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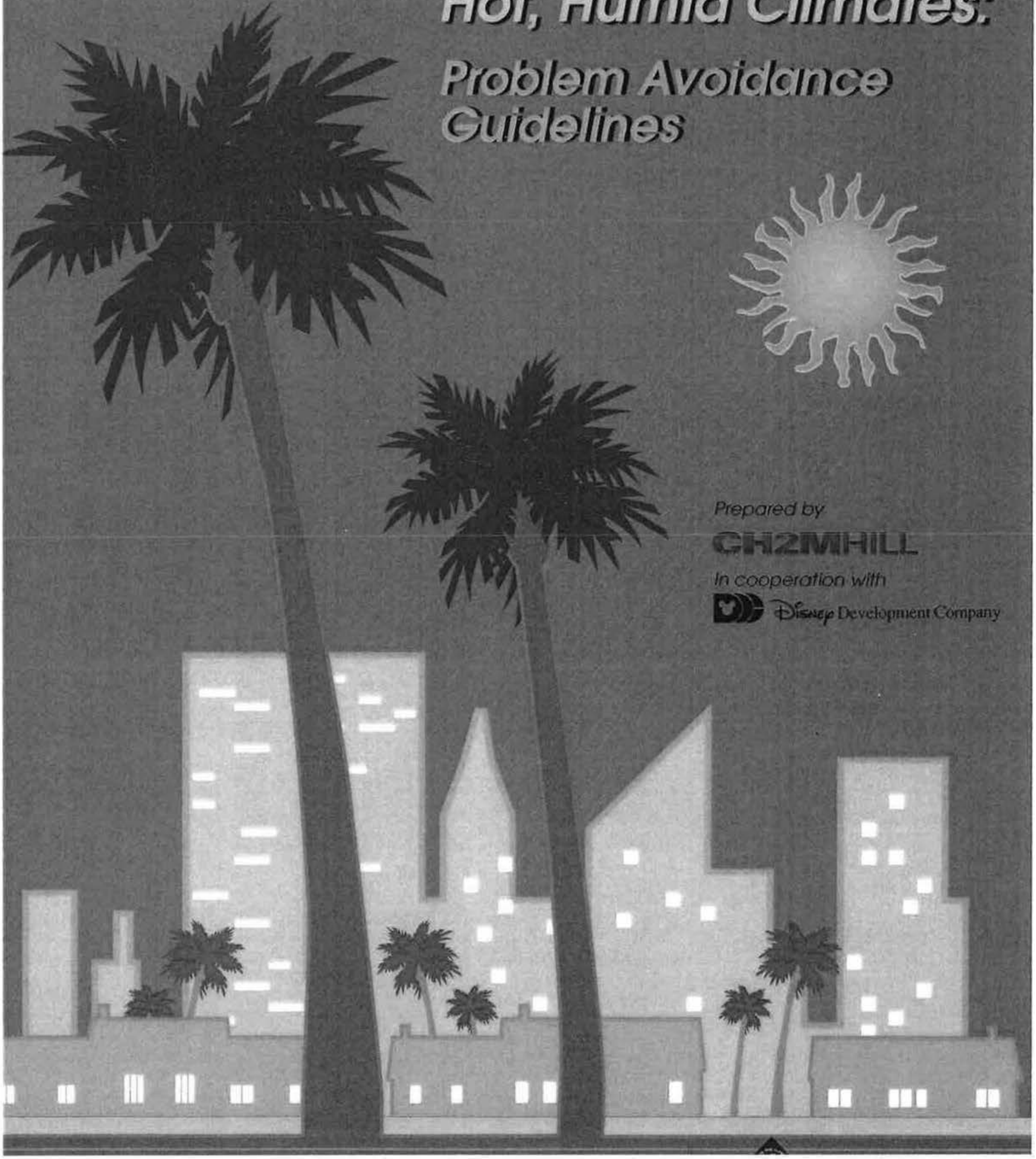
Preventing Indoor Air Quality Problems in Hot, Humid Climates:

Problem Avoidance Guidelines



Prepared by
CH2MHILL
In cooperation with
Disney Development Company

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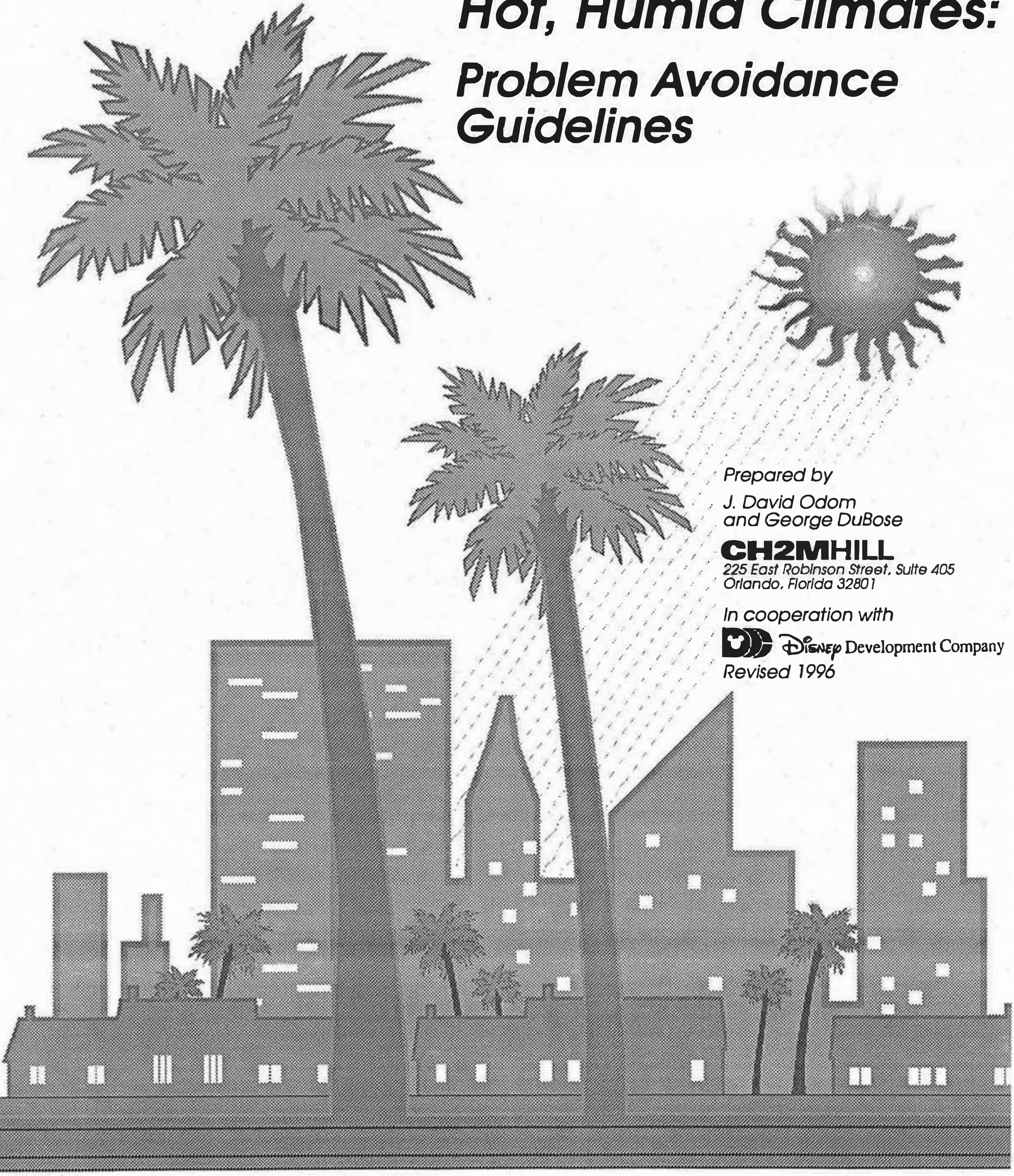

Prepared by

J. David Odom
and George DuBose

CH2MHILL
225 East Robinson Street, Suite 405
Orlando, Florida 32801

In cooperation with

Disney Development Company

Revised 1996

About This Manual

This manual was cooperatively developed by CH2M HILL and the Disney Development Company, Lake Buena Vista, Florida, whose name is used with written permission. In 1995, this manual won an Excellence award from the Society for Technical Communication in its annual Florida Technical Publications and Art Competition.

Proceeds from the sale of this manual will benefit the charity Give Kids The World, a nonprofit organization in central Florida that gives terminally ill children and their families an opportunity to visit Walt Disney World.

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Acknowledgments

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All inquiries should be addressed to CH2M HILL at this address:

CH2MHILL

Mr. J. David Odom,
or Mr. George DuBose
CH2M HILL
225 East Robinson Street, Suite 405
Orlando, Florida 32801
(407) 423-0030 (phone)
(407) 839-5901 (fax)

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Preface

Highlights

- ✓ *Using this manual, Disney Development Company has completed more than $750 million in construction, none of which has developed subsequent IAQ problems.*
- ✓ *Implementing the principles in the manual does not significantly increase design and construction costs.*

Introduction

Indoor air quality (IAQ) problems in facilities located in hot, humid climates are overwhelmingly caused by moisture intrusion. When moisture intrudes into a building's envelope and its occupied space, mildew begins to grow—and so do complaints from occupants about their health and comfort.

Newly constructed buildings in hot, humid climates exhibit a disproportionate share of IAQ problems, since any significant errors made during the design, construction, or operation of a building will often manifest themselves as moisture and mildew problems during the building's first cooling season. This manual was developed to address the errors that occur during new construction; the concepts presented here, however, are equally applicable to the remediation of IAQ problems in existing buildings.

The following aspects distinguish this manual from others on the same topic:

- It was prepared in cooperation with Disney Development Company, one of the largest developers in Florida. Disney's consistent adherence to the principles outlined here has eliminated IAQ problems in its new construction. Thus, this manual combines the experience of CH2M HILL, the largest environmental engineering firm in the United States, and Disney, one of the premier facility planning and management firms in the world.
- It focuses on solving IAQ problems without adding extra cost to building design and construction.
- Rather than following a topic-based organizational structure (for example, HVAC design, wall system design), this manual is process-oriented, going step by step through the typical design and construction phases. This format aids the reader in implementing the concepts presented.
- It is the only manual that deals exclusively with hot, humid climate-related problems, an environment where even relatively minor errors in the design, construction, or operation of buildings can have devastating results.

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Manual Overview

Prepared in Cooperation with Disney Development Company

This manual was first prepared in 1990 in a cooperative effort between CH2M HILL and Disney Development Company. This effort was undertaken because of the clear need for a manual that would define the roles and responsibilities of the design team, the contractor, and the building owner. The manual integrates IAQ-related technology into the process of designing and constructing a building and is oriented toward the practitioner who is actively involved in the design and construction of commercial facilities in hot, humid climates.

This manual has been revised repeatedly during the past 6 years, and each revision has incorporated constructive feedback provided by the designers, contractors, and staff of Disney Development Company and Walt Disney World Resorts Division. Disney Development Company has obtained outstanding results as a consequence of using this manual in its planning, design, construction, and operation of buildings.

Since its original publication, this manual has been used to complete construction projects totaling more than $750 million in construction value. All of these facilities are located in hot, humid areas; to date, not one exhibits the significant moisture and mildew problems characteristic of pre-manual design and construction.

The ongoing effort to improve and update this manual attests to our increased confidence in determining what actions during design and construction are most critical for avoiding mildew problems in hot, humid climates and what actions can be safely omitted without compromising future building integrity.

Seeks to Avoid Problems without Increasing Costs

We first developed this manual on the strong belief that taking steps during design and construction to avoid problems, even in hot, humid climates, would not significantly increase initial costs. That belief was founded on the following evidence:

- The results of a 1990 moisture and mildew survey published by the American Hotel and Motel Association (AH&MA). Among the most startling results of that survey were those showing that moisture and mildew problems occur more often in expensive construction than in moderately priced construction.
- Repeated observation that serendipity, or luck, accounts for the lack of major moisture and mildew problems in most unaffected facilities.

Thus, we concluded, if luck is the common denominator in avoiding moisture-related problems and moderately priced facilities are less likely to develop such problems, then successful moisture control and higher construction costs are not significantly related. In fact, if recommendations for controlling moisture intrusion in a particular

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building will significantly increase construction costs, those recommendations should be reevaluated.

To ensure that the recommendations included in this manual would not impose undue financial or scheduling burdens on the development team and thus would not fall into disuse, the recommendations were judged against these standards:

- Their importance in avoiding future moisture problems
- The effect of their implementation on project costs and schedule

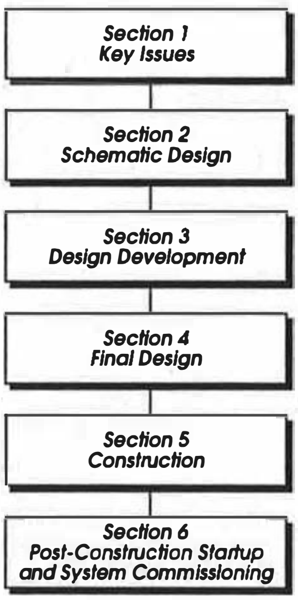
During the past 6 years, the absence of problems in buildings designed according to the resulting recommendations affirms our success according to the first standard. At the same time, design teams and contractors have eagerly provided constructive input on our success relative to the second standard, and the revisions in this edition are based on that input.

This manual is brief by design. It is not intended to provide detailed engineering data available in other documents or to substitute in any way for the detailed, professional design practice that is required in the building and construction process. Rather, this manual is intended to serve as a supplemental guide to be used along with existing professional reference materials. In effect, while other documents concentrate exclusively on the technology, this manual's intent is to incorporate sound technology into the process of designing and constructing facilities.

Organization Follows Design and Construction Process

The organization of this manual follows the normal process of facility design and construction. We chose that format for several reasons. First, it is more user-friendly for readers who are involved in the process. Second, although mildew-related IAQ problems are often first observed after building occupancy, their sources and the keys to their prevention usually lie much earlier in the process. Critical actions for success, therefore, must be taken earlier in the design and construction process.

Lastly, because making the right decisions at the right time is key to controlling costs, maintaining the project schedule, and avoiding future moisture problems, we wanted our manual to facilitate good decisionmaking. We have observed that the decisions made daily during design and construction often occur without a full understanding of their ramifications. We therefore recommend beginning the process with a set of prescriptive guidelines such as those provided in this manual, implementing strategic reviews at critical stages throughout the design and construction process, and ending the construction phase with sound HVAC system startup procedures. We are confident that following this manual's suggestions and recommendations will improve the soundness and timing of day-to-day decisions and ultimately avoid future moisture-related building problems.



This manual's organization leads the reader through key issues and strategies (Sections 1 and 2) and each phase in the design and construction processes (Sections 4 through 6).

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Acronyms and Abbreviations

AC	air-conditioning
ACEC	American Consulting Engineers Council
AH&MA	American Hotel and Motel Association
AHU	air-handling unit
ARI	Air Conditioning and Refrigeration Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ASTM	American Society for Testing and Materials
Btu/cfm	British thermal units per cubic foot per minute
CAV	constant air volume
cfh	cubic feet per hour
cfm	cubic foot per minute
°C	degrees Celsius
°F	degrees Fahrenheit
°Fdb	dry bulb temperature
°Fwb	wet bulb temperature
DOE	U.S. Department of Energy
DPIC	Design Professional Insurance Company
EIFS	exterior insulation and finish systems
FCU	fan-coil unit
fpm	feet per minute
ft^2	square feet
FSEC	Florida Solar Energy Center
HVAC	heating, ventilating, and air-conditioning
IAQ	indoor air quality
lb_w	pounds of water (or pints)
mm	millimeter
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
Pa	Pascal
PTAC	packaged terminal air-conditioner
PTWU	packaged throughwall unit
RH	relative humidity
SHR	sensible heat ratio
USAF	U.S. Air Force
VAV	variable air volume
VOC	volatile organic compound

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Section 1
Key Issues

Section Highlights

- ✓ Hot, humid climates present special challenges for controlling moisture and mildew.
- ✓ Conventional humid climate definitions fail to fully describe problem-prone areas.
- ✓ In hot, humid climates, problems are mainly the result of:
  - High ambient moisture
  - Improper interaction between the building envelope and the HVAC system
  - Misapplication of design principles
- ✓ New building failure is a function of unrealistic owner expectations, complexity of the design and construction process, and contradiction among project drivers (cost, schedule, and quality).
- ✓ This manual presents the CH2M HILL/Disney model for avoiding moisture and mildew problems at each step in the design and construction process.

Just months after occupying their new, multimillion-dollar municipal building, employees of a Florida county began complaining of chronic sinus problems, allergy attacks, headaches, and asthma—classic signs of sick building syndrome and building-related illness. The architects, engineers, and microbiologists tasked with finding the cause of these symptoms identified a problem that is becoming widespread nationwide—severe microbial contamination of the building. Mold and mildew were growing unchecked throughout the building's air-conditioning (AC) system and in many spaces within the building.

Figure 1-1. Although brand new, this municipal building was evacuated shortly after it opened because occupants were reporting health complaints. Mold and mildew were the culprits, and in the end, the problem will require more than $20 million to repair.

The mold and mildew were the direct result of excess moisture in the building, which was caused by a combination of rainwater leaks and a heating, ventilating, and air-conditioning (HVAC) system that pulled moist outside air into the building during the hours when the cooling system had cycled off. Once the HVAC system became infected with mold and mildew, it dispersed spores throughout the building. So, only a few years after opening its doors, the building underwent a major overhaul. The building's exterior was removed to help correct the problems that allowed rainwater to invade the building envelope (Figure 1-1). The roof and the AC system were also extensively modified. Ultimately, repairs and other associated costs will exceed $20 million.

Unfortunately, the problem faced by this Florida county is not an isolated one. Rainwater leaks occur in every climate, and in this case study, the leaks alone would probably have led to significant microbial contamination and building evacuation. However, the real devastation arose from the less obvious cause—improper interaction between the building envelope and the HVAC system.

Hot, humid climates are particularly susceptible to interior mildew problems. In these climates, new buildings are often hard hit with indoor air quality (IAQ) problems, mainly because of errors or compromises that occurred during design, construction, and initial operation. The costs of ignoring these problems are high in terms of employee absenteeism, worker compensation claims, deterioration of building structures and equipment, negative publicity, and potential liability.

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Preventing IAQ problems in hot, humid climates requires an understanding of certain key issues:

- Factors that contribute to the development of an IAQ problem
- Unique IAQ considerations for hot, humid climates
- Reasons for new building failure
- Steps that can be taken during design and construction to ensure future building success

IAQ Problem Factors

IAQ is defined by a set of ever-changing factors, including outside air quality, weather, building operation, type of mechanical systems inside the building, contaminants that may be present, and the types of occupants in the building. Building use can also a factor. Buildings that are designed for one purpose often end up being used for something entirely different. The new use may be incompatible with the original building design, and if the building owners are unaware of the need to adjust building design or operation to account for the new use, IAQ problems can result.

Most experts group all of these interrelated factors into the following four primary factors (Figure 1-2) that are common to every IAQ problem in every climate:

- ***Contaminant(s).*** Contaminants that can result in IAQ problems are generally classified into the following categories:

  ⇒ Combustion products (smoking and cooking)

  ⇒ Volatile organic compounds (VOCs) from solvents and cleaning fluids

  ⇒ Respiratory particulates (asbestos and dust)

  ⇒ Respiratory by-products (carbon dioxide)

  ⇒ Microbial organisms (fungi and bacteria)

  ⇒ Radionuclides (radon)

  ⇒ Odors (perfume, smoking, mold and mildew)

  These contaminants cause IAQ problems only when a specific set of conditions exists that promotes them or allows them to reach levels that cause reactions in susceptible building occupants. Sometimes, these conditions can be changed easily and the problem quickly remedied. For example, simply increasing the volume or distribution of outside air may reduce elevated levels of VOCs within a building to acceptable levels. At other times, however, such as when microbial problems occur, the conditions can be complex, requiring modification of both the HVAC system and the building envelope along with careful removal of the microbially contaminated materials. The major types of

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contaminants in a building can change depending on the building's location and condition, the climate, and the building use. Mold and mildew are the number one problem in hot, humid climates.

- ***HVAC system.*** The HVAC system is typically designed to control the temperature inside a building and, as a by-product, also controls relative humidity (RH). In so doing, the HVAC system should keep most people comfortable while they are inside. This system also helps control contaminants in a building in three ways: (1) by filtering contaminants out of the air before they reach the building occupants (filtration), (2) by diluting the contaminants in the air by adding fresh air (ventilation), and (3) by maintaining the right pressure balances between building spaces to keep contaminants from moving into the wrong place (pressurization). If the HVAC system fails to operate properly, IAQ problems usually occur.

- ***Pathways.*** Pathways involve both a route for contaminants to travel through a building and a mechanism like air pressure to push the contaminant along that route. Pathways are affected by the building design, the operation of the HVAC system, and the building use.

- ***Building occupants.*** People who spend an extended period of time (an 8-hour work day, for example) in a building are likely to report symptoms when IAQ problems occur. As such, they are a good barometer of the health of a building.

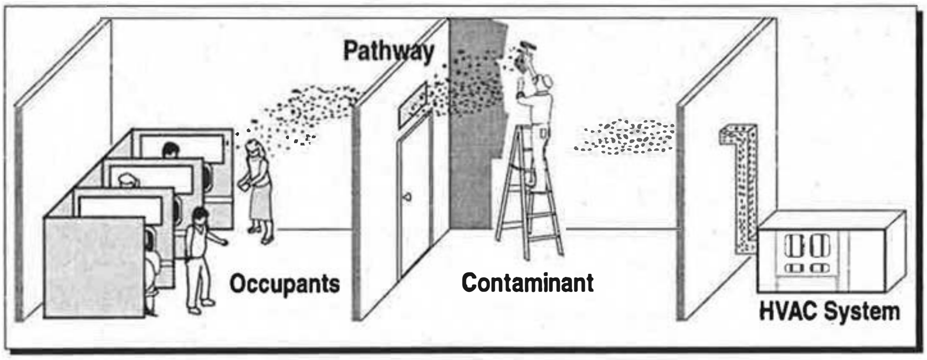

Figure 1-2. Four factors contribute to the development of an IAQ problem: (1) the presence of one or more contaminants, (2) an HVAC system that either fails to sufficiently dilute the contaminants or moves them through the building, (3) a pathway that enables the contaminants to reach the building occupants, and (4) one or more occupants who react to the contaminants.

All four of these factors must be present for an IAQ problem to exist. A change in any one of them can cause a dramatic change in the types of problems and symptoms that occur. If one is removed or eliminated, the IAQ problem will go away, either temporarily or permanently.

At a large office building in Los Angeles, workers in one section of the building were exposed to chemicals, including paints and adhesives,

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from another section of the building that was being renovated. The fumes were migrating to the workers' area through the HVAC system that served both areas. The workers sued the building owners and managers, as well as the contractors, product manufacturers, and installers, and won a large financial settlement. If the building owner or manager had been aware of the four IAQ factors and taken proactive measures, the problem could have been easily avoided. For example, the pathway or pressure that enabled the chemicals to reach the occupants could have been removed by setting up a temporary exhaust system in the renovation area and blocking the return vents to the building HVAC system. These simple steps would have prevented the chemical fumes from getting into the common HVAC system where they could travel to the occupied areas of the building.

Hot, Humid Climate Considerations

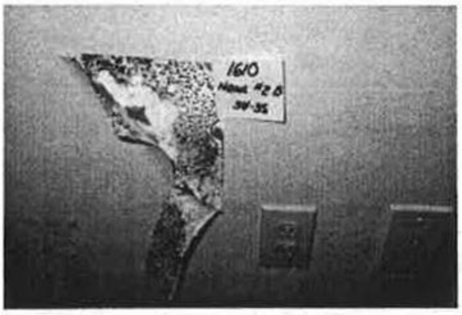

Figure 1-3. The combination of humid outside conditions and design errors resulted in severe mildew problems at this luxury resort, even before it opened. Shown here is mildew growth behind the wall covering in one guest room.

In the summer of 1988, construction of a large luxury resort was coming to a close. The resort was designed with vinyl wall covering on the interior side of the exterior walls. Because this wall covering had an impermeable finish, it functioned as a vapor retarder. The HVAC system consisted of a continuous toilet exhaust and packaged terminal air-conditioner (PTAC) units. The outside air exchange rate in each guest room averaged six times an hour, all from infiltration.

The combined effect of excessive outside air infiltration and a misplaced vapor retarder caused $5.5 million in moisture and mildew damage, even before the facility was opened (Figure 1-3). If these same design combinations had occurred in a more temperate climate, the problems would have been limited to increased energy consumption and possibly to complaints about guest comfort.

As illustrated by this case study, hot, humid climates present unique challenges that are often overlooked by the design and construction community. Meeting these challenges depends on a clear understanding of what areas of the country fall within the hot, humid climate zone and what unique aspects of this climate contribute to IAQ problems.

Definition of Hot, Humid Climate

The following American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) definition of humid climates is generally accepted in the HVAC industry (ASHRAE, 1989, p. 21.12):

> *A humid climate can be defined as one in which one or both of the following conditions occur:*

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(1) A 67°F [degrees Fahrenheit] or higher wet bulb temperature for 3500 hours or more during the warmest six consecutive months of the year.

(2) A 73°F or higher wet bulb temperature for 1,750 hours or more during the warmest six consecutive months of the year.

This definition is somewhat problematic. First, it is esoteric, making it difficult to interpret and apply to problem solving. Second, the area it defines (Figure 1-4) does not fully represent areas where problems are most likely to occur. Atlanta, for example, does not qualify as a humid climate under the ASHRAE definition, yet problem buildings are often found there.

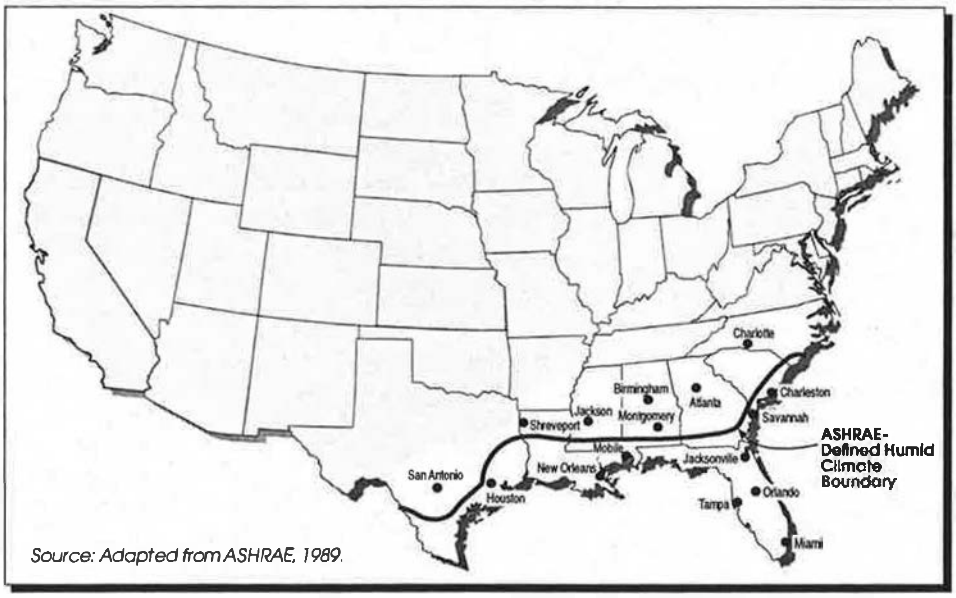

Figure 1-4. ASHRAE's definition of humid climates represents only a portion of the geographic area most susceptible to building failures related to humid climates.

Industry experience with building failures suggests the need for a new definition of humid climates that more clearly identifies the geography where problem buildings are more likely to be found and better explains why these problems occur at all. The following new definition is based on observations about latent and sensible load[1]:

A humid climate is defined as one where the average monthly latent load of outside air meets or exceeds the average monthly sensible load for any month during the cooling season.

Infiltration into a building of air with a high latent load will cause moisture to accumulate in building materials such as gypsum wallboard, with subsequent material degradation and mildew growth. This infiltration may also exceed the ability of the HVAC system to remove moisture from the supply air. On any given day in many

[1] *Latent load* is the moisture in outside air that is brought into the building and requires removal via dehumidification, whereas *sensible load* is the air temperature that is sensed and adjusted by the HVAC system, either by heating or cooling the air, to reach the established set point.

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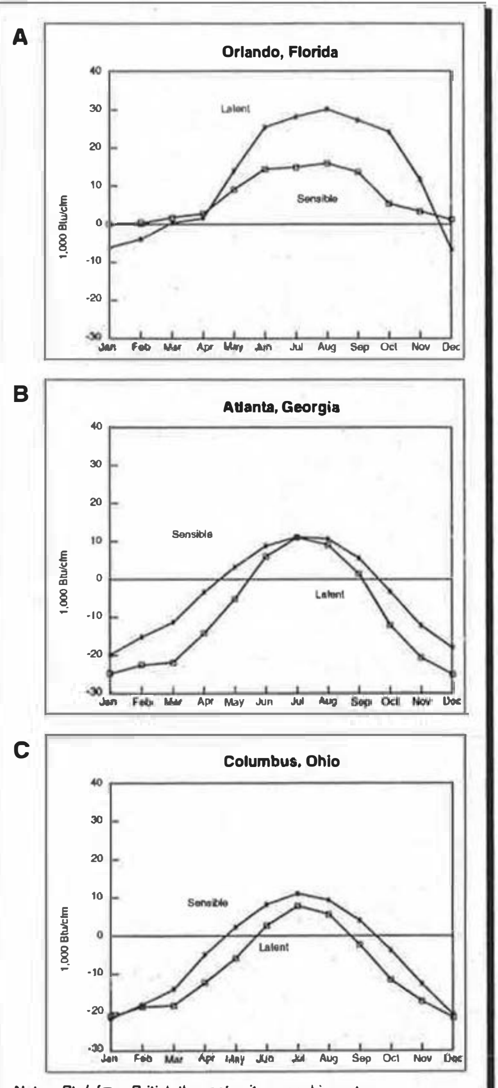
temperate areas, the latent load may be greater than the sensible load without causing problems; however, when these conditions persist for a longer period (a month, for example), the resulting moisture accumulation is sufficient to cause building failure.

The occurrence of a high latent load during the cooling season is a critical factor in building failure. Thus, defining hot, humid climates in terms of the relationship of sensible to latent load in ambient air expands the ASHRAE humid climate zone to include other parts of the United States that are highly susceptible to moisture-related building failures (Figure 1-4).



Notes: Btu/cfm = British thermal units per cubic meter.
Source: Peart and Cook, 1994.

Figure 1-5. Defining a humid climate in terms of latent and sensible loads expands the ASHRAE-defined area and more accurately identifies areas where moisture-related problems are likely to occur.

Comparing the latent and sensible loads for several major cities in different geographic regions (Peart and Cook, 1994) helps illustrate the new definition. Figure 1-5 shows the monthly average latent and sensible loads from outside air for Orlando, Florida; Atlanta, Georgia; and Columbus, Ohio. During the cooling season in Orlando (Figure 1-5a), the latent load far exceeds the sensible load of outside air. The effect of these conditions, which occur for more than half a year, is that any outside air drawn into the building envelope or occupied space will likely cause moisture accumulation and microbial growth problems. Furthermore, since this outside air is used for ventilating the building's occupied spaces, it presents a huge dehumidification challenge for the makeup air system. Clearly, under these conditions, Orlando is highly susceptible to moisture intrusion problems.

As shown in Figure 1-5b, Atlanta is much less susceptible to moisture intrusion problems than Orlando because, on an average monthly basis, the difference between sensible and latent load is small, particularly during the peak cooling months. Standard AC systems have a better chance of accounting for the latent load in Atlanta than in Orlando. Nevertheless, the latent load in Atlanta represents enough of a moisture accumulation risk that it belongs within the upper boundary of the humid zone. However, according to the map in Figure 1-4, Atlanta is outside the critical zone for humid conditions.

In the graph for Columbus, Ohio (Figure 1-5c), the latent load from outside air is consistently less than the sensible load. The reversal of the load relationship explains why buildings in Columbus are not likely to develop moisture-related problems from outside air intrusion, because any outside air that infiltrates into buildings in Columbus will be adequately dehumidified before it is cooled.

The new definition also explains why in certain areas of the country, building commissioning procedures are

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more critical than in others. For example, if the building exhaust systems are started before the AC and makeup air systems, as is typical, huge amounts of moisture may infiltrate into the building, depending on the outdoor conditions.

In applying the new humid climate definition, however, two qualifications must be made:

- As illustrated by the graphs in Figure 1-5, the definition is based on average climatological data. At certain times during the summer, the latent load of outside air can exceed the sensible load to a much greater extent than reflected in the graphs. Such episodes of extreme high moisture entering the building can cause problems despite seemingly safe average conditions and must be considered in problem prevention.
- If the building envelope has a misplaced vapor retarder, moisture accumulation problems can occur, even if a favorable sensible/latent load relationship exists. Condensed moisture behind the vapor retarder will never reach the AC system for proper dehumidification, but will accumulate in the wall system. Thus, architectural aspects of the building work in conjunction with outside conditions to create problems.

Typical Problem Causes in Hot, Humid Climates

Shortly after construction was completed, a seven-story, four-star hotel in Charleston, South Carolina, developed severe moisture and mildew problems. The investigators attributed the problems to rainwater intrusion through the hotel's exterior brick veneer (Figure 1-6). Following that diagnosis, the hotel owner spent over $10 million on renovations, including a completely redesigned and reconstructed building envelope.

The summer after the renovations were completed, the moisture and mildew problems returned. They returned because the investigators had focused on the envelope leaks and overlooked the significant secondary source of interior moisture (outside air infiltration).

Figure 1-6. Rainwater leaks masked a significant secondary source of IAQ problems at this luxury hotel, which developed severe moisture and mildew problems shortly after it was built.

In areas like Charleston, where hot, humid conditions persist, IAQ problems are largely due to a combination of the following factors:

- High ambient moisture
- Improper interaction between the building envelope and the HVAC system
- Misapplication of design and operation principles

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High Ambient Moisture

Given the high ambient moisture levels in humid climates during the summer months and the dehumidification limitations of many AC systems, excessive moisture accumulation within buildings and the resulting microbial growth are understandably major problems. Microbial-related IAQ problems in buildings can also occur in temperate climates, although bigger errors in the design, construction, or operation of a building normally must occur for problems to develop in these areas.

In all climates, anything that elevates the indoor RH or results in damp materials (leaky pipes, for example) for an extended period can cause microbial IAQ problems. Landscape irrigation systems, indoor swimming pools, and building humidification systems can provide enough moisture to create microclimates and microbial growth problems, even in dry climates. Buildings in Boise, Idaho; Denver, Colorado; and Kona, Hawaii, have all been hit with severe IAQ problems from microbial growth as a result of introduced moisture, despite the fact that they are considered arid, desert climates.

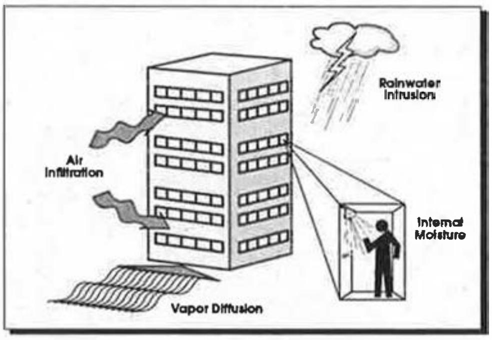

Figure 1-7. Moisture accumulation inside buildings comes from four main sources.

Moisture Accumulation. A 5-year study of 5,000 construction claims by the Design Professional Insurance Company (DPIC) found that the most prevalent building problems (corrosion, building material degradation, and mold and mildew) were moisture-related (*Engineering News-Record*, July 15, 1991). Moisture comes from four sources, which have different priorities depending on climate (Figure 1-7):

- ***Rainwater intrusion.*** Moisture present in building materials and on the site during construction can be a source of problems. Significant amounts of moisture can also result from water leaks within building systems or through the building envelope. In both hot, humid and temperate climates, rainwater leaks are a major source of building moisture and microbial growth problems.

- ***Infiltration of outside moisture-laden air.*** Infiltrated humid air, whether introduced by wind or through the HVAC system, can cause condensation on interior surfaces, including inside building cavities. Condensation and high RHs are important factors in creating an environment conducive to mildew growth and are the primary problems in hot, humid climates.

- ***Internally generated moisture.*** After construction, occupant activities and routine housekeeping procedures can generate additional moisture, contributing to the mildew problem.

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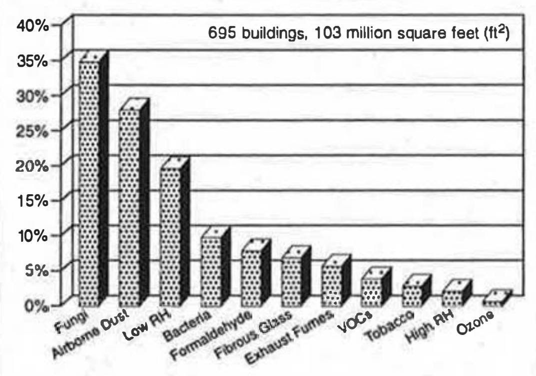
Normally, if no other significant sources exist, well-designed and properly operating AC systems can adequately remove this moisture.

- ***Vapor diffusion through the building envelope.*** Differential vapor pressure, which can cause water vapor to diffuse through the building envelope, is a less significant cause of moisture problems in buildings. Nevertheless, it is a mechanism to consider in building design and construction, particularly in hot, humid climates, and especially as it relates to wall system vapor retarder construction.

Problems from excess moisture can be controlled if proper humidity levels are maintained in a building. (ASHRAE recommends a range between 40 and 60 percent RH). Designers usually do not calculate or estimate quantities of moisture expected from the above sources as they design the building systems. Fortunately, in most cases, however, the amount of moisture from the four possible sources combined is insufficient to cause problems.

Microbial Growth. According to a 700-building, 10-year survey (Business Council on Indoor Air, 1991), microbial growth is the number one indoor air contaminant (Figure 1-8). In the hotel industry alone, fungi (mold and mildew) cause several hundreds of millions of dollars in repair costs annually (American Hotel and Motel Association [AH&MA], 1990). Unlike other types of indoor air contaminants, microbial growth (mold and mildew) are composed of living microorganisms. (For the purposes of this manual, the term *mildew* will hereafter refer to mildew, mold, fungi, and other forms of microbial growth.) The following four conditions must be present for mildew to grow:

- A food source (normally organic material)
- Temperature between 40°F and 100°F (4 degrees Celsius [°C] to 38°C)
- Adequate moisture
- A source of spores



Source: Adapted from Business Council on Indoor Air, 1991.

Figure 1-8. Microbial growth is the No. 1 IAQ problem in the nation.

These conditions are often present in buildings. Building materials are excellent food sources, the temperature and RH ranges conducive to growth are commonly found in buildings (either within the wall system or occupied space), and spores are always present in the air and on interior surfaces.

ASHRAE's moisture threshold for microbial growth of 60 percent RH (Figure 1-9) is commonly accepted, but using RH alone as the index for microbial growth overlooks the critical interrelationships among mildew growth rates, elevated RH, and ambient temperature. According to Brundrett (1990), once the threshold moisture conditions for germination of mildew spores has occurred, even a slight increase

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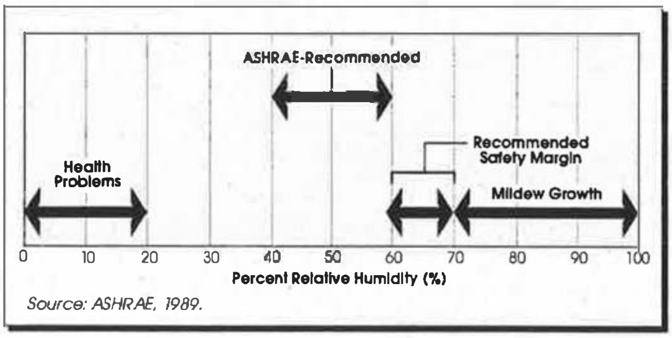

Figure 1-9. To control microbial growth, ASHRAE recommends keeping RH to within 40 to 60 percent.

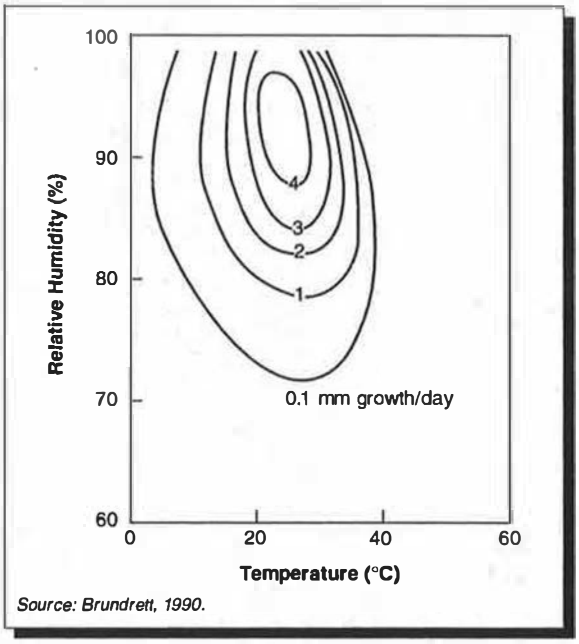

Figure 1-10. Rates of growth for Aspergillus ruber *show how a 10 percent increase in RH (72 to 79 percent) can increase the mildew growth rate by 1,000 percent (0.1 millimeter [mm] to 1.0 mm per day).*

in moisture load will cause the growth rate to rise exponentially (Figure 1-10). Furthermore, the moisture level at which germination begins is species-specific. For example, *Stachybotrys chartarum* (formerly called *Stachybotrys atra*) requires significantly higher amounts of moisture for initial germination than many other mildew species (that is, more than 90 percent RH versus 70 to 80 percent RH for the other species). Understanding this difference in moisture germination requirements is especially useful in pinpointing the source of moisture in a building. For example, the high level of moisture required for *Stachybotrys chartarum* is usually the result of plumbing leaks or rainwater leaks through the building envelope, not just high RH.

Because of its growth characteristics, simply removing mildew from affected materials and equipment will not resolve a mildew problem. Mildew will grow back, and the problems associated with it will reoccur. The real key is to modify the environmental conditions within the building to eliminate one or more of the four conditions required for microbial growth. The condition most easily controlled is excess moisture.

Interaction between the Building Envelope and HVAC System

In hot, humid climates, the interrelationship between the building envelope and the building HVAC system is especially critical. Many moisture and mildew-related IAQ problems in humid climates are often misdiagnosed as either exclusively envelope- or HVAC-related, because the complex relationship that exists between both systems is not always clearly understood.

Once moisture problems occur, many investigators fail to account for the fact that, on a cooling season basis, HVAC-induced moisture can equal or sometimes far exceed the amount of moisture attributable to rainwater leaks. Additionally, HVAC-induced moisture can mask, or obscure, rainwater leakage problems because it is often an envelopewide problem. This misunderstanding can lead to misdiagnosis, which often results in spending repair dollars modifying the building envelope to solve moisture, microbial growth, and other IAQ problems when simply modifying the HVAC system would have been less expensive and more effective.

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Building Envelope Considerations. Moisture-related IAQ problems can be avoided if the building envelope does the following:

- Adequately retards moisture or air movement into the building
- Allows any accumulated moisture to either drain to the exterior or evaporate

In hot, humid climates, the air barrier and vapor retarder in the building envelope must be adequate to control air and moisture flow through the wall system. This means that any air barrier or vapor retarder placed within the wall system must have the proper air resistance or moisture permeability and must be installed at the correct location within the walls. The presence of multiple vapor retarders within a wall system is a common problem, because many designers do not recognize many construction materials as effective barriers. For example, plywood is a relatively low permeability material that can function as a vapor retarder.

The point where cool surfaces meet warm, moist air is where condensation and excess moisture can occur. If moisture-laden outside air is retarded before it meets the first cool surface inside the building envelope (often called the "first plane of condensation"), then few problems will result. If this moisture is allowed to further enter a wall system, it will condense. Then, moisture and microbial growth problems can be a real threat. If the cool surfaces and moist air meet within the building space, then moisture problems can occur throughout the building, resulting in widespread mildew odors and complaints from occupants.

Thus, the building envelope plays a vital role in minimizing uncontrolled moisture and air movement into a building and in preventing moisture entrapment within the wall system. Although the building envelope contributes to moisture-related IAQ problems in hot, humid climates, in more temperate climates, it is not usually a factor in other common IAQ problems such as contamination from elevated VOCs.

HVAC System Considerations. The following factors relating to the HVAC system contribute to IAQ problems:

- Inadequate building pressurization and dehumidification
- Intrusion of high-moisture outside air
- Inside surfaces that promote or permit microbial growth

The HVAC system complements the building envelope by properly conditioning the building's interior, including the building envelope, and pressurizing the building with dehumidified air (called *exfiltration*). When negative building pressurization occurs in humid climates, the result can be multimillion-dollar moisture and mildew problems from intrusion and condensation of moist outside air.

HVAC systems that positively pressurize a building space by supplying unconditioned or only partially conditioned outside air will avoid

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infiltration of outside air through the building envelope. However, this same situation can result in moisture loads inside the building that exceed the dehumidification capabilities of the HVAC system. One of the most significant causes of moisture accumulation in existing buildings in hot, humid climates is an overemphasis on ventilation at the expense of proper dehumidification.

AC equipment is typically more efficient in cooling air than in dehumidifying it. As a result, unconditioned outside air brought into a building is often cooled to the desired temperature before it is properly dehumidified, creating elevated RH levels and microbial growth inside the building. Furthermore, because AC equipment is typically controlled by temperature (thermostat) instead of humidity (humidistat), the equipment never senses the elevated moisture level within the building space and, therefore, never fully removes it.

In any climate, the normal functioning of standard AC units can result in microbial growth. Just downstream of the cooling coils, the air is at or near 100 percent RH during the cooling season. This environment can be conducive to microbial growth and lead to IAQ complaints because the conditioned air (and any microbes it carries) is distributed inside the building.

Misapplication of Traditional Design Principles

Design practices appropriate for temperate climates are sometimes applied similarly in humid climates—with devastating results. For example, good design practice dictates providing certain levels of outside air into occupied spaces based largely on occupant density and space usage. However, in hot, humid climates, the highest priority is to maintain proper humidity levels at all times—during both occupied and unoccupied periods.

In addition, in spite of the proliferation of IAQ information, confusion still exists within the design community about several critical issues related to envelope performance in hot, humid climates. These issues include the integrity requirements of air barriers, weather barriers, and vapor retarders; the way all three barriers/retarders can be incorporated into one membrane; the location of these features within the building envelope; the effects of using multiple vapor retarders; and even the need for air barriers and vapor retarders in every facility.

This confusion about design, construction, and operational practices between humid and nonhumid climates accounts for many moisture and microbial growth problems. ASHRAE *Fundamentals* (1989) cautions that different climates present different problems, and buildings should be designed and operated accordingly. Although this is an obvious requirement, it is often not met.

Misunderstanding also exists about proper building pressurization or depressurization relative to outside conditions. Although almost every building designer will acknowledge the need to achieve a continuously pressurized building in hot, humid climates, these same designers almost always misunderstand the level to which a building must be

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pressurized and how these pressures should be measured. Furthermore, the general belief is that as long as the volume of makeup air being supplied exceeds the amount of air being exhausted, the building is properly pressurized. This belief does not take into account the partially connected interstitial spaces and the potential for uneven distribution of this makeup air within the building. Failure to account for these circumstances has resulted in devastating moisture intrusion problems in hot, humid climates.

Over the past few years, the Florida Solar Energy Center (FSEC) has found that building pressures as low as +1 pascal (Pa) relative to outside conditions are sufficient to prevent outside air infiltration problems. On the other hand, even a slightly depressurized building (-1 Pa relative to normal outside conditions) in hot, humid climates can develop devastating moisture and microbial growth problems when the building envelope traps this moisture.

The irony of the pressurization/depressurization issue is that despite the need for great accuracy in measuring building pressurization in hot, humid climates, measuring tools and methods are surprisingly crude and often inaccurate (smoke sticks, for example). As a result, the first sign of a problem is often health complaints by the building occupants or severe building material degradation.

Why New Buildings Fail

Although moisture intrusion and microbial growth are widespread in hot, humid climates, not all buildings get it. The reasons some buildings have problems and others do not are somewhat illusive. Two recent studies support the growing belief that avoiding serious building failure in any climate is primarily a matter of luck.

In April 1996, FSEC completed a 2-year, $500,000 study on the performance on commercial buildings in Florida. In this study, 69 out of 70 buildings surveyed were considered problem buildings to some degree. Problems ranged from excess energy use to materials degradation, comfort, and even potential health problems. All were the result of uncontrolled air flow caused by duct leaks and supply/ exhaust imbalances, among other causes. In summarizing their findings, the investigators state (FSEC, 1996, p. 1):

> *Perhaps the most profound and compelling finding of the study is that, given the present state of the practice, whether a building will avoid serious, or even catastrophic problems due to uncontrolled air flow [which introduces outside moisture], is primarily a matter of luck.*

A recent American Society for Testing and Materials (ASTM) report (*Engineering News-Record,* May 27, 1996, p. 12) similarly concludes that in the building industry, failures are largely the result of "poor institutional memory." Each project, according to ASTM, is treated as a "one-of-a-kind event [with the designer] getting lost in technical details."

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Regardless of the reason given—bad luck, poor institutional memory, an overemphasis on the details, or something else—buildings will continue to fail at disproportionately high rates, especially in hot, humid climates. So, in the final analysis, the development of IAQ problems and subsequent building failure can be attributed to the following factors:

- Unrealistic expectations of success by building owners who rely on the contracting process and building codes to protect their buildings from failure
- Complexity of the building construction process and failure of the design and construction team to recognize the interrelationships between the various technical disciplines
- Contradiction among the fundamental forces (cost, schedule, and quality) influencing decisionmakers throughout the design and construction process

Without a recognition of these underlying causes of building failure relative to IAQ and a commitment to making decisions to address these causes during design and construction, when many causes of IAQ problems occur, building owners will be left to depend on luck to discriminate between buildings with IAQ problems and those without.

Building Owner Expectations

Owners expect to avoid building failure by hiring the most experienced design and construction team available, providing an adequate (although often tight) budget and schedule for the team, and relying on quality control procedures and the contracting process to hold the team members accountable for their performance. Although the expectation for consistent building performance under these conditions is reasonable, it is not being realized. In fact, data from the AH&MA (1990) nationwide survey suggest that neither cost nor schedule can be directly correlated with success.

Furthermore, experience in Florida shows that high-priced construction is *more* prone to IAQ problems than low- or moderately priced construction. This relationship may exist because building systems and finishes used in high-priced construction are more susceptible to failure and microbial growth. Expensive buildings tend to have more complex and sophisticated HVAC systems, which are more likely to develop problems when under the control of an unsophisticated building manager. Plus, the plusher finishes found in more expensive buildings are often better food sources for microbes.

Most building designers and contractors think that following established building codes and repeating strategies used on past projects will guarantee success in new building construction. However, many buildings that develop IAQ problems in hot, humid climates meet or exceed the minimum standard requirements for building codes. The reason they fail is because satisfying codes alone does not ensure that the combination of design features selected for that building will

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work together to prevent IAQ problems. Relying on strategies used in past projects is also risky because the precise conditions under which a successful project was performed can rarely be duplicated.

Process Complexity

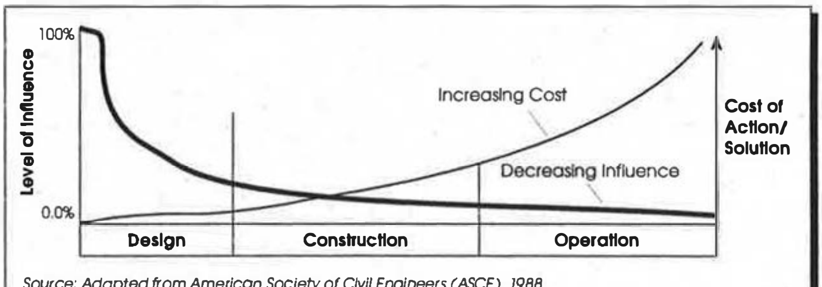
The design and construction of new buildings is a complex process involving hundreds of people making thousands of decisions spanning many years and requiring input from specialists in numerous technical and business areas. Decisions made daily during design and construction by specialists in one area often occur without a full understanding of their ramifications for IAQ, particularly when these decisions are combined with those made independently by specialists in other areas. Thus, making the right decisions at the right time within the context of the entire design is key to controlling IAQ problems.

Experience in building construction shows that specific combinations of design decisions will almost certainly produce conditions that are conducive to IAQ problems, whereas other combinations will produce much better conditions and allow a greater margin for error in constructing and operating the facility. These decisions are both architectural and mechanical (HVAC systems) and occur at various milestones throughout the design and construction process. Subsequent sections of this manual have guidelines to help the design and construction team recognize these critical decision points and ensure that the proper architectural and mechanical combinations occur.

Contradictory Forces

The three fundamental forces driving decisionmakers during the design and construction process are cost, schedule, and quality. As illustrated in Figure 1-11, the level of concern given each of these forces clearly changes over time. During the design phase, satisfying cost constraints is typically the biggest concern. In fact, many designers are contractually obligated to redesign a project at their own expense if their design exceeds the designated construction budget. The fact that the design team probably had little or no input into developing the budget makes meeting it particularly challenging.

Only during the final stages of construction, when "punch lists" are being developed and the owner is anticipating initial occupancy, does quality become the top priority. Unfortunately, any adjustments in the quality of design and construction that may be indicated are either too costly or too time-consuming to implement at this stage. Thus, even problems that are discovered at this point are often left uncorrected.



Source: Adapted from American Society of Civil Engineers (ASCE), 1988.

Figure 1-11. The best opportunities to prevent IAQ problems and control project costs occur in the early design and construction phases.

Model for Future Success

Despite the complexity of design and construction projects and the contradictory forces that drive the project team, steps can be taken during the critical project phases to avoid IAQ problems. The approach presented in this manual is based on a model developed by CH2M HILL and Disney Development Company to resolve moisture-related problems in new buildings. The premise of the CH2M HILL/Disney model is that at each stage in a project (design, construction, and operation), decisions essential to avoiding future IAQ problems can and must be made. The following three elements summarize the model and are integral to its success in improving the performance of new buildings:

- Establish specific design and construction guidelines at project inception
- Use periodic peer reviews throughout the design and construction process to compare results against the original construction guidelines
- Implement proper startup techniques for the HVAC system to verify correct operation of the building before occupancy

Design and Construction Guidelines

Early design and construction phases, particularly schematic design, present the best opportunities to prevent IAQ problems and control project costs. As shown in Figure 1-11, the relationship between level of influence and time is indirect, but a direct relationship exists between time and cost. Thus, the farther a project moves into the process, the more costly changes become and the less influence the design team members have over the final outcome.

Beginning the process with a set of prescriptive guidelines that address both the architectural and mechanical considerations affecting IAQ, like those presented in this manual, will maximize quality without adding cost to the final result.

Peer Reviews

Peer reviews, which are outside the normal quality control process, are a means of eliminating fatal flaws by adhering to a focused process with a specific purpose and scope. Peer reviews involve an independent expert, who evaluates specific aspects of the design and construction to determine the potential for IAQ problems to develop later. Although peer reviews are standard for structural designs to address safety issues, they have not been widely applied to address IAQ issues. The use of peer reviews for problem avoidance is not a new concept, and published guidelines (Figure 1-12) are available (American Consulting Engineers Council [ACEC] and ASCE, 1990).

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Peer reviews can occur once during the project, but they are most effective when they are iterative, occurring at various milestones throughout the design process. These milestones include schematic design, the 60 percent construction drawing phase, and the 90 percent construction drawing phase.

Implementing peer reviews is a low-cost way of monitoring results and avoiding mistakes that could lead to severe IAQ problems later. Cost data from peer reviews of facilities totaling more than $500 million indicate that peer reviews rarely exceed 5 percent of the total cost of design and 0.3 percent of the cost of construction. Clearly, this investment in peer review is worthwhile, considering that, historically, these reviews reveal cost-saving measures that more than compensate for the cost of the review.

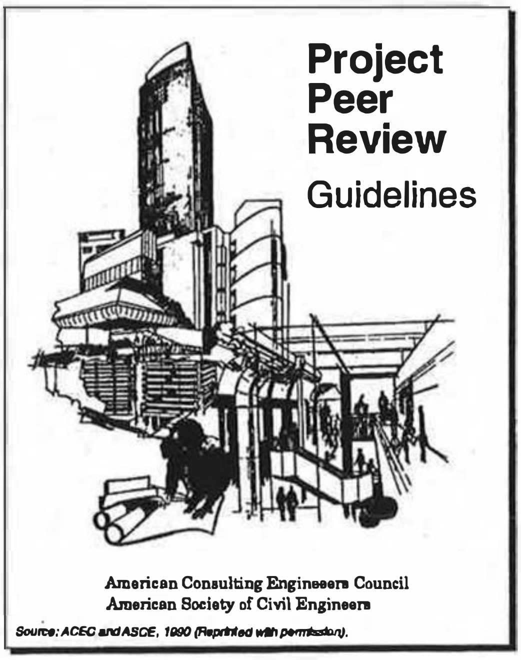

Figure 1-12. Following established peer review guidelines helps avoid mistakes during design and construction that could lead to costly IAQ problems later.

Proper HVAC System Startup

After specific design and construction guidelines have been established and periodic peer reviews to ensure their correct implementation have been conducted, the final step in the CH2M HILL/Disney process is HVAC verification testing. In addition to the normal measurements conducted during HVAC system startup (such as air flows), direct pressurization measurements are also strongly recommended. The exact procedures (discussed in Section 6 of this manual) include the measurement of individual pressures throughout the building, in both occupied and interstitial spaces. These verification measurements are necessary because, as previously discussed, typical procedures are not sufficiently accurate and lead to assumptions that are often incorrect.

Designers often proceed under the assumption that a building is a single pressure vessel, with air entering from one side and exiting from the other. In truth, as shown by FSEC (1996), buildings function as mutiple pressure vessels, some of which are only minimally connected to the supply or return air system. Operating under the wrong assumption about pressure relationships can lead to operational problems from unexpected pressure imbalances.

The subsequent chapters of this manual show how the CH2M HILL/ Disney model can be applied at each step in the design and construction process to prevent future moisture and mildew problems. Proof of the effectiveness of this model lies in the fact that since the Disney Development Company adopted it in 1990, more than $750 million in construction has been completed in hot, humid areas and not one building has developed the significant moisture and mildew problems characteristic of pre-model construction. This record of success is in direct contrast to the consistent problems that occurred before 1990. Notwithstanding this impressive record of success, the most startling result the Disney Development Company has seen since implementing the new model is that construction costs have decreased significantly more than the cost of implementing the process. In other words, the process improves building success and reduces initial construction costs.

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Section 2
Schematic Design

Section Highlights

- ✓ *During the schematic design phase, critical design issues are identified and decisions about design requirements are made.*
- ✓ *The permeability of the interior finish can greatly affect a design's potential for allowing moisture intrusion and mildew formation.*
- ✓ *Critical concepts on how the building will be ventilated, pressurized, and conditioned are developed during this phase.*

The schematic design phase is the first of the three design phases and is completed at approximately the 30 percent milestone of the project. During this phase, critical design issues are identified and decisions about design requirements are made. *This design phase offers the best opportunity to prevent future moisture and mildew problems.*

In essence, IAQ problems are symptoms of a broken process. The complexity of the building construction process and the failure to recognize interrelationships between different disciplines often worsens existing problems. The challenge is to provide an incentive for high quality early in the process—an incentive that is not driven by cost or schedule. After all, the owner's objective is quality, while the designer's and contractor's objective for the building is cost and schedule.

The most influential part of the process is early in the design when decisions as well as modifications can be made without significantly affecting costs. The least influential time to make changes is during the operation of the building. Although some changes can be made during construction, often the process has gone too far to allow changes. The schematic design phase is the phase most important in identifying critical design decisions. However, for this phase to be its most effective, sound design requirements must be established at this stage. This section presents those design decisions that *must* be made to avoid future IAQ problems. These guidelines act as a bridge between the architectural and mechanical disciplines for the most strategic issues, which include moisture intrusion and dehumidification.

Figure 2-1 summarizes the moisture control considerations typically associated with the schematic design phase. Although the responsibility for addressing the considerations can be divided according to architectural and mechanical functions, personnel in both disciplines should work together closely to prevent future problems. Effective interaction among design team members is crucial in creating a problem-free design.

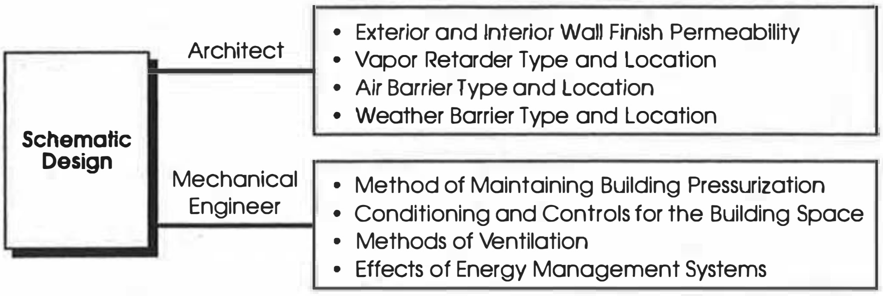

Figure 2-1. These issues must be considered in the schematic design phase.

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Decisions for Moisture and Mildew Control

Figure 2-2 highlights some typical design issues that must be considered by the design team during the schematic design phase and shows the relationship between the architectural and mechanical aspects of the design.

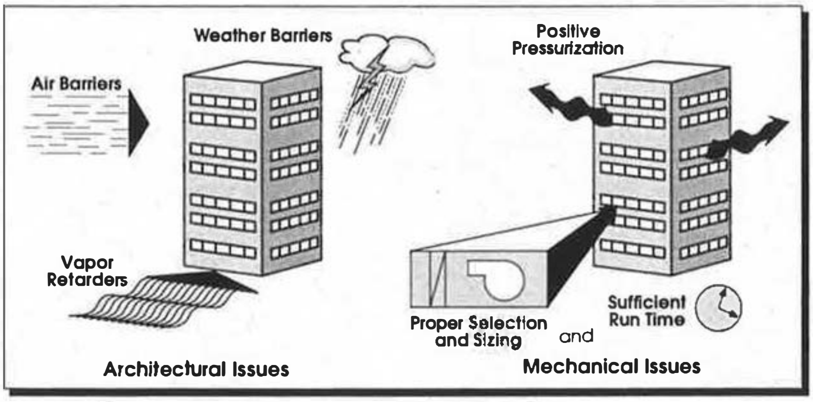

Figure 2-2. For a moisture- and mildew-free design, the design team must consider these issues.

While it is known that some design decisions will inevitably create a greater risk of moisture intrusion, the extent of a problem with moisture or mildew is determined by other less extensive decisions made after the fundamental design choices.

Many decisions made during the schematic design phase are based on costs directly linked to whatever aesthetic level the owner is trying to achieve for the completed building. This practice is strikingly illustrated by differences between economy and luxury buildings (Table 2-1).

The decision to use a particular type of AC system will normally not solely determine if a building will eventually have moisture and mildew problems. However, certain AC systems have a greater propensity for problems than others. For example, a variable air plume (VAV) system with a plenum return will often depressurize the building envelope enough to cause outside air infiltration and moisture migration into the wall system. This condition, coupled with a vapor retarder improperly placed within the exterior wall, will inevitably result in moisture accumulation, mildew growth, and IAQ problems.

As Figure 2-3 demonstrates, both architectural and HVAC decisions made during the schematic design phase affect the extent of problems with moisture and mildew. The remainder of this section discusses specific moisture-related issues for the typical architectural and mechanical design options considered during this phase.

- Architectural design considerations
  - ⇒ Vapor diffusion, air leakage, and rainwater leakage
  - ⇒ Wall system components for control of moisture intrusion
  - ⇒ Building layout for proper pressurization
- Mechanical design considerations
  - ⇒ Proper building pressurization
  - ⇒ Ventilation, dehumidification, and filtration
  - ⇒ Mechanical systems, including exhaust systems, makeup air systems, and AC systems
  - ⇒ Energy management issues and how they relate to moisture control issues

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TABLE 2-1
Design choices for different buildings are frequently guided by cost.

Domicidal Facilities	
Economy/Moderate Hotels and Dormitories and Many Assisted-Living Facilities	**Luxury/Deluxe Hotels, Dormitories, and All Hospitals**
Nonconditioned (or outside) corridors	Conditioned (or interior) corridors
No makeup air system	Ducted makeup air to guest room or indirect-fed makeup air system (if pressurized corridor is used)
PTWUs	Individual FCUs in room
Painted interior wall finishes	Vinyl interior wall finishes
Office Buildings (including Government Buildings, Courthouses, and Administration Buildings)	
Economy Class (or Class B)	**Luxury Class (or Class A)**
Single and/or multi-zone fan coil units or split systems	Central station CAV and/or VAV systems
Makeup air provided via individual zone units	Makeup air provided through central AHU, occasionally supplemented by a separate unit
Painted walls with lesser percentage of upscale finishes	Greater portion of upscale finishes such as vinyl wall covering, wood, and stone
Predominately modular office enclosures with small percentage of walled offices	Greater percentage of walled offices and less usage of modular enclosures

AHU = Air-handling unit.
CAV = Constant air volume.
FCU = Fan-coil units.
PTWU = Packaged throughwall units.
VAV = Variable air volume.

	Positive Building Pressurization	Negative Building Pressurization
Correct Wall Construction*	Mildew/Moisture Problems Unlikely in Wall System and Occupied Space	Possible Mildew/Moisture Problems in Wall System and Occupied Space
Incorrect Wall Construction*	Possible Mildew/Moisture Problems in Wall System; Unlikely Problems in Occupied Space	Probable Mildew/Moisture Problems in Wall System and Occupied Space

* *Wall construction* refers to vapor retarders and air and rainwater barriers.

Figure 2-3. Wall system and HVAC system design must interact to reduce the potential for moisture and mildew formation. This figure illustrates the need to coordinate the wall system design by the architect and the HVAC system design by the mechanical engineer so that positive building pressurization is obtained.

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Architectural Considerations

While no detailed designs are completed during the schematic design phase, decisions are made that form the basis of designs developed during the next phase (Design Development, Section 3). Available design handbooks for humid climates may not provide all the information necessary to complete comprehensive construction designs. The architectural design team, therefore, must use sound judgment in selecting the building envelope system during schematic design, including the weather and air barriers and the vapor retarder (Figure 2-4).

	Preferred Location within the Wall System	Integrity Requirements of the Component
Rainwater Barrier	Exterior Side of Stud Cavity	Nearly Perfect, or Must Have Water-Shedding Capabilities
Vapor Retarder	Exterior to the Thermal Insulation	As Good As Practical; Does Not Have to be Pinhole-Free or Have Joints Taped
Air Barrier	Anywhere In the Wall Assembly; Exterior Location Preferred	Nearly Perfect, and Imperfections Must be Compensated by Positive Pressurization

Figure 2-4. In hot, humid climates, the design, location, and installation of the air and weather barriers are more critical than for the vapor retarder.

Because all of the possible moisture-related issues in new construction are not always immediately apparent to an architect, design issues relating to the architectural aspects of construction must be addressed by the entire design team. For example, interior finishes are often selected simply for aesthetic appeal, initial cost, or ease of maintenance. However, the permeability of the interior finish (indicated by permeance rating) can greatly affect the moisture and mildew potential of a design, depending on the type of HVAC system being considered. Therefore, the mechanical engineer and the architectural design team members should all have input when selecting a wall system.

Vapor Diffusion

Vapor diffusion potential is a function of the vapor pressure differential across the building envelope (Figure 2-5). Hot, moist air has a higher pressure than cool, dry air. A large amount of vapor pressure results from a high moisture content. The vapor pressure at any moisture content is equal to the sum of all individual vapor molecule pressures. A large amount of water vapor creates considerable force; in fact, in some instances the pressure difference can be great enough to blister and peel paint on exterior siding as moisture in the wood is drawn out. Vapor diffuses through walls at a rate proportional to the vapor pressure difference. If one side of a wall is much drier than the other side, the vapor will diffuse faster (*The Dehumidification Handbook*, 1990).

The vapor diffusion mechanism does not typically induce significant moisture into a building and can generally be considered a negligible contributor to potential IAQ problems. This is particularly the case in conventionally air-conditioned commercial buildings with moderate temperature conditions as compared to specialty industrial buildings that require colder-than-normal interior temperatures.

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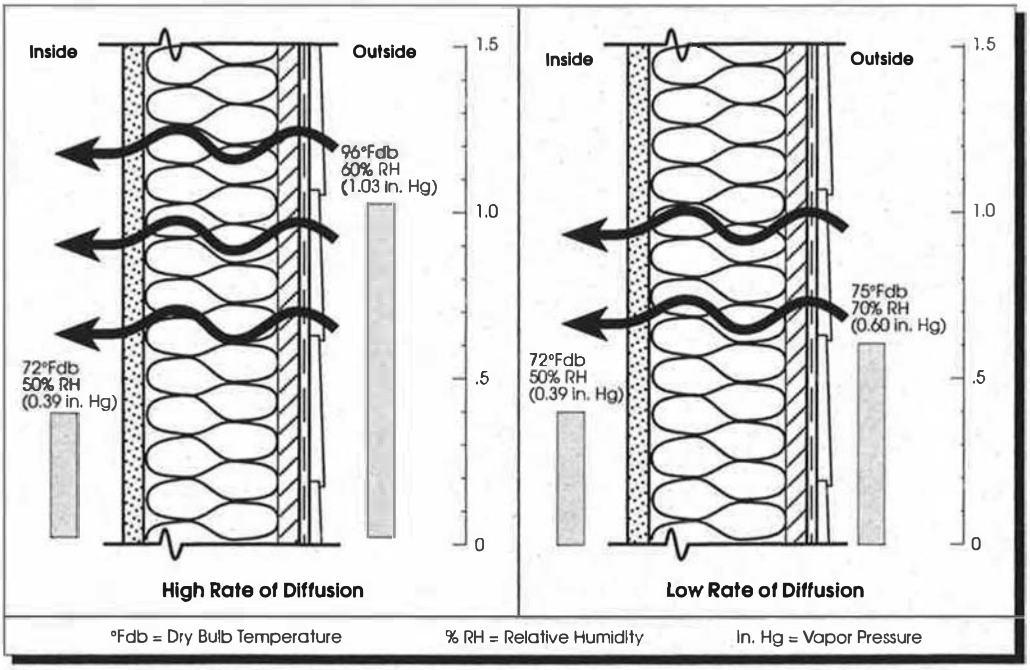

Figure 2-5. Vapor diffuses through a wall at a rate proportional to the vapor pressure difference across the wall.

Air Leakage

No building is hermetically sealed. That is, all buildings have some degree of air leakage openings inherent in the envelope construction, and this leakage carries a certain amount of moisture with it into the building (Figure 2-6). Although this leakage can typically be overcome with good positive pressurization, a tightly sealed building envelope will minimize air leakage *and* reduce the amount of air required by the HVAC system to achieve good pressurization. Moisture contributed by air leakage is a significant source and should be a serious concern in the design of the wall system. In fact, the design of the building envelope for minimizing air leakage is more critical than the design of the vapor barrier.

To illustrate this point, consider that the amount of moisture contributed to a building by the air that flows through a crack 1/16th inch thick by 1 foot long is just over 5 pints per day in a light breeze. In contrast, the amount of moisture contributed by vapor diffusion through a 10-foot by 50-foot painted block wall over the same period equals just under 1/3 of a pint (about 5 ounces). The most critical areas of envelope air leakage are gaps around windows and doors; joint openings at roof, ceiling, or floor lines; and perhaps the greatest contributor, the intentional installation of soffit or wall vent systems. These areas provide the most likely openings in a building envelope and are convenient pathways for air leakage and moisture intrusion into the building.

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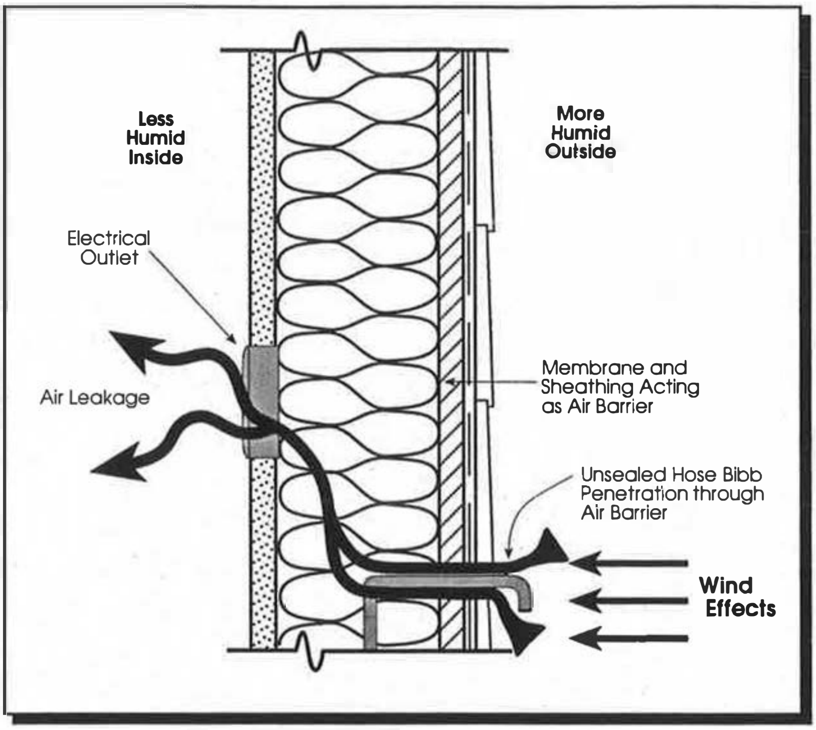

Figure 2-6. Air leakage into the building can be affected by typical building envelope penetrations.

Rainwater Leakage

In addition to moisture entering the building via vapor diffusion or air leakage, moisture as rainwater can be drawn into a building by gravity, capillary action, surface tension, air pressure differentials, or wind loads. The building envelope (exterior walls and roofing) acts as *the* interface between the interior and exterior of buildings. To avoid IAQ problems in the extreme weather conditions that exist in hot, humid climates, building envelope design must control water from all of these factors.

Weather-related moisture includes water intrusion from rainwater and groundwater. Rainwater and groundwater intrusion most severely affect the building envelope. Rainwater rarely affects HVAC systems or building interiors to the degree required to cause widespread building moisture problems. Water concentrates around window and door penetrations, the roof line and construction joints, and the base of exterior walls.

The following forces are most commonly applied to the building envelope:

- ***Gravity.*** The force of water entering by gravity is greatest on improperly sloped horizontal surfaces and vertical surfaces with penetrations. These areas must remove water from envelope surfaces through adequate sloping, correct drainage, and proper flashing.

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- *Capillary action.* This is the natural upward wicking force that can draw water from one source up into the envelope cavity. This occurs primarily at the base of exterior walls. Building components that cannot withstand a large amount of water exposure, such as plywood or gypsum board, can create environments conducive to microbial growth and/or component failure.
- *Surface tension.* This allows water to adhere to and travel along the underside of building components such as joints and window heads. This water can be drawn into the building by gravity or unequal air pressures.
- *Air pressure differentials.* If air pressures are lower inside the structure than outside the structure, water can be "driven" from the exterior to the interior of the building through microscopic holes in the building materials.
- *Wind loading.* Wind loading during heavy rainstorms can force water inside the building if the envelope is not resistant to these forces. For example, window gaskets that are not properly designed to flex with the window may create air gaps that can allow water into the building.

Wall System Components

Most wall systems used in new construction are framed wall systems, poured-in-place concrete, or masonry wall systems (concrete block or brick).

Framed wall systems consist of an interior wall finish system and an exterior wall finish system, separated by an air space (or cavity). The cavity, which normally includes insulation material for added thermal resistance, provides a potential path for the movement of moisture throughout the wall areas. Storefront wall systems and exterior insulation and finish systems (EIFS) are framed construction.

A concrete or masonry wall system is constructed of a structural wall material. If internal and external finishes are applied directly to the surface of the structural wall, air movement within the wall is restricted. However, if the interior finish is applied to a furred gypsum board attached to the structural wall, a potential pathway for air movement is created.

The primary wall system components requiring special attention for moisture control in humid climates (Figure 2-7) are listed below:

- Exterior wall finishes
- Vapor retarders
- Air infiltration and rain barriers and seals
- Insulation
- Interior wall finishes

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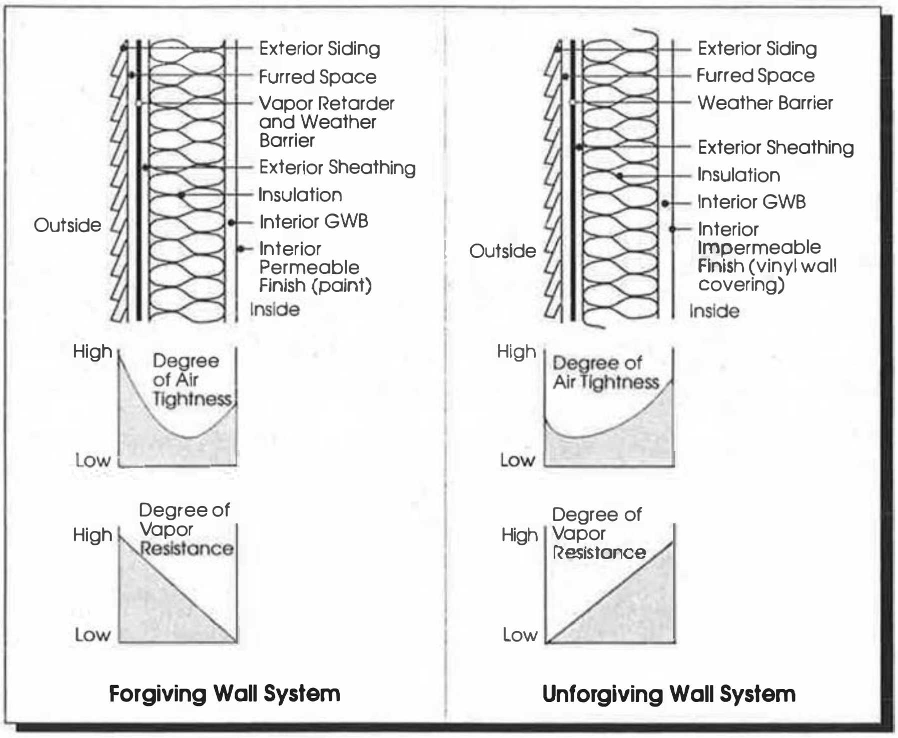

Figure 2-7. A "forgiving" (well designed) wall system for hot, humid climates has a high resistance to outside air and vapor movement. The component most responsible for restricting air and water vapor movement should be located toward the exterior of the wall system.

Exterior Wall Finishes

Materials commonly used as exterior finishes in construction include stucco, wood siding, concrete or masonry, brick veneer, and proprietary external finish systems that combine insulation and finish coatings (such as EIFS). In selecting the exterior finish material, the design team needs to consider the effects of moisture penetration and vapor and air migration, as well as aesthetics, to ensure consistency with the design intent. Consideration of porous materials such as concrete or masonry should include the ability of these materials to limit moisture and vapor migration into and out of the wall system, as well as their ability to act as air barriers. Often the aesthetic exterior finish of a concrete or masonry wall system is a paint or stucco type of application. These exterior finishes, as well as the structural concrete or masonry substrate, may be effective weather barriers but are ineffective vapor retarders and only partially effective air barriers.

Concrete block walls can have a permeance (vapor resistance) of 2 to 3 perms, whereas painted stucco finishes can have a permeance as high as 25 perms. Exterior paint systems with 1- to 3-mil dry-film thickness, such as commercial latex paints, can range from 5 to 10 perms (Figure 2-8). Paint systems are good examples of how requirements for temperate and hot, humid climates differ. In most parts of the country, exterior paint systems have high permeance ratings and interior paint systems have lower permeance ratings. In hot, humid climates, wall finish design requirements are just the opposite: exterior systems should have lower permeance ratings than interior paint systems.

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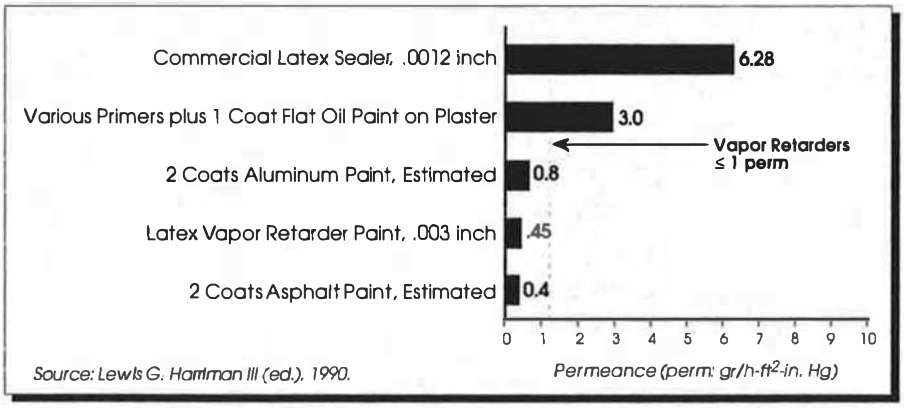

Figure 2-8. Many exterior paints and coatings can act as adequate vapor retarders.

Vapor Retarders

A vapor retarder is not required in all situations. The building envelope may perform as an adequate vapor retarder. Under many conditions, using an air barrier is more important than using a vapor retarder. While using a vapor retarder is not always necessary, if one *is* used, factors such as permeance, location, and use of multiple retarders become extremely important.

The type and location of the vapor retarder can affect moisture accumulation and mildew formation considerably. For example, a wall system vapor retarder located between the thermal insulation and the building's interior could reach a temperature below the dewpoint (point of condensation) of the outside air, allowing condensation to form on interior surfaces or in interior cavities. To avoid such problems, decisions regarding vapor retarders are best determined during the schematic design phase.

There are several types of vapor retarders (Figure 2-9). Rigid retarders include reinforced plastics, aluminum, and similar materials that are relatively impervious to moisture flow. They are mechanically fastened into place and may have sealed joints. Flexible vapor retarders include foil, laminated foils, treated papers, coated felts and papers, and plastic films. Joints in these materials must be sealed with another material. (Airtight joint sealing is not a requirement unless the vapor retarder is also acting as an air barrier and/or a weather barrier.) Some coating materials (such as epoxies) can also be classified as vapor retarders.

The permeance of a material is determined by how porous the material is. Different vapor retarder materials have different permeance ratings depending on how much vapor will diffuse through it during a given period and for a given area. For example, a .002-inch-thick aluminum foil sheeting has a permeance of .025, which means it passes .025 grain (1/7,000 of a pound) per hour per square foot of area for every inch of mercury column vapor pressure difference. By contrast, an 8-inch concrete block (limestone aggregate) passes 2.4 grains per hour, a rate 90 times greater than the aluminum foil, even though the block wall is 48,000 times thicker (*The Dehumidification Handbook*, 1990).

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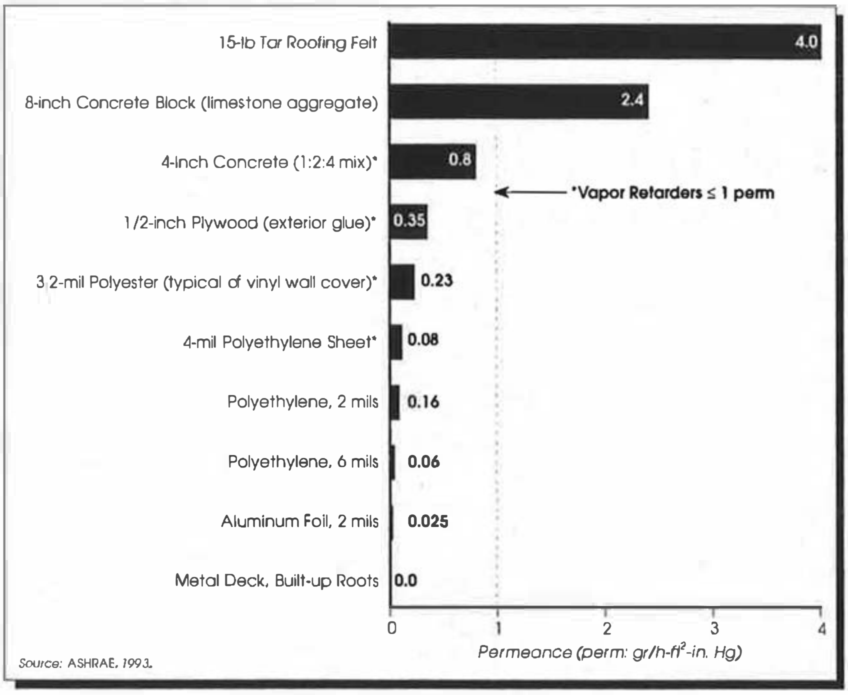

Figure 2-9. Vapor transmission rates among common construction materials differ dramatically.

Each of these vapor retarders can be used with the wall systems described previously. Typically, frame-type cavity walls include flexible vapor retarders. Designing the vapor retarder location for concrete or masonry wall systems can be more difficult than for a framed wall system. Applied coatings are particularly suited for concrete or masonry walls; applying the exterior finish system directly to the poured-in-place wall substrate is easier than including an interstitial space (or buildout) on the exterior of the wall substrate to install a vapor retarder. Moreover, the latter process may threaten the integrity of the wall. In selecting a vapor retarder for the exterior wall finish system, a vapor retarder paint may be considered.

The selected vapor retarder should have a permeance rating less than 1.0 perm. (However, in some fringe areas of hot, humid climates, a vapor retarder with a very low permeance rating may create problems because the vapor diffusion mechanism will reverse directions during winter months.) Although the design criteria may dictate a particular vapor retarder, or thickness thereof, the installation method can often mandate substitution. For example, a polyethylene sheet vapor retarder may meet design criteria but may not provide adequate resistance to tearing during field installation. The performance of a vapor retarder is reduced if penetrated, although avoiding all penetrations is not necessary.

Using two low-permeance finishes in a wall system, such as a polyethylene vapor retarder on the exterior and vinyl wall covering on the interior, should also be avoided. This arrangement can allow moisture to become trapped within a wall system without the ability to dry in either direction, thus promoting moisture accumulation and

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mildew formation. Using multiple vapor retarders within a wall system can be successful only if both rainwater intrusion and outside air infiltration are virtually eliminated. Thus, achieving and continually maintaining positive building pressurization is critical in this situation.

Air Infiltration Barriers and Seals

The decision to include a dedicated air barrier in the design is typically made at this point in the design process. An air barrier can play an important role in deterring infiltration from wind load or weather conditions and also can facilitate building pressurization. (Air barriers called *housewraps* are commonly used in northern climates for energy savings.) In hot, humid climates, the proper location of the air barrier may be the same as that of the weather barrier and vapor retarder. Therefore, a well-designed combination of air/weather/vapor barrier sometimes can be economically achieved.

An air barrier in a wall system, however, should never be viewed as an adequate envelope seal to offset a depressurized interior building space and prevent internally induced infiltration. The building envelope must work with the HVAC system to establish a pressurized building. Because cavities that may exist within a wall system provide potential pathways for outside air, maintaining proper pressurization is crucial to avoiding infiltration of outside air into these spaces.

Often, the building envelope components acting together can function as an effective air barrier. ASHRAE recognizes that a single piece of properly supported plywood or gypsum board sheathing can be an adequate air barrier. However, joined pieces of sheathing often will not be as effective unless the joints are reasonably well sealed. While the effectiveness of a vapor retarder diminishes linearly as the number of penetrations increases, the effectiveness of an air barrier diminishes exponentially as the number of joints, cracks, and crevices increases. Thus, the performance of an air barrier depends on its being as penetration-free as possible.

Wood products, including sheet goods and finished boards, are less effective as air barriers if normal installation methods are used. Because these exterior finish systems tend to allow air infiltration from wind and thermal effects, an additional means of limiting air (and moisture migration) through the wall system is required. A combination air/weather barrier should be installed on the exterior sheathing substrate, particularly in a framed wall system that uses wood products.

The effectiveness of combining insulation board and an exterior finish (i.e., EIFS) as air barriers depends on the overall integrity of the composite exterior system. If joints are reasonably plumb and tight, the system will protect the building envelope from infiltrating wind and outside air. Closed-cell and nonhygroscopic (nonabsorbent) insulation board are more resistant to vapor-diffused moisture than open-cell insulation board.

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Insulation

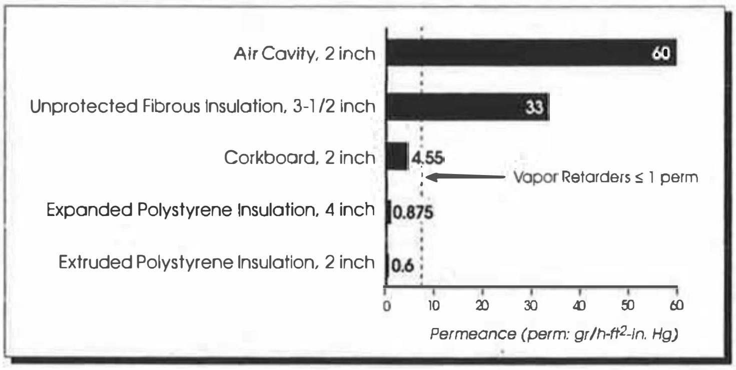

Figure 2-10. Some insulation types can also serve as effective vapor retarders. Special attention must be given to insulation thickness to achieve the desired permeance.

Using closed-cell, nonhygroscopic insulation can help minimize the high moisture levels that can develop in wall systems in humid climates. Insulation should be installed next to a vapor retarder whenever possible and should be inwardly located so that the vapor retarder does not reach the dewpoint during operation of the building AC system. Some insulation types can also be used as effective vapor retarders (Figure 2-10).

To avoid moisture problems, the design team must consider how direct contact with moisture-laden air affects wall structures. Thermal bridges that allow the structures to cool below the dewpoint of the ambient air may cause local condensation on the structural materials. For example, a metal stud framing system in a framed wall system can act as a thermal short-circuit or bridge, allowing condensation to occur on interior portions of the metal stud even though the wall may be well insulated.

Interior Wall Finishes

Interior finish selection is a critical consideration in humid climate design. The contribution of the interior finish to severe moisture and mildew problems in existing and new buildings is well documented. Using an impermeable interior finish without full consideration of infiltration, outdoor dewpoint temperatures, and the possibility of condensation at the primary vapor retarder location will often result in moisture entrapment and mildew problems.

Vinyl wall covering is a commonly used interior finish and normally has a low permeance (or a very high resistance) to water vapor migration through a wall system. A problem can develop, however, when outside air infiltrates a wall cavity, contacts a cooler surface, condenses, and cannot dry. (The vinyl wall covering's high vapor retarder characteristics prevents the condensation from drying.) The condensation will degrade the finish substrate, usually gypsum board, providing an excellent growth medium for mold and mildew. Consequently, vinyl wall covering should be limited to areas where moist air is unlikely to infiltrate (that is, interior walls) or in buildings where positive building pressurization can be ensured.

In general, the permeance of the interior finish material should be significantly higher than the permeance of the other components in the wall system. This difference will allow moisture vapor that enters the wall system to migrate into the conditioned space, where the vapor eventually will be removed by the AC system. To ensure success, all portions of the wall system located inwardly from thermal insulation must be more permeable than components external to the thermal insulation.

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Building Layout Considerations for Proper Building Pressurization

Uncontrolled movement of nonconditioned moist air into the structure has been identified as an important source of moisture to consider in designing buildings for hot, humid climates. The contribution of this particular source of moisture to moisture problems in hot, humid climates surpasses even rainwater leaks because water at least is subject to, and generally obeys, the laws of gravity. By contrast, air movement can enter a building from any direction. Thus, while making a building watertight is a formidable task, making it airtight is an impossible one.

Maintaining positive pressurization in a building is the best tool available to designers in preventing uncontrolled air flows; however, building layout significantly affects the ability of the system to achieve adequate pressurization. The uniformity of the layout from floor to floor, space usage, and construction style (atrium lobby areas or continuous slabs between all floors) will affect the HVAC system distribution and degree of pressurization required. Consequently, the building layout should be analyzed both vertically and horizontally for its effects on the pressurization. For example, a hospital might have certain areas under localized depressurization, such as laboratory spaces or areas with infectious control concerns. If these areas are placed on the perimeter of a building, infiltration through the building envelope and moisture problems are likely to result. If certain areas must be under localized negative pressures, they should be placed in the center of the building floor plan so that air travels from a conditioned adjacent space. In this manner, the air traveling to the depressurized space is conditioned and the HVAC system has a better chance of maintaining overall positive building depressurization.

An HVAC system should induce a slight positive pressure on a building, since this prevents infiltration through small cracks and openings. A positive pressure will cause air always to flow out of a building through joints and cracks such as those found at windows and closed doors. However, even a well-pressurized building cannot prevent infiltration through large openings like door entrances. Unless a rate of air flow of at least 150 feet per minute (fpm) can be achieved through these large openings, wind-induced air leakage into the building must be expected. It is not likely that nonindustrial building design and construction will achieve 150 fpm through large openings. For example, an open classroom window (12 square feet [ft^2]) would require an overpressurization of 1,800 cubic feet per minute (cfm) to achieve air flow at 150 fpm. However, certain architectural influences can help minimize air leakage through large openings.

- ***Vestibules.*** A double-door vestibule reduces the chance that a large direct opening exists at any given time.
- ***Tunnels.*** Entrances made of tunnel-like enclosures reduce wind counterflow through a building opening.

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- *Curtains.* In auxiliary or back-of-house areas, plastic strip curtains or fan air curtains help minimize wind-induced air leakage.

Mechanical Considerations

If improperly designed, constructed, and operated, building mechanical systems are likely to create moisture and mildew problems. Therefore, particular attention must be paid to the design, equipment selection, installation, and startup of these systems. The key factors that must be considered by the entire design team in the schematic design of building mechanical systems in humid climates are as follows:

- Maintaining building pressurization through proper control of exhaust, makeup air, and ventilation
- Properly selecting AC and control systems for adequate dehumidification and filtration

Pressurization

During the hot, humid months, outside air can carry a large moisture load. If outside air is drawn into the building envelope by negative pressure inside the building, it will travel through the wall system and into the interior space. Because air flow will always follow the path of least resistance, air can be carried down interior walls of a space if the walls are connected to the exterior envelope. As the air flows through the wall system and moves past the cool interior wallboard, the moisture in the air condenses and is deposited in the wall cavity, thus damaging the wallboard. The potential for moisture accumulation not only increases with decreasing interior temperatures but also increases with increased negative pressures (Figure 2-11).

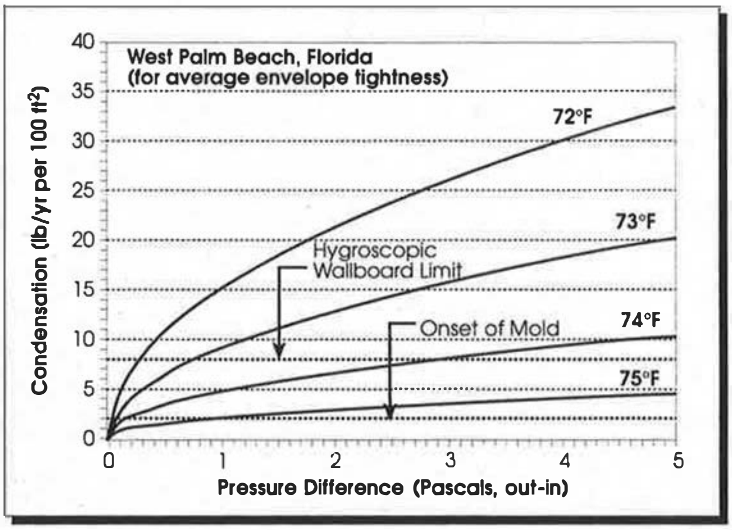

Figure 2-11. The potential for moisture accumulation increases with decreasing interior temperatures.

The following considerations must be addressed to ensure proper building pressurization:

- Control of mechanically induced depressurization
- Proper distribution of makeup air within the building spaces

Achieving positive building pressurization is sometimes difficult. Building pressurization must overcome any depressurization from stack effect, wind effect, and fan effect (Figure 2-12). The design team must consider how exhaust air systems will affect space pressures.

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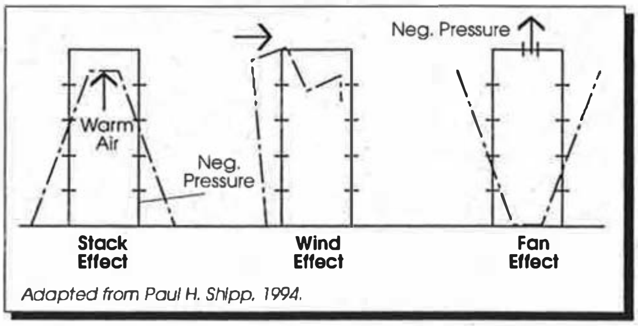

Figure 2-12. Building pressurization must overcome all forms of possible building depressurization.

For example, a toilet exhaust system in a building should be viewed as a method of addressing toilet odor and localized moisture only, not as a method of drawing outside air ventilation into a building. Typically, exhaust systems are designed and installed with exhaust rates exceeding those required to handle odor problems. Ventilation to control problems with air quality degradation should be achieved by designing and installing a makeup air system. Any air that is exhausted from a space must be supplemented with conditioned air from a makeup air supply system (Figure 2-13). Makeup air should never be supplied by infiltration of outside air.

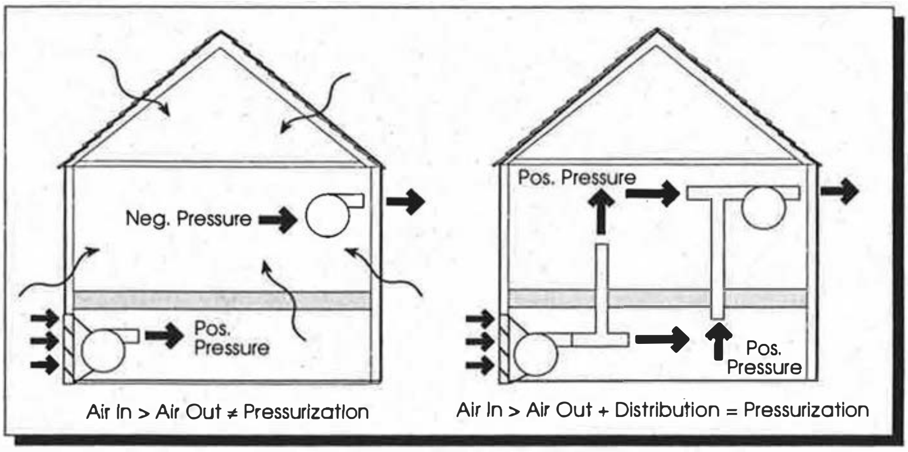

Figure 2-13. Achieving positive pressurization requires that interior building partitions not adversely affect the distribution of air.

Ventilation

Most ventilation building codes establish minimum ventilation requirements in relation to occupancy or space function. These requirements are usually based on ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality. This standard specifies the minimum acceptable outdoor air requirements for occupied spaces (if the space is unoccupied, this standard does not apply). *Ventilation* refers to supplying outside air to the space as well as expelling air from the building.

Providing conditioned outside air not only helps pressurize a building but also dilutes chemicals or particulate pollutants generated in the space. On the basis of ASHRAE standards, ventilation rates for different types of buildings and indoor activities have been developed to control air quality to certain pollutant concentrations and occupant exposures.

Outside air can also be induced in the space by the HVAC system as ventilation air. If the HVAC system introduces air into the space, the system must continuously dehumidify the air. If the air is not continuously and adequately dehumidified, the moisture added to the

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space might be greater than the AC unit's ability to remove it. This moisture source normally results in moisture-related mildew problems on the interior surfaces of the building (that is, interior finishes and the surface of furnishings).

Dehumidification

To provide proper dehumidification, an HVAC system must accomplish the following:

- Fully dehumidify the air that flows across the cooling coil
- Provide sufficient run time to remove moisture from the interior air despite the satisfaction of interior temperatures

Dehumidification of Air Flow

To fully dehumidify the air flow across the coil, the cooling coils must be sized properly to meet the sensible load (load associated with dry bulb temperature) and latent load (moisture in air associated with wet bulb temperature). This includes the combination of both outside air and return air. This air must be brought to a temperature that causes the moisture in the air to condense; this is known as *latent heat* (or *latent energy*) *removal*. Simultaneously, the cooling coil is reducing the sensible temperature of the air to offset the sensible energy generated in the space (lights, solar, people, equipment, etc.). A common range of temperature for the cooling of this air is between 50°F and 55°F. At this temperature, most HVAC system air flows will be at 100 percent RH (or complete saturation) and will effectively condense moisture from the air. Air provided to a space under these conditions has the best chance of maintaining interior conditions of 75 degrees Fahrenheit dry bulb (°Fdb) and 60 percent RH.

Run Time Needed for Dehumidification

If the system cannot provide sufficient dehumidification while it reacts to temperature control alone, it must continue moisture removal without affecting interior temperatures and occupant comfort. One manner of accomplishing this is by reheating, a form of simultaneously cooling and then heating to continue dehumidification while not overcooling the occupants.

Methods of reheating include direct or indirect gas-fired heating; hot water heating; hot gas reheating for refrigeration-based units; and for parts of the country that allow it, electric heating.

Devices added to the equipment, such as wraparound coils, can also provide a means of reheating. Wraparound coils simply transfer energy from the incoming cooling coil air stream to the exiting cooling coil air stream. These coils are available in a passive refrigeration-based unit or as a water-based system that uses pumps to move the water through the system.

In conventional HVAC systems, two different methods are typically used to dehumidify the air. The first is a cooling-based system that cools

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the air below its dewpoint. The moisture condenses on the cooling surface and is removed from the air. For example, a cooling-based system will cool an outside air stream from 95°Fdb (55 percent RH) to 77°Fdb. At 77°Fdb the air is at 100 percent RH and is saturated. If it is cooled below 77°Fdb to a temperature of 55°Fdb, 68 grains of moisture per pound of dry air are condensed out of the air and onto the cooling coil.

The second method of dehumidification is through the use of a desiccant that attracts the moisture in the air to its surface by introducing a low vapor pressure at the desiccant surface. The vapor pressure of the moisture in the air is higher, so moisture travels from the air to the desiccant. The desiccant then must be recharged through a heating process, which allows the moisture to be driven from the desiccant and discharged to another location besides the cooling air stream.

One of the best dehumidification strategies is a combination of desiccant and cooling systems, particularly for 100 percent outside air streams such as makeup air systems. Since air exits a cooling-based system at saturation, it only moves to a lower RH once it mixes with the room air and heat is added to it. The desiccant, on the other hand, enters the space with very low RH, and its RH increases to the room's RH level once the two air streams reach equilibrium.

Filtration

Air filtration should be selected according to the amount of outdoor air supplied by the air handler, the ability of the filter to capture airborne contaminants, and the relative pressure drop (as it relates to equipment static pressure capabilities and energy use). Chapter 25 of the *ASHRAE Handbook: HVAC Systems and Equipment* (ASHRAE, 1992) provides guidance to design teams and recommends filtration capacity for various applications. No matter how well designed a filtration system is, most moisture-related IAQ problems cannot be avoided by good filtration alone. Filtration systems are adequate for decreasing dust and dirt; however, they are not effective in addressing excessive moisture—the underlying problem.

Outdoor air can be the largest source of moisture introduced into the air handling system as well as the largest source of particulate contamination. Therefore, the greater the amount of outdoor air, the more efficient the filtration system must be, and the greater the required dust-holding capacity (Figure 2-14). Makeup air units will require filters with at least 60 percent efficiency (per ASHRAE Standard 52) and with a high dust-holding capacity; these are referred to as bag-type filters. Recirculated systems with prefiltered fresh air may be selected for filters with 25 to 30 percent efficiency.

Considerable debate has occurred within the industry regarding the use of fiberglass as a filtration medium because fiberglass particles break off and are carried into the conditioned air. The harmful effect of these airborne particles on human occupants is not well documented; nevertheless, other synthetic filter media are available and do not add

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more particulates to the air stream than they remove. A synthetic medium that does not promote biological growth should be considered, together with the proper filter media support. The use of paper products for media support is not recommended, because these products, when wetted, become an excellent food source and habitat for biological growth.

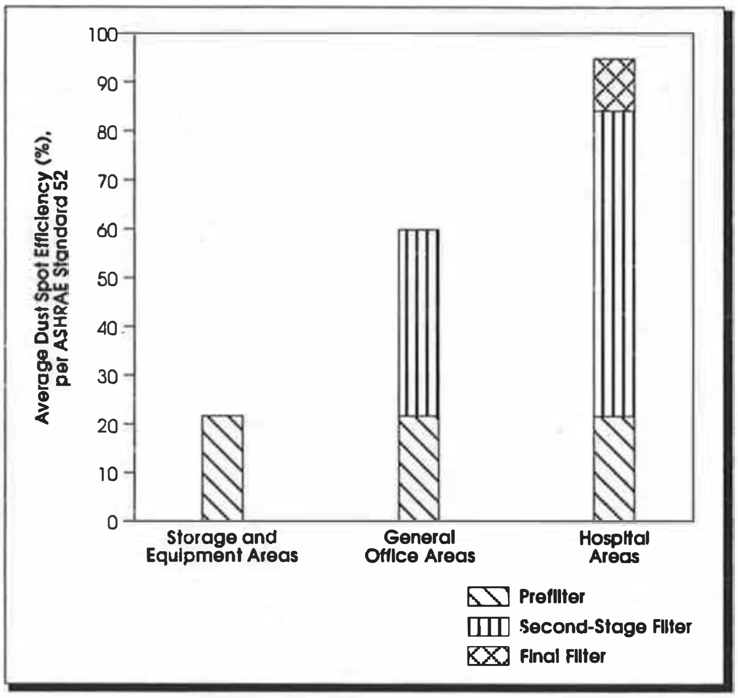

Figure 2-14. Air filtration needs vary according to the environment being filtered.

Mechanical Systems

Exhaust Systems

Two types of building exhaust systems are commonly used: localized and centralized. A localized system usually serves only one area, whereas a centralized system serves multiple areas and exhausts air through a negatively pressurized ductwork system.

Localized exhaust systems serving a single area are strongly recommended. A localized system normally functions only when the space is occupied, minimizing induced depressurization of the space. The run time should be set to the minimum required to ventilate the space (for example, most codes require 1 cfm/ft^2 for private bathrooms and 2 cfm/ft^2 for public bathrooms). The unit should not be operated when the space is unoccupied or when ventilation is not needed.

Centralized exhaust systems should not be used, or at least used minimally. If they must be used, the space served by the system must also be served by a makeup air system. The makeup system must be directly ducted and designed to maintain constant positive pressure in the space by providing a source of conditioned supply air. Proper balancing devices and interlock shutoffs or alarms to monitor the system must be provided to ensure that relative air supply and exhaust quantities are maintained at design levels.

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Selecting a centralized exhaust system during schematic design increases the importance of the design and construction decisions for avoiding mildew that must be made in the next design phase.

Makeup Air Systems

Two methods are used to provide makeup air—indirect and direct delivery. The first method pressurizes adjacent areas and allows air to enter different spaces via transfer air—for example, through the undercut of the door. The second distributes makeup air directly to individual spaces.

Using undercut doors will not ensure that a room is pressurized because door undercuts of 3/8 inch can typically transfer only about 10 to 20 cfm, while exhaust systems may operate at higher air flows. Directly ducting the makeup air system into each room is an effective alternative, but even a properly sized makeup air system to the room will pressurize the room sufficiently only when all the room's doors and windows are closed. Furthermore, directly ducting the makeup air into each room will make system balancing difficult and more expensive. If the rooms are exhausted by intermittent, individual exhaust fans, the efficiency of a directly ducted makeup air system becomes less critical and moisture intrusion is less likely.

In many buildings, the selection of 100 percent outside air makeup air systems or partial recirculation for supplying makeup air is at the discretion of the design team. Obviously, the unit sizes of the recirculation system will determine total cooling and heating capacities, but the overall air flows needed to maintain the desired pressure in the space will dictate the relative outside and recirculation quantities required.

AC Systems

The following paragraphs briefly describe the types of systems typically used in different applications and identify some of the selection considerations for humid climates.

Hospital Patient Rooms, Dormitory Rooms, and Hotel Guest Rooms. In terms of preventing moisture intrusion and mildew formation, the room environment presents the biggest challenge in domicidal design and construction. HVAC systems used for room spaces are usually simple compared with those used for other commercial buildings. However, room HVAC systems tend to present greater problems for moisture control because the occupant often has complete control of the system.

Chapter 8 of the *ASHRAE Handbook: Fundamentals* (ASHRAE, 1993) has defined a comfort envelope that describes acceptable temperature and RH levels for most individuals. Operating within this comfort envelope is usually satisfactory for the average individual, but not necessarily for *all* individuals. In addition to providing adequate comfort levels, RH (or dewpoint) should be maintained within limits that will prevent moisture damage to room furnishings and construction materials.

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Packaged FCUs. A fan-coil unit (FCU) is factory-assembled AC equipment requiring minimal field work for installation. Heating capacity is optional in this equipment, but a cooling function is always provided. These systems are available in configurations of single-zone, constant-volume; multi-zone, constant-volume; and single-zone, variable-volume. In the smaller size ranges, used in hotel guest room areas, temperature and humidity control options are limited. A residential unit is defined as a single-phase product, with a capacity of less than 65,000 Btu/hr. Design teams working on projects in hot, humid climates should recognize that the U.S. Department of Energy (DOE) has based the performance rating of these units on a moderate northern climate.

A two-pipe FCU usually includes a supply/return piped cooling coil and an electric coil for heating. Other two-pipe designs eliminate simultaneous heating and cooling and convert from chilled to heated water according to need.

The four-pipe FCU employs four separate pipe connections to provide a heating and a cooling source of water for conditioning the space. This unit can be used for heating, cooling, or simultaneous heating and cooling for humidity control. Each space is equipped with an individual conditioning system. The central water heating and chilling equipment allows fuel source flexibility while minimizing space requirements for air distribution.

PTWUs. Packaged throughwall units (PTWUs) are frequently chosen because of their relatively low cost, ease of installation, and ability to meet small sensible load requirements. One drawback of PTWUs, however, is that they do not have large latent load cooling capabilities, decreasing the unit's ability to provide outside air ventilation. Consequently, units for the room area must be sized carefully to ensure that the PTWUs can maintain RH, and any moisture load from outside air infiltration must be minimized.

Control Systems. Control systems are used to maintain conditioned spaces and vary greatly because of HVAC system complexity, the need for occupant control, and the need to control space temperatures and RH. Regardless of the design, when moisture removal will be required even though space temperature is satisfied, all the control systems should include a method for sensing and controlling both temperature and humidity. In humid climates, the most important consideration for design teams and building owners is controlling space RH. If infiltration of nonconditioned air is excessive in the interior space and the room unit senses only the space temperature, operating the cooling coil based on sensible control will not adequately dehumidify the space. Generally, infiltration of nonconditioned air is not considered in the design of room units, even with a continuous toilet exhaust system installed.

Classrooms. Classrooms often use the same kinds of equipment used in hospital patient rooms, dormitory rooms, and guest rooms. The critical difference, however, is that the occupancy of a classroom requires a much higher rate of ventilation than patient rooms. For example, a classroom may require ventilation rates for 30 to 35 students at 15 cfm each while a patient room may need to provide ventilation air for only

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two occupants. Greater dehumidification is therefore needed for the classroom. The use of PTWUs for both the sensible control of a classroom and the ventilation source (with the subsequent dehumidification requirements of the ventilation air) often fails in hot, humid climates. At ventilation air of 450 cfm for a typical classroom of 30 students, the unit sizing is driven by the latent load. The unit requires little run time for meeting the sensible load and consequently provides very little dehumidification of the space, resulting in problems with high humidity.

Central Public and Office Areas. The design of HVAC systems for central areas must address the same issues noted for rooms, including building pressurization and humidity control systems. In addition, the amount of outdoor air required can vary significantly by space type and should use ASHRAE Standard 62-1989 for recommended ventilation air quantities. The high ventilation rates pose additional challenges for the design, such as how to filter, cool, and dehumidify the outdoor air before it is introduced into the space.

When relatively large public areas are involved, most HVAC systems will have central air-handling units (AHUs) with some form of terminal unit for control of thermal zones. To meet energy code requirements, the more common type will be of the variable air volume (VAV) constant discharge air temperature type, rather than the constant air volume (CAV) variable discharge air temperature type.

VAV Systems. VAV systems can inherently control space humidity by maintaining constant discharge air temperature, while the quantity of air supplied to the space varies to meet space demands. The design team must address the following areas of concern:

- Maintaining building pressurization in all areas, including return plenums
- High latent load, with low sensible load area
- Reset of discharge air temperature
- Space RH control

Space pressurization can be enhanced by using nonducted return air systems; by using positive control of outdoor air quantities, based on ventilation requirements; and by using relief fans (to ensure that the building pressurization remains positive at all times) rather than return fans (which induce negative pressures).

Discharge air temperature reset for VAV air handlers should never be used unless space RH is monitored and used as a key indicator of system performance. If outdoor air is preconditioned, discharge air temperature reset is more forgiving but should be used only with space RH monitoring.

Terminal control units (boxes) need to be selected with the minimum ventilation required for each zone controlled. The amount of outdoor air required per zone will be a variable percentage of the total supply air to the zone. The minimum air flow position for temperature control must

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account for ventilation air, RH control, and space temperature control. This will typically require some form of reheat device in the terminal control unit.

CAV Systems. CAV variable discharge air temperature systems do not control space RH without active RH control systems. The discharge air temperature is allowed to vary to meet the space temperature requirements, not RH. Preconditioning of outdoor air is therefore necessary to keep the space RH a function of internal moisture gain. Controlling by space RH is recommended for all high latent load areas.

Building pressurization control is more easily accomplished by providing a fully ducted return system, with all joints sealed and tested for leaks, and properly controlling outdoor air quantity.

Space RH control will require using RH sensors mounted in the space or in the return air duct and using reheat systems.

The discharge air temperature, if controlled by the space temperature, must include an RH sensor to ensure proper control of humidity.

Control Systems

Energy management systems are methods to control energized energy-using systems, which are predominantly HVAC systems. Nonenergized (human) energy-using systems (for example, people controlling how HVAC equipment operates) can significantly affect the most energy-conserving design; such systems are not addressed in this manual.

Energy management in a facility depends entirely on the interaction of the occupants and the operations, maintenance, and janitorial staff in operating the environmental control systems of the interior space.

Most energy management systems are energy monitoring and control systems. They enable the building owner to monitor energy use and provide the necessary logic and communication systems to control how that energy is used. Because energy management systems often control the operating time of the AC systems, they can increase the likelihood that mildew will form by decreasing the AC equipment's dehumidification capability.

Energy savings can be realized without sacrificing proper temperature and humidity conditions. Most of these opportunities will occur in the public space systems and include the following:

- Waste heat recovery for reheat and/or humidity control
- Higher-efficiency condensing equipment or water chillers
- Variable-speed drives for fans and pumps
- Decoupled chilled water production plants with variable flow distribution systems for better load matching
- Premium-efficiency motors for fans and pumps
- Heat transfer from exhaust air quantities to pre-cool makeup air

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Section 3
Design Development

Section Highlights

✓ *The concepts developed in the schematic design phase are used to prepare draft design drawings and specifications.*

✓ *Mechanical considerations during design development must include the following:*

- *Identifying and quantifying moisture sources by calculating heating and cooling loads*
- *Selecting and sizing equipment*
- *Analyzing dehumidification capacity and dewpoint*

✓ *At this point, many architectural and mechanical specification sections for contract documents are developed.*

Design development is the second design phase and concludes when the design is approximately 50 percent complete. During this phase, the concepts developed in the previous phase are used to prepare draft design drawings and specifications. The moisture control considerations associated with design development are described in this section and summarized in Figure 3-1.

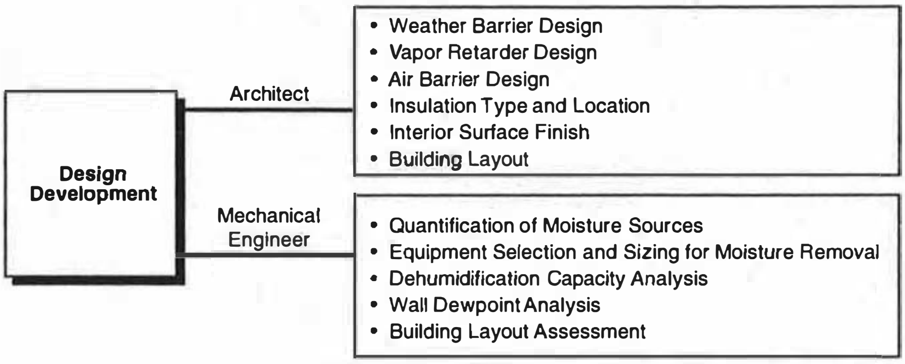

Figure 3-1. For optimal moisture control, these points should be considered during design development.

Architectural Considerations

Hermetically sealing a building to prevent nonconditioned outside air from infiltrating into a negatively pressurized building envelope is expensive and impractical. Although most designs include standard precautions against weather-induced moisture, designs for humid climates require special characteristics to avoid the intrusion of moisture-laden air and to control mildew formation. As shown in Figure 3-1, architectural considerations for moisture control in wall systems include the following:

- Air and weather barrier design
- Vapor retarder design
- Insulation type and location
- Interior surface finishes
- Building layout (discussed in Section 2)

The moisture control guidelines for these wall components vary depending on their locations on the interior or exterior of the building envelope and on the type of building construction.

Framed Construction

Exterior Cavity Walls

The exterior (storefront or side exterior) cavity wall design typically consists of an interior finish wall covering on gypsum wallboard, metal stud framing with batt insulation, gypsum sheathing, and an exterior finish system (Figures 3-2 and 3-3). A continuous vapor retarder applied toward the exterior of the wall system is often used in hot, humid climates.

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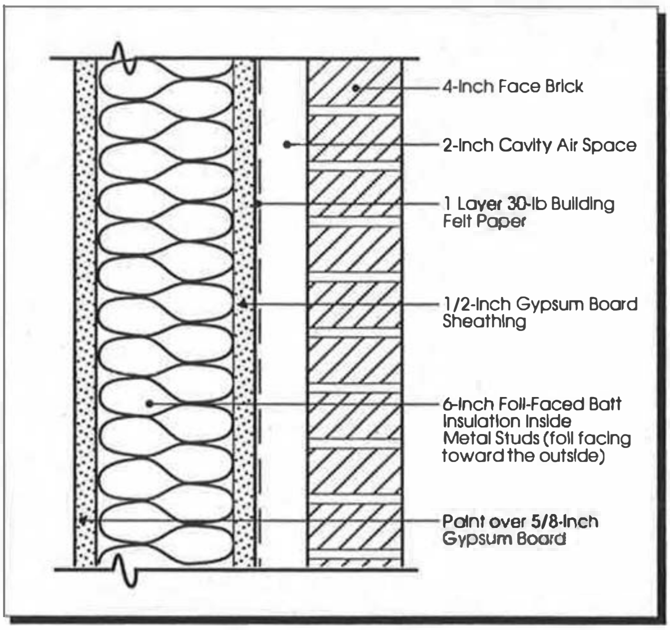

Figure 3-2. The 15-lb building paper will act as a primary air barrier (along with the sheathing) and as a secondary weather barrier. The foil-faced batt is the primary vapor retarder in this brick veneer/framed wall assembly.

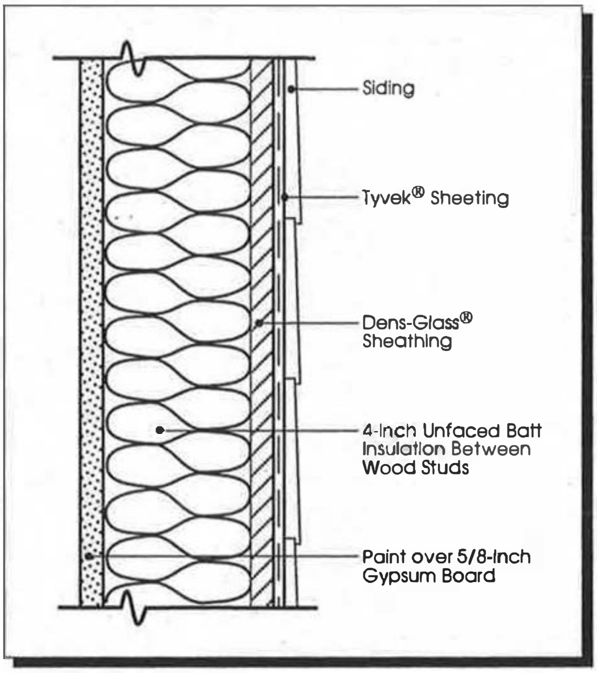

Figure 3-3. In this sliding/framed wall assembly, the Tyvek sheeting wrap acts as a primary air barrier and supplements the Dens-Glass® sheathing; the combination acts as a secondary barrier. This wall assembly has no vapor retarder.

The exterior wall construction should be continuous between rooms to maintain the integrity of the overall building envelope air barrier system, particularly at the forward structural column. If the construction runs from wall column to wall column, connections between the columns and framing must be carefully detailed to avoid air infiltration pathways.

Vapor Retarder. In hot, humid climates, the vapor retarder must be located on the nonconditioned side of the insulation in the exterior wall system. Applying the vapor retarder to the exterior surface of the exterior sheathing will help maintain the integrity of the vapor retarder during field installation. The vapor retarder specifications should require a rating using ASTM E96 and C355 testing methodologies.

Air Barrier. The pressurization of the building envelope depends on the effectiveness of the air barrier. As previously stated, hermetically sealing a building envelope is impractical. Consequently, if the building mechanical systems are inducing a negative pressure on the building envelope, an air barrier will not effectively prevent infiltration of humid outside air. However, if the building mechanical systems are inducing a positive pressure on the building envelope, a sheet-type air barrier will effectively restrict outside air infiltration. In hot, humid climates, the air barrier, the vapor retarder, and even the weather barrier can be in the same location, thereby simplifying wall system design.

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Insulation. Batt insulation faced with a vapor retarder is often used in framed construction. If a separate vapor retarder is installed in the wall system, including a vapor retarder (facing) on the batt insulation is unnecessary. However, if the facing makes installing the insulation easier, it can be included without negatively affecting moisture control. To ensure proper installation of faced insulation, wall sections (or details) should clearly indicate the location of the facing with respect to the exterior surface (for example, R-11 BATT INSULATION FOIL OR PAPER FACED OUT). Because these details may be contrary to the batt insulation manufacturer's instructions (which are intended for installation in more temperate climates), the details should clearly direct the installer to the proper location of the facing.

Interior Finish. Selecting an interior surface finish with the proper permeance is one of the most critical aspects of an exterior wall system design in hot, humid climates. Typically, the interior finish is selected for aesthetic appeal or ease of maintenance, with little regard for wall system performance. An interior finish should have a high permeance rating. As discussed in the subsection on wall dewpoint analysis, the mechanical engineer will use interior finish permeance ratings in performing the dewpoint analysis on the wall system.

Interior Walls

Interior walls typically consist of an interior finish on gypsum wallboard and metal stud framing. Because this wall system separates only conditioned areas, moisture diffusion is not a factor. Infiltrated outside air can, however, travel down these interior walls, thereby causing additional problems.

Concrete or Masonry Construction

Exterior Walls (Conditioned to Nonconditioned Areas)

An exterior poured-in-place (concrete) or masonry block wall typically consists of an exterior finish system (furred or directly applied), a concrete or masonry section, and an interior finish system that is either applied directly to the wall or applied indirectly to a furred gypsum wallboard system (Figure 3-4). In some areas, the interior finish system is applied to a furred wallboard system; in other areas, it may be applied directly to the concrete or block.

Vapor Retarder. The vapor retarder should be installed on the exterior of the wall system insulation. If the exterior finish system is furred from the concrete or masonry block, the vapor retarder can be applied within the furring space.

Air Barrier. An advantage to concrete or masonry construction is that an air barrier is inherent in its construction. Unlike a framed wall, an unpenetrated concrete or masonry wall usually provides a solid air barrier that is free from penetrations. This condition does not release the design team from designing a positively pressurized building envelope, however. A depressurized interior space will still induce the intrusion of outside air, even in a concrete or masonry wall system.

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Insulation. One of the advantages of insulation is that it keeps the primary vapor retarder (if one exists and is correctly located) from reaching the temperature at which condensation may occur. In a concrete or masonry wall system, a closed-cell nonhygroscopic insulation is recommended.

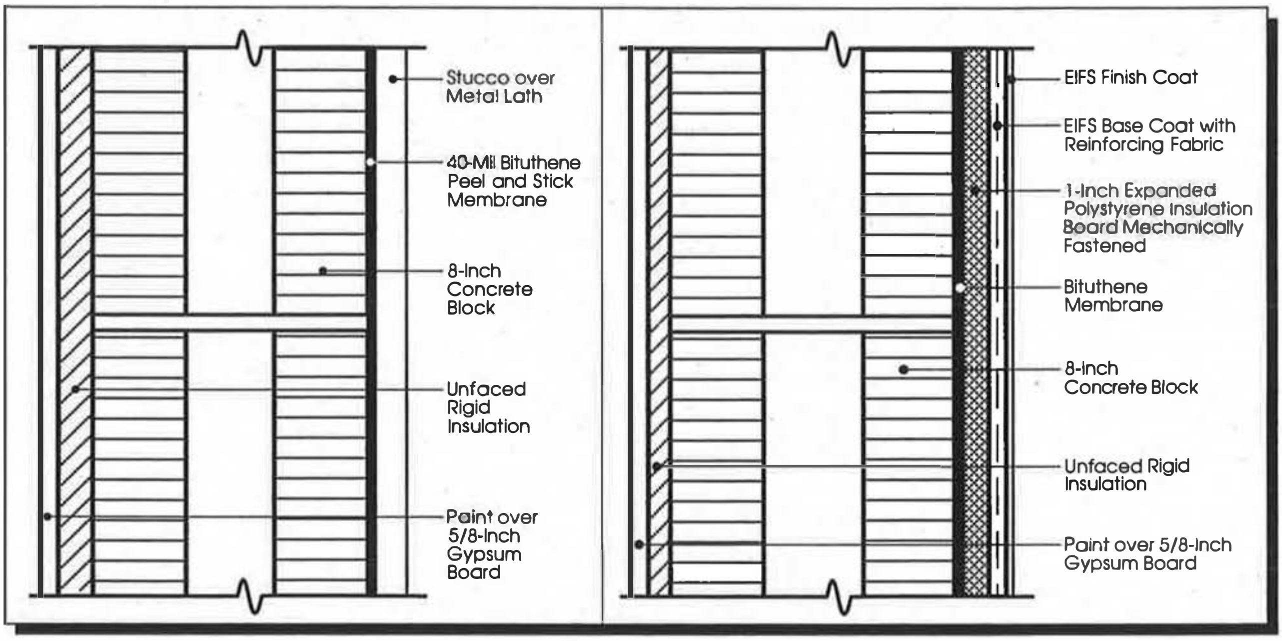

Figure 3-4. Although the use of a membrane in this stucco/concrete block wall assembly is a fairly new trend in the industry, a 40-mil "peel and stick" membrane will act as a primary air barrier, a primary vapor retarder, and a secondary weather barrier. If the membrane were omitted, the only weather and air barrier would be the stucco system; the primary vapor retarder could be the exterior paint or the rigid insulation.

Interior Walls

An interior concrete or masonry wall system typically includes a furred (or directly applied) interior finish system. Until a concrete or masonry system has fully cured, it is a source of moisture. Therefore, using permeable interior finish will allow this moisture to diffuse to the interior space of the building. However, if an impermeable interior finish is specified, application of the finish must be delayed until the concrete or masonry has reached equilibrium with desired environmental conditions. This delay is necessary for either directly applied or furring-installed interior finish systems.

Mechanical Considerations

Figure 3-1 lists important mechanical considerations for moisture control during design development: identifying and quantifying moisture sources by calculating heating and cooling loads, selecting and sizing equipment, and analyzing dehumidification capacity and dewpoint.

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Identifying Moisture Sources

To ensure that the building mechanical system will adequately dehumidify the space, potential sources of moisture or water vapor must be identified. The following are potential sources of moisture:

- Introduction of nonconditioned outside air through ventilation or infiltration
- Vapor transmission through the building envelope from differential vapor pressure (vapor diffusion)
- Moisture or latent load generated by occupant activities such as showering, respiration, and cleaning

Most design teams are conscious of internally generated moisture loads and select equipment that will adequately handle internally generated moisture. What they do not usually consider, however, is the added moisture load that can occur from outside the building from uncontrolled air flows. Externally generated sources are often more significant than the internally generated sources and may exceed the capacity of the HVAC system to dehumidify the space (Figure 3-5). For example, external induced moisture load inside a new hotel in central Florida resulted in a multimillion-dollar moisture and mildew problem within the first year of construction. Consequently, the most important mechanical consideration is to design the building mechanical system to avoid introducing nonconditioned outdoor air into the conditioned spaces or the building envelope.

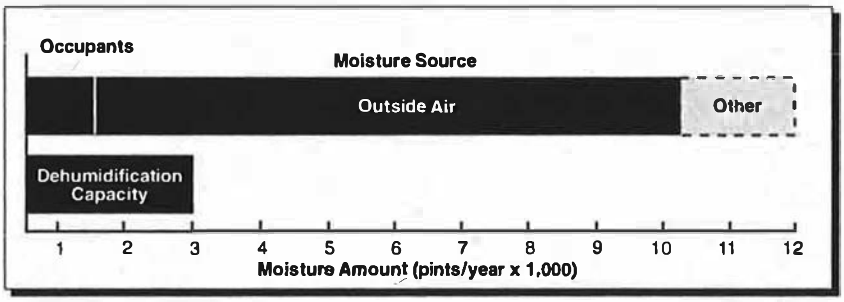

Figure 3-5. The addition of externally generated moisture can often exceed the HVAC system's ability to dehumidify the space.

Infiltration of Moist Outside Air

The building mechanical systems must provide a source of ventilation that maintains positive pressure in the conditioned spaces at all times under normal operation. Nonconditioned air should never be the source of makeup air for a building. To preclude its introduction, the system should be designed and installed to eliminate negative spaces (with respect to outside conditions) in the rooms, walls, or ceiling cavities.

As previously stated, one of the most common mistakes in designing the HVAC system is using a continuous exhaust system that does not maintain the space or exterior wall cavity at a positive or neutral pressure with respect to the exterior of the building. Using a continuous

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exhaust system on the interior space can lead to two consequences. First, nonconditioned air can infiltrate into the space, damaging the fixtures and furnishings if this air is not dehumidified by the AC unit (Figure 3-6). Second, nonconditioned air can infiltrate into the wall cavity because of negative pressures (Figure 3-7). This can occur from exhaust system leakage even if the mechanical system includes a makeup air system that maintains the room at a positive pressure (with respect to outside conditions).

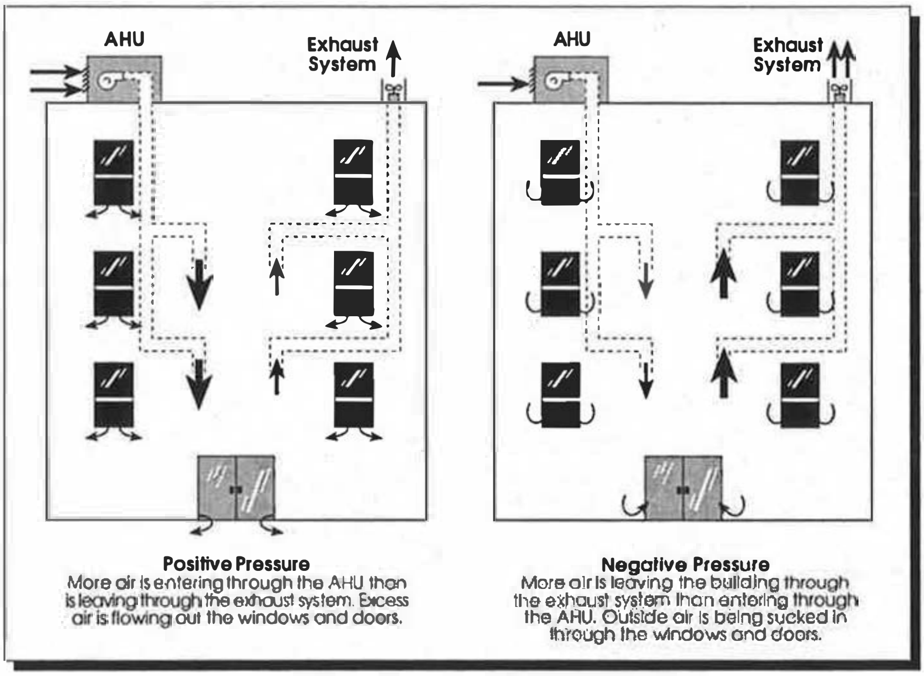

Figure 3-6. These diagrams show how building pressure affects air flow through a building.

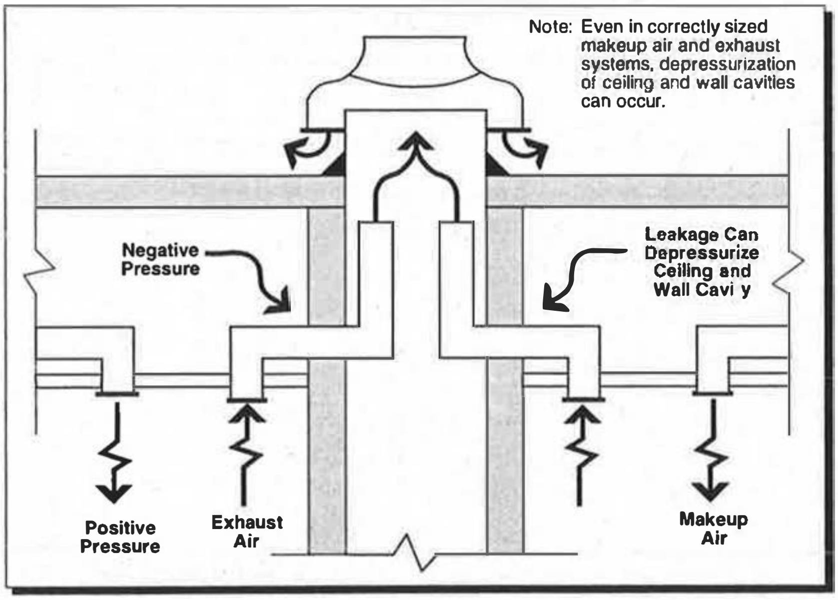

Figure 3-7. Even using a typical sub-duct exhaust system design such as this, preventing leaks is difficult.

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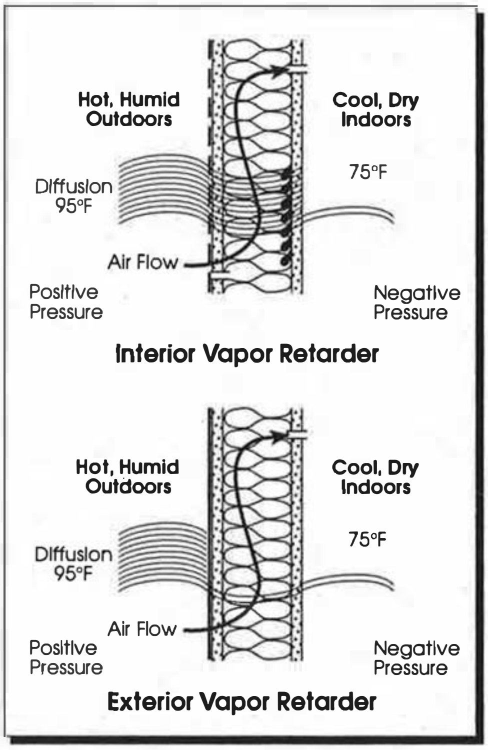

Figure 3-8. The same total vapor diffusion is experienced by both walls; to avoid problems, however, moisture is stopped at different locations. Both walls are subject to problems from uncontrolled air flow.

Regardless of the type of exhaust system, providing a completely sealed duct and/or chase is difficult. Each exhaust inlet device is balanced to the design air flow so that with the design makeup air system, a pressurized space can be achieved. Maintaining the proper balance for each interior space throughout the life of a building is a difficult task, and any leakage of the exhaust system from the toilet inlet device to the rooftop fan can allow nonconditioned air to infiltrate into the building envelope and wall cavities. This nonconditioned air will condense when it contacts a surface that is at or below dewpoint (Figure 3-8).

Moisture from Vapor Diffusion

Moisture from vapor diffusion typically affects the building moisture loads minimally. However, if the exterior portion of the building envelope is porous as well as permeable and the interior portion is porous as well as impermeable, the effect of vapor diffusion can be more significant. Vapor diffusion is discussed in Chapter 22 of the *ASHRAE Handbook: Fundamentals* (ASHRAE, 1993). Information that is not contained in that chapter can be obtained from textbooks dealing with thermal and mass transfer.

Vapor diffusion is difficult to estimate because of natural variables. Building envelope materials are subject to daily temperature extremes caused by shifting sunlight and shade on the walls or roof. However, using worst-case ambient temperatures in a steady-state analysis is usually sufficient for estimating vapor diffusion, especially if a vapor retarder is properly installed in the wall system.

As moisture vapor enters the space, it mixes with the existing interior space moisture and reaches approximately indoor design conditions. Consequently, interior space moisture gains from vapor diffusion are normally negligible. The primary benefit of a vapor diffusion analysis is to determine which wall components will be the first surface on which condensation may occur (Figure 3-8). Although moisture loads from vapor diffusion are typically not significant in space cooling load calculations, this analysis should be performed to verify and document the wall system design.

Occupant-Generated Moisture

Sensible (and less frequently, latent) heat gains from building occupants are considered in moisture load sizing. Because the HVAC system must be able to remove the combined occupant load, however, in a facility such as a hotel, the additional moisture load generated by bathing or showering must be added to system sizing. Occupant gains from normal activity are described in Chapter 22 of the *ASHRAE Handbook: Fundamentals* (ASHRAE, 1993). Moisture production from bathing and showering are described in Chapter 20 of the *ASHRAE Handbook: HVAC Systems and Equipment* (ASHRAE, 1992).

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AC Load Calculations

Chapter 23 of the *ASHRAE Handbook: Fundamentals* (ASHRAE, 1993) contains a complete description of methods of calculating cooling loads from ventilation and infiltration. The outside humidity during a typical year may be quantified to determine annual moisture load before designing and sizing the mechanical system. Annual humidity information can be obtained from weather data that report mean frequency of occurrence of dry bulb temperatures with mean coincident wet bulb temperatures for temperature ranges and corresponding hours of occurrence per year. One such source is AFM-88-29 (U.S. Air Force [USAF], 1988).

The data as presented by ASHRAE works best for sensible load calculations but does not always apply well for latent calculations. Latent sensitive areas require the knowledge of the highest vapor pressure likely to occur during the year. In hot, humid climates, the highest RHs are found during the morning and evening hours and occur at high values even during the winter. Also, the highest latent loads are usually found at lower dry bulb temperatures than the ASHRAE design data reflect.

The Dehumidification Handbook (1990) presents these findings in an evaluation of the 20-year weather data for New Orleans, Louisiana, beginning in 1965 (Figure 3-9). Using these data, the *Handbook* notes that the greatest RH is found between midnight and six in the morning. It also notes that the RHs remain above 75 percent for those morning hours even during the winter months. This information is most important for areas in buildings that do not receive any AC or heating and rely only upon ventilation for humidity control. Additionally, the implication is that for equipment sizing, the greatest latent load is found not at the highest dry bulb temperature but rather at more moderate dry bulb temperatures, often on a hot, rainy day (Table 3-1).

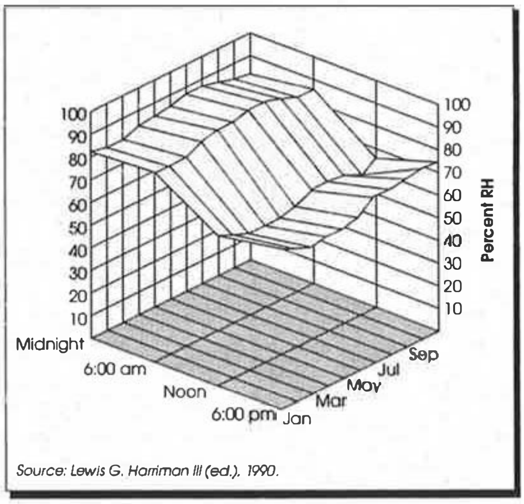

Figure 3-9. RH data for New Orleans indicate that the highest RH and latent cooling loads occur in early morning hours when temperatures are relatively low.

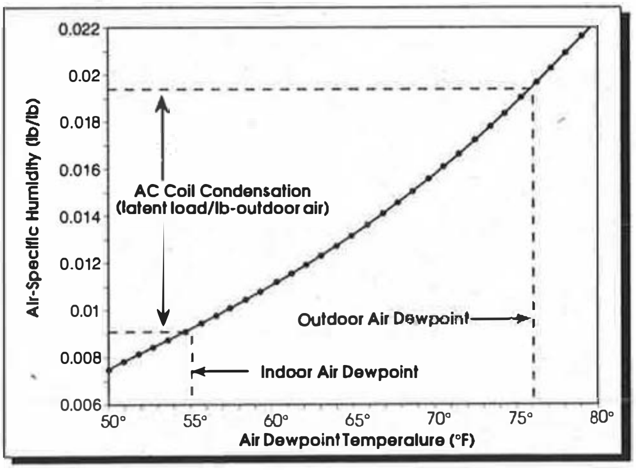

Figure 3-10. AC load calculations demonstrate the moisture capacity of the air.

The moisture load added to the space per pound of infiltrated dry air (lb_w/lb-DA) is calculated by subtracting the indoor humidity ratio from the outdoor humidity ratio and multiplying the resultant value by the hours per year (Figure 3-10).

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TABLE 3-1
The highest latent load does not occur at cooling and heating design times, which must be considered when sizing equipment to ensure adequate dehumidification.

	Cooling and Heating Data			Humidity Design Data		
	Summer		Winter	Moisture	Vp	Extreme
	°Fdb	°Fwb	°Fdb	(gr/lb)	(in. Hg)	(gr/lb)
Arkansas						
Little Rock	99	80	15	147	1.035	162
California						
Los Angeles	104	73	30	114	0.804	115
Merced	102	72	29	110	0.776	127
Sacramento	101	72	30	110	0.776	136
San Diego	83	71	42	106	0.748	141
San Francisco	82	65	35	86	0.608	100
District of Columbia						
Washington	93	78	14	137	0.965	167
Florida						
Jacksonville	96	79	29	142	1.000	179
Miami	90	79	45	142	1.000	162
Tampa	92	79	36	142	1.000	173
Georgia						
Atlanta	94	77	17	132	0.930	151
Macon	96	79	21	142	1.000	173
Savannah	96	80	24	147	1.035	179
Hawaii						
Honolulu	87	76	62	127	0.895	141
Kentucky						
Louisville	95	79	5	142	1.000	151
Fort Knox	94	79	4	142	1.000	179
Louisiana						
New Orleans	93	81	29	153	1.077	198
Shreveport	99	79	20	142	1.000	167
Mississippi						
Jackson	97	79	21	142	1.000	162
Missouri						
Kansas City	99	78	2	137	0.965	156
Saint Louis	97	78	2	137	0.965	162
North Carolina						
Asheville	89	75	10	123	0.867	136
Charlotte	95	77	18	132	0.930	136
Greensboro	93	77	14	132	0.930	141
Fayetteville	95	79	17	142	1.000	173
South Carolina						
Charleston	93	81	24	153	1.077	173
Columbia	97	79	20	142	1.000	156
Tennessee						
Knoxville	94	77	13	132	0.930	136
Memphis	98	80	13	147	1.035	173
Nashville	97	78	9	137	0.965	173
Texas						
Amarillo	98	71	6	106	0.748	123
Dallas/Fort Worth	102	78	18	137	0.965	179
Houston	96	80	27	147	1.035	198
Lubbock	98	73	10	115	0.811	123
San Antonio	99	77	25	132	0.930	162
Virginia						
Richmond	95	79	14	142	1.000	156
Roanoke	93	75	12	123	0.867	141
Puerto Rico						
Roosevelt Roads	89	72	67	153	1.077	173

in. Hg = Inches of mercury column.
gr/lb = Grains per pound.
°Fdb = Dry bulb temperature.
°Fwb = Wet bulb temperature.
Vp = Vapor pressure.

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For example, assume the applicable code requires 2 cfm toilet exhaust per square foot of toilet floor area for one hospital patient room. For a 40-ft^2 toilet area, this would be 4,800 cubic feet per hour (cfh) toilet exhaust. At 4,800 cfh, the annual infiltrated moisture load would be 9,942 lb_w/year in central Florida. The resulting infiltration of 9,942 lb_w/year is equivalent to pouring 6 gallons of water per day into the patient room, in addition to the normal moisture load (Figure 3-11).

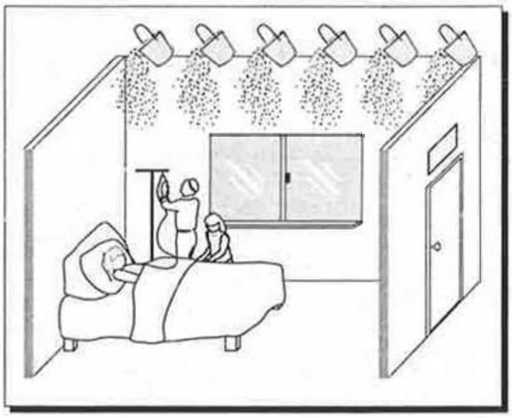

Figure 3-11. Allowing even small amounts of nonconditioned outside air to penetrate the building for an entire cooling season can dramatically increase the building's annual moisture load.

This infiltration will enter the patient room directly and will also enter the wall cavities. In the presence of an impermeable interior surface on the walls, any infiltration that penetrates the wall cavities will condense, accumulate, and then saturate the gypsum wallboard, thus creating an ideal environment for mold and mildew growth. To prevent moisture accumulation in the wall cavities, air infiltrating the wall system must be allowed to enter directly into the space from the outdoors and be removed by the AC unit. To achieve proper dehumidification under such conditions, the room would probably require overcooling.

Equipment and System Selection

If the HVAC system is improperly designed or constructed, no amount of operator effort and diligence can successfully combat the mildew problems that will result. Thus, selecting AC units of a type and style that can significantly minimize the potential for these problems is essential.

Equipment Selection

Considerations in unit selection include proper AC unit sizing for adequate dehumidification capacity of the occupant space, proper unit layout for control of infiltration and surface condensation, and proper control system design to ensure proper operation of the unit.

Sensible heat ratio (SHR) is the ratio of sensible cooling requirements to total cooling requirements, where total cooling is the sum of sensible and latent cooling requirements. AC equipment of the throughwall unit types (such as classroom unit ventilators or domicidal building PTWUs) have their rating system (Air Conditioning and Refrigeration Institute [ARI]) at a defined SHR that is not necessarily appropriate for hot, humid climates. Typical SHRs are 0.75 to 0.85 at rated conditions, and applications for these climates can require 0.50 to 0.65 SHRs, which indicates a greater portion of the load is of the latent cooling requirement. Therefore, the AC apparatus may not be able to remove the desired amount of moisture from the conditioned space.

A typical method of ventilation for many classrooms is the continuous introduction of outside air through individual unit ventilators. The unit ventilators condition this air when the classroom thermostat calls for cooling or heating. When the thermostat does not call for conditioning,

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the unit ventilators mixes outside air and recirculated classroom air and distributes it continuously during occupied hours.

A high school in South Carolina had an estimated moisture removal requirement for a cooling season of 4,692 gallons and the moisture removal capacity of the unit ventilators was found to be 1,429 gallons, with a potential dehumidification deficit of over 3,000 gallons. Additionally, the greatest possible unit ventilator run time was found to be 76 percent of summer operating hours, and even at the maximum run time, the unit ventilator could not provide sufficient dehumidification and moisture control of the classrooms. The outside air was found to be the greatest summer load on the classroom, followed by internal loads and then building envelope losses. In this case, the unit ventilators were insufficient for maintaining interior conditions below 60 percent RH by over two-thirds their capacity when used as a primary source of ventilation.

AHUs. Air distribution layout of the ductwork can affect the pressurization of the space. Excessive air leakage on either the supply- or the return-side ductwork will cause the supply or return air within the room to become unbalanced. If the supply-side ductwork of a unit is leaking air into the ceiling space, the unit may deliver less air than it returns. This imbalance can substantially depressurize the space, resulting in infiltration of nonconditioned air into the room or wall cavity (Figure 3-12a). Conversely, if the unit has a return-side leak, it will deliver more air than it returns from the space (Figure 3-12b). In this case, the mechanical space housing the unit and the attached wall systems would become depressurized. Depressurization could cause nonconditioned outside air to infiltrate the wall cavity, even if the room were at a positive pressure with respect to outdoor conditions. Preventing ductwork leakage is critical for controlling building pressurization.

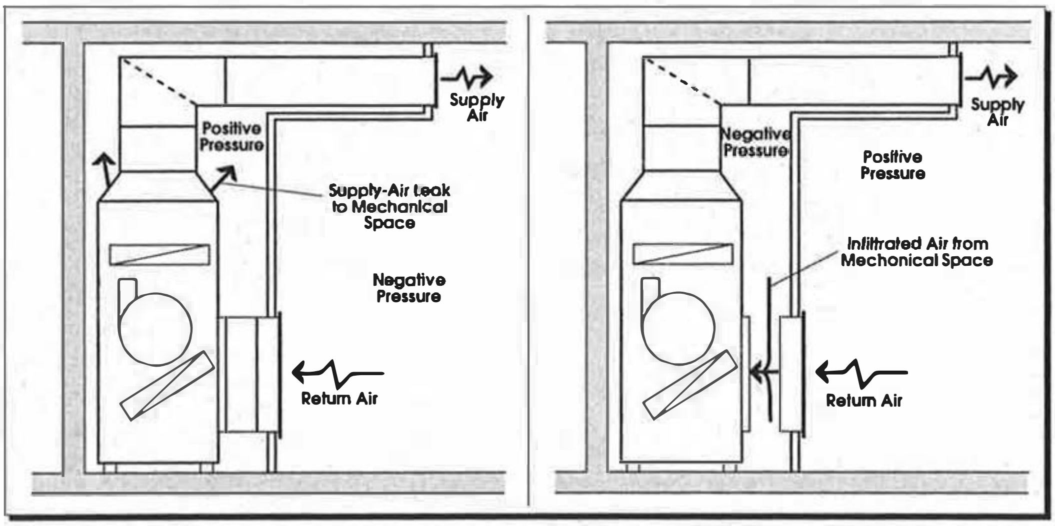

Figure 3-12a. This typical AHU installation with a supply-side leak pressurizes the mechanical space and depressurizes the room because more air is returned than supplied.

Figure 3-12b. In this scenario, the return-side leak depressurizes the mechanical space and attached wall and ceiling cavities and pressurizes the room because less air is returned than supplied.

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In a multiroom layout, the effects of the overall air distribution layout on the pressurization of the spaces are similar to the effects of supply/return ductwork but are more global. Each room should have a balanced or slightly positive supply and return air distribution system to avoid depressurization. For example, in an AHU system that supplies air to multiple rooms, a single, improperly located return air grille can cause some areas of the building to depressurize while other areas are pressurized (Figure 3-13). Connecting doors and wall partitions will isolate the supply and return balances, causing one to have a greater return balance than the other. As shown, the effects of the closed door can be largely counteracted by adding a low-pressure drop transfer grille between rooms or by providing an additional return air duct grille in each room.

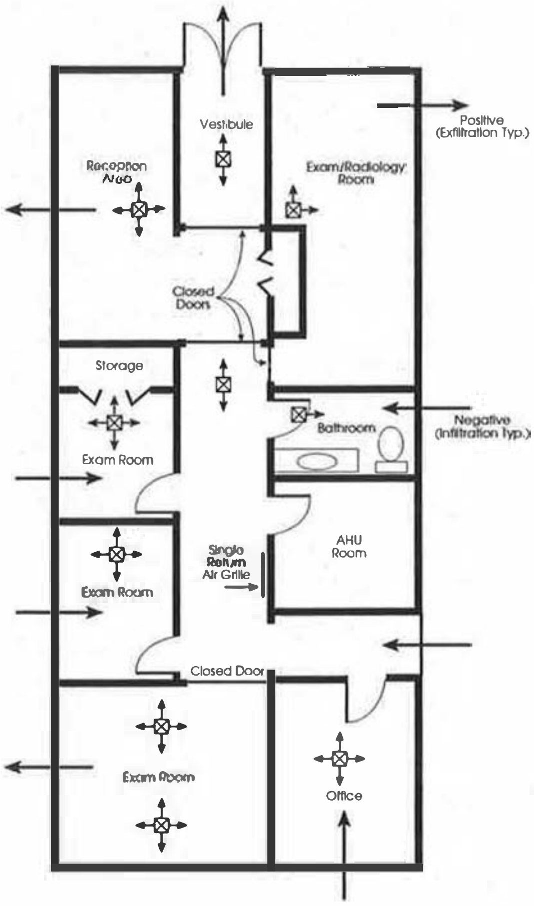

Figure 3-13. In this health clinic design, the single retum air grille causes depressurization of a large portion of the building because interior walls and doors restrict air flow back to the AHU.

PTWUs. PTWUs (for example, PTACs and unit ventilators) are typically installed in the exterior wall. They do not exhibit the typical supply and return duct leakage problems seen in many closet-installed AHU or FCU designs because the entire recirculation and outside air distribution system is on the interior of the unit casing and no external ductwork is used. A disadvantage of many PTWUs is that many filter only the return air. Consequently, as the filter becomes dirty and air pressure resistance through the filter increases, more unfiltered outside air is drawn into the unit. Because the PTWU may not be able to dehumidify the outside air to appropriate levels, the humidity of the room may increase. The PTWU unit selected should be designed so that the outside air stream and the recirculation air stream experience the same pressure, or a separate source of conditioned makeup air should be provided, with the outside air vent sealed.

The slinger style drain is a popular in PTAC units. This style does not fully drain the condensate from the unit but slings it back onto the condenser coil in an attempt to evaporate it to the atmosphere. Moisture may be returned to the air stream through leakage, and thus enters the room. To avoid increasing moisture loads to the room, the condensate drain system for PTAC units should be a full drainage system to an external source.

System Selection

The system design should focus on how the supply/return air systems can prevent negative building pressurization on an overall building basis, as well as for localized systems. In many cases, the total amount of outdoor makeup air can exceed the total exhaust air, and the building will still experience localized depressurization.

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As mentioned in Section 2, using relief fans is preferable to using return fans (Figure 3-14). The relief air fan should be controlled through increasing building static pressure, including VAV control through either fan inlet vanes, variable-speed drives, or multiple smaller fans. Using a relief fan may allow a ducted return air system on a VAV air distribution arrangement, without inducing depressurization of the ceiling plenum or building envelope.

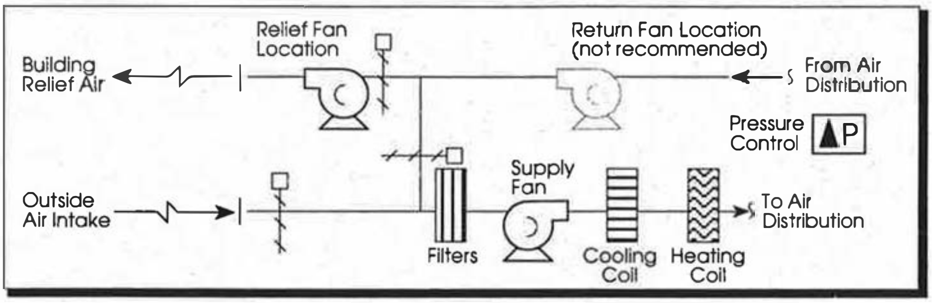

Figure 3-14. Using relief fans helps ensure a more positive building pressure.

If the design team decides that a return fan arrangement is necessary, a return fan tracking system, using air flow measuring stations and static pressure monitoring, will be required. Unfortunately, even when return fan systems are properly designed, they are not fail-safe. Failure will usually create building depressurization that may go unnoticed for a considerable time, allowing irreversible damage to the building envelope.

Another design consideration is the use of a blow-through air handler versus a draw-through arrangement (Figure 3-15). The blow-through type is preferred for two reasons: the drain pan condensate removal is enhanced by the fan pressure, and the discharge air temperature from the cooling coil does not require subcooling to account for fan-generated heat. These factors reduce the potential for poor condensate removal and high discharge air temperatures, resulting in less moisture carryover. A side benefit of the lower discharge air temperatures is reduced energy requirements for the water chiller or cooling system.

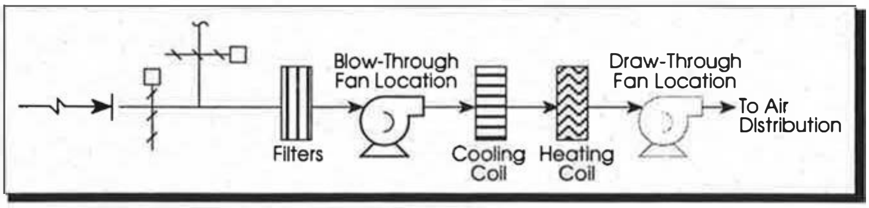

Figure 3-15. Using a blow-through fan arrangement helps ensure positive condensate drainage and requires less energy use in the cooling system, through higher refrigerant suction pressures or higher chilled water temperature requirements.

Recommended air handler fan locations are shown in Figures 3-14 and 3-15. Cooling coil and moisture condensate drain pans should be specified to be corrosion-resistant and sloped for proper drainage to a bottom outlet. (A moisture eliminator may be added downstream of a cooling coil to ensure moisture removal without carryover into the supply air.) Many manufacturers are aware of these issues and have

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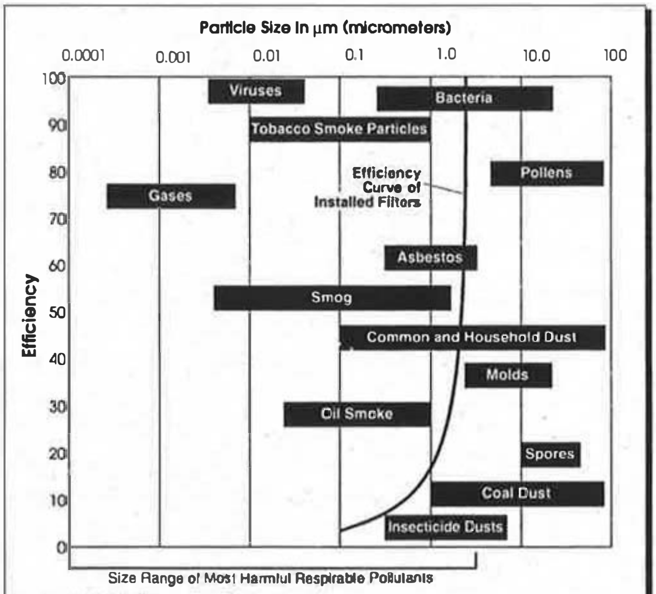
opted to provide a bottom drain outlet instead of the traditional side outlets. This allows better drainage of coil condensate without residual standing water.

Often the use of a fully ducted supply and return VAV system is used. The use of fully ducted returns are typically selected for the reduced cost in above ceiling fire/smoke considerations as compared to a return ceiling plenum system. This system, however, can depressurize large areas of a building while other areas remain positively pressurized. For example, a hospital in North Mississippi chose to use a VAV system with fully ducted return distribution system. The VAV system served the hospital auxiliary areas such as administration, recovery areas, and birthing operating rooms. As in every VAV system, once the room temperatures were satisfied, each individual VAV box closed to its minimum set point. In the areas closest to the AHU, the return grill was still demanding full return air flows, thereby depressurizing each room.

Filtration

Filters in HVAC systems can be designed to remove solids such as bioaerosols (microbial organisms) and fiberglass particulates as well as pollutants in gaseous forms. Impingement filters (made of woven fabric) remove solids of different sizes; absorber filters (including activated carbon) remove different kinds of gases or vapors. Impingement filters are rated according to how effectively they remove solids; any one filter will remove varying sizes of solids with different efficiencies (Figure 3-16).



Source: Adapted from Osmonics, Inc.

Figure 3-16. Many filters installed in HVAC systems are only 25 to 30 percent efficient, which is not adequate to handle large amounts of outdoor air contaminants.

Many filters selected for HVAC systems are rated at a nominal 20 to 25 percent efficiency in accordance with ASHRAE Standard 52-76, Dust Spot Efficiency, and are typically adequate for 80 percent removal of 3-micrometer (µm) particles, 20 percent removal of 1-µm particles, and less than 5 percent removal of 3-µm particles. Filters for the removal of gases or vapors are not installed. Current industry trends and ASHRAE recommend using 65 to 85 percent dust spot efficiency filters for removing solids. Absorption filters are not necessary if the outdoor air does not contain excessive levels of gases or vapors, or if buildings are not expected to generate gas or vapor pollutants internally.

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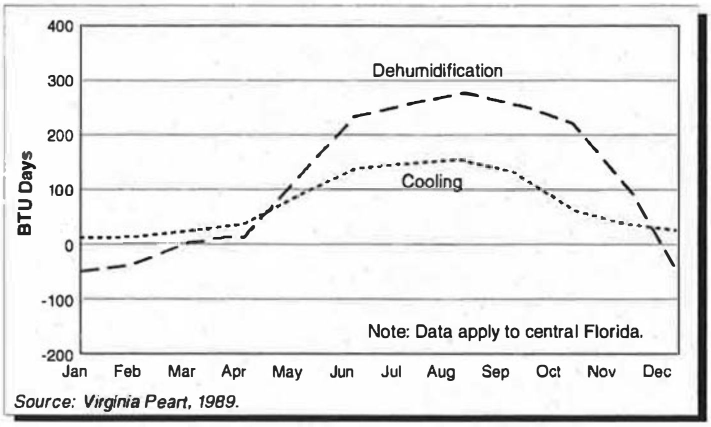

Figure 3-17. Dehumidification and cooling requirements of outside air vary by season and, during the summer, can exceed HVAC system capabilities.

Controls

Controls for Unit Run Time and Dehumidification

AC units are typically sized according to the peak design cooling load. The cooling load is often standardized for a number of areas and sensed by a room thermostat, which regulates AC unit run time based on temperature, not RH. Run time is a critical variable in the ability of the unit to dehumidify the space. If the unit is sized properly to match the room sensible load and to maximize unit run time, the room will be dehumidified adequately. If the unit is improperly sized, however, when the room sensible load falls below the peak design load, the AC unit will run for a shorter period and could fail to dehumidify the room properly (Figure 3-17).

If the AC units are controlled strictly by room temperature without monitoring the RH of the room, the operating time of the cooling system should be estimated to determine if adequate dehumidification will occur. Cooling requirements vary considerably from location to location within a building. When the load calculations for the occupied spaces are completed, the moisture load factors discussed early in this section must be included in the equipment sizing and all latent loads must be considered. AC units are usually sized according to the highest possible sensible load because buildings are usually well insulated. When the rooms are only slightly loaded, the air-conditioning units tend to run for short periods and fail to maintain adequate space moisture conditions. Therefore, estimated run times should be analyzed to determine anticipated latent heat removal under average monthly (or annual) conditions.

Run times can be established using weather data (bins) from AFM 88-29 (USAF, 1988) or hourly weather data from other sources such as the National Climatic Data Center (NCDC) or the National Oceanic and Atmospheric Administration (NOAA). The variation in loads must be calculated according to each exposure and level in the structure. The AC units should be sized for adequate cooling capacity, but the design team must avoid the tendency to oversize. Cooling coil capacity must consider the latent load, which can be significant in humid climates and can require more heat transfer surfaces than might be expected. This analysis ensures that the unit selected best matches the loads it must handle.

Controls for Ventilation

Another key element in temperature control strategies is to ensure that all fresh air from outdoors is properly conditioned before being supplied to the occupied space. For example, a retail store in Northern Florida was conditioned primarily through a single 25-ton split system. The control sequence required that the AHU fan operate continuously

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while conditioning was cycled on and off by a single space thermostat. Space humidity was found to vary wildly because the system was able to meet space temperature settings quickly, yet never met appropriate humidity levels during the summer.

As discussed in Section 2, the easiest method for accomplishing proper control of the supply air is to maintain a constant discharge air temperature of approximately 55°F and to use a reheat coil to maintain space temperature. This will create space conditions within the comfort range acceptable to most occupants and will maintain an acceptable RH level. The difficulty in this approach lies in the ability of the technique to meet energy code requirements. Some cases may require other approaches, such as hot gas bypass reheat or heat pipes.

Another approach to controlling space conditions properly is supplying pre-conditioned outdoor air to the AHUs. This has the effect of requiring the air handlers provide sensible cooling only, unless considerable internal moisture is present. If that is the case, the space RH must be monitored to ensure that humidity levels are acceptable and that dehumidification is provided when RH levels are too high.

HVAC System Components and How They Contribute to IAQ Problems

Each HVAC system is generally made up of two major parts: the AHU and the distribution system. The various individual components included in these parts can each influence IAQ problems, particularly moisture-related IAQ problems. These different parts of an HVAC system can affect IAQ problems:

- Outdoor air intake
- Mixing plenum and dampers
- Filters
- Cooling and heating coils
- Distribution system

Outdoor Air Intake

Outdoor air intakes can become obstructed, thereby reducing outdoor air flow. The reduced outdoor air flow affects not only the ventilation rates of a building but also the critical pressurization control of a building. While operators have a great degree of influence over the outdoor air intake cleanliness and operation of dampers, some problems can be eliminated if insect screens are not used. Bird screens with the larger mesh size are preferable to the small mesh of an insect screen. If insect control is necessary, the filters should be relied upon for this task.

Mixing Plenum

Many mixing plenums include combination dampers to regulate outside and return air quantities. Building pressurization can be affected if these dampers do not operate properly.

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Design of the damper system often considers only that positive pressurization is achieved at maximum air flow conditions. The designer should always analyze pressurization at minimum air flow conditions to verify that the return and outdoor pressure drops will still result in sufficient outdoor air flows to maintain ventilation and positive building pressurization. The mixing box construction should also avoid using insulation liners to provide a surface less likely to encourage microbial growth. Lastly, because hot, humid climates are typically geographic areas with considerable rainfall, these plenums should have drains to remove rain water carryover that might occur. This reduces the chance of having a microbial growth site in the ductwork.

Filters

The design of the filter system should consider that filters must be installed tightly in the frame to avoid air bypass leakage. The previous discussion in this section and in Section 2 addresses more specifically the design criteria for sizing and filter media selection.

Cooling and Heating Coils

Cooling coil design is very important in hot, humid climates not only for overall performance capacity but also for air velocities across the coil. Moisture carryover can be important for cooling coils. Many designers require air flow velocities as low as 425 fpm for cooling coils with air streams up to 20 percent outdoor air. Cooling coils in 100 percent outdoor air streams may require velocities as low as 200 fpm to avoid carryover of moisture and achieve appropriate dehumidification.

Each cooling coil will have a condensate pan; better drainage is achieved with a center and bottom outlet. As with drain pan design in all climates, the drain trap must be designed with sufficient depth to overcome system pressures, including negative system pressures of a drawthrough fan arrangement.

Ductwork Distribution

The return air system can often be the source of difficult IAQ problems. Systems that use the ceiling plenum as a common return can be hard to balance (that is, provide the required amounts of supply and return air flow). Because the ceiling plenum is negatively pressurized, nonconditioned air from the outside can be drawn through openings in the building envelope, adding extra moisture to the building. That extra moisture can raise the inside RH, making occupants uncomfortable, and also create conditions conductive to mold and mildew growth. Additionally, as discussed earlier, even small amounts of supply or return air ductwork leakage can affect pressurization in localized areas of a building or even buildingwide. Return air ceiling systems in particular must have low pressure drops to avoid many of the pressurization problems they can cause.

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Wall Dewpoint Analysis

Each major exterior wall system used in construction should be analyzed to determine all of the following:

- Where dewpoint will occur
- What the temperature profile will be
- Where the primary vapor retarder will be located
- How far moisture will be allowed to penetrate (vapor pressure profile)

These concepts are discussed in the *ASHRAE Handbook: Fundamentals* (Chapters 20, 21, and 22; ASHRAE, 1993). Completing a version of the *ASHRAE* Handbook's Figure 10 (Page 20.15) for each major wall type will facilitate wall dewpoint analysis.

The procedure for calculating water vapor diffusion involves analyzing each wall system component, including thickness, permeance to vapor transmission, and thermal resistance (R-value). The first step is to determine what indoor/outdoor temperatures should be used to identify wall surface dewpoint. The lowest possible indoor wall surface temperature can often be much lower than the indoor design conditions. For example, the surface temperature of a wall that receives discharge from the room AC unit supply register can be as low as 60°Fdb. Likewise, exterior surface temperature can exceed outdoor design conditions, especially on nonreflective dark exterior surfaces.

A temperature profile can then be developed for each wall system (Figure 3-18a). In a properly designed system, the dewpoint temperature of outside air conditions will occur in the insulation as long as there are no thermal bridges (such as metal studs). It is important to compare the location of the dewpoint with the proposed location of the vapor retarder to determine if the barrier will remain above the dewpoint of outside air conditions.

The next objective in the dewpoint analysis is to verify which wall component functions as a primary vapor retarder and then compare its location to the location of surface condensation (dewpoint surface). To determine the primary vapor retarder location in the wall system, the saturation vapor pressures at each wall component surface interface must be determined and compared to the vapor pressure resistances of the component.

The location within the wall system where diffused moisture vapor will condense will be the point where the vapor pressure equals the saturation pressure. To develop a vapor pressure profile through the wall system, the vapor pressure drop across each wall component (Figure 3-18b) must be determined. The procedure for developing a vapor pressure profile is similar to that for developing a temperature profile through the wall system; software is now available to help develop this analysis.

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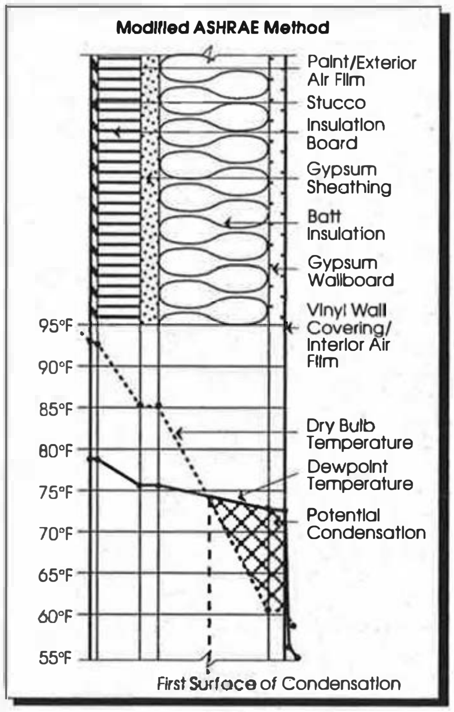

Figure 3-18a. Determining the temperature profile of the exterior wall system identifies the surfaces where condensation will occur.

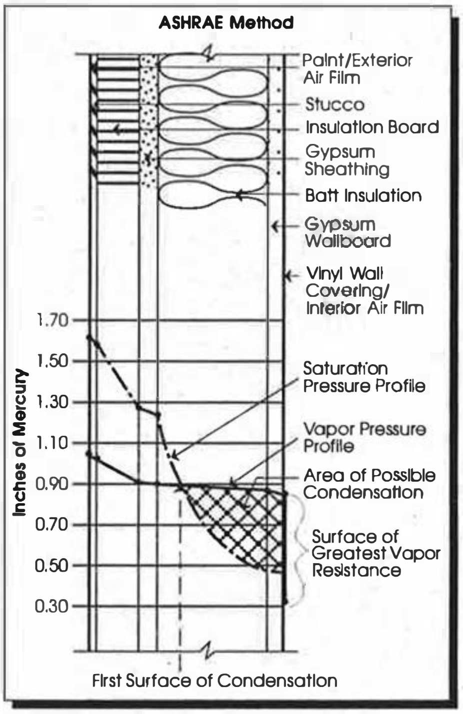

Figure 3-18b. Determining the saturation and vapor pressure profiles of the exterior wall system is also necessary for maximum moisture control because this helps identify wall components that may trap moisture.

Specifications Development

At this point in the design process, many of the architectural and mechanical specification sections for the contract documents are developed. The following sections are of particular concern in controlling moisture and mildew problems:

- Division 7
  - ⇒ Building insulation
  - ⇒ Air barrier
  - ⇒ Vapor retarder
- Division 9
  - ⇒ Gypsum wallboard
  - ⇒ Air barrier
  - ⇒ Gypsum wallboard (or plywood) sheathing
- Division 15
  - ⇒ Equipment selection
  - ⇒ Controls
  - ⇒ Testing and balancing
  - ⇒ HVAC system commissioning

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If the specification sections are prepared in the standard Construction Standards Institute (CSI) format, each section will typically include the following parts:

- Part 1: General
- Part 2: Products
- Part 3: Execution
- Part 4: Payment

The Execution portion of the individual specification section is critical because field installation mistakes make moisture- and mildew-related problems more likely to occur during construction.

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Section 4
Final Design

Section Highlights

- *The final design phase has two objectives:*
  - *To revise the draft design and specifications according to recommendations made during earlier design phases*
  - *To verify the design and specifications to ensure compliance with the design intent*
- *Moisture control issues and their proposed remedies should be carefully documented throughout the design.*
- *A final peer review by an independent party of the critical issues should be performed at this phase.*

The final design phase has two objectives: to revise and complete the draft design and specifications according to recommendations made during earlier design phases and to verify that the design and specifications comply with the design intent (Figure 4-1). Addressing moisture control issues while these tasks are being completed will further protect against mildew forming later during construction and operation.

Figure 4-1. These are the two moisture control objectives of the final design phase.

Moisture control issues and their proposed remedies should be carefully documented throughout the design process to help achieve the desired quality in the completed project. At a minimum, for each project element, the system designer should prepare and submit to the design team the information described below to document the decisions made throughout the design process. The documents should be reviewed by the entire design team. In particular, they should be reviewed by a person knowledgeable about both mechanical and architectural systems in humid climates. Any review comments should be addressed at the end of each design review and their disposition noted for future reference. Changes in the design should be incorporated into the appropriate documents for use in the next phase of the project. The moisture control items that should be prepared and evaluated during each design phase are described in the remainder of this section.

Schematic Design Phase Documentation

During the schematic design phase, the architect typically prepares the following items. They should be reviewed from the perspective of avoiding future mildew problems:

- Preliminary design for the wall system
- Initial specifications for interior and exterior finishes
- Building layout considerations

Few system modifications are normally prepared by the mechanical engineer during this phase. Therefore, few of the critical conceptual decisions made affect mechanical systems. The designer, however, should define and submit the following information for review:

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- Final revisions of design criteria for all spaces
- Final revisions of dewpoint calculations and moisture migration profiles for all wall systems
- Final revisions of mechanical system equipment and concepts

Design Development Phase Documentation

The mechanical systems are usually selected during this phase and architectural wall systems are finalized. The following information relating to design development of these mechanical and architectural systems should be submitted for review during final design:

- Revised design criteria (if any) for HVAC system sizing and equipment selection
- Revised wall moisture migration and dewpoint calculations under maximum heating and cooling conditions
- Room load calculations for various room locations (first floor, top floor, corner, interior), including sensible and latent load requirements
- Public area load calculations, including sensible and especially latent requirements
- Complete descriptions of guest room systems, including heating, cooling, dehumidification, ventilation, makeup air, and controls
- Complete descriptions of public area systems, including heating, cooling, dehumidification, filtration, ventilation, building pressurization, and controls
- Preliminary layouts of proposed systems identifying major components, schematic duct layouts, and control element locations
- Outlines of proposed specifications for major equipment, including heating, cooling, dehumidification, ventilation, and controls

Final Design Phase

During final design, the documents that form the basis of the construction contract are prepared. They must be complete and must include all details necessary to define the contractual requirements, including startup and commissioning of the systems. The following information should be reviewed before the construction documents are issued:

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- Revised design criteria, if any
- Revised wall, roof, and ceiling moisture migration and dewpoint calculations, if changes were made
- Revised room load calculations for various room locations (first floor, top floor, corner, interior), including dehumidification requirements, if changes were made
- Revised public area load calculations, including dehumidification requirements, if changes were made
- Descriptions of any changes to room systems, including heating, cooling, dehumidification, ventilation, makeup air, and controls
- Descriptions of any changes to public area systems, including heating, cooling, dehumidification, ventilation, building pressurization, and controls
- Complete working drawings of all architectural and mechanical systems
- Complete specifications of all architectural and mechanical systems
- Installation and testing requirements of interior wall finish systems
- Start-up sequencing of all HVAC systems to eliminate infiltration of nonconditioned outside air
- Complete testing requirements for all HVAC systems, including documentation requirements
- Final commissioning requirements for project acceptance and closeout

Peer Review

Peer reviewers provide independent design reviews and technical guidance to promote technically sound, budget-conscious designs. By providing such services, these advisors can help ensure a high level of design quality. Use of a peer review checklist such as that provided in Table 4-1 is highly recommended.

Value Engineering

A value engineering analysis is intended to evaluate alternative, more cost-effective methods of obtaining the same results. In evaluating an alternative suggested by a value engineering team, the design team, together with the owner, must make an informed technical decision as well as a sound business decision based on cost and risk. The design team is responsible for assessing any risks associated with accepting an alternative suggested by value engineering, including the potential for future moisture accumulation and mildew formation.

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TABLE 4-1
Using a design document peer review checklist such as this is highly recommended.

General Documentation

- ❑ Basis of design
- ❑ Heating/cooling load calculations
- ❑ Vapor transmission calculations

Specification Review

Division 1: General Requirements

- ❑ Temporary heating/cooling dehumidification
- ❑ Construction schedules
- ❑ Startup and testing of systems

Division 7: Thermal and Moisture Protection

- ❑ Building insulation
- ❑ Exterior insulation and finish systems (EIFS)
- ❑ Vapor retarders

Division 9: Finishes

- ■ Gypsum wallboard systems
  - ❑ In situ testing specified
  - ❑ Mildewcide specified
  - ❑ Environmental conditions specified
- ■ Wall and ceiling coating
  - ❑ Material type
  - ❑ Mold/mildew supported
  - ❑ Permeability specified
- ■ Wall coverings
  - ❑ Material type
  - ❑ Mold/mildew supported
  - ❑ Permeability specified

Division 15: Mechanical

General Mechanical Requirements

- ■ Mechanical insulation
  - ❑ Internal/external duct insulation
  - ❑ Cold piping insulation, nonhygroscopic
  - ❑ Pipe shield to avoid insulation compression
  - ❑ Continuous vapor barriers
- ■ AC equipment
  - ❑ Internal insulation specified
  - ❑ Condensate drain pans sloped with bottom outlets
  - ❑ Low-permeability finishes

Mechanical

- ■ Air distribution plans
  - ❑ Ductwork types
  - ❑ Volume control

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TABLE 4-1 (CONTINUED)
Using a design document peer review checklist such as this is highly recommended.

- ❑ Pressure class
- ❑ Sealing requirements
- ❑ Relief air path

- ■ Return/exhaust air systems
  - ❑ Duct type
  - ❑ Pressure class
  - ❑ Sealing
  - ❑ Ducted variable air volume (VAV) return system
- ■ Outside air supply systems
  - ❑ Location of intakes
  - ❑ Ventilation air quality
  - ❑ Control of ventilation air quantity
- ■ Air-handling equipment
  - ❑ Type
  - ❑ Location for access/maintenance
  - ❑ Condensate drainage
  - ❑ Filtration type
- ■ Cooling equipment
  - ❑ Type
  - ❑ Location for access/maintenance
  - ❑ Control requirements
- ■ Piping system
  - ❑ Hot piping/insulation requirements
  - ❑ Cold piping/insulation requirements
  - ❑ Plumbing requirements
- ■ Control diagrams
  - ❑ Return/exhaust fan control
  - ❑ Supply air temperature control
  - ❑ Building pressurization control
  - ❑ Humidity control
  - ❑ Chilled water temperature control
  - ❑ Ventilation air quantity control
- ■ Equipment schedules
  - ❑ AC equipment includes outdoor air requirements
  - ❑ Reasonable exhaust fan static pressure requirements
  - ❑ Air terminal units minimum air quantity too low
  - ❑ Mold/mildew supported by filtration media
- ■ Ductwork
  - ❑ Duct types
  - ❑ Pressure clarifications

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TABLE 4-1 (CONTINUED)
Using a design document peer review checklist such as this is highly recommended.

- ❑ Joint materials
- ❑ Seal class
- ❑ Leakage tests

- ■ Control systems
  - ❑ Type of controls
  - ❑ Startup/training specified
- ■ Sequence of operation
  - ❑ Air-handling equipment
  - ❑ Exhaust/return air equipment
  - ❑ Makeup air interlocked
- ■ Air and water systems, testing, adjusting, and balancing
  - ❑ Independent test agency
  - ❑ Test sequence correct
  - ❑ Leakage tests of systems
  - ❑ Water balance required
  - ❑ Thermal balance required
- ■ HVAC system commissioning
  - ❑ Startup sequences
  - ❑ Pressurization testing
  - ❑ Confirmation of basis of design

Architectural Drawing Review

- ■ Floor plans
  - ❑ Exterior zones
  - ❑ Ceiling plenums
  - ❑ Nonconditioned areas
  - ❑ Mechanical equipment spaces
- ■ Building sections
  - ❑ Exterior zones
  - ❑ Wall/ceiling/floor interfaces
  - ❑ Soffits
  - ❑ Conditioned/nonconditioned areas
- ■ Wall sections
  - ❑ Components shown
  - ❑ Vapor retarders shown
  - ❑ Cavity walls
  - ❑ Floor/ceiling interfaces
- ■ Room finish schedule
  - ❑ Vinyl wall coverings

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Section 5
Construction

Section Highlights

- ✓ *During construction, issues related to moisture control in the following areas are addressed:*
  - *Construction materials*
  - *Construction sequencing*
  - *Field changes*
  - *Inspection*
- ✓ *A testing and monitoring program should be conducted.*
- ✓ *Proper construction sequencing can minimize moisture problems.*

During the construction phase, issues related to moisture control in construction materials, construction sequencing, field changes, and inspection are addressed. Proper sequencing of construction and monitoring and control of construction-related moisture (Figure 5-1) can significantly contribute to the prevention of moisture and mildew in new buildings.

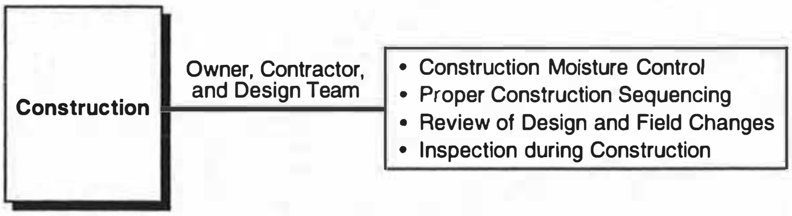

Figure 5-1. These moisture control considerations should be addressed during construction.

Moisture and mildew problems associated with construction moisture differ considerably from those resulting from a depressurized building envelope and/or improper wall system design. The patterns of mildew formed as the result of construction moisture will be more random and will correlate more closely with exterior building features such as flashing and windows. Reducing the potential for moisture- and mildew-related problems during construction generally requires a thorough understanding of moisture-related construction problems, proper attention to construction sequencing, effective temporary control of space conditions, and diligent testing and monitoring to identify problems before extensive damage has occurred. Typically, the most serious weather-related construction moisture problems result when the final stages of construction are completed in the summer or early fall. Because ambient humidity levels are higher during these times, materials are less likely to dry naturally.

Significant moisture and mildew problems in new construction are often attributed to the so-called "drying out of the building." In reality, however, such problems are rarely associated with moisture being released from the new construction materials: in general, the moisture is introduced from some external source.

Construction-Related Moisture Control

Moisture control during construction can be easily minimized if the construction contractor is aware of, and sensitive to, the weather conditions in hot, humid climates. Moisture problems evident in the wall system during construction and installation are typically limited to building system and plumbing leaks and weather conditions, particularly rainfall. Although the construction of a building, especially

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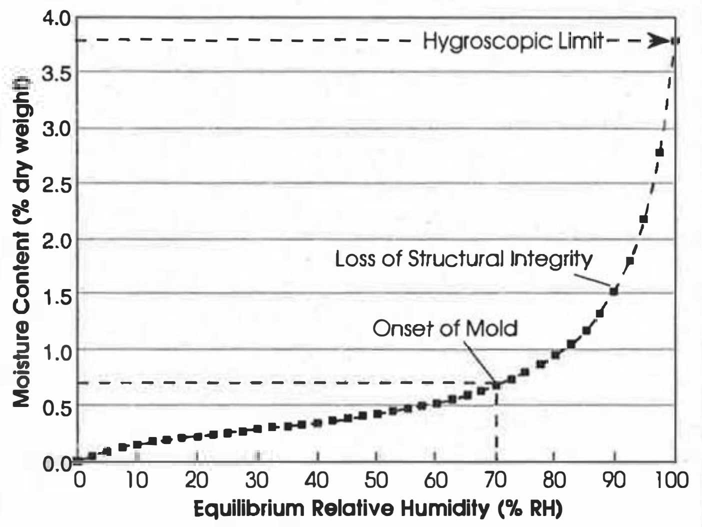
a large building, is a complicated endeavor, some simple, common-sense methods can be used to control the effects of construction-related moisture.

Building system leaks may be evident when the mechanical systems are initially tested and operated. Proper hydrostatic testing of the piping systems should eliminate most of the potential piping leaks. The primary moisture control concern during construction is the repair of any damage to the building envelope or wall systems that resulted from leaks or inclement weather. This is especially pertinent to systems with an impermeable interior finish. Moisture damage from leaks or rain is most often manifested as saturated gypsum wallboard near plumbing, AC equipment, fire sprinkler pipes, and roof leaks.

Diagnosing Moisture Problems During Construction

The contract design documents should include a testing and monitoring program developed by the design team and adhered to by the construction contractor. Tests of the building substrates (for example, gypsum board) performed before the interior finish is applied will consist primarily of *in situ* moisture level measurements. The contract design documents should include the unacceptable moisture level threshold (Figure 5-2).



Source: D.M. Burch, NISTIR, 1991.

Figure 5-2. Contract design documents should include moisture level thresholds for wall system materials, such as this example of the moisture storage capacity of interior gypsum wallboard.

The work involved in conducting a monitoring program is not extensive and can be accomplished in two parts: monitoring the wall systems before the interior finish is applied and monitoring after the finish is applied. In most cases, the first monitoring phase can be a simple, visual walk-through inspection of the building. Visible mildew growth,

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stained wallboard, standing water, or roof leaks offer good indications of the extent of damaged areas. Substrate moisture testing measurements should still be taken in both damaged and undamaged areas to document the conditions.

After the interior finish has been applied to the wall system, documentation and monitoring should be more intensive, especially if the interior finish is impermeable. Because an impermeable finish will trap moisture in the wall system and not allow it to dry, damage is usually not apparent until mildew odors or stains appear.

Substrate testing and monitoring typically involves placing a small conductivity probe meter on the gypsum wallboard or sheathing and measuring the moisture level of the material. A Delmhorst Instruments Model BD-8 meter is often used. The contract documents should require the construction contractor to purchase, use, and maintain this testing apparatus throughout construction.

A typical monitoring program for measuring substrate moisture could involve at least 15 percent of the total rooms as well as any areas where water intrusion has occurred. A typical program could use this methodology:

- Take readings at all walls within a room, including the exterior wall and all interior partition walls.
- Take readings at staggered heights, such as one-third, one-half, and two-thirds of the distance up the wall.

If a reading exceeds the specified threshold, the extent of the damaged areas should be delineated by taking additional readings on each side of the affected area and above and below it until readings below the threshold are obtained. This will allow an outline of the damaged area to be mapped out quickly for repair. If the damaged wall system consists of an insulated cavity, the insulation should be replaced and the opposite side of the wall should be tested to determine if it is damaged.

Identifying patterns and trends of elevated moisture levels in the building envelope and/or the interior surfaces can be an important diagnostic tool. The wet areas of a wall system can provide strong indications of the moisture source. Moisture damage results from four separate sources:

- Intrusion of weather-induced moisture
- Infiltration of outside moisture-laden air
- Moisture contributed by vapor diffusion
- Moisture that is internally generated by human or operational activities

Moisture problems created by outside air infiltration and vapor diffusion should be negligible during construction. Generally, moisture problems other than rainwater leaks are not introduced until the building's AC system begins operating.

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Construction-Induced Moisture (Weather and Building System Leaks)

Damage from weather-related moisture intrusion (Figure 5-3) is typically restricted to the exterior envelope and the upper floor of a building. For obvious reasons, water penetration as a result of rain will most severely affect the exterior envelope of a building, with water concentrating around window and door frames, roof line and construction joints, and the base of exterior wall systems.

Construction-Related Moisture

- **Sources**
  - Roof and wall leaks
  - Plumbing leaks
  - Wet materials
- **Distinguishing Characteristics**
  - Random pattern
  - Not seasonal
  - Rapid decrease of moisture as building dries
  - Occurs more often in exterior wall systems
  - Typical locations
    - Base of walls
    - Around windows
    - Top floors (roofs)
    - Near plumbing systems

Figure 5-3. Damage from weather-related moisture intrusion can occur year-round.

Weather-induced moisture intrusion is not seasonal. Although inclement weather may occur more frequently in some seasons than others, some rainfall occurs throughout the year.

Infiltration-Related Moisture

Infiltration-related moisture problems will not occur unless the building is conditioned and condensation can occur. During hot and humid months, infiltrated outside air can carry a large moisture load. If outside air is drawn into the building envelope by negative pressure inside the building, it will travel through the wall system and into the interior space. Because air flow will always follow the path of least resistance, air can be carried down interior walls if the walls are connected to the exterior envelope. As the air flows through the wall system and moves past the cool interior wallboard, the moisture in the air condenses and is deposited in the wall cavity.

Infiltration Moisture

- **Source**
  - Moisture transported by convected air
- **Distinguishing Characteristics**
  - Similar patterns
  - Follows air flow along paths of least resistance (often along demising walls)
  - Seasonal (summer)
  - Affects outlets (electrical)
  - Associated with greater negative pressures
  - Occurs on conditioned side of thermal insulation within wall

Figure 5-4. Infiltration moisture problems occur most often during hot, humid summer weather.

Because they are a function of the high moisture content of outside humid air and the cooling of the interior space, infiltration moisture problems are seasonal. Moisture in the building envelope increases during the summer and significantly decreases during the winter. The potential for infiltrated moisture to be deposited in the building envelope is directly related to the interior temperature of the building, the moisture content of the outside air, and the amount of outdoor air infiltrating the building wall systems. The distinguishing characteristics of infiltration-related moisture problems are shown in Figure 5-4.

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Moisture from Vapor Diffusion

Moisture problems from vapor diffusion also will not occur unless the building is conditioned. The pattern of moisture damage from vapor diffusion (Figure 5-5) is shown by wetting of the exterior wall system. The vapor diffusion mechanism is a function of the vapor pressure differential across the building envelope. Hot, moist air has a higher vapor pressure than cool, dry air. In an attempt to reach equilibrium, moisture in outside air with high vapor pressure will diffuse through the building envelope in a search for a condition of cooler air and lower (interior) vapor pressure. This mechanism does not apply to partitions between interior spaces, which are conditioned equally on either side and therefore have equal vapor pressures. Although the vapor diffusion mechanism can be associated with significant vapor pressure differentials, most materials have a relatively high resistance to diffusion; therefore, the amount of moisture transported by this means is typically negligible. Additionally, vapor diffusion through a wall system is transient and can reverse the flow direction, even within 24 hours. Vapor diffusion problems are accentuated by very cold walls or building spaces, very permeable exterior surfaces, and very impermeable interior surfaces.

Vapor Diffusion

- **Source**
  - Moisture migration via vapor diffusion
- **Distinguishing Characteristics**
  - Confined to exterior walls
  - More evident in overcooled areas
  - Seasonal (summer)
  - Linked to improper vapor retarder installation

Figure 5-5. Problems resulting from vapor diffusion can be associated with significant vapor pressure differentials.

Internally Generated Moisture

Human activity inside the building can generate moisture (Figure 5-6). This is usually not an issue during construction, since this internally generated moisture is usually within the moisture-removal capacity of the mechanical systems. If the level of internally generated moisture exceeds the dehumidification capacity of the mechanical systems, moisture damage to soft goods such as draperies, bedding, interior wall surfaces, and carpets may result. Internally generated moisture is more likely to cause moisture damage inside a wall system in northern climates than in hot, humid climates.

Internally Generated Moisture

- **Source**
  - Inhabitants and their activities
- **Distinguishing Characteristics**
  - Occurs around moisture sources (baths)
  - Not generally seasonal but may be worst in winter
  - Occurs on room side of wall

Figure 5-6. Mechanical systems are typically able to control internally generated moisture before problems start.

Temporary Controls

During the final stages of construction, when the building envelope is intact and interior finishes are being applied, building materials begin to dry out. Because the mechanical systems are usually not performing

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at optimal levels during this time, it is critical that no additional moisture be added to the building, especially from the outside. In addition, any temporary controls of the building HVAC systems must prevent the building from achieving negative pressurization. Maintaining positive (or, at a minimum, neutral) pressure will help prevent the intrusion of moisture from outside air into the roof or ceiling and wall cavities. A plan for temporary controls may include statements such as the following: .

- The contractor shall energize, operate, and maintain HVAC equipment before the interior finishes are installed. After the building or room is fully weatherized and before interior finishes are applied, the HVAC system shall be operated 24 hours per day for a minimum of 3 days, until a constant temperature of 75°F (plus or minus 2°F) and a constant humidity level of 58 percent RH (plus or minus 2 percent) can be demonstrated to the owner.
- Throughout the installation of finishes and until the owner's final acceptance, the HVAC system will remain in 24-hour operation.
- If mechanical systems are not performing at optimal levels when interior finishes are installed, the HVAC contractor will provide additional temporary dehumidifiers (portable units) and cooling units to meet required conditions. In lieu of temporary dehumidifiers, an increased monitoring program may be acceptable.

Construction Sequencing

Sequencing the construction to preclude any introduction of moisture into the space or wall system would be ideal but is unrealistic. Proper construction sequencing to prevent moisture- and mildew-related problems, however, *is* possible and does not require changing the overall industry standard sequencing of new construction. Environmental conditions that will minimize the effects of moisture damage during construction should be established by the design team and included in the contract design documents. Such conditions include outlining minimum thresholds of acceptance for vapor retarder, gypsum wallboard, and interior finish installation, as well as for mechanical systems functionality.

To safeguard against future moisture- and mildew-related problems, the design team should review this information for certification of compliance with the contract design documents and overall satisfactory performance of the architectural and mechanical building systems.

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Section 6
Post-Construction Startup and System Commissioning

Section Highlights

- ✓ *Commissioning is the culmination of tasks completed during design and construction.*
- ✓ *Commissioning procedures should be performed by an independent team contracted directly by the owner or construction manager.*
- ✓ *Sequencing of startup and commissioning is critical.*

Procedures and Goals

Post-construction startup and system commissioning is the last phase in the construction process. However, commissioning should begin during the design phase, when the building system design team defines the parameters within which the systems are to function. Tasks typically associated with this phase are shown in Figure 6-1.

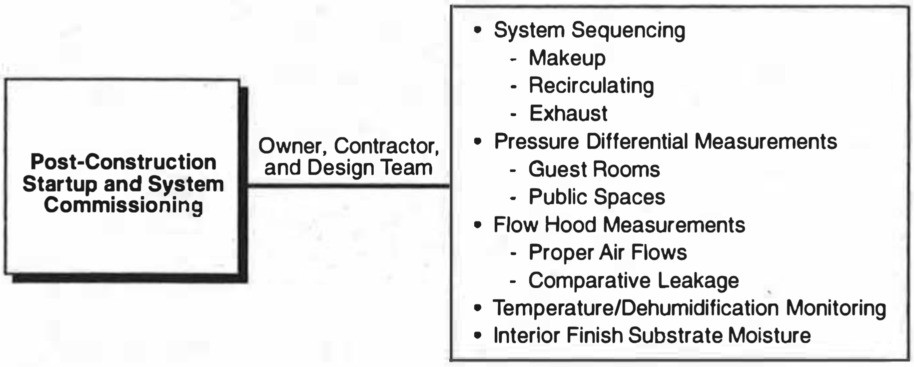

Figure 6-1. These moisture control considerations should be addressed during post-construction startup and system commissioning phases.

A fundamental difference exists between the goals of the test-and-balance process and the building commissioning process: the former evaluates the building systems from a microscale perspective, and the latter evaluates them from a macroscale perspective. In essence, the building commissioning process evaluates the total building's performance and how all the HVAC systems are interacting to achieve the design intent of proper pressurization, dehumidification, and ventilation.

Commissioning the building systems is a critical step in the construction process, particularly when one goal is to prevent moisture and mildew problems. During this process, the preventive measures specified by the design team will be validated. Commissioning procedures are performed independently of the testing and balancing procedures required by the contract design documents and should be performed by an independent team contracted directly to the owner or construction manager. The commissioning procedure should be reviewed by the design team to ensure the following: (1) that the commissioning process will verify the criteria it is intended to verify, (2) that those criteria are within the established design allowances, and (3) that the criteria meet the design team's goals for overall system operation.

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Besides a commissioning plan's typical procedures, the performance goals of the post-construction and system commissioning of a building should include the following:

- To verify that the building is fully pressurized (this includes both occupant space and building cavities)
- To verify that the HVAC system is dehumidifying properly (this includes the proper dehumidification of air across the cooling coil and the proper moisture removal within areas that generate high moisture)
- To verify dry interior finish substrates (this includes interior drywall surfaces)

The sequence of commissioning is critical to avoid problems that may occur even with a properly designed and constructed building. For example, during the final stages of construction, a combination of events may occur that results in depressurization of the building despite the fact that the building will eventually operate as a fully pressurized building.

The Commissioning Plan

In general, a commissioning plan should include strict constraints on the sequence of system operations. It includes the following major categories as well as any appropriate inclusion of key moisture control tasks.

System Startup Sequencing

Controlled startup sequencing (Figure 6-2) is critical to avoid problems. It consists of energizing and commissioning, *in the following order*, all make-up air systems, all recirculating systems (AC systems), and any exhaust systems. The recommended sequence of system startup, although contrary to the normal startup sequence, is critical to avoiding problems.

Step 1. Makeup Air = Pressurization

↓

Step 2. Air-Conditioning = Dehumidification

↓

Step 3. Exhaust = Moisture/Odor Removal

Figure 6-2. A controlled HVAC system startup sequence is critical to avoid moisture problems.

System Dehumidification Capacity

The dehumidification capacity of each system component is ordinarily verified within the context of commissioning. Specifically, the instantaneous performance of the cooling coil must be verified, as well

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as the available moisture removal capacity from the space. This procedure should ensure that the air conditioner is dehumidifying the space sufficiently, instantaneously, and continuously. This is particularly important for components that are controlled solely according to sensible temperature of the space occupant.

Moisture Level of Interior Finish Substrate

The moisture levels of the interior finishes should be continuously verified by the contractor during construction. However, at the conclusion of construction and during the commissioning of the building, an independent verification of the substrate moisture level should be made if any problems (or suspected problems) have occurred. The testing should be verified against the standards recommended by the manufacturer of the substrate.

Several test methods are available for determining the overall ability of the mechanical systems to pressurize the building interior space and envelope, maintain proper dehumidification, and control moisture in material:

- Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (ASTM E779-87; normally used only when problems have occurred and the suspected source is outside air leakage through the building envelope)
- Pressure differential measurements, using micromonometers, between building spaces and between the building and outside
- Ambient condition measurements and monitoring (temperature and RH) at various building locations
- Air flow measurements of mechanical systems
- Moisture measurements in substrates

Commissioning Tests

The remainder of this section provides a general description of available testing and measurement equipment and the philosophy underlying tests designed for application during building systems commissioning. Not all of these tests are necessary for every construction project.

Measuring Building Air Leakage Rates

The air flow test uses a calibrated air flow orifice and fan system to determine the effective air flow leakage area of the room envelope. The room is either pressurized or depressurized by the fan with respect to its surroundings, and the air flow required to maintain a series of pressure gradients is measured. Effective leakage areas are calculated from the results of the measurements.

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The intent of the air flow test is to determine the propensity of the room and its different components to leak air under given pressure gradients (blower door tests) and to identify major air leakage sites. The results of this test can be used to compare the envelope's air barrier characteristics with published standards. This test can also be used to measure ductwork leakage rates, which can result in building depressurization, outside air infiltration, and moisture problems.

Measuring Air Exchange Standards

An inert gas that is not present in the natural environment is generally used to trace the air exchange rate between the room and its surroundings under typical operating conditions. A small quantity of the tracer gas (often sulfur hexafluoride [SF_6]) is injected into the room and allowed to mix with the room air thoroughly. The concentration of this gas is then measured periodically using a gas chromatograph to determine the rate at which its concentration decays in the room air. The air exchange rate is directly proportional to the logarithmic decay of the tracer gas over time. The intent of the air exchange test is to determine the extent to which the room exchanges air with its surroundings under various operating conditions.

Measuring Pressure Differential

Pressure measurements (Figures 6-3a and 6-3b) are taken for two reasons. They are used as a preliminary means of identifying areas where pressure differences might cause envelope leakage or infiltration problems, and they are also used in more detailed studies to identify the degree to which the room's wall cavities are at similar or different pressures with respect to adjacent spaces. That occupant building spaces and adjacent wall cavities have identical pressures is a very common misconception. In fact, measuring the occupant spaces with respect to outside conditions is often assumed to be all that is necessary to evaluate building pressurization. Making this incorrect assumption has caused frequent misdiagnoses of moisture problems in hot, humid climates.

Pressure differential measurements identify the potential for air flow between building spaces. No air will flow across even a large opening unless a pressure gradient (driving force) exists. Conversely, small holes and cracks with relatively large pressure gradients across them can exhibit significant air flows. For example, the pressure gradient between the room and the cavities behind electrical outlets and other features that normally penetrate the room drywall can be measured using a micromonometer.

Measurements should be taken in all areas after the HVAC systems have been tested and balanced. Measurements should be taken at varying system air flows (that is, maximum and minimum air flows of any VAV systems).

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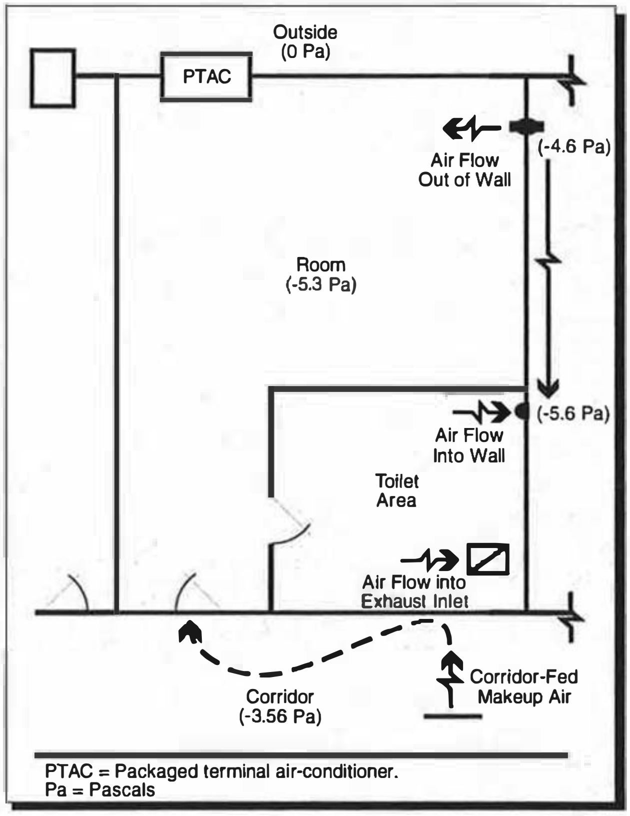
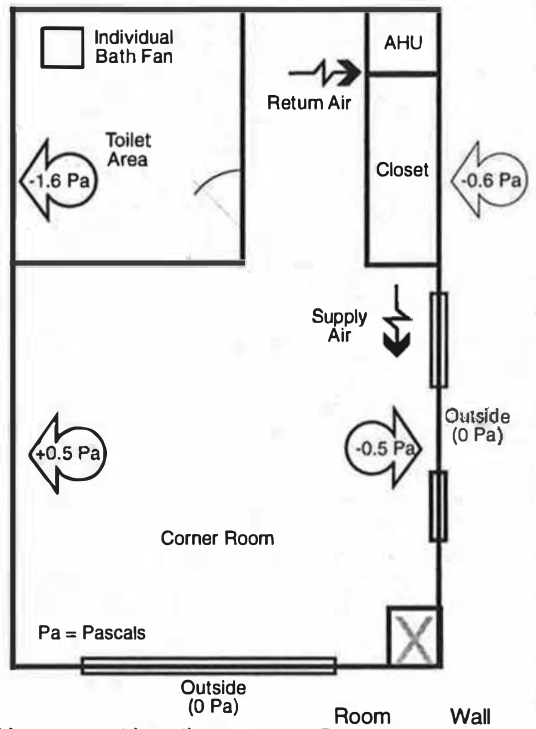


Figure 6-3a. These pressurization measurements show that air was entering the exterior building envelope and traveling down the demising wall. (Measurements were obtained from a building experiencing moisture and mildew problems from outside air infiltrating into the building envelope.)



Measurement Location	FCU	Room Pressure	Wall Pressure
Outlet at Exterior Wall	On	+3.5	-0.5
	Off	+0.5	-0.5
Outlet at Demising Wall	On	+2.5	-0.5
	Off	+1.7	+1.7
Penetration in Closet Wall	On	+4.0	-0.6
	Off	+2.5	+2.5
Vanity Outlet	On	+3.2	-1.6
	Off	+1.8	+1.6

Figure 6-3b. Pressurization commissioning indicated that it is possible to have pressurized rooms and depressurized wall systems, both with respect to outside conditions. (Measurements were obtained from a building in central Florida that was significantly damaged by moisture and mildew.)
As shown here, even small negative pressures with respect to outside conditions can have devastating results in hot, humid climates. This building also had a misplaced vapor retarder on its demising walls, which trapped moisture that intruded via air infiltration.

For example, hotel room measurements should be taken as follows:

- Between the room, the corridor, and the exterior to verify that the corridor has a higher positive pressure than both the room and the exterior, and that the room has a higher positive pressure than the exterior
- Between the room, the demising wall cavities, and the exterior to verify that the room has a higher positive pressure than both the cavities and the exterior, and that the cavities have a higher positive pressure than the exterior

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Measurements in public areas of hotels will differ from those taken in guest rooms. In public areas, HVAC systems are more dynamic and will vary air flows more than in guest rooms. Measurements in the public areas should be taken as follows:

- Between the space and the exterior to verify that the space is positive to the exterior
- Between the space, the above-ceiling cavity, and the exterior to verify that the space is positive to both the cavity and the exterior, and that the cavity is positive to the exterior
- Between the space, the interior wall cavities, and the exterior to verify that the space is positive to both the cavity and the exterior, and that the cavity is positive to the exterior

Measuring Ambient Building Conditions

These consist of both dry bulb and wet bulb measurements. From these, RH and dewpoint can be readily calculated. In seeking to prevent moisture control problems, dewpoint is usually the more important factor. Even if the air temperature and RH change, the dewpoint is an absolute measure of the moisture content of the air and thus tends to remain more constant. This concept is important because pressure-induced air flows in cavities often travel long distances directly behind interior surfaces before entering the room. Under these conditions, the dry bulb temperature of the pressure-induced air is likely to be near the room temperature. On the other hand, unless significant condensation of absorbed moisture occurs along the air flow pathway, the dewpoint temperature of the air is likely to remain close to its original condition.

When the moisture content of the room air and outside air are sufficiently different but outside dewpoints are lower than interior temperatures, dewpoint measurements can be used like tracer gases to locate leaks in buildings. The pressure gradients between building interiors and the outside are often caused by the AHU. If pressure-induced leakage from the outside of the building into the air handling unit enclosure exists, dewpoint measurements taken inside the return plenum to the AHU can differ significantly from the room's dewpoint temperature.

AC run time measurements should be taken to estimate the effectiveness of dehumidification of the interior spaces. This is particularly important for any areas with HVAC systems controlled through temperature only, such as guest rooms in hotels. The measurements should be taken over time to ensure that the interior conditions are kept at designed dry bulb and wet bulb temperatures. Both private and public spaces should be evaluated.

Measuring with Flow Hoods

Flow hoods (Figure 6-4) indicate the volumetric air flow into or out of mechanical systems by measuring the average pressure gradient across the cross section of a known flow orifice. Flow hoods are most often used by

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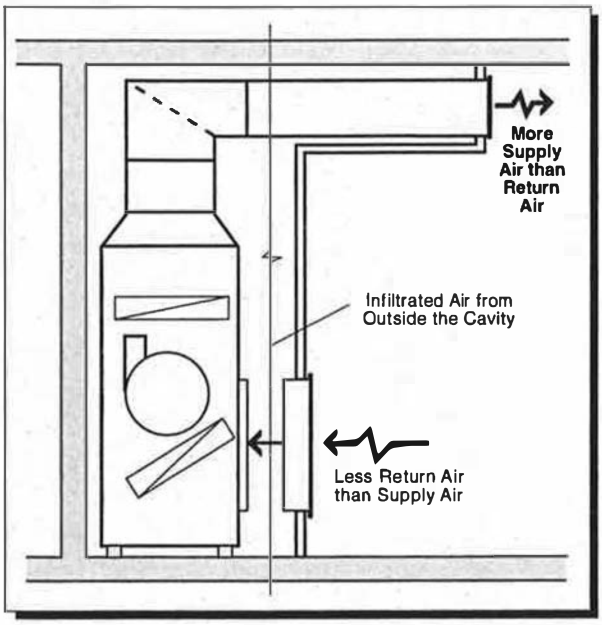

Figure 6-4. Besides testing pressurization, air hood measurements can sometimes quickly detect large ductwork leakage by comparing supply and return air quantities, but only if there is not equivalently large leakage in both the supply and return ductwork.

mechanical system contractors to balance air handler systems so that each space receives the specified quantity of conditioned air, and they often can provide a fairly easy (although not very precise) means of determining if a mechanical system is pressurizing or depressurizing a space.

For example, if the air flow into the return system of the unit is less than the air flow out of the supply ducts, the unit is probably pressurizing the conditioned space by drawing air from outside the conditioned space into the air handling unit return (indicating a return duct leak or outside air connection). On the other hand, if the measured supply air flow is less than the measured return air flow, the conditioned space may be depressurized by the loss of supply air to some location outside the conditioned space (indicating a supply duct leak).

If the system has equal supply and return leaks, the air flows will be equal and the conditioned space is likely to be under neutral pressure. Therefore, flow hood measurements cannot establish the extent to which a mechanical system is leaking: they can only measure supply or return air flows at outlets.

Measuring Moisture

A sample of measurements large enough to verify the contractor's efforts during construction, if conducted, should follow the procedures outlined in Section 5. This effort is often justified only if problems are suspected.

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Section 7
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About the Authors

J. David Odom is vice president of IAQ services with CH2M HILL in Orlando, Florida. For more than 10 years, he has been solving IAQ and moisture, mildew, and corrosion problems in buildings throughout the country. He specializes in building diagnostics and performance testing, moisture and mildew control, and evaluation and remediation of building envelope and HVAC systems.

Mr. Odom has directed project teams providing IAQ services for more than 500 buildings, including major resort and courthouse renovations in Florida. Additionally, he has managed IAQ problem avoidance peer reviews for facilities totaling more than $700 million in construction value. In addition to resorts and courthouses, he has investigated hospitals, prison facilities, office buildings, schools, and commercial facilities. For the Atlanta Committee for the Olympic Games (ACOG), Mr. Odom served as an executive on loan and evaluated the Olympic Village for potential IAQ problems.

Mr. Odom has authored more than 20 technical papers on IAQ and has coauthored two manuals on the subject: *Moisture and Mildew Control Guidelines for New Construction* and *Preventing Indoor Air Quality Problems in Hot, Humid Climates: Problem Avoidance Guidelines*. He has conducted symposiums at the University of Florida, Clemson University, and Valencia Community College. He is also a member of *Indoor Air Review's* editorial review board.

George DuBose is a mechanical engineer with CH2M HILL in Orlando, Florida. He specializes in building diagnostics as well as design and remediation of HVAC systems in buildings with IAQ problems. He is well versed in the use of specialized diagnostic techniques, including blower door testing, thermographic evaluation, pressure differential testing, and tracer gas testing.

Mr. DuBose has served as project manager on HVAC and building envelope design modifications costing in excess of $20 million. He has investigated IAQ problems in projects involving several hundred buildings and has provided mechanical designs for industrial and commercial projects throughout the United States. As a project mechanical engineer, he has managed the assessment and remediation of building envelopes for moisture intrusion problems, including remedial work totaling more than $30 million for major resorts, courthouse complexes, colleges, and hospitals. Mr. DuBose is a member of the American Society of Mechanical Engineers (ASME), NIBS, and ASHRAE. He serves on two ASHRAE technical committees: TC4.9, Building Envelopes, which studies envelope performance, and TC9.9, the Building Commissioning/Research Committee.

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