Test. It can also be used as a troubleshooting tool for a problem economizer to help evaluate the need for baffles or air blenders and the most effective location for them.

Mixed Air Low Limit Test

This test is used as a template to evaluate the performance of a mixed air low limit cycle. This control strategy is used to prevent nuisance freezestat trips at start-up on systems where the economizer dampers are controlled in sequence with other heat transfer elements based on discharge temperature. A portion of the test can also be used to evaluate a system that is experiencing nuisance freezestat trips for the need for a mixed air low limit cycle.

High Turndown Ratio Test

This test is used to evaluate the potential for mixing, temperature control and minimum outdoor air control problems in the economizer section on VAV systems that have the potential to operate over a wide range of flow rates. It can be used as a follow up test if the Actuator Stroke Test, the Temperature Traverse Test, or Flow Linearity Test indicate the potential for problems.

Flow Linearity Test

This test is used to evaluate the flow pattern that results in the system as the economizer strokes from 100% return air to 100% outdoor air and back again. It also looks at linkage arrangements and provides guidance in evaluating the potential impact of the linkage arrangement on the test results. It can be used as a follow up test if the Actuator Stroke Test, the Temperature Traverse Test, or High Turndown Ratio Test indicate the potential for problems.

Pressure Relief Door Test

This test provides a template for a variety of options that allow the settings of pressure relief doors to be verified while minimizing the risk to the air handling system.

Chapter 6: Filtration

6.1. Theory and Applications

Nearly all HVAC systems employ a filtration system. The level of filtration can vary widely. A bird screen prevents the entry of animals and small objects, low efficiency roughing filters protect the heat transfer elements and maintain a basic level of cleanliness in the system, and Ultra Low Penetration Air filters (ULPA) can have efficiencies of 99.999% on 0.3 micron test particles.[1] The level of filtration selected by the designer is related to the requirements of the process. These requirements are driven by the need to maintain indoor air quality (IAQ), protect the occupants from airborne hazards and contaminants, or maintain cleanliness in an occupied zone or production area. The requirements can be set by the owner's staff, a health care facilities infections control department, building codes, health care licensing requirements, industry standards, or Environmental Protection Agency requirements for effluents. For hazardous exhausts, scrubbers may also be employed in the exhaust stream. (Refer to Chapters 15 and 16, respectively, for a discussion of hazardous exhaust and scrubbers.)

Most filters use a mechanical process that physically captures the contaminants by adhering to the filter media. However, there are other technologies employed, including electrostatic attraction and air washing. The air washing approach often yields other benefits in the HVAC process such as humidification and cooling on the supply side, and neutralization of hazardous vapors in the scrubber on the exhaust side. Some systems employ chemical filters that are treated with a catalyst designed to react with the air stream and remove odors and other gaseous contaminants.

Due to the nature of their construction, some filters are considered flammable. As such, they may require U.L. classification for application in certain systems depending on the requirements of the local code authority and the insurance underwriter. In rare instances, fire suppression is required for large filter banks.

In addition to having a major impact on IAQ, filters can have a significant impact on energy consumption in the system due to the pressure drops associated with them. Both of these factors make commissioning the filters and their related framing and monitoring systems critical for ensuring a system's IAQ performance and energy efficiency. Proper monitoring and change out procedures combined with creative approaches to achieving the desired filtration efficiency at low pressure drop can significantly reduce the operating cost and waste streams associated with the HVAC equipment.

---

[1] As a general frame of reference, a human hair is approximately 100 microns in diameter.

6.2. Commissioning the Filtration System

The following tables outline the benefits and background information associated with testing filtration systems. These tables are linked to related information throughout the Guide. For additional functional testing information, refer to *Chapter 6 Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

6.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. All filters represent a continuous pressure drop that is related to the efficiency level of the filter and the design of the filtration media. Because of this pressure drop, filters create an ongoing energy burden in the air handling system. By working with the designer, owner, and operator, an informed commissioning provider can help the operating staff find the right balance between the frequency of filter change-outs (labor costs) and the filter pressure drop (energy cost). Appendix C.2 contains sample calculations for the horsepower savings associated with reduced pressure drops as well as the operating cost savings associated with these pressure drops over the life of the filters. Some filter manufacturers offer software that can perform this calculation. 2. Commissioning of the filter pressure drop monitoring system ensures that the filter change-out cycles are optimized and that excessive pressure drops are not introduced into the fan system.
Other Benefits	1. The proper installation and maintenance of the filters and their holding frames is critical for maintaining the desired IAQ level. Start-up and continuous commissioning can be a major contributor to the success of the filter installation. 2. Commissioning of the filter pressure drop monitoring system is critical for ensuring that the filters do not collapse due to excess pressure drop, allowing unfiltered air to bypass the filter bank and degrade the IAQ of the system and facility.

6.2.2. Functional Testing Field Tips

<table>
<tr><th>Item</th><th>Comments</th></tr>
<tr><td>Purpose of Test</td><td>Most filter functional testing is targeted at three areas.
1. Ensuring that the filters and frames installation provides the intended level of filtration.
2. Ensuring that the monitoring and indication systems are in place to allow proper filter maintenance.
3. Ensuring that the installed system provides the required level of filtration by directly measuring the performance based on particle counts, air patterns, and effluent analysis.
The commissioning provider can also be an advocate for filtering required during the temporary operation of the air handling systems. See Section 13.5.6: Indoor Air Quality for more information.</td></tr>
<tr><td>Instrumentation Required</td><td>Instrumentation requirements will vary from test to test, but typically includes the following instrumentation in addition to the standard tool kit listed in Chapter 6: Functional Testing Basics:
1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures.
2. A Borozine gun or smoke sticks to allow the airflow patterns near the filter holding frames to be viewed and analyzed.
3. For situations where the areas downstream of a HEPA or ULPA filter must be entered, clean suits and/or clean room gowns, gloves, boots, hair covers, and masks will be required.
4. For applications where filters or scrubbers must be qualified based on performance, special equipment including particle generators, particle counters, and chemical analyzers will be required depending on the test protocol. In many instances, retaining the services of a firm specializing in this type of work will be desirable. These costs should be taken into consideration when establishing the commissioning budget for systems with these requirements.</td></tr>
<tr><td>Test Conditions</td><td>Some filter commissioning functions are passive, relying primarily on visual inspection and procedural controls to verify performance. Other functions require that the system be operating at its rated air flow to allow clean filter pressure drop to be verified and filter to frame, frame to frame, and frame to casing leakage to be checked. For qualification tests, the air handling and scrubbing equipment will need to be fully functional.</td></tr>
</table>

Time Required to Test	Visual inspections and pressure drop monitor calibrations and verifications typically take 15 to 30 minutes per filter bank unless the filter bank is unusually large. Operating inspections for pressure drop and leakage can take 30-60 minutes depending on the rigor of the test and the size of the filter bank. Qualification testing will take at least 4 to 8 hours for two people per filter bank in an air handling unit application, with larger filter banks requiring more effort than smaller banks. Qualification testing of ceiling filters serving large areas such as clean rooms and surgeries can take several days to several weeks for a crew of workers. The length of time required will be a function of the size of the room, the rigor of the test, and the ceiling height. In addition, working in ultra clean environments requires special dress and site-specific training which can add to the time required to perform day-to-day tasks.
Acceptance Criteria	The acceptance criteria associated with filter testing will vary with the rigor of the test. For pressure drop indicator calibrations, the acceptance criteria will be related to the accuracy of the instrument being calibrated as well as the accuracy of the test instrument. Generally, instruments rated for 5%-10% of full-scale accuracy will be sufficient as long as the full-scale pressure drop is matched to the dirty pressure drop of the filter. An instrument rated for 0 to 1 inches w.c. ±0.05 inches w.c. monitoring a filter with a change-out requirement of 0.9 inches w.c. is adequate. An instrument rated for 1 to 10 inches w.c. ±0.5 inches w.c. monitoring this filter would not be satisfactory. The acceptance criteria for qualification-based testing is usually set by the Owner's requirements, by Health Care Facility Licensing standards, or by environmental or code compliance requirements for the effluent.
Potential Problems and Cautions	1. Inspection of filter banks in operating machinery requires the cautions normally associated with working in closed proximity to rotating equipment, exposed wiring, steam injection systems associated with humidity control systems, active control elements, and hot and cold surfaces. Of particular concern is the need to pass through doors that will have significant opening and closing forces generated on them by the static pressure differences between the unit's interior and exterior. 2. When working down stream of any filter bank, remember that you, the commissioning provider, are basically a contaminant. The severity of contaminate you represent depends on the level of filtration upstream of your location. You should not enter any portion of the air handling system that is down stream of filters with dirty shoes. The further into the system you go, the cleaner your attire needs to be. You may want to carry disposable booties or a clean pair of shoes for the clean sections of an air handling system on an active construction site. Proper attire is critical when working down stream of HEPA or ULPA filters. In many locations, the Owner will require full clean room or surgical garb. Even if the Owner does not require this, it is considered good practice in may situations. Given the high cost of the filters ($300 or more per module) and the penalties associated with downstream contamination, take these simple steps to ensure cleanliness. Similar considerations apply when changing out the filters, even when working in the upstream compartment.

6.3. Non-Copyrighted Tests

The following test, found in the CTPL, contains a filter pressure drop test. The test can be easily modified to fit different buildings and systems.

Air Handler Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, Commissioning Tests Version 2.05, 1998.

Several functional tests for filtration have been identified for future development, and may be included in later versions of the Guide.

Filtration Tests for Future Development

Link to a list of tests related to the filtration section that have not yet been developed.

6.4. Supplemental Information

Link to the plans for future development of supplemental information that will be useful in solving problems identified during commissioning and design review.

Chapter 6 Future Development

Chapter 6: Tests for Future Development

Filtration Tests for Future Development

Indicating gauge verification test

Clean filter pressure drop test

Frame leakage test

HEPA filter certification test

UV and chemical filter tests

Chapter 7: Preheat

Figures

7.1. Theory and Applications

This chapter focuses on heating elements that are in the preheat position in an air handling unit. Preheat elements are the first element in the air stream following the intake and prefilter, which is a position that allows them to protect the rest of the system and building from freezing air. Frequently, this heating element is a coil that uses steam, hot water, or electricity as an energy source. In some situations, the heating element is a fossil fuel fired furnace or an energy recovery coil.

From a psychrometric and HVAC process standpoint, not all heating elements are the same. The specific function they provide depends on:

- The location of the coil in the system relative to other components.
- The manner in which the coil is connected to its supply of heating energy (to prevent freezing).
- The manner in which the coil is controlled.

If the preheat element is to successfully provide the intended function, it is critical that these issues be taken into consideration when the system is configured and the heating element is selected and connected. Failure to do so can result in, at a minimum, the inability to provide the required level of performance and, in the worst case, can damage coils and building elements due to freezing.

The differences between preheat, reheat, warm-up, and heating processes in the air handling unit are also emphasized in this chapter. Many heating elements are labeled as preheat elements, but not all of them are properly configured to perform that function reliably. Preheat is required by an air handling system if it will see operating conditions that will result in supply temperatures that:

- Are lower than required to maintain the design conditions at the load served.
- Will subject the system, its components, and/or the loads served to air at subfreezing temperatures and thereby cause damage by freezing.

True preheat applications are typically found on 100% outdoor air systems and on systems with high outdoor air fractions relative to their total supply flow. Unless they are located in an extreme environment, most air handling systems serving office environments will seldom require preheat if their minimum outside air percentage is 20-30% of the supply flow rate and good mixing is achieved. In Section 5.1.2, a discussion on the relationship between minimum outside air and preheat illustrates this concept.

Generally, for 100% outdoor air systems, the coil inlet conditions are set by the worst-case outdoor conditions on record for the area. For recirculating systems, the coil inlet conditions are based on the worst-case mixed air conditions (the maximum anticipated minimum outdoor air requirement and the minimum anticipated return air temperature).

The preceding paragraph made reference to the *worst-case outdoor conditions on record for the area*. It is important to recognize that these conditions may be significantly different than the heating design conditions for the area. Notice that the ASHRAE 99% design numbers are exceeded for 1% of the hours in a year (about 90 hours). There are some locations where the design condition is above freezing but temperatures occasionally fall below freezing. A design based on the design values would presume that the installation did not have to deal with subfreezing air. The reality of the situation, as represented by the extremes, is that the system would in fact see subfreezing temperatures. A design that did not reflect this contingency could experience significant operating problems or even failures when the subfreezing weather occurred. These problems will be a nuisance in most cases and could be crippling to some facilities serving critical health care or production loads.

In contrast to preheat elements, heating elements that are located downstream of the air handling system's cooling coils are referred to as being in the reheat position. The summertime cooling coil discharge temperature is typically set based on the amount of dehumidification required to achieve adequate dehumidification for the occupied zone (see *Chapter 8: Cooling)*. The required volume of air, when supplied at this temperature, can overcool the occupied zone under some load conditions. Typically, overcooling can occur in situations where the flow to the occupied zone is set based on air change requirements, ventilation requirements, or make-up air requirements rather than being set by space sensible gains and temperature requirements. Clean rooms and hospital surgeries are good examples of applications where this can occur due to the high air change rates associated with maintaining cleanliness. In these situations, the reheat coil is used to warm the discharge air off the cooling coil as necessary to prevent overcooling of the space while still maintaining the required air flow and space humidity condition. Reheat is an energy-intensive process since it is intentional simultaneous heating and cooling. These functions are discussed in greater detail in *Chapter 10: Reheat* and are mentioned here in order to distinguish the preheat process from the reheat process. Figure 7.1 illustrates a system that has both a preheat coil and a reheat coil.

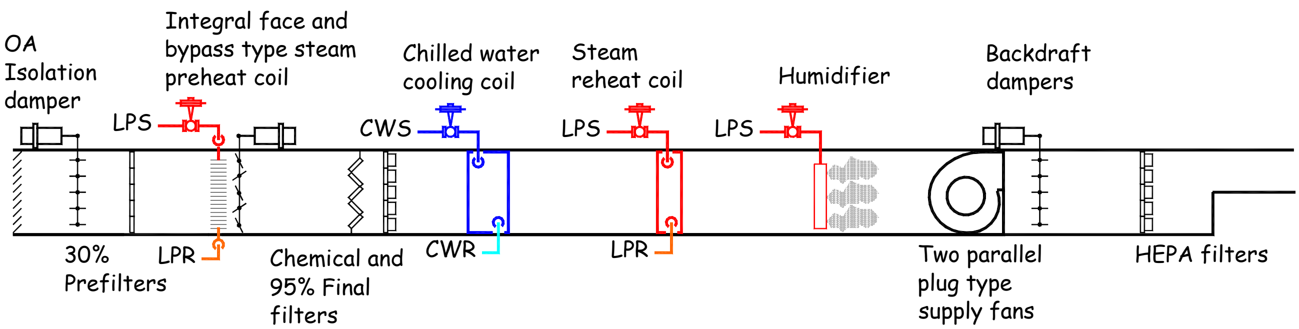


Figure 7.1 Make-Up Air Handling Unit with Preheat and Reheat Coils

This 100% outdoor air unit has both a preheat and a reheat coil. The preheat coil first raises the temperature of the air sufficiently to protect the rest of the unit and the area served from sub-freezing temperatures. The integral face and bypass design allows the coil to handle sub-freezing air without danger of freezing the condensate. The reheat coil is located after the cooling coil. The cooling coil discharge temperature is set to deliver saturated air with a specific humidity level as required to maintain the space humidity conditions in the summer. Since the air may overcool the space, the reheat coil warms the air as necessary. Either coil could provide a warm-up function, although it would be an energy intensive process given the system brings in 100% outdoor air.

Some system designs provide the reheat function at the zone location rather than at the central system location. This allows the reheat process to be limited to only the areas requiring it due to the specific needs of the zone while optimizing the central system supply temperature based on the needs of the critical zone.

Systems can also provide the reheat function at both the zone and the central system. Zone reheat coils are often installed in air handling systems that serve a mix of interior and perimeter zones. While the terminal units associated with the perimeter and interior applications are often physically identical and controlled by identical control sequences, there are significant HVAC process differences that need to be considered, since interior zones reheat, but unlike perimeter zones, never have net loss of heat (heating load).

Heating elements located in either the preheat or reheat position can be used for heating in instances where the losses from the zone exceed the internal gains. In this case, the energy that is put into the heating element is used to offset energy losses from the space - a true space heating application. Contrast this with preheat elements, where the energy is required to warm up outdoor air, or reheat elements, where the energy is required to control the HVAC process as necessary to hit the target conditions in the occupied zone. Similarly, elements in either preheat or reheat location can provide the warm-up function often required when a scheduled air handling system is shut down during unoccupied periods and the outdoor conditions result in a net loss of energy from the space.

Many air handling systems will have preheat, reheat, heating, and warm-up requirements for some portion of their operating cycle. Consider the following. If you improved the insulation on the area served by the air handling system, you might lower or even eliminate the heating and warm-up requirements associated with a net energy loss from the space. However, the insulation would not eliminate the preheat requirements or the reheat requirements (although it may modify them) unless you changed the airflow and/or humidity requirements for the zone. These are subtle but important distinctions because the different functions require different control strategies.

Verifying the proper control sequence for preheat elements is an important aspect of commissioning. Table 7.1 contrasts the preheat, reheat, heating, and warm-up processes, summarizing the information in the preceding paragraphs.

Table 7.1 Comparison of the Preheat, Reheat, Heating, and Warm-up Processes

	Preheat	Reheat	Heating	Warm-up
Function	Offset heating requirements associated with ventilation and make-up air; protect the system and building from sub-freezing air.	Offset unnecessary sensible cooling that was done to provide dehumidification to meet the space design requirement.	Offset space sensible losses through the building envelope associated with the rate of heat transfer exceeding the rate of heat gain in the perimeter zone.	Similar to the heating coil but also must pick up the accumulated loads that occur as the building and its contents cool off during the unoccupied cycle.
Load Offset by Heating Energy	Make up and ventilation air heating load	False cooling load	Perimeter heating and infiltration loads	Accumulated perimeter heating and infiltration loads
Location	First element after the intake for 100% outdoor air systems; first after the mixing box for recirculating systems	After the cooling coil.	Not critical but first after the mixing plenum provides some measure of protection for the rest of the system.	Not critical but first after the mixing plenum provides some measure of protection for the rest of the system.
Installation	Configure to handle air at subfreezing temperatures.[2]	None that is special to the function.	None that is special to the function.	None that is special to the function.
Control	Controlled to maintain a safe (above freezing) leaving air condition under all operating modes and sequenced with other elements to avoid energy waste. The freezestat must be downstream of the preheat coil if it will see sub freezing entering air temperatures.	The cooling coil discharge temperature setpoint is selected based on design humidity requirements[3], while the reheat coil is controlled based on space temperature requirements. The freezestat must be upstream since the reheat coil would not typically be configured for subfreezing air.	Sequence with other system functions to prevent simultaneous heating and cooling and to prevent using heating when the system is not on minimum outdoor air. The freezestat must be upstream since the coil would not typically be configured for subfreezing air.	Sequence with other system functions to prevent simultaneous heating and cooling and to prevent using outdoor air during the warm-up cycle. The freezestat must be upstream since the coil would not typically be configured for subfreezing air.

Notes:

1. Heat transfer elements should always be located downstream of the first set of prefilters in order to protect them from atmospheric dust and dirt and/or dust and dirt returned from the area served.

2. Occasionally, in a moderate environment, preheat is required due to high ventilation rates but the ambient conditions and return air conditions are such that the entering air temperature to the preheat coil will never be below freezing under any condition.

3. In a climate with very low humidity, the cooling coil discharge temperature setpoint may be selected based on temperature requirements, not humidity.

7.2. Commissioning the Preheat

The following tables outline the benefits and background information associated with testing preheat systems. For additional functional testing information, refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

7.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. Ensuring proper sequencing with the other heat transfer elements in the air handling system will minimize the potential for simultaneous heating and cooling, thereby saving both heating and cooling energy. 2. Ensuring proper sequencing with the economizer and minimum outdoor air functions will minimize the potential for heating unnecessary volumes of outdoor air, thereby saving heating energy. 3. Addressing items 1 and 2 also ensures that there will be no ripple effects associated with inappropriate preheat element control. One example is unnecessary fan energy triggered by the demand for additional flow from terminal equipment supplied with warm air. 4. Verifying that control valves close off completely helps ensure that simultaneous heating and cooling do not occur. 5. Addressing item 4 also ensures that there will not be cooling and heating water energy waste associated with the distribution network due to the unnecessary heating medium leakage and the effort made by the cooling system to offset it. 6. Verification of the correct shut down sequence for the heating source serving face and bypass type preheat coils during warm weather eliminates an ongoing parasitic burden from the system. 7. Addressing item 6 also ensures that there will not be energy waste in the supporting utility systems caused by the parasitic load.
Other Benefits	1. Proper preheat operation will help to ensure that the potential for nuisance freezestat trips is minimized. See Section 5.4.6 Nuisance Freezestat Trips for details on this problem. 2. Proper preheat operation will protect the other system components and the building elements from failure due to freezing and the subsequent water damage that typically follows this type of failure.

7.2.2. Functional Testing Field Tips

<table>
<tr><th>Item</th><th>Comments</th></tr>
<tr><td>Purpose of Test</td><td>The purpose of the test procedure used with the preheat element will vary with the requirements of the system served. In general, testing will be targeted at:
1. Verifying the proper control sequence and integration of that sequence into the overall air handling unit sequence.
2. Verifying the stroke of the control valve to ensure that they close completely.
3. Verifying the installation and functionality of the design features targeted at ensuring that the coil can safely and reliably deal with subfreezing air.
4. In some instances, flushing and pressure testing of the coil may be required.
5. In some instances, verifying the coil capacity may be required. Tests targeted at verifying that the installed conditions will allow the coil to perform as intended may prove to be more cost effective that tests targeted at documenting absolute capacity.</td></tr>
<tr><td>Instrumentation Required</td><td>Instrumentation requirements will vary from test to test but typically will include the following tools. A general tool kit is described in Chapter 2: Functional Testing Basics.
1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. This equipment can also be used to verify flow rates.
2. A stethoscope or similar sound sensitive device can be useful for listening for valve leakage sounds when verifying that the valve is fully closed.
3. For capacity testing, flow measuring equipment capable of measuring the flow of the heating energy source to the necessary degree of accuracy will be required.</td></tr>
<tr><td>Test Conditions</td><td>1. Some of the tests associated with the preheat coil heating source can be accomplished prior to the completion of the air handling unit. For example, pressure tests, flushing, some control valve shut-off test processes, and source side flow tests can all be accomplished with or without air handling unit operation.
2. Other tests, like freezestat testing, interlock testing, discharge control loop testing, and tuning and capacity testing will require that the air handling system be operational and moving the design volume of air, but not necessarily fully under control. Safety systems should be operational to protect the machinery and occupants in the event of a problem during the test sequence.
3. Testing the integrated performance of the preheat element with the rest of the system will require that the individual components of the system be fully tested and ready for integrated testing. In many cases, the building or at least the portion of the building served by the system must be substantially complete and under load.</td></tr>
</table>

4. Simulating a real preheat load in the field is a practical impossibility. In most instances where capacity verification is required, it will be verified based on achieving a target temperature rise above the current ambient conditions, or based on documenting coil performance under the given conditions and then modeling the coil under those same conditions. A capacity test may be limited by the elevation of the actual inlet temperature above the design inlet temperature, the temperature of the heat supply source, and the length of time and conditions under which is it possible to operate the system with an elevated discharge temperature. Often, this condition can be used to simultaneously load test the cooling system although the load is a sensible load rather than a sensible and latent load. An example of one of the more limiting test situations would be load testing a preheat coil on a hot day with a coil supplied by a low temperature water system.
5. As an alternative, it is possible to wait for near design conditions and perform the capacity test at that time. This approach is a more realistic test of the coil and also allows the control functions to be evaluated under more realistic conditions. However, it requires that the test process and instrumentation be prepared in advance and that the test team can respond quickly to reach the site and perform the test before the weather changes. This approach also requires that the load served by the system be able to deal with a potentially disruptive test process with little advanced warning.
6. Valve leakage tests and tests that are targeted at verifying valve stroke, spring range, and sequencing should be conducted with the pumping system operating at its peak differential pressure. The differential pressure across the valve plug can have a significant impact on the close-off rating and shift the operating spring range of the valve.

Time Required to Test

1. Some of the simpler tests like and interlock test or a valve shut-off test can be accomplished in an hour or less with one or two people.
2. More complex tests like a capacity test can require several hours and several team members to set up and monitor all of the necessary functions, especially if multiple operating points are to be evaluated. This test can be complicated by the need to quickly travel to the site with short notice to run a test while ideal test conditions prevail.
3. Tests that require referencing back to a model require some time to either develop or support the development of the model that will be used to evaluate the coil's performance. If the modeling capability does not exist in-house, then it may be necessary to retain the coil manufacturer's services if the modeling requirement has not been included in the pricing package.
4. Field-testing to lab or factory standards is expensive and a practical impossibility in many instances.

Acceptance Criteria

1. Control valve leakage testing should reveal no detectable leakage. Some of the larger globe valve designs, especially balanced double-seated designs, are not capable of complete and total shut-off. Most valves of this type have specifications for maximum leakage tolerances. Valves that are rated bubble tight should be capable of producing no detectable leakage when stroked fully closed.
2. To prevent unintentional simultaneous heating and cooling, the control

element range should match the requirements of the control sequence and not overlap the range of any other elements served by the same signal.

3. Capacity test results should be evaluated in the light of the accuracy of instrumentation and the actual conditions at the time of the test.
4. The preheat element control should repeatedly and reliably integrate with the overall system control strategy in a manner that provides the intended function and level of performance.

Potential Problems and Cautions

1. Testing preheat coils with subfreezing entering air conditions subjects the coil to the danger of freezing if it has not been properly applied and set up. The system and building can be subject to freezing conditions in the event that there is a problem during the test that causes the preheat element to fail to perform. Therefore, testing should proceed in a logical sequence that verifies primary interlocks and safety systems prior to verifying more complex control processes, integrated control functions, and tuning loops.
2. Some test procedures, either by design or by failure of the element under test to perform as intended, can cause air handling system discharge temperatures to become significantly elevated above normal. This can pose several problems including:
   a. Occupant discomfort.
   b. Disruption of the process served by the system and potential damage to product
   c. Inadvertent activation of fire dampers. See Section 13.5.2: Fire and Smoke Dampers, and Section 13.5.3: Air Hammer, under the discussion on fusible links.
   d. Inadvertent activation of heat detectors and rate of rise detectors and subsequent false fire alarm and building evacuation.
   e. Test plans should provide for these contingencies by taking steps such as disabling key fire detection elements for the test and ensuring that fusible links have been selected to tolerate any temperature that can be produced in the system.
3. Overly rapid stroking of valves and dampers during a test process can cause air, water, and steam hammer problems in the duct and piping systems serving the preheat element.
4. Functionally testing an electric preheat element during the summer months while the cooling plant is in operation can cause several significant problems including:
5. Distribution system load conditions that exceed design and switch gear ratings can trigger trips in the primary switchgear resulting in unscheduled and unanticipated outages.
6. Demand peaks well in excess of those that would normally be encountered during normal operation due to the demand that the coil places on the system concurrently with the refrigeration equipment. In locations with high demand charges and ratcheted demand schedules, these peaks can incur a significant cost penalty and lasts for the duration of the ratchet even though the actual period of use was brief, perhaps less than half an hour. A ratcheted demand schedule invokes the peak demand charge seen by the system for a number of months past the

month in which the demand was established. In many cases, the ratchet is 11 months; i.e. a demand peak set in July will be paid for every month for the next 12 months unless a higher demand peak is set in a subsequent month. For example, if a functional test were to operate a 160 kW preheat coil for 10 or 15 minutes during July when the cooling plant was already operating at peak capacity and the building internal loads were already established, then the coil would probably establish 160 kW demand peak that would not have occurred in a real operating situation and which will probably not be seen again. If this peak occurred on a utility network that had a demand charge of $15 per kW with a 12 month ratchet clause, then the Owner would have to pay $2,400 per month (160kW times $15 per kW) every month for the next 12 months (total of $28,800) for that 5 or 10 minutes of electric coil operation during the functional test. As a frame of reference, a 10,000 cfm, 100% outside air make up air handling unit rated for a 50°F temperature rise across the preheat coil could require a 160kW electric preheat coil if that was the method selected to meet the heating load. The demand charges quoted are typical for a project in the Midwest in the late 1990's.

7.3. Typical Problems

Applying the wrong control strategy to the preheat coil can easily produce the desired occupant comfort, but at a significant energy or process control penalty. For example, an economizer-equipped system should be controlled to drive to minimum outdoor air in an effort to maintain discharge set point before the preheat or heating coil is allowed to become active. Failing to ensure this sequencing and simply controlling for a fixed heating coil discharge temperature could result in a significant amount of unnecessary preheat energy consumption. The system would be heating outside air that is actually being brought in for cooling purposes if the economizer is not positioned to minimum outdoor air prior to heating the mixed air stream.

The impact of a misapplied heating coil sequence can ripple out through the rest of the system. A heating coil that was controlled as if it were a reheat coil (based on space temperature and not sequenced with the cooling coil), in an application where reheat was not necessary, could waste an enormous amount of energy due to unnecessary simultaneous heating and cooling. On a VAV system, this effect could ripple out into the fan energy consumption profile if the system supply temperature was raised enough to cause the terminal equipment to demand more flow than was necessary to satisfy the loads.

In contrast, a reheat coil that was controlled in sequence with the cooling coil and economizer dampers (as if it were a heating coil) probably would save energy but at the cost of losing control of the desired space design conditions. Sequencing the reheat function with the other air handling system functions would most likely result in space humidity conditions that were above the required specification. This deviation for the design humidity requirement could have an impact on IAQ, product quality, occupant comfort, and may even result in conditions that degrade the building structural and architectural elements.

7.4. Non-Copyrighted Tests

The CTPL contains the following tests that have some component that focuses on preheat or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

EMS and Point Verification Checks

Link to EMS Pre-functional Tests and Points Checkout Procedure.

This document contains damper and valve tests appropriate for preheat coils in certain applications, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

Air Handler Functional Test (Seattle City Light)

Link to an Air Handler Functional Test

This document contains procedures appropriate for preheat coils in certain applications, as prepared for Seattle City Light by Mike Kaplan.

Air Handler Functional Test (PECI)

Link to an Air Handler Functional Test

This document contains procedures appropriate for preheat coils in certain applications, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

Several functional tests for preheat have been identified for future development, and may be included in later versions of the Guide.

Preheat Tests for Future Development

Link to a list of tests related to the preheat section that have not yet been developed.

7.5. Supplemental Information

Supplemental information has not been developed at this time for the preheat section. Link to the plans for future development of supplemental information that will be useful to solve many problems typically identified during commissioning and design review.

Chapter 7 Future Development

Chapter 7: Tests for Future Development

Preheat Tests for Future Development

The following verification checks and functional tests are not incorporated in the CTPL and are listed for reference. This section will be developed in a future revision of the FT Guide.

Quick Operational Verification Test for use During a Scoping Study

Steam Trap Test

Control Valve or Control Damper Stroke Verification Test

Control Valve Leak-by Test

Control Damper Leak-by Test

Interlock Test

System Operation

Ambient Conditions

Freezestat test

Degree of testing (circuit vs. switch contacts vs. element)

Capacity test

Field testing considerations

- Sensor accuracy issues
- Load issues
- Testing to lab or factory standards vs. testing to prove that the coil should perform as designed because it has been supplied with the necessary utilities

Measuring steam flow in the field

Chapter 8: Cooling

Figures

8.1. Theory and Applications

Cooling is one of the primary functions provided by air-handling systems. With mild ambient temperatures and a properly configured system, an air handling unit can often provide cooling for a significant portion of its operating cycle using outdoor air in an economizer cycle. This process is the subject of *Chapter 9 Economizer and Mixed Air*. When outdoor conditions are not suitable to meet the cooling requirements of the load, then other mechanized processes are required. Common approaches to mechanical cooling include:

- **Chilled water or glycol:** Refrigeration equipment generates cold water or glycol, which is then pumped to coils located in the air handling units to cool and dehumidify the air stream. There are small packaged air-cooled chillers in addition to the larger chillers common in central chilled water plants serving large buildings, campuses, and industrial sites.

  Capacity control is typically achieved by modulating the flow of water through the coil or by bypassing air around the coil. Generally, modulating the water flow is the most desirable approach since it has the potential to save chilled water pumping energy. Where dehumidification requirements lead to the need for reheat, mixed air or return air can bypass around the cooling coil for discharge temperature control while the chilled water coil valve is controlled to provide adequate dehumidification.

- **Direct expansion refrigeration:** Refrigerant flows through the evaporator coil in the air handling system, often referred to as the DX coil (short for **D**irect e**X**pansion), to cool the air. Compressors and condensers, included as a part of the air handling package or located remotely, move the refrigerant through the piping and coil system and allow the heat absorbed in the air handling unit to be rejected to atmosphere.

  Capacity control is achieved on the refrigeration side by an expansion device at the coil coupled with compressor unloading and hot gas bypass. Compressor unloading systems are generally step devices, which limit capacity modulation. At low load conditions, the compressors will cycle and unconditioned air will pass through the system during the off cycle, which can cause problems. Hot gas bypass can be used to maintain compressor operation continuously regardless of load, but this is an energy intensive solution since it maintains an active cooling coil at the expense of false loading the compressor. Face and bypass dampers are sometimes encountered for air-side capacity control, but they must be used with extreme caution since the low air flow rates that occur across the coil when the dampers are in bypass can cause severe problems in the refrigeration circuit.

- **Heat pumps:** Heat pumps are a variation on the direct expansion refrigeration approach typically found in package and unitary equipment. When the air handling system requires cooling, the system works like a traditional direct expansion system. But, if the air handling unit requires heat, the system reverses and uses the coil in the air handling unit as a condenser and the coil used to reject heat to the atmosphere as the evaporator. The system cools the outdoors to heat the air stream in the air handling unit. Heat pumps allow electric heat generation for significantly less cost than electric resistance heating.

- **Direct and indirect evaporative cooling:** Systems that use the cooling effect associated with evaporating water are often used in environments with relatively low web-bulb temperatures. The direct approach cools the air by spraying water onto a media and allowing it to evaporate into the air stream. The air leaves the process cooler and with a higher specific moisture content. The process lends itself to locations where the ambient wet bulb is below 65-70ºF and with high make-up air requirements since the air is not recirculated.

Indirect evaporative cooling uses a direct evaporative process to cool a secondary air stream; usually the exhaust stream from the area served or an outdoor air stream. This secondary air stream is then used to cool the primary air stream serving the space using a heat exchanger. Some systems combine heat recovery with the indirect evaporative cooling package. The wet economizer process is a special case of the indirect evaporative cooling approach.

There are also processes that combine direct and indirect cooling approaches to yield a supply dry bulb temperature that is 10ºF or more below the wet bulb temperature of the secondary air. Generally, the process uses a direct evaporative cooling in the secondary air stream (usually exhaust from the area served) followed by a heat exchanger, which allows the evaporatively cooled secondary air to indirectly cool the primary air. Then primary air passes through a direct evaporative cooling process.

Evaporative cooling can improve the capacity and reduce the demand of a direct expansion chiller or condensing unit by precooling the condenser air. Evaporative cooling can also be used in series with other refrigeration processes to improve their effectiveness and reduce demand. The evaporative process will add energy from the spray pump motor, the secondary air fan motors, and added air flow resistance, but the reduction in energy requirement in the downstream refrigeration process can often yield a net energy savings.

- **Wet economizers:** This process is a special case of the indirect evaporative cooling process. From the air handling unit perspective, the cooling source looks like a chilled water system. But the chilled water is generated via cooling towers or dry coolers. The chilled fluid is then pumped to the loads and serves a traditional chilled water coil. Some systems employ a heat exchanger between the circuit to the cooling towers or dry coolers and the circuit serving the loads. Other systems use the water directly. Advantages of this approach include:

  1. **The ability to generate chilled water without the operation of a chiller** This can be a significant factor in dry environments where evaporative cooling processes are highly effective. It also can be significant for processes facilities like clean rooms where the nature of the load served makes the filtration requirements and pressure control problems associated with handling large variable volumes of outdoor air impractical, thus eliminating traditional economizer approaches.

  2. **Elimination of the outdoor air and relief duct systems associated with the economizer process** Only ventilation make up air and its associated exhaust need to be provided to the air handling system. The same pipes that bring chilled water to the system when it is generated by the chiller plant provide economizer cooling.

  3. **Elimination of the economizer dampers and its related control systems** The cost and complexity associated with a traditional economizer is no small matter as can be seen from *Chapter 9 Economizer and Mixed Air*.

  Disadvantages of wet economizers include:

  The need to operate cooling towers in sub-freezing weather: Operating cooling towers in subfreezing weather is not a casual undertaking. Using the towers to generate chilled water for the fall, winter and spring months will add a lot of wear to the towers.

2 **Additional cooling tower and fan energy:** Obviously, the need to operate cooling towers on a year round basis will add operating cost. However, this may be offset to some extent by reductions in fan energy associated with eliminating all but the minimum outdoor air duct and relief system. The average filter pressure drop may also be lower since the filters will last longer and load more slowly when they don't have to deal with the large volumes of outdoor air associated with a traditional cycle.

3 **Additional pumping energy:** The other obvious energy burden associated with a wet economizer cycle that is absent in a traditional economizer approach is the need to run pumps to move water to the loads and the cooling towers. Dry coolers will also have spray tree pumps that must operate to achieve the evaporative cooling effect necessary for many of the operating hours.

In some situations, wet economizer pumping and tower fan energy costs may be viewed as an attractive alternative to the control systems, operating issues and the cost and real-estate represented by a traditional economizer system, especially when one central plant can serve multiple air handling systems on a large site.

- **Well water:** While becoming less common, there are instances where running well water through the air handling unit cooling coil is used to provide cooling. The advantage is low energy cost, at the cost of water usage and disposal costs. From the air handling unit perspective, the process is nearly identical to a chilled water cooling process although the potential for scale, corrosion, and other problems related to using raw water continuously need to be addressed. Cooling coils constructed with cleanable tubes may be desirable in this application.
- **Recovered cooling energy:** It is often possible to recover cooling energy from HVAC processes with high exhaust flow rates. In most cases, it will be necessary to supplement this recovered energy with additional cooling, but the recovery process can make a significant difference in the size of the equipment required and the electrical demand and energy consumption associated with it. Thus it can generate both first cost and operating cost savings.

The *ASHRAE Systems and Equipment Handbook* contains chapters with detailed information on most of these cooling technologies.

8.2. Commissioning the Cooling System

The following tables outline the benefits and background information associated with testing cooling subsystems. For additional functional testing information, refer to *Chapter 6: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

8.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. Cooling is one of the more energy and resource intensive processes that occur in an air handling system. Common cooling processes use electricity, and many of the processes also will consume water in significant quantities. Proper commissioning of these processes will ensure that cooling energy and water resources are not wasted, and that the cooling function is fully integrated with air handling system. 2. Ensuring proper sequencing of mechanical cooling with the other heat transfer elements in the air handling system will minimize the potential for simultaneous heating and cooling, thereby saving both heating and cooling energy. 3. Ensuring proper sequencing of mechanical cooling with the economizer will minimize the potential for cooling and dehumidifying unnecessary volumes of outdoor air. 4. Proper sequencing also ensures that there will be no ripple effects associated with inappropriate cooling element control. One example is unnecessary reheat energy triggered by over cooling and over-dehumidifying the supply air stream. 5. Verifying that control valves close off completely helps ensure that simultaneous heating and cooling do not occur. 6. Verifying valve close off also ensures that there will be not ripple affects associated with pumping extra cooling and heating water through the distribution network due to the chilled water leakage and the effort made by the heating system to offset it. 7. Proper commissioning and adjustment of the various capacity control mechanisms (expansion valve, unloading system, hot gas bypass) for Dx cooling coils will ensure that the coil heat transfer performance is optimized and minimize the energy penalty associated with hot gas bypass operation.
Other Benefits	1. Proper commissioning and adjustment of the supply temperatures from the cooling process will ensure that adequate dehumidification is provided, thereby helping to ensure good IAQ. 2. Proper commissioning of the water make up and level control systems for evaporative cooling processes will help ensure that water consumption rates are commensurate with the cooling provided and that short circuiting of the evaporative section via the sump is prevented. 3. Proper commissioning of the refrigeration specialties and piping for a Dx coil will help ensure reliable and trouble free operation of the compressor.

8.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	The purpose of the cooling system test procedures will vary with the requirements of the system served. Regardless of the approach used, verifying the proper control sequence and integration into the overall air handling unit sequence and terminal equipment sequence is essential. In addition, capacity verification may be required. Tests targeted at verifying that the installed conditions will allow the coil to perform as intended may be more cost effective that tests targeted at documenting absolute capacity. For water/glycol based systems, testing will also be targeted at: 1. Verifying the stroke of the control valve to ensure that it closes completely. 2. In some instances, flushing and pressure testing the coil may be required. For evaporative systems, testing will also be targeted at: 1. Verifying the performance of the spray pumps and spray system. 2. Verifying the performance of the water quality control, level control and blow down system. 3. Verifying the operation and performance of any freeze protection equipment such as basin heaters, heat and heat trace. 4. Verifying the performance of any humidification process associated with the evaporative cooling process. For Dx systems, testing will also be targeted at: 1. Verifying the adjustment and performance of the refrigeration control devices such as the expansion valve, the hot gas bypass system, the compressor unloading system, the head pressure regulating system, etc. 2. Verifying the installation and proper connection of the refrigeration piping to the Dx coil including appropriate accessories like sight glasses, refrigerant dryers, service valves, solenoid valves, and wells for expansion bulbs and testing superheat. 3. Verifying the evacuation and subsequent charging of the refrigerant circuit.

Item	Comments
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard tool kit listed in the *Chapter 6: Functional Testing Basics*: 1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. This equipment can also be used to verify flow rates. 2. A stethoscope or similar sound sensitive device can be useful for listening for valve leakage sounds when verifying that the valve is fully closed. 3. For capacity testing, flow measuring equipment capable of measuring the flow of the cooling energy source to the necessary degree of accuracy will be required. 4. Evacuation verification of Dx coils prior to charging may require an absolute mercury manometer. 5. Verification of refrigerant charge requires an accurate scale. 6. Test equipment suitable for verifying water quality may be required to verify the performance of the water quality control system for evaporative cooling equipment.

Item	Comments
Test Conditions	1. Some of the tests associated with the cooling source serving the cooling element(s) can be accomplished prior to the completion of the air handling unit and terminal system(s). For example, pressure tests, flushing, some control valve shut-off test processes, make-up and blow down control tests, and cooling source flow tests can all be accomplished without air handling unit and terminal equipment operation. 2. Other tests, like discharge control loop testing and tuning, cooling element capacity control, and capacity testing will require that the air handling system and its terminal equipment be operational and capable of moving the design volume of air, but not necessarily fully under control. Safety systems should be operational to protect the machinery and occupants in the event of a problem during the test sequence. 3. Testing the integrated performance of the cooling element with the rest of the system will require that the individual components of the system be fully tested and ready for integrated testing. In many cases, the building or at least the portion of the building served by the system must be substantially complete and under load. 4. Simulating a real cooling load (both the sensible and latent components) in the field is a practical impossibility, which places a complication on performance tests. In most instances where capacity verification is required, it will be verified based on achieving a target dry bulb and wet bulb temperature depression below the current ambient conditions, or based on documenting coil performance under the given conditions and then modeling the coil under those same conditions. Preheat coils or reheat coils and humidifiers coupled with full recirculation may provide a method to approach simulating a design load condition, but these techniques are not without their difficulties and risks for the system and area served, especially tests that cause the indoor temperatures and relative humidity to be elevated significantly above normal. Limitations to testing include outdoor conditions at the time of test and conditions under which is it possible to operate the in the test mode. It may be possible to combine the cooling capacity test with capacity testing of other elements in the system like the preheat element. 5. As an alternative, it is possible to wait for near design conditions and perform the capacity test at that time. This approach is a more realistic test of the coil and also allows the control functions to be evaluated under more realistic conditions. However, it requires that the test process and instrumentation be prepared in advance and that the test team can respond quickly to reach the site and perform the test before the weather changes. This approach also requires that the load served by the system be able to deal with a potentially disruptive test process with little or no advanced warning. For the commissioning team, this test routine can be difficult if significant travel time is required to reach the test site. 6. Valve leakage tests and tests that are targeted at verifying valve stroke, spring range, and sequencing should be conducted with the pumping system operating at its peak differential pressure. The differential pressure across the valve plug can have a significant impact on the close-off rating and shift the operating spring range of the valve.

Item	Comments
Time Required to Test	1. Some of the simpler tests like and interlock test or a valve shut-off test can be accomplished in an hour or less with one or two people. 2. More complex tests like a capacity test can require several hours and several team members to set up and monitor all of the necessary functions, especially if multiple operating points are to be evaluated. This test can be complicated by the need to quickly travel to the site with short notice to run a test while ideal test conditions prevail. 3. Tests that require referencing back to a model require some time to either develop or support the development of the model that will be used to evaluate the coil's performance. If the modeling capability does not exist in-house, then it may be necessary to retain the coil manufacturer's services if the modeling requirement has not been included in the pricing package. 4. Field-testing to lab or factory standards is expensive and a practical impossibility in many instances. 5. Tests targeted at verifying refrigeration system evacuation prior to charging usually require that the system hold vacuum for a period of time ranging from 8 to 24 hours. If the test fails, then additional time will be required to allow for a repair and then a repeat of the test cycle. This process can be a significant cause of lost productive time and additional travel expense.
Acceptance Criteria	1. Control valve leakage testing should reveal no detectable leakage. Some of the larger globe valve designs, especially balanced double-seated designs, are not capable of complete and total shut-off. Most valves of this type have specifications for maximum leakage tolerances. Valves that are rated bubble tight should be capable of producing no detectable leakage when stroked fully closed. 2. The control element range should match the requirements of the control sequence and not overlap the range of other elements served by the same signal to prevent unintentional simultaneous heating and cooling. 3. Capacity tests results should be evaluated in the light of the accuracy of in instrumentation and the actual conditions at the time of the test. 4. The cooling element control should reliably integrate with the overall system control strategy in a manner that provides the intended level of performance with the minimum amount of energy consumption. 5. For Dx coils, the evacuation test should reveal no significant gain in pressure other than what can be attributed to ambient temperature change after the system has been evacuated. 6. For Dx systems: a. The expansion valve should be capable of maintaining the recommended level of superheat under all load conditions. b. The hot gas bypass control system should only function after the compressor system has unloaded to minimum capacity and there is no other way to maintain an active coil face without cycling the compressor off. c. The pump down cycle (typical on larger systems, but not

Item	Comments
	necessarily provided on small tonnage and fractional tonnage equipment) should allow the compressors to evacuate the evaporator coil prior to shut down. d. Sight glasses should be free of bubbles and of indications of moisture under all load conditions. e. For systems that must operate at low ambient temperatures, the head pressure control systems should demonstrate that it has been adjusted to ensure proper performance of the compressor and expansion valve.
Potential Problems and Cautions	1. In most states, a license is required to perform any work that might release refrigerant to the atmosphere. Fines and other penalties can be substantial. Therefore, if you are not certified for this work, you should either become certified or retain a certified technician to work with you for any testing that requires connecting to the refrigeration circuit. 2. Refrigerant that is accidentally discharged from a system can be a health hazard and suitable precautions should be taken when working around refrigerant piping that is under test. Potential problems include allergic reactions, asphyxiation, and freeze burns. 3. Poorly installed, operated, and maintained evaporative coolers can be a source of infection for Legionnaire's disease and other micro-biologically related effects like mold, mildew, spores, etc. When working around this type of system, suitable precautions should be taken to prevent inhalation and contact with equipment or materials that could contain spores or other disease carriers. Respirators, gloves, and eye protection may be desirable if there is evidence of mold, mildew, algae or other growth. This problem is more likely with existing systems that are being retro-commissioned rather than new equipment. 4. For Dx systems, crank case heaters should be activated and verified as recommended by the manufacturer prior to starting any compressors. (Usually, this is required for at least 24 hours prior to start-up.) 5. Testing should proceed in a logical sequence that verifies primary interlocks and safety systems prior to verifying more complex control processes, integrated control functions, and tuning loops. 6. Some test procedures, either by design or by failure of the element under test to perform as intended, can cause air handling system discharge temperatures to become significantly above or below normal, which can pose the following problems: a. Occupant discomfort. b. Disruption of the process served by the system and potential damage to product c. Where heating coils are used to simulate cooling load, they can cause inadvertent activation of fire dampers. See Section 13.5.2: Fire and Smoke Dampers, and Section 13.5.3: Air Hammer, under the discussion on fusible links. They can also cause inadvertent activation of heat detectors and rate of rise detectors and subsequent false fire alarm and building evacuation. Test plans should provide for these contingencies by taking steps such as

Item	Comments
	disabling key fire detection elements for the test and ensuring that fusible links have been selected to tolerate any temperature that can be produced in the system. 7. Overly rapid stroking of valves and dampers during a test process can cause air and water hammer problems in the duct and piping systems serving the cooling element. 8. Functionally testing an electrically driven refrigeration processes element during the winter months for buildings and systems equipped with electric heat can cause several significant problems including: a. Distribution system load conditions that exceed design and switch gear ratings can trigger trips in the primary switchgear resulting in unscheduled and unanticipated outages. b. Demand peaks well in excess of those that would normally be encountered during the normal operation of the building due to the demand that the coil places on the system concurrently with the refrigeration equipment. See the additional discussion on this topic in *Chapter 7: Preheat*. 9. Overly vigorous adjustment of the superheat on an expansion valve can cause liquid refrigerant to pass through the evaporator without being vaporized and damage the compressor. All superheat adjustments should be made gradually with time allowed for the effect of each adjustment to stabilize and by someone qualified to perform the adjustment. 10. Dx cooling controllers should be carefully inspected to ensure that there is no logic or setting that will rapidly cycle the compressor when the program is activated. Built-in interlocks in the refrigeration equipment should not be relied upon to offer this protection, although many systems include them. At initial start-up, it may be desirable to be prepared to respond to this type of problem to prevent damage to the compressor or its starter. Test sequences that subject the system to large volumes of untreated air should be avoided, especially if the system or area it serves has been subjected to conditions that could have lowered surface temperatures below the dew point of the outdoor air. For example, shutting down the cooling system on a 100% outdoor air unit after performing a capacity test that has cold soaked the duct and the area served by the system without shutting down the fan will most likely cause condensation in the duct and on the surfaces in the area if it is humid outside. Humid might be hot and humid as one might encounter in Florida, or it could be the conditions that exist on a rainy 60ºF day in the Pacific Northwest during the spring or fall. In both cases, the dew point of the outdoor air is probably below the surface temperature in the duct system down stream of the cooling coil and could even be below the surface temperatures in the zone served if the cooling capacity test has been running for a while. The resulting condensation could lead to IAQ problems and damage finishes, materials and supplies. 11. Evaporative cooling processes typically require that more attention be paid to the potential for freezing including taking note of the actual extremes temperatures seen at the site that exceed design conditions.

8.2.3. Design Issues Overview

Item	Comments
Do the cooling element design temperatures and configurations ensure adequate dehumidification under all operating modes?	Most cooling systems are intended to perform dehumidification in addition to sensible cooling. The dehumidification provided is highly dependent upon the leaving temperature condition from the cooling element. Misapplied discharge temperature reset sequences can raise supply temperatures to the point where adequate dehumidification is not provided. This can also occur if face and bypass dampers are used on the coiling coil without providing some means to control the cooling coil discharge temperature and ensure flow through the cooling coil to provide the desired dehumidification. Dx systems with limited turn down capacity and no hot gas bypass capability can also have problems with dehumidification during the portion of the operating cycle when the compressor is off while the fan remains in operation. It can be particularly troublesome if the compressor is significantly oversized for the load it served, either by design or by the current load condition.
Is the quality of the water supply for the evaporative cooling element suitable?	By their nature, evaporative cooling processes will accumulate the solids and other non-volatile elements inside of the equipment as the water evaporates. Water supplies with mineral content or other contaminates can lead to scaling and other problems that can make maintenance difficult, elevate the risk of harboring microorganisms in the equipment, and shorten equipment life. Special water treatment processes may be required to prevent these problems.
Are filters required for the direct evaporative cooling processes to ensure that the quality of the evaporative media and heat exchangers is not compromised by accumulations of dust washed out of the air stream?	By their nature, direct evaporative coolers will function as air washers, even if they have not been designed for this function. If this has not been provided for in the design of the cooling element, its performance and air flow through the air handling system can be rapidly compromised by an accumulation of dirt in the filter media and on the heat exchanger surfaces. Thus prefilters may be required, including an allowance in the fan system pressure specification to handle the added pressure drop, both clean and dirty.
Has the cooling element been protected from freezing?	Cooling elements that employ water must be protected from freezing. In many environments, this will mean that a freezestat must be provided at a minimum and that the operation of evaporative systems must be locked out so they are not inadvertently operated during freezing or subfreezing weather. Systems with large outdoor air fractions may require preheat and the decision as to whether or not to provide it should consider both the design conditions as well as the recorded seasonal extremes. Evaporative cooling systems may also require basin heaters, heat trace on the make-up, blow down and distribution piping, and isolation dampers to close off their inlet from the outdoors when the unit is not operating. The final step in protecting cooling elements from freezing is to include a well thought out commissioning process for the components that provide the protection.

Item	Comments
If the cooling element provides dehumidification, has it been configured prevent IAQ problems and water damage?	Draining the condensate from dehumidification associated with the cooling process frequently becomes a commissioning and operational problem. Key considerations to design for good drainage include: 1. Drain pans need to extend far enough past the cooling coil to ensure that they collect all of the condensate, including droplets carried off of the coil element under all operating conditions. 2. Tall cooling coils may require intermediate drain pans to prevent excessive carry-over from the lower portions of the cooling element under heavy dehumidification loads. The intermediate pan catches and removes condensate generated by the upper portions of the cooling element so that it does not have to flow over the lower portions of the cooling element to reach a drain pan. Minimizing the water flowing through the lower portions of the coil reduces the potential for carry-over. 3. Drain pans should be constructed to ensure that all accumulated condensate will flow to the drain line connection. 4. Corrosion resistant drain pan construction is highly desirable. Stainless steel has better corrosion resistance and is easier to clean than galvanized metal. Similar considerations also apply to coil frames and other metals use to fabricate cooling elements. 5. Drain pans should be insulated to prevent condensation problems associated with the temperature of the condensate itself. 6. For air handling equipment located above sensitive areas, consider providing a secondary drain pan and/or moisture alarms that will notify the operating staff of any overflow problems with the primary drain pan. A few extra dollars in first cost can have a quick pay back water damage from an overflowing drain pan is avoided. 7. While the drain pan's primary function is to remove condensate from a dehumidification process, it also provides a measure of protection from water damage in the event of a frozen coil. It may be desirable to take this aspect into consideration during the design and sizing of the drain lines serving the drain pan. 8. If the trap on the condensate drain is intended to provide protection from infiltration of untreated air into the unit (an important consideration on some process applications) then trap primers may be required to keep the traps full when dehumidification is not occurring. 9. Traps on rooftop equipment may be subject to failure due to freezing if not properly located or protected.

8.3. Typical Problems

The following problems are frequently encountered with cooling elements.

8.3.1. Condensate Drainage Issues

Most cooling processes dehumidify the air, which can generate considerable mounts of condensate. Thus, cooling elements that dehumidify have drain pans that drain this condensate away from the cooling element to prevent indoor air quality problems and water damage to the unit and the area located below the cooling coil. The design issues that lead to poor draining of condensate, a typical problem found during testing, are described below.

Since there is generally a pressure difference between the interior and the exterior of the unit, draining the condensate is not as convenient as simply making a hole in the bottom of the drain pan. Generally, a trap is required to ensure consistent drainage of condensate from the drain pan. Without the water seal provided by the trap, air flowing through the drain line into the unit can interfere with the drainage process and cause the drain pan to overflow, especially when there is a significant pressure difference between the inside and outside of the unit casing at the cooling element location.

Figure 8.1 illustrates the features of a typical trap applied to a draw-thru unit where the pressure at the cooling element location generally will be lower than the pressure outside of the casing. Figure 8.2 illustrates how this trap operates. Similar principles apply to traps on blow-through cooling elements except that the pressure at the cooling element will generally be higher than the pressure outside the unit and the location of the trap outlet relative to the connection to the drain pan needs to be adjusted accordingly.

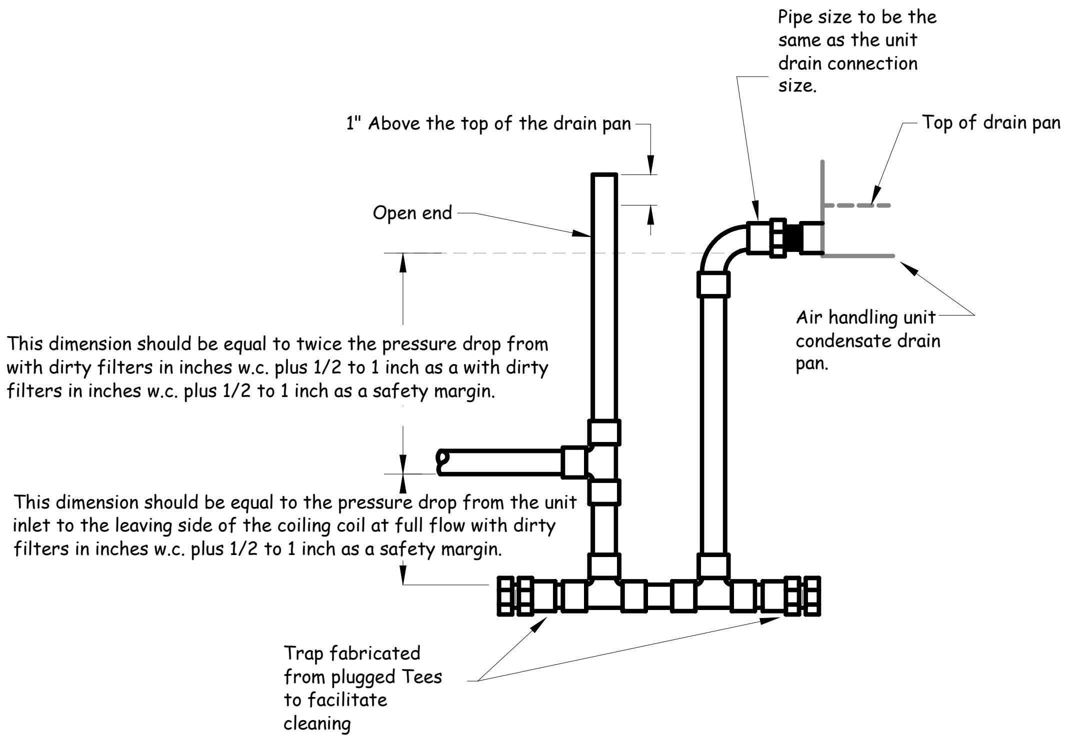


Figure 8.1 Typical Draw Through Air Handling Unit Drain Trap

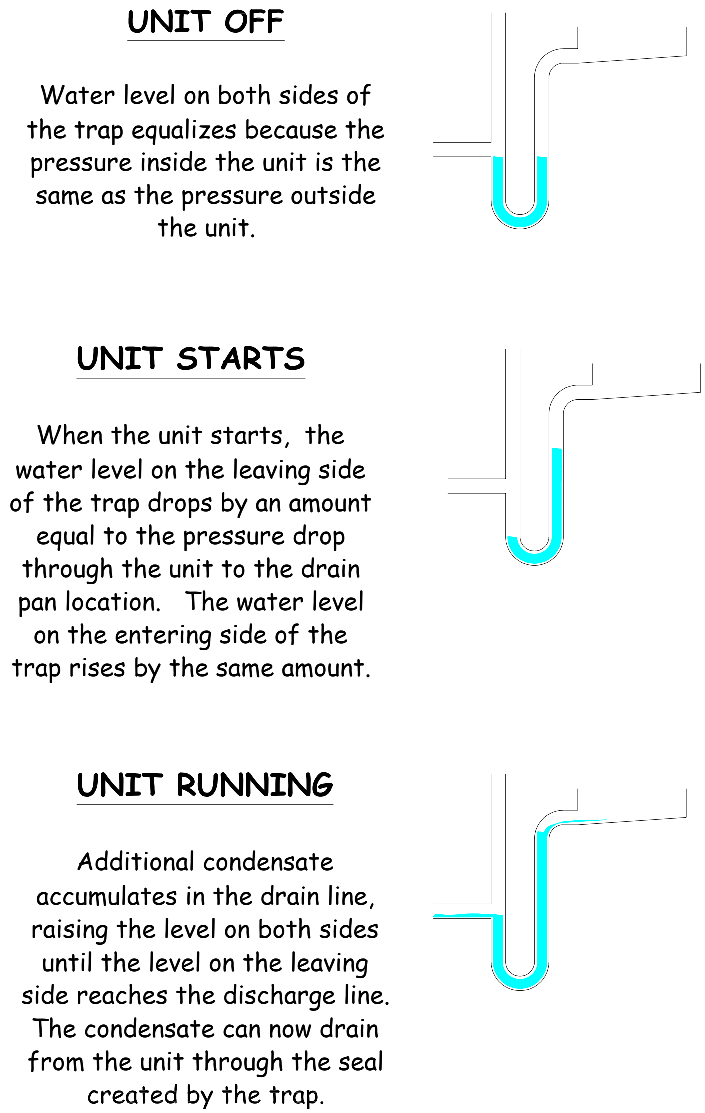


Figure 8.2 Draw Through Air Handling Unit Drain Trap Operation

Overflowing drain pans lead to a variety of short term and long term problems including:

- Water damage to the unit and the areas surrounding it.
- IAQ problems associated with standing water in undrained portions of the unit casing and moisture entrapment in the casing insulation materials.
- IAQ and water damage problems associated with water carried through the fan and blown into the discharge duct system.

At the beginning of the dehumidification cycle, the trap will be dry and reverse flow through the trap could potentially interfere with drainage until the trap becomes primed with condensate. In most instances, this will not be a problem because the dehumidification loads tend to be non-instantaneous in nature; i.e. a light load is initially encountered which allows the trap to prime despite reverse flow and without backing-up condensate in the drain pan.

If the trap is dry, then unfiltered, untreated air can flow into the unit in draw-through applications. In most commercial situations, this relatively small volume of untreated air is not a concern. But, the contamination introduced thought this pathway can cause contamination on systems with large drain outlets serving sensitive processes like a clean room. If the trap must provide a seal in addition to ensuring consistent drainage, then the design needs to be arranged to keep the traps primed and protect them from freezing.

8.3.2. Carry-over issues

When a cooling element is dehumidifying, it will tend to have a coating of water on the surfaces in contact with the source of cooling. Typically, these surfaces will also have air flowing past them. As a result, water droplets tend to be blown off of the element. The smaller droplets will evaporate and the larger droplets will fall from the air stream in a short distance. The condensate drain pan extends beyond the cooling element location to catch these drops as they fall out of the air stream. Where space constraints prevent an appropriate condensate drain pan extension, eliminators can be installed downstream of the coil to provide a surface to intercept and remove the droplets from the air stream. Using eliminators adds pressure drop and thus an energy penalty.

If the accumulation of water on the surface becomes too heavy or the airflow velocity becomes too high, water can be carried past the drain pan or even blown back off of the eliminators, resulting in water damage and IAQ problems. Conditions that can lead to carry-over include:

- **Excessive coil face velocities** Generally, the rule of thumb is to keep coil face velocities below 450 to 500 fpm both to prevent carry-over as well as to minimize the energy burden associated with the coil pressure drop.
- **Excessive dehumidification load** This condition can be created by coil entering conditions that are in excess of design or by operating the coil with a refrigerant temperature lower than design (usually reflected by chilled water that is colder than the design condition or a saturated evaporator pressure lower than design).
- **Poor condensate removal** If condensate is allowed to accumulate on the coil surface due to an inadequately arranged drainage system, then carry-over can occur. This typically happens with tall coils that are not provided with intermediate drain pans, if the drain lines from the intermediate pans become clogged or if the drain pans are not draining quickly enough.

8.3.3. Refrigeration piping and specialty issues

Unit erected refrigeration systems often encounter problems that are related to poorly configured and installed refrigeration-piping circuits. Often the design documents do not provide an adequate level of detail to describe the specialties required and the refrigerant related piping details necessary to ensure reliable performance. In addition to causing problems with cooling capacity, poorly executed piping systems can lead to compressor failures. Items to consider include:

- Expansion valve, distributor and capillary tube selection.
- Proper expansion valve equalizer line connection.
- Hot gas bypass selection and control.
- Liquid line solenoid valve selection and control.
- Pressure and temperature port requirements for proper set-up and adjustment.

- Service valve and isolation valve requirements to minimize refrigerant loss during procedures that open the piping circuit.
- Subcooling requirements.
- Head pressure control during low ambient operation.
- Suction line traps on systems with significant elevation changes between the evaporator and condenser.
- Double suction riser design for systems that can vary capacity via unloading systems.
- Refrigerant dryer selection and provisions for service.

Whether factory or field installed, there are specialty devices in most refrigeration systems that require some attention during start-up.

- Proper superheat adjustment.
- Proper hot gas bypass adjustment.
- Proper head pressure regulator adjustment.
- Proper charge.
- Refrigerant system cleanliness and freedom from moisture.
- Adequate provisions for monitoring and checking all of these parameters.

The *ASHRAE Refrigeration Handbook* as well as the Trane Company's *Refrigeration Handbook* are excellent resources for further detail.

8.3.4. Dehumidification control

The energy and comfort implications of inadequate humidity control are significant for commercial office buildings. Producing very cold conditions off the cooling element will dehumidify the air, whether it is required or not. Examples include low temperature air applications and efforts to provide additional sensible cooling due to the inability to meet the current load. The extra dehumidification causes the process to use more energy than is necessary. There is a direct energy impact due to the extra moisture that is condensed as well as an indirect energy impact, since the higher condensate burden will also increase the coil pressure drop. Supplying low temperature air will often result in a building with a relative humidity 10 to 30% lower than required, which works against the low temperature air fan energy savings. Carry-over of this extra condensate can also become a problem.

Processes that result in elevated leaving air temperatures can provide less dehumidification than is necessary. For example, reset schedules may elevate the discharge air temperature in an effort to save energy without limits for humidity control. Additionally, processes that control the cooling element directly from space temperature can lose control of humidity, especially when coupled with high outdoor air loads. These examples can become particularly troublesome in humid environments where the sensible load in the area served is relatively low while the outdoor air requirements are relatively high. At a minimum, the lack of dehumidification can cause comfort and product quality problems, but can frequently lead to IAQ problems in the system and in the building envelope.

8.3.5. Evaporative cooling issues

Evaporative cooling processes are inherently air washing processes. If inadequate filtration is provided, the media on an evaporative cooling unit that has not been designed to function as an air washer can quickly become fouled, leading to cooling and airflow capacity problems as well the potential for IAQ concerns. Most direct evaporative coolers rely on the sump water level to provide a seal at the bottom of the evaporative cooling section. If the water level is not properly controlled, air can bypass the cooling process by flowing under the media through the sump, resulting in loss of performance. If the water level is allowed to remain in continuous contact with the media, problems with slime and algae can occur.

Regardless of the exact approach used, maintenance is an important consideration for any evaporative cooling process. Issues to consider include:

- **Inspection requirements** Usually evaporative equipment will require more frequent inspection at the air handling unit location as compared to a Dx or chilled water cooling coil. Most of this effort will be targeted at the water distribution equipment and ensuring it is thoroughly wetting the media, that the system is generally free of scale and debris, and that the water level control system is functioning properly. Water levels that are too high can cause problems with the wetted media and water levels that are too low can cause air to short-circuit around the evaporative cooling section.
- **Scaling** The high evaporation rate associated with this process can easily lead to scale problems. Scale needs to be detected and removed from the system when it shows up to ensure good performance, equipment longevity, and minimize the potential for micro-biological growth, particularly Legionnaire's Disease. Spray nozzle performance and thus system performance can be significantly degraded by scale or erosion at the nozzle.
- **Bleed rate, make-up, and general water quality** Proper adjustment of these parameters is essential to prevent problems with scale and performance. Water treatment cannot be as freely applied in direct evaporative cooling systems since the water and air stream are in intimate contact. Thus algae and scale control are far more dependent on the quality of the water supply, indirect controls, and inspection. This can be particularly important in controlling the potential for Legionnaire's Disease. Any water treatment chemicals that are use must be registered for use with evaporative coolers with an appropriate agency such as the US EPA.

8.4. Non-Copyrighted Tests

The CTPL contains the following tests that have some component that focuses on cooling or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

Air Handler Test (Seattle City Light)

Link to an Air Handler Functional Test, as prepared for Seattle City Light by Mike Kaplan.

Air Handler Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

AHU Functional Test (CES Guidelines)

Link to an Air Handler Functional Test as prepared for PG&E by Bill Malek and Bryan Caluwe in the *Comprehensive Commissioning Services Guideline*.

8.5. Supplemental Information

Supplemental information has not been developed at this time for the cooling section. Link to the plans for future development of supplemental information that will be useful to solve many problems typically identified during commissioning and design review.

Chapter 8 Future Development

Chapter 9: Humidification

9.1. Theory and Applications

Active humidification systems are complex, expensive to operate, and maintenance intensive, so these systems are seldom employed unless they are essential. Eliminating unnecessary humidification systems can yield substantial benefits. Active humidification is an energy intensive process that can also create moisture problems if not properly designed, installed and implemented. Thus, the commissioning of these systems can be critical to their success.

Humidification systems are typically applied to health care facilities and process environments. A health care application in an arid environment may actually require humidification for some areas even during the summer months when HVAC processes in most environments would be dehumidifying. In the past, computer facilities also were prime candidates for humidification to ensure that equipment was free from static electricity, thereby eliminating problems associated with electrostatic attraction. Current computer technology has largely eliminated this need, but it is a good idea to review the computer equipment manufacturer's requirements.

Once the decision to actively humidify is made, the method of providing it will need to be evaluated. Methods for humidification include:

- Direct or indirect steam injection
- Evaporative approaches
- Compressed air driven
- Ultrasonic
- Air washers
- Sprayed coils

Ultrasonic humidification is a new technology that has the potential to provide humidification for a fraction of the energy cost associated with some of the more traditional systems. Regardless of the method of providing the humidification, it is critical that the humidified area be properly designed for the environment that will be produced. In most instances, these considerations will need to be applied to all portions of the building that can directly interact with the humidified area. Successful operation of most humidification systems is highly dependent on the control system serving it. Key considerations include the sensing technology employed and the safety and operational interlocks provided.

Another important consideration for any humidification application is that adequate absorption distance be provided downstream of the humidifier. This ensures that all of the water added to the air by the humidification process is fully vaporized before it encounters any surfaces upon which moisture droplets could impinge.

When considering humidification, it is important to remember that the measurements are frequently made in terms of *relative* humidity, the vapor content of the air relative to what it could hold *at the current drybulb temperature*. For example, air that is saturated at 55ºF (100% relative humidity) will have a relative humidity of 50% when heated to 75ºF. The specific humidity and dew point of the air are unchanged. Thus, if an air handling system was serving an area by supplying 55º air and the area was to be maintained at a relative humidity of 50%+/-5%, it would be necessary to deliver air at or near saturation at the discharge of the unit. While easy and nearly impossible to avoid the saturated discharge condition when in a cooling cycle where moisture is being extracted from the air by passing it over a condensing cooling coil, it can be difficult to achieve it in a humidification cycle where moisture is added to the air stream via active humidification.

9.2. Commissioning the Humidification System

The following tables outline the benefits and background information associated with testing humidification systems. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

The third table, Section 9.2.3 Design Issues Overview, presents issues that can be addressed during the design phase to improve system performance, safety, and energy efficiency. These design issues are essential for commissioning providers to understand even if design phase commissioning is not a part of their scope, since these issues are often the root cause of problems identified during testing.

9.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	Humidification processes tend to be energy intensive. The obvious costs are in the direct energy and water consumed to vaporize liquid water into the air stream. The parasitic burdens associated with the jacket heating systems used by direct and indirect steam injection systems may lead to significant energy costs. The 2 to 4ºF temperature rise in the HVAC air stream serves no useful purpose when humidification is not required. In addition to representing unnecessary heating energy consumption, this temperature rise often represents a load on the chiller plant. The parasitic loads associated with keeping a steam distribution system active to serve a humidifier can also be significant, especially in situations when there are no other requirements for steam. Thorough commissioning of the humidification system will help ensure that humidification is only being provided to the extent necessary and that the parasitic loads are eliminated or minimized when humidification is not required.
Other Benefits	In addition to using unnecessary energy, excessive humidification wastes water and water treatment resources. Poorly implemented, misapplied, or out of calibration control systems can cause operational problems ranging from poor humidity control to “rain” out of the duct system. These problems results in costs to the Owner due to reduced employee comfort and productivity, increased production problems, product quality control problems, IAQ problems, surgical procedure and infection control problems, and damage to building components and systems. Proper commissioning can minimize or prevent these adverse impacts.

9.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	Humidification system functional testing is generally targeted at the following areas: 1. Verification of system performance and capacity. 2. Verification of operational interlocks. 3. Verification of safety interlocks.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will typically be available in the standard tool kit listed in *Chapter 2: Functional Testing Basics*. For applications where humidity levels must be precisely controlled, a precision hygrometer may be necessary to verify performance.
Test Conditions	In most instances, the humidification element will need to be in place to verify the functionality of the control, safety and interlock systems although it may be possible to verify some of the operational and safety interlocks without actually operating the humidifier. Verification of the capacity control and performance of the system will require operating under a variety of load conditions. Humidification loads can be very difficult to simulate, thus testing of the system will need to occur under conditions where humidification is actually required. Test the system under low load as well as peak load conditions. It is not uncommon for a system that has been tuned to perform satisfactorily at design or near design conditions to have problems operating at low loads. As a result, multiple site visits spread out over the course of the first operating year should be anticipated when commissioning humidification systems.
Time Required to Test	Operational and safety interlock tests can often be accomplished in an hour or less. Tests targeted at verification of the capacity control system and overall system performance often require observation over the course of a day or more with hour long periods of relatively intense activity interspersed with periods of low activity where monitoring of the system performance is the primary function. Often, this type of testing can be coordinated with other tests. Multiple site visits to test under actual load conditions (both design and low load) can be costly, especially if there are no other tests to be performed concurrently and/or the site location requires travel time. For example, if a project is started up and commissioned during the summer months, it is likely one or two additional trips will be required to the site during the fall and winter months to properly commission the humidification system. If there are no other tests or observations to be made while at the site, then the commissioning provider's productivity may be low during portions of the test cycle where the response and performance of the system is simply observed.
Acceptance Criteria	Acceptance criteria for the various humidification system tests will vary with the test performed. In general, the equipment and systems need to meet the requirements of the design intent as documented on the construction documents. Safety interlocks should shut down the

	humidification process when they are tripped. Operational interlocks should shut down the humidification process when conditions are not appropriate for humidification. Capacity control systems should be able to match the performance of the system to the current load condition when operating at design as well as low load. The capacity control system should also remain in control of the process during the sudden load changes associated with start-up and shut down without tripping limit controls or experiencing operational problems like "rain" from the ducts.
Potential Problems and Cautions	The excess moisture injected into an HVAC system by an out of control humidification process can quickly lead to significant water damage. Caution should be exercised when subjecting the system to test conditions that could result in loss of control of the humidification process. Examples of these test conditions include step changes like start-ups, major set point changes or shut downs, as well as functional tests of the limit control systems in which the capacity control system is overridden to create the actual limit situation. It is a good idea to station personnel in the vicinity of the humidifier who are trained and prepared to manually shut down the humidification process. If the humidifier equipped HVAC system is started up and commissioned during a period of time when the humidification system is not required, then it may be best to lock-out/valve out the humidifier until suitable conditions exist to allow it to be commissioned under load. An active but untested and untuned humidifier can quickly cause problems when it begins operating for the first time without any formal commissioning.

9.2.3. Design Issues Overview

Issue	Comments
Is the building designed to support a humidified environment?	Surface temperatures of walls, windows, ducts, piping, and equipment in the humidified environment all need to be considered in light of the ambient dew point when the humidification system is active to avoid condensation problems. The location of vapor barriers also becomes an important consideration. Failure to take these issues into account can result in significant performance problems and IAQ concerns.
Are areas adjacent to the zone that is actively humidified designed as if they were humidified environments?	The difference in vapor pressure between the humidified zone and the non-humidified zone will cause vapor to migrate from the area that is actively humidified to the other areas in the building regardless of their need for humidification. Thus, the humidity level in all areas of a building with humidified zones will tend to be elevated even if humidity is not actively controlled at all locations.
Do the design conditions for the system reflect the true, worst case situation for the location?	Since maintaining the required humidity level is critical for many projects with active humidification systems, it is wise to look at the performance of the systems on the worst-case days, not just the design days.
Is the sensing technology employed appropriate for the requirements of the load served?	The sensing technology used by humidification control systems is not as robust or accurate as the more familiar temperature and pressure sensing technology encountered in HVAC systems. The newer technologies have made significant improvements over what was available a decade ago, but high levels of accuracy (+/-3% or better) are expensive and maintenance intensive.
Have appropriate safety interlocks been provided?	Operating a humidifier without air flow can cause significant damage to the air handling equipment and area served in the form of condensed moisture and “rain” out of the duct system. Operating without an adequate water level for electrically motivated evaporative systems can ruin the humidifier. The lack of robustness in some control technologies makes high limit controls an important consideration in many applications.
Have appropriate operational interlocks been provided?	Steam injection technologies require a warm-up cycle to ensure that steam, not large water droplets, is injected into the air stream. This technology also requires control to shut down the jacket heating system when humidification is not required to eliminate an unnecessary temperature rise and related energy waste. Evaporative technologies require reliable, well-maintained make up and blow down and may also require some sort of treatment for the make up water to prevent excessive scaling.
Is the physical configuration of the system in the area of the humidifier appropriate?	To successfully add moisture to the air stream of an HVAC process without causing water damage to the system or area served, the physical configuration of the system at the humidifier location must be properly configured. The airflow over the humidification element should be uniform and at a relatively low velocity. Adequate distance should be provided downstream of the humidification element for the moisture that has been added to become completely vaporized. As a general rule, the lower the velocity of the air stream, the lower the absorption distance requirement becomes for complete vaporization of the moisture injected by the humidifier. Most systems providing a high relative humidity level in the occupied zone

will require generating nearly saturated air at the discharge of an air handling system that is providing air at or below the space sensible temperature; i.e an air handling system providing a cooling process. In extreme cases, it may be necessary to reheat the air prior to the humidification process to enable the desired relative humidity level to be generated in the area served.

9.3. Non-Copyrighted Tests

No functional tests specific to humidification systems are currently available in the Commissioning Test Protocol Library. Several functional tests for humidification have been identified for future development, and may be included in later versions of the Guide.

Humidification Tests for Future Development

9.4. Supplemental Information

Link to the plans for future development of supplemental information that will be useful in solving problems identified during commissioning and design review.

Chapter 9 Future Development

Chapter 9: Tests for Future Development

Humidification Tests for Future Development

- Scoping study cross check vs. cooling coil
- Air flow interlock test
- Limit control test
- Outdoor air interlocks test
- Jacket heater interlocks test
- Make-up and blow down test
- Operational test
- Capacity test
- Sequencing test

Chapter 10: Reheat

Figures

Tables

10.1. Theory and Applications

Reheat is one of the many processes that can be provided by a heat transfer element in an HVAC air handling process. Not all heating coils are reheat coils due to their location in the system, their method of control, and the way they are connected to the source of heat (to prevent freezing). In contrast to preheat elements which are located before the air handlers cooling coil, heating elements that are located downstream of the air handling system's cooling coils are referred to as being in the reheat position. *Chapter 7: Preheat* includes a summary table comparing the various operations that place heat in an air handling unit's air stream. Commissioning efforts during design and construction, as well as retrocommissioning efforts for existing buildings, have great potential to save energy at the cooling plant, at the heating plant, and at the air handling unit due to improved reheat.

The reheat process is employed when the discharge temperature required to dehumidify an air stream results in air that will overcool the area when delivered in the required volume. Therefore, reheat is required to maintain space temperature control. The reheat process allows for precise control of relative humidity levels, but since reheat processes involve simultaneous heating and cooling, they are especially energy intensive. As a result, many building codes and efficiency standards limit or prohibit the use of reheat for some applications. However, there are situations where the process is unavoidable if the required space conditions are to be maintained. Common examples include:

- **Surgeries, Labor and Delivery Rooms, and other Health Care Applications** Air flow rates, temperature, and humidity specifications are often determined in a health care facility by hospital code and licensing requirements.
- **Laboratories** The need for large exhaust quantities leads to the need for large make-up air quantities in laboratories. In the summer, this make up air must be cooled sufficiently to dehumidify, then reheated for space temperature control.
- **Clean Rooms** Semiconductor manufacturing, pharmaceuticals, and advanced technology fabrication areas frequently face challenges presented by high air change rates set by cleanliness requirements and high exhaust rates set by safety requirements. As a result, the reheat loads for these types of facilities can be significant.
- **Loads with High Ventilation Requirements and Relatively Low Cooling Requirements** This category of reheat load is the most common one encountered in commercial buildings. Conference rooms, theaters, auditoriums, and other large places of assembly are particularly prone to requiring reheat when loads are low. But, office zones can also need reheat, especially where one zone serves a lightly loaded common office space.

Surgeries are good examples of why reheat is necessary in some applications. Table 10.1 illustrates ASHRAE recommendations for surgeries, which are typical of the requirements that are found in many hospital licensing standards.

Table 10.1 ASHRAE Surgery HVAC Requirements

Item	Requirement
Total air change rate	25 per hour[2]
Outdoor air change rate	5 per hour
Design temperature capability[1]	Capable of maintaining 62 to 80ºF
Minimum humidity level	45% relative humidity
Maximum humidity level	55% relative humidity

1. The system needs to be capable of maintaining any temperature with-in the specified range. The surgeon usually determines the set based on the procedure or personal preference.
2. As a frame of reference, most office building loads can be satisfied with 6 to 10 air changes.

Figure 10.1 illustrates a psychrometric analysis of the requirements in Table 1. Since the space temperature set point is determined by the requirements of the procedure and preference of the surgical team, system serving more than one operating room during the summer months (when there is a dehumidifying requirement) may need to provide the cooling coil discharge air temperatures for the 62º room while simultaneously serving the 80º room. With a typical summer (dehumidifying) design relative humidity level of 50%, the supply temperature for a typical office with a normal latent load will be in the 54 to 56ºF range. However, achieving the lower humidity requirements for a surgery will require a much colder discharge temperature at the cooling coil to ensure adequate dehumidification, as can be seen in Figure 10.1. Since the airflow rate cannot be varied and is relatively high, the high temperature room will require a significant amount of reheat to keep from overcooling. In fact, at the high air change rates required by the licensing standards, even the low temperature room may require some reheat if there are minimal internal gains to the space.

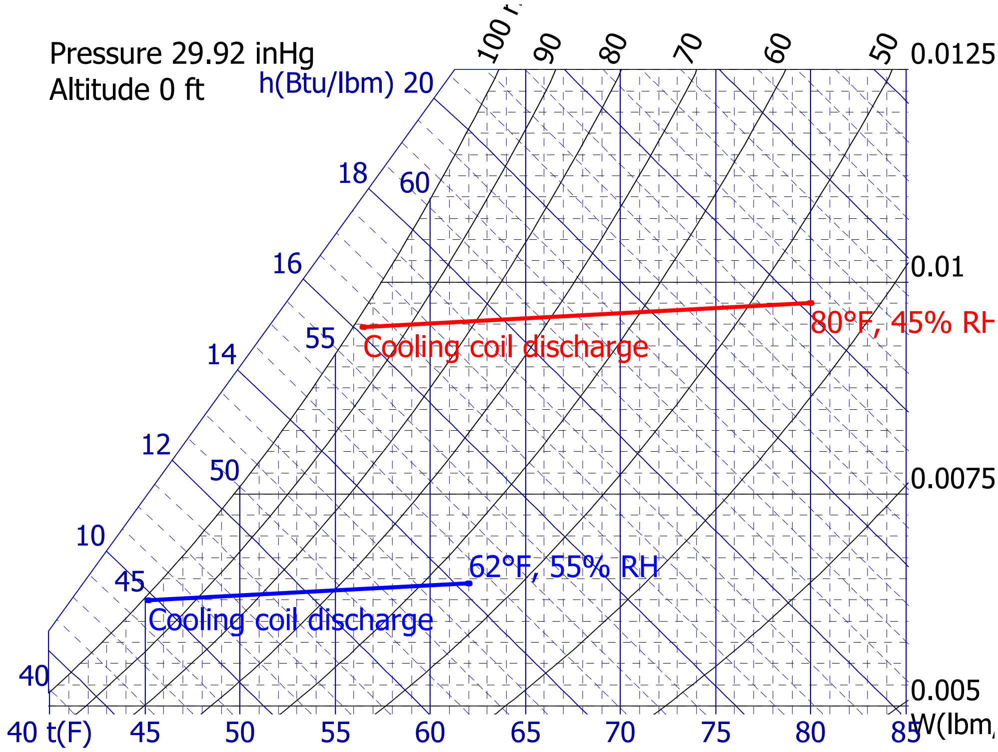


Figure 10.1 Cooling coil discharge conditions necessary to meet the two extremes in the ASHRAE surgery HVAC requirements

In industrial and health care applications, it is not uncommon for the reheat coil to be located in the central air-handling unit with supplemental coils provided at the terminal location. In commercial buildings, reheat is nearly always provided at the terminal location. The primary exception to this is for systems serving theaters and places of assembly.

When reheat coils are located at the terminal equipment location, there is a very subtle but important point to recognize. For all air systems, reheat coils serving perimeter zones will frequently provide space heating in addition to the reheat function. In the winter months, when there is a net loss of heat from the space, the coils must first reheat the air from the supply temperature to the space temperature to offset unnecessary cooling. Then the coils must heat the supply air to a level above the space temperature to make up for the losses from the space.

When the internal heat gains begin to exceed the losses through the building envelope (and for interior zones year round) the reheat coil heats the supply air to the room temperature or less[1]. Although we think of this as a "summer" operating mode, the transition point for many buildings is at a temperature much lower than what would traditionally be called summer. Figure 10.2 illustrates that the transition point to using reheat is above 50°F.

The difference in perimeter and internal load requirements over the course of a year is a good argument for segregating perimeter zones from interior zones so they can be served by different air handling systems. Doing this will allow the perimeter air handling system

[1] If there are not heat losses from the space and only the potential for internal heat gains, then if all of the internal gains are off (lights, computers, office equipment) or not present (occupants) then delivering air at the space temperature would be the only way to maintain space temperature. Of course, if this is the case, then you may want to consider a way to simply shut down the zone and save the fan energy in addition to the reheat energy. The one exception to this is for a warm-up cycle, where elevated supply temperatures may bring a space up to occupied temperature more quickly.

supply temperature to be reset to a much greater extent during winter months. Concurrently, the supply temperature for the system serving interior zones can be maintained at a lower level to ensure that their temperature needs, which are relatively immune to the outdoor environment, are met.

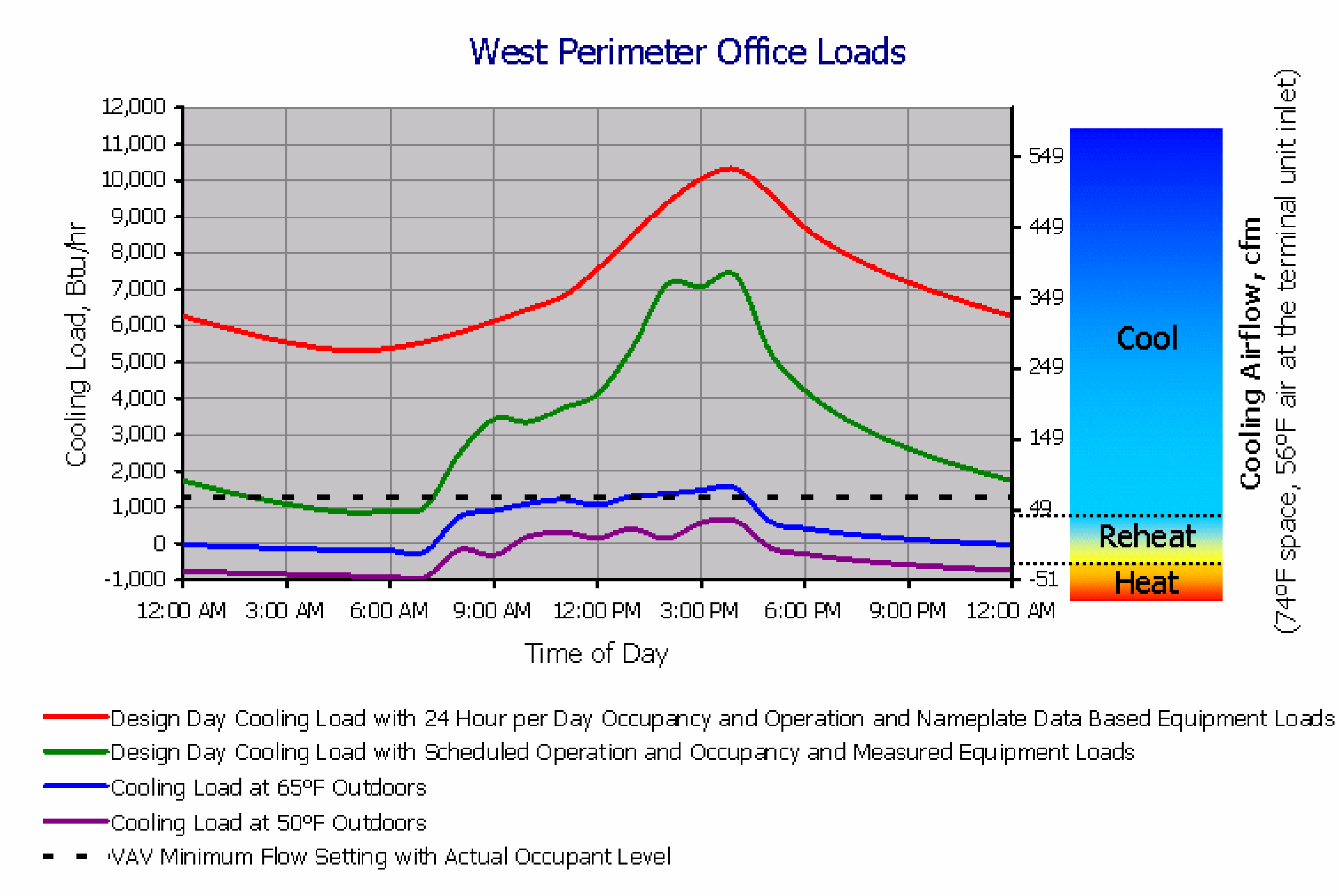


Figure 10.2 Load Conditions for a Perimeter Office

Figure 10.2 compares load conditions for a typical 120 square foot office. Note the difference between the “design” cooling load, which assumes everything operates at name plate, 24 hours per day with full occupancy at all hours, and the actual peak cooling load. Also note that any time the zone flow demand is less than the minimum flow setting required for ventilation (black horizontal line), the zone will be operating at this constant minimum air volume with reheat. For example, the zone transitions from a net heating load to a cooling load at about 50°F (the purple line crosses 0 Btu/hr at about 10 am). While this zone is a net cooling load, it requires reheat since the minimum airflow for ventilation delivers more cooling than the zone requires. This extra cooling is reheated away until the cooling load in the zone exceeds the cooling delivered by the minimum airflow. Therefore, between 50°F and 65°F outdoor temperatures, the zone is in reheat mode assuming the 56F inlet temperature to the terminal unit is necessary for other zones with cooling loads. When outdoor temperatures are above 65ºF, the zone no longer requires reheat. Notice that the minimum flow setting is critical in determining the required reheat.

Where reheat loads are inevitable and significant, they can often be served relatively easily with recovered energy via low temperature hot water. Many times the heat that would otherwise be thrown away in the cooling towers can provide the necessary energy for reheat during summer and moderate weather. For additional information, see *Making Energy Intensive HVAC Processes More Sustainable via Low Temperature Heat Recovery* from the proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings.

10.2. Commissioning Reheat Equipment

The following tables outline the benefits and background information associated with testing reheat systems. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

The third table, *Design Issues Overview*, presents issues that can be addressed during the design phase to improve system performance, safety, and energy efficiency. These design issues are essential for commissioning providers to understand even if design phase commissioning is not a part of their scope, since these issues are often the root cause of problems identified during testing.

10.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. For central system reheat coils, ensuring proper sequencing with the other heat transfer elements in the air handling system will minimize reheat, thereby saving both heating and cooling energy. 2. For terminal equipment reheat coils, ensuring that the minimum flow rate on the terminal unit reflects the actual occupant load rather than a design value based on the number of seats or some other criteria will lead to greater VAV turn down and minimize reheat thereby saving heating energy, cooling energy and fan energy. See Figure 10.3 for an illustration. 3. Verifying that reheat control valves close off completely helps ensure that simultaneous heating and cooling do not occur unless reheat is truly necessary. 4. Addressing reheat valve close off also ensures that there will be not ripple affects associated with pumping extra cooling and heating water through the distribution network due to the unnecessary heating medium leakage and the effort made by the cooling system to offset it. 5. Optimizing discharge temperature reset schedules to maximize discharge temperatures within the constraints of dehumidification and zone cooling requirements will minimize the reheat burden. 6. Optimizing discharge temperature reset also ensures that there will not be ripple effects in the air handling system and its supporting utility systems caused by the parasitic load.
Other Benefits	1. Properly coordinated and applied reheat will prevent problems with indoor air quality due to inadequate dehumidification. 2. In health care applications, properly coordinated and applied reheat will help ensure patient health and comfort and compliance with governing regulations related to licensing requirements. 3. In laboratory and process applications, properly coordinated and applied reheat will ensure worker safety and product quality.

10.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	The purpose of the test procedure used with the reheat element will vary with the requirements of the system served. In general, testing will be targeted at: 1. Verifying the proper control sequence and integration of that sequence into the air handling unit sequence and terminal equipment sequence. 2. Verifying the stroke of the control valve to ensure that they close completely. 3. In some instances, flushing and pressure testing of the coil may be required. 4. In some instances, verifying the coil capacity may be required. Tests targeted at verifying that the installed conditions will allow the coil to perform as intended may prove to be more cost effective that tests targeted at documenting absolute capacity.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard tool kit listed in the *Chapter 2: Functional Testing Basics*: 1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. This equipment can also be used to verify flow rates. 2. A stethoscope or similar sound sensitive device can be useful for listening for valve leakage sounds when verifying that the valve is fully closed. 3. For capacity testing, flow measuring equipment capable of measuring the flow of the heating energy source to the necessary degree of accuracy will be required.
Test Conditions	1. Some testing of the heating source that serves the reheat element(s) can be accomplished prior to the completion of the air handling unit and terminal system. For example, pressure tests, flushing, some control valve shut-off test processes, and heating source flow tests can all be accomplished without air handling unit and terminal equipment operation. 2. Other tests, like discharge control loop testing and tuning, VAV sequence testing and tuning, and capacity testing will require that the air handling system and its terminal equipment be operational and capable of moving the design volume of air, but not necessarily fully under control. Safety systems should be operational to protect the machinery and occupants in the event of a problem during the test sequence. 3. Testing the integrated performance of the reheat element with the rest of the system will require that the individual components of the system be fully tested and ready for integrated testing. To truly test integrated performance, the building or at least the portion of the building served by the system should be substantially complete and under load. 4. Simulating a full reheat load in the field is typically possible under most outdoor ambient conditions by manipulating the other elements of

Item	Comments
	the air handling system as necessary to produce the required flow rates and entering air conditions at the reheat element. Often, this condition can be coordinated with a simultaneous load test of other elements in the unit such as the preheat or the cooling systems although the sensible and latent components of the load may not be correct for a true cooling capacity test. 5. Valve leakage tests and tests that are targeted at verifying valve stroke, spring range, and sequencing should be conducted with the pumping system operating at its peak differential pressure. The differential pressure across the valve plug can have a significant impact on the close-off rating and shift the operating spring range of the valve.
Time Required to Test	1. Some of the simpler tests like an interlock test or a valve shut-off test can be accomplished in an hour or less with one or two people. 2. More complex tests like a capacity test can require several hours and several team members to set up and monitor all of the necessary functions, especially if multiple operating points are to be evaluated. 3. Tests that require referencing back to a model require some time to either develop or support the development of the model that will be used to evaluate the coil's performance. If the modeling capability does not exist in-house, then it may be necessary to retain the coil manufacturer's services if the modeling requirement has not been included in the pricing package. 4. Field-testing to lab or factory standards is expensive and a practical impossibility in many instances.
Acceptance Criteria	1. Control valve leakage testing should reveal no detectable leakage. Some of the larger globe valve designs, especially balanced double-seated designs, are not capable of complete and total shut-off. Most valves of this type have specifications for maximum leakage tolerances. Valves that are rated bubble tight should be capable of producing no detectable leakage when stroked fully closed. 2. To prevent unintentional simultaneous heating and cooling, the reheat control valve range should match the requirements of the control sequence and not overlap the range of any other elements served by the same signal. 3. Capacity tests results should be evaluated in the light of the accuracy of instrumentation and the actual conditions at the time of the test. 4. The reheat element control should repeatedly and reliably integrate with the overall system control strategy in a manner that provides the intended function with the minimum amount of energy consumption possible. Given that the process is a reheat process, it will, by definition, simultaneously heat and cool. The goal of the design and performance tests should be to ensure that this occurs only when necessary.
Potential Problems and Cautions	1. It is important that the design and test plan recognize the difference between preheat, reheat, heating and warm-up elements and functions. This is discussed in detail in *Chapter 7: Preheat*. By nature of its location, a reheat coil cannot protect the system from damage due to subfreezing air. In fact, a reheat coil may not in fact be able to deal safely with subfreezing air and may require protection of its own in

Item	Comments
	environments where such exposure could occur. 2. Some test procedures, either by design or by failure of the element under test to perform as intended, can cause air handling system discharge temperatures to become significantly elevated above normal. These high discharge temperatures can pose the following problems: a. Occupant discomfort. b. Disruption of the process served by the system and potential damage to product c. Inadvertent activation of fire dampers. See Section 13.5.2: Fire and Smoke Dampers, and Section 13.5.3: Air Hammer, under the discussion on fusible links. d. Inadvertent activation of heat detectors and rate of rise detectors and subsequent false fire alarm and building evacuation. Test plans should provide for these contingencies by taking steps such as disabling key fire detection elements for the test and ensuring that fusible links have been selected to tolerate any temperature that can be produced in the system. 3. Overly rapid stroking of valves and dampers during a test process can cause air, water, and steam hammer problems in the duct and piping systems serving the preheat element. 4. Functionally testing an electric reheat element during the summer months while the cooling plant is in operation can cause several significant problems including: a. Distribution system load conditions that exceed design and switch gear ratings can trigger trips in the primary switchgear resulting in unscheduled and unanticipated outages. b. Demand peaks well in excess of those that would normally be encountered during the normal operation of the building due to the demand that the reheat coil places on the system concurrently with the refrigeration equipment. See *Chapter 7: Preheat, Potential Problems and Cautions* for more discussion of demand peaks.

10.2.3. Design Issues Overview

Issue	Comments
Is the operation of the reheat element properly integrated with the terminal and air handling unit control sequences?	Reheat, by its nature is an energy intensive process. To minimize this intensity, it is essential that the operation of any reheat elements be fully integrated into the operation of the terminal equipment and fan system. Integration requires making sure that the minimum flow setting is appropriate to the load served. The sequence should be arranged to ensure that reheat only occurs under minimum flow conditions. See Figure 10.3 for an illustration. Increasing the air flow rate while reheating will often work against the intended heating effect as can be seen from Figure 10.4.
Is the design robust enough to allow the system and its components to be tuned to different, less than design load variations encountered in the field, thereby minimizing reheat and fan energy requirements?	The side bar in Section 10.3 Typical Problems illustrates how important providing a robust flexible design can be when this design is coupled with proper tuning in the field. Providing a system that has flexible capacity beyond the current requirements may be a desirable feature, but failing to tune the minimum zone flow to match the current loads it serves can waste a lot of energy.
Has the design taken all possible steps to minimize the reheat load while meeting the needs of the process?	Minimizing the load is a good first step in any design process, but it can have double or triple savings implications in reheat systems. Not only is heating energy eliminated, cooling energy during the summer months is also impacted. Both of these savings can show up as lower pumping distribution energy requirements. Finally, lower reheat loads often go hand in hand with lower flow rates and thus less fan energy.
Have efforts to minimize the reheat load compromised the ability of the air handling system to properly dehumidify?	It is important not to get carried away with reheat savings. As Einstein once said "Everything should be made a simple as possible, but not simpler." Similarly, the reheat load should be made as small as possible, but no smaller. Elevating cooling coil discharge temperatures too much can result in inadequate dehumidification, which can lead to poor IAQ, reduced comfort, and loss of product, especially in hot and humid environments.
Does the reheat load lend itself to being met by recovered energy that is otherwise being discarded on the site?	Many times, a little creative thinking will reveal ways to serve the reheat load with recovered energy that is currently being rejected to the atmosphere. The ACEEE paper referenced previously provides some examples of how to use recovered energy for reheat in new and existing construction.
Have electric reheat coil interlock, safety, and control systems been designed to deliver reliable performance over the range of load conditions that could be encountered by the system?	Many energy codes prohibit the use of electric reheat coils. However, even where prohibited in new construction, commissioning providers often encounter them on retrocommissioning projects. Where electric reheat is not prohibited, it is often applied in an effort to lower first cost at the cost of higher operational costs. When encountered, they can often present the commissioning provider with an array of operational problems that are not encountered with systems that use steam or hot water. Common problems include: ▪ Minimum flow rates driven by the capabilities of the airflow safety switches rather than the requirements of the zone served. ▪ Defeated operating schedules resulting from nuisance high limit safety trips that occur from the residual heat that remains at the coil location when the fan system is shut down with the coils operating at full capacity

instead of cycling the coils off and allowing them to cool down for a few minutes before cycling the fan off.

- Poor zone temperature control as the result of the staged capacity control strategies typically provided unless more costly SCR controls are specified and correctly installed and commissioned.

10.3. Typical Problems

10.3.1. Minimum Ventilation Rate Set Too High

Minimum airflow rates for VAV boxes are often in the design stages, based on the design occupancy levels. While this practice seems reasonable, in reality there is often a large difference between the design loads and the actual loads. Design loads are often based on variables like the number of chairs in the office, without taking into account that all chairs will not be filled simultaneously. The actual minimum flow setting required is generally better represented by only one person being in the office most of the time. Setting the minimum airflow rate higher than necessary leads to high reheat loads when the minimum level would overcool the space. As long as the flow demanded by the zone is below the flow supplied by the minimum airflow, the system will act as a constant volume reheat system.

The story in the side bar is one example of how taking steps to ensure that the design and implementation of a reheat system is matched to the actual loads can save a significant amount of energy. Additional discussion of this topic can be found in the *Document Review Design Brief*, which can be downloaded free of charge from the Energy Design Resources web site at www.energydesignresources.com.

Ventilation rates and schedules that match reality result in reheat costs that match the Owner's pocketbook: *On the scoping study for a retro-commissioning project, the commissioning provider noticed that the boilers serving an office complex were firing at a 30% to 50% duty cycle during the summer months. Since the loads served were primarily offices, this seemed like a good indicator of a retro-commissioning opportunity. Further investigation revealed that the complex was being ventilated for an occupant level that was approximately 3 times greater than the actual level. A contributing factor was that virtually all of the air handling systems on the site were being operated around the clock to serve a few zones on each system. By adjusting ventilation rates to match the actual occupant levels and implementing scheduling at the zone level, over $60,000 per year in operating costs were avoided in the form of reheat energy at the boilers and chillers and fan energy at the air handling units. The payback for the effort was well under one year.*

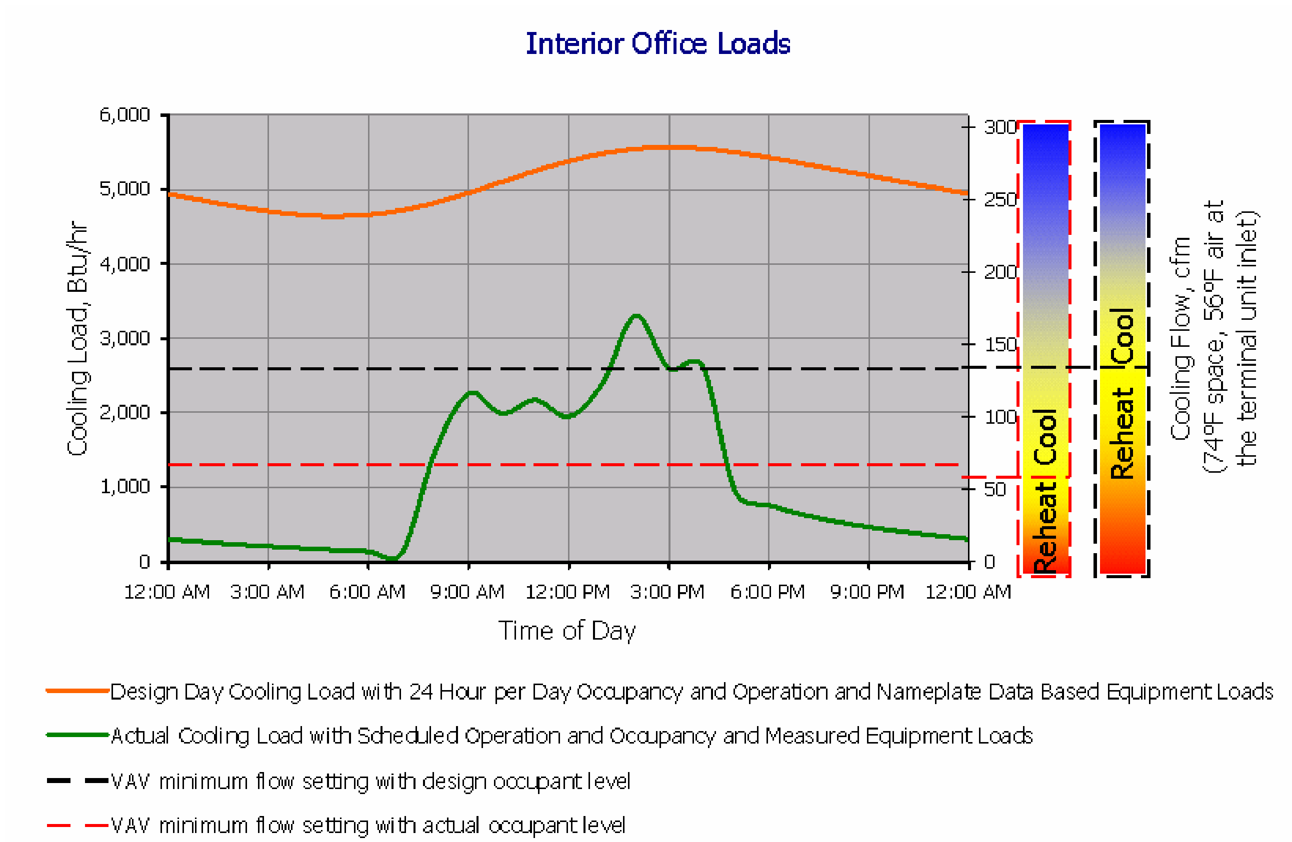


Figure 10.3 Load Conditions for a Perimeter One Person Office

This plot shows the loads for the office illustrated in Figure 10.2 if it was an interior zone. Without the influence of solar and transmission effects, the difference between the actual design day load and the design load is even more significant.

In Figure 10.3, both the minimum flow setting with design occupant levels and the minimum flow rate with actual occupant levels are shown. With the design minimum flow, almost the full daily operation relies on reheat to meet the desired space conditions. With the actual minimum flow required, the zone does not need reheat during the entire day.

10.3.2. Ineffective Use of Reheat for a Net Heating Load

You may have encountered a system that could not meet the perimeter heating requirements because the same air handler served the perimeter zones as the interior zones, which required cold air all year. In efforts to increase the reheat capacity to meet this perimeter heating load, it is a common mistake to increase the airflow to the zone. In fact, increasing the airflow does not lead maximum capacity. This result stems from the difference between the reheat function and the heating function, discussed previously. The reheat function increases the delivered air temperature from the air handler's discharge air setpoint (51.6°F in the example below) to the room temperature. The heating function increases the delivered air temperature above the room temperature in order to meet the heating load. By increasing the airflow, the reheat coil must reheat more air up to the room temperature before the heating load can actually be met. Supplying less flow of hotter air to the space results in more comfortable conditions, reduced reheat energy, and reduced fan energy.

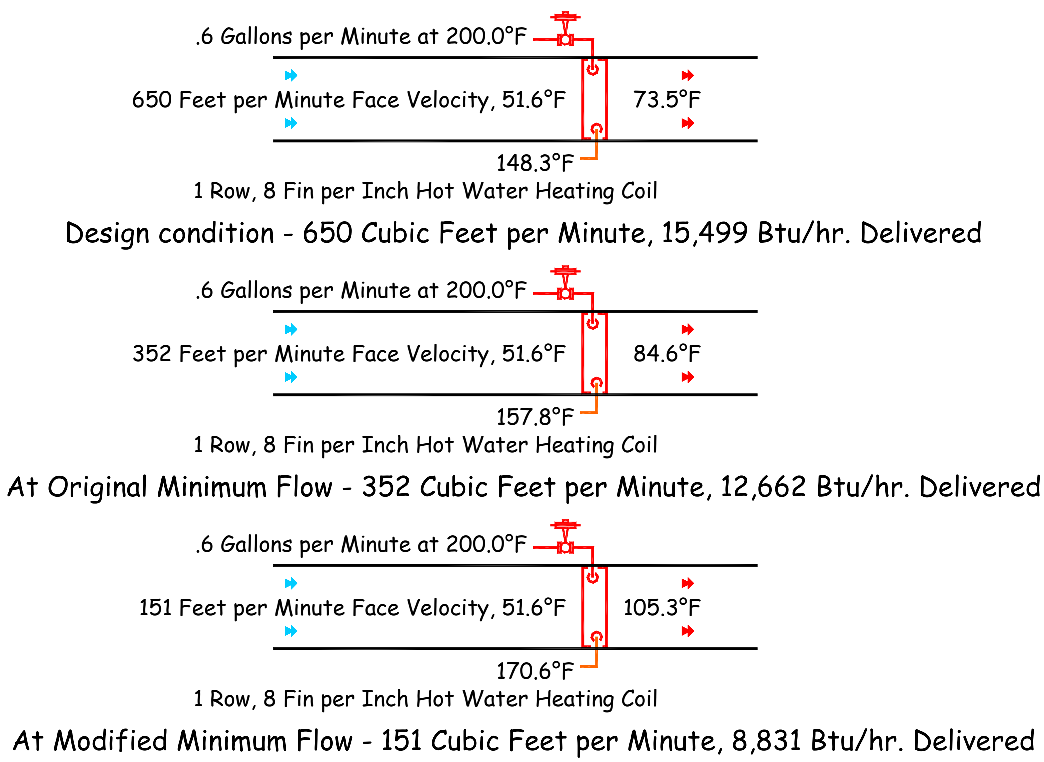


Figure 10.4 Effect of Increasing Air Flow Rate at a Reheat Coil.

This drawing illustrates a reheat coil serving a perimeter zone where the minimum flow rate was adjusted to match the current occupant load. The control sequence was modified to heat at minimum air flow, rather than increase air flow along with the reheat function. Notice how the modified performance delivers much warmer air while at the same time, the reheat burden has bee minimized. In the design condition, the coil delivered a lot of air but all of the available capacity was used up in simply offsetting unnecessary cooling (reheat). Serving a space with a design temperature of 71ºF using a high volume of air at 73.5ºF provided very little heating capacity and made a for a drafty environment.

10.4. Non-Copyrighted Tests

Some terminal unit functional tests include testing the minimum terminal unit damper position during heating mode for reheat coils located at the zones. See *Chapter 14: Terminal Equipment* for links to these non-copyrighted functional tests.

The CTPL contains the following tests that have some component that focuses on optimizing discharge air temperature reset schedules to reduce reheat burdens and reducing simultaneous heating and cooling through control sequence functional testing. These tests can be easily modified to fit different buildings and systems.

Air Handler Functional Test (Seattle City Light)

Link to an Air Handler Functional Test, as prepared for Seattle City Light by Mike Kaplan.

AHU Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

.

Chapter 11: Warm-up

Figures

11.1. Theory and Applications

The warm-up function is often required when a scheduled air handling system is shut down during unoccupied periods and the outdoor conditions result in a net loss of energy from the space. In most instances, the warm-up process can be provided by heating elements located in the system for some other purpose such as preheat, reheat, or space heating. Occasionally, a heating element dedicated to the warm-up function will be encountered. The topic of preheat is covered in *Chapter 7: Preheat* and reheat is covered in *Chapter 10: Reheat*. Space heating is discussed in both of these chapters. *Chapter 7: Preheat* also contains a summary table comparing the various heating processes commonly encountered in air handling systems.

There is more to the warm-up process than simply bringing the air temperature in the space up to the desired set point. All of the mass in the space including the walls, floors, ceilings, and furnishing must also be warmed up. When a building is shut down and allowed to cool off, it begins to lose the thermal energy stored in its mass.[1] The thermal mass will delay the rate at which the building temperature drops off relative to the outdoor temperature. Once the mass is cooled off, it will also delay the rate at which the building mass regains that heat relative to the indoor temperature once the systems are restarted.

Most warm-up processes occur prior to occupancy. Thus, it is possible to minimize the energy consumption for the cycle by locking out any ventilation air requirement associated with occupancy and operating the system in full recirculation mode. The exhaust systems that operate in conjunction with the ventilation air/minimum outdoor air requirement should also be locked out during the warm-up cycle when their associated make up air is not available. Locking out the exhaust systems will save fan energy and help prevent the building from becoming negative relative to atmosphere and creating an unnecessary infiltration load. It is essential that sequences that eliminate ventilation air during the warm-up process for energy conservation purposes be configured, adjusted and controlled in a manner that guarantees that appropriate ventilation and make up air will be provided when the spaces are occupied and/or the exhaust systems are placed in operation.

Alternatively, some other method of warm-up may be desirable such as a sequence using an independent perimeter heating system that does not rely on the make up air system for warm-up.

[1] In humidified environments, the building materials can represent a significant humidification load if the relative humidity in the building drops during the off cycle and moisture is lost to the surroundings.

11.2. Commissioning the Warm-Up Process

Section 11.2.1 Functional Testing Benefits helps the reader analyzing the cost effectiveness of functional testing the warm-up process. Section 11.2.2 Functional Testing Field Tips focuses on practical considerations during functional testing that will help the reader better understand how to perform the functional tests. Section 11.2.3 Design Issues Overview presents issues that can be addressed during the design phase to improve system performance, safety, and energy efficiency. These design issues are essential for commissioning providers to understand, even if design phase commissioning is not a part of their scope, since these issues are often the root cause of problems identified during functional testing.

11.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. For central system based warm-up processes, ensuring proper sequencing with the other heat transfer elements in the air handling system as well as the normal operating sequence will minimize the potential for simultaneous heating and cooling, thereby saving both heating and cooling energy. 2. For terminal equipment using the reheat coils for warm-up, ensuring that the flow rate used by the terminal unit during the warm-up cycle maximizes the heat available for warm-up and minimizes the cycle length without sacrificing energy efficiency. Higher flow rates at the terminal reheat coils do not necessarily translate into quicker warm-up times and more warm-up capacity, as can be seen from Figure 10.4 in *Chapter 10: Reheat*. When ventilation loads cannot be eliminated, the terminal unit flow rate should be at minimum. 3. Where appropriate, commissioning tests targeted at verifying that make up air and exhaust systems are not operated during the warm-up cycle will result in energy savings due to lower make-up air heating requirements and less fan energy. 4. Verifying that control valves close off completely helps ensure that simultaneous heating and cooling do not occur unnecessarily. Where coils serving other functions in the system provide warm-up, this will typically be checked as a part of the testing of the other functions. Dedicated warm-up coils will require that this function be checked independently. 5. Addressing control valve close off also ensures that there will be not ripple affects associated with pumping extra cooling and heating water through the distribution network due to heating leakage and the effort made by the cooling system to offset it. 6. Properly coordinated and applied warm-up will ensure that scheduled operation of the fan systems is maintained because the operating staff will be able to count on comfortable zones at the beginning of the occupied cycle without resorting to setting extended hours of operation.
Other Benefits	Properly applied warm-up will improve equipment life and reduce maintenance requirements by ensuring that the scheduled hours of system operation are not extended due to periodic difficulty in achieving morning warm-up. This can be particularly significant in terms of filter life.

11.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	Because the heating elements used for warm-up usually perform other functions in the HVAC system they serve, the purpose of the test procedure for the warm-up process will verify that the warm-up function is properly integrated with the other heating functions and the overall operation of the system. Where dedicated warm-up elements are provided, additional testing to verify valve stroke, pressure, flushing, and capacity may also be required. The functional testing tips associated with these tests will be similar to those outlined under this topic in *Chapter 7: Preheat* and *Chapter 10: Reheat*.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard tool kit listed in the *Chapter 2: Functional Testing Basics*: 1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. This equipment can also be used to verify flow rates. 2. A stethoscope or other sound sensitive device is useful for listening for valve leakage sounds in verifying that the valve is fully closed. 3. For capacity testing, flow measuring equipment capable of measuring the flow of the heating energy source to the necessary degree of accuracy will be required.
Test Conditions	Simulating a warm-up load can be difficult during moderate weather and summer months. It may be possible to over-cool the building by running the cooling equipment overnight or over the weekend. Then test the warm-up cycle by shutting down the system and verifying the normal morning restart. This test may require temporary manipulation of the outdoor air temperature input, as well as the cost of overcooling. These actions may be marginally beneficial due to the less critical nature of the warm-up process. For systems that must be tested during warm weather, a more palatable approach might involve verification of the control sequence supplemented by trend analysis during the first heating season. In most cases, the fact that the warm-up element performs other functions in the system probably will mean that the necessary utility and support processes were in place when the primary function provided by the element was tested. However, for dedicated warm-up elements, many of the considerations outlined under this topic in *Chapter 7: Preheat* and *Chapter 10: Reheat* will also apply.
Time Required to Test	Considerations are similar to those outlined in *Chapter 7: Preheat* and *Chapter 10: Reheat*.
Acceptance Criteria	Considerations are similar to those outlined in *Chapter 7: Preheat* and *Chapter 10: Reheat*
Potential Problems and Cautions	1. It is important that the design and test plan recognize the difference between preheat, reheat, heating and warm-up elements and functions. This is discussed in detail in *Chapter 7: Preheat* 2. Reference *Chapter 7: Preheat* and *Chapter 10: Reheat* for other potential problems and cautions.

11.2.3. Design Issues Overview

Issue	Comments
Can the warm-up cycle be accomplished without ventilation air to minimize energy consumption?	Significant energy savings may be realized by eliminating ventilation during the warm-up cycle, especially for systems with large outdoor air percentages. This can only be done if the area served is unoccupied during the warm-up process. For systems with large outdoor air percentages, an alternative warm-up process such as independent perimeter heating may be beneficial.
Will elevated heating water supply temperatures during the warm-up cycle provide improved performance and limit the warm-up cycle time and pump energy?	Heating water systems can be quite flexible. Elevating the supply temperature of the water serving a coil can increase its capacity significantly.
Does the configuration of the distribution network for the heating medium necessitate special considerations during warm-up?	For air handling units served from a central system, unregulated warm-up processes can cause operational problems in both the distribution network and at the heating plant. For buildings served with multiple air handling systems that use electric heat for the warm-up process, an unregulated process can lead to excessive demand charges.
Do zoning and system selections need to take the differences between interior and perimeter zones into account to improve the benefits of set back and accommodate the needs of a warm-up cycle?	The location of a zone can make a significant difference in its response to temperature setback during the unoccupied mode and the requirements to warm-up it when the occupied mode is reinitiated. On large buildings or buildings with significantly different envelope conditions at various points on the perimeter, it may be wise to segregate zones with different warm-up and setback characteristics to different HVAC systems if the building will spend a significant amount of time unoccupied and the climate varies. Remember, most office buildings only will have tenants in them for 2,600 to 3,000 hours per year out of a possible 8,760 hours per year.

11.3. Typical Problems

The following problems are often encountered when dealing with warm-up processes.

11.3.1. Unacceptable Cycle Length During Extreme Weather

The HVAC system may be able to raise the ambient air temperature to the desired set point quickly and hold it there with relative ease, but the occupants may still perceive the space as cold because all of the surfaces around them are still at a temperature below the ambient space temperature. If the surfaces are massive, this condition will persist for some time.[2] Thus, it may be desirable to modify setback temperatures based on ambient outdoor conditions and the location of the space.

Buildings frequently handle ambient conditions that are outside of the typical design day. For some buildings, a long shutdown for a holiday or weekend during extreme weather may result in an excessively long warm-up cycle. This can lead to several problems including:

- The building is not brought up to temperature by the time of occupancy, resulting in occupant discomfort. To combat this problem, scheduled operation is often changed to start much earlier. If the earlier start persists in the long term, energy is wasted.
- For some systems, the "learning process" used by the optimized start-stop sequence will become distorted by the extended warm-up requirement. This distortion can lead to unnecessarily long warm-up cycles during less extreme weather and energy waste.

Modifying the night set-back temperatures as a function of outdoor conditions may eliminate the need for continuous operation. Initially, the set points for warm-up and set-back can be set at the building's design day values or parameters agreed to with the design team. The operators can then be trained to optimize the settings as they gain experience with the building's characteristics. Consider the following issues when adjusting the set back temperature:

- **Outdoor temperature** A few degrees of difference in set back temperature setpoint can make a significant difference in how often a zone or system operates in set back mode and how long it takes the zone or system to warm back up. Trending the building decay in temperature over time relative to ambient temperature may reveal a condition that merits a change in set back temperatures for certain outside air temperatures.
- **Zone location** The location and envelope conditions for any given zone may influence the setback temperature selected for it. Interior zones will tend to cool of more slowly than perimeter zones. The presence or lack of a roof load and the how well the zone is sealed from infiltration will also impact the rate at which it loses energy.
- **Wind and day time sky cover** Wind can be a significant factor in how a building loses energy during an unoccupied cycle, especially if the building does not have a tight envelope.

[2] You can paint yourself a picture of this by deploying a data logger on a project with a set back cycle during the winter months. Bury one probe in the middle of the files in the middle drawer of a full filing cabinet. Dangle another one in free air, next to the space temperature sensor if it has one. Put a third probe outside where it can see the true outdoor air temperatures. Gather samples once every 30 minutes and look at simultaneous plots of the three temperatures over the weekend in the spring or fall compared to a weekend in mid winter.

11.3.2. Warm Up During Moderate Weather

In some climates a short warm-up cycle may be necessary after a weekend or long holiday shutdown during moderate weather. But, if the weather conditions are moderate enough that the building heating plant is not in operation since it is not "heating season" then there may be no heat to warm-up with. Without a source of supplemental heat, it can take a very long time to bring a cold building up to temperature using only the internal gains. This lack of heating can be prevented triggering the operation of the heating plant if the warm-up process calls for heating. Be sure that the warm-up process and night setback temperatures are tuned to the building. See the sidebar for an example of this problem.

If the building's heating plant is difficult to start-up and shut down, then delaying the shut down until ambient conditions are such that a warm up cycle will not be required may be a more practical alternative. However, this alternative will probably be more costly due to the parasitic loads associated with keeping the heating plant operating to serve a small, infrequent load.

Nothing to Warm Up With: *A project engineer for a control contracting firm was caught off guard one Monday morning when his company received a string of irate phone calls regarding a project that had just been occupied. The client's new building was "freezing cold" after being off for a holiday weekend in the fall. The problem occurred because the building heating plant was programmed to shut down when ambient temperatures rose above 65ºF since the load calculations indicated that there was no heating load above that temperature due to the insulated envelope and the internal gains in the building. Over the weekend, the weather had been above 65ºF, but never above 70º. As a result, the internal temperatures in the building had drifted back into the upper 60's ºF. When the fans started and dutifully entered their warm-up cycle on Monday, there was no heat for them to warm up the building with. The heating plant was not in operation due to the outdoor temperatures being above its activation temperature. The problem was solved by adding a line to the control program that started the heating plant if a warm up cycle occurred, in addition to starting the plant based on outdoor temperature.*

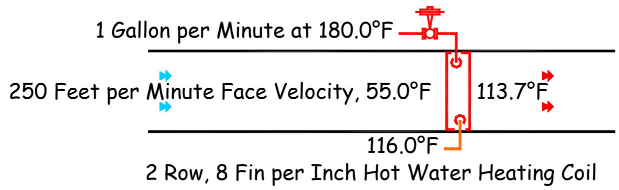
11.3.3. Warm Up Load Control Problems

One common approach to warm-up for systems served by hot water or steam is to simply open all of the heating valves to full capacity and run that way until the system comes up to temperature. This approach should be used with caution for the following reasons:

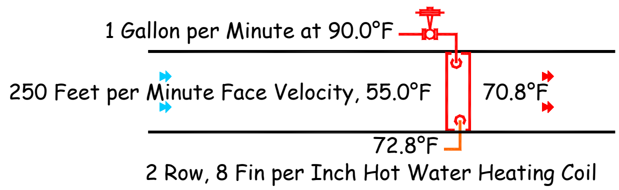
- On systems with significant diversity, the flow or heating capacity imposed by the wide-open valves can exceed the installed capacity of the plant. Even if the capacity is available, wide-open valves can cause problems related to the sudden change it imposes on the system.
- In water systems, loads that are closest to the plant can short circuit the loads at the end of the pumping network especially if balancing valves have not been installed and set to provide design flow with a wide open control valve and/or flow regulating valves are not provided.
- The wide-open valves may also cause the distribution pumps to run at peak capacity, which adversely impacts electrical demand in large plants. This high flow rate produces little added benefit since the rate of increase in heat transfer drops off as hot water flow rate increases towards 100%.
- For loads served by steam plants, wide-open valves can adversely affect the pressure in the distribution header. In extreme situations, water can be drawn out of the boilers and into the distribution system due to excessive velocities through the outlet nozzle on the boiler, which can lead to problems like water hammer.
- Systems that are served by electric heat need to consider the demand implications of having all of the heating elements go into the full heat mode simultaneously. The demand spike created could result in utility charges that exceed the costs associated with staging the start-up of the systems over a longer time interval, even though such an approach would involve more fan operating hours.

Instead of fully opening the heating valves (or staging electric heating coils fully on), the following methods can be used to help control the warm-up cycle:

- Design the warm-up sequence so that the heating valves at the zone level are controlled to maintain zone set points. Controlling the valves will also provide some commissioning and operational flexibility by allowing the warm-up temperature supplied by a system to be tuned to the loads it serves.
- If the heating coil is located at the air handler, control the heating valve to produce about 120°F discharge air. This control process will reduce overheating compared to letting the coils run wild, especially for air handlers located closest to the hot water pumps. Using 120°F discharge air in a warm-up cycle instead of 70°F discharge air significantly increases a coil’s capacity as seen in Figure 11.1. This approach takes advantage of standby heating capacity to shorten the warm-up cycle without a commensurate increase in flow requirements and pump energy. The method has the added benefit of exercising the stand-by capacity in the system, thus verifying the reliability of the system.



A reheat coil at its minimum flow setting serving a terminal unit with a design flow of 500 cfm. Performance with elevated supply water temperatures.



The same coil but served at the design temperatures associated with normal operation of the low temperature hot water system

Figure 11.1 Coil Performance with Elevated Supply Temperatures

The example in Figure 11.1 shows the benefits of elevated hot water supply temperatures for a low temperature hot water system (from an energy recovery process). The low temperature water increased the length of the warm-up process. Programming the steam heat exchanger control system to briefly increase the supply temperature for the warm up cycle during extreme weather significantly lowered the warm-up cycle time with minimal disruption to the hot water system's operation. Note that the flow is unchanged despite the significant increase in leaving air temperature.

11.4. Non-Copyrighted Tests

The CTPL contains the following tests that have some component that focuses on optimum start-stop and warm-up control functional testing. These tests can be easily modified to fit different buildings and systems.

Air Handler Functional Test (Seattle City Light)

Link to an Air Handler Functional Test, as prepared for Seattle City Light by Mike Kaplan.

AHU Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

Chapter 12: Fans and Drives

12.1. Theory and Applications

The fan is the heart of the air handling system since it is one of the most significant energy users in a building. Commissioning and re-commissioning fans and drives is a key factor for ensuring that a building's efficiency goals are met over the life of the building.

There are both indirect and direct components to a fan's energy consumption. The indirect component relates to the system the fan serves. The fan must impart enough energy to the air stream to overcome the system's resistance to flow. This energy consumption can be significantly altered by:

- Fan installation considerations like system effect
- Duct and fitting design and their related pressure drops
- Component pressure drops
- Duct system leakage
- Duct system thermal loss

These topics are discussed in *Chapter 13: Distribution*, and *Chapter 15: Return, Relief and Exhaust System*.

The direct fan energy component relates to how efficiently the fan can covert the energy going into its prime mover (usually electricity into a motor) into air flow and pressure in the fan system. This energy consumption is a function of the following items:

- Fan efficiency
- Motor efficiency
- Drive system efficiency and adjustment

The fan horsepower equation (Equation 12.1) is a function of several fundamental components: flow rate, static pressure, fan efficiency, and motor efficiency. Application of this equation to fan system analysis is discussed in detail in *Appendix D: Calculations*. Commissioning efforts should be targeted at these factors to ensure system efficiency, performance, and reliability.

$$\boldsymbol{Horsepower} = \left(\frac{\boldsymbol{Q} \times \boldsymbol{P_S}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}} \right)$$

Where:

$\boldsymbol{Horsepower}$ = The horsepower at the terminals of the motor (includes motor efficiency losses)

$\boldsymbol{Q}$ = The flow for the fan in cubic feet per minute (cfm)

$\boldsymbol{P_S}$ = The static pressure for the fan in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Equation 12.1 Fan Horsepower

The fundamental technology associated with the fans, coils, casings and other major system components is well established. Most of the advances in technology that improve the performance of these components are related to the drive systems and control systems, not with the components themselves. Drive and control systems can be readily upgraded as technological improvements warrant. This easy upgrade is in direct contrast with a more complex machine like a chiller where technology changes are continually improving performance, and where this technology is generally an integral part of the machine's package.

If one examines a reasonably well-maintained 50-year-old airfoil centrifugal fan and a similar unit right off of the production line, one will probably see only modest performance differences. Over time, the shaft and/or bearings in the older fan may have required replacement, and the wheel periodic cleaning. However, it is likely that the fan is capable of moving air as efficiently as the newer fan. Through attention to proper maintenance and equipment location (indoors rather than outdoors), fans can be a lasting component of the air handling system.

12.2. Commissioning Fans and Drives

The following tables outline the benefits and background information associated with testing fan and drive systems. These tests can be used in a retro-commissioning process to define and correct existing operational issues. The tables are linked to related information throughout the Guide. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

12.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	Fan energy constitutes a significant portion of a building's overall energy consumption. Even minor improvements in efficiency can have a major impact on the energy consumption pattern associated with a building. A well executed commissioning plan for the fans and their associated drive systems ensures that the systems are set up for peak efficiency and that this efficiency will persist.
Other Benefits	The fan and its associated assembly of components that constitute the air handling unit represent a significant investment in terms of material and labor resources. Commissioning efforts targeted at ensuring operating flexibility and good maintenance practice can promote the longevity of the installation, thereby optimizing the initial investment's life cycle and improving the sustainability of the building systems.

12.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	1. To ensure that the fan and drive system have been installed and arranged in a manner that promotes efficient performance in the operating environment. 2. To ensure installation and maintenance practices that promote the persistence of efficiency and equipment longevity.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard tool kit listed in *Chapter 2: Functional Testing Basics*: 1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. 2. Most current technology inverter-type variable speed drives can be programmed to indicate their current power consumption. For other VFD technologies and for non-drive equipped systems, a data logger capable of continuously monitoring three phase power and other related parameters is useful for optimizing the system's efficiency and documenting the operating performance in various modes.
Test Conditions	1. Tests that are targeted at verifying design parameters and settings for the fan and its enclosure can generally be performed after the assembly of the air handling unit but prior to its start-up.

	2. Other tests targeted at the interlocks and fundamental control functions, loop testing and tuning, and capacity testing will require that the air handling system be operational and moving the design volume of air, but not necessarily fully under control. Safety systems should be operational to protect the machinery and occupants in the event of a problem during the test sequence. 3. Testing the integrated performance of the fan and drive with the rest of the system will require that the individual components of the system be fully tested and ready for integrated testing. In many cases, testing integrated performance will also require that at least the portion of the building served by the system be substantially complete and under load. 4. For variable flow systems, capacity testing will often involve forcing the system in to a full flow configuration. Usually this requires delivering flow in excess of the current requirements in many of the zones. Manual adjustments to discharge temperatures and local reheat valves can mitigate the impact of this on occupants, but some comfort problems may be created. In situations where control of building pressure relationships is critical, forcing the system to run at full flow when it is not required by the actual load conditions may have adverse effects on the desired pressure relationship. These issues should be taken into consideration when developing the system test plan.
Time Required to Test	1. The time required to test can vary from less than an hour for one person for simple interlock verifications up to a day or more for a team to verify the fan's integrated performance with the air handling system. 2. The time associated with the integrated system testing will not be purely focused on the fan and will yield benefits in relation to other system components and functions. Thus, when budgeting for this sort of testing, it is reasonable to assume that a number of components and their interactions will be tested simultaneously. 3. Capacity testing and integrated performance testing will involve coordinating the activities of multiple parties. This coordination should be taken into consideration when developing the projects commissioning budget and schedule.
Acceptance Criteria	1. Network failures should not result in unsafe system operating modes. The recovery from the failure should safely return the drive to the network. 2. Drive settings and adjustments should provide for safe and reliable system operation at peak efficiency levels in all operating modes. 3. Capacity tests results should be evaluated in the light of the accuracy of in instrumentation and the actual conditions at the time of the test. 4. The fan and drive control should reliably integrate with the overall system control strategy in a manner that provides the intended function and level of performance.
Potential Problems and Cautions	1. Applicable cautions as outlined in *Chapter 2: Functional Testing Basics* should be observed. 2. Safety and interlock testing, verification of some of the drive settings, and loop tuning efforts will place the system at risk. Appropriate precautions and procedures should be in place to protect the personnel

	and machinery involved in the test process, including plans for quickly aborting the test.

12.2.3. Design Issues Overview

Item	Comments
Does the unit have good access for control installation, maintenance, and component replacement?	Access to the fan and its related components is critical for ensuring the persistence of energy efficiency and other commissioning related benefits. 1. Piping should be arranged to ensure that access panels are not blocked, service routes remain open, and components such as coils and fan shafts can be removed and replaced without shutting down adjacent systems or central plant equipment. 2. Fan scrolls should be provided with access doors to allow the wheel to be inspected and cleaned. 3. Coils should be provided with space between then and access to that space to facility inspection and cleaning and allow for the installation of control elements in their proper location. For example, space is required between a preheat coil and the next coil downstream to allow the freezestat to be installed downstream of the preheat coil (which by design will see subfreezing entering air temperatures and should be capable of handling them safely).
Have variable speed drive installation and operation requirements been taken into account?	1. Most VFD manufactures have some specific requirements regarding the length, routing, and general configuration of the power circuit from the drive to the motor. Failure to pay attention to the requirements can cause operational problems in the electrical system and in severe cases, cause failures in switchgear, drives, and transfer switches. 2. Many VFDs can be damaged if they start against a reverse spinning motor. This condition is likely to occur in parallel fan systems, even if they are equipped with backdraft dampers. No damper is 100% leak proof, and it does not take much reverse flow to set a fan wheel in motion. Most drives also have a feature to handle reverse flow, usually called DC injection braking. The process pulses the motor with a DC signal before starting and accelerating it. The DC signal brakes the rotating armature. Usually there are adjustments that need to be made to tailor this feature to the load served in addition to activating it. Verifying this feature is properly set and functioning should be part of the commissioning process both during the pre-start checks as well as the functional tests. 3. Many drives are supplied with bypass contactors that allow the motor to run at full speed if the drive fails. In some cases, the system could be damaged by full speed fan operation when the loads were configured for minimum flow conditions. 4. The drive should be configured and wired to ensure that all safety interlocks are effective in all possible selector switch configurations (local, auto, hand, inverter, bypass, etc.). Some drives are arranged to allow the safety interlocks to be effective when the drive is operating but not effective if the drive is bypass. Some drives can also be configured so that if they are placed in the local mode, any external interlock (external to the drive circuit board) will be ignored. This feature may be desirable in process applications, but it is highly undesirable in most

Item	Comments
	HVAC applications. Verifying that the drive is properly set and functioning should be part of the commissioning process both during the pre-start checks as well as the functional tests.
Are the VFDs and the motors compatible?	Motors that are not rated for VFD applications may have a reduced life if used with a VFD. In retrofits, it is desirable to evaluate the motor's capabilities relative to the drive. Even it budget constraints prevent a motor replacement when the drive is installed, the potential for a future problem and early failure can be anticipated. In new installations, the drives and motors should be coordinated to be compatible with each other.
Does the VFD shaft need to be grounded?	The variable voltages, magnetic fields and harmonics associated with VFD operation can induce currents in the motor shaft that have no path to ground other than through the bearings for most conventional motors. Evidence suggests that these eddy currents can lead to premature bearing failures, perhaps in a matter of years on some motors. Shaft grounding kits installed on the motor provide a direct path from the shaft to ground via a brush system.
Is the drive arrangement suitable for the application?	Given the wide array of drive options available, it is important to tailor the selection to the application. 1. If direct drives are applied, then fan speed adjustment for balancing purposes will have to rely on less efficient approaches like discharge dampers, or will require that a variable speed drive be included as a part of the package. 2. A variable speed drive on a constant volume fan may represent false economy. While it does minimize balancing efforts and eliminate the need for a final sheave change or adjustment to set the fan speed, the drive results in a loss in fan system efficiency that increases in magnitude as the speed is reduced (see *Chapter 12: Supplemental Information*). The drive also introduces operating complexity, first cost, potential electrical system harmonic problems, and multiple failure mode possibilities into the system. These issues coupled with the efficiency reduction will probably outweigh any modest savings in balancing costs achieved. 3. Variable pitch sheaves provide flexibility and a good intermediate stepping stone between start-up and final balanced speed as a system is brought on line. But some of their disadvantages may make the installation of a fixed pitch sheave as the final step in the balancing effort a desirable feature to include in the project.
Could the fan motor run in the wrong direction?	For most axial fans, if the impeller were to run in the opposite direction, it would move air in the opposite direction. With centrifugal fans, running the impeller backwards will still provide flow in the correct direction, but the performance will be degraded significantly. Reverse flow or back-draft through most fan wheels will cause them to spin in the reverse direction. Forward curved fan wheels will spin in the wrong direction if air is blown through them in the right direction but they are not energized. For most single phase motors, if the motor is spinning in the wrong direction when power is applied, the fan will simply run in the wrong direction. The rotational direction of most three phase motors used for HVAC applications is tied to the phase rotation established by the way the windings are connected to the distribution system. Thus, if the motor is

Item	Comments
	spinning backwards when voltage is applied, it will reverse and run in the proper direction. However, the sudden reversal in direction can cause the problems discussed in the Control System Design Guide, *Chapter 3: Selection and Installation of Control and Monitoring Points*, *Section 3.4.1.9. Multi-Speed Motor Interlocks*. Problems can also occur with variable speed drives when they attempt to start against a reverse rotating motor. Systems with operating conditions that could cause backflow should be designed and installed to safely and reliably deal with any problems. Both normal and failure modes need to be considered. Common examples of situations where backflow potential exists include: 1. Systems with parallel fans or air handling units. Don't forget that parallel fan terminal units have fans that are essentially in parallel with the supply fan. 2. Systems with series fans: the supply and exhaust fans associated with a 100% outdoor air systems and the fans in series powered fan terminal boxes relative to the supply fan.
Does the air handler specification include desirable options?	Most fans and air handling units are available with an array of options, some of which are desirable in most installations and others of which are only required for special installations. Examples include: 1. Access doors in casings and fan scrolls. 2. Lubrication lines extended to be accessible from the exterior of the unit. 3. Baseline vibration characteristics measured at the factory. 4. Premium efficiency motors. 5. Special vibration isolation provisions. 6. Scroll drains (essential for exhaust fans located outdoors and discharging in the up-blast configuration) 7. Factory installed back draft dampers. 8. Non-sparking or explosion proof construction for hazardous locations. 9. Special coatings for handling abrasive or corrosive fluid streams.

12.3. Typical Problems

The following problems are frequently encountered with fans and drives.

12.3.1. Static pressure requirements in excess of design

A typical problem found during commissioning or retro-commissioning is high static pressure in the fan system. In creating excess static pressure that is not required to operate the system, a fan wastes significant amounts of energy. This problem arises because fan selections often fall into a range where there is a difference between the design brake-horsepower (bhp) requirement and the actual motor horsepower installed due to the standard horsepower ratings available in motor product lines. The difference between available sizes can become quite significant for larger fans. For example, a fan with an 82 bhp motor requirement would probably come with a 100 hp motor. If the fan was unable to deliver design flow against the installed system static requirement, then there would be a lot of margin for speeding the fan up to achieve the design requirement without overloading the motor (assuming the operating point did not end up in a different fan class requirement). This safety net may be desirable, as the excess motor capacity allows problems to be solved in the field. But, the added energy consumed by the fan beyond that intended by the design will become an energy burden that will persist for the life of the system.

Extra diligence during design and construction can prevent conditions that add unanticipated static pressure to the system, thus averting the need to run the fan at an operating point in excess of design. If the balancing team discovers that they have excess system static pressure, there are ways to lower static pressure that will allow the system to function at or near its intended design point rather than adding on ongoing energy burden to the project by simply throwing energy at the problem. An example of such a situation is contained in Example 2 in *Appendix C : Calculations*.

12.3.2. Improper belt drive system adjustment

While simple in concept, there are some critical parameters associated with the installation and adjustment of this belt drive systems that are often ignored, resulting in belt failures, poor performance, noise, reduced equipment life and energy waste.

Alignment of the drive and motor sheaves is a critical step in the belt installation process. Without proper alignment, belts will run less efficiently, wear out more quickly, and, in extreme cases, be thrown off the drive sheaves.

Over-tensioning the belts can cause problems with bearings and shafts due to the excessive loads imposed. In addition, new belts will stretch during the first 8 to 24 hours of operation; belts that have been properly set initially will require re-tensioning after they have run. This contingency is often overlooked to the detriment of the drive system efficiency.

Multiple belt drives will function best if factory matched belt sets are installed. This ensures that the drive loads are equally distributed between all of the belts, equalizing wear and life.

The T.B. Woods Company offers a very good guide to proper belt drive selection and adjustment on their web site at http://www.tbwoods.com/Literature/.

12.4. Non-Copyrighted Tests

The Commissioning Test Protocol Library contains the following tests that have some component that focuses on fans and drives or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

EMS and Point Verification Checks

Link to EMS and Point Verification Checks, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The procedures contain calibration tests, which may be appropriate for some of the sensors associated with the fan control system.

Air Handler Functional Test (Seattle City Light)

Link to an Air Handler Functional Test, as prepared for Seattle City Light by Mike Kaplan.

The test contains some procedures that appropriate for fans and variable speed drives in certain applications.

AHU Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The test contains some procedures that may be appropriate for fans and variable speed drives in certain applications.

AHU Functional Test (Malek and Caluwe)

Link to an Air Handler Functional Test as prepared for PG&E by Bill Malek and Bryan Caluwe in the *Comprehensive Commissioning Services Guideline*.

These tests are mainly for contractors to figure out how to test performance and for commissioning providers to verify the contractor's plans, which may have some components that are useful to fan and drive testing in some applications.

Variable Speed Drive Test 1

***Link to a Variable Speed Drive Functional Test* as prepared for the USDOE and FEMP by PECI *Version 2.05 Commissioning Tests*, PECI. 1998.**

Variable Speed Drive Test 2

Link to a Standard Commissioning Procedure for Variable Frequency Motor Drives as prepared for Seattle City Light in the *Building Commissioning Assistance Handbook.*

Exhaust Fan Test

Link to a functional test for a simple exhaust or supply system start-up.

This particular test was developed to place a simple make-up and exhaust system into operation about one third of the way through the construction cycle to allow the power company to energize the transformers. This test illustrates some of the contingencies that need to be taken into account when bringing a system on line prior to completion of a project. Temporary start up is discussed in *Chapter 2: Functional Testing Basics*.

Several functional tests for fans and drives have been identified for future development, and may be included in later versions of the Guide.

Fan and Drive Tests for Future Development

Link to a list of tests related to fans and drives section that have not yet been developed.

12.5. Supplemental Information

Supplemental information for fans and drives has been developed to provide necessary background information for functional testing.

Fans and Drives Supplemental Information

Chapter 12: Fans and Drives Supplemental Information

Figures

12.5.1. Fans

Although fans come in a wide variety of designs, shapes, sizes, and configurations. They generally, they fall into two categories:

- **Centrifugal fans** This type of fan imparts kinetic energy to the air primarily by centrifugal force. In essence, the air is drawn into the center of the fan wheel where it is captured and contained by blades. These parcels of air are then "flung" to the periphery of the wheel.[1] The wheel itself can have an inlet on one side (Single Width, Single Inlet or SWSI) or an inlet on both sides (Double Width, Double Inlet or DWDI). The design of the blades on the wheel can have a significant impact on efficiency, performance and cost. Common designs are forward curved, backward included, airfoil, and radial.[2]
- **Axial fans** This type of fan uses aerodynamic effects to impart velocity to the air as it passes through the impeller. Generally, the air travels along the axis of the fan and impeller as compared the a centrifugal design where the air enters the impeller by flowing parallel to the shaft, but exits the impeller radially relative to the shaft. Generally, the impeller for this type of fan will be resemblance to an airplane propeller, but with many more blades.

12.5.2. Capacity control strategies

Regardless of the design, the rotating nature of the fan wheel can create significant structural loads on the shaft, wheel, bearings, and housing. Issues related to these factors are accounted for in the fan class rating. A fan with a wheel that is rated Class II has a higher speed and pressure capability than the same fan with a wheel that is rated Class I. Therefore, some caution must be used when changing fan speeds in the field to be sure that the new operating point is still within the fan's class rating.

There are a variety of techniques used to control fan capacity. The most common include:

- **Discharge dampers** Dampers located on the outlet of the fan can simply throttle the fan. Basically, the discharge damper increases/makes worse, the system effect associated with the fan outlet, thereby degrading its performance. Generally, this is probably the least expensive but also the least desirable approach due to the efficiency implications of a damper on the fan discharge. It can also be quite noisy.
- **Inlet vanes** Inlet vanes modify the performance of the fan by "pre-swirling" the air as it enters the eye of the fan. This has the effect of changing the shape of the fan performance curve as can be seen in *Figure 16* of *Chapter 13* of the *2000 ASHRAE Systems and Equipment Handbook*. This approach is much more desirable than a discharge damper, but not as desirable as a variable speed approach. The emergence of affordable and reliable variable speed drive technology has displaced this approach, but when VAV systems first emerged, it was a common means of achieving the required capacity control and is still found on many existing systems or on systems where the variable speed drives have been eliminated by a value engineering effort.

---

[1] It's the same effect you experienced as a child on the merry-go-round at the playground.

[2] While less common than the other designs, radial blade fans are sometimes found in exhaust systems, especially exhaust systems that handle materials like dust or other particulate matter or where high pressures are required.

- **Blade pitch** Varying blade pitch is a efficient but mechanically complex approach to controlling capacity on axial fans. The effect is very similar to a speed change as can be seen from Figure 17 in *Chapter 13* of the *2000 ASHRAE Systems and Equipment Handbook*. Most fans that use this approach require additional maintenance in the form of periodic lubrication, inspection and over-haul of the mechanical vane pitch control system.

- **Variable speed** Currently, this is probably the most common approach to controlling fan capacity due to its efficiency, mechanical simplicity, and steadily improving first cost. Commonly referred to as VSD technology (for Variable Speed Drive), it is not necessarily mean VFD technology, which is a subset. Before modern electronic technology made semi-conductor based Variable Frequency Drives a practical and affordable reality, there were a variety of more exotic approaches used including:

  - **Variable speed DC motors** These were complex and costly and were usually found only on industrial or very large commercial applications.

  - **Hydro-mechanical clutches** This technology employed hydraulics and a clutch system to vary the speed of the output shaft relative to the input shaft. They too were not common on commercial HVAC systems and tended to have relatively high mechanical losses.

  - **Variable pulley systems** Often termed "pulley pincher" drives[3], these systems did find somewhat wide application on commercial HVAC systems. The devices functioned by moving the sides of an adjustable drive pulley towards or away from each other. This changed the effective pitch diameter of the pulley, and thus, the output speed. While capable of modulating speeds, the devices tended to be hard on belts and had relatively high mechanical losses.

  - **Solid-state variable frequency drives** Typically called VFDs or invertors[4], current technology drives of this type provide a nearly ideal solution to the fan capacity control problem. In and of themselves, they tend to be more efficiency than some of the other approaches (see Figure 12.1 for a typical efficiency plat), but they also tend to maintain the fan efficiency at or near the selected efficiency as they vary its capacity by changing speed. However, this is not without its complications, but paying careful attention to design and commissioning issues can readily overcome any problems and the advantages typically outweigh the disadvantages.

---

[3] For those who are wood workers, this is basically the same approach as is used for varying speed on a Shopsmith® multipurpose tool.

[4] This is a reference to the electronic process going on in most drives; basically the drives take alternating current, rectify it to direct current perform their "magic", and then invert the direct current to create an alternating current out put with the desired frequency and other electrical characteristics necessary to control the motor.

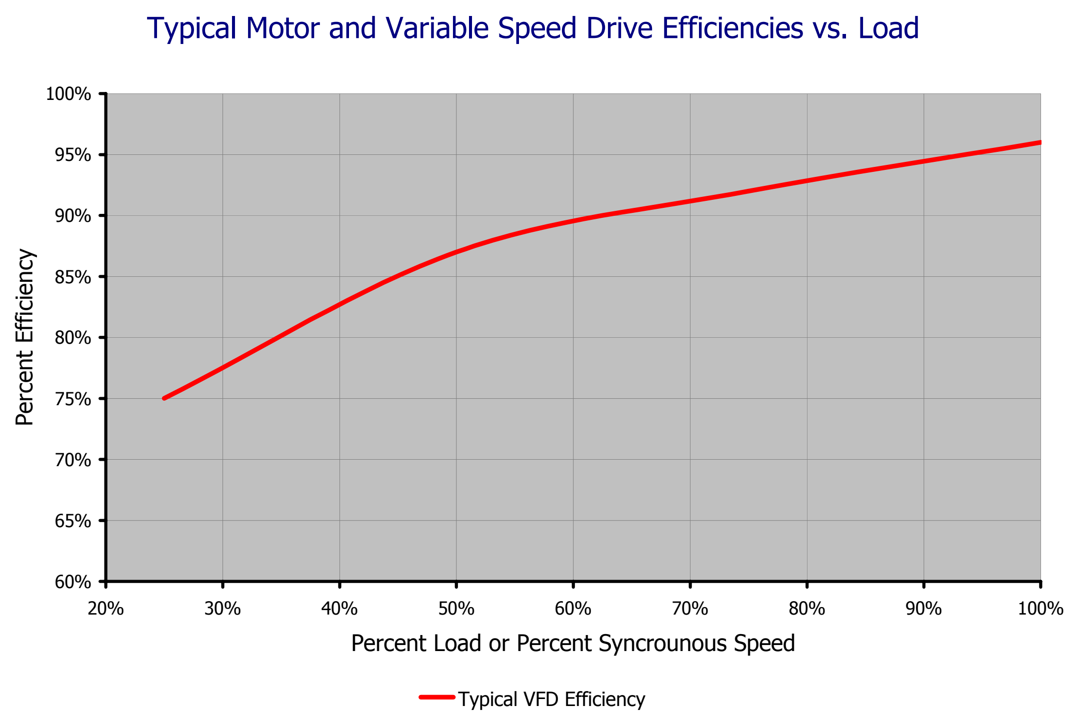


Figure 12.1 Typical VFD Efficiency vs. Speed

While efficiency does decay with load, these drives will generally deliver better efficiency and less decay than some of the other alternatives like variable pulley systems.

Regardless of the technique used, capacity control systems will subject the fan and its components to a wide array of continuously varying performance conditions. The interaction of the multiple operating points with the fan components, system components, and building can lead to a number of surprising and unanticipated problems, especially for larger fans with a lot of power. Examples include:

- On one late 1990's project the resonance between the large air handling unit fans and the building resulted in vibration in the building's structural system under certain operating conditions.
- In a semiconductor facility, resonance between process exhaust fans and sensitive machinery in the process clean room caused quality control problems.
- Over the years, there have been multiple occurrences of fan failure related to resonate frequency problems including axial fans shedding blades and centrifugal fan wheels disintegrating.

These problems can be difficult to predict and often show up as commissioning issues. Often, the most viable approach to solving them is to make sure the design incorporates features that will allow you to solve the problem if it occurs. For example, avoiding operation at the triggering condition can solve most of these types of problems. And, most current technology variable speed drives will allow you to program in multiple frequency ranges that the drive will "jump over" as it is commanded through its speed range. Thus, ensuring that the drives that will be supplied for your project include this feature can give the start-up and commissioning team the tools they need to solve this type of problem when if it crops up. Another desirable feature to include in the project is vibration analysis and documentation under a variety of operating modes for large fans, especially if they will be operating at variable capacities and speeds. It is also possible to do tests on the building structure to determine it's resonate frequency and then use that information for setting up the drive systems. The project structural engineer may also be able to predict the range of resonate frequencies anticipated for the structure and this information can be reviewed by the rest of the team in light of the anticipated operating parameters for the system to allow potential problems to be identified and addressed during design.

12.5.3. Drive systems and arrangements

In all but direct drive applications, some sort of sheave or pulley and belt system will typically be associated with a fan and its motor. It is not uncommon for one of these pulleys to be supplied in an adjustable configuration to allow the speed of the fan to be easily adjusted by the balancing contractor in the field. While desirable from this standpoint, there are several draw backs to adjustable pulleys or sheaves:

- **Belt service life** Most V-belts will provide the best service life if they run with their outside perimeter (the flat part at the open end of the V cross section) slightly above the edge of the sheaves they are installed on. If an adjustable pitch sheave requires significant adjustment, it is not uncommon for the outside perimeter of the belt to run below the top of the sheave sides. This results in extra wear on the belt and can reduce service live significantly.
- **Loss of setting** Despite its advantages, adjustability can also be the downfall of adjustable pitch sheaves. It is not uncommon for the balanced setting of the sheave to be lost inadvertently when the belts are replaced, especially if the mechanic performing the work has not been trained regarding adjustable sheaves and mistakenly thinks that the adjustability feature is a convenient way to tension the belt(s) or make the set of belts that they happen to have with them fit. As a result, the once balanced system ends up out of balance and performance suffers. If the new setting delivers less air than was intended, then capacity problems may show up at a later date when design loads show up on the system. If the settings deliver more air than was intended, energy can be wasted, especially if the system is one of the constant volume reheat systems frequently found in hospital or process environments. Both problems can lead to pressure relationship problems if the misadjusted fan happens to be an exhaust fan. If the exhaust is hazardous, a loss of airflow can create a dangerous condition in the area served by the fan that may not be immediately detected.

Fans and there prime movers come in a variety of mounting arrangements. AMCA Standard 99-86 illustrates these along with other standards related to fans and air handling units including dimensioning, motor positions, etc. This information can also be found in most manufacturers fan catalogs. Usually, one or more of the following considerations will dictate the specific arrangement:

- **The needs of the HVAC process, prime mover and drive system** Some HVAC applications may be sensitive to potential by-products from the drive system and therefor, may which to place the entire drive assembly outside of the conditioned air steam. Similarly, certain HVAC process may be a hostile environment for belts or motors and installing them outside of the air stream will improve their serviceability and service life. This can be particularly important for exhaust systems handling hazardous and/or explosive or flammable materials where a motor in the air stream could be a source of ignition.
- **The arrangement of the fan** By their nature, the arrangement of some fans precludes some of the drive arrangements. In addition, physical constraints of the fan installed location may place limitations on the type of drive arrangement that might be used.

- **Service requirements** Some arrangements may make service of the motor or fan wheel impossible in the installed location or may block access to some other component in the fan room (see Figure 12.2)

Figure 12.2 Motor and Drive Arrangement Block Access

On this new construction project, access to the inlet side of this SWSI fan, which was difficult to begin with, will be totally blocked by the belts and belt guard between the motor and shaft (red circles). It was too late to solve the problem on this project but a different arrangement may have prevented it. On this project, the maintenance staff will need to remove the belt and drives to inspect the fan wheel.

- **Balancing** A belt and pulley system provides a convenient way to adjust fan speed for balancing purposes. Direct drive fans do not have this option and require other methods to adjust for final balance such as adjustable blade pitch or a variable speed drive. Adjustable blades to not have to be automated but are labor intensive to set as compared to a sheave change. Variable speed drives are attractive from an ease of use standpoint, but add unnecessary cost, complexity, and failure modes to a constant volume system.
- **Heat gains** Because they are doing work on the air stream and air is compressible, all fans will show a temperature rise across them, even if the motor is not in the air stream. This temperature rise is called fan heat and can be calculated by converting the fan brake horsepower into btu's per hour and then solving the following equation for the fan temperature rise:

$$\textit{Sensible Heat Gain} = 1.08 \times \textit{Flow} \times \textit{Fan Temperature Rise}$$

Where:

$\textit{SensibleHeatGain}$ = The fan brake horsepower at the current operating condition converted to Btu/hr

1.08 = A units conversion constant

$\textit{Flow}$ = The flow rate at the current operating condition in cfm

$\textit{FanTemperatureRise}$ = The fan heat in °F

If the motor is located in the air stream, then the motor efficiency losses will also show up as a part of the temperature rise.[5] For large fans with large motors, this can be a significant load on the system that could be avoided by locating the motor outside of the air stream. These advantages have to be weighed against the complications this can introduce for some arrangements in terms of sealing the drive shaft where it penetrates the casing and vibration isolation.

- **Vibration and sound isolation** The method by which vibration and sound isolation will be accomplished can also affect arrangement selection. Mounting the entire fan and drive on an isolation mount will allow the assembly to be further soundproofed by locating it inside an acoustically treated fan casing at the cost of placing the motor in the air stream. By their nature, direct drive fan usually have their vibration isolation problems addressed by the motor mounting arrangement. A hidden but sometimes significant aspect of the vibration isolation technique relates to how the equipment will be seismically restrained (see Section 2.15 Supplemental Information for details).

[5] This temperature rise can be calculated in the same manner as the fan heat but the motor horsepower (vs. fan brake horsepower) at the current operating condition is used.

It is becoming increasingly common for manufactures to provide two parallel fans in packaged equipment. Usually space constraints, redundancy requirements, or both drive this design. When employed, there are several issues that need to be considered.

- **Backdraft** Even if the intent of the design is to always run two fans, it is quite likely that at some point in time a failure in the power system, drive system or fan itself will result in one fan needing to operate while the other sits idle. Backdraft dampers are commonly employed to prevent air from the active fan from recirculating into the inactive fan. However, if not carefully applied, there can be some operational difficulties that will show up during the commissioning process.
- **Surge** When two identical fans are operated in parallel, there is a potential for surge to occur between the two fans.[6] This is because it is very difficult to create two fans that are exactly identical and then get them operating at exactly the same point on their performance curve. Since the fans are coupled to the same system and but that system places them at slightly different points on their operating curves, pressure fluctuations can occur as the fans shift around and interact, trying to find a mutually agreeable operating point. The effects from this can range from unnoticeable to noise to (in rare cases) fan damage.

Chapter 18 of the *2000 ASHRAE Systems and Equipment Handbook*, AMCA publications 99-86, 200, 201, 202-88, and 203, and the *Trane Fan Engineering Handbook* are all excellent resources for additional detailed information regarding the topics outlined above.

[6] This should not be confused with the surge that can occur in a single fan if it is operated at a point on its curve where the pressure difference across it fights with the fans ability to generate that pressure difference causing sporadic flow reversals through the impeller.

Chapter 12: Tests for Future Development

Fan and Drive Tests for Future Development

The following verification checks and functional tests are not incorporated in the CTPL and are listed for reference. This section will be developed in a future revision of the FT Guide.

Variable Pitch Blade Functional Test

Capacity Control Test

Discharge pressure

2/3 rule

Optimized

Loss of Network Communications Failure Mode Test

Safety and Automation Interlock Functionality Test

Hand-Off-Auto

Inverter-Bypass

Variable Speed Drive Optimization Test

LAT Reset Interaction Test

VFD Parameter Settings Test

Capacity Test (Reference TAB report)

Seismic considerations for fan mounts

Belt tensioning and re-tensioning

Blade pitch

Variable Speed Drive Programming and Programmable Settings

External interlocks

Local control

DC injection braking

Acceleration and deceleration settings

Programmable outputs

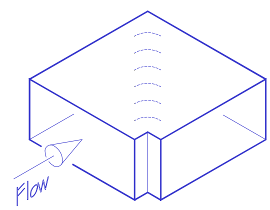
Chapter 13: Distribution

13.1. Theory and Applications

The distribution system provides the path between the air handling system and the terminal equipment that distributes the conditioned air. While relatively passive in nature, it can often account for a significant portion of the system's energy consumption due to the static pressure requirement it imposes on the fan. The few active components in the distribution system can be critical to life safety functions and can impose significant damage on the system if they function inadvertently and without adequate safety measures in place to protect the system.

Subtle differences in the way a duct fitting is fabricated can make significant differences in the pressure losses associated with the fitting. For example, the *ASHRAE Duct Fitting Loss Coefficient Tables* document five different turning vane designs with loss coefficients that vary from a low of 0.11 to a high of 0.43. Duct fittings and pressure drops are discussed in detail in Section 13.4 Supplemental Information.

There are two equations associated with evaluating the pressure loss through a duct fitting. As shown in Appendix D, the first is used to evaluate the loss as shown in Equation 13.1.



$$\Delta p_{fitting} = C_o p_{velocity}$$

Where:

$\Delta p_{fitting}$ = Fitting pressure loss in inches water column

C_o = Local loss coefficient

$p_{velocity}$ = Velocity pressure in inches water column, usually based on entering velocity

Equation 13.1 Duct Fitting Pressure Loss

This equation states that the loss through a fitting is a function of an experimentally determined loss coefficient and the velocity pressure associated with the velocity of the air flowing through the fitting. Equation D1-5 is used to convert the duct velocity to its corresponding velocity pressure.

$$V = 4{,}005\sqrt{p_{velocity}}$$

Therefore:

$$p_{velocity} = \left(\frac{V}{4{,}005}\right)^2$$

V = Velocity in feet per minute

4,005 = A units conversion constant

$p_{velocity}$ = Velocity pressure in inches water column

Equation 13.2 Velocity Pressure as a Function of Velocity

Notice that the velocity pressure is a function of the square of the velocity. That makes it a powerful relationship in HVAC systems. If you double the velocity through a fitting (i.e. you double the flow since flow and velocity are directly related), you will increase the pressure loss through the fitting by a factor of four. The magnitude of the loss will be a function of the loss coefficient, with a smaller coefficient resulting in less pressure loss.

13.2. Commissioning the Distribution System

The following tables list benefits and background information associated with distribution system commissioning. Section 13.2.1 Functional Testing Benefits helps the reader evaluate the benefits of the testing the distribution system, which should be taken into account when analyzing the costs and benefits of functional testing. Section 13.2.2 Functional Testing Field Tips focuses on practical considerations during functional testing. These considerations are intended to help the reader better understand how to perform the functional tests, with cautions about potential problems. Section 13.2.3 Design Issues Overview presents issues that can be addressed during the design phase to improve system performance, safety, and energy efficiency. These design issues are essential for commissioning providers to understand, even if design phase commissioning is not a part of their scope, since these issues are often the root cause of problems identified during system testing.

13.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	Most of the energy benefits to be realized from distribution system commissioning and testing are related to minimizing and avoiding pressure drops. There are also significant gains to be realized by ensuring that the systems will be fabricated and installed in as leak-free a manner as is warranted by the project's requirements. There are three components to this. 1. The design review process offers an opportunity to improve the design of the duct system and fittings and the manner in which the design is presented. The goal of this aspect of the review is to minimize the static pressure requirements associated with achieving the design intent. Duct leakage standards can also be set to match the requirements of the system and project at this time. By more closely detailing the design at critical locations and putting controls in to support the implementation of these details during construction, the designer saves energy in the form of reduced operating static pressure. They can also lower the safety factors associated with their equipment selections, thereby improving the match between the selected equipment and the real-time operating requirements of the system, which further improves efficiency by optimizing the equipment selection. The optimized equipment selection can also ripple back through the project to reduce first cost and conserve resources due to smaller motor sizes and the smaller electrical services associated with them. 2. The second opportunity occurs during the construction observation process. During this phase of the project, the designer and commissioning provider proactively ensure that the design intent for the distribution duct system, as defined in the contract documents, is realized in the field. They also can proactively participate in the resolution of the inevitable existing conditions conflicts that occur in a typical construction process to ensure that the field solutions will not impose an unnecessary static pressure penalty on the system. These activities help ensure that the as-installed system will meet its targeted

operating point, and thus, its targeted energy consumption.

3. The final opportunity occurs during the testing and start-up phases of the project. Through targeted verification checks and functional tests, the commissioning provider can verify that leakage requirements have been met and that the intended operating efficiencies are achieved. The commissioning provider can work with the testing and balancing team to test portions of the system where the balancing work indicates that the pressure drops are in excess of what was anticipated to identify and eliminate the root cause of the problem. The static pressure should be reduced when possible, rather than increasing the operating static requirement of the system, a common solution applied in the field when the motor has capacity available beyond the design brake horsepower requirement. This is the final step in ensuring that the operating efficiency targets set by the original design are achieved by the system in the field.

Many of the techniques utilized to troubleshoot pressure drop and capacity problems for new construction can also be used in a retro-commissioning environment to analyze systems for areas that have excessive pressure drops that may warrant the installation of an improved fitting design.

Appendix C: Calculations contains detailed descriptions and examples of techniques that can be used to project potential savings due to elimination of pressure drops and savings due to elimination of leakage (leakage calculations to be presented in a future revision of the Guide).

Other Benefits

1. Fire and smoke dampers are important components of the life safety system in any building. Coordinated testing of these devices in the manner discussed in this chapter can minimize problems associated with obtaining occupancy permits and can help ensure that ongoing service requirements can be carried out.
2. In a retro-commissioning environment, performing testing targeted at identifying and correcting high pressure drop problems in the duct system can reduce the fan energy requirements for a system. In some cases, this effort may return enough capacity that it allows an existing system to handle additional loads, thereby conserving resources and capital costs by eliminating the need to purchase and install additional central air handling capacity.
3. Functional testing of duct static pressure safety systems and pressure relief doors can help prevent major system failures. Preventing these failures improves the reliability of the systems that can show up as improved tenant satisfaction and lower risk of lost product or process down time in production environments. Resources are also conserved simply because if there is not system failure, there is not damage to repair.
4. Ongoing construction observation during system fabrication and installation can help ensure good indoor air quality by catching poor installation practices early and preventing potentially contaminated duct or duct liner from being installed without being cleaned or replaced.

13.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	Testing in the air handling distribution system is generally targeted at one of four areas: 1. Testing targeted to identify and resolve excessive pressure losses. 2. Testing targeted to identify and resolve excessive leakage. 3. Testing targeted at ensuring the viability and reliability of life safety equipment and systems. 4. Testing targeted at ensuring the functionality of the safety systems designed to protect the operating machinery.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard tool kit listed in *Chapter 2: Functional Testing Basics*, Section 2.11: Basic Tools, Instrumentation, and Equipment: 1. A duct leakage-testing machine. This is often available from the sheet metal contractor, but may require certification if it has not be certified recently. 2. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. 3. Duct fitting pressure loss tables. 4. NFPA Codes 90A and B. 5. Vernier calipers and micrometers (for verification of sheet metal gauges) 6. SMACNA Duct Construction Standards 7. SMACNA HVAC Air Duct Leakage Test Manual
Test Conditions	Test conditions will vary with the test being performed. 1. Most pressure drop testing needs to be performed with design or near design flow occurring in the system or in the branch tested. 2. Leakage testing needs to be arranged to ensure that only one pressure class is tested at a time and so that leakage from the temporary closure plates is not a significant component of the overall leakage documented by the test or can be accounted for by some means. 3. Ideally, fire and smoke damper acceptance testing needs to be coordinated to occur after all other systems and equipment in the vicinity of the dampers has been substantially complete. These acceptance tests also need to be coordinated with any external authorities having jurisdiction, such as a City Inspector, Fire Marshall, or Insurance Underwriter to be sure that their criteria will be met and occupancy permitting will not be delayed.
Time Required to Test	Time required to test is highly dependent on the test being performed. 1. Leakage testing typically requires 15 to 30 minutes per test section for the actual test. Preparation time on the part of the sheet metal contractor can be significantly longer than this. 2. Pressure drop testing can be time consuming if a pressure gradient must

be established for the entire system, but individual readings will average 5-15 minutes depending on how difficult access is. Developing a system diagram and theoretical pressure gradient can take 4-16 hours depending on the complexity of the system, the availability and reliability the of existing documentation, the level of familiarity with the required calculations held by the analyst, and the amount of field inspection required.

3. Damper acceptance testing can take between 5-15 minutes per damper depending on how difficult access is. Systems with engineered smoke control cycles and numerous operating modes can take much longer, especially if significant coordination is required between several trades to achieve success. This topic will be covered in more detail in *Chapter 17: Management and Control of Smoke and Fire*.

Acceptance Criteria

Acceptance criteria for the various distribution system tests will vary with the test performed. In general, the equipment and systems need to meet the requirements of the design intent as documented on the construction documents. Leakage and pressure drop requirements will generally be controlled by the duct and fitting fabrication techniques employed by the sheet metal contractor. In turn, the specification language, any referenced standards, and details provided on the drawings typically sets technique that will be employed. Tests for life safety related equipment will also need to meet the requirements of the applicable codes and standards, (typically NFPA 90A and B) as well as any local codes or industry related standards that may apply. (State licensing requirements for health care facilities are a good example).

Potential Problems and Cautions

Generally, the cautions employed should follow those outlined in *Chapter 2: Functional Testing Basics*. In particular, testing fire and smoke dampers in active systems places the system at risk for failure due to air hammer and related effects and proper precautions should be taken to minimize this risk.

Releasing and resetting any fire damper should be undertaken with caution due to the sharp sheet metal edges that can be encountered and the high spring forces associated with the closure mechanisms.

Opening access doors on active systems can expose personnel to significant forces created by the operating pressures on the doors, and they should proceed with caution when opening, closing, or going through these doors. They are also at risk for being trapped inside an active unit if the pressures pull the doors closed behind them. Personnel should take appropriate precautions to prevent this including working in teams and making sure that someone on the site knows where they will be working and when they expect to be finished.

Testing safety systems such as permissive interlocks, static switches, and pressure relief doors can place the operating system at risk, the exact level of which is determined by the rigor of the test. Appropriate cautions and controls should be in place when performing these tests to thwart any problems and limit the exposure of the system to damage in the event that the component under test were to fail to perform its intended function.

13.2.3. Design Issues Overview

Issue	Comments
Duct aspect ratio and duct size	Large ducts can operate at high velocities even if they are also operating at a low friction rate. High velocities imply high velocity pressures and higher losses through fittings. A poor fitting on a large duct can have pressure loss that is four or five times larger than the same fitting design applied in a smaller duct operating at the same friction rate. Supporting discussion and example calculations are included in *Chapter 13: Supplemental Information*, Section 13.5.1.1: General Rules.
Duct fitting design	Subtle differences in the way duct fittings are fabricated can have major impacts of the pressure drop (and therefore energy requirement) associated with the fitting. See *Chapter 13: Supplemental Information*, Section 13.5.1: Duct Fittings and Pressure Drops, for supporting discussion and Figure 18.1 for an illustration. Improvements can often be realized without an increase in first cost and sometimes with a reduction in first cost just by folding the sheet metal a different way. An example of the importance of attention to geometry is presented in *Chapter 13: Supplemental Information*, Section 13.5.1.3: Duct Fittings. Simply specifying SMACNA standard construction does not adequately address this issue. Figure 13.4 shows the numerous SMACNA design options.
Fan inlet and outlet conditions	The arrangement of the inlet and outlet ducts on the fan can have a significant impact on its performance and energy consumption. Refer to *Chapter 13: Supplemental Information*, Section 13.5.1.2: Fan and System Effects, Figure 13.1 for an illustration.
Flex duct selection and installation	Flex duct runs and bends can have significantly higher pressure drops than equivalent sheet metal sizes. Use should be limited or other accommodations made. See *Chapter 13: Supplemental Information*, Section 13.5.1.4: Flex Duct, for details.
Damper locking mechanisms matter	Some manual balancing damper locking designs are more robust than others, and the balancing settings made with them tend to persist longer. The avoided operations and maintenance issues associated with the better locking mechanisms quickly pay for the modest added first cost. For an example, see *Chapter 13: Supplemental Information*, Section 13.5.1.5: Manual Balancing Dampers.
Fire and smoke damper selections can significantly impact energy use	Using air foil or "out of the air stream" blade designs can reduce the pressure drop through fire and smoke dampers by 50% or more, saving significant energy over the life of the system for a modest increase in first costs. For details, see *Chapter 13: Supplemental Information*, Section 13.5.2: Fire and Smoke Dampers. The payback period for installing the increased efficiency dampers can be less than a year if the dampers are specified in the original design and have no retrofit costs associated with them. *Appendix D.2.3* illustrates a calculation to estimate the energy savings associated with airfoil blade smoke isolation dampers instead of the conventional design.
Sudden damper closures can	The pressure pulses generated by an air hammer event have rise times that

generate air hammer effects that can explode or implode duct work	are less than a second and magnitudes that exceed 15 inches w.c. (see Figure 13.8). Systems that are prone to this sort of problem need to be designed to minimize the potential for damage. For details on what systems may be at risk for air hammer and how to avoid this problem, see *Chapter 13: Supplemental Information*, Section 13.5.3: Air Hammer.
Duct leakage specifications need to be suited to the needs of the project	Duct leakage represents wasted energy. In some cases, the leakage can cause problems with maintaining the desired pressure relationships. A perfectly air tight duct system is a practical impossibility and the leakage rate is a function of a variety of parameters. Design leakage specifications and testing should be tailored to the needs of the project and the operating conditions the duct system will see. Additional information can be found in *Chapter 13: Supplemental Information*, Section 13.5.4: Duct Leakage.
Duct insulation affects energy consumption and IAQ	Duct insulation can save energy by preventing undesirable temperature changes in the distribution system, especially VAV systems operating at low flow rates. It can also prevent condensation on cold ducts and the indoor air quality and corrosion problems associated with it. Internal insulation can improve the acoustic characteristics of a system but may be more prone to IAQ problems. For this reason, internal insulation is not permitted by some jurisdictions in some applications. For more details on these issues, refer to *Chapter 13: Supplemental Information*, Section 13.5.5: Duct Insulation.
Providing good indoor air quality starts at design	Appropriate design application of duct liner and insulation can minimize indoor air quality problems due to condensation and microbiological growth. But to be effective, the material specifications need to be supported by specification requirements regarding protection of the ductwork from contamination during construction and under conditions of temporary operation. These specifications should be enforced through construction monitoring. Filtration requirements for temporary operation may actually exceed the requirements for normal operation due to the nature of the dust, the operating status of the systems and the location of the dust source. More details on these issues are presented in *Chapter 13: Supplemental Information*, Section 13.5.6: Indoor Air Quality.
Leak-free construction, cleanliness, drainage, and equipment access all are design issues that need to be considered for under floor plenums	While simple and attractive in concept, the successful design, specification and construction of under floor plenums can be quite challenging. Advantages are described in *Chapter 13: Supplemental Information*, Section 13.5.7: Under Floor Plenums. Achieving leak free construction is difficult, and the leaks that occur tend to be hundreds of small ones instead of a few large ones. Equipment locations that are not carefully considered in light of the proposed floor plan can result in major access problems when service is required. By design, the plenums will be the lowest points on the floor, and thus are subject to contamination problems due to normal debris and flooding if there is a leak above them. These issues are described in Section 13.5.7.3: Leakage, Drainage, Cleanliness and Equipment Access Requirements.
Under floor plenums can implement several different air distribution strategies, all of which require different design and control approaches	Displacement ventilation (see Section 13.5.7.1) and Under floor air distribution (see Section 13.5.7.2) both use under floor plenums as a delivery system for the supply air. However, the design and control approaches associated with these two distribution strategies are quite different and not directly interchangeable. In addition, both approaches are cooling strategies and thus are not readily adaptable to serving perimeter

	heating loads.
Seismic restraint requirements need to be clearly specified and detailed in the contract documents and submittals	Requirements for longitudinal and lateral bracing need to be clearly defined to allow the field staff to interpret them properly. The information on the contract documents and submittals needs to be supplemented with field observation during construction to verify proper interpretation. Some structural designers may require field testing of the anchor systems to verify load carrying capacity, a process that may involve the commissioning agent. Floating equipment bases and other spring isolated devices need to be sized and snubbed to withstand the design seismic loads and may require field adjustment to achieve the design intent.

13.3. Non-Copyrighted Tests

The following tests focus on the distribution system or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

13.3.1. CTPL Functional Tests

The Commissioning Test Protocol Library contains the following test that has a component focused on air handling distribution systems or related operational and performance issues.

Air Handler Functional Test

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The test contains a high static pressure alarm and shutdown test, smoke conditions test, manual smoke pressurization system test, and supply fan isolation damper test.

13.3.2. Under Floor Plenum Leakage Test

This test is not part of the CTPL database. PECI created the test to cover a level of instructional detail not currently found in the CTPL.

Functional Test for Plenum Leakage

Link to supporting information on how and why to perform the plenum leakage functional test, as well as the test form itself.

13.4. Supplemental Information

There are many hyperlinks throughout *Chapter 13* that reference supplemental information regarding the distribution system. In addition to accessing this information by clicking the hyperlinks, the supplemental information document can be accessed using the link below.

Distribution System Supplemental Information

Chapter 13: Distribution System Supplemental Information

Figures

Tables

This section provides supporting information for the functional testing and design review concepts described in the overview tables in Section 13.2 Commissioning the Distribution System. Energy saving opportunities, indoor air quality protection, and system safety cautions for the distribution system are presented to help commissioning providers identify and solve problems in the field. Since many of the issues discussed here involve distribution system design, designers and commissioning providers can use this information during the design process and design review to aid in preventing future operating problems.

13.5.1. Duct Fittings and Pressure Drops

The design and fabrication of the duct fittings in an air handling system can have a significant impact on the static pressure requirements for a system and, therefore, a significant impact on energy consumption and its ability to meet the design intent.

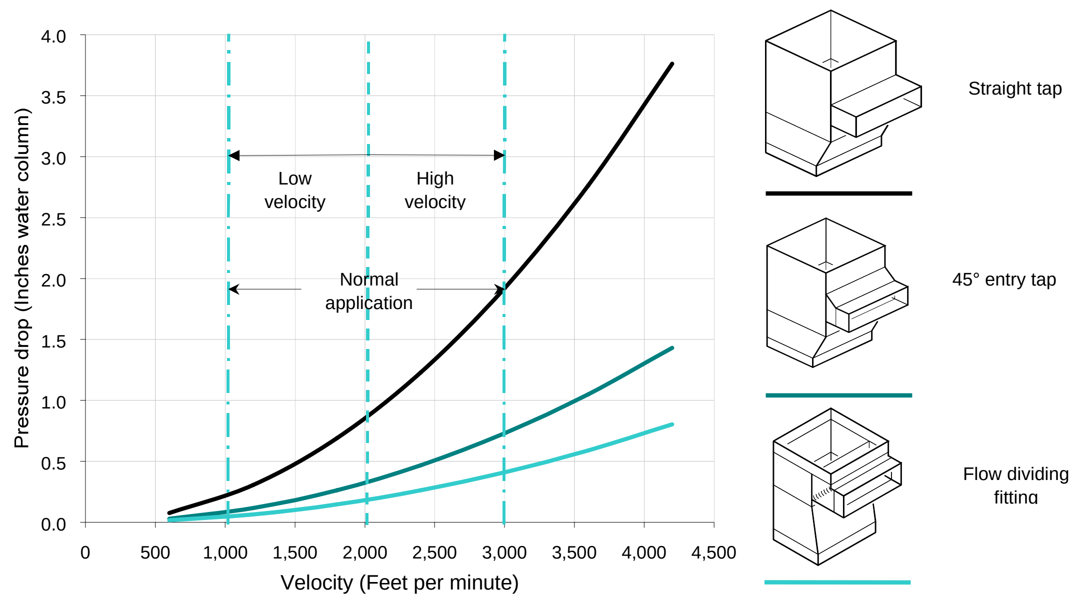


Figure 13.1 Pressure Losses Through Different Riser Connection Fitting Designs

(Courtesy of the Energy Design Resources Design Details Design Brief)

A subtle difference in the design of a fitting can have a large impact on its pressure drop. The challenging nature of the problem is often complicated by the fact that duct systems are often not well detailed. Even with adequate details, the fittings are fabricated in a three-dimensional world from representations on two-dimensional plans. In many instances, the subtle detail that significantly affects the fitting pressure loss is not apparent when viewed in plan. The 45° entry fitting shown in Figure 13.1 is a good example. When viewed in plan, the portion of the fitting that angled up at 45° would simply show up as a line, if it were shown at all. A sheet metal worker would need to understand the requirement for this type of connection from some other aspect of the construction documents or simply based on their knowledge of good practice. If they missed it and made a straight tap, they could easily double the static pressure requirements to move air into the branch from the riser, as can be seen from the graph.

The commissioning provider is in a good position to proactively promote the installation of low-pressure drop fittings through the design and construction process. During design review, the commissioning provider can help the designer understand how to best depict the fitting designs selected for the project in order to ensure their successful implementation in the field. Based on past experience and field testing, the commission provider may also be able to flag potential problem areas like the riser connection shown in Figure 13.1 and help the design team come up better solutions before the project ever reaches the field.

During the construction process, the commissioning provider can help ensure that the designer's goals are realized by observing the construction and interacting with the craftsmen to help them understand the intent of the design. Most craftsmen will want to provide a better product if they are given some guidance in the process and can implement the improvement within the constraints of their construction budget. Many of the improvements associated with good fitting design can be realized by simply folding the same piece of sheet metal in a different manner with little if any measurable increase in cost. In some cases, the improved fittings will reduce the pounds of sheet metal required.

Finally, during the start-up and functional testing of the project, the commissioning provider can target tests to verify that the systems are delivering air at or below the static pressures intended by the design. In addition, they can carry the lessons learned from these field tests back into the design process, further improving subsequent projects. The following sections target key areas for reducing system static and energy requirements. Additional information can be obtained by logging onto www.energydesignresources.com and downloading the following design briefs (located under Publications / Design Briefs), which are available at no cost:

- **Design Details** This brief illustrates how paying attention to the details of system design can yield big benefits in terms of first cost, operating cost, and improved performance.
- **Design Review** This brief provides guidance and techniques that can be used for design and construction review.
- **Field Review** The final brief in the series discusses approaches that can be used in the field to make sure that the design details are properly implemented by the trades people who fabricate the project.

13.5.1.1. General Rules

There are a few general rules with regard to duct fitting losses. The most important is that the duct fitting loss is a function of the velocity pressure in the duct, and that duct velocity pressure is a function of the square of the flow rate. In practical terms, it means that the pressure losses associated with a poor fitting in a low velocity duct system will be much less than the losses associated with the same fitting in a higher velocity duct system.

A second important rule is that the ratio of perimeter to cross sectional area for a large duct is generally much smaller than it is for a small duct. In practical terms, the velocities in a large duct will be much higher than they are in a smaller duct when designed at equal friction rates. As a result, the potential for a poor fitting to cause a static pressure problem is much higher in the larger ducts associated with an air handling system. Tables 18-1 and 18-2 illustrate some of these effects.

Table 13.1 Different Options for Moving 10,000 cfm at a Nominal 0.2 in.w.c./100 ft.; 2 inch Pressure Class Duct

Duct Size - inches			Aspect Ratio	Cross Sectonal Area - sq.ft.	Perimeter - ft.	Ratio of Cross Sectional Area to Perimeter	Gauge	Pounds of Sheetmetal per lineal foot of duct	Velocity - fpm
Height	Width	Diameter							
N/A	N/A	29	N/A	4.59	7.59	0.60	24	9.10	2,180
27	27	N/A	1.00	4.88	8.83	0.55	26	8.00	2,051
18	41	N/A	2.28	5.13	9.83	0.52	24	11.37	1,951
14	56	N/A	4.00	5.44	11.67	0.47	24	13.49	1,837
12	70	N/A	5.83	5.83	13.67	0.43	24	15.80	1,714

Note - Round duct weight information based on spiral construction.

The bottom line is that efforts to correct fitting design problems that are targeted at the duct mains will yield the most benefit for the effort and resources spent. Velocities in the mains and major duct branches in most air handling systems run in the 1,500 to 2,500 fpm range. The velocity pressures associated with these velocities are 0.15 to 0.39 inches w.c. The loss coefficients for most fittings will be direct multipliers of these numbers. In contrast, the velocities in the smaller distribution ducts serving small terminal equipment and diffusers are often below 800 fpm or a velocity pressure of 0.04 inches w.c. Thus, the difference between a poor elbow with a loss coefficient of 0.9 vs. a well-designed elbow with a loss coefficient of 0.15 may only save 0.03 inches w.c. in the low velocity network leading up to a diffuser. That same improvement in fitting design located in the main supply duct where the velocities might be running at 2,500 fpm could save 0.29 inches w.c. This static pressure savings translates into a 1/2 to 3/4 horsepower savings on a 10,000 cfm system depending on the motor and fan efficiency.

Table 13.2 Velocities and Velocity Pressures in Small vs. Large Ducts at Equal Friction Rates

Duct Size - inches			Aspect Ratio	Cross Sectonal Area - sq.ft.	Perimeter - ft.	Ratio of Cross Sectional Area to Perimeter	CFM Capcity at a Friction Rate of .15 in.w.c. per 100 ft.	Velocity - fpm	Velocity Pressure - in.w.c.
Height	Width	Diameter							
N/A	N/A	6	N/A	0.20	1.57	0.13	130	662	0.03
N/A	N/A	48	N/A	12.57	12.57	1.00	32,000	2,546	0.40
6	12	N/A	2.00	0.50	3.00	0.17	420	840	0.04
24	48	N/A	2.00	8.00	12.00	0.67	16,500	2,063	0.27

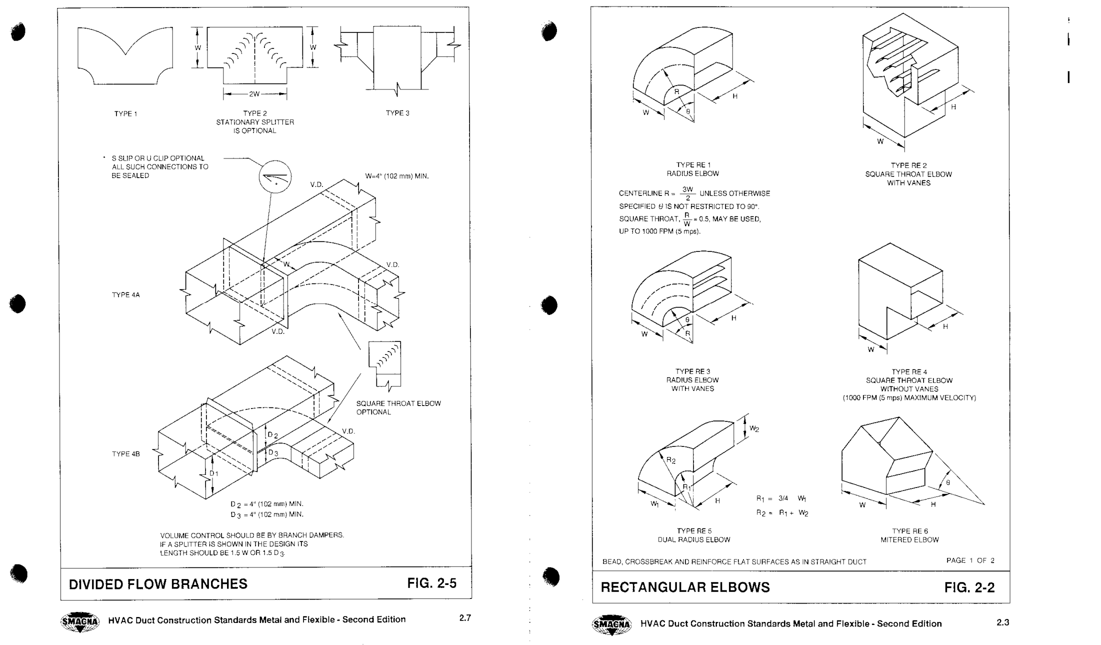


Figure 13.2 SMACNA Design Options, all with Different Pressure Loss Coefficients

(Images from the SMACNA Duct Construction Standards for Low Pressure Systems)

Finally, simply specifying SMACNA construction standards will not guarantee a good fitting solution from a pressure drop standpoint. Figure 13.2 illustrates only a few of the wide variety of elbow and fitting designs included in SMACNA standard. The standard provides for a variety of fitting configurations and then allows the contractor to tailor what they use to the design requirements of the project. The design documents need to be clear on the design requirements in order to help the contractor select the best fitting design for a given application.

13.5.1.2. Fans and System Effect

As can be seen from Figure 13.3, the orientation of a fan's discharge relative to the system that it serves can have significant impact on its performance.

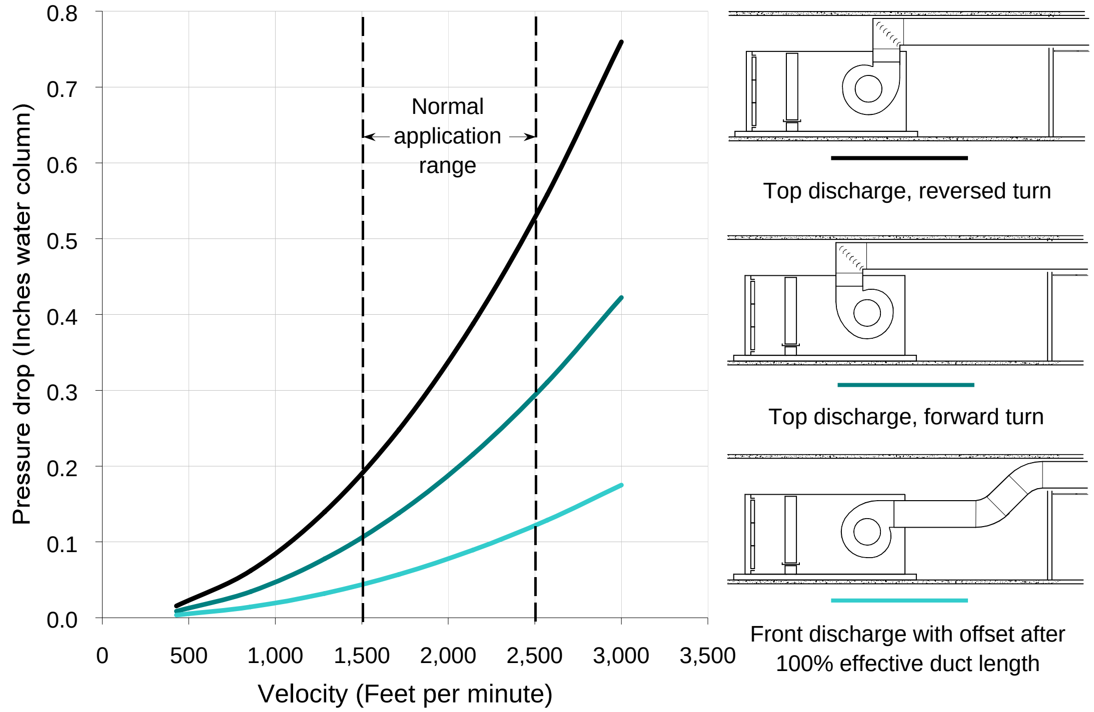


Figure 13.3 Pressure Losses Associated with Different Fan Discharge Conditions

(Courtesy of the Energy Design Resources Design Details Design Brief)

Similar effects can occur with poor inlet arrangements. By monitoring and participating in the design, shop drawing review, and construction process, the commissioning provider can help ensure that the fan orientations are optimized for the project conditions.

13.5.1.3. Duct Fittings

Figure 13.4 is another example of how a common fitting geometry can cause significant pressure loss problems. Often, a designer working on a plan encounters a situation where a duct needs to be relatively square ahead of a turn, but wide and flat after the turn. An obvious solution to the geometry problem is to increase the width in the turn and then reduce the depth after the turn.

But, as can be seen from Figure 13.4, this geometry can impose a significant pressure loss penalty on the system due to the turbulence created by the expansion in the elbow. The better geometry is to make the dimension change with a standard elbow, followed by a transition. This configuration may actually cost less to fabricate since it involves the same number of fittings but may involve less sheet metal.

Another interesting and common phenomenon is the interaction of two closely spaced fittings. The distorted velocity profile exiting the first fitting results in the performance of the second fitting being worse than predicted. As a result, the overall loss through the combination is higher than projected by the fitting coefficients if no correction is made for their close proximity, as illustrated in Figure 13.5.

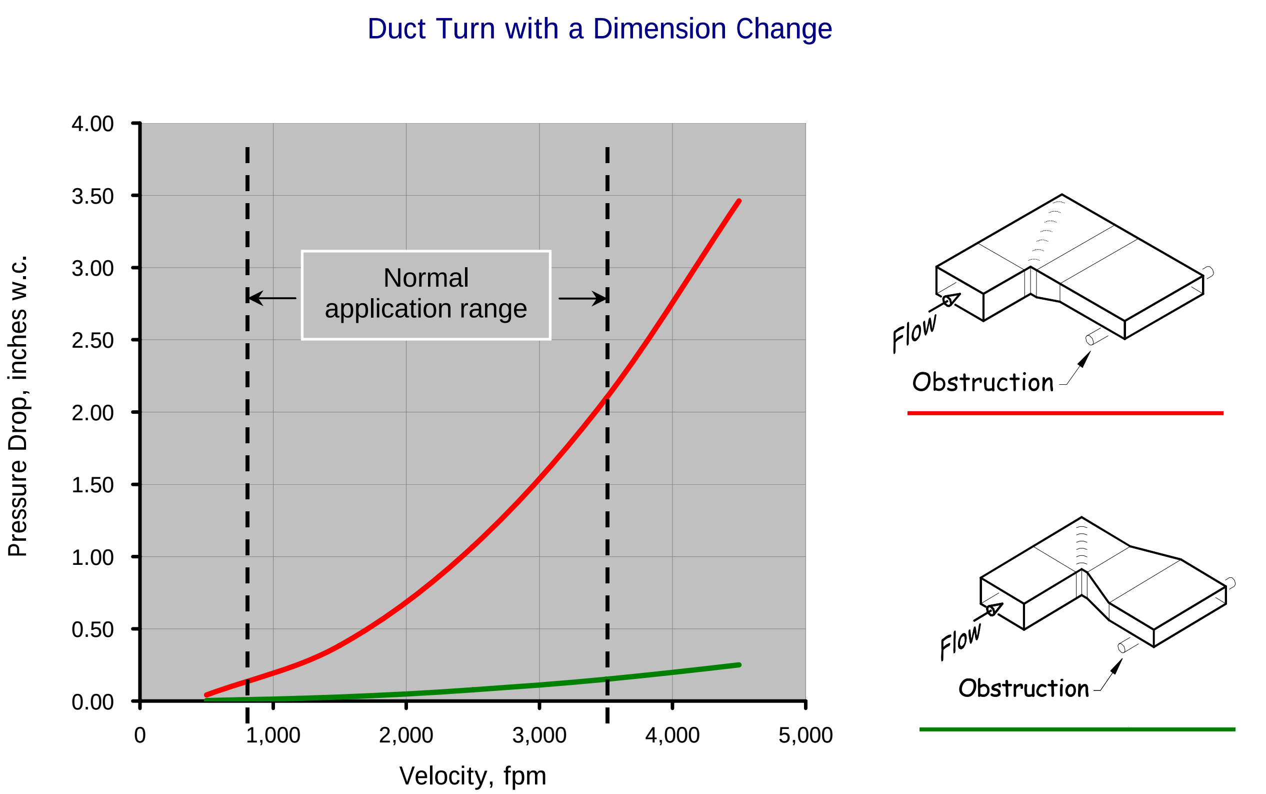


Figure 13.4 The Impact of an Expanding Elbow on System Pressure Loss

(Courtesy of the Energy Design Resources Design Details Design Brief)

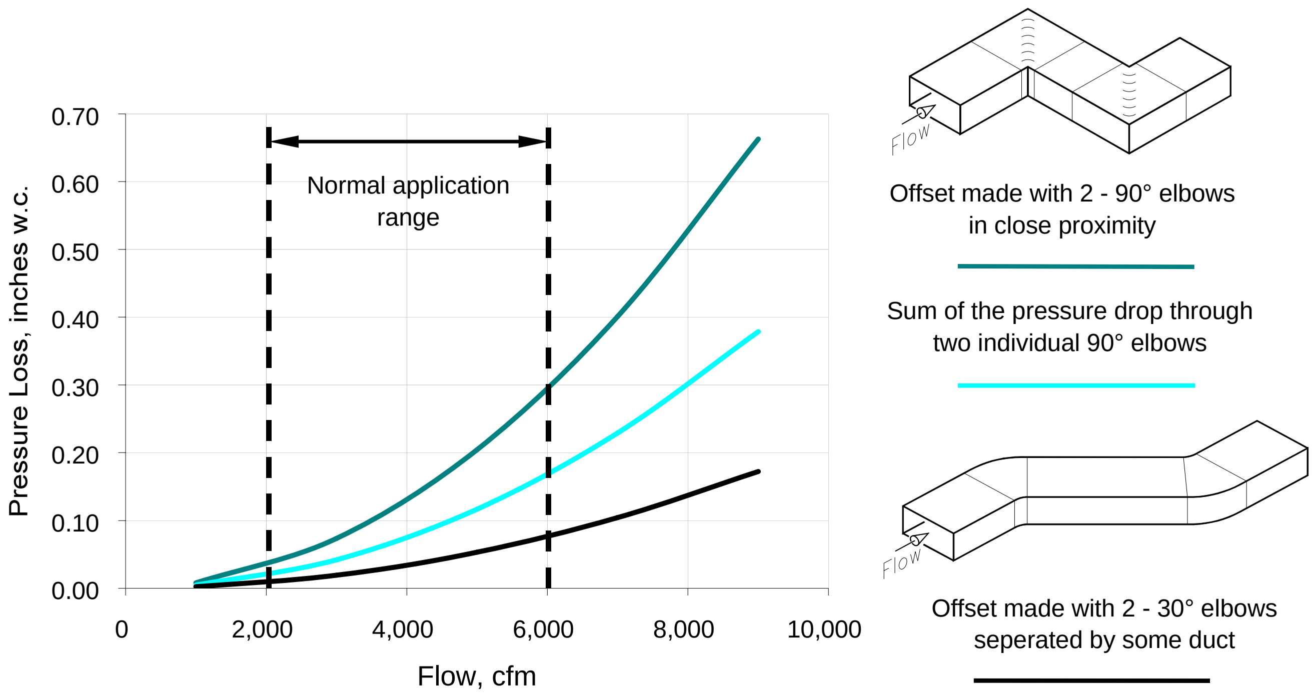


Figure 13.5 The Impact of Fitting Proximity to Each Other on Overall Pressure Loss

(Courtesy of the Energy Design Resources Design Details Design Brief)

13.5.1.4. Flex Duct

Improperly applied and supported flex duct can cause numerous operating problems. The sagging duct between supports that are spaced too far apart in effect adds close-coupled elbows to the system. Sagging aggravates the loss coefficient associated with the flex duct itself, which is often high relative to an equivalent diameter sheet metal duct due to the rougher interior surface conditions. It is also easy to make a very sharp turn with the flex duct, which may solve a space problem but can result in a very high pressure loss at the turn. These problems can be alleviated to some extent by:

- Minimizing the use of flex duct to the extent possible.
- Properly supporting the duct to minimize sagging.
- Making any turns with gradual radius to minimize bend losses.
- Oversizing the duct relative to an equivalent sheet metal size in situations where long runs or sharp turns are unavoidable.

All of these items are good to watch for during the construction observation associated with the commissioning process as well as when troubleshooting a system with high pressure loss problems in a retrocommissioning environment.

13.5.1.5. Manual Balancing Dampers

Manual balancing dampers are another seemingly inconsequential and passive item that can cause in significant energy waste and performance problems if the dampers do not retain their balanced settings. Losing balancing settings can cause the following problems:

Figure 13.6 Two Different Manual Damper Handles with Different Locking Arrangements

- **Comfort complaints**, which usually translate into labor cost in addition to any associated wasted energy cost.
- **Higher energy consumption** due to higher airflows and the possibility for unnecessary reheat. The energy waste can be particularly problematic on a constant volume reheat system where a damper vibrating open and increasing air flow to a space can be totally masked by the reheat process and therefore go undetected for years.
- **Loss of pressure relationships**, which can be critical in health care and manufacturing applications. In a hospital, an improper pressure relationship can compromise patient safety. In a clean room, an improper pressure relationship can lead to contamination of the product and a loss of tens of thousands of dollars.

Figure 13.6 illustrates to different types of manual damper handles commonly found in HVAC systems. Notice how the handle on the right locks by tightening the wing nut located a significant distance away from the shaft it is serving. This configuration gives the locking mechanism a good mechanical advantage over the forces generated on the shaft by the air flowing past the damper blade. Contrast this with the arrangement for the handle on the left, which achieves the locking action by friction between the nut, handle and support bracket, all of which are concentric with the damper shaft. Experience has shown that, when applied at velocities above 800 to 1,000 fpm and/or to large damper blades, the handle style on the right will have a much better chance of maintaining is original setting compared to the handle style on the left. Often, this benefit can be obtained by simply asking the contractor to provide the handle style on the right where appropriate as long as the request is made before materials are ordered and the duct is fabricated. Including this requirement in the contract documents will guarantee that the more persistent approach is used and provide the leverage needed to motivate a change if a problem is encountered during commissioning.

13.5.2. Fire and Smoke Dampers

Fire and smoke dampers are an integral part of most distribution systems and are critical links in the life safety systems and cycles associated with most buildings. Ensuring their functionality is an important aspect of commissioning the project, even though it may not directly affect system efficiency, which is often the real target of many commissioning efforts.

But, there is an efficiency-related aspect of fire and smoke damper selection that can have a measurable impact on energy consumption that is related to their pressure drop. Most fire and smoke dampers are a permanent fixture in the airflow path and thus represent a permanent pressure drop on the system. Selecting the dampers to minimize their pressure drop can often achieve measurable energy savings. Generally, there are two things that can be done to minimize the pressure drop associated with fire and smoke dampers.

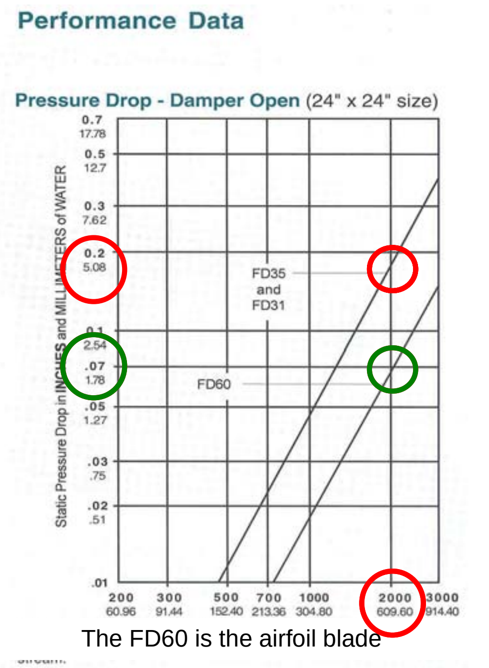


Figure 13.7 Airfoil Blade vs. Nonairfoil Blade Damper Pressure Drops

(Image courtesy of the Ruskin catalog)

Curtain type fire dampers can be provided in configurations that allow the folded blades to be totally out of the air stream in the retracted position. If sufficient space exists above the damper in its installed location to permit this, then providing this type of damper can reduce the pressure losses associated with the installation compared to an equivalent damper design that places the retracted blades in the air stream.

Smoke dampers and combination smoke and fire dampers nearly always have shaft-mounted blades that rotate around the blade axis when actuated, very similar to conventional control dampers. By providing airfoil type blades in these applications in place of the more conventional flat plate blade, significant operating savings can be realized. These pressure drops are shown in Figure 13.7.

Both of these energy saving features will most likely have some small incremental first cost associated with them. However, in most cases, the energy savings will pay for any added first cost in the first years of operation. Deferring this energy savings feature for retrofit would require removal of the existing dampers and installation of the new dampers, and the cost would be several orders of magnitude above the incremental cost difference associated with installing the energy efficient damper in the first place.

13.5.3. Air Hammer

A supply air duct high static pressure switch set at the duct pressure class rating shuts down and locks out fans to protect the air distribution system from excessive pressures that could damage ducts. This type of switch will protect the equipment from a relatively gradual over pressurization or continued operation at an over pressurized condition. Over-pressurization is created by a restriction in airflow that pushes the fan up its operating curve, and the peak on the operating curve is higher than the rated static pressure of the duct system. An example of a situation where a high static pressure switch might be desirable would be a large system that was equipped with smoke isolation dampers where the potential exists for the fan to start with the isolation dampers closed.

High static pressure switches **will not** protect a system from the effects of air hammer that can occur when fire dampers or smoke isolation dampers close suddenly with the system in operation. A fan that is moving approximately 25,000 cfm is literally moving a ton (2,000 pounds) of air a minute. In a typical commercial duct system, this air is moving at a velocity of 1,500 to 2,000 fpm or more, which correlates to a speed of 17 to 23 mph. A spring-loaded fire damper or pneumatically actuated smoke damper can close very quickly, often in a matter of seconds. If the dampers close quickly, the sudden stoppage of the moving air can generate pressures well in excess of the peak on the fan curve in fractions of a second, as can be seen from Figure 13.8. Note the high magnitude of the pressure pulse created, (both positive and negative) and the short pressure rise time. The pressures will be positive upstream of the damper as the air piles up against it and negative down stream of the damper due to the piston effect created by the mass of air moving away from it. Damage to the damper can be significant as shown in Figure 13.9.

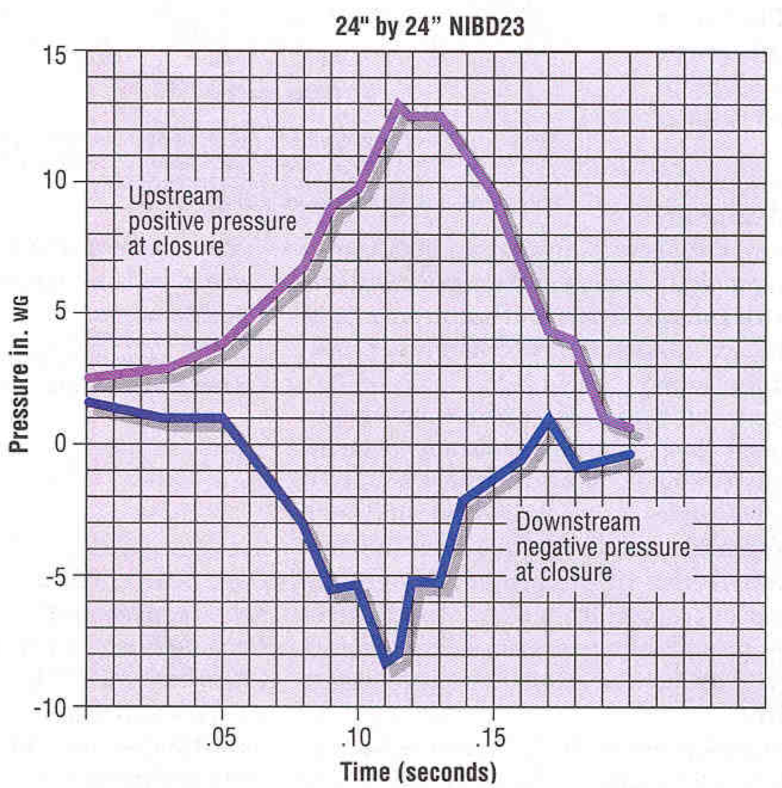


FIGURE 3. Static pressure versus time upstream and downstream of a fire damper when suddenly closed. Courtesy of Ruskin.

Figure 13.8 Magnitude and Rise Time for an Air Hammer Generated Pressure Pulse

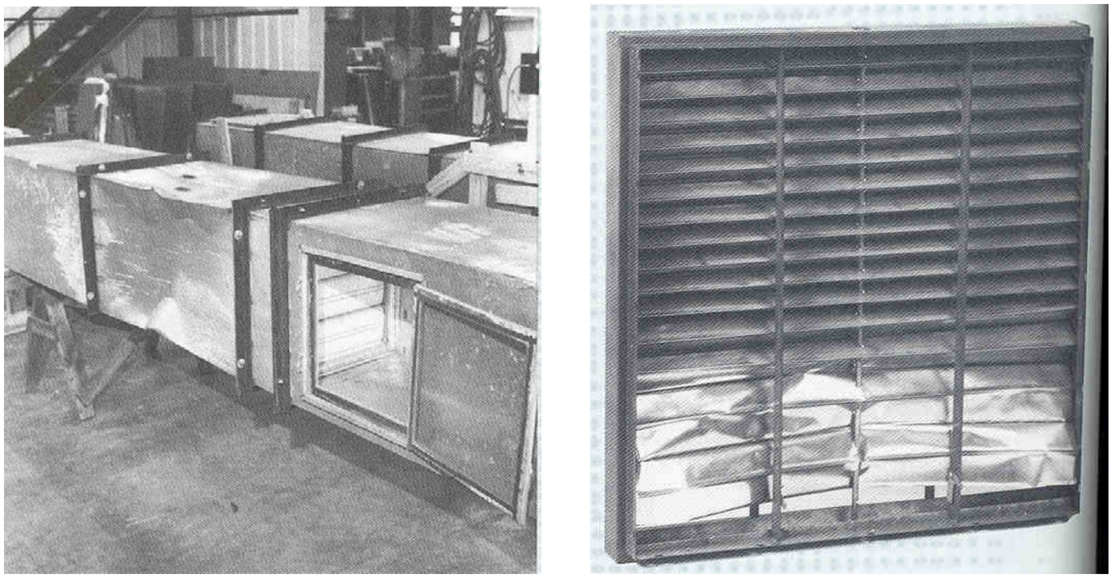


Figure 13.9 Duct and Damper Damage due to Air Hammer

(Image courtesy of the Ruskin Catalog)

Potential for Air Hammer Damage

Protecting the system from this problem can be difficult, but it is not impossible. The first step is to determine the potential for the problem to occur. Exact solutions are difficult, but by evaluating a few key criteria, one can usually assess the risk and decide if any action is necessary. Items to consider are:

- **Are the System Flow Rates and/or Velocities High?** Since air hammer depends on air velocity and flow, it tends to be a more likely problem for systems moving large volumes of air or air at high velocities. Large volumes of air equates to large masses in motion with significant inertia due to the mass. High velocity air has inertia due to the rate of movement. Thus, a 2,000 cfm supply system with duct velocities in the 1,000 to 1,500 fpm range may not represent much of a risk of failure due to air hammer. But a 2,000 cfm process exhaust system with duct velocities running in the 3,000 to 4,000 fpm range to entrain vapor and particulate matter may have a high risk of failure. Systems that have both large mass flow rates and high velocities represent the biggest risk, especially if other risk factors are present.
- **What is the Percentage of Total Flow System Flow That Could Be Stopped by the Sudden Closure of Any One Damper?** The systems that are the most susceptible to air hammer move most of the air through one damper assembly prior to branching out to serve different spaces. If a triggering event were to occur[1] in such a

[1] Examples of triggering events might include the following:

- An uncontrolled blast of heat from a heating coil due to a steam valve that failed open melts the fusible links of the fire damper in the duct main leaving the equipment room.
- The air main serving the pneumatically actuated, normally closed smoke isolation damper on the discharge of the supply fan pops off the barbed tee where it splits to the actuators, causing a sudden and total loss of actuating pressure and resulting in the nearly instantaneous closure of the dampers by the actuator springs.

system, it would cause all of the air flow to suddenly stop, and there would be no branch ducts to act as pressure relief paths for the pressure pulse that was created. If the duct system branches ahead of the problem dampers and some of the branches do not have fire dampers, at least in the immediate vicinity, then it is less likely that all of the airflow will be simultaneously stopped with no open branches to relieve the pressure pulse.

- **What are the implications for ease of repair and loss of service?** The potential penalties of taking the risk of duct failure and responding to the failure must be compared to taking measures to prevent the problem. The difficulty repairing the section of ductwork and the implications of an extended loss of service for the load served by the system should be considered. For systems where the length of duct at risk is relatively short, the duct is reasonably accessible for repair, and the implications of losing the ability to move air are not severe, the best strategy may be to simply accept the risk and minimize the potential for an event through a proactive inspection and maintenance program. In this case, a loss in service may mean some discomfort or loss of control in the space but will not place life, machinery, or product at risk, or create an excessive exposure to liability. A system where the duct at risk is a short run located in an accessible mechanical room serving an office environment where no lawyers or surgeons work is a good example of such a system.

  On the other hand, if the system contains a long run of duct at risk in a difficult to access location and/or serves a load where loss of airflow could place life or machinery at risk, result in a significant loss of product, or if it is a system serving surgeons or lawyers, then taking steps to minimize or prevent a duct explosion or implosion may be highly desirable. Systems serving clean rooms or surgical suites are good examples of this type of system. Systems serving offices in a high rise building where the air handling equipment is on one level and the duct system leaves the unit and travels to a different floor in a fire-rated chase with fire or smoke dampers leaving the chase is another good example.

Protecting a System from Air Hammer

If you are working with a system that meets one or more of the risk criteria listed above, then it would be advisable to explore options that will help protect the system from air hammer. It is fairly unlikely that the system will see a fire or smoke damper closure due to and actual fire or smoke condition during its life, but it is highly likely that it will see an accidental closure of a fire or smoke damper at some point due to a false alarm or linkage failure. The likelihood is especially high during start-up and testing. There are several measures that can be used to protect the system from air hammer.

Restrict the Operating Speed of Smoke Dampers This measure is relatively easy to implement and is probably a good idea on any smoke damper. Most codes allow for up to two minutes for the closure time for a smoke or combination smoke/fire damper. Taking advantage of this time limit will go a long way towards preventing air hammer problems in the duct system.

Figure 13.10 Precision Metering Valve and Restrictor Fittings

Both of these devices can be used to slow down the actuation time of a pneumatic smoke damper. The metering valve on the left allows the rate of closure to be precisely adjusted, while the restrictor fittings on the right allow no adjustment but also are much less expensive. The inline check valve (lower right) can be piped in parallel with any of the restrictors to allow quick opening/slow closing action to be achieved.

Electrically driven smoke dampers will have their operating speed restricted to some extent simply due to the operating time associated with a typical electric actuator. Typically, they will take at least 15 seconds to go full stroke and can take 30-60 seconds or more.

Pneumatic actuators tend to be very rapid and must be slowed down by restricting the air flow to the cylinder. In-line restrictor fittings can be installed in the line to each actuator or in the air mains to the actuators at the panel. Installing the fitting in the panel makes it more accessible and minimizes the number of restrictors. However, it does not protect the system from sudden damper closures due to a pneumatic line failure from the panel to the damper assembly. Installing the restrictor fitting at the actuator location immediately ahead of the actuator will avert this problem and provide the safest installation.

Restrictor fittings are available with a variety of port sizes from most of the control system manufacturers. It may take field testing and experimentation to find the correct orifice size for a project to provide the best rate of closure. Another option is to use a micrometer-type needle valve available from many of the precision valve manufacturers. The needle valve will allow the rate of closure to be custom tailored to the project, but is significantly more expensive since these metering valves are manufactured for process requirements.

In either case, a quick opening, slow closing feature can be provided by piping a check valve in parallel with the restrictor so that air can flow to the actuator quickly to open the damper, but must flow through the restrictor when it is bled from the actuator to close it. Some of the process grade metering valves have this feature built into them allowing both functions to be obtained in one assembly.

2 Install Fusible Links With Temperature Ratings Higher than the Maximum Temperature that can be Produced by the System This measure is also relatively easy to implement and should be considered on any system with fire dampers. In addition to preventing air hammer, installing the appropriate fusible links will help prevent nuisance fire damper closures triggered by non-fire events.

Fusible links come in a variety of ratings in addition to the standard 165°F rating (212°F and 285°F are common examples). Figure 13.11 shows a picture of typical links and some information about link options. In most instances, the code requires that the link be rated above the highest temperature that will be encountered under any of the systems operating modes with an upper limit of 350°F. It is important to select links that are rated above the highest temperature that will ever be encountered in the system. There are several situations that can result in system temperatures in excess of 165°F in the course of normal operation but are not recognized at the time of design or shop drawing review when the link rating can be easily changed. As a result, when these conditions are encountered in the operating system, they cause the fire dampers to release for non-life safety reasons. At a minimum, this can result in a flow outage and an emergency maintenance call to locate and reset the offending fire damper. Often, lack of an available replacement link in the repair parts stock makes this an arduous process. Common conditions that can lead to inadvertent fire damper trips include:

Figure 13.11 Fusible Links Before (top) and After (bottom) Failure

Most fusible links are simply two pieces of metal connected with solder with a very specific melting temperature. There are also electrical switches that use a bimetallic sensing element to provide the fusible link function. These devices are especially useful for electrically actuated combination fire and smoke dampers. At least one manufacturer that offers a manually resettable link uses a bimetallic trigger, avoiding the need to stock replacement links to address random failures.

- **Warm-up Cycles** During a warm-up cycle, air temperatures are often significantly above what would typically be encountered in the system. In some instances, the warm-up cycle fully opens the heating valve and circulates the warmest air available until the space is up to temperature. If the heating medium is of a relatively high temperature, such as low pressure steam, which can easily produce 200-230°F air if the coil is uncontrolled, the air circulated in a warm-up cycle can be above the standard fusible link rating.

- **Freeze Prevention Cycles** Some systems fully open the heating valve in the air handling unit during the off cycle in an effort to prevent freezing of any water coils in the unit. When this occurs, the stagnant air inside the air handling unit casing will approach the temperature of the heating medium, which can be in the range of 180-200°F on water systems and over 240°F for steam. When the unit starts, this slug of warm air is moved out of the unit and down the duct system and can melt the fusible links on the fire dampers.

3 Radiant Temperature Effects If a reheat coil or heating coil is located in the line of site of a fire damper and its fusible link, the radiant temperature from the coil can melt the fusible link if the surface temperature of the coil is elevated above the rating of the link. Usually, this problem occurs when the air handling system is shut down but the flow to the terminal reheat coils is not shut down. Since there is no flow over the coil, the coil surface temperature and the stagnant air in the vicinity of the coil approach the temperature of the heating medium.

4 **Reinforce the Duct System Upstream of the Damper to Withstand the Pressure Pulse** If the duct run at risk is shorter small, then the most cost effective solution may be to simply make the duct strong enough to withstand the pressure pulse should it occur. This strategy can have added benefit by minimizing duct rumble and break-out noise.

5 **Install Pressure Relief Doors** Several manufacturers offer pressure relief doors designed to blow open and create a pressure relief path when the pressure difference across them exceeds the rated setpoint. Figure 13.12 illustrates some typical product offerings along with a picture of one installed in a system.

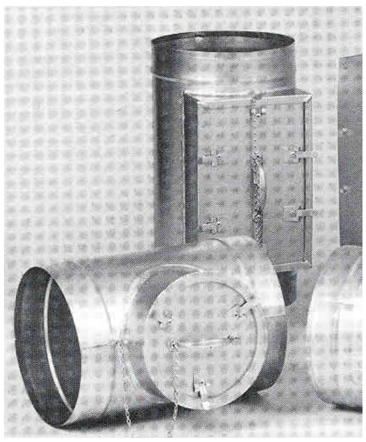


Figure 13.12 Pressure Relief Door Product Offerings and A Typical Installation

The pictures to the left illustrate one type of pressure relief door where the function is combined with the fire damper access door. The picture on the right is a different product installed in a working system. This particular product is purely a pressure relief device. This door is to relieve negative pressure and opens into the unit, so the conduit in front of it will not interfere with its operation. Notice the warning placard advising operating staff to keep clear of the area where the door will swing if it blows open. Both devices can be reset by manually reclosing the door after a trip. *(Left picture courtesy of the United McGill web site. Right picture by PECI)*

Generally, the doors are rated for a given wide-open pressure drop at a given flow rate. When applying them in a situation where they may need to relieve the air handling system's rated flow with the system operating (compared to a situation where a safety switch will shut down the fan on an over-pressure condition and the doors are just providing a relief path to protect the duct from a pressure pulse), they need to be sized to match the requirements of the system so that the pressure drop through the open blow-out door at the required flow rate will not exceed the rated pressure of the duct system.

The doors are released by a mechanism that applies the force created by the pressure difference acting on the door area against a spring via an over-center lever system. So, there is some minor movement of the door away from its seat and gaskets that increases as the pressure differences approaches the trip point. As a result, the doors will introduce some leakage into the system, especially at higher differential pressures. This data is cataloged by the manufacturer. The leakage should be included in the overall leakage allowance associated with the system.

Finally, when applying doors on a unit, bear in mind that the air that is being relieved ultimately needs to have an exit path. A pressure relief door that blows open to a confined and sealed area, like the service corridor built into large, custom roof top air handling systems may only transfer the over-pressure problem from the air handling unit casing to the enclosure envelope. Usually this problem can be addressed by providing a louvered and screened opening through the enclosure wall. The leakage from the doors into the service corridor coupled with the louvered opening can provide an added benefit by ventilating the service corridor, which can improve the reliability of controls, drives and other electronic equipment during extreme weather.

13.5.4. Duct Leakage

Air that leaks from the distribution duct system often represents wasted energy both in terms of the fan energy used to covey the air, and the HVAC process energy used to heat, cool, humidify, dehumidify, filter and otherwise condition the air. Therefore, controlling duct system leakage is an important step in controlling the overall energy consumption rate and efficiency of a system.

It is important to keep the following points in mind:

- A totally leak free duct system is a practical impossibility, but proper construction practice can yield reasonably leak free systems.
- Leakage from a duct that is downstream of the terminal equipment and ends up in the conditioned space may not be critical unless it is significant enough to prevent space temperature or pressure relationships from being maintained.
- Significant leakage from a duct system in a given area can impact pressure relationships in adjacent areas. This factor can be important in Health Care and Laboratory environments. Troubleshooting pressure relationship problems may involve some duct leakage testing to determine if duct leakage is impeding the achievement of the desired pressure relationships.

Figure 13.13 Duct Leakage Testing Machine

Most duct leakage testing machines are relatively simple devices consisting of a variable speed fan to provide the air necessary pressurization the system and calibrated orifice plates used to measure the fan's airflow. The airflow moved by the fan to pressurize the system represents the system leakage at the test pressure produced by the fan.

- The leakage classification specified for a duct system should reflect the requirements of the system and the operating conditions it will see. For example, fabricating and sealing a small, low pressure duct system to a high leakage classification may not yield measurable benefits and may actually waste more time, energy and other resources than it conserves.
- Leakage is generally related to the surface area of the sheet metal that comprises the duct system. Therefore, an extensive duct system will tend to leak a larger percentage of its total capacity when constructed to a given leakage classification than a relatively short, compact duct system constructed to the same leakage classification.

- Existing leakage guidelines, standards, and testing techniques are generally aimed at duct leakage. The leakage from the housings and casings associated with the terminal units, air handling units, diffusers, and other devices that will ultimately be connected to the duct system can be as significant if not more significant than the leakage from a well-constructed duct system. The design leakage allowances and the specified quality criteria for this equipment needs to take this into account. In some cases, independent testing of large equipment such as the air handling units or the supply plenums associated with clean rooms may be warranted.

The Sheet Metal and Air Conditioning Contractors' National Association (*SMACNA)* is an excellent source of procedural and background information on duct system leakage testing. Refer to the SMACNA *HVAC Air Duct Leakage Test Manual*, which can be found at *www.smacna.org*.

13.5.5. Duct Insulation

Most supply duct systems carry conditioned air and therefore require insulation. This insulation performs two important thermal functions and can also provide some acoustical benefit. From a thermal standpoint, the insulation ensures that the conditioned air arrives at the load at the desired temperature and is relatively unaffected by heat gains or losses through the walls of the duct between the central conditioning equipment and the terminal equipment. For ductwork handling cold air, the insulation also ensures that the surface temperature of the distribution system is maintained at a temperature that is above the dew point of the ambient environment around the duct, thereby preventing condensation. The amount of insulation required to do this will vary with the ambient temperature and humidity levels and the internal conditions inside the duct. For instance, a duct that carries 46°F 95% relative humidity air to a clean room in a roof- mounted duct in Florida will need more insulation than it would once it was inside the conditioned area.

Similar considerations apply to hot ducts, but the condensation issues are reversed. For instance, if the clean room duct discussed in the preceding paragraph (which would carry humidified air in the winter) were located on a roof in a Northern climate, the winter time ambient temperatures might cool the internal surface of the duct sufficiently to condense the humidity out of the supply stream on the inside of the duct unless the insulation was sufficient to prevent this from occurring.

Since the heat gains into the duct system are related to the surface area and the heat transfer coefficients, small ducts (with relatively large surface areas for the cross section they contain - See Table 13.1 and Table 13.2) carrying air at low velocities can show surprisingly high temperature rises in short distances if they are not insulated. These ducts contain a low mass flow rate and therefore, require very little energy input to cause a temperature change. In addition, they have an extensive surface area over which to transfer heat relative to their volume. High temperature rises may occur in VAV systems operating at low flows where the ductwork downstream of the terminal unit was not insulated as a cost saving measure. Temperature rise can also be a problem on any long, low velocity, low capacity, uninsulated duct system.

When responding to a condensation problem, remember that a relatively small leak from a duct carrying cold air can create the illusions of inadequate insulation due to the localized cooling and condensation it creates. This condition can be difficult to detect on externally insulated duct systems since the point of the leak may actually be some distance from the point where the air escapes from under the insulation and causes condensation.

Hangers and other thermally conductive materials that are indirect contact with a cold duct can end up causing condensation problems due to the cooling effect they experience by direct contact with the cold duct surface. Solving this problem usually involves insulating the hangers to a point where the conduction no longer lowers the surface temperature below the ambient dew point.

Duct systems are often insulated by using a duct liner rather than external insulation. This has the advantage of minimizing labor costs since the duct is insulated during fabrication and does not require insulation in the field. It also improves the acoustical qualities of the duct, both in terms of transmitted noise and radiated noise. However, the liner does provide an environment conducive to microbiological growth and for this reason can be an indoor air quality (IAQ) concern. In certain environments, like health care and clean room systems, codes or quality control standards prohibit the use of duct liner for these reasons.

13.5.6. Indoor Air Quality

In addition to the duct liner IAQ concerns outlined in the preceding section, the condensation issues discussed previously also have IAQ implications. Condensation inside the duct can lead to internal microbiological growth. Condensation outside the duct can cause moisture problems with other building materials, leading to both degradation and microbiological activity.

Cleanliness during construction relates to IAQ during occupancy. If the duct work on site becomes contaminated with water, construction dust, or debris prior to installation, it can result in air quality problems that are costly to correct at a later date. Figure 13.14 contrasts ductwork that was protected on a project with some that was not.

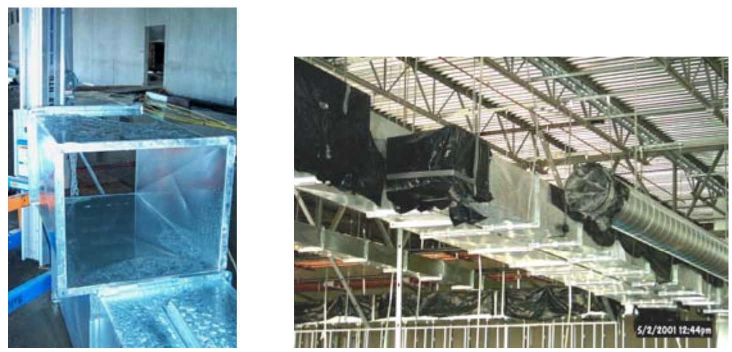


Figure 13.14 Protected and Unprotected Duct During Construction

Operating the systems to provide temporary heat or cooling during construction may also compromise IAQ if filtering is not properly applied and maintained. During the final phases of most construction projects, considerable dust can be generated by some of the finishing operations such as drywall sanding and concrete floor leveling.   This dust requires special considerations in terms of filtration that may not be addressed by the filters provided with the system for the design operating conditions. The dust from these operations is much finer than in a typical building environment and will pass through some lower efficiency filters that might be used. Therefore, adequately protecting the duct system from this dust may require using higher efficiency filters during construction than will be installed for normal operation, perhaps as high as 90-95% (ASHRAE dust spot rating). In addition, it will most likely be necessary to provide filters with a similar efficiency rating at the return and exhaust grill locations to protect the duct system from abnormal dust volumes entrained in the return and exhaust streams. Higher efficiency filtration is also advisable on the supply diffusers since there will be periods of time when the systems will be off-line or running in unusual configurations that could result in back-flow through the supply system, contaminating it from the diffuser location back.

13.5.7. Under floor plenums

Under floor supply plenums have been used in Europe for years and are starting to become common in the United States. Two subtly different cooling approaches are used with this distribution system: displacement ventilation and under floor air distribution. Both approaches utilize an under floor supply plenum as:

- A distribution technique that is flexible and easily modified when the area served is reconfigured.[2]
- A distribution technique that promotes a general upward flow of air through the occupied zone, thereby improving the removal of contaminants and the overall ventilation effectiveness.
- A distribution technique that tends to require lower static pressures and therefore less fan energy as compared to a more conventional overhead air approach.

Since air is introduced at floor level under both approaches, the supply temperature generally needs to be higher than that associated with a conventional cooling approach in order to avoid drafts and occupant discomfort. This higher supply air temperature requirement can cause humidity control and condensation problems in hot and humid environments if the processes at the central air handling equipment are not designed properly to prevent it. Since both approaches are a cooling technology, perimeter heating loads need to be addressed by an independent system.

Both approaches are often combined with task/ambient cooling where an effort is made to provide each occupant with some localized control of their environment using a mini HVAC system that, at a minimum, allows them to control the rate and direction of the ventilation and cooling air injected into their space. Some systems supplement this with radiant heat capabilities, supplemental cooling capabilities, white noise systems, and task lighting control systems. Many of the systems can provide localized occupancy control of all of these parameters with an occupancy sensor arranged to be triggered only by the zone's occupant.

13.5.7.1. Displacement Ventilation

Displacement ventilation introduces air at a near neutral temperature (i.e. at a temperature very close to the desired space temperature) into the space at a low velocity and near the floor level. As the heat gains in the space warm this air, it starts to rise. The design goal is to have the air be warmed to the design space temperature by the time it reaches the "occupied zone" between 4 and 6 feet above floor level. The heat gains in the space continue to warm the air and it rises above the occupied zone. As a result, the air exits the space at temperatures that are above the design space temperature. This design approach aims at creating temperature stratification in the space. This approach is in direct contrast to the more conventional distribution approach in which the goal of the diffusers is to induce secondary air flow into a relatively cold air stream supplied to the space resulting in complete mixing and a relatively uniform space temperature throughout the space.

Displacement ventilation allows less air to be moved by the air handling system as compared to the more conventional approach, which saves fan energy. To function as a true displacement ventilation system, the supply air must be introduced at very low velocities to ensure that no mixing will occur and to promote stratification. The low velocity tends to place a cap on the maximum amount of cooling that can be handled by the approach. Some

[2] In a modern office, this is an important consideration due to the high turn-over or "churn" rates. When properly executed, under floor plenums allow a space to be reconfigured very quickly by simply relocating the floor tiles that contain the diffusers, electrical outlets and communications outlets to match the new requirements.

systems work around this by providing supplemental, recirculating-type cooling systems in areas with higher loads than can be met by displacement ventilation alone.

13.5.7.2. Under floor air distribution

Under floor air distribution is similar to a more conventional distribution approach since the air flow rates associated with it are high enough that mixing occurs in the occupied zone, in contrast with displacement ventilation, where the goal is to avoid mixing and promote stratification. Under floor air distribution realizes some of the improved ventilation effectiveness benefits associated with displacement ventilation since the general flow through the space is from floor to ceiling. However, the higher air change rates associated with it defeats the stratification effect promoted by displacement ventilation. The air in the occupied zone tends to be more uniform in temperature, just as it would with a conventional overhead distribution system. Since supplying air at floor level requires a higher delivery temperature than that associated with a conventional system in order to avoid occupant discomfort, the net air flow rate associated with this approach will tend to be higher than the air flow associated with an overhead system. This increased air flow tends to increase the fan energy requirements. However, the lower supply system static requirements often outweigh the increased flow requirement, and the net effect is reduced fan energy compared to a conventional overhead system.

13.5.7.3. Leakage, Drainage, Cleanliness, and Equipment Access

Regardless of the approach used, the under floor supply plenum is an integral part of the air handling system, and the integrity of the plenum is critical to system performance. Excessive leakage from the plenum will result in poor performance and energy waste. During the construction and commissioning of a project that is using this technology, extensive efforts need to be made to properly seal the plenum and maintain its cleanliness. A functional test aimed at documenting the “as built” leakage rate is also advisable. In addition, remodeling and renovation projects and movement of the building over time could adversely impact the performance of the plenum. For these reasons, the following recommendations apply to systems using this distribution technique.

- Include requirements for sealing penetrations in all specifications and work orders for remodeling or renovation projects in the area. Any opening made through the floor, an exterior wall, or an interior wall that separates the office area from adjacent areas of the building needs to be sealed around the penetration. Conduits that serve as raceways between these areas need to be sealed internally in addition to having the pipe sealed to the surrounding structure. New walls or other cavities that extend from the plenum concrete floor slab into or through the occupied zone and the ceiling plenum should have the stud cavities and any other internal passages sealed to prevent air migration between pressure zones via these spaces.
- Periodically re-test the plenum leakage rate and compare it to the “as built” leakage rate documented in the commissioning process. When and if significant changes become apparent, perform additional investigation to identify and repair leaks. The test procedure associated with making this test should be included in the commissioning documentation for the project.
- When servicing equipment located in the raised floor area, minimize the amount of time that floor tiles are removed. The opening created by removing one floor tile can represent a significant leak in the plenum and may adversely affect system performance and comfort in other areas of the space.

Plenum cleanliness and water control are also important aspects related to the indoor air quality (IAQ) delivered by this type of system. During construction, the following precautions should be taken in this regard:

- Floor drains or sumps and sump pumps should be installed to provide a way of removing water from the plenum. Water could enter the plenum through a variety of sources including a leak or overflow from a plumbing fixture in a space above or adjacent to it, a leak in any HVAC or other process piping running in the plenum, or a leak through the building envelope. Floor drains should be equipped with trap primers to ensure that the water seal in the traps is maintained and prevent odor and rodent problems in the plenum. It may also be desirable to equip the traps with backwater valves that will close to prevent flow out of the sewer system into the plenum in the event of a sewer line blockage.
- Duct, pipe, and conduit runs should be supported on Unistrut™ or similar channels to provide a free and clear drainage path from any point in the plenum to the nearest floor drain or sump. Figure 13.15 illustrates this.
- Where junction boxes are secured directly to the floor, extension rings should be installed and the wiring should be arranged so all terminations and splices occurred in the extension ring, thereby elevating them above the first 1" to 1-1/2" of water accumulation in the event of a flood.
- Moisture detectors should be installed and wired to the DDC system to provide an alarm in the event that water does begin to accumulate in the floor plenum.

Figure 13.15 Typical Under Floor Plenum Piping, Duct, and Conduit Installation

Work orders and specifications for work in the plenum area should include language directed at maintaining these provisions. Preventive maintenance schedules should include verification of the integrity of the back water valves and the operation of the trap primers and moisture detectors.

Equipment access also needs to be considered during design when under floor plenums are used. Terminal equipment that is located in the plenum can become a nightmare to service if it is situated so that filing cabinets, desks and other office furniture must be moved in order to gain access for routine service requirements. A better approach is to locate the equipment so that it can be serviced by removing tiles that are located in the corridor and walkway areas in the office space. This can create some traffic problems in the office for the tenants when equipment is being serviced but usually is preferable to having to interfere with the productivity of a worker in an office or cubicle.

Chapter 14: Terminal Equipment

14.1. Theory and Applications

The terminal equipment associated with an HVAC system provides the interface between the HVAC process that conditions the air and the occupants and processes occurring in the space. For the HVAC system to be perceived as successful by the end users, the terminal equipment must reliably perform its intended function, otherwise the system will not fulfill its design intent, regardless of the level of performance at the central system.

The most common functions provided by terminal equipment are control of space temperature and indoor air quality. In addition to these functions, terminal humidity control and filtration systems are often employed in health care environments. These additional functions are also common in industrial processes like clean rooms and environmental chambers.

In many ways, the efficiency and proper adjustment of the processes used by the terminal equipment will ultimately set the overall efficiency of the air handling system. In many instances, the terminal equipment will directly or indirectly control the system flow rates and distribution temperatures. In addition, many of the central system design and performance parameters will be set by the requirements of the terminal equipment. For instance, the inlet static pressure requirement for the terminal equipment will be an important part of the design static pressure specified for the air handling unit. Some of the system and terminal equipment parameters are interactive. Minimum outdoor air settings at the central air handling unit are set based on the occupant level expected in the various zones. The minimum flow settings on the terminal units are set based on the central system's minimum outdoor air setting. If the terminal units are poorly commissioned or improperly adjusted relative to the actual loads they are serving, significant amounts energy can be wasted.

14.2. Commissioning the Terminal Equipment

The following tables outline the benefits and background information associated with testing terminal equipment systems. These tests can be used in a retro-commissioning process to define and correct existing operational issues. The tables are linked to related information throughout the Guide. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

14.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. Terminal equipment can ultimately set the overall energy consumption of the systems they serve. Thus proper commissioning of the terminal equipment is critical to ensuring the efficiency of the overall system. 2. Many current technology DDC terminal unit control systems are capable of a wide variety of control strategies. These control strategies will produce a comfortable and safe environment when viewed from the occupants' perspective, but they can have widely varying energy consumption associated with them. Matching the terminal control strategy to the requirements of the zone in a manner that provides a comfortable environment in the least energy intensive manner is critical to the overall efficiency of the building. 3. It is not unusual for an air handling system to have hundreds of terminal units. Large buildings can have a thousand or more terminal units associated with their air handling systems. Often, the drawings and other information used to install and program the terminal equipment uses a standard detail that is applied to all similar units, typically with a note like "Typical of VAV units 1-23, 29, 40-55, 75-80, and 98". One mistake in the detail or its interpretation can result in hundreds of field problems, leading to excessive energy consumption, IAQ problems, or other performance issues. 4. Many terminal unit control problems can mask each other. For example, excessive air flow may be masked by excessive reheat. Functional testing during start-up and as a part of an ongoing commissioning process, coupled with the diagnostic capabilities of current technology DDC systems can go a long way towards detecting and correcting these problems before the result in significant energy waste. 5. Many of the energy optimizing strategies employed on central systems will provide additional benefits if employed at the terminal unit level, by allowing the feature to be tailored to the requirements of the zone rather than the requirements of the overall system. Scheduling and demand controlled ventilation are good examples. Realizing these significant energy benefits requires that: ▪ Design phase commissioning ensure that these strategies are correctly applied, ▪ Functional testing ensure that they are tailored to the real world requirements of the zone, and ▪ Ongoing commissioning adjusts the zone settings to the changing requirements over the life of the building.

Other Benefits	1. Maintaining control of comfort conditions at the zone level has been shown to be influential in employee productivity. Financially, this can have even bigger implications than the energy efficiency benefits associated with proper control. 2. Maintaining control of zone temperature humidity, pressure and cleanliness criteria can be critical in process functions to ensure product quality. The financial implications of producing and delivering a poor product can be orders of magnitude larger than the energy penalties associated with poor control. 3. Control of zone air flow is crucial in maintaining proper IAQ. Loss of control of IAQ can result in discomfort or unhealthy conditions. Poor IAQ can have significant liability implications for the Owner, and the financial implications can be even greater than the energy penalties associated with poor control

14.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	Due to the high number of terminal units frequently associated with air handling systems, most terminal system functional testing verifies the performance of the equipment through spot-checking randomly selected units. The process assumes that someone other than the commissioning provider (usually the controls contractor and the testing and balancing contractor) has verified all functions on all units. The commissioning provider's functional tests are targeted at ensuring the integrated performance of the terminal unit components with each other, with the air handling system, and with the load served. The number of terminal units tested is typically based on some minimum percentage of the total and modified upward if the testing reveals a high failure rate.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following in addition to the standard tool kit listed in *Chapter 2: Functional Testing Basics*: 1. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. This equipment can also be used to verify flow rates and calibration of the flow measuring elements on terminal equipment. 2. Flow hoods for use with the meters in item 1 to allow zone flow levels to be verified at the diffuser locations. 3. Particle counters for verifying cleanliness in applications where terminal filtration is employed.
Test Conditions	1. Generally, all other system functions need to be functional and stable to allow terminal equipment testing to proceed. The terminal equipment is dependent on the systems that provide their design inlet static pressure. Without control of the static pressure and flow delivered to the terminal equipment, it can be difficult to assess if an observed deficiency is the result of a terminal unit problem or a central system problem. 2. Ideally, the conditions in the zone will reflect the occupied conditions,

	and perhaps even the design conditions. Sometimes, achieving design loads can be difficult, and the initial testing effort will need to be supplemented with ongoing trending during the first year of operation to verify that the design intent is met.
Time Required to Test	There can be a wide range of variability in the time associated with terminal system testing, since the number of terminal units that exist and are tested varies based on the building and commissioning requirements. On a per terminal unit basis, the time required can vary from 15 to 30 minutes for simple systems with successful test results to hours or even days for complex systems and/or systems where the tests reveal major control problems. Qualification testing can be particularly time consuming in surgeries and clean rooms if a rigorous humidity, temperature, particle count, and sound test regime is specified. Generally all terminal units serving loads deemed critical should be functionally tested in addition to a random sampling of other units. On some projects, all zones may be tested if the processes they serve are subject to significant penalties in terms of loss of product, loss of productivity, energy inefficiency, or occupant safety if their terminal unit control functions are not properly implemented. A commissioning provider's time to test can be adversely impacted if many of the terminal units fail the tests. When this occurs, the commissioning provider is forced to retest the failed units and may also be forced to test a higher percentage of the units on the project. On a project with a lot of problems and a large terminal unit count, the time required to complete terminal unit testing and troubleshooting can quickly spiral out of hand. These factors should be carefully considered when preparing the project specifications, budgets, and bids. Many commissioning providers include language in the specifications that obligates the contractor to pay the added costs incurred by repeated test failures and/or the need to test additional units due to poor performance of the initial test sample. If initial tests on the first two or three terminal units reveal poor performance, it may be desirable to suspend testing of additional terminal units pending further work by the contractor.
Acceptance Criteria	Terminal system functional testing acceptance often has the following two components: ▪ The acceptance of a given terminal unit based on its ability to reliably perform the required control functions. ▪ The acceptance of the project's terminal systems based on the successful performance of a designated percentage of the units. For example, the project acceptance might initially be based on testing 20% of the terminal units, selected at random. If 90% of the units tested perform satisfactorily, the project will be accepted without further testing, pending correction of any deficiencies in the tested units and perhaps some focused testing and repair based on those deficiencies. If less than 90% of the terminal units fail to perform, then the number of units tested may be increased by another 10%, and so on. It is important to adjust the test requirement percentages so they are realistic for the project. For example, specifying that 20% of the terminal units will be tested and the project will pass if 90% of those tested are satisfactory may be meaningless on a project with 5 zones of control. Similarly, specifying testing of 100% of the terminal units and requiring a

	98% success rate may be more rigor than is required for a spec office building with 300 zones.
Potential Problems and Cautions	1. Testing the terminal equipment will affect the conditions in the zone under test and may generate unacceptable zone conditions, especially if the unit fails the test. The potential impact of testing on zone conditions should be considered when planning and scheduling testing and may preclude testing with the zones occupied. 2. Design and installation problems can be quickly replicated across hundreds of units due to standard detailing and installation practices. Similarly, a test procedure that has a bug can be replicated across the units. Therefore, it is advisable on projects with many zones to test run your test procedures prior to replicating the necessary paperwork. 3. Due to high zone counts, problems with terminal unit testing can rapidly escalate into significant man-hour commitments. 4. Most terminal unit tests will manipulate the various settings in the units to force certain operating conditions and observe the results. It is critical that all parameters be returned to the correct settings and that the terminal units be verified as resuming normal function following the test. This is important with any functional test, but especially critical for terminal units since they have such a direct impact on zone comfort and IAQ conditions and on the efficiency of the system serving them.

14.3. Non-Copyrighted Tests

The CTPL contains the following tests focused specifically on testing terminal equipment. Most of these tests can be easily modified to fit different buildings and systems.

Terminal Unit Prefunctional Checklist

Link to a Terminal Unit Prefunctional Checklist, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

VAV DD, Series Fan, No Coil Test

Link to a VAV Dual Duct with Series Fan, No Coil Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

VAV DD, No Coil Test

Link to a VAV Dual Duct No Coil Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

VAV, Cooling Only Test

Link to a VAV Cooling Only Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

VAV SD, HW Reheat Test

Link to a VAV with Hot Water Reheat, Single Duct Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

Terminal Unit Cx Procedure

Link to a Terminal Unit Standard Commissioning Procedure, as prepared for Multnomah County *Oregon Document Review* by Mike Kaplan.

14.4. Supplemental Information

Supplemental information has not been developed at this time for the terminal equipment section. Link to the plans for future development of supplemental information that will be useful to solve many problems typically identified during commissioning and design review.

Chapter 14 Future Development

Chapter 14: Terminal Equipment Supplemental Information

14.5.1. Terminal Control Requirements

Temperature Control, Ventilation Control, and Loads

Trimming Humidity Levels

Final Filtration

Localized Pressure Control

14.5.2. Types of Terminal Equipment

Temperature and Flow Control

Temperature Only Based Control

Flow Based Control with Temperature Reset

Single Zone

Constant Volume, Reheat

Variable Volume, With and Without Reheat

Fan-powered, Parallel and Series

Multizone and Double Duct

Induction

Terminal Heat Pumps

Terminal Cooling

14.5.3. Trim Humidifiers

14.5.4. Filtration

Local Filter Banks

Filtration Ceilings

14.5.5. Pressure Control

Large Zones

Lab Hoods and Processes

14.5.6. Terminal Related Energy Conservation Strategies

Scheduling at the Terminal Level

Demand Based Ventilation Control at the Terminal Level

14.5.7. Testing by Sampling

Chapter 15: Return, Relief and Exhaust

15.1. Theory and Applications

Return, relief, and exhaust systems provide the network that moves the air delivered by the supply distribution system back to the air handling location. The air is then re-circulated or exhausted out of the building as required for ventilation purposes, building pressure control purposes, or to control contamination from processes. Many of the issues associated with the return, relief, and exhaust duct system are very similar to those associated with the supply duct system as outlined in *Chapter 13: Distribution*. The issues associated with the return, relief and exhaust fans and their drive systems are very similar to those discussed in *Chapter 12: Fans and Drives*. These chapters should be referenced to supplement the information in this chapter.

15.1.1. Return and Relief Systems

For air handling systems that can recirculate some of the supply air, it is necessary to provide a return system to move the air from the space served back to the air handling unit location. If the air handling system is equipped with an economizer cycle (see *Chapter 5: Economizer and Mixed Air*), it is also necessary to provide a relief path to allow the extra outdoor air introduced by the cycle to exit the building and prevent building pressure control problems. On some systems, this relief air is called exhaust air, but should not be confused with exhaust air that is provided for the purpose of control of contaminates and compliance with ventilation requirements.

In most cases, the return and relief path associated with an air handling system share the same network of duct and plenum space. The return and relief path are differentiated at the air handling unit location where the return path connects to the mixing chamber of the air handling unit and the relief path exits the building. In some cases, the relief dampers are located remotely relative to the air handling equipment to minimize the potential for recirculation into the outdoor air intake.

Ideally, the pressure drop through the return-relief network should be the same in the 100% return cycle and the 100% relief cycle. In doing this, the designer can minimize the potential for flow variation due to varying static pressure requirements in the different flow paths as the economizer system modulates from full return to full relief. Unfortunately, the configuration of many buildings and their mechanical spaces often dictates that one flow path is longer than the other. The difference in pressure drop between the return path and relief path can impact system performance in several ways:

- Building pressure relationships can vary with the position of the return and relief dampers.
- System balancing needs to occur with the system configured to operate with the worst-case pressure drop.
- Non-linearity can be introduced into the economizer cycle due to varying inlet pressures at the return and relief dampers. This non-linearity can be a destabilizing influence on the control loop associated with the economizer. The loop tuning can be affected as the seasons vary, and loop tuning can in general be more difficult.
- Non-linearity can be introduced into the return and supply fan volume control systems which can have a destabilizing influence on their control, resulting in loop tuning difficulties.

Return and relief air can be collected in ducted systems, plenums, or combinations of the two. Ducted returns usually add first cost to the project and require more coordination to fit the system with other systems located above the ceiling and in the mechanical space. Ducted returns provide the following advantages:

- Better opportunities for controlling sound
- Better methods for controlling pressure relationships
- Better resistance to tampering and contamination in areas where security is a concern.

Plenum systems make use of the existing ceiling cavity space to collect the return and relief air, and thereby have the potential to reduce construction costs and minimize coordination problems. However, plenum returns have the following disadvantages:

- Subject to leakage problems similar to those described for under floor plenums in *Chapter 13 Distribution*.
- Subject to cross talk and sound transmission between adjacent spaces without sound treatment on the return grills.
- More difficult to establish and maintain building pressure relationships with than ducted returns.
- More prone to security breeches.

High-rise buildings commonly use the mechanical shaft that houses the supply ducts and piping systems as a return pathway, eliminating the need for a return duct running the height of the building. When this occurs, it is important that the designer establish a shaft size large enough to keep the return velocities and pressure drops to an acceptable level based on the available free area after accounting for supply ducts, piping, conduit and other obstructions. In most situations of this type, the shaft will be fire rated and the penetrations into it from the ceiling return plenum or duct system will need to be protected by a fire damper mounted in the shaft wall.

Pipe, conduit and other materials installed above the ceiling in a return or relief plenum that are flammable or could generate smoke or noxious fumes in a fire must be U.L. listed as suitable for plenum use. This requirement often places some restrictions on the type of cable, pipe, and insulation that can be installed on a plenum-equipped project.

Air handling systems with a relatively short path from the occupied space to the air handling unit and relief locations can often be designed so that the supply fan can pressurize the space slightly, thereby controlling infiltration and providing the necessary force to move the air back through the return system or relief system. Systems with short return paths but long relief paths may require relief fans that operate when necessary to move air through the relief system on the economizer cycle. Systems with long return paths generally will require a return fan that is sized to handle the worst-case static pressure requirement for the return/relief system.

Control of the return and relief fans and dampers is generally integrated into the economizer control system, the building static pressure control system, and/or the supply fan volume control system. Additional information on these control functions can be found in *Chapter 18: Integrated Operation and Control*.

15.1.2. Exhaust Systems

Independent, fan-powered exhaust systems are required in most buildings to ensure that the outdoor air ventilation rates are maintained, control moisture accumulation, and remove contaminates. Building mechanical codes and industry standards like *ASHRAE Standard 62-2001 - Ventilation for Acceptable Indoor Air Quality* typically set required flow rates. In most commercial buildings, a make-up air system must replace the air that is removed from the building in order to prevent building pressurization problems due to the exhaust flow. Make-up air functions are often combined with other air handling requirements in the air handling systems that supply air based on the building loads. Bringing the make-up air in with the main air handling systems often reduces the energy requirements associated with the make-up air due to energy recovery effects from return air. For a more detailed discussion, see Section 5.1.3 Building Pressure Control and Return Air Heat Recovery.

Exhaust systems need to be interlocked with their make-up air systems to ensure that both systems function together to prevent abnormal and potentially dangerous pressure relationships from developing. On large systems, this situation could easily occur if one system were started without the other system starting. Large systems may also require a specialized start-up sequence that ensures that both systems come up to speed at the same time.

Variable flow supply systems often require variable flow exhaust systems to maintain the desired pressure relationships. These systems can be expensive and time consuming to start-up and maintain, but the energy savings associated with minimizing make-up air and exhaust air flows justifies the complexity. However, if these more advanced approaches are employed, the initial and ongoing commissioning of the systems is critical to success. Without commissioning, the failures and problems that can occur often result in operating and other costs that can be far in excess of the costs associated with a more energy intensive but less complex design.

Large exhaust systems are often good candidates for energy recovery strategies. A well-designed and implemented energy recovery cycle can often recover a significant portion of the energy required to treat the make-up air from the exhaust stream, especially the preheat energy.

In order to maintain proper pressure relationships, the make-up air must be introduced into the building in a manner that allows it to provide ventilation and reach the exhaust system via a reasonably unrestricted path. Frequently, doors to areas that have exhaust paths require an undercut if no make-up air is supplied directly to the space. Janitor's closets and small bathrooms are good examples of this type of situation. Codes usually limit the amount of undercut that is acceptable for a variety of reasons. In situations where the undercut is not sufficient to allow the necessary flow without excessive pressure drops, transfer grills can be provided between the adjacent spaces to facilitate the flow. If the wall through which the air is being transferred is part of a fire or smoke rated assembly, the transfer opening will require protection in the form of a fire damper, smoke damper, or smoke curtain.

15.2. Commissioning Return, Relief, and Exhaust Systems

The following tables outline the benefits and background information associated with testing the return, relief and exhaust systems. These tests can be used in a retro-commissioning process to define and correct existing operational issues. The tables are linked to related information throughout the Guide. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

15.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency and Other Benefits	1. Energy efficiency related benefits and other benefits for return, relief, and exhaust system commissioning are similar to the benefits associated with the supply side distribution system (*Chapter 13: Distribution*, Section 13.2). 2. Energy efficiency related benefits and other benefits for return, relief, and exhaust fans are similar to the benefits associated with the supply fan and drive systems (*Chapter 12: Fans and Drives*, Section 12.2.1: Functional Testing Benefits).

15.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test **Instrumentation Required** **Test Conditions** **Time Required to Test**	1. The background information for return, relief, and exhaust systems are similar to the information associated with the supply side distribution system (Section 13.2). 2. The background information for return, relief, and exhaust fans are similar to the information associated with the supply fan and drive systems (Section 12.2.1).
Acceptance Criteria	In addition to the acceptance criteria listed in *Chapter 13: Distribution*, and *Chapter 12: Fans and Drives*, some exhaust systems can have acceptance criteria that is related to code, OSHA dictated hazard control functions, process cleanliness, or control functions. The system designer should be familiar with these requirements and specify compliance criteria in the contract documents.
Potential Problems and Cautions	In addition to the cautions listed in *Chapter 13: Distribution*, and *Chapter 12: Fans and Drives*, working with or around hazardous exhaust may require that additional safety precautions be included in the test procedures. Typical exposure hazards may include: 1. Viral, microbiological, or radioactive contamination in exhaust systems serving laboratory system or pharmaceutical processes. 2. Acids or caustics in exhaust systems serving scrubbers. 3. Fine dust and particulates in exhaust systems serving dust collection systems and dust generating processes. 4. Explosive atmospheres in exhaust systems conveying explosive gasses or serving percholric acid hoods. 5. Non-breathable atmospheres and toxic fumes in process and laboratory exhaust systems. MSDS sheets should be available onsite for any toxic substances used in the construction process or by the Owner in their processes. Consult and coordinate with the system Owners, designers, and the Owner's Environmental Health and Safety Manager for all testing of potentially hazardous exhaust systems. Differences in static pressure requirements between the return and relief path can introduce instabilities into economizer and return and supply fan volume control loops making them more difficult to tune.

For return and relief systems, the functional testing requirements will be similar to those described for the supply fans and supply distribution system. Guidance on these topics can be found in Chapters 17 and 18, respectively. Guidance on the integrated operation of the return, relief, and exhaust system testing can be found in *Chapter 9: Economizer and Mixed Air* and *Chapter 18: Integrated Operation and Control*.

Hazardous and special exhaust systems require functional testing targeted at ensuring that special design requirements are met. Usually, these tests will by highly customized to the particular project. Testing often involves coordination with multiple parties and special preparations to execute. These considerations are similar to those associated with the testing of smoke control systems in *Chapter 17: Management and Control of Smoke and Fire*.

15.3. Non-Copyrighted Tests

The Commissioning Test Protocol Library contains the following tests that have some component that focuses on preheat coils or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

Standard Exhaust Fan Cx Procedure

Link to an Exhaust Fan Commissioning Procedure by Mike Kaplan, Multnomah County, *Oregon Document Review.*

Exhaust Fan Pre-Functional Checklist

Link to an EXHAUST FAN PREFUNCTIONAL CHECKLIST as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, PECI. 1998.

Air Handler Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The test contains a Fan Off Test, Return Fan Volume Control functional test, Return Fan Static Pressure Static Pressure Functional Test, On-Floor Return Fan Operational functional test, High Static Pressure Alarm and Shutdown Test, Smoke Conditions and Manual Smoke Pressurization System Test.

15.4. Supplemental Information

This section provides educational information that will be useful for solving problems identified during commissioning and design review.

15.4.1. Special Exhaust Fans and Systems

Some processes that occur in buildings have special requirements for the way that their exhaust is handled that are set by the nature of the area or process exhausted, the material or vapors entrained in the exhaust, and the velocities required to capture and contain the contaminates that are generated by the process. The exhaust from these processes may require special treatment prior to discharge including filtration or scrubbing (See *Chapter 22 Scrubbers* for additional information). These special exhaust systems may also require special materials of construction and wash-down and protection systems due to the vapors and materials entrained in the exhaust. Fans serving these systems may also need to incorporate these special materials and other features to safely handle the effluents. In most cases, the design requirements for these systems will be set by a variety of sources including the requirements of the process, building code requirements, and insurance underwriting requirements. There are several NFPA standards that relate to these systems. The following is a list of some examples of these special exhaust requirements.

- **Kitchen Hoods** Kitchen exhaust systems use exhaust flow to control odors, remove moisture and steam generated by dishwashing and cooking, and remove heat. The exhaust and make-up requirements for the areas served are often quite high, and the systems providing the air are often some of the most energy intensive in the building. Thus, these systems are good candidates for energy conservation and recovery strategies and worthy of ongoing commissioning targeted at maintaining them at peak operating efficiency. Often, the ducts, hoods, and other equipment associated with kitchen exhaust systems are constructed of stainless steel or welded black iron to minimize the potential for failure due to corrosion and to control a fire due to the accumulations of grease.
- **Lab Hoods** Laboratories use hood that require sufficiently high exhaust rates to ensure that odors and fumes generated in them are captured and removed from the occupied zone.
- **Hazardous exhaust** Frequently, these odors and fumes are hazardous and require special hood designs, system designs, materials of construction, and treatment of the effluent prior to discharge. Examples include acids, caustic vapors, noxious gasses, Volatile Organic Compounds (VOC's), biologically contaminated air, radioactively contaminated air, and dust. Many of the more exotic exhausts will only be encountered on production sites or at laboratory facilities.

    Percholoric acid hoods are often encountered in teaching laboratories at schools and universities. Perchloric acid exhaust will generate a precipitate that is essentially a contact explosive, and thus requires special materials of construction, fans, and a wash-down and drainage system. Caution is required when working on this type of system to prevent injury due to an explosion triggered by a tool striking some of the precipitate.

    Biologically, radioactively, and acid contaminated exhausts are often encountered in health care facilities and the laboratories serving them. Emergency rooms can be required to include special provisions in their HVAC systems related to tuberculosis, and the exhaust may be considered biologically contaminated. Similar conditions may arise with the exhaust from isolation rooms. Radiology departments can have radioactively contaminated exhaust from some of the preparatory areas as well as acid exhaust from some of the film processors that are employed. Some of these exhaust streams require filtration prior to discharge with HEPA filters installed in housings that allow the filters to be bagged and sealed as they are removed. These filters then must be disposed of as hazardous waste.

    Ethylene Oxide is frequently used to sterilize equipment and materials in health care facilities and requires special handling.

    Training shops in educational facilities often require special exhaust systems to handle dust and fumes associated with metal and wood-working operations and automobile body work. The exhaust from paint booths can be explosive in addition to being noxious and requires special treatment for both. The fine dust carried in a wood shop exhaust system can also be an explosion hazard.

Regardless of the exact nature of the special exhaust, the location of the fan relative to the termination point of the system is a very important feature in hazardous exhaust systems compared to a general exhaust system. In order to minimize the potential for the hazardous effluent to escape from the system, the exhaust fans serving hazardous exhaust need to be located at the termination point of the system so that the entire duct system is held at a negative pressure relative to the surrounding environment. This ensures that any leakage will be from the clean and safe area into the hazardous air stream. As a result, most fans handling this sort of exhaust need to be located on the roof or exterior of the building.

It is not unusual in a retrocommissioning environment to discover a fan system that violates this rule. When this occurs, it is important to bring it to the Owner's attention because the fumes that may leak from the pressurized discharge duct can create life safety problems and cause corrosion in the building envelope and structural members located in the vicinity.

In most instances, the general arrangement and design of the fans used for exhaust systems are identical to those used elsewhere in the HVAC system, and the information found in *Chapter 12: Fans and Drives* applies. Some applications, like dust control systems, require special wheel designs that are capable of handling entrained materials without damage to the fan. In small hazardous exhaust systems, especially perchloric acid systems, an ejector type fan may be used. This fan employs the venturi principle to move the exhaust by injecting a high velocity airstream into the exhaust path, thus eliminating moving parts from the flow path.

Many applications also require special materials of construction for the fans and ducts including special coatings and finishes, explosion proof construction, non-sparking construction, and special bearing and drive arrangements. Scroll access doors are desirable in HVAC applications, but are critical for exhaust system applications to ensure that the internal components of the fan can be inspected and serviced. Some fans may be required by code to have a special rating for the intended service.

Roof-mounted fans should always have their discharge duct arranged to minimize the entry of water. This orientation can require a special approach to the design of the discharge if the fan must also discharge directly upward at a high velocity to ensure that the effluent is discharged safely to atmosphere and mixed with the ambient air. Roof-mounted fans should be equipped with a scroll drain to clear any water from the scroll that gets past the discharge duct rain protection. If the fan serves a hazardous exhaust stream, the effluent from the drain may be considered hazardous and require special treatment. Effluent from the wash-down systems associated with some fans may also be considered hazardous wastewater.

In some instances, the special materials of construction cause a ripple effect in special requirements. For example, some acid resistant duct materials are considered flammable by code authorities and insurance underwriters. As a result, the duct systems constructed of these materials require fire suppression systems, usually in the form of sprinklers. The sprinklers, being exposed to potentially corrosive exhaust, require special treatments and coatings to protect them and special installation connections (typically, flexible metallic hose) and arrangements to allow them to be removed for inspection and service. Since a sprinkler discharge inside the duct system will fill the ducts with water, the ducts need to be supported in a manner that could withstand the weight of the duct if it were filled with water. In addition, the duct needs to have drainage access in the event that the sprinkler system activates. The effluent from this drain will probably need to be treated as hazardous waste. And finally, the discharge connections of the duct need to be arranged to trap water in the duct so that a sprinkler discharge does not flood the expensive and delicate process machinery served by the system.

Chapter 16: Scrubbers

Figures

16.1. Theory and Applications

Scrubbers are specialized exhaust systems that clean the effluent from a process prior to discharge to the atmosphere. Scrubbers are essentially air washers that use acids, caustics, filtration, and chemical reactions to neutralize harmful substances in the exhaust stream. They are common on industrial sites and are also starting to show up on some commercial, institutional, and educational projects as air quality standards continue to tighten.

The scrubber itself is usually a component of a scrubbed exhaust system and will typically be located at the termination point of the system, immediately ahead of the exhaust fans. Scrubbers consist of an enlarged section of the duct that contains the various spray trees, filtering elements, drift eliminators, containment basins, and pumping systems required to perform the process. Many scrubbers are partially filled with balls or other media designed to allow the passage of air while providing extensive surface area for the neutralizing reactions to occur.

Often, these units are located on the exterior of the building, partially for access reasons, but also because it creates less of a safety concern in dealing with some of the noxious and toxic substances used to react with the process stream and neutralize the effluent. As a result, there can be a significant number of support systems associated with their operation that can also require commissioning, including heat trace, water make-up, chemical make-up, fire and explosion protection, and waste water treatment.

Figure 16.1 Typical Process Scrubber

This scrubber is associated with a silicon wafer plant and is designed to remove Nitrous Oxide (NOx) from the exhaust coming off of certain processes in the plant. Each of the large, rectangular shaped objects is a stage in the scrubbing process. The exhaust fans associated with the system are on the elevated platform. The vertical ducts at the top of the picture are the fan discharges, which were designed to dissipate the effluent plume to atmosphere. The prevailing winds were a significant factor in their design.

16.2. Commissioning Scrubbers

The following tables outline the benefits and background information associated with testing scrubber systems. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

16.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency and Other Benefits	1. Energy efficiency related benefits and other benefits for scrubbers are very similar to the benefits associated with the return, relief and exhaust systems (see *Chapter 15*) 2. Scrubbers can be energy and resource intensive machines due to the pumps and fans associated with their operation as well as the supply and waste streams associated with treatment of the exhaust. Properly commissioning these systems and then employing continuous commissioning helps ensure that they continue to function at peak their performance, minimize the resources consumed and waste generated, and have a high level of reliability, which is critical from an environmental, health, and safety standpoint. Reductions in the waste stream can have a strong ripple effect by reducing the resource consumption of the waste water treatment system and fresh water used in the process.

16.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test **Instrumentation Required** **Test Conditions** **Time Required to Test**	1. The background information for scrubber systems is very similar to the information associated with the return, relief and exhaust systems (see *Chapter 15: Return, Relief and Exhaust*). 2. In addition, scrubber testing will generally have highly specialized and customized instrumentation and coordination requirements. In the general sense, these requirements are similar to those associated with testing Smoke Control Systems in *Chapter 17*, and the information presented in that section's background information table may provide some guidance in preparation of a scrubber functional test. The testing of scrubber systems will be time and labor intensive, but will be critical to safety, environmental protection, and efficiency.
Acceptance Criteria	In addition to the acceptance criteria listed in *Chapter 15: Return, Relief and Exhaust*, scrubbers can have acceptance criteria that are dictated by the Environmental Protection Agency (EPA). The system designer should be familiar with these requirements and have specified compliance in the contract documents. The designer should be able to direct you to the governing codes and standards for performance that will allow you to determine the required acceptance criteria. Generally, an Owner who requires systems of this type will have someone on staff who is charged with overseeing installation and operation. This person will be a key player in any commissioning process and may be the most familiar with the specific requirements for the scrubbers on the project. In any case, it is

	advisable to coordinate with the local EPA office to ensure that their testing criteria and requirements are addressed, including requirements to witness the tests and their documentation requirements.
Potential Problems and Cautions	In addition to the cautions listed in *Chapter 15: Return, Relief and Exhaust*, working with or around hazardous scrubbers may require special clothing and protective equipment including air quality monitors, self contained breathing apparatus, acid suits, and emergency response and confined space entry training. It may be necessary to contract with a firm specializing in this type of work. In addition, extensive coordination with the project site's environmental health and safety staff will be required to ensure that site hazard control regulations are maintained. This important process can be time consuming and should be taken into consideration when establishing budgets.

16.3. Non-Copyrighted Tests

The CTPL contains the following tests that have some component that focuses on scrubbers or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

Exhaust Fan Cx Procedure

Link to a Exhaust Fan Commissioning Procedure as prepared by Mike Kaplan, Multnomah County, *Oregon Document Review.*

Exhaust Fan Pre-Functional Checklist

Link to an Exhaust Fan Prefunctional Checklist as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, PECI. 1998.

Air Handler Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The test contains a Fan Off functional test, Return Fan Static Pressure functional test, On-Floor Return Fan Operational functional test, High Static Pressure Alarm and Shutdown Test, Smoke Conditions Test, and Manual Smoke Pressurization System

Chapter 17: Management and Control of Smoke and Fire

17.1. Theory and Applications

While simple in concept, making a smoke control cycle work involves the coordination and interaction of just about every trade involved in the project, and the solutions to potential problems can be both subtle and complex. Major reasons behind the complexities of commissioning a smoke control system are described below.

- **For the proper pressure relationships to be achieved and maintained during the smoke control cycle, the building envelope and various compartments must be relatively airtight.** This requires significant attention to the details of construction and sealing by trades such as carpenters, masons, steelworkers, and dry wallers, all of whom do not typically think of their work as being associated with the successful performance of the mechanical system.
- **The fire and smoke detection command and control logic is often split between the fire alarm system and the HVAC control system.** The fire alarm system has the inputs required to determine the state of a fire and the smoke it might be generating in the building. The HVAC control system directly interfaces with the mechanical systems that may be used by the smoke control process, but the HVAC control system typically relies on commands from the fire alarm system or manual inputs from the firemen responding to the fire to determine the proper state of the various fans and dampers.
- **The numerous components associated with making the smoke control system work are located all over the facility.** These components are often in difficult to access or concealed locations. Testing requires multiple parties stationed at multiple locations, all of whom are capable of understanding and communicating the status of various components to the test coordinator.
- **Extended operation in the smoke control or fire mode, as is often the case during initial commissioning or re-testing can subject the building and its occupants to conditions that can cause discomfort or damage in some cases.** Careful monitoring of the smoke control process during testing is essential to prevent unanticipated damage to the envelope, the building's systems, or the building's contents.
- **Barometric pressure and stack effect in a high-rise building can affect the test results given the relatively low pressure differentials that most smoke and fire management systems operate under.**

Because of all of these factors, false starts and numerous repeat tests are the rule, rather than the exception during smoke control system testing. The process of testing theses systems can take considerable time, both during initial testing and the retesting cycles that must occur to ensure the operational readiness of the smoke control systems. When working with these systems, either in a new construction environment, a facilities operations environment, or a retrocommissioning environment, the people involved in the testing need to take all of these factors into consideration and set their time and resource budgets accordingly.

Fire and smoke management systems are employed as life safety systems and are often dictated by code requirements for certain building types, sizes and configurations. In process and production environments, they can be employed to protect machinery and the area surrounding a fire from contamination and to provide a clean and clear path for the fire fighters to extinguish the fire quickly. It is not unusual for these smoke control requirements in production environments to be driven by insurance requirements rather than code due to the capital liability represented by loss of production and/or damage to equipment that could result from even a small fire. For instance, many clean room facilities have extensive smoke management systems because adjacent processes could be severely compromised by relatively small amounts of the contaminants generated in a fire.

Smoke and fire management and control systems generally provide some or all of the functions outlined in the following paragraphs. In some situations, the process is an automated cycle controlled based on inputs from smoke detectors and other components in the fire alarm system. In other situations, it is simply a manually initiated process controlled from a fireman's command and annunciation panel located somewhere in the main entry space of the building. A more detailed treatment of the subject can be found in the *ASHRAE Applications Handbook* and the *ASHRAE Principles of Smoke Management.*

Fire Management

Fire management is typically provided by compartmentalization using fire rated assemblies like the walls and floor to contain the fire in a given area for some defined interval of time. The HVAC and mechanical trades must interface with this compartmentalization any time their systems penetrate them. All penetrations must be sealed or otherwise protected to maintain the integrity of the fire separation. Typically this is accomplished by fire-stopping around the penetrating system and, in the case of ducts, by providing *fire dampers* that will contain the fire on one side of the separation.

Smoke Management

Smoke management systems are designed to modify, dilute, redirect or otherwise influence the movement of smoke in a building experiencing a fire, but not necessarily to control it or limit its movement.

Smoke Control

Smoke control systems are intended to limit and control the movement of smoke during a fire. The most common approach involves pressurizing the areas on either side of the compartment where the fire is located and exhausting the fire area. This method creates a "pressure sandwich" which tends to move air (and thus smoke) from the protected areas towards the fire and move smoke out of the fire area. While this does introduce fresh oxygen to the fire area, most systems are aimed at protecting the occupants and equipment in the adjacent compartments to allow evacuation and to allow firemen to gain clear access to the fire to extinguish it. The fire management techniques, equipment, and constructions employed around the fire compartment are relied upon to contain the fire rather than smother it by denying it air, which often will increase the smoke generated.

Stair Pressurization

Stairwells are frequently the primary escape routes for the occupants of a building in a fire emergency. In addition, the stairwells may be the primary access routes for the fire fighting teams responding to the emergency. Thus, it is critical that they remain clear of smoke for as long as is necessary to safely evacuate the building and bring the fire under control. Most high rise buildings employ a stairwell pressurization system to keep the stairs clear of smoke while operating at a low enough pressure that an average person can open the doors to enter or exit the stairwell on their way to safety.

Elevator Pressurization

Most elevator pressurization systems are designed to allow the elevators to be used by the fire fighting team responding to the fire. However, some efforts have been made to design systems to protect elevators to a level that would allow them to be used for the evacuation of handicapped individuals. While small amounts of smoke may be tolerated in the elevator if it is being used to fight a fire, smoke in an elevator used for evacuation purposes is unacceptable. In addition, if the elevator is being used to evacuate, the entry and exist paths to the elevator also need to be kept free of smoke. In both instances, the piston effect created by the elevator moving up and down the shaft can cause significant problems in controlling smoke in the elevator cab and in the areas adjacent to the shaft.

17.2. Commissioning Smoke and Fire Management and Control Systems

Due to the customized nature of smoke control systems, most test procedures will need to be developed as custom procedures for the project in question using components from the information available here and in the CTPL. The time to do so should be taken into consideration when developing the budget for commissioning this type of system.

The following tables outline the benefits and background information associated with testing smoke and fire management and control systems. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

17.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	The primary focus of any smoke control system testing is to ensure that the life safety and/or property protection functions are provided as designed. There are some energy-related benefits associated with making sure that the system reverts to normal modes after going into the emergency operating mode, but they are of secondary importance.
Other Benefits	Monitoring compartmentalized systems (like pressurized stairwells) during construction to ensure a reasonably leak-free construction can help to ensure that the pressurization systems will achieve their design intent without having to increase motor sizes or replace equipment. The energy implications associated with this are fairly small given the limited operation of the smoke control cycle. The primary benefit associated with making sure that the pressurized compartments are built in an air-tight manner is that it will expedite commissioning of the life safety functions by eliminating the need to do extensive leak testing and repair and/or equipment upgrades if the compartments fail to adequately pressurize.

17.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	To ensure the operational readiness of the smoke control system for the life safety and property protection functions associated with its design intent and required by the governing codes. In most instances, it will be necessary to successfully demonstrate the operation of this system to obtain an occupancy permit. Insurance underwriting is also may be tied to the successful completion of this test.
Instrumentation Required	Instrumentation requirements will vary from test to test but typically will include the following instrumentation in addition to the standard tool kit listed in the *Chapter 2: Functional Testing Basics*: 1. A duct leakage testing machine or blower door test set-up can be useful for troubleshooting compartments with excessive leakage rates. This instrument is often available from the sheet metal contractor, but may require certification if it has not be certified recently. 2. Inclined manometers, Magnehelics™, Shortridge Air Data Multimeters™, and other instruments capable of measuring and documenting low air static and velocity pressures. 3. NFPA Codes 90A and B as well as any other applicable codes governing the installation on a particular project. 4. A complete set of mechanical system, fire alarm system, and smoke control system drawings including a detailed narrative of the required operating sequence. 5. Multiple pairs of walkie-talkies are invaluable for performing this type of testing, especially in large buildings where multiple parties need to report results from a variety of locations.
Test Conditions	1. The building envelope needs to be substantially complete for the area to be tested. An incomplete envelope can cause problems with achieving the required pressure relationships that may cause the test to fail due to no fault of the mechanical systems. 2. All related systems should be completely operational. Interlock wiring and programming between the fire alarm system and control system needs to be fully functional and verified, as well as the interlocks between the control system and the mechanical equipment associated with the cycle.
Time Required to Test	The time required to test will vary from several hours in buildings with a few simple functions like elevator and stair pressurization to several days or weeks for a complex building with a complex smoke management or control cycle. Much coordination is required and many components must interact reliably for the test to be successful.
Acceptance Criteria	1. Performance per the design intent to the satisfaction of the authority or authorities having jurisdiction. Usually, this is the City Fire Marshall. In some cases, usually related to process or production facilities, the engineering representative from the insurance underwriter will also have significant input in acceptance or rejection of test results. 2. Successful, reliable, and repeatable recovery/return to normal operation after the test.

Potential Problems and Cautions	1. Perform practice runs of the test prior to calling the inspectors for certification. While simple in concept, smoke control systems are operationally complex and generally will take several test runs to find and correct all of the bugs and achieve reliable results. 2. Use extreme caution when performing a test during subfreezing weather. Many control sequences assume that if a fire were to occur, then sacrificing cooling coils and plumbing to freezing is an acceptable compromise in the interest of life safety and property protection. During testing, subfreezing air can quickly damage equipment and systems, making a return to normal operation difficult or impossible following the test. 3. Many smoke control cycles involve closing dampers against moving air streams and creating strong pressure gradients between various portions of a building. These pressures can cause problems with unanticipated opening and closing forces on doors and *air hammer*, especially the first time the test is run due to improper adjustments and bugs in the system logic.

17.3. Non-Copyrighted Tests

The CTPL contains the following test which has some component that focuses on management and control of smoke and fire, or related operational and performance issues. This test can be easily modified to fit different buildings and systems.

Air Handler Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The test contains a Smoke Conditions Test, Manual Smoke Pressurization System Test, and Supply Fan Isolation Damper Test.

17.4. Supplemental Information

The following information is intended to provide general guidance for functional testing of smoke and fire management and control systems.

17.4.1. Coordination

As indicated earlier in this chapter, fire and smoke management systems will often engage nearly every trade involved in the project. This involvement can be in the form of direct participation in the installation and start-up of the systems, or it can be indirect in the form of providing structures, construction, and management that will support the successful operation of the systems.

17.4.2. Certification Test

In most instances, the certification of the smoke and fire management and control functions will be one of the final steps in obtaining an occupancy permit. Without the occupancy permit, the owner will not be able to use the facility. If the owner cannot use the facility when anticipated, the following problems can arise:

- Delayed move-ins by tenants may lead to financial recourse against the owner if the tenants have liquidated damage clauses included in their lease agreements
- Delays in projects where work in one section of the building is contingent upon completion of another section so business functions can be moved to accommodate the construction.
- Delays in production.

All of these factors make timely procurement of the occupancy permit, and thus, timely certification of the smoke and fire management and control systems of paramount importance. There may be ways to work around unfinished drywall, sensor calibration problems, and final balancing, but if you aren't able to successfully certify the life safety systems, you won't be getting an occupancy permit.

For these reasons, those responsible for testing the smoke and fire management and control system should consider the following strategies:

- **Anticipate several test cycles and plan the testing schedule accordingly.** Because of the extensive coordination required between people and systems to achieve reliable smoke and fire management and control system operation, it is wise to anticipate that more than one test effort will be required to achieve the desired results. Even in a well-coordinated test, where all of the parties have made a concerted effort to prepare the portion of the system they are responsible for, a nuance may be missed. For this reason, it is seldom a good idea to invite the code official to be present for the first test of a system, especially a complex system.

- **Determine which systems are critical to successfully performing the test.** Make sure these systems are on the critical path for completion prior to the first scheduled test date.
- **Determine if there are any environmental conditions that would preclude extensive testing in the smoke management and control mode.** For example, if systems are not capable of handling 100% outdoor air at temperatures below freezing safely, then functional testing and certification testing the systems in the winter months could be extremely difficult. Similar considerations apply to systems in hot and humid environments in the summer. These outside conditions may prevent the testing necessary to meet the construction and occupancy schedule. If these conditions exist, they need to be brought to the team's attention and resolved while there is still some flexibility in the schedule. The day of the certification test is the wrong time to bring up how the ambient conditions will affect the testing.
- **Develop a procedure with system diagrams that describe the test sequence in detail.** Use this procedure in planning meetings with all parties involved to define responsibilities and clarify expectations. Use this plan during the actual testing to document the test results.
- **Plan on completing the final certification test well in advance of the scheduled date of occupancy and the date upon which the final inspection for an occupancy permit will occur.** Based on schedule changes, adjust the testing schedule accordingly or advocate against the change if it will not provide sufficient time for the test plan.

17.4.3. Leakage

Having a leaky compartment can make achieving the required smoke control system test results difficult, especially in the case of stairwell pressurization systems. Small details related to the construction of the stairwell can have significant impacts on its rate of leakage. If a compartment will not pressurize, performing a leakage test and a detailed inspection for leakage paths may be advisable before speeding up motors or ordering larger motors.

17.4.4. Door Opening Forces

With positive pressure relationships in the stair towers and potentially negative pressure relationships established on the fire floor by the "pressure sandwich" used to control smoke, the force required to open a door to the stairwell can become significant. The concern is that someone might not be able to open the door against the pressure differential induced force, and thus would be unable to enter the stairwell. Most codes restrict this force, which often requires that a pressure control system be provided for the stairwell. Inspectors often want this stairwell pressure control system to be demonstrated as a condition of acceptance, selecting the fire floor and doors to test at random. Prior to the inspector's test, it is advisable to have placed the system in the worst-case operating mode and then tested the door-opening forces. Verifying the exact technique that the inspector will be using to measure the force may also be desirable, since the results can vary depending on the measurement method. This verification process may involve setting up the "pressure sandwich" on every floor and then testing all doors, which can be time-consuming.

A quarter inch crack just ain't that important kid: *On a 13 story high rise building, the design-build mechanical contractor was having a difficult time pressurizing the stairwells. Frustrations and tensions were mounting because adjustments that ran the pressurization fan motors up to the limits of their service factor still were not producing the desired results. Time was running out if an occupancy permit was to be secured and the tenants were to be allowed to move in on schedule. Many of the new tenants would not have any office space if they were not allowed to move in on schedule. An engineer for the mechanical contractor noticed that an architectural detail relating to how the shaft wall met the slab and structural steel in the stairwell at each floor resulted in a 1/4" to 1/2" crack all the way around the perimeter of the stair shaft at each floor. When he pointed this out as a potential reason that the stairs were not pressurizing, the general contractor's foreman chuckled and said, "A quarter inch crack just ain't that important kid." The general contractor changed his mind after a quick calculation revealed that the net area associated with the crack was 20 to 30 square feet when the perimeter at all floors was taken into consideration. That was the same as having two of the stairwell doors standing wide open all of the time. Caulking the crack solved the pressurization problems and the fans were returned to the original speed settings specified by the designer.*

17.4.5. Piping and Condensation Protection

Many smoke and fire management and control systems use the HVAC air handling equipment to provide the make-up and exhaust air capacity required for the smoke control and management functions. Usually to meet these air flow requirements, the system is placed in a 100% outdoor air operating mode. While this mode of operation may be normal for the system when it is on an economizer cycle, many HVAC systems serving office buildings do not have the preheat capacity or coil piping configurations to allow them to handle 100% outdoor air safely when the outdoor air temperatures are below freezing. It is not uncommon for the design philosophy in these situations to be that the water coils will be sacrificed if necessary in the interest of life safety, and the control system actively jumps out the freezestat during the smoke cycle. While this concept is reasonable in the context of a real fire, it is worthy of careful consideration in the context of smoke and fire management control system testing and false alarms.

While it is unlikely that most buildings will experience a fire event of sufficient magnitude to trigger a smoke management and control cycle in the course of their operating life, it is highly likely that they will experience a false alarm that will trigger the cycle. This event could occur on the coldest or hottest day of the year or when nobody is in the building to respond to the problem in a timely manner. As a result, one or more of the following situations may occur:

- If it is below freezing, the water coils in the unit may freeze. Freezing can occur in a matter of minutes. If it is extremely cold, the water can freeze even if the circulating pumps are operating. If the system remains in this mode for an extended period of time during subfreezing weather, plumbing and sprinkler lines in the building can freeze, especially lines in close proximity to supply diffusers or in the path of infiltration that might be caused by the 100% exhaust portion of the control cycle.
- If it is warm and humid outside, the introduction of significant volumes of hot and humid unconditioned air into the building can result in water damage from condensation, especially if the chilled water plant or cooling system was off-line when the problem occurred. When the humid air comes in contact with equipment and building materials with a surface temperature below its dew point, the water will condense onto the cooler surface. The condensation can damage finishes and, in the case of laboratories, surgeries, and process plants like clean rooms, the condensation can ruin materials and products.

It is important to assess how susceptible the system is to problems with introducing 100% outside air during extreme weather. At a minimum, these issues should be discussed with the Owner and the design team to understand how they anticipated dealing with these occurrences. Document the procedures in the project's operating manuals and commissioning reports. These issues can also impact how long the functional testing will take and what preparatory steps need to be taken to allow the testing to proceed without endangering the equipment or building materials and finishes.

Even if the owner is willing to accept the risk of damage due to a false trip of the system, there are still issues to deal with if the commissioning and acceptance phases of the project occur during extreme weather. In most instances, troubleshooting problems with the system will require sustained operation in the smoke control cycle for much longer than would be required for a certification test. If the schedule cannot be adjusted to allow the testing to be performed during moderate weather, it may be necessary to *drain coils* for the duration of the test process and/or only test for short intervals of time. These changes can significantly extend the test cycle and make troubleshooting more difficult.

Even if the preparatory testing can be performed prior to the acceptance test, if the acceptance test falls on a day when the weather is extreme, it will be necessary to take the appropriate precautions to protect the systems. It may be necessary to develop a contingency procedure that will allow the project team to quickly drain coils and take what ever other steps are necessary immediately before the demonstration to the code

Chapter 18: Integrated Operation and Control

Figures

18.1. Theory and Applications

From a holistic perspective, air handling systems represent some of the most complex, interactive systems tested in the course of commissioning a project. Components must interact successfully under a wide array of operating conditions. Instabilities in part of the system can often cascade into system-wide or even building-wide problems. Further complicating the situation, the time constants and other parameters associated with system and control loop stability vary with the seasons and the age of the equipment. A system that is stable in one operating mode may exhibit erratic performance when the seasons change or fouling of a heat transfer surface shifts performance outside of the original operating envelope. The true test of whether or not an air handling system is performing according to its design intent is how well the various components are integrated with each other.

Just as proper integrated operation of the air handling equipment relies heavily on the robustness of the individual components and the thoroughness of the commissioning targeted at these components, the content of this chapter relies heavily on the content of the other system component chapters. To understand how the various components function together in an integrated fashion, one first must understand the individual components, and then build on that knowledge.

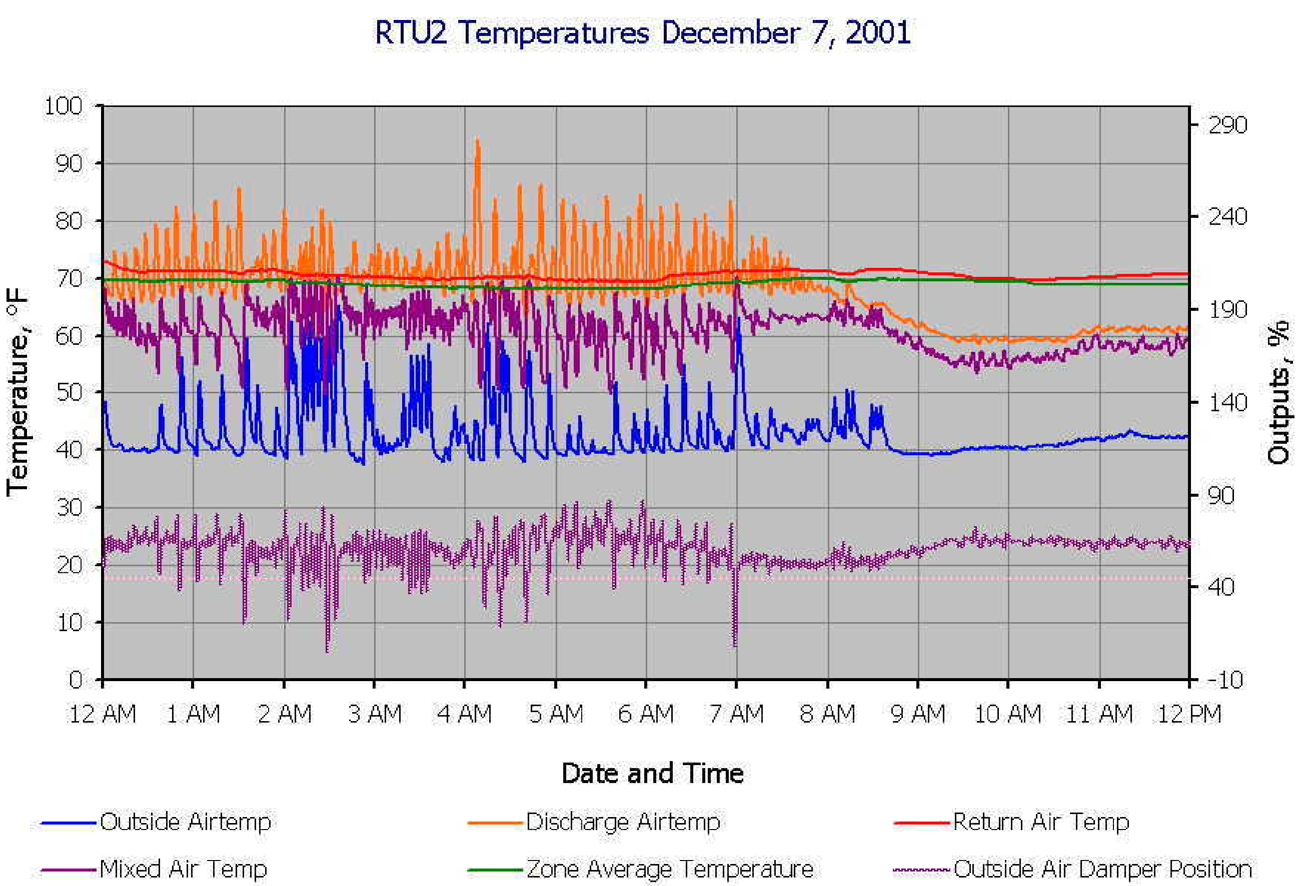


Figure 18.1 Instability in one loop triggers instability elsewhere in the system

Systems can mask problems when viewed from the perspective of the occupants of the space.

In this example of a VAV system in Figure 18.1, instability in the hot water valve loop triggered problems with the economizer control loop, the fan speed control loop, the relief damper control loop, and building wide functions triggered by outdoor air temperature. During the trend window, the most common indicator of acceptability - occupant comfort - was satisfactory. As can be seen from the stable zone temperature in Figure 18.1, a dysfunctional system can appear to be working fairly well if the acceptance criteria is occupant comfort.

In this example, even though the zone temperatures were tracking set point reasonably well, nearly all control functions of the system were erratic for significant portions of the test window. In addition, the relief problems associated with the building static pressure control instability coupled with a poor outdoor air sensor location resulted in outdoor air temperature being influenced by the relief air. Consequently, the false and rapidly changing outdoor air temperature reading caused functions that were based on outdoor air to be activated and then deactivated on a relatively short time frame. This trend, while revealing the symptoms, also gave strong clues as to the root cause. When the heating valve was forced closed by another control function related to the space conditions, everything stabilized, which was a strong indicator pointing to the hot water valve as a root cause. Thus, the first step in solving the problem involved tuning the hot water valve control loop and relocating outdoor air sensor. Once these problems were solved, other issues could be addressed.

The problems documented by the trending had been occurring for days or even weeks but had gone unnoticed by the building occupants because their primary indicator of functionality, space temperature, was fine. The thermal inertia of the building and the system interactions completely masked the problem from the occupants perspective.

2 Independent control functions that are satisfactory when tested on their own can become unstable in the context of overall system performance.

It is important to test the independent control functions prior to testing the integrated functionality of a system. For example, systems may have independent control loops for the various heat transfer elements (i.e. the heating coil, cooling coil, economizer dampers, etc.), which are then integrated to maintain the leaving coil air temperature. Without verifying that each of these components is fully operational, the root cause of problems that occur during integrated testing will be more difficult to identify since malfunctions in one loop can lead to problems in the others.

Proper integrated operation of air handling equipment is critical if the system design efficiency is to be realized. Problems like those depicted in Figure 18.1 can waste significant amounts of energy and lead to premature equipment failure. These problems often go undetected due to the capacity of HVAC systems to compensate and show little noticeable disruption at the occupied space.[1]

For more information regarding the application and tuning of PID control loops, see Section 18.4 Supplemental Information.

[1] For example, it is quite common to find a reheat coil masking the effects of an out-of-control or improperly adjusted minimum flow setting on a VAV terminal by simply reheating the excess flow as necessary to maintain space temperature.

18.2. Commissioning for Integrated Operation and Control

The following tables outline the benefits and background information associated with testing for integrated operation and control of the entire air handling system. These tests can be used in a retro-commissioning process to define and correct existing operational issues. The tables are linked to related information throughout the Guide. Refer to *Chapter 2: Functional Testing Basics* for guidance related to all functional testing activities, regardless of the component or system being tested.

18.2.1. Functional Testing Benefits

Benefit	Comments
Energy Efficiency Related Benefits	1. Commissioning to verify the integrated functionality of the air handling system ensures that the system will operate at peak efficiency and to the fullest realization of its design intent. 2. The detailed trend analysis often associated with integrated control system functionality testing will frequently reveal inefficient operation that is masked. This masking prevents the problem from being observed via more common indicators, such as occupant comfort. Integrated testing techniques can identify and eliminate the root cause. 3. Integrated control system functional testing will often uncover nuisance problems that could cause the systems to be operated in a more energy-intensive manner to prevent the nuisance problem. Uncovering and correcting these nuisance problems helps ensure the persistence of the system's efficiency, especially when supplemented by training and smart alarms to help provide ongoing monitoring of select issues. 4. Many energy conservation strategies involve successfully optimizing interactive relationships among the components of the air handling system. Testing the integrated performance of the components in light of the conservation strategy employed helps to ensure that the original design intent is met.

18.2.2. Functional Testing Field Tips

Item	Comments
Purpose of Test	Integrated functional testing of control strategies adds an additional level of reliability to the performance of the system by verifying that each independently commissioned component also functions as intended when interacting with the rest of the system. Integrated functional testing carries functional testing beyond the individual system elements and into the complex interactions that will occur during the system's operating cycles.
Instrumentation Required	Instrumentation requirements typically will include the standard toolkit listed in *Chapter 2: Functional Testing Basics*. Since integrated testing looks at the interactions of the system over time, extensive trending capabilities in the EMS is essential. Even with an EMS trending capability,

	supplemental data loggers can provide a means to gather data where rapid sample times are required and data that is not monitored by the EMS. In the absence of an EMS, it may be necessary to augment the number of data loggers available in the commissioning provider's stock by renting additional loggers and input modules for the duration of the start-up process and perhaps a significant portion of the warranty year. This added cost should be considered when preparing budgets and bids.
Test Conditions	Integrated testing can only occur after all other components in the system are deemed complete and in a state of operational readiness. If the responsible parties do not feel they are ready to have their particular component tested in relationship to the system-wide interactions, then proceeding with integrated testing may produce inconclusive results since problems may be blamed on equipment that was not fully commissioned. However, integrated testing may reveal that a component that was certified as being ready for test was not ready. This problem is one of the reasons for performing integrated testing.
Time Required to Test	The time required to test will vary with the testing technique used (active or passive), the specific test procedure employed, and the test preparation and follow-up time. Passive testing relies on the actual system interactions in the operating environment to reveal problems through trend logging. This passive testing process can last for months or even through the first year of operation. In this situation, the activity and effort associated with the testing is concentrated at the following points in the process: a. Trend files must be set up and/or data loggers must be deployed at the beginning of the process. b. During trending, the trend data is downloaded and analyzed at a number of points in the process. Typically, these points will occur after an operational change or by season. Common points are at the end of the first week of scheduled operation, after a week of peak heating and cooling operation, and after a period of the "swing season" weather that occurs in the spring and fall. c. At the conclusion of the process, data loggers must be removed from the system and final reports must be written. At a minimum, it is probably wise to plan on 8-16 man-hours each time data is retrieved and analyzed. For complex systems or systems that display numerous integration problems, this commitment can easily double or triple, especially for the first analysis cycle. Reporting the findings can additional man-days to the process depending on the formality of the report and the level of rigor. Active functional testing relies on the observation of the interactive system response as triggered by forced inputs simulating certain operational situations like a design heating load or a design cooling load. Active testing can require similar trending set-up efforts as passive testing, but the actual test, analysis, and reporting window is usually over the course of several days or weeks.
Acceptance Criteria	In general terms, the system will be acceptable if it can function efficiently in an integrated fashion and reliably navigate the day-to-day changes that are introduced by the dynamics of building use and ambient environment.
Potential Problems and	Passive testing is relatively safe since the systems are simply observed in the daily operating state, and the results of the operations are analyzed.

Cautions	During passive testing, problems may occur that could have been actively tested and found. For instance, the lack of a robust power recovery routine after an actual power outage may be found through the trend analysis, but after damage has been caused. Active testing attempts to uncover problems by forcing or triggering them. For instance, removing and then restoring power at the primary switchgear location simulates the response of a building to a power outage. While the outcome may have happened during an unforced power outage, this test can be a safer arrangement since potential problems can be anticipated in a test mode. These issues are discussed in greater detail in *Chapter 2: Functional Testing Basics*.

18.3. Non-Copyrighted Tests

Since the testing associated with this area involves the integrated functions of all of the components of the air handling systems, additional guidance may be found by referencing the tests contained in the other chapters, especially in the context of how the components should function independently of the system. Generally, the components and subsystem must be functioning properly if their operation is to be successfully integrated into the air handling system functionality as a whole.

The CTPL contains the following verification checks and functional tests that include testing integrated operation and control functions. Some of these tests were written for a specific building, and others are general with a description of what to force, then what to trend. Some are very specific for the indicated test function and include actual step-by-step test procedures. These procedures can be adapted for use directly on your projects or can be used as a guideline for developing your own, custom test procedures for integrated control functions.

18.3.1. CTPL Tests

The CTPL contains the following test focused specifically on testing control systems. This test can be easily modified to fit different buildings and systems.

EMS and Point Verification Checks

Link to EMS and Point Verification Checks, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The CTPL contains the following tests that have some component that focuses on integrated operation and control or related operational and performance issues. These tests can be easily modified to fit different buildings and systems.

Air Handler Functional Test (PECI)

Link to an Air Handler Functional Test, as prepared for the USDOE and FEMP by PECI, *Commissioning Tests Version 2.05*, 1998.

The test contains a Return Fan Volume Control Test, Static Pressure Reset Test, Discharge Temperature Reset Test, Minimum Outside Air Temperature Control Test, and Building Static Pressure Control Test.

Air Handler Functional Test (Seattle City Light)

Link to an Air Handler Functional Test, as prepared for Seattle City Light by Mike Kaplan.

This test contains a Scheduled Start/Stop and Unoccupied Setback/Setup Test, Optimum Start-Stop Test, Discharge Air Temperature Reset Test, Fan Volume Control Normal Operation Test, VFDs Only, and Fan Volume Control Normal Operation Test, Non-VFD Systems.

The following three tests are a part of *A General Commissioning Acceptance Procedure for DDC Systems* as prepared by Ken Gillespie, Pacific Gas & Electric Co., November 2001.

DDC Functional Test Procedure — **Link to the General DDC Functional Test Procedure**

DDC Sequence of Operations Test — **Link to the DDC System Sequence of Operation Test**

DDC System Operation Trend Test — **Link to the DDC System Operation Trend Test**

Thirteen additional tests and example files that are a part of PG&E's *General Commissioning Acceptance Procedures for DDC Systems* are available by accessing the CTPL with the Review ID# as follows:

Tests and Example files	CTPL Review ID#
Verification checks: includes prerequisite documentation form, hardware checks form, software checks form, training checks.	#511-517, #520
Example project forms and tests	#522-524, #526, #528

EMS Commissioning Test (Seattle) — **Link to an EMS Standard Cx Procedure as prepared for Seattle City Light in the *Building Commissioning Assistance Handbook***

The tests include a Pre-Verification Inspection, EMCS Installed Characteristics, Installation Verification, Controls Calibration, Functional Performance Verification, and General Performance Tests, Scheduled Start/Stop and Unoccupied Setback/Setup Test, Optimum Start/Stop Test, Discharge Air Temperature Reset Test, Heating Water Temperature Reset Test, and Chilled Water Temperature Reset Test.

EMS Commissioning Test (Mult. Co.) — **Link to an EMS Standard Commissioning Procedure, as prepared for Multnomah County *Oregon Document Review* by Mike Kaplan.**

The tests include Controls Documentation, Model Verification, Installation Checks, Controls Checkout Documentation Table, Controls Spot check, Table, Misc. Procedures, Valve Stroke

Calibration and Operation Test, and Functional Performance Verification with Two sample custom functional tests.

EMS Commissioning Test (Malek & Caluwe)

Link to an EMS Cx Procedure as prepared for PG&E by Bill Malek and Bryan Caluwe in the *Comprehensive Commissioning Services Guideline.*

The tests include a Verification and Functional Performance Test Plan, a Pre-startup Inspection Checklist, and a Verification Test Checklist with detailed example test procedures for chiller plant control, chiller demand control, air handler control, (supply fan speed control, Fire safety venting, return fan speed control, cold deck control), mixing box and 1-zone checkout procedures, and VAV box control under TRAV.

18.3.2. Relative Calibration Test

The relative calibration test is not part of the CTPL database. PECI created the test to cover a level of instructional detail not currently found in the CTPL. This test provides additional educational information to supplement the test protocol, including a discussion of benefits and field tips.

Relative Calibration Test (PECI)

Link to the Relative Calibration Functional Test, developed by PECI.

18.3.3. Tests for Future Development

Several functional tests for fan casings have been identified for future development, and may be included in later versions of the Guide.

Integrated Operation Tests for Future Development

Link to a list of tests related to the integrated operation and control of all of the components of the air handling unit. These tests have not yet been developed.

18.4. Supplemental Information

Since testing for integrated operation and control involves tuning the control loops, the following supplemental information has been provided to guide the implementation of PID control.

Overview and Applications of PID Control

Additional areas of supplemental information have not been developed at this time for the integrated operation and control section. Link to the plans for future development of supplemental information that will be useful to solve many problems typically identified during commissioning and design review.

Chapter 18 Future Development

Chapter 18: Overview and Applications of PID Control

Figures

Introduction

This section describes the proper application of proportional plus integral plus derivative (PID) control algorithms. PID control can enhance building performance and increase efficiency. However, the misapplication of PID control can cause more problems than it solves. The theory behind PID control and the advantages it offers for precision and energy conservation are presented. The guidelines describe appropriate applications for PID control.

PID Theory

Proportional Only Control = Proportional Offset

For a system operating under proportional-only control, there will always be a difference between the value of the controlled point and the set point, except at the specific load condition where the control loop has been tuned. This difference between the set point and the value achieved is called the "proportional offset" or "proportional error".

The magnitude of the offset depends on the throttling range (proportional band) of the controller. The throttling range of the controller is the change in input which causes the controlled device to go through its full stroke. For example, a temperature controller with a 10ºF throttling range that is controlling a normally closed valve with a 4-20 ma span would require a 10ºF temperature change at its input sensor to generate the full 16 mA change at its output and make the valve modulate from fully closed to fully open.

A typical calibration procedure adjusts the controller so that its controlled device is at mid-stroke when the control point is exactly equal to the set point. Consider a discharge temperature controller with a 10ºF throttling range that modulates a chilled water valve to maintain 56ºF set point. The controller has been calibrated so that the valve is at mid-stroke when the controller output is 12 mA (halfway between 4 and 20 mA). In this configuration, the discharge temperature would need to fall 5ºF below the set point to fully close the valve and rise 5ºF above the set point to fully open the valve. Therefore, when the cooling load is low, the discharge temperature will tend to stabilize below the set point, and when cooling load is high, the discharge temperature will tend to stabilize above the set point.

To reduce proportional offset, the throttling range is often made very small. Unfortunately, a small throttling range leads to instability, where the controller oscillates above and below the set point (hunting). Tuning a proportional-only controller is the process of finding the smallest possible throttling range that will provide stable system performance under all operating conditions. Figure 18.1 illustrates what happens as the throttling range is reduced on a system.

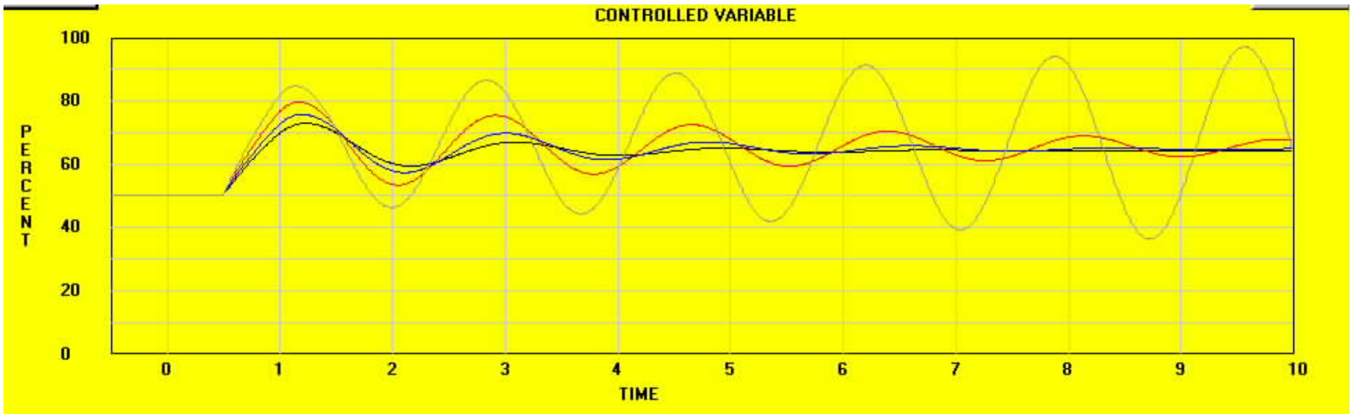


Figure 18.1 Effect of Narrowing the Controller Throttling Range

The black line (darkest) represents the response of a well-tuned proportional control system to an upset or change in the system, like a set point change. Notice that initially there are a few oscillations, then the system finds a new stable operating point at a different valve position. The blue line is the response of this same system after the throttling range has been decreased to the point where it starts to become unstable. The red and the gray lines are the results of further decreases in the throttling range. Note that in the case of the gray line, the magnitude of the oscillation is increasing indicating that the system is unstable.

Each controller should be tuned to the system it serves. Each system will have a minimum throttling range below which system operation will no longer be stable. It is not uncommon for proportional-only control in large HVAC systems to require throttling ranges of 5ºF-10ºF for stable performance. The large throttling range results in large offsets from the desired set point for many of the system's operating conditions. The offset from setpoint can lead to energy waste.

Using PID Control to Eliminate Proportional Offset

The PID (Proportional plus Integral plus Derivative) control algorithm, when properly applied, can eliminate the entire proportional offset associated with proportional-only control. Unfortunately, PID control is more complex than proportional control to tune and maintain. Universal application without considering if the process warrants the added complexity can cause problems with system performance.

An offset for a discharge air temperature set point can result in large reheat loads, which can be eliminated with the addition of integral control.

In addition to improving the precision of the control system, eliminating proportional offset can have significant energy savings for HVAC systems (see sidebar). This section first describes how the integral function eliminates proportional offset. By adding the derivative function, the controller can be more responsive to changes in operating conditions.

The integral function responds to accumulated offset over time (thus the term integral) and adjusts the output of the controller to eliminate the offset. Consider an upset in the system such as a set point change, start-up, or a change in cooling load. Integral gain describes how quickly the integral function will increase the output of the controller relative to the change in output from the proportional response. The integral gain is typically measured in "repeats per minute", which refers to how many times the integral action will repeat the initial proportional response each minute. A higher integral gain (in repeats per minute) means that the integral function is responding more quickly to a continued deviation from the set point.

The derivative function responds to the rate of change of the proportional offset over time (thus the term derivative), adjusting the output of the controller to minimize the rate of change. When properly applied, the derivative function reduces the time that a system will take to meet set point relative to proportional plus integral control. Derivative gain is usually measured in “minutes”, a reference to how long it would take the integral gain to respond to an upset and increase the output of the controller by the same amount as the derivative gain, which is applied immediately in response to the upset. The derivative action will only occur during an upset when there is change in the offset over time.

Figure 18.2 illustrates the response of one system to a proportional-only control loop, a proportional plus integral control loop, and a proportional plus integral plus derivative control loop. The control loop has been upset from 50% to 70%. Notice how the addition of integral control eliminates the proportional offset and the addition of derivative control reduces the peak offset.

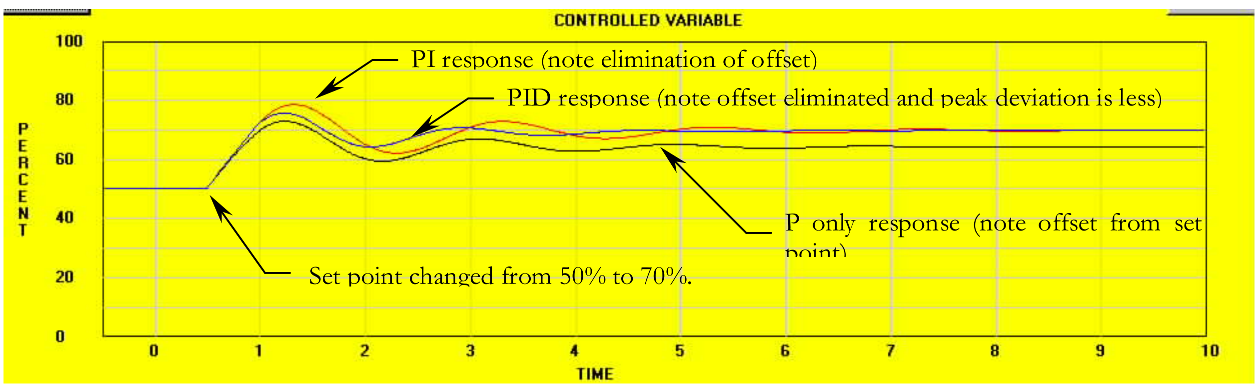


Figure 6 – The Effect of Proportional, Integral, and Derivative Control Response on System Performance

In most cases, the biggest benefit associated with PID control for an HVAC application is the elimination of the proportional offset via the integral function. Derivative action can minimize the process swing associated with a system upset, but the benefits associated with this are often quite modest or insignificant in an HVAC application.

Figure 18.2 The Effect of Proportional, Integral, and Derivative Control Response on System Performance

Guidelines for Application of PID Control

Successfully applying PID control requires knowledge of when it should and should not be used. This section presents PID application guidelines and examples of typical HVAC applications for proportional-only, proportional plus integral, and proportional plus integral plus derivative control.

Use proportional-only control in situations where high precision is not required or warranted by operational or economic concerns. Simple, well-tuned proportional-only control can provide sufficient control for space temperature. In general, most problems with proportional-only control can be traced to low-end equipment, poor maintenance and calibration, and poor space temperature sensor location. Integral and derivative action will not solve these more fundamental problems and will significantly increase the initial setup and maintenance time for the system. Proportional-only control also can be applied to secondary backup or limit control loops such as mixed air low limit control. (For an explanation of mixed air low limit control, see the Functional Test Guide for Air Handlers, Section 9.6.2: Limit Control.)

The application of proportional plus integral plus derivative control to cascaded or highly interactive control loops may yield problems. It often is better to use PID for the critical loop and allow the other loops to function as proportional-only loops.

Apply proportional plus integral control in situations where precision is required. Controlling chilled water temperature or building static pressure requires precision that proportional plus integral control can provide. In these situations, minor offsets from set point can lead to significant operational problems.

The integral function is usually applied in conjunction with the proportional function. If integral action is to be added to a well-tuned proportional-only control loop, a concurrent reduction in the proportional gain (increase in throttling range) will be required to keep the system in stable operation.

One problem with the application of integral control is called integral wind-up. Since the integral function accumulates proportional offset over time, the accumulated value will increase as long as the offset is positive (the controlled variable is above set point) and decrease when the offset is negative (the controlled variable is below set point). There are situations where the offset can accumulate to very high (or low) values, so that the system takes a significant time to recover from the accumulation.

For example, if a cooling coil cannot keep up with the cooling load, the controller accumulates positive offset. The chilled water valve will remain fully open even when the cooling load decreases and the offset is negative until the accumulated positive offset has been balanced by the accumulated negative offset. In this situation, the system will overshoot below the desired set point before the accumulated offset value is reduced to the point that the valve begins to modulate closed. The result can be poor system performance and wasted energy.

Most controllers incorporate an anti-windup feature, which works with varying degrees of success. Integral wind-up can also be avoided by forcing the output of the control loop to zero anytime the component it serves is off. If the control loops remain active, the controller attempts to achieve set point and commands the valves open. In this case, when the system restarts, the control loops have accumulated offset since the equipment was off. The system can have difficulty recovering and meeting set point.

2 To have any benefit, derivative control must be carefully applied and adjusted. Derivative control is difficult to apply properly. Generally, HVAC systems can be made to perform quite well without using derivative control. Since most HVAC processes are relatively steady state operations and changes occur gradually over time, derivative control provides little additional value for most HVAC control loops.

While eliminating proportional offset by adding integral control can save large amounts of energy, minimizing the peak swing in proportional offset through derivative control improves performance more than it affects precision and energy costs. Derivative control can prove to be beneficial in situations where systems experience significant deviations in the controlled parameters at start up and controlling devices that are marginally oversized.

When applying proportional, integral, and derivative control, enough gain for each function should be used, but not too much. If an insufficient amount of proportional and integral gain is added for PI control, the result will generally be better than if PI control were not used. But when adding derivative gain, not using enough derivative control provides no real benefit, and using too much can cause problems such as system instability.

Reference

The material in this document has been drawn from the following paper:

Sellers, David, "An Overview of Proportional plus Integral plus Derivative Control and Suggestions for Its Successful Application and Implementation", *Proceedings of the International Conference for Enhanced Building Operations*, Austin, Texas, July 17-18, 2001. Paper available at the PECI website: **http://www.peci.org/papers/index.html**

Chapter 18: Integrated Operation and Control Tests for Future Development

Building Restart Test

Control Loop Step Change Test

Supply Discharge Temperature Control Test

Supply Static Pressure Control Integration

Building Static Pressure Control Integration

Appendix A: Overview of the CTPL

A.1. Introduction

Pacific Gas and Electric (PG&E) has compiled a library of functional test procedures called the Commissioning Test Protocol Library (CTPL). The CTPL is currently made up of four components: 1) a collection of non-copyrighted commissioning protocols, 2) a database containing summaries and reviews of non-copyrighted and copyrighted commissioning protocols, 3) protocol templates, and 4) a library for archiving new commissioning protocols. PG&E's research brings together the best publicly available commissioning test procedures in the industry into a Microsoft Access© database. As a part of the Functional Testing Guide for Air Handlers work, PECI summarized all publicly available tests in the CTPL that relate to air handling equipment. The Functional Testing Guide user can open these procedures using links in the Functional Test Guide, which are located in the relevant chapters of the Test Guide.

After the summary, an excerpt from the "About This Product" document that accompanies the CTPL is provided for reference.

A.2. Non-Copyrighted Air Handling System Procedures

The non-copyrighted procedures in the CTPL related to air handling systems are summarized below. The procedure can be opened directly by clicking on the CTPL Review ID#.

A.2.1. Full AHU Pre-functional Checks

Author	ID#
Kaplan	ID#52-55
Seattle City Light (Same as Kaplan tests. Pre-functional and functional tests in same document)	ID#183-#188
PECI	ID#269
Malek and Caluwe	ID#488
PECI Calibration and Leak-by test procedures (sensor calibration methods, valve and damper stroke, and coil valve leaks)	ID#272

A.2.2. Full AHU Functional tests

Author	ID#
Kaplan	ID#56-#63
Seattle City Light	ID#188

These two documents contain essentially the same functional test forms, which include the tests listed below.

- Scheduled Start/Stop and Unoccupied Setback/Setup Test
- Optimum Start/Stop Test
- Discharge Air Temperature Reset Test
- Fan Volume Full Capacity Test
- Flying Start Test (VFDs only)
- Fan Volume Control Normal Operation Test, VFDs only
- Fan Volume Control Normal Operation Test, non-VFD systems

Author	ID#
PECI	ID# 289

The procedures contain 1-5 steps for each functional test in the list below. The test forms are written for a specific building, but can be modified to fit different projects. This protocol checks all of the modes of operation of a cooling air handler unit to verify that it is operating as designed.

- Device calibration checks for valves, dampers, and VFD
- Unit startup
- Fan volume control, static pressure, and isolation damper
- Economizer
- Duct static pressure control, alarms, and reset
- Discharge temperature reset
- Smoke conditions
- Warmup control
- Freeze condition
- Night purge
- Minimum outside air
- Building static pressure
- Filter pressure drop
- Chilled water valve

Author	ID#
Malek and Caluwe	ID#536

These functional tests for air handlers are written for the commissioning provider to verify testing plans written by a contractor.

A.2.3. VFD Tests

Author	ID#
PECI Pre-functional checks for VFDs Most of the VFD protocols are included in the full AHU tests.	ID#288
PECI VFD Functional performance tests The protocol gives the functional test procedure for a VFD controlling a VAV air handler to a constant duct static pressure and includes a capacity test to insure that energy use is minimized.	ID #419
Seattle City Light Standard Cx Procedure for Variable Frequency Motor Drives (overlaps with Full AHU procedures)	ID#243

A.2.4. Terminal Unit Tests

Author	ID#
PECI - Terminal Unit (TU) Pre-functional Checklist	ID#287
PECI - VAV Dual Duct with series fan	ID#415
PECI - VAV Dual Duct without fan	ID#416
PECI - VAV cooling only	ID#414
PECI - VAV w/ hot water reheat, single duct	ID#417
Kaplan - Terminal Unit Standard Cx Procedure	ID#114

A.2.5. Exhaust Fan Tests

Author	ID#
Kaplan – Exhaust Fan Pre-functional Checklist and Functional Tests	ID#103-108
PECI – Exhaust Fan (any belt-driven fan) Pre-functional checklist	ID#280

A.2.6. Exhaust Air Heat Recovery Functional Tests

Author	ID#
Seattle City Light – Standard Cx Procedure for Exhaust Air Heat Recovery Systems	ID#214

A.2.7. Economizer Functional Tests

Author	ID#
PG&E General Commissioning procedures for economizers	ID#495-509

This document includes:

- Project/building description and sequences documentation
- Acceptance and responsibilities
- Verification checks
- Operational checks (exercise dampers, fire alarm economizer damper, economizer mode checks, controls program checks)
- Functional checks (forced response and sequence of operation testing - fans on/off, morning Cool-Down or Warm-up, normal operating modes, Fire/smoke alarm, freeze protection)
- Economizer performance test
- Economizer operational trending
- M&V Savings Calculation using Performance Trending Tests.

Author	ID#
PECI Economizer Test – Part of the Model Commissioning Plan and Guide Specifications, but this was not reviewed for the CTPL.	CTPL_Economizer_PECI

A.2.8. TAB Tests

Author	ID#
PECI - Test and Balance Functional Test Plan: TAB Checkout	ID #413
PECI - Test and Balance Functional Test Plan: Review Checklist	ID #286

A.2.9. EMS Pre-functional and Functional Tests

The Functional Test Guide provides explanation and information about functional testing of air handling systems, but does not fully cover DDC control system commissioning procedures. DDC commissioning is beyond scope of the Guide, but the following example procedures are publicly available through the CTPL.

Author	ID#
PECI - EMS pre-functional checks and points checkout	ID#278
Seattle City Light - EMS Standard Cx Procedure ▪ Pre-verification inspection: EMCS, installed characteristics, controls calibration ▪ Functional Performance Verification: Scheduled Start/Stop and Unoccupied Setback/Setup Application Software Test, Optimum Start/Stop Application Software Test, Temperature Reset Application Software Tests	ID#200
Kaplan - EMS Standard Cx Procedure This version is somewhat different than Building Cx Assistance Handbook. ▪ Pre-functional verification: Controls documentation, Model Verification, Installation checks ▪ Misc. procedures: Valve stroke calibration and operation test ▪ Functional Performance Verification: Two sample custom functional tests	ID# 115-119

Author	ID#
Malek and Caluwe - EMS Cx Procedure ▪ Verification and functional performance test plan ▪ Pre-startup inspection checklist ▪ Verification test checklist ▪ Functional Performance test checklist All procedures tell in general what to force, then what to trend - except the mixing box procedures are actual step-by-step test procedures.	ID#531-533
PG&E - DDC Cx Procedures Due to the 17 separate documents for the PG&E DDC commissioning tests, direct links are provided to only the three functional test documents. All other document ID# are listed below to access using the CTPL.	
▪ Verification checks: includes prerequisite documentation form, hardware checks form, software checks form, training checks.	ID#511, 512, 513, 514, 515, 516, 517, 520
General DDC functional test procedures ▪ General Procedure	
▪ DDC System Sequence of Operation Test	ID#521
▪ DDC System Operation Trend Test	ID#519
▪ Example project forms and tests	ID#518, 522, 523, 524, 526, 528

A.3. CTPL Overview[1]

A.3.1. Summary

As part of a commissioning related market transformation program, Pacific Gas and Electric's (PG&E) Customer Energy Management New Construction unit has undertaken a project to initiate the development of a library of commissioning test protocols. PG&E believes that the building commissioning process as outlined in ASHRAE Guideline 1-1996, when properly applied to buildings, can result in buildings with superior systems, efficiency, and occupant comfort. PG&E is interested in promoting the commissioning process among its customers and believes that a library of well-written, cost-effective verification check and functional test protocols that includes a template to produce new ones is needed by the commissioning industry. Our long-term objective is to help create a readily accessible library

[1] Excerpts taken from "About this Product" in the CTPL Release 1.3. Full document available in the CTPL.

of verification check and functional test protocols archived in an updateable informational database. For owners and providers new to commissioning, the library is intended to help reduce the amount of work required to fully and adequately commission a building and its systems, thereby streamlining the process. For experienced owners and commissioning practitioners, the library will provide a state of the art source for procedures. The library will also provide insight into the best practice currently available, aiding all parties interested in commissioning.

Our major focus has been to identify, in the current literature, component, equipment, and sub-system level protocols that could be integrated into an overall system specific test(s) tailored to a particular building, system or manufacturer. We also identified gaps where they appeared to exist. Project scope included identification of test protocols for lighting, including lighting controls and daylighting and HVAC systems, sub-systems and equipment including: boilers, furnaces & hydronic heating systems, chilled water plants, cool storage systems, commercial refrigeration, HVAC air handling units, heat pump systems, roof-top units, unitary fans, condensing units, and terminal units. After completing the literature search and document review, this list has grown to include among others, energy management and control, service hot water, steam heating, wastewater treatment and electrical equipment.

To aid in classifying protocols, we developed working definitions for what we concluded were the two basic classes of commissioning protocols: verification checks and functional tests. See A.3.3 Protocol Definitions below for definitions. These classes were then subdivided into sub-classes and types. A literature search was then performed to identify both copyrighted and publicly available commissioning test protocols, which we then collected, cataloged using a detailed review matrix, and indexed in a database (Microsoft Access 97®).

The review matrix provided a consistent method of identifying the key elements of the commissioning procedure under review. Protocols that were practical and provided clear, meaningful instructions and acceptance criteria were preferred over those that were impractical or poorly written. As a standard reference, a quality protocol was expected to include the test name, the conditions under which the test is to be performed, test duration, data to be gathered, method and location of measurements required, instrumentation and data acquisition requirements including measurement tolerance, results to be obtained including analysis calculations if required, specific measurable acceptance criteria and any notes of caution to the user. Any special requirements that must be obtained or defined by the individual performing the test should also be listed along with a place to record actual test conditions, names of the test personnel, and results.

Each review included an evaluation of protocol practicality and cost vs. benefit. The evaluation required the reviewer to first score the likelihood of the material under review producing the desired result, and then rate each for complexity, skill required of the user, cost effectiveness, repeatability, as well as its relevance to the library being developed. Procedures and protocols that provided the most potential for improved system performance, efficiency and reliability were scored higher than procedures and protocols that were technically viable but of less practical value in the real world, day-to-day operating environment. See A.3.5 Document and Protocol Review Matrix below for more information on the review matrix.

To date, the review team has evaluated 80 documents or accumulations thereof, and completed 523 individual protocol review summaries. Allowing for multiple protocols per review, nearly 630 different protocols have been identified. Utilizing the data gathered from these reviews, the project team developed a draft of a systems-based commissioning protocol template. Eighteen separate template forms with detailed input fields and instruction sets were created for the various protocol classes, sub-classes and types. Subsequent to the initial releases of the database library, a questionnaire was developed to poll users on potential improvements. From this input, two new test procedures were developed; one for economizers and the other for DDC systems, to help refine the template forms and develop new ones as needed. This revised protocol templates document, which now includes 20 forms, is provided with Developmental Release 1.3. See A.3.6 Commissioning Test Protocol Templates for examples of these template forms.

The deliverables developed as part of this project have been assembled into an informational database product that includes four primary components: a document and protocol review database, a library of existing commissioning related protocols that we had permission to include, a user protocol archive and the protocol templates document.

The document and protocol review database includes the document and protocol review tables, a document review form and a protocol review form, each allowing the user to enter new reviews, a document search engine, a protocol search engine, and an updateable review statistics table (**Stats**) that tracks the types of protocols identified. Numerous enhancements to user functionality and instruction sets have been provided in Developmental Release 1.3.

The library of protocols provides a number of non-copyrighted commissioning related documents in Microsoft Word© rich text format that can be used as a resource for creating new protocols. These protocols can be viewed if an electronic copy of the protocol in MS Word format is placed in the "*/documents*" subdirectory.

A new user protocol section, added in Developmental Release 1.3, allows the user to archive any new commissioning protocols they might develop or acquire. The protocol can be viewed if an electronic copy of the protocol in MS Word format is placed in the "*/user_protocols*" subdirectory. The user can also browse through the input screens and view the index.

The database Library is now available in Microsoft Access 97® and Access 2000®. It is anticipated that it will be enhanced by and coordinate with the current CEC/PIER Functional Test Guide project being developed by LBNL and PECI.

A.3.2. Acknowledgements

Definition development – Thanks to Ted Cohen, past chair of ASHRAE GPC1-1989R, Karl Stum, Chad Dorgan, and Gerald Kettler, current members of ASHRAE GPC1-1996R, and Mike Kaplan, Pete Keithly, Gretchen Williams, and J. R. Andersen via the Building Commissioning Association's e-forum. Thank you all for providing your wonderful comments and insight.

Literature search – Thanks to Marlene Vogelsang, Resource Specialist at the Pacific Energy Center who helped identify material for consideration via information database web searches and to Rich Fromberg and Marlene who recently conducted a related search.

Document and protocol reviews – The project team of Rich Fromberg, Manny D'Albora, Robert Davis, John Blessent and Ken Gillespie expended over 500 hours of review time to get this job done. Thanks team.

Template development – Created by Ken Gillespie with comments from Karl Stum and Dave Sellers. Many thanks to Mike Kaplan for contributing the initial protocols that were the foundation for this effort.

Database design and construction – Manny D'Albora, Robert Davis, Ken Gillespie and Ernie Limperis. Ernie is the master database builder of this product. Thanks Ernie.

Project creation and funding – Many thanks to Karl Stum and Dave Sellers who helped write the scope of work. No job of this size can be completed without funding. Many thanks to Grant Duhon, Misti Bruceri and Alyssa Newman for their commitment and support.

Database Review - Many thanks to Karl Stum, Dave Sellers, David Shipley, Mary Ann Piette, Norman Bourassa, Keshwar Ramjattan, Jeffrey Rees, Mark Banas, Tav Cummins, Mark Williams, Ron Wilkinson, Tom Anderson, Joan Hitchner, Satu Paiho and Daniel Choiniere for their comments and/or completion of the Upgrade Project Questionnaire.

A.3.3. Protocol Definitions

Our first goal was to create working definitions for categorizing the various types of commissioning test protocols, beginning with those found in ASHRAE Guideline 1-1996. This process proved to be more difficult than we originally imagined and generated some very interesting dialog. After four iterations, eight participants, communicating via e-mail and BCA's e-forum, settled on working definitions for the project. We found that each party had their own reference frame for what commissioning meant to them and how it was to be implemented.

Process oriented definitions, such as those found in Guideline 1-1996, become less meaningful, even confusing, when applied outside the context of the process defined in the guideline. In an effort to overcome this, we chose to develop definitions that were more focused on task and less on process. This provided a fairly straightforward approach to categorization as we developed the review matrix.

The definitions chosen are as follows:

> "verification checks - those full range of physical inspections and checks that are conducted to verify that specific components, equipment, systems, and interfaces between systems conform to a given criteria. These checks typically verify proper installation, start-up and initial contractor check-out, prior to equipment being functionally tested."
>
> "functional tests - those full range of tests that are conducted to verify that specific components, equipment, systems, and interfaces between systems conform to a given criteria. These tests are typically used to verify that a sequence of operation is correctly implemented or that a design intent criteria has been met. They typically are done after equipment is placed in full operation."
>
> Performance tests, which include efficiency, capacity, load, monitoring and M&V or savings protocols, are considered a subset of functional tests.

A.3.4. Literature Search

The team then turned to the task of collecting, cataloging, and indexing publicly available commissioning test protocols. We also reviewed unique proprietary procedures for reference with respect to the test approach and presentation format, but the actual documents are not included in this product.

Our scope required that at a minimum the following list of references were to be obtained for review.

- ASHRAE Guideline 1 – 1996 - The HVAC Commissioning Process
- Model Commissioning Plan and Guide Specifications, PECI
- NIST HVAC Functional Inspection and Testing Guide
- Montgomery County Commissioning Specifications
- University of Washington Commissioning Specifications
- United States Army Engineering and Housing Support Center Standard HVAC Control Systems Commissioning and Quality Verification User Guide
- Multnomah County Standard Commissioning Procedures
- National Environmental Balancing Bureau Procedural Standards for Building Systems Commissioning
- ASHRAE Standard 150P – Method of Testing the Performance of Cool Storage Systems
- ASHRAE Guideline 14P – Measurement of Energy and Demand Savings
- PG&E's CES Commissioning Guideline, 1995
- PG&E's CoolTools™ Chilled Water Plant Design and Performance Specification Guide
- PG&E's Roof-top Unit Performance Analysis Tool Case Study

We used a number of resources to identify and collect other relevant literature, identifying a significant portion of the material for consideration via informational database web searches. We were greatly surprised to see the vast number of citations that came from the advanced science and research community. We were also able to utilize the annotated bibliography from a recent CEC PIER project, Method for Determining Measurement Accuracy and Storage Frequency for Improved Building Energy Efficiency, by Rich Fromberg and Steve Blanc. The team selected and acquired 126 products in electronic and/or hardcopy format. In addition, we included a few products outside our scope to evaluate how other commissioning environments present their requirements.

Literature search matrixes and resource lists are provided below.

Major Category Key Words

Building Commissioning	Healthcare Facilities
Building Performance	Hospitals
Building Performance Monitoring	HVAC Systems
Colleges	Institutional Buildings
Commercial Buildings	Laboratories
Commercial Laboratories	Measurement and Verification
Commercial Refrigeration	Office Buildings
Commissioning	Performance Test (ing)
Commissioning Plan	Process Control
Commissioning Specification	Quality Control
Commissioning Report	Re-commissioning
Commissioning Test	Retro-commissioning
Campus Facilities	Testing, Adjusting, and Balancing
Campuses	Universities
Energy Analysis	Verification Test (ing)
Functional Performance Test (ing)	

Subcategory Key Words

Air-handler (Test)	Diagnostic (Test)	Outdoor Air Ventilation Rate (Test)
Asynchronous Drive (ASD) (Test)	DDC Controls (Test)	Packaged Rooftop Unit (Test)
Boiler (Test)	DX Rooftop Equipment (Test)	Performance Based Codes (Test)
Building Automation System (BAS) (Test)	Economizer (Test)	Performance Measurement
Building Pressurization (Test)	Efficiency (Test)	Performance Monitoring
Checklist	Energy Efficiency (Test)	Performance (Test)
Chilled Water (Test)	Energy Management & Control System (ECMS) (Test)	Protocol
Chiller (Test)	Energy Management System (EMS) (Test)	Pump (Test)
Clean Room (Test)	Fan (Test)	Sequence of Operation (Test)
Commissioning (Test)	Functional Performance (Test)	Test and Balance
Commissioning Plan	Heat Pump (Test)	Test Instrumentation
Commissioning Specification	HVAC Air Handling (Test)	Test Method
Condensing Unit (Test)	HVAC System Controls (Test)	Test Procedure
Control Valve (Test)	Hydronic Heating (Test)	Testing
Controls (Test)	Instrumentation (Test)	Testing, Adjusting, and Balancing
Cool Storage (Test)	Instruments (Test)	Thermal Storage (Test)
Cooling Tower (Test)	Lighting Controls (Test)	Variable Air Volume (VAV) Box (Test)
Cooling Tower Fan (Test)	Maintenance (Test)	Variable Frequency Drive (VFD) (Test)
Damper (Test)	Measurement (Test)	Ventilation Effectiveness (Test)
Data Collection	Measurement & Verification	Verification (Test)
Data Requirements	Method of Test	Unitary Fan (Test)
Daylighting Controls (Test)	Mode of Operation (Test)	

Test = test, protocol, method of test, test method, test procedure, checklist

Potential Literature Sources: papers, conference proceedings, articles, books, other publications, course materials, personal correspondence

ACEEE (ACEEE.org)	Heating, Piping and Air Conditioning (HPAC)
Association of Energy Engineers (AEE)	International Solar Engineering Conference
American Society of Mechanical Engineers (ASME)	IEEE
ASHRAE Handbook(s)	I? Facility Managers Association (IFMA)
ASHRAE Journal	Industrial Energy Technology Conference
ASHRAE Research projects	National Conference on Building Commissioning (PECI)
ASHRAE Transactions	Northwest Energy Efficiency Alliance
California Energy Commission	PEC Resource Center
Control Engineering	San Diego State University
EPRI HVAC Research Center, Madison, Wisconsin EPRI Web (www.epriweb.com)	Texas A&M University-Energy Systems Laboratory

ESource	University of Colorado—Joint Center for Energy Management (JCEM)
Florida Design Initiative (http://fcn.state.fl.us/fdi/index.html)	University of Washington

Search Database Sources:

Compendex Engineering Index, Engineering Information, Inc.
Department of Energy Science and Technology
Gale Group Trade & Industry, The Gale Group
ICONDA-International Construction Database, Fraunhofer-IRB
INSPEC, Institution of Electrical Engineers
NTIS, National Technical Information Service

A.3.5. Document and Protocol Review Matrix

Once the products were acquired, our next task was to review, categorize, and index them. To identify, classify and evaluate the protocols as consistently as possible, we developed a detailed review matrix, which evolved as our reviews progressed. The document and protocol review database includes summaries of the 78 products identified as worthy of further review. It should be noted that as hard as we tried, the review team did not always make similar judgments in completing the reviews.

A.3.6. Commissioning Test Protocol Templates

With support from outside experts, the team analyzed the assembled library, identifying the advantages and disadvantages of the various approaches for executing and documenting verification checks and functional testing and to identify gaps where additional protocols are needed. We developed an improved universal approach through the use protocol templates that would enable standardization and systemization of both testing methods and documentation formats. While completing the reviews, particular attention was paid to how each protocol was presented. The review matrix provided a consistent method of identifying the key elements of the commissioning procedure under review. Did the protocol clearly communicate its requirements and the data to be obtained? This information was used to guide template development.

Test protocol templates (detailed input forms) with required input fields that can fit into a database were developed based on the working definitions developed previously and the protocol categories identified in the documents and protocol reviews. In evaluating the various types of protocols, a significant portion of them have been developed by two firms, PECI and Kaplan Engineering, both of which, used various combinations of narrative and tabular procedures to communicate the requirements of a particular test. It was felt that this approach was suitable depending upon the requirements of the specific template, but that the detailed requirements listed in the Overview should be adhered to. Instruction sets were developed for each template. Templates were developed for the following: System Title Page; Verification Checks General Instructions; Operator Interview (*retrofit only*); Documentation Checks; Equipment Installation Checks; Nameplate Data Checks; Installed Characteristics Checks; Operational Checks; Balance Report Checks; Controls Related Checks; General Run Checks; Verification Completion Log; Functional Tests General Instructions; Comfort/Air Flow Tests; Forced Response Tests; Operational Trend Tests; Sequence of Operation Tests; Performance Tests. It is anticipated that any number of these templates could be grouped together in systems procedure.

Analyzing the database for potential gaps revealed some interesting results. Remembering that only a portion of the current literature has been reviewed and that a more detailed analysis could reveal different results, we believe that public domain protocols for the following sub-systems and protocol types need to be developed: condenser water treatment; economizer control; outside air ventilation, building pressurization/infiltration; HVAC air handler capacity; terminal unit dumping; energy management system hardware & software.

A.3.7. CTPL Information Database Tool

The ultimate project goal was to assemble a Customer Support Tool based on the resources developed by the preceding tasks. Tool specifications were as follows:

- Search for information based on key words and other criteria such as test protocol technique or approach and/or equipment type, author, source, etc.
- The original data in the infobase library shall be totally protected so that the user cannot modify it in any way other than by creating and editing copies.
- Paste test protocols selected from the Library of Non-Copyrighted Documents into template forms for editing and/or modification and use by the user of the tool.
- Save modified procedures to the New Protocol Library; index for later use.
- Print selected procedures directly from the infobase without conversion to another file format for processing.
- Provide instructions for using the infobase.
- Provide a brief discussion of the project and the intended use of this product.
- Allow the infobase data structure to be expanded to include additional categories for new procedures developed by the user and/or to support additional procedures.

The database plan provides for four primary components: a document and protocol review database, a library of existing non-copyrighted commissioning related documents, a protocol template database and a New Protocol Library. The review database, the library of protocols, the user protocol library and a revised protocol templates document have been completed and are included in the tool.

Appendix B: Functional Testing Guide Resources

Books and Guidelines

ASHRAE Resources

Members and non-members can order copies of the handbooks and other useful resources through the ASHRAE bookstore on their website. www.ashrae.org.

ASHRAE. *ASHRAE Guideline 1 – 1996: The HVAC Commissioning Process,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA. 1996.

ASHRAE, *ASHRAE Handbook: HVAC Systems and Equipment*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.

ASHRAE, *ASHRAE Handbook: Fundamentals*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.

ASHRAE, *ASHRAE Handbook: Refrigeration*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.

ASHRAE, *ASHRAE Handbook: HVAC Applications*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.

ASHRAE, *Principles of Smoke Management,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA, 2002.

Gatley, Donald, *Understanding Psychrometrics*, American Society of Heating, Refrigerating,and Air-Conditioning Engineers: Atlanta, GA, 2002.

ASHRAE Duct Fitting Data Base - ASHRAE recently released an electronic duct fitting data base that will quickly calculate the pressures loss for a wide array of fitting configurations based on inputs like the flow rates and duct sizes. It will allow you to quickly compare various fitting options on the fly during design, in the course of design review, and when troubleshooting in the field.

Other Resources

AMCA Publications

The Air Movement and Control Association Inc. publishes several documents that can be valuable references and guides for air handling systems. They are all available by ordering on line from their web site at www.amca.org or contacting them at:

Air Movement and Control Association International Inc.
30 West University Drive
Arlington Heights, Illinois 60004

847-394-0150

Miscellaneous Books and Articles

Colen, H.R., *HVAC Systems Evaluation*, RS Means Company, Inc. 1990.

Haines and Wilson, *HVAC Systems Design Handbook: Second Edition*, McGraw-Hill, Inc., 1994.

Honeywell, *Engineering Manual of Automatic Control for Commercial Buildings*, 1997.

Pacific Gas and Electric Company, *CoolTools: A Toolkit to Optimize Chilled Water Plants*, available at http://www.hvacexchange.com/cooltools/guides_frm.htm

Portland Energy Conservation, Inc., *Energy Management Systems: A Practical Guide*, O&M Best Practices Series, October 1997.

Portland Energy Conservation, Inc., *Portable Dataloggers: Diagnostic Tools for Energy-Efficient Building Operation*, O&M Best Practices Series, September 1999.

Portland Energy Conservation, Inc. and Oak Ridge National Laboratory, *A Practical Guide for Commissioning Existing Buildings*, National Technical Information Service: Springfield, VA. April 1999.

SMACNA

Sheet Metal Contractors National Association, *HVAC Duct Construction Standards, Metal and Flexible,* 1993.

This publication contains details and standards for the fabrication and installation of commercial and institutional duct systems and accessories.

Sheet Metal Contractors National Association, *HVAC Systems, Duct Design*, 1990.

This publication is a fundamental design manual for commercial and light industrial HVAC systems offering the designer options for energy efficient design methods, materials and construction.

Sheet Metal Contractors National Association, *HVAC Duct Systems Inspection Guide*, 2000.

This manual contains guidelines for inspection of commercial HVAC duct systems for compliance with SMACNA's standards and includes checklists for ductwork and fire dampers.

Papers and Magazine Articles

Data Logging and Trend Analysis

Heating Piping and Air Conditioning published a series of articles on Data loggers, Trending, and Trend analysis. These articles as well as others published in the magazine can be downloaded for a nominal fee by visiting http://www.hpac.com/.:

Selecting Data Loggers: Fundamental questions to ask before buying a system
December 2002

Installation of Data Loggers: "Aliasing" and other pre-installation considerations
January 2003

Data Logger Operation Tips: Working with data: trend analysis and spread-sheeting February 2003

Commissioning Data Loggers: Caulk, duct-tape, flashlights, and other essential tools March 2003

A Picture is Worth a Thousand Words; "Tricks of the Trade" for converting your control system's trend data into graphics As of May, 2003, this article is in press and will appear in a future issue.

Friedman, Hannah; Piette, Mary Ann; *Comparative Guide to Emerging Diagnostic Tools for Large Commercial HVAC Systems,* 2001, Ernest Orlando Lawrence Berkeley Lab can be downloaded from the PECI web site at http://www.peci.org/.

Commissioning Air Handling Systems and Related Equipment

Luskay, Larry, and David Sellers, *Why the "Simple Underfloor Air Distribution System" Isn't Quite as Simple as It Seems*, Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy-Efficient Economy: Washington, D.C., 2002.

Sellers, David, *Commissioning Control Valves*, HPAC Engineering,

http://www.peci.org/papers/cxctrlvalve.pdf

Sellers, David, *Dampers: Good Commissioning Begins at Design*, HPAC Engineering, September 2000.

http://www.peci.org/papers/dampers.pdf

Sellers, David, Irvine, Linda, *Commissioning to Meet Space Qualification Criteria vs. Energy Consumption Optimization Focused Commissioning*, Proceedings from the 2001International Conference on Enhanced Building Operations.

http://www.peci.org/papers/qualvseffy.pdf

Sellers, David, *Using Utility Bills and Average Daily Energy Consumption to Target Commissioning Efforts and Track Building Performance*, Proceedings from the 2001International Conference on Enhanced Building Operations.

http://www.peci.org/papers/utilbills.pdf

Sellers, David, *An Overview of Proportional plus Integral plus Derivative Control and Suggestions for Its Successful Application and Implementation*, Proceedings from the 2001International Conference on Enhanced Building Operations.

http://www.peci.org/papers/pid.pdf

Sellers, David, *Using Extended Surface Air Filters in Heating Ventilation and Air Conditioning Systems: Reducing Utility and Maintenance Costs while Benefiting the Environment*, 2001.

http://www.peci.org/papers/filters.pdf

Sellers, David, *The Versatile Valve for HVAC Applications*, HPAC Engineering, June 2002.

http://www.peci.org/papers/versavalve.pdf

Dillard, William M. and Salmon, Justin S., *Coil Cleaning: Myths And Misrepresentation* is available on the Contracting Business Interactive web site. It includes a coil cleaning case study along with some interesting information and can be viewed at:

http://www.contractingbusiness.com/editorial/serviceclinic/coil_cleaning.cfm

Williams, Gerald J., *Fan Heat, its Source and Significance* was published in the January 1989 issue of Heating, Piping, and Air Conditioning is an excellent reference if you are trying to understand fan heat and pump heat, the similarities and differences between them, and how they can impact system performance.

Pearson, Dennis and Skumatz, Lisa A., Non-Energy Benefits Including Productivity, Liability, Tenant Satisfaction, and Others: What Participant Surveys Tell Us about Designing and Marketing Commercial Programs, is included in the proceedings from the 2002 ACEEE Summer Study on Energy Efficiency in Buildings contains data that may be useful in evaluating the financial impacts of lost productivity or product which can occur as a direct result of a fouled coil's inability to handle the load it is intended to serve. Proceedings can be obtained by visiting:

http://www.aceee.org/

Websites

DDC Online: DDC-Online provides unbiased information on Direct Digital Controls (DDC) and an easy searchable guide to DDC manufacturers.

http://www.ddc-online.org/

Energy Use Intensity Factor Benchmarking Information and Tool - An EUI benchmarking tool is available from the Oakridge National Laboratory that will guide you through the process of benchmarking your building's energy use against national data for different building types.

http://eber.ed.ornl.gov/benchmark/bldgtype.htm

Power Systems Engineering - The Power Systems Engineering site has good technical information on electrical testing and electrical distribution systems. They are actively involved in the electrical commissioning field.

http://www.powerstudies.com/

Straight Line Control Inc. - Straight Line Control offers a very comprehensive PID loop theory and turning manual as well as a very inexpensive loop tuning training software package. Both are well worth the money and can be ordered on line. A demo version of the training software can be downloaded.

http://members.aol.com/pidcontrol

Coad Engineering Enterprises - This is Bill Coad's company web site. Mr. Coad is a consulting principal and past Chairman/CEO of The McClure Corporation (dba McClure Engineering Associates). He is also immediate past President of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). As an educator, he has served as a Lecturer in Mechanical Engineering for 12 years at Washington University in St. Louis. For 17 years he was an Affiliate Professor at Washington University, teaching graduate courses in Mechanical Engineering and serving as a thesis advisor in building environmental systems design.

The web site has a monthly discussion topic related to some aspect of HVAC engineering. The first two discussions on Psychrometrics and creating your own psych chart are especially informative.

http://www.coadengineering.com/

Magazines

Heating, Piping, and Air Conditioning - This is HPAC's site and it contains archives of articles and columns. Most of the columns can be downloaded for free. Feature articles have a nominal cost associated with them to comply with copyright laws.

www.hpac.com

Control Engineering Magazine - To order a copy of "Reference Guide to PID Tuning" visit www.controleng.com/info and request number 367 for the August 1998 North American Issue of Control Engineering. The site also has a lot of good information on all aspects of control as well as related technologies like variable speed drives. It all can be downloaded for free.

http://www.controleng.com/

ASHRAE Journal - This is the monthly ASHRAE publication that is part of the membership benefits. Members also have access to past articles via the website.

Engineered Systems - This magazine focuses on the HVAC industry and includes regular feature articles on commissioning. Visit their web site to view past articles and subscribe:

http://www.esmagazine.com/

Sensors Magazine - This is a great way to keep up on emerging sensing technologies that are in place or will show up in the HVAC industry. Visit their web site to view past articles and subscribe:

http://www.sensorsmag.com/

PM Engineer Magazine - This publication deals with the hydronic systems that frequently supply utilities to air handling systems.

http://www.pmengineer.com/

Energy Design Resources - This energy-efficient design site contains numerous design guides and case studies. The following is a list of topics, may be of interest to commissioning and operations personnel. **www.energydesignresources.com**

Integrated Energy Design	Air conditioning and Ventilation
Lighting	Drivepower
Building Commissioning	Energy Management Systems
Daylighting	Glazing
Building Simulation	Lighting Controls
Building Integrated Photovoltaics	Chiller Plant Efficiency
Design Details	Design Review
Field Review	Design for your Climate
Economizers	HID Fluorescent Lighting
Indoor Air Quality	Options and Opportunities
Performance Based Compensation	Radiant Cooling
Smart Buildings	Underfloor Air Distribution

Blender Products Inc. - The Blender Products web site has some good technical information on mixing as well as how air blenders can be used to improve it.

http://www.airblender.com/education.htm

Minco - Minco has a lot of good on-line/downloadable reference information about temperature sensors and temperature measurement practice

http://www.mincocom/support/

Omega Engineering - Omega has a lot of good technical information on all types of sensor technology. Most of it can be downloaded for free.

http://www.omega.com/

Pumps and Processes - This is the web site for Pumps and Processes magazine. It has a lot of useful information on pumps. Many of the articles can be downloaded for future reference.

http://www.pumps-processes.com/

Organizations

Building Commissioning Association - The BCA is a professional organization dedicated to "promoting building commissioning practices that maintain high professional standards". The BCA newsletter and other publications can be accessed through the site as well as upcoming events and member information.

www.bcxa.org

Iowa Energy Center - This site is the home of DDC on line, which is an extremely useful and informative site all about DDC control systems. One of the key features are generic system architecture diagrams for approximately 20 different vendor's systems including key performance information that will help you make an "apples to apples" comparison to be made of different systems. There is also a section on DDC control system basics and input/output technology and equipment.

www.energy.iastate.edu

ASHRAE - In addition to the psych chart resources listed above, the ASHRAE site has a wealth of industry related information and publications available for purchase including all of the ASHRAE standards. Many of the items can be downloaded in .PDF format. Members can search and download copies of articles from the ASHRAE Journal.

www.ashrae.org

NETA - The International Electrical Testing Association site has resources that focus on electrical system commissioning and testing. In addition, NETA publishes an excellent magazine that focuses on those topics and can be ordered via the web site. Two free sample copies can be obtained, and then, if you like it, you can subscribe.

www.netaworld.org

PECI – Portland Energy Conservation, Inc. is a non-profit corporation that promotes and provides commissioning services, research, and training. The website contains many commissioning and operations resources, including a model commissioning plan and guide specification, relevant papers and case studies, and a summary of available procedural guidelines, specifications, and functional tests.

www.peci.org

LBNL – Lawrence Berkeley National Laboratory Building Technologies Department develops window, lighting and glazing technologies that save energy and maximize visual and thermal comfort of building occupants. The Commercial Building Systems Group explores different ways to integrate the efforts of the other Program groups (windows, lighting and simulations) with the goal of developing innovative building construction and design techniques.

The Control System Design Guide and the Functional Testing Guide were funded through the High Performance Commercial Building Systems (HPCBS) program administered by LBNL. The HPCBS website provides information about the latest building energy research in California.

http://buildings.lbl.gov/hpcbs/ (High Performance Commercial Building Systems)

http://eetd.lbl.gov/btp/abs/index.html (Commercial Building Systems Group)

http://eetd.lbl.gov/btp/btp.html (Building Technologies Department)

Tools

- **ASHRAE Psychrometric Charts -** ASHRAE sells both an electronic psychrometric chart as well as a psychrometric program that runs on a Palm Pilot. The electronic chart is full featured and runs on a PC.

  The Palm Pilot program only plots one point, but gives all of its properties if you enter any two. Its fairly inexpensive and is available by download.

  www.ashrae.org

- **Akton Associates Inc. Psychrometrics Charts -** This is another source for an electronic psychrometric chart that is similar to the ASHRAE product.

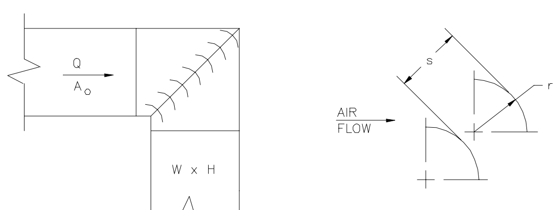
  www.aktonassoc.com

- **ASHRAE Duct Fitting Data Base** - ASHRAE recently released an electronic duct fitting data base that will quickly calculate the pressures loss for a wide array of fitting configurations based on inputs like the flow rates and duct sizes. It will allow you to quickly compare various fitting options on the fly during design, in the course of design review, and when troubleshooting in the field.

Tel:
Fax:
ASHRAE DUCT FITTING DATABASE
Version # 2. 02.05
Thursday, February 06, 2003

(CR3-9) Elbow, Mitered, 90 Degree, Single-Thickness Vanes 1 1/2-in. Vane Spacing (Brooks 1993)

INPUTS			OUTPUTS	
Width (W, in.)	12.0		Velocity (Vo, fpm)	2000
Height (H, in.)	12.0		Vel Pres at Vo (Pv, in. wg)	0.25
Flow Rate (Q, cfm)	2000		Loss Coefficient (Co)	0.11
			Pressure Loss (in. wg)	0.03



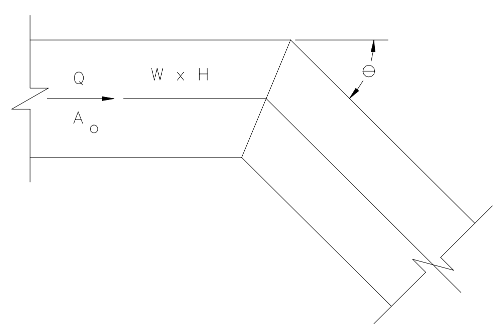
r = 2.0 (50), s = 1.5 (40)

02/06/2003 version: 2.02.05

Tel:
Fax:
ASHRAE DUCT FITTING DATABASE
Version # 2. 02.05
Thursday, February 06, 2003

(CR3-6) Elbow, Mitered (Idelchik 1986, Diagram 6-5)

INPUTS			OUTPUTS	
Width (W, in.)	12.0		Velocity (Vo, fpm)	2000
Height (H, in.)	12.0		Vel Pres at Vo (Pv, in. wg)	0.25
Angle (Theta, deg.)	90		Loss Coefficient (Co)	1.18
Flow Rate (Q, cfm)	2000		Pressure Loss (in. wg)	0.29



02/06/2003 version: 2.02.05

Figure 1 - Sample output from the ASHRAE Duct Fitting Data Base Comparing High Velocity Elbows

Figure 1 is a comparison that was generated using the fitting data base software in the field in a matter of minutes on a laptop computer. Field observation had revealed that vanes had not been installed in the return system and the tool output was used to demonstrate in which cases adding vanes would be critical to achieving the required performance.

Appendix C: Calculations

C.1. Introduction

The information in this appendix illustrates calculation techniques that can be used to evaluate the energy and resource savings associated with system improvements. The techniques illustrated provide relatively fast, conservative savings calculations. However, the results of these calculations will only be as good as the inputs and assumptions made in performing them. Thus, PIER, LBNL, and PECI assume no responsibility for how they are applied beyond the teaching purposes of this guide. The information in this Appendix supports practical use of the calculations during the commissioning process.

These calculations can be used in the following ways:

- To quickly evaluate the potential for savings to guide the commissioning or retro-commissioning process.
- To give the Owner cost savings information regarding a particular modification.
- To provide useful information for troubleshooting purposes.
- As the basis for more detailed analysis where more exact results are required.

It is always good to understand the degree of certainty associated with the technique you are using and the factors that can affect that degree of certainty. The examples of each calculation include discussions of the limitations of the calculation technique and the assumptions underlying the equations that are used. These issues should be carefully assessed in light of your project's specific needs.

The calculations will tend to be focused on one component of a system, but the result can often be extrapolated to other similar components in the project. What seem to be small savings for one component can quickly expand to large savings in the context of entire project. The case study in Section C.2.7 provides an example for savings from static pressure reduction.

Most energy savings that are achieved will persist for the life of the system if properly supported by training and ongoing monitoring. Unless there are significant changes in the way the system is used and operated, the potential to achieve the savings predicted after the initial implementation will persist year after year.

In most cases, the savings can be leveraged to pay for the work necessary to make the improvement. This is often presented in terms of simple payback; if you invest $4,500 in a measure that will save $1,000 per year, then the simple payback is the implementation cost of $4,500 divided by the annual savings of $1,000 or 4.5 years. This approach is a straightforward way to make a conservation decision. However, it probably understates the financial benefits associated with the avoided costs, like the interest that could be earned on the money that is now available for investment elsewhere. Utility rate fluctuations are also not addressed by simple payback calculations, but are real operating costs.

Economic calculations such as a net present value or return on investment (ROI)are examples of techniques that can be employed to help make more informed decisions. While a detailed discussion of these topics is beyond our scope, applying more complex cost-benefit evaluation techniques may be warranted depending on the proposed modification.

C.2. Fan Energy Savings Due to Static Pressure Reduction

C.2.1. Overview

Reducing the static pressure that a fan must overcome will reduce the horsepower required by the fan to move a given volume of air. Over time, this reduction in horsepower results in energy savings. Determining the magnitude of the energy savings available through a reduction in static pressure can provide valuable insight for making changes such as a revised duct fitting during the design phase. If the duct geometry was already installed, knowing the energy savings that could be achieved by an improved geometry will allow the cost effectiveness of a variety of options to be evaluated including:

- Removal and replacement of the fitting.
- Reduction in system supply air temperature to reduce the air flow requirement through the fitting, thereby yielding a net energy savings (trading refrigeration energy for fan energy).
- Shifting load to a different system to reduce the flow requirements through the fitting.

Calculations can also be used as a troubleshooting tool. For example, the balancer's data may reveal that the fan system will not be able to achieve design capacity without a larger motor and electrical service. In this case, strategies could be used to reduce the static pressure so that the existing motor can handle the load.

Reducing static pressure has immediate and long-term benefits. In the immediate time frame, it may reveal a less costly way to achieve the design intent than what would be associated with a motor replacement, which could get into problems with the electrical service to the motor and the speed and pressure limits associated with the fan class. In the long term, the system will use less energy to achieve the design intent.

To many, it may just seem easier to put in the larger motor. But hopefully, after reviewing the information contained in this appendix, it will become clear that the calculations and effort involved in a little bit of analysis are not complex and can yield significant benefits in terms of first cost and ongoing operating cost savings.

C.2.2. Equations

The equations that will be discussed determine the fan energy by evaluating the mass flow rate in the system (derived from the cubic feet per minute of air that the system is moving) and the kinetic energy imparted to that mass flow rate (derived from the system static pressure).

There are two main steps in the evaluation. The first step is the calculation of the horsepower savings. The second step is calculating energy savings due to this fan horsepower reduction. In some cases, calculating fan horsepower reduction is the only step necessary because it may provide enough information for a decision all by itself. For example, if you wish to understand if a pressure reduction will bring the system's horsepower requirements back into the range of a motor's capability, then the energy savings will not be as important as the potential for reducing horsepower.

C.2.2.1. Horsepower

The equation used to calculate the horsepower savings associated with a reduction in static pressure is as follows. Inputs for the variables associated with the calculation can be obtained from a variety of sources.

$$\textbf{\textit{Horsepower}} = \left(\frac{Q \times P_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}} \right)$$

Where:

$\textbf{\textit{Horsepower}}$ = The horsepower saved at the terminals of the motor (includes motor efficiency losses)

Q = The flow rate which is experiencing the reduction in static pressure in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction associated with the improvement in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Equation C.1 Horsepower Associated with a Reduction in Static Pressure

Determining Flow

The result generated from the equation will only be as good as the information used to generate it. Flow can be obtained from a field measurement, the testing and balancing report, the equipment submittal, or information on the construction documents. For the current project conditions, a field measurement is often the best input. But it is often difficult to obtain this information if the commissioning provider does not have the equipment or time to perform a traverse of the system. The following discussion focuses on various ways to determine air flow.

Balance Reports: Information from the balance report can often be used and adjusted based on more easily observed parameters like a coil pressure drop, motor amperage, or speed. For example, if the balance report indicated that when the system was balanced at the design flow of 10,000 cfm, the pressure drop through the wet cooling coil was 1.25 in.w.c., then you might check the cooling coil pressure drop at the current operating condition and see if it is near what the balance report documents. If it is, then the system is probably moving about the same amount of air as it was when it was balanced.

If the cooling coil pressure drop does not match the balance report value, then you can use the balance report data to project the current flow rate based on the fan laws.[1] Some caution must be used with using the fan laws because they only apply to a system in one configuration.

[1] The fan laws or fan affinity laws are a set of relationships that can be applied to a fan system to predict new operating parameters based on existing operating parameters. They are discussed in detail in a variety of sources including the *ASHRAE Systems and Equipment Handbook* in the *Fans* chapter and the *NEBB Testing Adjusting Balancing Manual for Technicians* under *Air Systems.*

- If someone repositioned a major balancing damper on a constant volume system after it was balanced, that changes the system curve and the fan law relationships cannot be used to project the fan's performance in the new configuration. If the change was relatively minor, then you can probably assume you would be "close enough" but you should view the result with a little less confidence than if you knew that the system was in the exact same configuration as the day it was tested.
- Filter loading can also change the system curve.
- A VAV fan system is constantly changing its system curve. To use the fan laws to project the system's performance based on the balance report data, you would have to return the system to the configuration it was in when it was balanced.

Coil Pressure Drop: The coil pressure drop itself can be used to project the flow rate since pressure drop across it will correlate with the flow. The condition of the cooling coil can have an impact on the pressure drop. The most common modifier is if the cooling coil was wet when the reading was taken because it was dehumidifying. If it was dry, then the pressure drop at a given flow rate will be less than when it was wet. Equipment shop drawings will often document both the wet and dry pressure drop for the cooling coil. The cleanliness of any coil will also affect its pressure drop. If filter maintenance has been good, then it is fairly likely that the coil cleanliness has not changed much from when it was first installed, but a visual inspection will quickly verify this.

You could also take a pressure drop across some other component, like a heating coil, as a cross-check. Most heating coils are shallower than cooling coils and therefore, have less pressure drop to measure. But, they can provide an easily obtained cross check against the information from the cooling coil.

Motor amperage: As an indicator of flow, motor amperage should be used with caution since it is not a direct indicator of horsepower due to the variation in efficiency and power factor associated with different motor load conditions (See Figure C.1 for an example). Motor kW is a little better since it eliminates one of these variables, but it is a more complicated field measurement to make since it requires a kW meter with volt and amperage inputs from several phases compared to a simple clamp-on amperage reading. In addition, the fan could be using the same horsepower as when it was balanced but moving a different amount of air if the fan speed was adjusted to accommodate a system modification for which there is not a balancing record. The fan speed could also have been inadvertently modified during a belt change if the fan or motor are equipped with a variable pitch sheave.

Filter Pressure Drop: Although filter pressure drops are easy to obtain using the indicators typically provided, they generally are bad indicators of flow because the filter pressure drop can vary drastically both with loading and with make and model.[2] Even if the balance report says "clean filters" and you are looking at clean filters, a bit of skepticism is advisable unless you know that the filters you are looking at are the exact make and model that was in the system when the balancer did their measurements.

Fan Static Pressure: Fan static pressure is also a less desirable measure of performance than some of the other indicators. True fan static pressure is difficult to measure in the field for a variety of reasons including the need to correct for the velocity pressure entering the fan and the turbulent conditions that exist in the fan discharge. In

---

[2] As a side note, the filter pressure drop indicators can often be used to take a measurement across some other component if you can come up with a little tubing and a drill to make some holes.

addition, the fan can produce the same static pressure at a different flow rate if its speed has been changed.

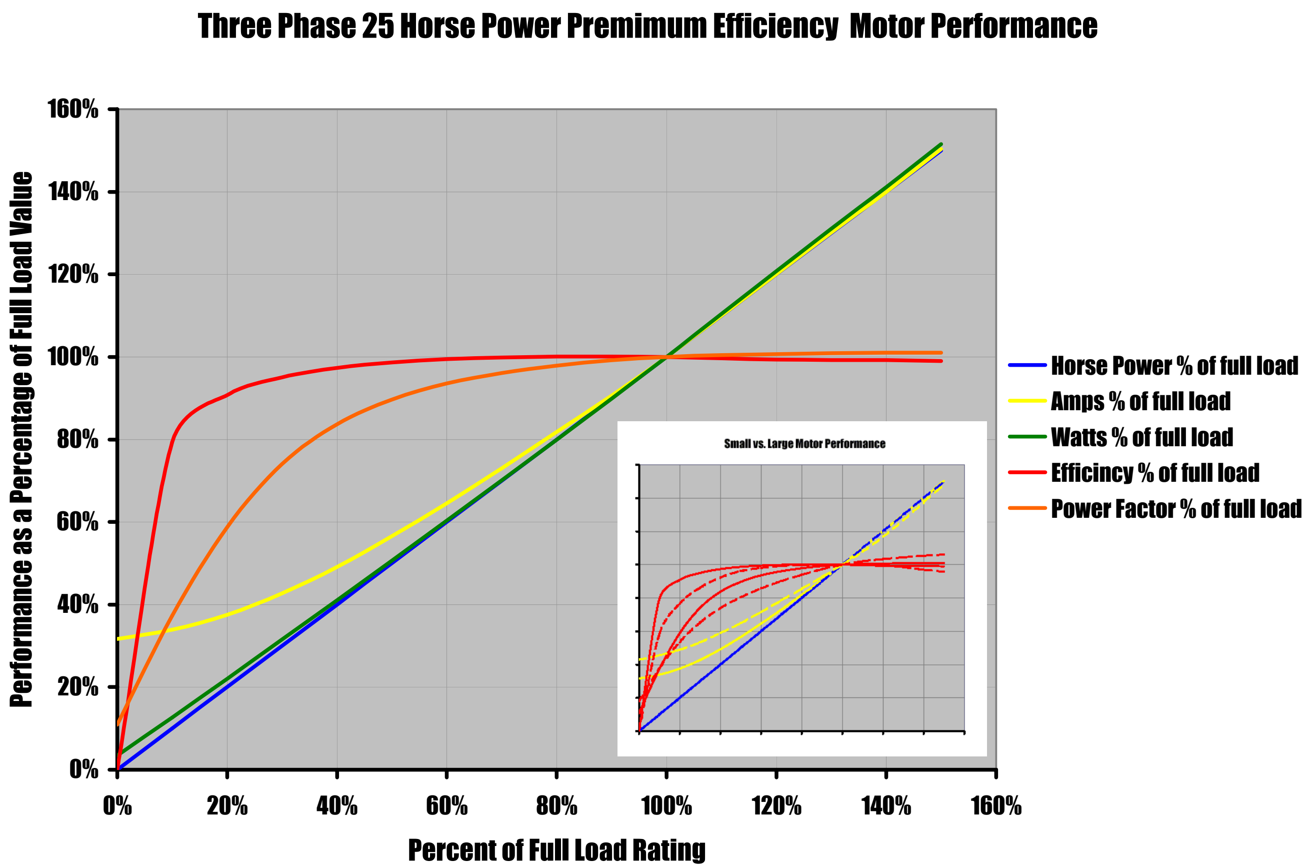


Figure C.1 Motor amperage, efficiency, power factor, and kW as a function of the actual shaft load for a 25 horsepower energy efficient motor

Notice how the motor amps and watts do not follow the motor load as the power factor and efficiency drop off towards the low load conditions. Amperage is more misleading than watts as an indicator of load. These effects also vary with motor size. Generally, smaller motors exhibit poorer part load performance and correlation between amps and actual shaft load, with some small motors drawing 40-50% or more of their rated amps with no load on the shaft. The inset graph compares a 1 hp (dashed lines) and a 25 hp (solid lines) motor. (Note that the Y axis is in terms of percent of full load value to allow multiple parameters to be compared on the same axis. This means an efficiency or power factor point of 80% means 80% of the full load efficiency or power factor value for the motor, not 80% efficiency or power factor.)

Determining Static Pressure

Static pressure can be obtained by direct measurement in situations where you are trying to understand the energy penalty associated with a loss. Static pressure savings for different equipment configurations (for example, airfoil blade vs. flat plate blade dampers) can be determined from manufacturer supplied performance data. Static pressure savings for different fitting geometries can be estimated by calculating the loss for each fitting design based on information available from ASHRAE, SMACNA or manufacturers specializing in prefabricated fittings.

The Units Conversion Constant

The units conversion constant is simply a factor used to allow the result to be expressed in terms of horsepower based on the inputs of flow rate, head, and efficiency. If you examine the numerator of the equation, you will notice that if you multiply the volumetric flow rate (cubic feet per minute) by the appropriate factors (like density), you can convert it to mass flow rate (pounds per hour). You will also notice that, by using the appropriate multiplication factors you could convert the pressure or head in terms of inches water column to feet water column. If you multiply pounds per hour by feet, you get foot-pounds per hour, which can be converted to horsepower by the appropriate conversion factor. The units conversion constant 6356 is simply what you get when you multiply all of the conversion constants together (0.0765 pound of air per cubic foot of air times 1 foot per 12 inches times 60 minutes per hour, etc., etc., etc.).

In this case, the conversion constant includes a factor for converting cubic feet of air to pounds of air based on air at standard conditions. That means that when we calculate something with this equation and the air is at anything other than standard conditions then the result will not be exactly correct because temperature, barometric pressure, and humidity content will affect the density of the air. In this particular case, the equation will provide reasonably accurate results for any of the temperature and pressure conditions typically encountered in HVAC systems at elevations between sea level and three or four thousand feet. For higher elevations and higher air temperatures, it will be necessary to either adjust the units conversion factor or view the result with a slightly more conservative eye.

Fan Efficiency

Fan efficiency is a dimensionless variable that takes into account the mechanical efficiency with which the fan wheel is able to take air and move it to a higher pressure level. Not all of the energy that goes into the fan shaft will end up in the air stream. Things that work against efficiency include bearing losses, aerodynamic losses and friction through the fan, leakage from the high pressure side back to the low pressure side, and the efficiency of the velocity to pressure and pressure to velocity conversions that occur as the air moves through the fan. Larger fans will generally be more efficient than smaller fans for any particular type of fan. Efficiencies can also vary with design (airfoil centrifugal, vane axial, propeller) as well as the operating point on the fan's curve and manufacturer. Table 1 of *Chapter 18* of the *2000 ASHRAE Systems and Equipment Handbook* provides a good comparison of the typical efficiency and other performance characteristics of various fan designs. This table can be used as a source for the efficiency term in our equation if specific information is not available from the manufacturer. As a general rule of thumb, efficiencies can vary form around 55% for a propeller or small centrifugal fan up to about 85% for a large double width, double inlet airfoil centrifugal fan.

Motor Efficiency

Motor efficiency is also a constant that takes into account the losses associated with converting electrical energy into rotating shaft energy, the function of the motor. Things working against motor efficiency are losses due to the resistance of the copper to electrical current flow, imperfections in the iron and other magnetic elements that result in imperfections in the magnetic field, fan losses associated with the inefficiencies of the cooling fan, aerodynamic effects associated with the rotor spinning in air, and bearing losses. As can be seen from Figure D1-1, efficiency will vary with motor size and motor load. It will also vary by manufacturer as a function of motor construction and the quality of the materials used.

Horsepower

Horsepower (the result of the calculation) can be converted to kilowatts (kW) for calculating the electrical energy savings, as will be illustrated in the next section. Horsepower and kW are power terms; i.e. the rate of doing work. Horsepower-hours and kilowatt-hours (kWh) are energy terms.

C.2.2.2. Energy

Converting the horsepower obtained from Equation D1-1 into annual energy savings is a fairly straightforward process. Horsepower is an expression of a rate of performing work; i.e. the rate at which energy is being used. If you multiply the rate at which energy is being used by the time over which the use occurs, the result is the energy consumption.

In our case, we would like to know the savings in terms of electrical energy and electrical cost savings, so it is desirable to turn the horsepower term into kW, a simple units conversion. If we choose the number of hours per year that the system operates as the period of which the savings occurs, we will obtain the annual energy savings for the proposed modification. Multiplying this accumulated annual energy savings by the current electrical rate will provide the annual dollars saved. These calculations are illustrated in Equation D1-2.

$$\boldsymbol{kW} = \boldsymbol{Horsepower} \times 0.746\left(\frac{\text{kilowatts}}{\text{horsepower}}\right) \text{(A)}$$

$$\boldsymbol{kWh}_{/\,\boldsymbol{Annual}} = \boldsymbol{kW} \times \boldsymbol{Hours}_{\boldsymbol{Annual}} \text{ (B)}$$

$$\boldsymbol{\$}_{\boldsymbol{Annual}} = \boldsymbol{kWh}_{/\,\boldsymbol{Annual}} \times \boldsymbol{Utility\ Electrical\ Rate} \text{ (C)}$$

Where:

$\boldsymbol{kW}$ = The kW saved at the terminals of the motor (includes motor efficiency losses)

$\boldsymbol{Hours}_{\boldsymbol{Annual}}$ = The annual number of operating hours for the system in which the change will be made

0.746 = A units conversion constant

$\boldsymbol{kWh}_{/\,\boldsymbol{Annual}}$ = The annual electrical energy savings

$\boldsymbol{\$}_{\boldsymbol{Annual}}$ = Annual cost savings

$\boldsymbol{Utility\ Electrical\ Rate}$ = The utilities net price for electrical energy in terms of \$ per kWh

Equation C.2 A, B, and C - Projecting Energy Savings from a Horsepower Reduction

C.2.2.3. Static Pressure at Different Flow Conditions

For constant volume systems, Equation C.1 and Equation C.2 will allow the savings associated with a static pressure reduction to be estimated with a reasonable degree of accuracy. For variable air volume systems, the problem becomes a bit more complicated. As the fan volume is changed, all of the terms in Equation C.1 will vary with the flow variation and load variations associated with it. Thus, an exact solution would require the evaluation of equations Equation C.1 and Equation C.2 at each incremental flow condition. This is a significant undertaking that either requires a lot of time for manual calculations or developing a model of the system in a computer based building simulation program.

Since we are simply trying to understand the approximate savings and we need to make our evaluation fairly quickly, we need to come up with a technique that will take the variation in the variables into account but not require extensive calculations. Towards that end, the following paragraphs will examine each of the variables in Equation C.1 in light of what occurs to them as the flow in the system varies.

- **Fan efficiency** will vary with load, as can be seen from the information presented in the ASHRAE Systems Manual reference. But, if the flow variation is accomplished via a reduction in speed, as is the case with most current technology systems, the variation in this parameter as the load drops off will be relatively minor, especially if the system only turns down to 40% or 50% of peak flow.[3]

- **Motor efficiency** will also vary with load as can be seen from the information presented in Figure D1-1. But, we can also see from the figure that the variation is relatively minor until the load on the motor drops below 40 or 50%. Since the power required by a fan varies as the cube of the flow rate[4], a 50% flow reduction results in the fan only requiring 12.5% of the horsepower it required at full flow if nothing else was changed[5]. As a result, the decaying motor efficiency is applied to a relatively small power level and the impact is still fairly insignificant in the big picture unless the system spends a lot of time at the very low load condition. This cubic relationship is not exactly true for a VAV system since it is actually operating on a set of system curves created by the modulation of the terminal units and the fan laws can only be applied to a fixed system. Systems that vary their speed to reduce flow tend to mimic the effect of following a fixed system curve and will achieve a result very close to that predicted by simply assuming a fixed system curve and that the fan affinity laws apply. For systems that use other approaches like inlet vanes, blade pitch variation, or simply pushing the fan up the curve, the fixed system curve assumption is not as good, but it is a valid indicator of a trend that is useful in evaluating what will happen as the load on the system drops.

- **Static pressure** drops through various components in the system will vary roughly with the square of the flow. Equation D1-3 illustrates this. In reality, the exponent in the equation is not exactly "2" but for the purposes of most HVAC calculations, rounding it to "2" will provide satisfactory results.

  Thus, if the flow rate is reduced by 50%, the pressure drop through any given component that experiences the flow reduction will be reduced to 25% of the value associated with the full flow condition. The square law relationship makes this a fairly powerful effect in terms of our evaluation since our calculation is targeted at evaluating energy savings associated with a static pressure reduction. Thus, we probably need to consider the impact of this relationship on our result, especially if the system spends a significant number of hours at a reduced flow condition. Otherwise we could overestimate the energy savings. Note that this effect does not impact the projected <u>*horsepower*</u> reduction

---

[3] The referenced ASHRAE handbook also provides information on the effect of inlet vanes and blade pitch variation on fan performance if these techniques are employed to control flow rate in a system. Trane provides similar information *in Fans and Their Application in Air Conditioning* available from Trane's Commercial Bookstore that can be accessed through the Trane web site www.trane.com. Both of these resources could be used to evaluate the impact of other flow variation techniques on energy consumption if you find yourself dealing with such a system.

[4] This is another one of the fan affinity laws. These laws were referenced previously in the discussion of the flow term in equation D1-1. They are discussed in detail in a variety of sources including the *ASHRAE Systems and Equipment Handbook* in the *Fans* chapter and the *NEEB Testing and Balancing Manual* under *Air Systems.*

[5] A 50% reduction is a reduction by 1/2. Thus, based on the fan laws, the power requirement would be reduced to $(1/2)^3$ or 1/8 or 12.5% of the requirement at 100% flow.

at design flow. It only affects the accumulated energy savings achieved by this horsepower reduction over time.

$$P_{New} = P_{Old} \times \left(\frac{Q_{New}}{Q_{Old}}\right)^2$$

Where:

P_{New} = The static pressure at the new flow condition to be evaluated.

P_{Old} = The static pressure at the old or original flow condition, usually the design condition.

Q_{New} = The flow at the new flow condition to be evaluated.

Q_{Old} = The flow at the old or original flow condition, usually the design condition.

Equation C.3 The Square Law

There are a variety of ways that reduced static pressure can be taken into account in a simplified calculation scenario.

1. One of the easier approaches is to assume that the net affect of the flow variation is as if the system operated continuously at some reduced percentage of its design capacity. For instance, the average fan flow could be derived from the fan's daily load profile. The static pressure requirement at this reduced percentage can be evaluated using the square law. Then the energy savings calculation can be done as if the system were a constant volume system that saw this modified pressure loss continuously.
2. A variation on option 1 is to bracket the savings by evaluating the fan system operation at two different reduced percentages of its design capacity. For instance, you might reflect back on your field experience as a commissioning agent and realize that many of the drives on the office building VAV systems that you have worked on seem to spend a lot of time running at 65 to 80% of maximum speed. So, you could decide to evaluate the option you are proposing at two points; one as if the fan ran continuously at 65% speed, and one as if the fan ran continuously at 80% speed and assume that the truth lies somewhere in between.
3. A more rigorous approach is to evaluate the fan at a variety of load conditions based on a load profile of some sort. In other words, if the load profile indicates that the flow will vary from a maximum of 100% to a minimum of 40%, you would evaluate the performance in even increments between 40 and 100%, perhaps every 10%. This would involve the following steps for each increment:
   - Calculate the static pressure at the reduced flow rate based on the square law using Equation C.3.
   - Calculate the horsepower at the reduced static pressure and flow rate based on Equation C.1.
   - Calculate the energy required at the reduced flow rate and static pressure based on the results of the horsepower calculation and the hours per year that the fan spends at that condition based on the daily load profile and the number of days per year. Equation C.2 B and C would be used.
   - Add up the total energy savings and multiply it by the electrical rate to determine the annual cost savings. A spreadsheet makes this process less arduous than it sounds, but it will take some time and is only as good as the accuracy of the inputs. If you are making a lot of assumptions, then you may be better off using

one of the less rigorous techniques and simply being more conservative in how you use the result in your recommendations.

The discussion of the factors that change in Equation C.1 for VAV systems made reference to the system's load profile. Determining the actual load profile for the system would, at first glance, seem to be one of the more complex and difficult tasks. However, there is actually quite a bit of information available in this regard for most common HVAC applications. In addition, the project engineering records, and perhaps even trend data you have collected as a commissioning provider on other projects will contain information that can help you develop load profile information. In addition, many projects are required to document their load calculations or energy consumption calculations in the information submitted for review by approval authorities.

Even if this information is not documented, the engineer of record should have some form of a load calculation in their files for the project. Many firms use computer programs to calculate loads and energy consumption patterns, as seen in Figure C.2. The flow values were developed by solving the sensible heat equation (Cooling Load in Btu/hr = 1.08 x Flow Rate in cfm x Difference between the supply temperature and space temperature in degrees F) for flow using the space load and typical supply and space temperatures. This spreadsheet is included in the link below:

Load Profile Example

Link to go to a spreadsheet that will help you create a load profile.

This sort of profile information can also be obtained from the *ASHRAE Handbook of Applications*. The chapter on *Commercial and Public Buildings* contains a table with load profiles, typical design criteria, filtration requirements, and other useful information for a variety of common buildings. Similar information can often be derived for less common building types based on the information presented in other chapters.

For the purposes of the static pressure reduction energy savings evaluation, the exact magnitude is not as important as the shape of the curve and average values. Expressing the information in terms of percentage of the peak value provides a frame of reference that can be easily transferred from project to project.

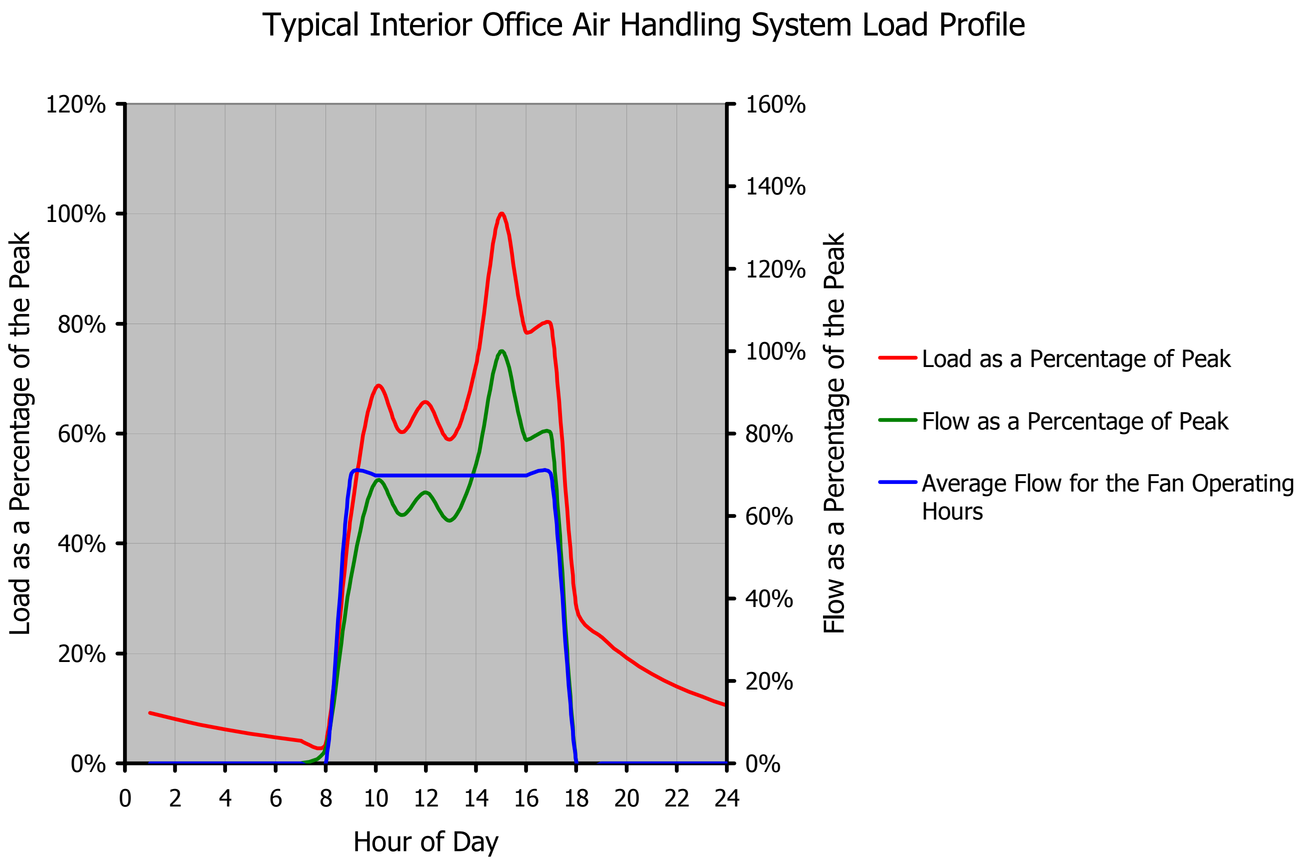


Figure C.2 Typical Interior Office Area Load Profile

The shape of this profile is fairly typical for a system serving interior loads in an office area with 9 to 5 occupancy. The peak will vary with the actual loads and minor variations in the shape will occur as a function of work or break schedules. In this example the average flow rate for the occupied hours is 80% of the maximum. Experience has shown that the average flow value for this type of occupancy will vary from 65% to 85% of the maximum.

C.2.2.4. Duct Fitting Pressure Losses

Subtle differences in the way a duct fitting is fabricated can make significant differences in the pressure losses associated with the fitting. For example, the *ASHRAE Duct Fitting Loss Coefficient Tables* documents 5 different turning vane designs with loss coefficients that vary from a low of 0.11 to a high of 0.43. Many people would be surprised to learn that there even were 5 different turning vane designs let alone that the pressure drops associated with them could vary by a factor of 4. The physical differences between the different designs are minor details like the length of the trailing edge and the spacing and thickness of the vanes.

There are two equations associated with evaluating the pressure loss through a duct fitting. The first is used to evaluate the loss as shown in Equation C.4.

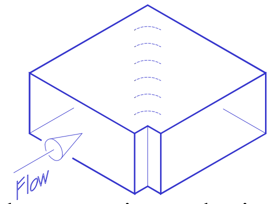
$$\Delta p_{fitting} = C_o \, p_{velocity}$$

Where :

$\Delta p_{fitting}$ = Fitting pressure loss in inches water column

C_o = Local loss coefficient

$p_{velocity}$ = Velocity pressure in inches water column, usually based on entering velocity



Equation C.4 Duct Fitting Pressure Loss

This equation states that the loss through a fitting is a function of some experimentally determined loss coefficient and the velocity pressure associated with the velocity of the air flowing through the fitting. Since the loss is expressed in terms of velocity pressure, Equation D1-5 is used to convert the duct velocity to its corresponding velocity pressure.

$$V = 4{,}005\sqrt{p_{velocity}}$$

Therefore :

$$p_{velocity} = \left(\frac{V}{4{,}005}\right)^2$$

V = Velocity in feet per minute

4,005 = A units conversion constant

$p_{velocity}$ = Velocity pressure in inches water column

Equation C.5 Velocity Pressure as a Function of Velocity

Notice that the velocity pressure is a function of the square of the velocity. That makes it a powerful relationship in HVAC systems. If you double the velocity through a fitting (i.e. you double the flow since flow and velocity are directly related), you will increase the pressure loss through the fitting by a factor of four. The magnitude of the loss will be a function of the loss coefficient, with a smaller coefficient being better (lower loss, lower energy, better efficiency) than a large one.

Fitting loss coefficients are available from a variety of sources. One of the most extensive compilations is contained in the *ASHRAE Duct Fitting Loss Coefficient Tables*, available from the ASHRAE bookstore. Many of the fittings in the Tables are also included in the *ASHRAE Handbook of Fundamentals*. Using these equations to evaluate the loss through a fitting is demonstrated in a subsequent example.

C.2.3. Additional Savings

When a static pressure reduction is implemented, there are other savings that occur in addition to the static pressure reduction savings. In most instances, the changes will be relatively minor and will simply add a safety factor to the projected savings. Knowing these additional savings can be useful when they may become significant, either due to the size of the system or the nature of the energy source or process.

C.2.3.1. Fan Heat Reduction Savings

When you reduce the fan energy that goes into a system, you reduce the fan heat that goes into the system (see the side bar if you are not familiar with fan heat). When a static pressure reduction reduces the fan energy it also reduces the fan heat, which reduces the cooling load and saves energy.

If you reduce the cooling load on the system, then you reduce the cooling load on the central plant, which saves both cooling energy and the energy to power the auxiliary systems that are associated with the plant. If the plant is simply an air-cooled condensing unit, then the condensing fans will probably run a little less. If the plant is a central chilled water plant, then distribution pumping cooling tower fan energy will be reduced.

If the static pressure reduction results in a measurable reduction in the fan heat, then it will cause a measurable drop in the discharge temperature of the air handling unit, all other things being equal. This can have several effects if no other action is taken.

- For VAV systems, the system flow rate will tend to decrease if nothing else changes because the air has additional capacity to cool due to the lower supply temperature. Depending on what is controlling the system supply temperature (fan discharge or coil discharge) it will probably be desirable to adjust the setpoint of the controller by an amount corresponding to the reduction in discharge temperature associated with the reduction in fan heat.
- For constant volume reheat systems, the reheat load will go up if nothing else changes because of the additional cooling capacity represented by the lower supply temperature.

Fan Heat: *Because the fan is doing work on the air, some of the work shows up as a temperature rise across the fan. You may have noticed how the tire pump gets warm when you pump up your bicycle tire, which is the same phenomenon. If the fan system is developing any static pressure, you can measure this temperature rise in the field with a thermometer capable of detecting half degree changes (use the same thermometer to take the inlet and outlet temperature readings so that calibration errors between thermometers do not mask the effect). If you know the flow rate in the system, you will discover that if you plug the fan heat into the sensible heat rise equation (sensible heat = 1.08 times the flow rate times the temperature difference) and convert the result to horsepower, it will correlate well with the fan's brake horsepower requirement for the current operating condition. This temperature rise will occur in a system with the motor out of the air stream. If the motor is in the air stream, then the motor efficiency losses also contribute to the temperature rise that you are measuring.*

If the system is a true constant volume reheat system operating the reheat coil for the purposes of humidity control, (as is often the case in clean rooms and hospital surgeries) then the reheat energy will go up while the fan energy goes down. This occurs because the fan heat was providing some of the reheat energy. In most cases, there will still be a net improvement in energy use unless the reheat function is being provided by an electric reheat coil, in which case it will probably just balance out the fan energy savings.

In summary,

1. If the fan heat was supplying reheat that was necessary anyway, then the net savings associated with the static pressure reduction will be reduced by the additional cost associated with the reheat process.
2. If the cooling coil discharge temperature can be raised and still maintain the necessary humidity level, then reducing the fan heat simply eliminates an unnecessary reheat load. In this case, all of the energy savings associated with the fan static pressure reduction will be realized.

For the purposes of our discussion, what matters is to know that these issues exist and to account for them appropriately in the recommendations that come out of the analysis.

C.2.3.2. Resource Savings

In many cases, measures that save energy will also save other resources. For example, when reducing static pressure by changing filter designs from a conventional design to an extended surface area design, additional savings can be realized due to longer change-out cycles (see Chapter 6: Filtration).

1. Costs could be reduced because the filters will probably last longer and require replacement less frequently.
2. Labor will be conserved because the man-hours required to change filters will be reduced due to the longer change-out cycle.
3. Disposal costs may be reduced because there will be fewer filters to break down and haul off to the land fill. In some locations, this will be a direct reduction in the cost of waste disposal for the site. Even if there is no cost savings, reducing waste makes the building more sustainable.

Recognizing other significant benefits besides energy savings is important because they may provoke additional interest and economic incentive to move a project forward.

C.2.4. Example 1: Airfoil Blade Smoke Isolation Dampers

Consider the following situation. You are involved in a design review for a project that is modifying a 20,000 cfm constant volume air handling system in a hospital serving a portion of its laboratory facility. At the completion of the first phase, the modified system will operate for about 10 hours a day, Monday through Friday and for about 5 hours on Saturdays to serve the newly remodeled laboratory area. After about a year, the system will operate 24 hours per day, 7 days per week. In reviewing the documents you notice that the smoke isolation dampers located in the unit's main supply duct have been specified with a conventional flat plate design. Since the velocity through the duct at that particular area is in the 2,000 fpm range, you begin to wonder if there might be a static pressure savings associated with using an airfoil blade design. Consulting the catalog for one of the manufacturer's reveals that a savings in the range of 0.10 inches w.c. can be achieved by switching to the airfoil blades. So you decide to do a calculation to determine what this translates to in terms of horsepower and energy to see if there might be a viable payback for the incremental cost difference associated with using the airfoil blade design instead of the conventional design.

C.2.4.1. Horsepower Reduction Calculation

The horsepower calculation is accomplished using Equation C.1 as follows:

Assumptions:

- Damper performance information is based on the manufacturers data as shown in Figure C.3.
- Pressure drop through the conventional damper = 0.065 inches w.c. @ 2,000 fpm.
- Pressure drop through the airfoil blade damper = 0.170 inches w.c. @ 2,000 fpm.
- Savings associated with airfoil blades = 0.105 inches w.c.
- Air handling unit performance is based on the value for the modified system as documented on the drawings you are reviewing.
- System flow rate = 20,000 cfm.

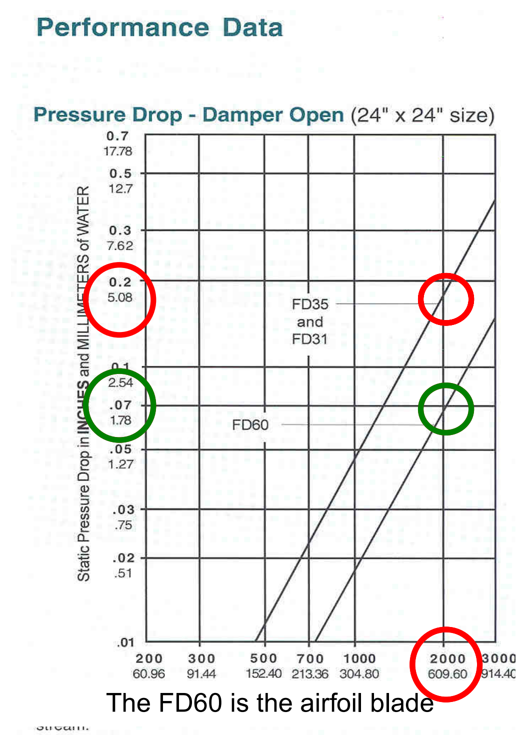


Figure C.3 Comparative Damper Pressure Drops

You don't have specific information on the fan or motor. But, you know that the existing fan is a Double Width, Double Inlet (DWDI) airfoil type centrifugal fan and decide to assume a nominal efficiency based on past experience and information presented in the *ASHRAE Equipment and Systems Handbook* chapter on fans. You also know that as a part of the retrofit, the existing fan is to be provided with a new, premium efficiency motor, so you assume a motor efficiency based on some catalog information that you have for premium efficiency motors.

Calculation:

$$\textbf{\textit{Horsepower}} = \left(\frac{\boldsymbol{Q} \times \boldsymbol{P}_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}} \right)$$

Flow rate = $\boldsymbol{Q}$ = 20,000 cfm

Static pressure reduction = $\boldsymbol{P}_{saved}$ = 0.11 in.w.c.

Assumed fan efficiency = $\boldsymbol{\eta}_{fan}$ = 75%

Assumed motor efficiency = $\boldsymbol{\eta}_{motor}$ = 89%

Fan horse power reduction = ***Horsepower*** **=** 0.5 hp

The 0.5 hp savings does not seem like much in terms of magnitude, but you know that it can add up over time. Since this system will run 24 hours per day in a year, you decide to proceed with an energy calculation to see what sort of savings you might achieve both in the immediate future as well as a year out. Equation C.2 converts your horsepower figure to kW to allow you to proceed with the energy calculation.

$$kW = Horsepower \times 0.746 \left(\frac{\text{kilowatts}}{\text{horsepower}} \right)$$

Power reduction = ***Horsepower*** **=** 0.5 hp. as calculated above

kW = 0.37 kW

C.2.4.2. Constant Volume System Energy Savings

Since the system is a constant volume system, the energy savings calculation is relatively straightforward. In this particular instance, there are two conditions that we are concerned with; the savings during the first year of operation when the system will run on a schedule, and the savings for subsequent years when the system will begin to run 24 hours per day. Equation C.2 B and C are used for the calculation.

Assumptions:

Constant volume system operation is assumed. The current system operating hours are assumed to be 2,860 hours/year based on information from the facilities engineering department indicating that the lab will be open Monday through Friday from 7am through 5pm and Saturday from 7am through noon. Assuming that the fan will run for all hours of lab operation is reasonable and conservative since it will probably start earlier to ensure that the spaces are comfortable by the time the facility is occupied. It will also run occasionally during the unoccupied hours as necessary to accommodate the night set back and set up functions.

The operating hours after the first year, when more functions are moved to the new lab from other locations are assumed to be 8,760 hours per year; i.e. round the clock operation.

The current electrical rate is assumed to be $0.090 per kWh. This was obtained from raw utility bill data by taking the most recent months charges and dividing them by the consumption associated with them. The resulting electrical rate includes demand charges as well as energy charges. If the proposed modification was going to significantly alter the building's peak demand, then it might be necessary to evaluate the impact on demand separately from the impact on energy. In our case, the impact on demand will not be significant.

The kW savings per hour at design flow are assumed to be as calculated previously; i.e. 0.37 kW per hour.

Calculation:

$$kWh_{/\ Annual} = kW \times Hours_{\ Annual}$$

$$\$_{\ Annual} = kWh_{/\ Annual} \times Utility\ Electrical\ Rate$$

Power reduction associated with the reduction in static pressure = ***kW*** =0.37 kW as calculated previously.

Operating hours = ***Hours*** = the assumed hours of operation as discussed above.

Annual energy savings at the current operating schedule = kWh_{Annual} = 1,062 kWh.

Annual cost savings at the current operating schedule = $\$_{Annual}$ = $96 per year.

Annual energy savings at the future operating schedule = kWh_{Annual} = 3,253 kWh

Annual cost savings at the future operating schedule = $\$_{Annual}$ = $293 per year

This calculation is for a 10 square foot damper, nominally 24 inches high by 60 inches wide. Based on pricing from a major manufacturer, its cost is probably in the range of $800 - $900 for a conventional design. Going to an airfoil blade design will add 15% to 20% to this cost, or, $120 to $180. So, the payback for going to the more efficient damper would be less than two years when the system was operating on a schedule. In a year or so, when the system is placed in a 24 hour per day operating cycle, the payback drops to less than a year.

There are several important points concerning the point at which the change to an airfoil damper is made.

1. While not a huge number in the context of the overall utility budget, the savings generated are enough to generate a quick payback if the change is made before the dampers are purchased.
2. It is important to catch items like this during design review or shop drawing review, and prior to damper fabrication or installation. If the damper was already fabricated but not installed, then the modification still may be viable in light of the proposed 24 hour per day operation. But, the payback would be much less attractive; probably somewhere in the range of 2 or 3 years because a new damper would have to be purchased and the one that had already been fabricated would be restocked (unlikely) or scrapped (more likely and not particularly sustainable).
3. If the damper had been installed, either in new construction or, if you were looking at this problem in a retro-fit application on a retrocommissioning project, then the replacing the

damper may be difficult to sell because the savings would need to support the purchase and installation of a new damper, not just the incremental cost difference. The installed cost could easily be 2 to 4 times the damper cost, especially in an existing situation where access may be difficult and require disruption to tenants and removal and replacement of finishes.

In situations where more than the incremental first costs are incurred, the simple payback might stretch out into the 8 to 10 year range. For a long term Owner with an energy conscious attitude, this still might be viable, but would take second place to other projects with better paybacks. As will be illustrated in a subsequent calculation example, there may be other more pressing concerns driving the need to replace the damper. In those instances, the energy savings may simply be a way to make the replacement less painful to swallow.

C.2.4.3. Variable Volume Energy Savings Calculation

The system we were considering was a constant volume system. But, per the discussions in Section C.2.2.3, we know that flow variation could have a significant impact on our results. To illustrate this as well as the technique to evaluate it, assume that the system we have been studying operated as a VAV system serving interior office spaces with a load profile similar to what is depicted in Figure C.2.

In many cases, the first step may be to see what the horsepower savings is at design flow to allow us to understand if any further effort is justified. This is the same calculation we did in our previous example as discussed in Section C.2.4.1 Horsepower Reduction Calculation.

Assuming that we decide that additional investigation is merited, the next step is evaluate the energy savings on a VAV system, which is different than for a constant volume system. The key decision to make in this step is deciding how to reflect the system's load profile in the annual energy savings calculation. A variety of techniques were discussed in Section D.1.2.3: Static Pressure at Different Flow Conditions. For the sake of time, we decide to use Option 1 and see where that leads us.

We will generate a load profile using some information we obtained from the engineer's hour-by-hour load calculations for one of the zones the unit serves, as illustrated in Figure C.2. From this information we know that the average flow rate when the system is running will be about 70% of the peak design flow. So, our first step in the process is to use the square law (Equation C.3) to evaluate the pressure drop of the damper at the lower flow condition.

Assumptions:

Pressure drop through the conventional damper = 0.065 inches w.c. @ 2,000 fpm

Pressure drop through the airfoil blade damper = 0.170 inches w.c. @ 2,000 fpm

Savings associated with airfoil blades = 0.105 inches w.c.

System flow rate = 20,000 cfm

Average flow rate as a percentage of design = 70%
(from the load profile we generated with the engineer's data)

Flow rate to be used for the evaluation = 14,000 cfm

Calculation:

$$P_{New} = P_{Old} \times \left(\frac{Q_{New}}{Q_{Old}} \right)^2$$

Design flow rate = Q_{Old} = 20,000 cfm

Static pressure reduction at the design flow rate = P_{Old} = 0.11 in.w.c.

Reduced flow rate = Q_{New} = 14,000 cfm

Static pressure reduction at the reduced flow rate = P_{New} = 0.05 in.w.c.

After completing the calculation, we realize that we could have also evaluated this revised pressure loss at the lower flow rate using the damper manufacturers curves at the lower velocity associated with the lower flow rate (1,400 feet per minute vs. 2,000 feet per minute at design). When we look at the damper curves as a cross check, we discover that the values match.

Notice how the static pressure reduction is much lower than the reduction in flow due to the square law. The reduced static pressure saved will have a noticeable impact on our savings compared to a constant volume system.

The actual evaluation of the energy savings is identical to what was used before except the horsepower savings will be based on the reduced static pressure as shown below. Our assumptions with regard to flow and pressure are as indicated in the square law calculation. We will assume the same motor and fan efficiency that we used for the previous constant volume system calculation.

Calculation:

$$Horsepower = \left(\frac{Q \times P_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}} \right)$$

Flow rate = Q = 18,000 cfm

Static pressure reduction = P_{saved} = 0.05 in.w.c.

Assumed fan efficiency = η_{fan} = 75%

Assumed motor efficiency = η_{motor} = 89%

Fan horsepower reduction = ***Horsepower =*** 0.17 hp. or 0.13 kW.

As expected, this is a much smaller reduction in horsepower than was associated with the constant volume system because it is based on the average flow rate the system will see, not the design flow rate. At design conditions, we will still see the horsepower reduction predicted for the system at design flow. But, since the system does not spend all of its hours operating at that condition, we need to evaluate the energy consumption based on a horsepower that is representative of the average system operating condition. As indicated previously, there are a variety of ways to do this with varying levels of rigor. We simply chose to use one of the simpler approaches to the problem.

To continue the energy savings calculation, we simply use the fan kW we just calculated for the variable volume application in Equation C.2 B and C for the two operating modes we are interested in (scheduled and unscheduled) as illustrated below.

Calculation:

$$kWh_{/\,Annual} = kW \times Hours_{Annual}$$

$$\$_{Annual} = kWh_{/\,Annual} \times Utility\ Electrical\ Rate$$

Power reduction associated with the reduction in static pressure = ***kW*** =0.13 kW as calculated previously.

Operating hours = ***Hours*** = the assumed hours of operation as discussed for the constant volume system.

Annual energy savings at the current operating schedule = kWh_{Annual} = 364 kWh.

Annual cost savings at the current operating schedule = $\$_{Annual}$ = \$33 per year.

Annual energy savings at the future operating schedule = kWh_{Annual} = 1,116 kWh

Annual cost savings at the future operating schedule = $\$_{Annual}$ = \$100 per year

So, while the savings are not nearly as significant as they were for the constant volume system, they still justify the incremental cost associated with going to the higher efficiency dampers *as long as the change can be made prior to fabrication and installation of the dampers*. The lower savings potentials magnify some of the contingencies discussed previously regarding making this change after the dampers are fabricated and installed or in a retrofit application.

C.2.4.4. Extrapolating the Savings

Even though the savings projected by the preceding calculations may appear to be relatively small to some, it is important to remember they were the savings associated with one component in a system. In many cases, there will be other locations in the system where these savings will be duplicated. There may be other similar systems on the project with similar savings opportunities.

For example, in many buildings, it would not be unusual for the duct leaving the air handling unit to turn and run down the corridor outside the equipment room, then, at some point, to exit the corridor to serve a load. When the duct exited the corridor, it would likely penetrate a fire and smoke separation similar to the one it penetrated leaving the mechanical room. Thus, there would be a second smoke isolation damper with a similar savings potential.

In addition, it is likely that the system would have a return air path that parallels the supply duct route. Even if the return system was a plenum return, the places where openings were provided to allow the air to pass into the corridor ceiling from the area served by the air handling unit, and to allow the air to pass from the corridor to the mechanical room would need to be protected to match the rating of the separation where the penetration occurred. Thus, there would be two additional smoke isolation dampers in the return system. Because the return velocities would be low relative to the supply flow, the damper areas would be significantly larger. Therefore, for the return smoke isolation damper calculation, the energy savings would be lower and the first cost would be higher, relative to the supply damper. The return velocities would be about half of the supply velocity, which would imply that the damper area would be twice that of the supply. Consequently, the first cost associated with the return damper would be twice as much as that associated with the supply damper since the damper costs are directly related to the damper area. The operating cost savings associated with the return damper would be one quarter of that associated with the supply damper since the operating costs are related to the pressure drop and the pressure drop is a function of the square of the flow rate (see Equation C.3 and the related discussions of the square law).

Thus by making a few assumptions and spending a few minutes reviewing the plans, the savings calculated for one component can be quickly compounded to reflect the savings and cost potentials for the system. The system wide savings can then be applied to similar systems on the project and also be used as a database for subsequent projects. See the case study in Section C.2.7 for an example of a project where these techniques were used to extrapolate the savings from one calculation to an entire building to considerable advantage.

C.2.4.5. Sample Spreadsheet

The calculation of savings from using airfoil smoke dampers is actually simple to perform once you are familiar with the process. You may even find yourself making rough field estimates based on the equations with nothing but a calculator. To provide a basis for more formal calculations for reports and to automate the evaluation process, the following spreadsheet is provided.

Damper Static Pressure Reduction Example

Link to go to a spreadsheet that performs the calculations described in Example 1.

This spreadsheet can be used to gain a greater understanding of the calculation procedures and as a starting point for calculations on your projects.

C.2.5. Example 2: Meeting the Fan Horsepower Rating

Even though energy savings are important, they sometimes pale in comparison to a field problem where the failure of a system to perform could cost significant capital to correct. Consider the following scenario.

The 35,000 cfm VAV air handling system on your project is failing to deliver the required airflow. In an effort to correct this, the balancing contractor has increased the fan speed until the system's 25 hp motor is producing 28.75 hp by running in into it's service factor. After the adjustment, the contractor retested the system. Unfortunately, the results are not good. The test data indicates that the system is still short of capacity and that it will take 29.25 brake horsepower to achieve the required flow rate with the system as it exists. To provide for dirty filters, 30 or more brake horsepower is probably a more realistic assessment of the problem. The contractor checked the fan curve and determined that the fan will still be within its class rating at the proposed operating point and has started the construction paperwork process that will install a new motor on the system. This will be expensive because in addition to the motor, the variable speed drive serving the system will need to be replaced to handle the higher current requirements associated with the larger motor size. Accusations are already starting to fly, with the Owner making a strong statement regarding his unwillingness to pay for the change *and* his unwillingness to accept a system producing less than design performance. The designer indicated that the problem was no doubt the result of the contractor not complying with SMACNA duct construction standards referenced by the project specifications. The sheet metal contractor is staring at the one line duct installation drawings wondering exactly where in the duct system he should have used a different one of the myriad of duct fitting designs covered by the SMACNA standard to prevent the problem.

This is a difficult problem for everyone involved, and situations like this do come up in the field. Frequently, the problem is solved by throwing more energy at it in the form of higher fan speeds, more brake horsepower, and as suggested in this case by the balancing contractor, larger motors. All of these solutions penalize the system's energy efficiency for the life of the system. By solving the horsepower equation we have been discussing for static pressure, we may be able to gain a different perspective on the problem.

Specifically, it might be worth asking "how much static pressure would need to be eliminated from the system in order to reduce the horsepower requirement to a level that could be handled by the motor?" Once this static pressure was identified, analysis supplemented by focused pressure drop testing may reveal a relatively inexpensive modification that will provide the necessary level of performance without having to throw more power and energy at the problem. Such a solution could provide benefit for everyone involved by minimizing the expense associated with correcting the problem and improving the energy efficiency of the building for its life.

In our example, we need to achieve enough horsepower savings to allow the system to deliver design flow without overloading the motor. Strictly speaking, the motor is rated for 25 hp, and some would say it is in an overloaded state if the horsepower exceeds that value. On the other hand, most motors have a service factor rating and the motor can be safely operated at a load condition that exceeds its nameplate power rating by the amount of the service factor. Typically, service factors are in the range of 1.10 to 1.15. Running the motor at a power level in excess if its nameplate means that the motor will be drawing current in excess of its nameplate. The motor will tend to run hotter which can affect the service life of its windings.

As a starting point, solve Equation C.1 for pressure difference and determine how much of a static pressure reduction is required to get the system back to where the motor can provide design flow running at its service factor limit.

Assumptions:

Solving Equation C.1 results in the following relationship:

$$P_{Saved} = \frac{\boldsymbol{Horsepower} \times 6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}}{\boldsymbol{Q}}$$

Where:

$\boldsymbol{Horsepower}$ = The horsepower savings required at the motor terminals

$\boldsymbol{Q}$ = The system design flow rate in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction required to achieve the desired horse power savings in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Equation C.6 Static Pressure Reduction Required to Achieve a Target Horse Power Reduction

The horsepower requirement project to achieve design flow = 29.25 hp. This comes from the projection made by the balancer based on the current operating point via the fan affinity laws.

The horsepower available running the motor into its service factor = 28.75 hp. This is the maximum acceptable loading for the motor. If we can get below this, it would be good because it would provide a safety factor and some room for the filters to load. This value is a defined limit that will help us establish a target for eliminating pressure drop.

The minimum horsepower savings desired = 0.50 hp. The system flow rate = 35,000 cfm. This flow rate is the system's design requirement, established by the contract documents and design intent.

Calculation:

$$P_{Saved} = \frac{\boldsymbol{Horsepower} \times 6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}}{\boldsymbol{Q}}$$

Flow rate = $\boldsymbol{Q}$ = 35,000 cfm

Desired horsepower reduction = $\boldsymbol{Horsepower}$ = 0.50 hp.

Assumed fan efficiency = η_{fan} = 79% (based on shop drawing information)

Assumed motor efficiency = η_{motor} = 89% (based on shop drawing information)

Required static pressure reduction = P_{saved} = 0.06 in.w.c.

Interestingly enough, it takes only a minor reduction (0.06 in.w.c.) in static pressure to bring the system performance back to a point where the existing motor it is adequate. In many instances, this revelation may throw a new light on the problem since it opens the door to a variety of options other than installing a larger motor and a bigger drive.

Methods to analyze and reduce system static pressure include:

1 Generate a field measurement-based pressure gradient diagram for the system and compare it to the one predicted by the engineer's calculations. This type of functional testing can often be done in coordination with the balancing contractor. Given the relative simplicity of this effort, it would be desirable to undergo this process before a taking any other steps, regardless of the outcome of any other analysis of the problem. To make the fan selection, the engineer should have performed a static pressure calculation for the system, and, given the nature of the current problem, they should be willing to share the information with the rest of the team in an effort to solve the problem without incurring additional cost. Even in situations where there is not a readily available pressure gradient diagram, like a retrocommissioning process or a non-engineered system modification, generating the required information is not that difficult once you have been through the process a couple of times. The *ASHRAE Handbook of Fundamentals* can provide guidance in this process and also includes numerous fitting loss coefficients, duct friction charts, as well as examples of this type of calculation.

Once a calculated pressure gradient diagram has been generated, field testing can be used to compare the predicted performance with the actual performance by taking readings at various locations in the duct system. If the actual losses in a given section do not correspond well with the prediction, investigation is probably warranted to determine if there is some obstruction in the duct system that is causing the unexpected pressure loss. This investigation may require an internal inspection of the system, and an access panel may need to be cut. But, in the context of the cost to change a motor, the cost of adding an access door or two will be inconsequential. In many cases the inspection that the doors enable will reveal that the problem is due to a problem like missing turning vanes, a duct liner that has come loose and is caught on the duct reinforcing rods, or an elbow or a workman's jacket that was inadvertently left in the duct and now is lodged against some turning vanes. Even if no problems are revealed and a motor change is the only solution, having verified that there are no unwarranted, easily eliminated restrictions in the duct prior to undertaking this expense usually justifies the cost of the access panel.

The following links will provide some useful information with regard to this process.

Static Pressure Loss Spreadsheet

The static pressure loss calculation spread sheet and the pressure gradient diagram can be used to gain a greater understanding of the calculation procedures and as a starting point for your own calculations.

System Diagram

Link to the system diagram associated with the pressure gradient diagram and static pressure loss calculation. (.PDF)

2 One place where it is often possible to eliminate static pressure from the system is at the filter bank. If the system has prefilters, it may be possible to simply run without them at the expense of having to change the final filters more frequently, assuming that the final filters are ahead of any of the unit's internal components. Switching from conventional filters to extended surface area filters for the final filters can mitigate this. Extended surface area filters can provide nearly twice the dust holding capacity of conventional designs and do it at much lower initial pressure drops, often 50% less. These filters are discussed in greater detail in Chapter 10: Filtration. (Even if the system doesn't have static pressure problems switching to these filters can provide energy and resource conservation benefits that may be desirable).

3 Another possible place to eliminate static pressure is at a major fire or smoke damper in the common supply duct. As can be seen from Figure C.3 and the previous calculation example, switching to an airfoil blade design can often save a significant amount of static pressure. This approach has the disadvantage of requiring that the existing dampers be replaced, which will cost time and money and will probably require a system outage. But it may be more economical than a motor and drive replacement, especially if the sheet metal contractor is forced to do the work at his cost due to the way his contract is interpreted. In the bigger picture, this approach has the advantage of reducing the system energy requirement instead of increasing it. This provides a long-term benefit to the Owner, which can be a useful incentive for obtaining their approval and assistance in performing the work.

4 Another option similar to that described in item 3 is to modify a fitting in the duct system to improve the losses through it. Figures 18.1, and 18.3 through 18.5 in *Chapter 18 Distribution*, provide some examples of the savings potential associated with this option. The prime targets for this approach are fittings near the discharge of the fan and fittings in the large distribution ducts because the velocities in these ducts tend to be relatively high even though their friction rates are relatively low (see Table 18.2 and the related discussion in Chapter 18). Obviously, this approach also will require an outage and material and labor expenditures, but in some cases, these costs could be lower than changing the motor.

The biggest advantage for an approach that eliminates static pressure instead of adding motor horsepower is that it improves the efficiency of the HVAC system for the life of the system. In our case, assuming an average flow rate of 70% of design due to the impact of the load profile, the annual operating savings are in the range of $35 to $106 depending on the hours of operation. While this is not a lot of money, it's better than adding operating cost and represents a savings that will be realized every year of the system's life.

Horse Power Reduction Example

Link to a spreadsheet that performs the calculations described in the preceding example.

This spreadsheet can be used to gain a greater understanding of the calculation procedures and as a starting point for calculations on your projects.

C.2.6. Example 3: Measuring the Impact of Turning Vanes

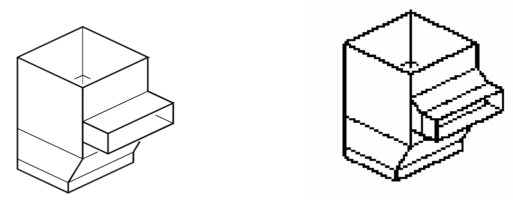


Figure C.4 Subtle Differences in Fitting Design Make Big Differences in Performance

The difference between the design of these two fittings is very subtle. The one on the right has a 45° flare where the branch connects to the duct and the one on the left doesn't. Yet, at 2,000 fpm (a common duct riser velocity), the pressure loss through the one on the left could be 2 to 3 times as high as the one on the right. (See Figure 13.1 in *Chapter 13: Supplemental Information*)

Translating the duct design information on the contract drawings to a real duct system that fits in the confines of the existing conditions presented by the building structure and architectural elements often requires interpretation and compromise on the part of the tradesmen installing the system. In addition, the hectic pace of construction can cause details to be missed or misinterpreted by less experienced field personnel. For duct systems and fittings, subtle differences in interpretation can often make big differences in the pressure loss associated with a fitting as can be seen from Figure C.4 and the referenced figure in Chapter 13. On a one line duct drawing, where the riser may show up as a rectangle and the connection to it simply as a line touching the rectangle, there would be very little guidance for the field staff to tell them that they should use the better fitting. Even in a two line drawing, a note or an elevation detail would be required to really make things clear.

One line drawings also leave the need for turning vanes open to interpretation. SMACNA construction standards show how to build elbows in a variety of ways, including without vanes. The specification may require turning vanes, but many times the tradesmen actually hammering the duct together never see the specs and are working from the drawings, past experience, and some general instructions from their foremen. Consider the following example.

You are doing a walk-through of a section of your project where the ceiling is about to be installed. A week ago, when you were last on site, the sheet metal contractor had just been starting to run the duct through this area, which is the first portion of the system outside the mechanical room. Now, the trunk duct has been run through the area and is ready for extension to the next area scheduled for renovation. In addition, the distribution terminal equipment and ducts for the area have been run. As you walk around looking at the installation, you notice that the tell-tale line of screws across the corners of a mitered elbow that usually indicate that turning vanes are missing. You remember that the drawings for the system are one line drawings, so the vanes themselves would not actually show up on them. You start to wonder how big a problem this might be, so you run a few quick calculations using Equations Equation C.4 and Equation C.5.

First you look at one of the small distribution ducts.

Assumptions:

You assume a flow rate of 350 cfm based on the information on the drawings. The 12 by 6 inch duct size is easy to find by simply measuring it. Since it is externally insulated, you don't have to worry about adjusting the dimensions for duct liner. These two pieces of information allow you to determine the velocity in the duct since the flow is equal to the area of the duct multiplied by the velocity through that area. In this case, the result is a velocity of 700 feet per minute.

The next piece of information you need is the loss coefficients for the different elbow designs (with and without turning vanes). But, having had problems with fittings before, you carry copies of the *ASHRAE Fundamentals Handbook* loss coefficient tables for some of the more common fittings with you in your clipboard for reference on just such an occasion. Referring to the tables, you determine that the best turning vane design in a mitered elbow will result in a loss coefficient of 0.11. For a mitered elbow with no turning vanes, the coefficient is an alarming 1.03, nearly 10 times that of the fitting with turning vanes. You now have everything you need to do the math.

Calculation:

Calculate the velocity pressure using Equation C.5.

$$p_{velocity} = \left(\frac{V}{4{,}005}\right)^2$$

Velocity pressure = $p_{velocity}$ = 0.031 in.w.c.

Next calculate the loss for the two different elbow designs, with and without vanes, using Equation C.4.

$$\Delta p_{fitting} = C_o p_{velocity}$$

Loss for the elbow with no turning vanes = $\Delta p_{Fitting}$ = 0.031 in.w.c.

Loss for the elbow with turning vanes = $\Delta p_{Fitting}$ = 0.003 in.w.c.

Difference (avoided pressure drop if vanes are installed) = 0.028 in.w.c.

You start to relax a little bit. The missing turning vanes in the small distribution duct will have a minimal impact on the performance of the system and probably will not matter. But, you decide to perform the same calculation for the elbow in the duct main that also appears to be missing turning vanes because the velocities are higher there. Using a similar procedure, you obtain the following results.

Flow rate = 20,000 cfm

Duct height = 24 inches

Duct width = 60 inches

Velocity = 2,000 fpm

Velocity pressure = 0.25 in.w.c.

Loss for the elbow with no turning vanes = 0.26 in.w.c.

Loss for the elbow with turning vanes = 0.03 in.w.c.

Difference (avoided pressure drop if vanes are installed) = 0.23 in.w.c.

The impact here is far more significant due to the higher velocities. Since larger ducts contain a much greater volume of air for a given perimeter, they have a much higher air handling capability at a given friction rate as compared to smaller ducts, see Table 13.1 in *Chapter 13: Supplemental Information*. That's the good news. The bad news is that it means the velocities are higher and the implications of a poor fitting design are much more significant. In our example, both ducts had been sized at the same friction rate; 0.10 inches w.c. loss per 100 feet of duct, a common low velocity, low pressure system standard. But, the velocity in the larger duct was nearly three times that in the smaller duct, and the velocity pressure was nearly 9 (three squared) times that in the smaller duct due to the square relationship between velocity pressure and velocity.

Based on the results of your calculation, you decide to bring the subject up with the project team. The foreman checks into it reports that the vanes are not there. You suggest that the three of you have a discussion with the designer about the problem. The elbows in the low velocity distribution duct system will probably be O.K., especially since the area you were looking at was the first zone off of the main and will probably have more static than it needs and since vanes will be provided for the rest of the project. Asking the contractor to fix the problem in the main and letting the problem go unless the balancing contractor cannot get design flow in one of the branch ducts may represent an attractive compromise to everyone.

Had you not detected the problem, it may have never been picked up. While significant, the extra 0.23 in.w.c. of loss represented by the missing vanes in the elbow in the main may have been overcome by simply speeding up the fan when it failed to deliver the design performance. At 20,000 cfm, the extra static represents a little over one horsepower, and, if the brake horsepower requirement of the system was below the motor capability by that much, speeding up the motor would be a viable and quickly achieved solution to any design flow problems created by the missing vanes. If the system was a constant volume system and operated 10 hours per day, the annual energy penalty associated with speeding up the motor to make up for the missing vanes would be in the range of $200 per year. If the system ran continuously, it would amount to over $600 per year.

Duct Fitting Pressure Loss Example

This spreadsheet performs the calculations described in the preceding example. The energy and horsepower calculations are also included.

This spreadsheet can be used to gain a greater understanding of the calculation procedures and as a starting point for calculations on your projects.

C.2.7. Case Study: Under 60 Minutes of Effort, Over $60,000 Savings

As an example of how a small savings potential can compound into a large savings potential, consider the following example drawn from a high-rise project. A 20 story high-rise building has 16 air handling systems, all of which are located in a mechanical space above the 20th floor. Distribution duct work is contained in several large, fire and smoke rated mechanical chases that penetrate through the full height of the building, which also serve as return paths back to the air handling systems. All duct and return air penetrations entering and leaving these chases are protected with fire or combination fire and smoke dampers, depending on the chase rating at the location. The supply ducts for all of the systems carry significant volumes of air and are large with relatively high velocities despite the low friction rates (see Table 13.2 in *Chapter 13: Supplemental Information*).

In the course of reviewing the shop drawings for the combination fire and smoke dampers on the project, the commissioning agent looked at the installed location for the dampers on the plans to see if the actuator locations shown on the shop drawings would allow sufficient space for the actuators to be maintained when the dampers were installed in the congested areas around the chase. As he looked at the drawings, he noticed that for all of the systems, a second smoke isolation damper was shown on the drawings, typically within 10 to 30 feet of the combination fire/smoke damper installed at the chase. A little digging around in the construction documents revealed that the second damper was:

- From a smoke rating standpoint, identical to the damper in the ducts at the shaft wall penetration.
- Controlled to close any time the air handling unit it was associated with was off to comply with the NFPA 99A requirements for smoke isolation dampers on air handling systems over 15,000 cfm. The damper at the chase was required to maintain the integrity of the separation provided by the shaft wall. It was controlled to close any time there was a fire alarm and open if commanded to do so from the smoke management system control panel in the lobby.

Duct velocities in the vicinity of the dampers were in the 2,000 to 2.500 fpm range, so the damper represented a significant pressure drop, even with the airfoil blade design that was to be provided. Based on past experience and the wording of the code, the commissioning agentdecided to investigate the following ideas:

- **Could the combination smoke and fire damper at the chase also provide the smoke isolation function?** If the control sequence associated with it were modified to include closing the damper when the air handling unit associated with it was off, the need for the second smoke damper currently in series with the combination fire and smoke damper would be eliminated.
- **What energy penalty is associated with the second damper in terms of pressure loss?**
- **What first cost penalty is associated with furnishing, installing and controlling the second damper?**

Since the commissioning agent had been involved in other projects where a smoke and fire damper associated with protecting a rated separation had also been used to provide the smoke isolation function for an air handling system, he thought that eliminating the second damper may represent a viable first cost and energy cost saving opportunity. To understand the potential savings associated with this, he took the following steps:

1 Using Equations Equation C.1 and Equation C.2 A, B, and C and the pressure drop for the dampers shown on the shop drawings, he determined that eliminating the damper from one of the typical systems could save around $275 in operating cost due to the elimination of approximately 0.18 inches w.c. of static pressure from the system.

2 The extra dampers were worth $75 to $95 per square foot, depending on the exact configuration. Installation could easily double this cost when wiring, control, and commissioning were considered. Therefore, the installed cost for the potentially redundant damper could easily be in the $150 to $190 per square foot range.

3 The supply duct for the unit had a cross sectional area of nearly 16 square feet. Based on the information above, the damper probably represented an equipment cost of approximately $1,200 to $1,500 and an installed cost of double those figures.

4 On the return side, even though the return smoke isolation dampers at the shaft were associated with multiple units, and thus could not be considered redundant, each unit had its own return damper associated with its economizer cycle. Based on past experience, the commissioning agent knew that these dampers could be furnished with a smoke rating and could be used to provide the smoke isolation function as well as the economizer function. If that were possible on this project then there were first cost and energy savings available by eliminating the redundant return smoke isolation dampers.

5 To evaluate the savings potential, the commissioning agent used the following fairly simple assumptions:

- Since the return velocities were about half of the supply velocities, the return damper area would be about twice the supply damper area. Since the damper cost was generally related to the damper area, the savings in first cost for the return damper would be about twice that associated with the supply damper.
- Since the return velocities were half of the supply velocities, the pressure losses through the return damper could be anticipated to be one quarter of those associated with the supply dampers, due to the “square law” (see Equation C.3). Since the operating costs are directly related to the pressure losses, the operating costs associated with the possibly redundant return dampers could be anticipated to be about one quarter of those associated with the supply damper.

6 Based on the preceding calculations, the net savings potential for the system the commissioning agent appeared to be:

- Operating cost savings in the range of $340.
- First cost savings in the range of $7,500 to $9,000.

7 Since there were 15 identical or nearly identical air handling systems, it was reasonable to assume that similar savings potential existed for all of them.

In other words, after about an hour of effort, the commissioning agent had identified the potential to save $5,500 per year in operating cost and $120,000 to $140,000 in first cost. The operating cost savings will be realized every year of the system’s life cycle. In this case the systems had a 25-year design life cycle.. Thus, the accumulated operating savings had significance beyond the $5,500 per year identified in the analysis.

The calculations performed were far from exact. What they did do was identify the potential for significant first and operating cost savings. Based on his analysis, the commissioning agent spent another 15 minutes to write an RFI (Request For Information) suggesting that perhaps, the redundant dampers could be eliminated and that this concept was worthy of additional evaluation. As a result, the topic was discussed at the next construction meeting.

Since the project was experiencing some budgetary pressure, the first cost savings were very attractive to the Owner. The magnitude of the savings potential coupled with the fact that they could be evaluated from some fairly straightforward math and easily obtained costs (damper square footage times cost per square foot) made additional analysis unnecessary. It turned out that the code authority associated with the project happened to be present at the construction meeting. After studying the situation for a few minutes, the code authority agreed with the commissioning agent's assessment. As a result, the next day, the general contractor initiated the paper work required to remove the dampers from the project. The $275 in savings identified by the actual calculation performed by the commissioning agent had mushroomed into the potential for thousands of dollars in energy savings per year and tens of thousands of dollars in first cost

C.3. Future Development

The following calculations may be developed in a future version of the Calculation Appendix.

- Humidification load from airflow and humidity ratio differential
- Total load from air flow and enthalpy change.
- Estimating fan static requirements in the field
- Checking condensate drain line sizes and trap dimensions
- Predicting fan performance based on a known operating point and fan curve.
- Damper sizing
- Valve sizing
- Implications of leakage from an under floor plenum based on a pressure test
- Estimating loads
- Extended surface area filters savings

Appendix C.2.2.3 Load Profile Example

Deriving a Load Profile from Project Engineering Data

Interior Office - Interior cubicle served by AHU 2, Typical of 50 served by the unit

Summer

Hours	Actual Load Scheduled and observed occupancy Total Btu/Hr	Actual Load Scheduled and observed occupancy Percentage of peak	Actual Load Scheduled and observed occupancy In terms of CFM	Actual Load Scheduled and observed occupancy (off when unoccuppied) Percentage of peak	Actual Load Scheduled and observed occupancy (off when unoccuppied) Average Percentage
1	304	9%	16	0%	0%
2	266	8%	14	0%	0%
3	233	7%	12	0%	0%
4	204	6%	10	0%	0%
5	178	5%	9	0%	0%
6	156	5%	8	0%	0%
7	137	4%	7	0%	0%
8	120	4%	6	4%	0%
9	1483	45%	76	45%	70%
10	2255	68%	116	68%	70%
11	1989	60%	102	60%	70%
12	2171	66%	112	66%	70%
13	1946	59%	100	59%	70%
14	2392	72%	123	72%	70%
15	3301	100%	170	100%	70%
16	2590	78%	133	78%	70%
17	2628	80%	135	80%	70%
18	930	28%	48	0%	0%
19	758	23%	39	0%	0%
20	633	19%	33	0%	0%
21	538	16%	28	0%	0%
22	462	14%	24	0%	0%
23	401	12%	21	0%	0%
24	349	11%	18	0%	0%

Peak Load	3301			Peak load / [1.08 x (space temp - supply temp)]
Max CFM	#DIV/0!			
Average CFM over 24 hours		57		
Average as a percentage of the peak		42%		
Average CFM over occupied hours		119		
Average as a percentage of the peak		88%		
Space temperature design point		74	°F	
Space humidity design point		50%	RH	
				(from psychrometric chart)
Average sensible heat ratio		0.95		
				(from psychrometric chart)
Coil discharge air temperature		53	°F	(from fan and duct gains)
Estimated temperature rise		3	°F	
Supply air temp at grill		56	°F	

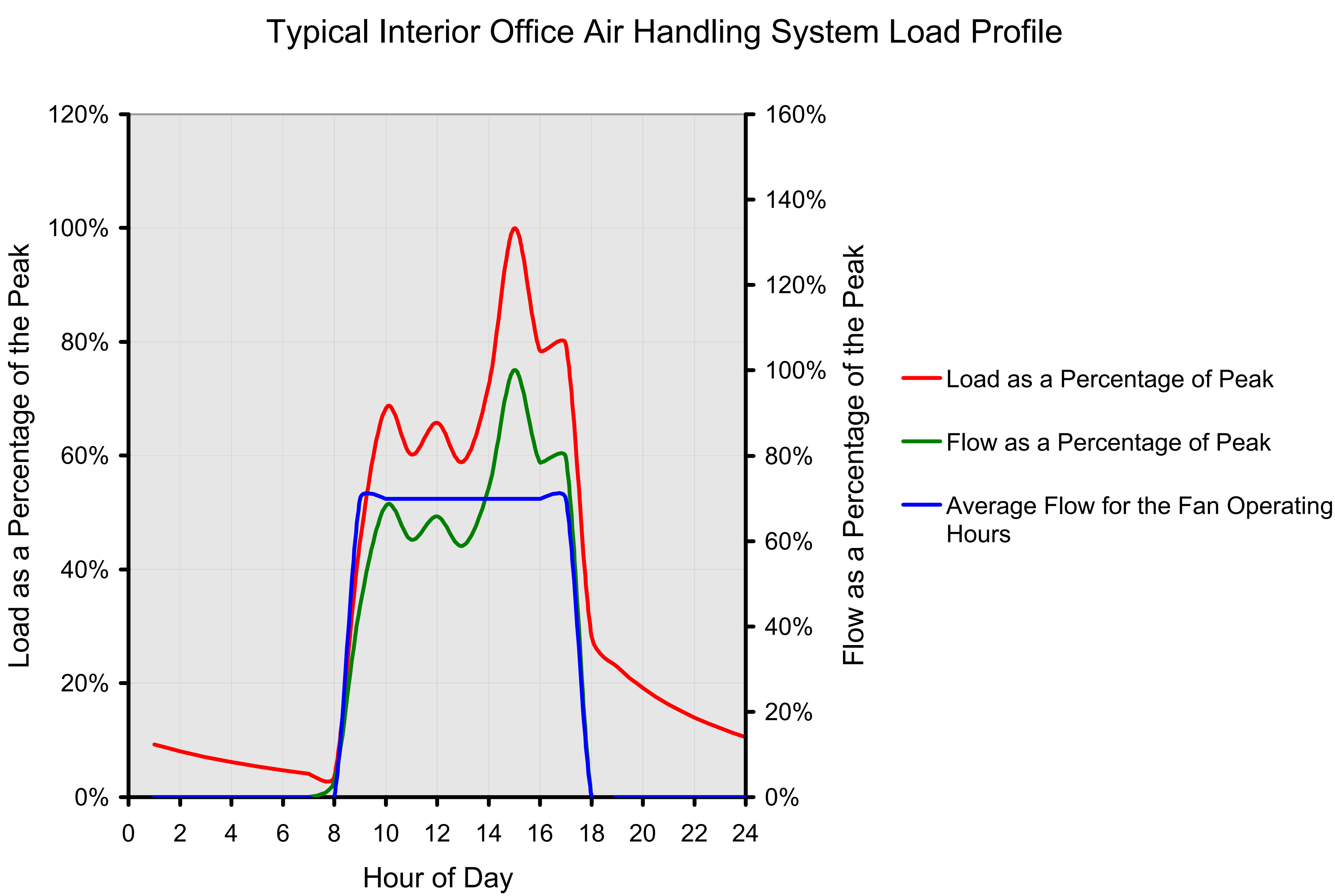
Minimum flows assume:

20 cfm per person

30% Outdoor air setting at the AHU

File name = Creating a Load Profile.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.



Typical Interior Office Air Handling System Load Profile
120%
100%
80%
60%
40%
20%
0%
Load as a Percentage of the Peak
160%
140%
120%
100%
80%
60%
40%
20%
0%
Flow as a Percentage of the Peak
0
2
4
6
8
10
12
14
16
18
20
22
24
Hour of Day
Load as a Percentage of Peak
Flow as a Percentage of Peak
Average Flow for the Fan Operating Hours

Calculating Fitting Pressure loss for high velocity ducts

Assumptions:

$$V = 4{,}005\sqrt{p_{velocity}}$$

Therefore :

$$p_{velocity} = \left(\frac{V}{4{,}005}\right)^2$$

V = Velocity in feet per minute

4,005 = A units conversion constant

$p_{velocity}$ = Velocity pressure in inches water column

$$\Delta p_{fitting} = C_o p_{velocity}$$

Where :

$\Delta p_{fitting}$ = Fitting pressure loss in inches water column

C_o = Local loss coefficien t

$p_{velocity}$ = Velocity pressure in inches water column, usually (but not always) based on entering velocity

Flow rate =	20,000 cfm
Designer's target design friction rate =	0.10 inches w.c. per 100 ft. of duct
Duct height =	24 inches
Duct width =	60 inches
Velocity =	2,000 fpm
ɔss coefficient for a mitered elbow with no turning vanes =	1.03 (from ASHRAE Handbook, fitting CR3-6)
Loss coefficient for a mitered elbow with turning vanes =	0.11 (From ASHRAE Handbook, fitting CR3-9)

Calculation:

Velocity pressure =	0.25 in.w.c.
Loss for the elbow with no turning vanes =	0.26 in.w.c.
Loss for the elbow with turning vanes =	0.03 in.w.c.
Difference (avoided pressure drop if vanes are installed) =	0.23 in.w.c.

Appendix D.2.5 Example 3 - Savings Associated with an Improved Duct Fitting Design at a Riser Connection

Assumptions:

$$P_{New} = P_{Old} \times \left(\frac{Q_{New}}{Q_{Old}}\right)^2$$

Where :

P_{New} = The static pressure at the new flow condition to be evaluated.

P_{Old} = The static pressure at the old or original flow condition, usually the design condition.

Q_{New} = The flow at the new flow condition to be evaluated.

Q_{Old} = The flow at the old or original flow condition, usually the design condition.

$$Horsepower = \left(\frac{Q \times P_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}}\right)$$

Where :

Horsepower = The horsepower saved at the terminals of the motor (includes motor efficiency losses)

Q = The flow rate which is experiencing the reduction in static pressure in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction associated with the improvement in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Savings associated with having the turning vanes =	0.23 inches w.c.
System flow rate =	20,000 cfm

Calculation:

Horsepower savings to be used for the energy calculation based on the reduced flow rate

Flow rate =	20,000 cfm
Static pressure reduction =	0.23 in.w.c.
Assumed fan efficiency =	75% (estimated)
Assumed motor efficiency =	89% (from energy efficient motor performance da
Fan horse power reduction =	1.09 hp.
kW =	0.81 kW

File name = Fitting Loss Calculation.xls, ıta in file)

File name = Fitting Loss Calculation.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Appendix D.2.5 Example 3 - Savings Associated with an Improved Duct Fitting Design at a Riser Connection

Assumptions:

Constant volume system operation

Current system operating hours =	2,860 hr/yr (5 days at 10 hr./day and 1 day at 5 hr./
Operating hours after the first year =	8,760 hr/yr
Current electrical rate =	$0.0900 $/kWh
kW savings per hour at design flow =	0.81 per hour (from previous calculation)

Calculation:

Annual savings at current operating schedule =	2,321 kWh
=	$209 per year
Annual savings at future operating schedule =	7,108 kWh
=	$640 per year

File name = Fitting Loss Calculation.xls,

/day, 52 wk/yr)

File name = Fitting Loss Calculation.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Assumptions:

$$V = 4{,}005\sqrt{p_{velocity}}$$

Therefore :

$$p_{velocity} = \left(\frac{V}{4{,}005}\right)^2$$

V = Velocity in feet per minute

4,005 = A units conversion constant

$p_{velocity}$ = Velocity pressure in inches water column

$$\Delta p_{fitting} = C_o p_{velocity}$$

Where :

$\Delta p_{fitting}$ = Fitting pressure loss in inches water column

C_o = Local loss coefficient

$p_{velocity}$ = Velocity pressure in inches water column, usually (but not always) based on entering velocity

Flow rate =	350 cfm
Designer's target design friction rate =	0.10 inches w.c. per 100 ft. of duct
Duct height =	6 inches
Duct width =	12 inches
Velocity =	700 fpm
oss coefficient for a mitered elbow with no turning vanes =	1.03 (from ASHRAE Handbook, fitting
Loss coefficient for a mitered elbow with turning vanes =	0.11 (From ASHRAE Handbook, fitting

Calculation:

Velocity pressure =	0.031 in.w.c.
Loss for the elbow with no turning vanes =	0.031 in.w.c.
Loss for the elbow with turning vanes =	0.003 in.w.c.
Difference (avoided pressure drop if vanes are installed) =	0.028 in.w.c.

File name = Fitting Loss Calculation.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

CR3-6)
CR3-9)

File name = Fitting Loss Calculation.xls,
Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Appendix D.2.5 Example 3 - Savings Associated with an Improved Duct Fitting Design at a Riser Connection

Assumptions:

$$P_{New} = P_{Old} \times \left(\frac{Q_{New}}{Q_{Old}}\right)^2$$

Where :

P_{New} = The static pressure at the new flow condition to be evaluated.

P_{Old} = The static pressure at the old or original flow condition, usually the design condition.

Q_{New} = The flow at the new flow condition to be evaluated.

Q_{Old} = The flow at the old or original flow condition, usually the design condition.

$$Horsepower = \left(\frac{Q \times P_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}}\right)$$

Where :

Horsepower = The horsepower saved at the terminals of the motor (includes motor efficiency losses)

Q = The flow rate which is experienci ng the reduction in static pressure in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction associated with the improvemen t in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Savings associated with having the turning vanes =	0.028 inches w.c.
System flow rate =	350 cfm

Calculation:

Horsepower savings to be used for the energy calculation based on the reduced flow rate

Flow rate =	350 cfm
Static pressure reduction =	0.028 in.w.c.
Assumed fan efficiency =	75% (estimated)
Assumed motor efficiency =	89% (from energy efficient motor performance da
Fan horse power reduction =	0.002 hp.
kW =	0.002 kW

ıta in file)

File name = Fitting Loss Calculation.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Appendix D.2.5 Example 3 - Savings Associated with an Improved Duct Fitting Design at a Riser Connection

Assumptions:

Constant volume system operation

Current system operating hours =	2,860 hr/yr (5 days at 10 hr./day and 1 day at 5 hr./
Operating hours after the first year =	8,760 hr/yr
Current electrical rate =	$0.0900 $/kWh
kW savings per hour at design flow =	0.002 per hour (from previous calculation)

Calculation:

Annual savings at current operating schedule =	5 kWh
=	$0.45 per year
Annual savings at future operating schedule =	15 kWh
=	$1.37 per year

/day, 52 wk/yr)

File name = Fitting Loss Calculation.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Appendix D.2.4. Example 2 - Static Pressure Reduction Required to Bring a Fan System Back Into Its Motor's Nameplate Rating at Design Flow

Assumptions:

$$P_{Saved} = \frac{\textbf{Horsepower} \times 6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}}{Q}$$

Where :

Horsepower = The horsepower savings required at the motor term inals

Q = The system design flow rate in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction required to achieve the desired horse power savings in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Horsepower requirement project to achieve design flow =	29.25 hp.
Horsepower available running the motor into its service factor =	28.75 hp.
Minimum horsepower savings desired =	0.500 hp.
System flow rate =	35,000 cfm

Calculation:

Pressure drop required to bring the system performance back to a point that can be handled by the existing motor

Flow rate =	35,000 cfm
Desired horse power reduction =	0.50 hp.
Assumed fan efficiency =	79% (based on shop drawing information)
Assumed motor efficiency =	89% (based on shop drawing information)
Required static pressure reduction =	0.06 in.w.c.

Pressure drop for the energy savings evaluation based on the reduced flow rate using the square law

Design flow rate =	35,000 cfm
Static pressure reduction at the design flow rate =	0.06 in.w.c.
Reduced flow rate =	24,500 cfm
Static pressure reduction at the reduced flow rate =	0.03 in.w.c.

Horsepower savings to be used for the energy calculation based on the reduced flow rate

Flow rate =	24,500 cfm
Static pressure reduction =	0.03 in.w.c.
Assumed fan efficiency =	75% (estimated)
Assumed motor efficiency =	89% (from energy efficient motor performance data in file)
Fan horse power reduction =	0.18 hp.
kW =	0.13 kW

File name = Motor Horsepower Reduction Estimate.xls,

Appendix D.2.4. Example 2 - Static Pressure Reduction Required to Bring a Fan System Back Into Its Motor's Nameplate Ratin

Assumptions:

Constant volume system operation

Current system operating hours =	2,860 hr/yr (5 days at 10 hr./day and 1 day at 5 hr./
Operating hours after the first year =	8,760 hr/yr
Current electrical rate =	$0.0900 $/kWh
kW savings per hour at design flow =	0.13 per hour (from previous calculation)

Calculation:

Annual savings at current operating schedule =	385 kWh
=	$35 per year
Annual savings at future operating schedule =	1,181 kWh
=	$106 per year

File name = Motor Horsepower Reduction Estimate.xls,

/day, 52 wk/yr)

File name = Motor Horsepower Reduction Estimate.xls,
Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Horsepower Savings Calculation for a 20,000 cfm system

Assumptions:

$$\textbf{Horsepower} = \left(\frac{Q \times P_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}} \right)$$

Where :

Horsepower = The horsepower saved at the terminals of the motor (includes motor efficiency losses)

Q = The flow rate which is experiencing the reduction in static pressure in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction associated with the improvement in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

ressure drop through the conventional damper =	0.065 inches w.c. @ 2,000 fpm
Pressure drop through the airfoil blade damper =	0.170 inches w.c. @ 2,000 fpm
Savings associated with airfoil blades =	0.105 inches w.c.
System flow rate =	20,000 cfm

Calculation:

Flow rate =	20,000 cfm
Static pressure reduction =	0.11 in.w.c.
Assumed fan efficiency =	75% (estimated)
Assumed motor efficiency =	89% (from energy efficient motor performance data in file)
Fan horse power reduction =	0.50 hp.
kW =	0.37 kW

File name = Static Pressure Reduction Energy Savings.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Appendix C.2.4 Example 1 - Energy Savings Associated with Airfoil Blade Smoke Isolation Dampers Instead of the Conventional Design

Energy Savings Calculation for a 20,000 cfm system

Assumptions:

Constant volume system operation

Current system operating hours =	2,860 hr/yr (5 days at 10 hr./day and 1 day at 5 hr./day, 52 wk/yr)
Operating hours after the first year =	8,760 hr/yr
Current electrical rate =	$0.0900 $/kWh
kW savings per hour at design flow =	0.37 per hour (from previous calculation)

Calculation:

Annual savings at current operating schedule =	1,062 kWh
=	$96 per year
Annual savings at future operating schedule =	3,253 kWh
=	$293 per year

Horsepower Savings Calculation for a 14,000 cfm system

Assumptions:

$$P_{New} = P_{Old} \times \left(\frac{Q_{New}}{Q_{Old}} \right)^2$$

Where :

P_{New} = The static pressure at the new flow condition to be evaluated.

P_{Old} = The static pressure at the old or original flow condition, usually th e design condition.

Q_{New} = The flow at the new flow condition to be evaluated.

Q_{Old} = The flow at the old or original flow condition, usually th e design condition.

$$Horsepower = \left(\frac{Q \times P_{Saved}}{6{,}356 \times \eta_{FanStatic} \times \eta_{Motor}} \right)$$

Where :

Horsepower = The horsepower saved at the terminals of the motor (includes motor efficiency losses)

Q = The flow rate which is experienci ng the reduction in static pressure in cubic feet per minute (cfm)

P_{Saved} = The static pressure reduction associated with the improvemen t in inches water column (in.w.c.)

6,356 = A units conversion constant

$\eta_{FanStatic}$ = The fan static efficiency

η_{Motor} = The motor efficiency

Pressure drop through the conventional damper =	0.065 inches w.c. @ 2,000 fpm
Pressure drop through the airfoil blade damper =	0.170 inches w.c. @ 2,000 fpm
Savings associated with airfoil blades =	0.105 inches w.c.
System flow rate =	20,000 cfm
Average flow rate as a percentage of design =	70% (from the load profile we generated with the engineer's data)
Flow rate to be used for the evaluation =	14,000 cfm

Calculation:

Pressure drop for the evaluation based on the reduced flow rate using the square law

Design flow rate =	20,000 cfm
Static pressure reduction at the design flow rate =	0.11 in.w.c.
Reduced flow rate =	14,000 cfm
Static pressure reduction at the reduced flow rate =	0.05 in.w.c.

Horsepower savings to be used for the energy calculation based on the reduced flow rate

Flow rate =	14,000 cfm
Static pressure reduction =	0.05 in.w.c.
Assumed fan efficiency =	75% (estimated)
Assumed motor efficiency =	89% (from energy efficient motor performance data in file)
Fan horse power reduction =	0.17 hp.
kW =	0.13 kW

Appendix C.2.4 Example 1 - Energy Savings Associated with Airfoil Blade Smoke Isolation Dampers Instead of the Conver

Energy Savings Calculation for a 14,000 cfm system

Assumptions:

Variable volume operation

Current system operating hours =	2,860	hours per year
Operating hours after rennovation =	8,760	hours per year
Current electrical rate =	$0.0900	$/kWh
kW savings per hour at design flow =	0.13	per hour (from previous calculation)

Calculation:

Annual savings at current operating schedule =	364	kWh
=	$33	per year
Annual savings at future operating schedule =	1,116	kWh
=	$100	per year

File name = Static Pressure Reduction Energy Savings.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.

Appendix C.2.4 Example 1 - Energy Savings Associated with Airfoil Blade
Deriving a Load Profile from Project Engineering Data

Interior Office - Interior cubicle served by AHU 2, Typical of 50 served by the unit

Summer

Hours	Actual Load Scheduled and observed occupancy Total Btu/Hr	Actual Load Scheduled and observed occupancy Percentage of peak	Actual Load Scheduled and observed occupancy In terms of CFM	Actual Load Scheduled and observed occupancy (off when unoccupied) Percentage of peak	Actual Load Scheduled and observed occupancy (off when unoccupied) Average Percentage
1	304	9%	16	0%	0%
2	266	8%	14	0%	0%
3	233	7%	12	0%	0%
4	204	6%	10	0%	0%
5	178	5%	9	0%	0%
6	156	5%	8	0%	0%
7	137	4%	7	0%	0%
8	120	4%	6	4%	0%
9	1483	45%	76	45%	70%
10	2255	68%	116	68%	70%
11	1989	60%	102	60%	70%
12	2171	66%	112	66%	70%
13	1946	59%	100	59%	70%
14	2392	72%	123	72%	70%
15	3301	100%	170	100%	70%
16	2590	78%	133	78%	70%
17	2628	80%	135	80%	70%
18	930	28%	48	0%	0%
19	758	23%	39	0%	0%
20	633	19%	33	0%	0%
21	538	16%	28	0%	0%
22	462	14%	24	0%	0%
23	401	12%	21	0%	0%
24	349	11%	18	0%	0%

Peak Load	3301			
Max CFM	#DIV/0!			Peak load / [1.08 x (space temp - supply temp)]
Average CFM over 24 hours		57		
Average as a percentage of the peak		42%		
Average CFM over occupied hours		119		
Average as a percentage of the peak		88%		

Space temperature design point	74	°F	
Space humidity design point	50%	RH	
			(from psychrometric chart)
Average sensible heat ratio	0.95		
			(from psychrometric chart)
Coil discharge air temperature	53	°F	(from fan and duct gains)
Estimated temperature rise	3	°F	
Supply air temp at grill	56	°F	

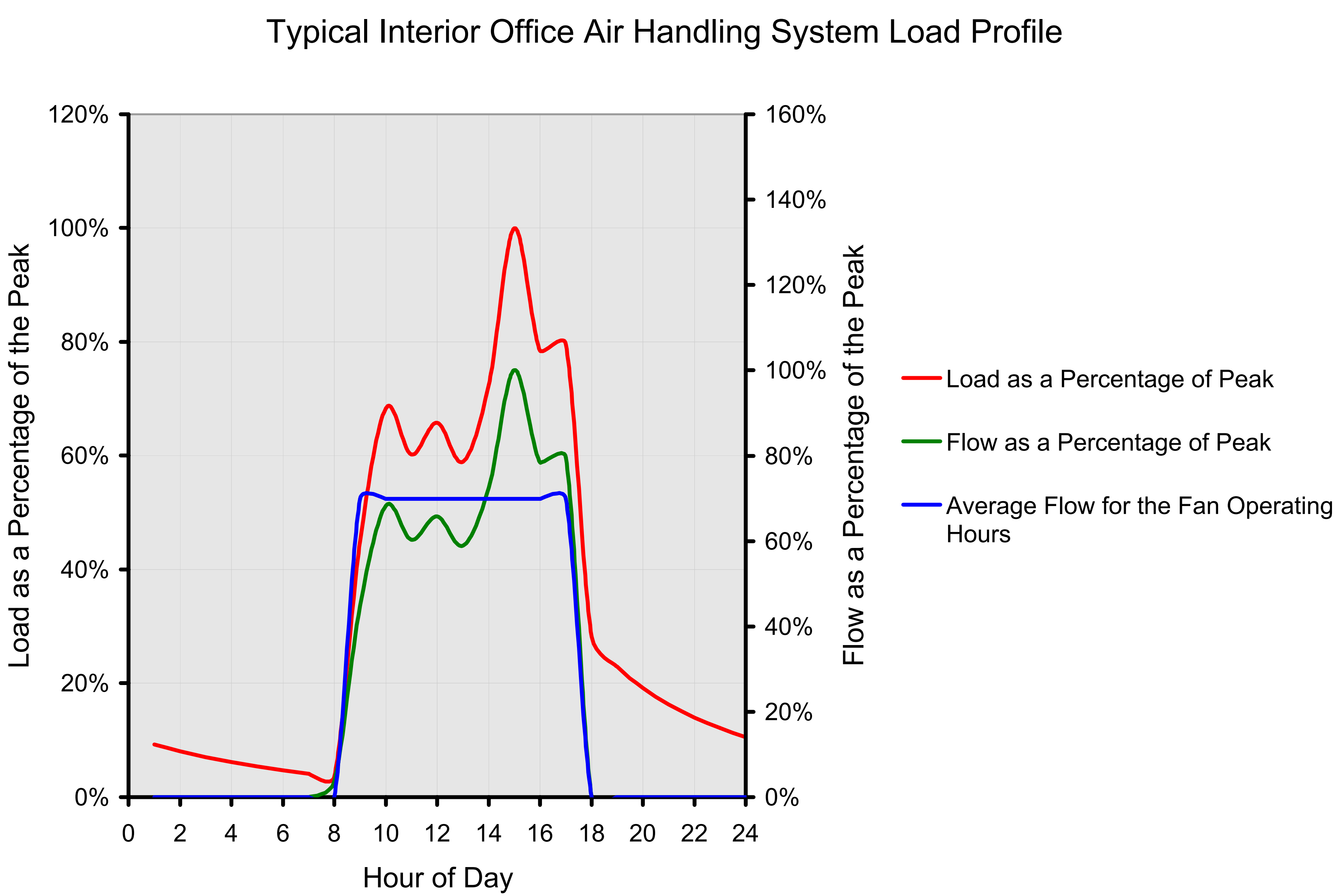
Minimum flows assume:

20 cfm per person

30% Outdoor air setting at the AHU

File name = Static Pressure Reduction Energy Savings.xls,

Calculations are subject to the assumptions and inputs. PIER, LBNL, and PECI assume no responsibility thier application and use.


Typical Interior Office Air Handling System Load Profile
Load as a Percentage of the Peak
Flow as a Percentage of the Peak
Hour of Day
0%
20%
40%
60%
80%
100%
120%
140%
160%
0
2
4
6
8
10
12
14
16
18
20
22
24
Load as a Percentage of Peak
Flow as a Percentage of Peak
Average Flow for the Fan Operating Hours

Appendix D.2.4 Example 2 - Static Pressure Reduction Required to Bring a Fan System Back Into Its *Static Pressure Loss Calculation*

Duct System Static Pressure Calculation

Assume 11'6 floor to floor except 13' for 7th floor

System - ACU-4

ITEM	DESCRIPTION	FLOW RATE cfm	SECTION LENGTH Feet	DUCT HTH. In.	DUCT WTH. In.	DUCT DIA. In.	DUCT VEL. Fpm
0	Outdoors						
1	Intakc louver	13,680					#DIV/0!
2	O.A. Damper	13,680		20.00	72.00		1,368
3	O.A. Duct	13,680	52	20.00	72.00		1,368
4	Mixing Plenum	13,680					#DIV/0!
5	Filters	13,680					#DIV/0!
6	Cooling coil (wet)	13,680					#DIV/0!
7	Reheat coil	13,680					#DIV/0!

8	Fan casing	13,680					#DIV/0!
9	System effect - fan discharge	13,680		27.00	33.00		2,211
10	Y branch, 60°, with conversion to round	13,680		27.00	33.00		2,211
11	16" round duct	4,970	2			16.00	3,560
12	Radiused 90° round elbow	4,970				16.00	3,560
13	16" round duct	4,970	2			16.00	3,560
14	Fire damper	4,970				16.00	3,560
15	16" round duct	4,970	2			16.00	3,560
16	Radiused 90° round elbow	4,970				16.00	3,560
17	Sound attenutator	4,970				16.00	3,560
18	16" round duct	4,970	4			16.00	3,560
19	Radiused 45° round elbow	4,970				16.00	3,560
20	16" round duct	4,970	14			16.00	3,560
21	Offset down	4,970				16.00	3,560
22	16" round duct	4,970	5			16.00	3,560
23	Y branch, flow through run	4,970				16.00	3,560
24	Conical reducer with branch, flow	3,500				16.00	2,507
25	10" round duct	1,600	12			10.00	2,934
26	Radiused 45° round elbow	1,600				10.00	2,934
27	10" round duct	1,600	2			10.00	2,934
28	Radiused 90° round elbow	1,600				10.00	2,934
29	10" round duct	1,600	14			10.00	2,934

30	7th floor connection, flow through run	1,600				10.00	2,934
31	10" round duct	1,360	12			10.00	2,494
32	6th floor connection, flow through run	1,360				10.00	2,494
33	9" round duct	1,100	6			9.00	2,490
34	Offset	1,100				9.00	2,490
35	9" round duct	1,100	6			9.00	2,490
36	5th floor connection, flow through run	1,100				9.00	2,490
37	9" round duct	840	12			9.00	1,901
38	4th floor connection, flow through run	840				9.00	1,901
39	9" round duct	580	6			9.00	1,313
40	Offset	580				9.00	1,313
41	9" round duct	580	6			9.00	1,313
42	3rd floor connection, flow through run	580				9.00	1,313
43	7" round duct	320	3			7.00	1,197
44	Radiused 90° round elbow	320				7.00	1,197
45	7" round duct	320	2			7.00	1,197
46	Radiused 90° round elbow	320				7.00	1,197
47	Close fitting interation	320				7.00	1,197
48	7" round duct	320	8			7.00	1,197
49	Radiused 90° round elbow	320				7.00	1,197
48	7" round duct	320	3			7.00	1,197
49	7" flex duct	320	1			7.00	1,197

50	Air valve	320		4.00	4.00		2,880
51	Plenum loss	320		4.00	4.00		2,880
52	Grill loss	320		4.00	16.00		720
53							#DIV/0!
54							#DIV/0!
55							#DIV/0!

Formulas used

Velocity = 4005 x (Velocity Pressure)$^{1/2}$

quivalent length for system effect calcs, outlet velocity over 2,500 fpm = Velocity x (Duct area $^{1/2}$)/10,600

Estimated static requirement for the window terminal unit - 4" damper = 0.98 in.w.c.

Estimated static requiement for a unit with a 5" damper (see below) = 0.55 in.w.c.

System total with this unit = 6.31

System total with this unit and a lower loss attenuator = 5.88

ITEM	DESCRIPTION	FLOW RATE cfm	SECTION LENGTH Feet	DUCT HTH. In.	DUCT WTH. In.	DUCT DIA. In.	DUCT VEL. Fpm
1	7" flex duct	320	1			7.00	1,197
1	Air valve	320		5.00	5.00		1,843
2	Plenum loss	320		5.00	5.00		1,843
3	Grill loss	320		5.00	5.00		1,843

imated static requiement for a unit with a 6" round damper (see below) = 0.41 in.w.c.

System total with this unit = 6.17

System total with this unit and a lower loss attenuator = 5.74

ITEM	DESCRIPTION	FLOW RATE cfm	SECTION LENGTH Feet	DUCT HTH. In.	DUCT WTH. In.	DUCT DIA. In.	DUCT VEL. Fpm
1	7" flex duct	320	1			7.00	1,197
1	Air valve	320				6.00	1,630
2	Plenum loss	320				6.00	1,630

3	Grill loss	320				6.00	1,630

Motor's Nameplate Rating

VEL. PRESS. In.w.c	LOSS COEFF. Co	CAT. LOSS In.w.c.	FRIC. RATE In.w.c per 100 ft.	SECTION OR ITEM LOSS in.w.c	PERCENT OF TOTAL	RUNNING TOTAL Clean filters In.w.c.	RUNNING TOTAL Dirty filters In.w.c.
						0.00	0.00
#DIV/0!	N/A	0.15	N/A	0.15	2.2%	-0.15	-0.15
0.1167	0.52	N/A	N/A	0.06	0.9%	-0.21	-0.21
0.1167	N/A	N/A	0.05	0.03	0.4%	-0.24	-0.24
#DIV/0!	N/A	0.20	N/A	0.20	3.0%	-0.44	-0.44
#DIV/0!	N/A	0.90	N/A	0.90	13.4%	-0.69	-1.34
#DIV/0!	N/A	0.71	N/A	0.71	10.5%	-1.40	-2.05
#DIV/0!	N/A	0.42	N/A	0.42	6.2%	-1.82	-2.47

#DIV/0!	N/A	0.20	N/A	0.20	3.0%	-2.02	-2.67
0.3047	1.00	N/A	N/A	0.30	4.5%	3.77	3.77
0.3047	0.21	NA	NA	0.06	0.9%	3.70	3.70
0.7899	NA	NA	0.95	0.02	0.3%	3.68	3.68
0.7899	0.15	N/A	N/A	0.12	1.8%	3.56	3.56
0.7899	NA	NA	0.95	0.02	0.3%	3.55	3.55
0.7899	0.19	NA	NA	0.15	2.2%	3.40	3.40
0.7899	NA	NA	0.95	0.02	0.3%	3.38	3.38
0.7899	0.15	N/A	N/A	0.12	1.8%	3.26	3.26
0.7899	0.81	NA	NA	0.64	9.5%	2.62	2.62
0.7899	NA	NA	0.95	0.04	0.6%	2.58	2.58
0.7899	0.07	NA	NA	0.06	0.8%	2.52	2.52
0.7899	NA	NA	0.95	0.13	2.0%	2.39	2.39
0.7899	0.25	N/A	N/A	0.19	2.9%	2.20	2.20
0.7899	NA	NA	0.95	0.05	0.7%	2.15	2.15
0.7899	0.13	NA	NA	0.10	1.5%	2.05	2.05
0.3917	0.13	NA	NA	0.05	0.8%	2.00	2.00
0.5365	NA	NA	0.73	0.09	1.3%	1.91	1.91
0.5365	0.07	NA	NA	0.04	0.6%	1.87	1.87
0.5365	NA	NA	0.73	0.01	0.2%	1.86	1.86
0.5365	0.15	N/A	N/A	0.08	1.2%	1.78	1.78
0.5365	NA	NA	0.73	0.10	1.5%	1.68	1.68

0.5365	0.14	NA	NA	0.08	1.1%	1.60	1.60
0.3876	NA	NA	0.60	0.07	1.0%	1.53	1.53
0.3876	0.13	NA	NA	0.05	0.7%	1.48	1.48
0.3865	NA	NA	0.80	0.05	0.7%	1.44	1.44
0.3865	0.25	N/A	N/A	0.09	1.4%	1.34	1.34
0.3865	NA	NA	0.80	0.05	0.7%	1.30	1.30
0.3865	0.13	N/A	N/A	0.05	0.7%	1.25	1.25
0.2254	N/A	N/A	0.55	0.06	0.9%	1.18	1.18
0.2254	0.13	N/A	N/A	0.03	0.4%	1.15	1.15
0.1075	N/A	N/A	0.30	0.02	0.3%	1.14	1.14
0.1075	0.25	N/A	N/A	0.03	0.4%	1.11	1.11
0.1075	N/A	N/A	0.30	0.02	0.3%	1.09	1.09
0.1075	0.14	N/A	N/A	0.01	0.2%	1.08	1.08
0.0894	N/A	N/A	0.32	0.01	0.1%	1.07	1.07
0.0894	0.15	N/A	N/A	0.01	0.2%	1.06	1.06
0.0894	N/A	N/A	0.32	0.01	0.1%	1.05	1.05
0.0894	0.15	N/A	N/A	0.01	0.2%	1.04	1.04
0.0894	N/A	N/A	N/A	0.00	0.1%	1.03	1.03
0.0894	N/A	N/A	0.32	0.03	0.4%	1.01	1.01
0.0894	0.15	N/A	N/A	0.01	0.2%	0.99	0.99
0.0894	N/A	N/A	0.32	0.01	0.1%	0.98	0.98
0.0894	N/A	N/A	0.64	0.01	0.1%	0.98	0.98

0.5171	N/A	N/A	N/A	0.43	6.3%	0.55	0.55
0.5171	1.00	N/A	N/A	0.52	7.7%	0.03	0.03
0.0323	1.00	N/A	N/A	0.03	0.5%	0.00	0.00
#DIV/0!	N/A	N/A	N/A	0.00			
#DIV/0!	N/A	N/A	N/A	0.00			
#DIV/0!	N/A	N/A	N/A	0.00			
			TOTAL	6.74			
TOTAL with lower loss attenuator				6.31			

VEL. PRESS. In.w.c	LOSS COEFF. Co	CAT. LOSS In.w.c.	FRIC. RATE In.w.c per 100 ft.	SECTION OR ITEM LOSS in.w.c				
0.0894				#VALUE!				
0.2118				0.12				
0.2118	1.00			0.21				
0.2118	1.00			0.21				

VEL. PRESS. In.w.c	LOSS COEFF. Co	CAT. LOSS In.w.c.	FRIC. RATE In.w.c per 100 ft.	SECTION OR ITEM LOSS in.w.c				
0.0894				#VALUE!				
0.1656				0.08				
0.1656	1.00			0.17				

0.1656	1.00			0.17				

REMARKS	Calculation 1
Assumption/allowance	Blade angle =
Assumption/allowance	
Roll filters, loss based on fully loaded Farr 30/30 rating	
Based on the value from the ACU-1 shop drawing, assume similar	
Based on the value from the ACU-1 shop drawing, assume similar	

Assumption/allowance	
Assume that you loose 1 velocity head	
Based on ASHRAE SR5-17	Branch flow/Total flow =
Could be as low as Co = .27	
	Through flow/Total flow
	Through flow/Total flow

	Through flow/Total flow
	Through flow/Total flow
	Through flow/Total flow
	Through flow/Total flow
	Through flow/Total flow
AMCA	stance between/Duct diameter =

Difference between velocity pressures	
Assumed air valve size, assume loss of all velocity pressure	
Assume discharge over 4 - 4" square grilles	

REMARKS	Calculation 1
Difference between velocity pressures	
Assumed air valve size, assume loss of all velocity pressure	
Assume discharge over 4 - 4" square grilles	

REMARKS	Calculation 1
Difference between velocity pressures	
Assumed air valve size, assume loss of all velocity pressure	

Assume discharge over 4 - 4" square grilles	

MISC. CALCULATIONS

	Calculation 2	Calculation 3
0.00	blade lengths/Duct perimeter = 1.96	

0.36	Branch area/Total area = 0.23	
0.70	Through area/Incoming area = 1.00	
0.46	Through area/Incoming area = 0.39	

0.85	Through area/Incoming area = 1.00	
0.81	Through area/Incoming area = 0.81	
1.00	Through area/Incoming area = 1.00	
0.69	Through area/Incoming area = 1.00	
0.55	Through area/Incoming area = 0.60	
3.43		

MISC. CALCULATIONS

	Calculation 2	Calculation 3

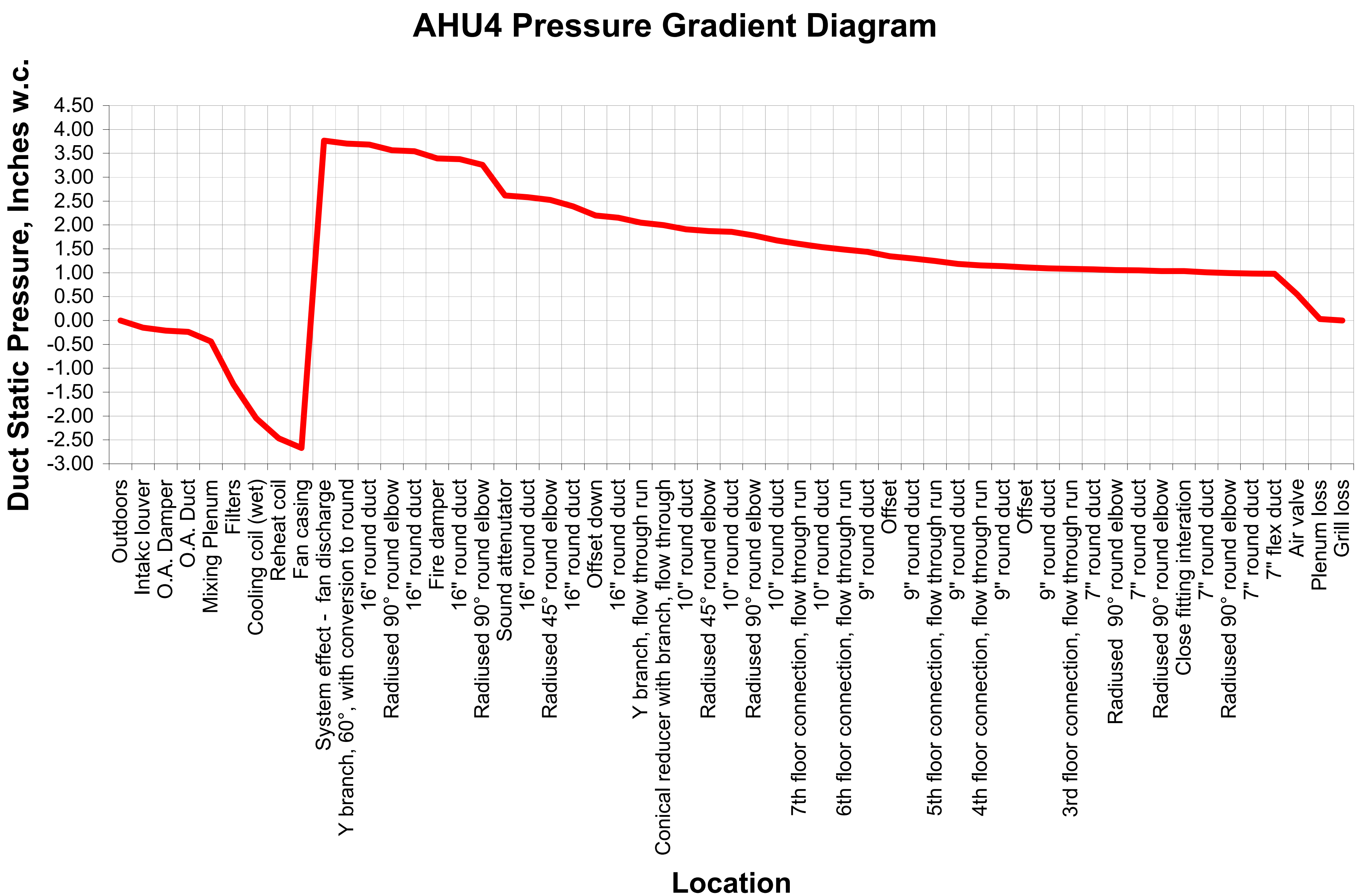
MISC. CALCULATIONS

	Calculation 2	Calculation 3

	Calculation 4

	Calculation 4

	Calculation 4


AHU4 Pressure Gradient Diagram
Duct Static Pressure, Inches w.c.
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
Outdoors
Intakc louver
O.A. Damper
O.A. Duct
Mixing Plenum
Filters
Cooling coil (wet)
Reheat coil
Fan casing
System effect - fan discharge
Y branch, 60°, with conversion to round
16" round duct
Radiused 90° round elbow
16" round duct
Fire damper
16" round duct
Radiused 90° round elbow
Sound attenuator
16" round duct
Radiused 45° round elbow
16" round duct
Offset down
16" round duct
Y branch, flow through run
Conical reducer with branch, flow through
10" round duct
Radiused 45° round elbow
10" round duct
Radiused 90° round elbow
10" round duct
7th floor connection, flow through run
10" round duct
6th floor connection, flow through run
9" round duct
Offset
9" round duct
5th floor connection, flow through run
9" round duct
4th floor connection, flow through run
9" round duct
Offset
9" round duct
3rd floor connection, flow through run
7" round duct
Radiused 90° round elbow
7" round duct
Radiused 90° round elbow
Close fitting interation
7" round duct
Radiused 90° round elbow
7" round duct
7" flex duct
Air valve
Plenum loss
Grill loss
Location

Future Development of Supplemental Information

The following supplemental information outlines are provided as reference. Each of these sections may be developed in a future revision of the Functional Testing Guide. For examples of chapters with Supplemental Information sections developed, refer to ***Chapter 5: Economizer and Mixed Air***, and ***Chapter 13: Distribution***.

Chapter 6: Filtration

Filter types

Package style

Standard vs. extended surface area

HEPA and ULPA

Chemical

UV

Efficiency rating

ASHRAE dust spot

MERV

HEPA

Other measures

Pressure drop rating

Clean

Dirty

- Design allowance and Structural rating

Interactive effects

Relationship to energy consumption

Monitoring

- VAV system effects
- Indicators: Draft gauge, Magnehelic, Photohelic

Change-out considerations

- Trade-offs
- Long service life issues

Start-up and temporary filtration issues

Operational issues and concerns

Weight

Access

Water logging

Icing

Blow through and collapse

Mounting

Fire suppression

Chapter 7: Preheat

Technologies

Heating Technologies

Hot water and glycol

Low temperature hot water and glycol

Steam

Condensate return considerations

Air and water source heat pump

Electricity Gas furnaces

Energy recovery (see separate section)

Water and Steam Coils

Coil Construction

Rows

Fins

Circuiting

Cleaning and heat transfer paths

Special Considerations for Steam

Electric Coils

Coil Construction

Special Control Considerations

Gas Furnaces

Furnace Construction

Special Control Considerations

Special Considerations for Preheat Coils

Water and Steam Coils

Modulated flow across the mains

Pumped coil

Distributing tube coil

Face and bypass

Conventional

Integral face and bypass

Electric Coils

SCRs

Demand control

Gas Furnaces

Modulation

Control

Approaches

- Modulation
- Face and bypass damper
- Sequenced vs. Independent Loop

Special considerations

- High turn down ratios
- Condition at shut-down
- Interlocks with outdoor conditions

Chapter 8: Cooling Systems

Cooling psychrometrics

Components

Coil Construction

Piping and relationship to pressures

Operational issues

Freezing

Maintenance

Cooling technologies

Control

Approaches (reference previous)

Cooling considerations

Apparatus dew point

LAT relationship to humidity control

Impact of depressed EWT

Carry-over and eliminators

Chapter 9: Humidification

Humidification psychrometrics

Humidification approaches

Direct steam injection

Indirect steam injection

Evaporative

Compressed air driven

Control

Approaches

Limit

Interlocks

Outdoor air conditions

Air flow

Jacket heating

Warm up

Shut down

Chapter 14: Terminal Equipment

Terminal Control Requirements

Temperature Control, Ventilation Control, and Loads

Trimming Humidity Levels

Final Filtration

Localized Pressure Control

Types of Terminal Equipment

Temperature and Flow Control

Temperature Only Based Control

Flow Based Control with Temperature Reset

Single Zone

Constant Volume, Reheat

Variable Volume, With and Without Reheat

Fan-powered, Parallel and Series

Multizone and Double Duct

Induction

Terminal Heat Pumps

Terminal Cooling

Trim Humidifiers

Filtration

Local Filter Banks

Filtration Ceilings

Pressure Control

Large Zones

Lab Hoods and Processes

Terminal Related Energy Conservation Strategies

Scheduling at the Terminal Level

Demand Based Ventilation Control at the Terminal Level

Testing by Sampling

Chapter 18: Integrated Operation and Control

Interactions of a Typical Closed Loop Control Cycle

Cascading Instability

Loop Tuning Parameter Shifts Associated Variable System Operating Parameters

Seasonal Changes

Aging Equipment

Variable Control Sequences

Variations in Performance with Variations in Load

Interactions Outside of the Air Handling System

Interactions with Central Utility Systems

Recovery from Power Failures

Recovery from Alarm Trips

Unusual Effects due to Extended Outages

Unusual Effects Associated with System Start-up during Construction

Approaches to Integrated Testing

Passive Testing