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APR 80   R J MOORE, L G SPIELVOGEL, C W GRIFFIN   N62467-76-C-0696

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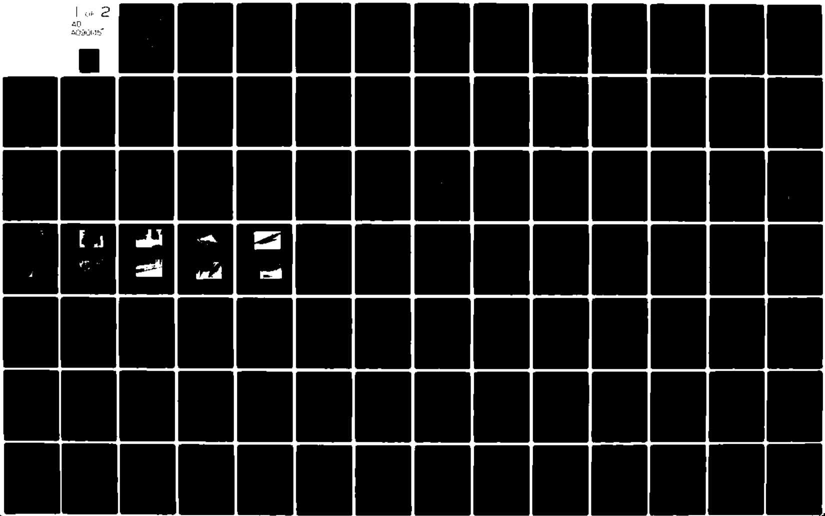

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AIRCONDITIONED BUILDINGS IN HUMID CLIMATES

GUIDELINES FOR DESIGN, OPERATION AND MAINTENANCE

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THIS REPORT SETS FORTH DESIGN CRITERIA FOR AVOIDING & SOLVING MOISTURE PROBLEMS IN AIR CONDITIONED BUILDINGS IN HUMID CLIMATES.

AIRCONDITIONED BUILDINGS IN HUMID CLIMATES.

GUIDELINES FOR DESIGN, OPERATION, AND MAINTENANCE.

Prepared for

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Naval Facilities Engineering Command
P. O. Box 10068
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AIRCONDITIONED BUILDINGS IN HUMID CLIMATES

GUIDELINES FOR DESIGN, OPERATION, AND MAINTENANCE

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INTRODUCTION

This publication sets forth design criteria for avoiding and solving moisture problems in airconditioned buildings in humid climates. These moisture problems span a broad spectrum notably:

- Mold and mildew on exterior building surfaces.
- Peeling, blistering, flaking and bleeding of paint on both exterior and interior surfaces.
- Interior odor.
- Uncomfortably high levels of interior humidity.
- Property damage resulting from condensation in and on building walls and roof.
- Insulating losses resulting from condensation in building walls and roof.

Remedies for these conditions sometimes demand drastic changes from normal architectural and mechanical design practices used for colder, drier climates. Solutions to moisture problems in humid climates often entail a reversal of normal design practice. In most locations in the continental United States, vapor retarders, formerly called "vapor barriers," should be located on the inside of the building envelope, to retard vapor migration from the warmer, more humid interior toward the generally colder, drier exterior. But in warm, humid climates, where the vapor-pressure gradient is normally reversed (i.e., toward the building interior from the warmer, more humid exterior), a vapor retarder's correct location is near the outside surface of the building envelope. Because of the practical difficulty in applying a properly sealed and flashed, puncture-free vapor retarder, it is, however, generally advisable to omit a vapor retarder and rely instead on an exterior finish of low vapor permeability.

Many normally effective heating, ventilating, and air-conditioning (HVAC) design practices become similarly unacceptable in humid climates. For one example, the popular room fan-coil HVAC units, which can give satisfactory service in colder climates, cannot perform satisfactorily in humid climates. In a humid climate, a room fan-coil unit can satisfy only one of two basic airconditioning criteria: control of either temperature or humidity, but not both simultaneously.

As another example, installation of a so-called "economy cycle" in a humid climate will provide no economy, while frequently increasing cooling energy consumption and moisture problems. In colder climates, an economy cycle can reduce cooling energy consumption by permitting shutdown of refrigeration machines and circulating outside air through airconditioned spaces when outside air temperatures drop below 60°F or 70°F. But in climates where the temperature seldom, or perhaps never, drops to 70°F, an economy cycle merely provides a needless avenue for invasion of humid outside air, via air leakage through the economy-cycle dampers.

Humid and Fringe Climates Defined

The definition of humid and fringe climates emerges from a correlation of observed and reported moisture problems with the atmospheric conditions, as indicated by wet-bulb temperature at geographic locations where these problems were encountered. See Table 1-1. For purposes of this publication, a humid climate need satisfy only one or both of the following conditions:

a. 67°F or higher wet-bulb temperature for 3,500 or more hours during the warmest six consecutive months of the year, and/or

b. 73°F or higher wet-bulb temperature for 1,750 or more hours during the warmest six consecutive months of the year.

For wet-bulb temperatures and their hours of occurrence in various locations, consult Engineering Weather Data, Departments of the Air Force, the Army, and the Navy, AFM 88-29, TM5-785, NAVFAC P-89, 1 July 1978. (This book can be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, as Stock No. 008-070-00420-8 for $8.65.) See figures 1-1 and 1-2.

The severity of humid-climate conditions in some tropi-

TABLE 1-1

HUMID AND FRINGE CLIMATES

	WARMEST 6 MONTHS HOURS PER YEAR	
	HUMID CLIMATE	FRINGE CLIMATE
67°F or higher wet bulb temperature	3,500	3,000
73°F or higher wet bulb temperature	1,750	1,500

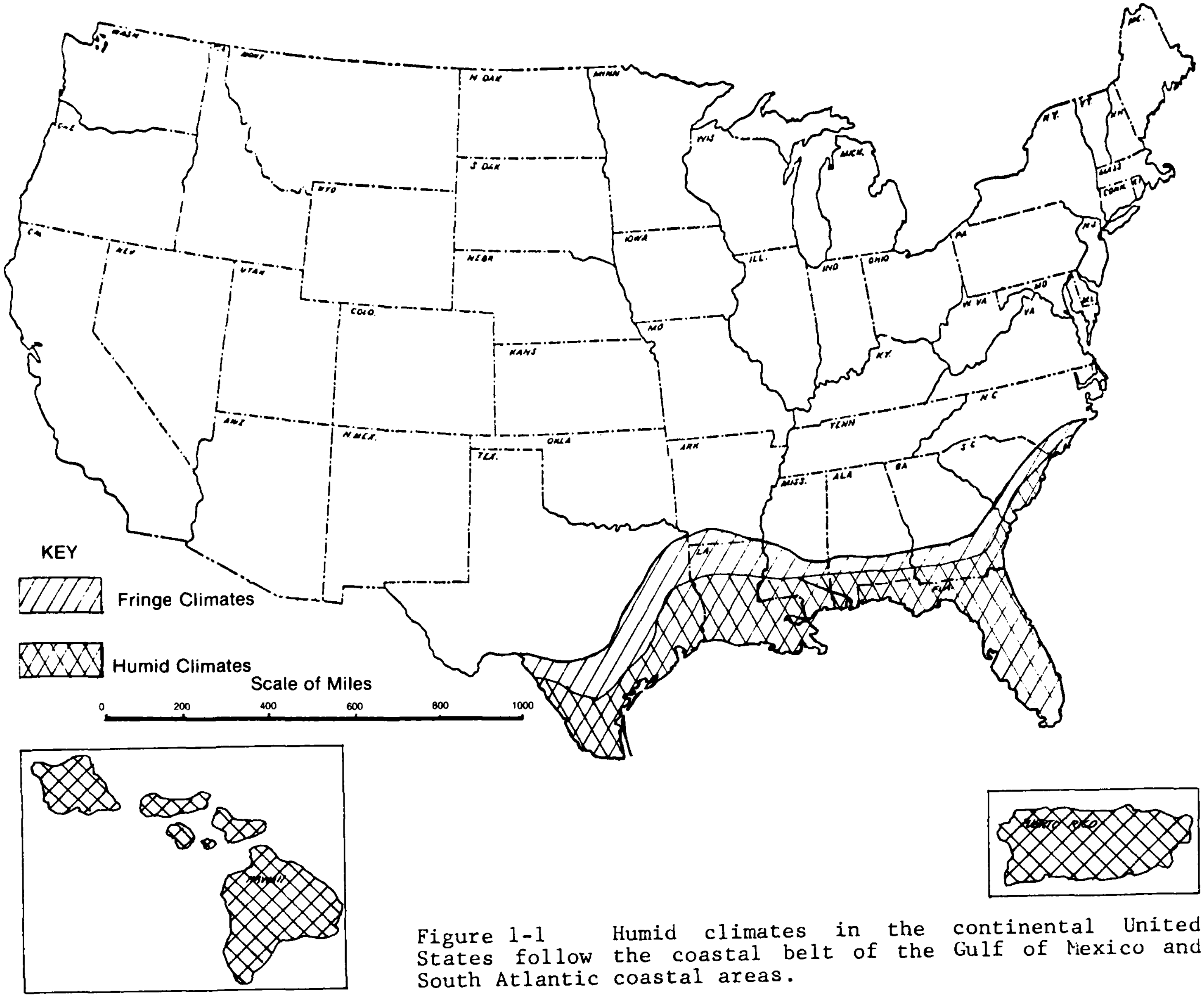


Figure 1-1 Humid climates in the continental United States follow the coastal belt of the Gulf of Mexico and South Atlantic coastal areas.

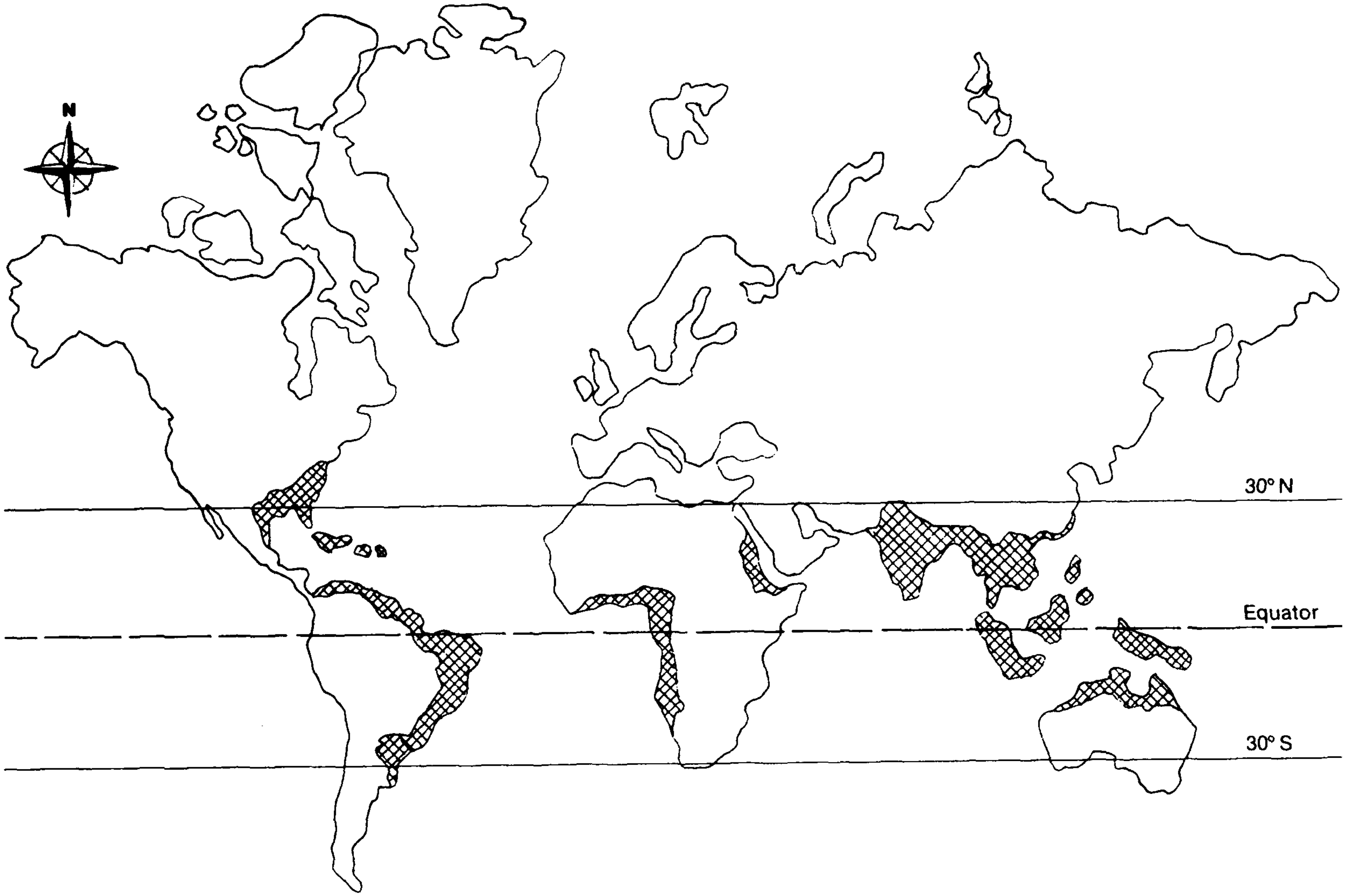


Figure 1-2 Humid climates generally occur in latitudes 30°S to 30°N, in low coastal regions. For any specific location, the designer must consult weather records.

cal locations is also illustrated by computer analysis of hourly weather data for one year from four locations: Cubi Point, Olongapo, Republic of the Philippines; Agana, Guam; Barbers Point, Honolulu, Hawaii; and Diego Garcia, Indian Ocean. All four locations record ambient dew point temperatures almost perpetually above the maximum dew point of of 61.5°F in the ASHRAE comfort envelope (roughly 72°F - 79°F temperature, 20% - 70% RH) as shown on Fig. 1-3. Guam, Diego Garcia, and the Philippines have more than 7,000 annual hours, more than 80% of the time, at ambient dew point of 72°F or greater. These conditions indicate the need for continuous dehumidification, and probably continuous cooling.

Table 1-2 summarizes the results of the computer weather analysis, compared with U.S. Navy design criteria.

Depending upon local experience with moisture problems, use of some humid-climate design criteria may be desirable in locations that do not quite qualify under the foregoing conditions. Among these fringe areas are several locations in Southern United States -- notably Alabama, Arkansas, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas. See Fig. 1-1.

"Fringe" locations will generally satisfy one or both of the following conditions:

a. 67°F or higher wet-bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year, and/or

b. 73°F or higher wet-bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year.

DEW POINT ANALYSIS

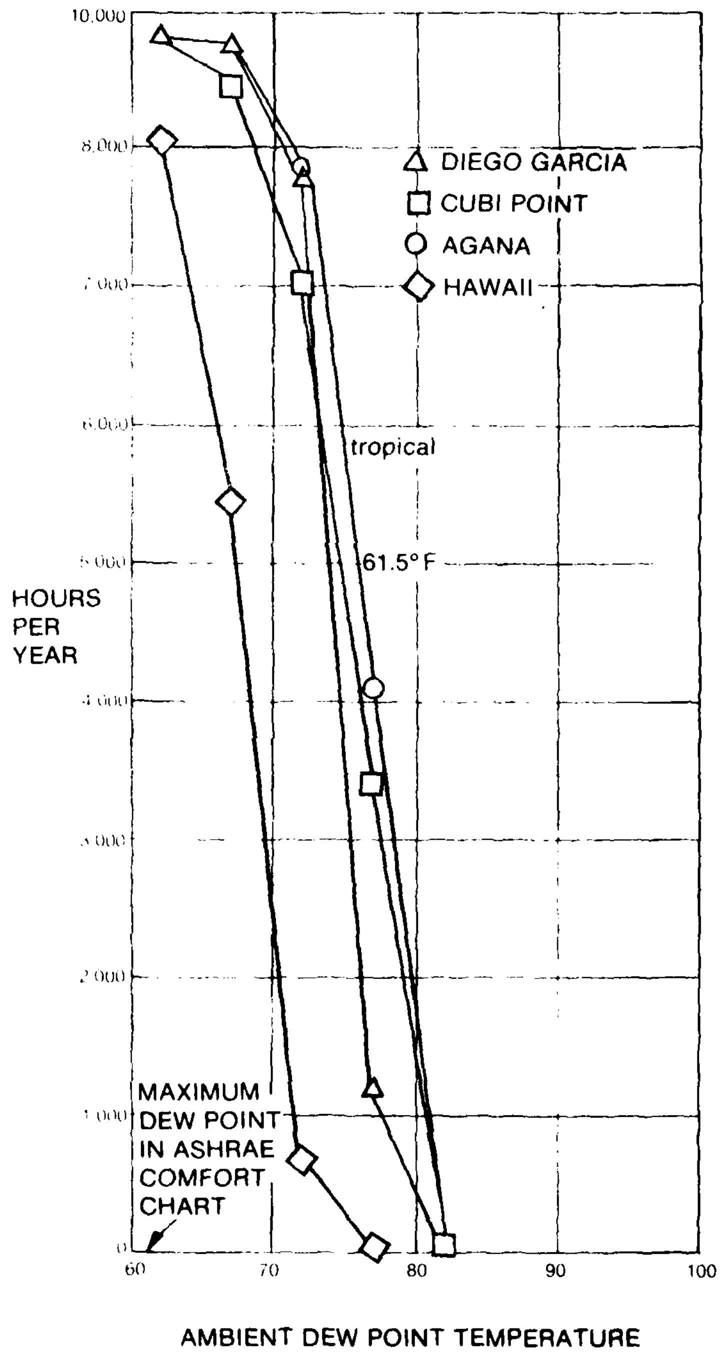


Figure 1-3 In three of the four weather-analyzed climates, ambient dew point remains perpetually above the 61.5° maximum dew point within ASHRAE comfort criteria. Such conditions require continuous dehumidification, and probably continuous cooling.

WEATHER SUMMARY

	WEATHER STATIONS			
	CUBI POINT R.P.	AGANA GUAM	BARBERS POINT HI.	DIEGO GARCIA I.O.
COMPUTER ANALYSIS				
Maximum Dry Bulb	97	89	88	90
Minimum Dry Bulb	69	70	58	68
Maximum Dew Point	82	80	77	83
Minimum Dew Point	59	47	49	62
Heating Degree Days	0	0	0	0
Cooling Degree Days	6240	5692	3945	5405
NAVFAC P-89				
Dry Bulb-1%	95	89	87	90
Dry Bulb-2-1/2%	93	88	86	89
Dry Bulb-5%	91	87	85	88
Dry Bulb-99%	69	72	60	71
Dry Bulb-97-1/2%	70	73	62	72
Wet Bulb-1%	81	80	77	81
Wet Bulb-2-1/2%	80	80	76	81
Wet Bulb-5%	80	79	75	80
Heating Degree Days	0	0	1	0
Cooling Degree Days	6285	5865	3929	5854

Table 1-2. Weather summary for the four computer-analyzed humid climates show generally close agreement with U.S.Navy design criteria.

There are several factors that might prompt a decision to design to humid-climate criteria in fringe locations. Professional judgment must be exercised to establish to what degree humid-climate design criteria are applied and the types of buildings to which they are applicable. The more significant factors that would influence a decision to use humid-climate design criteria include (a) use of an airconditioning system with limited humidity-control capability, (b) buildings with high levels of internal moisture, or (c) special building uses -- e.g., 24-hour daily operation or highly variable cooling loads, both tending to increase the percentage of operating hours at light cooling loads, thus increasing the difficulty of achieving comfort-zone dehumidification. In fringe locations, it may not be necessary to utilize all the humid-climate design criteria, or to use them to the extent indicated for humid climates, depending upon the judgment of the designer.

Field Investigations and Research

These recommendations follow extensive field investigations of buildings, both with and without moisture-related problems, in the Pacific (Hawaii, Guam, and the Philippines) and in Southeastern United States (South Carolina, Louisiana and Florida). Moisture problems in Southeastern United States were similar, but less severe than in the more humid, tropical Pacific locations.

Field investigations under the most severe humid conditions highlighted the moisture problems in the Pacific. These field investigations had several general purposes:

- To observe moisture problems in buildings in humid climates.
- To evaluate the results of numerous remedial modifications designed to alleviate these moisture problems.
- To provide a basis for recommendations in light of observed problems and previous remedial efforts.

Research through the bibliography on moisture problems complemented the field investigations as a basis for the recommendations.

In many cases, no definitive research or studies have been made to provide precise values. Therefore, some of the recommendations herein represent the best currently available values. Hopefully, more research will provide better answers in the future.

TWO

MOISTURE PROBLEMS IN HUMID CLIMATES

As background for understanding the design principles and recommendations presented in later chapters, this chapter reviews moisture problems observed during field surveys conducted in the Pacific and Southeastern United States. These problems were observed in an original inspection trip to the Pacific in 1976, a trip to Southeastern United States in 1977, followed by a second trip to the Pacific in August, 1978, at the peak of severe humidity conditions, to evaluate remedial measures taken in the two-year interim.

Airconditioned buildings in humid climates exhibited the following problems:

- Mold and mildew on walls and other building surfaces.
- Peeling, blistering, flaking and bleeding of paint from exterior and interior surfaces.
- Weakened and collapsed suspended ceilings, rusted metal, and other property damage from interior condensation.
- Insulating losses due to water absorption.

Sources of the problems included poor installation and maintenance, as well as poor design, and, for HVAC systems, poor operating and maintenance practices as well.

Exterior Mold and Mildew

Discoloration -- in specks, spots, streaks, or patches of varying shades and intensity -- is a major problem resulting from surface condensation. These discolorations first appear as fuzzy, powdery surface growths, with colors ranging from predominant dark grays and black to yellowish or green tints.

The fungi responsible for this staining mildew constitute a special class of threadlike, microscopic plants or mold that lack chlorophyll and the ability to manufacture food via photosynthesis. Fungi require oxygen, warm temperatures, and moisture for growth into familiar mold and mildew. Under favorable conditions of temperature and humidity, fungi spores proliferate at a fantastic rate, measured in millions per minute per square foot of fungus-covered area. Prevailing dry-bulb tropical temperatures between 65°F and 95°F are ideal for fungus growth. Temperature is thus the uncontrollable factor. The controllable factor is moisture -- e.g., exterior surface condensation, interior RH, etc.

Exterior mold discoloration occurs most frequently on shaded walls, projecting columns, cantilevered floor slabs, and interior corners. A particularly bad example of mold growth occurred on the egg-crate construction of a building on Guam. Concrete window frames (mullions, heads, and sills) projected 18 to 24 in. out from the exterior wall plane, framing 2 x 3-ft. window openings. They were excellent shading devices, shielding the building from direct solar radiation heat gain through the glass. But they provided ideal surfaces for mold growth, especially on rain-wetted surfaces at the sill and head projections and wall areas immediately above.

As the next chapter will explain, this egg-crate mold growth was promoted by thermal bridges -- i.e., heat-conductive materials extending continuously through the building envelope's cross-section. The heat-conductive material creates a "thermal bridge" linking inside and outside. This thermal bridge lowers exterior surface temperature while raising interior surface temperature.

Another building with mold growth attributable to the cool exterior surfaces produced by thermal bridges was located in Guam. Heavy mold growth covered eyebrows cantilevered 2 ft. beyond wall plane, walls immediately above the eyebrows, and wall areas flanking the eyebrow-shaded window openings, all areas of low surface temperature and concentrated rainwater splashing or runoff. Again, mold growth occurred on wet and cool surfaces.

Mold growth was observed where runners for exterior sliding louvered doors were located within a few inches of the building, thus allowing water to be trapped between the bottom runner and the building wall. Moreover, one portion or another of the area between the runner and the building was always shaded by the louvered door. As a consequence, even with the sun shining on that building face, the water that collected behind the louvered door location never had an opportunity to evaporate.

Condensation also occurred on exterior, exposed metal door frames as well as the door edges, usually where uninsulated doors were shaded.

In addition to condensation on exterior surfaces, rainwater ponding promotes mold growth on many building surfaces. Some exterior walkway canopies, structurally attached to buildings, exhibited mold and mildew because they retained water. Sloping these surfaces to drain away from the building would easily correct this problem, since the drained horizontal surface would normally receive some solar radiation and air movement.

Mold and mildew also form on the vapor-retarder jackets of chilled-water piping suspended from covered walkways, which shelter it in its distribution network to several buildings from central refrigeration plants. Problems here include not only the mold-covered vapor-retarder jackets, but also the large cooling-energy losses resulting from the water-saturated pipe insulation. As the cooling energy losses increase (due to ever-increasing water absorption by the pipe insulation), the vapor-retarder jacket's exterior surface temperature tends to approach the chilled-water temperature. And since the chilled-water temperature is almost always below the ambient dew point temperature, condensation occurs on the jacket surface, thus further enhancing mold growth.

Painting Errors

Gross flaws in painting, both interior and exterior, were observed. Paint applied only four months before was peeling, with little or no adhesion to substrate surface. Mold and mildew covered painted surfaces, which exuded offensive odors. Paint was used thoughtlessly: highly impermeable enamels applied to surfaces requiring breathing paint, and vice versa. Many substrates were obviously wet when painted.

The problem of condensation on cold surfaces was evident in paint observed in the Philippine Islands. Paint was peeling from outer edges of exposed concrete walkway canopies. These canopies were structurally contiguous with the building interiors. They consequently acted as thermal bridges, their surface temperatures reduced by the cool interiors. When the trapped resulting moisture later evaporated under solar heat, the resulting expansion caused the observed peeling and blistering.

Some of the worst paint problems were encountered at a building on Guam. A painted exterior surface, pocked with blisters up to 1/2-in. diameter and 1/4-in. projection, exuded a dark brown liquid, which drained down the wall when punctured by a serviceman preparing the surface for repainting. No effort had been made to sterilize or prekill the existing fungi before start of the preparation work.

Another building on Guam presented a stark contrast in good vs. bad painting practice on two adjacent concrete surfaces, 5 feet apart. One surface, painted with enamel, displayed all the familiar problems -- blistering, cracking, peeling, spalling, and mold. The other had a cement fill coat of white Medusa cement wash, with none of the typical paint defects: no mold, and no water staining. It was shedding exterior water, but the permeable coating was allowing the passage of water vapor into the building's interior, where it promoted mold growth as well as high interior humidity. Thus the cement-wash exterior finish, while satisfactory insofar as the exterior surface is concerned, is not a generally satisfactory solution.

Painting problems include not only defective coatings on the buildings, but also health threats to workmen exposed to fungal infections of ears, eyes, and lungs, while removing defective, mold-covered paint from existing surfaces scheduled for repainting. Observed paint-removal methods --notably, the predominant method of grinding paint surfaces down with an electrically powered wheel on masonry surfaces -- provide no protection from these fungal health threats. Chapter 5, accordingly, contains a recommendation for workmen who remove mold-covered paint to wear air-supplied, protective suits.

Steel substrates should be painted with vinyl coating system or silicone alkyds. Wood surfaces require latex primer and latex top coat for breathing. Spot priming should be emphasized.

Property Damage from Interior Condensation

Interior condensation causes varied property damage. A major source of this damage is chilled-water piping running through or above the conditioned space. Carrying water at temperatures around 40°F to 50°F, this piping ranges as much as 40°F to 45°F below the ambient dew point temperature. The pipe insulation becomes saturated as the condensing water vapor accumulates in the insulation. Condensation of ambient moisture then begins to form on the vapor-retarder jacket, because the wet insulation has suffered a drastic thermal-resistance loss. As the condensation accumulates on the jacket, it begins to drip onto ceiling tiles. As absorbed water accumulates in ceiling tiles, the tiles begin to sag. Additional dripping water forms a puddle in the sagging tile, which sags still further. When its water-weakened fibers can no longer resist the increasing water load, it fractures and spills the water to the floor below.

The HVAC systems provide another source of interior moisture in the fan-coil units' cooling-coil drain pans and the chilled-water piping within the fan-coil units. Drain pan outlets become clogged and overflow, damaging those rooms as well as the rooms below when the overflowing water drips down. In rooms with high RH, condensation can rust diffusers, registers, and metal enclosures around fan-coil units.

Moisture condensed in fan-coil units creates even more serious problems than general condensation. The perpetually wet piping and drain-pan surfaces collect lint, mold, mildew, and scale. Drain-pan pitch is seldom checked; standing water is perpetual. Wall-mounted fan-coil units become collectors for debris and items placed on them.

Even worse is the effect of this perpetual moisture on the HVAC system itself. It impairs HVAC system operation, thus perpetuating a vicious spiral that reduces interior humidity control and aggravates the whole moisture-generating process. Scale-encrusted cooling coils lose efficiency and capacity as heat-transfer surface . Control valves, thermostats, and wiring in this moist environment corrode and malfunction more frequently.

Roof Problems

Flat roofs in humid climates pose the same general problems as roofs in colder, drier climates. But there are several distinguishing characteristics.:

- Membrane blistering and slippage are more prevalent problems in humid climates because they are associated with high roof-surface temperatures, which persist for longer intervals in humid climates.

- Generally higher wind-uplift pressures occur in humid climates, which often coincide with hurricane or typhoon belts.
- Use of a vapor retarder between deck and insulation is a positive detriment, because of the undirectional, downward vapor flow characteristic of humid climates, with their persistent high exterior wet-bulb temperatures.

A classic example of slippage occurred on the roof of a New Orleans, Louisiana building. It resulted from use of low softening-point mopping asphalt on too steep a slope. (See Chapter 4, "Recommendations for New Construction," for slope limits on various grades of asphalt.)

This same roof also exhibited extensive blistering, attributable to faulty workmanship, but also aggravated by the extended hot weather and consequently high roof-surface temperatures, which increase the air-water vapor pressure within the blisters and promote their growth.

Other flaws in the roofs at this New Orleans location included:

- Insufficient aggregate surfacing with poor embedment in membrane flood coat.
- Poor perimeter flashing and gutter details. Counterflashing was incorrectly secured atop copings and caulked, instead of under the copings or in properly wedged and caulked reglets.

- o Use of a single drain, which, if clogged, could impound water and threaten leakage through vulnerable base flashings.

Vulnerability to wind-uplift pressures was noted in several locations. In Pensacola, Florida, a building recently reroofed with a superimposed roof system of fiberglass insulation and a white, mineral-surfaced, two-ply 90-lb. selvage membrane, was highly vulnerable to wind-uplift pressure. Judged by a walking tour of this roof, this new insulation was loose. Moreover, no new or superimposed metal edging had been provided and anchored to nailers at the roof periphery. Since most wind blowoffs start at the periphery, with local flashing failure progressing into the membrane area, this roof appears to be a prime candidate for blowoff during the next hurricane.

Roofs on Guam and the Philippines, typhoon areas, appear highly vulnerable to blowoffs. In an effort to reduce termite damage, wood is scarce on roofs in these regions. Properly treated wood is needed to provide nailer anchorage at perimeters and openings against wind uplift pressure.

Wind-scouring of aggregate, as well as wind blowoffs, is a problem in this Pacific area. (See Chapter 4, "Recommendations for New Construction.") Another aspect of the wind problem in typhoon areas concerns the need to raise base flashing height above the normal 8 in., to prevent wind-driven rain from penetrating the wall above the base flashing.

Roof-mounted equipment in Guam and the Philippines was poorly flashed. In these typhoon areas, rooftop locations for HVAC units and other equipment that could otherwise be located inside constitutes bad practice for several reasons. Not only does it subject this equipment to wind damage avoided by placing it inside the building; it also subjects this equipment to highly accelerated corrosion from rain and weather, especially in the salt-air atmospheres of seashore locations. Obviously, air-cooled condensers and cooling towers should be located outside.

Many roof problems observed in humid climates reflect misguided efforts at economy. Here are some examples:

- On roofs in Guam, omission of a 4-foot perimeter strip of insulation board over canopies ultimately resulted in blisters, because the transition was improperly handled. There was no cant strip at the vertical terminating edge of the insulation board. That omission caused a void where the membrane changes elevation. Trapped moisture caused blisters, and the moisture-weakened felts split.
- Also on the Guam building's roof, where a copper fascia was anchored to the deck with galvanized nails or bolts, galvanic action between the two dissimilar metals was corroding bolts, nails, and even the copper.

- Roofs on Guam and the Philippines apparently received no maintenance. Roofs in the vicinity of trees had leaf and twig-clogged drains, gutters, and eave boxes.
- On a roof in Charleston, South Carolina, poorly flashed roof blowout hatches were leaking.
- On this same building, transite wall-cladding joints lacking neoprene gaskets, or caulking, leaked badly in the higher sections from wind-driven rain.
- On another building, the roof had a good roof membrane, but poor sheet metal work in gutters, eave boxes, etc. Exterior metal, painted over an unprimed surface was peeling.

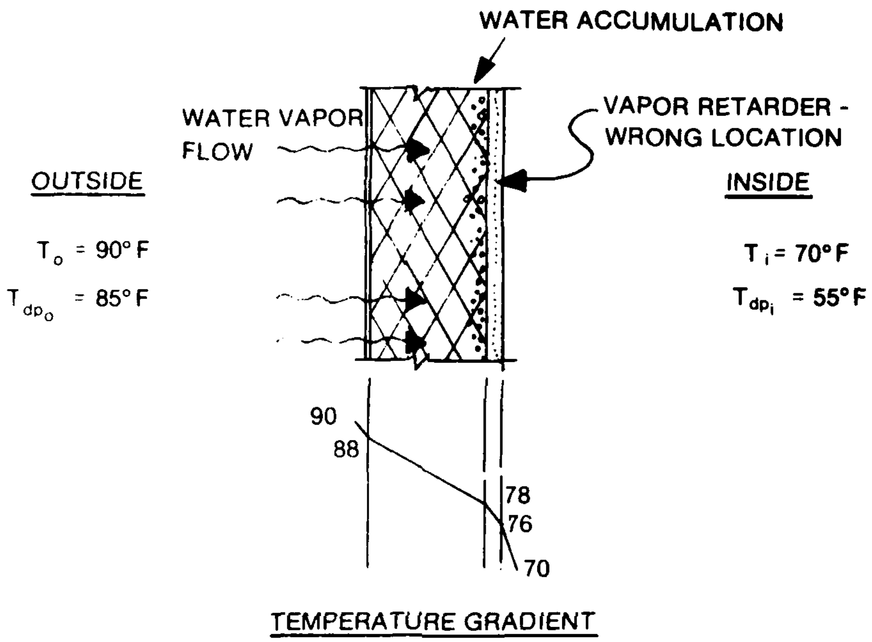


Figure 2-1 Placing a vapor retarder near the interior face of a wall in a humid climate permits the penetration of water vapor under a continuously high vapor-pressure gradient (up to 0.5 in. Hg. or more), with unidirectional inward flow throughout the year in tropical humid climates. Since the vapor retarder is normally at or below ambient dew point temperature, it causes condensation and accumulation of water within the wall cross section, drastically reducing the thermal resistance of any insulation in the wall.

Slovenly Field Installation

Field observation of several modernization projects on Guam revealed slovenly installation work. Wall insulation was not only inadequate, but non-uniform. The workmen failed to install it continuously, and compressed it to fit around wall-incorporated piping and wiring.

Vapor retarders were installed capriciously: some erroneously located near inside surfaces, others properly located near outside surfaces (see Fig. 2-1). Regardless whether or not they are properly located, vapor retarders are relatively ineffective, since it is impracticable to seal joints and holes and to prevent field punctures. It is better to rely on an impermeable exterior finish, complemented by a more permeable interior surface finish designed to prevent entrapment of moisture within the building envelope.

HVAC Problems

Failure of fan-coil unit HVAC systems to provide comfort in humid climates was demonstrated by field investigations at all humid-climate locations. None of the rooms that were instrumented had conditions within the ASHRAE comfort envelope at any time during the 24-hour daily cycles for which measurements were recorded, as shown on Fig. 2-2. This general failure occurred despite attempts in preceding years to improve HVAC fan-coil units' dehumidification performance and to improve operation of central chilled-water plants.

The HVAC systems' failure generally inspired counterproductive efforts to relieve the situation, with uncomfortable occupants opening windows, "jumpering" -- i.e., disabling controls, and over-cooling rooms -- all of which generally worsened the situation.

One monitored building in the Philippines achieved a satisfactory RH of below 60%, but at the expense of overcooling to 69°F - 70°F. Another on Guam, though close to the comfort envelope, nonetheless suffered humidity high enough to cause interior mold growth. An oversized airconditioning unit, operating with only light sensible cooling load, could not control humidity. On Guam, another building equipped with a typical fan-coil system, was consequently far from the comfort envelope, with RH around 80%. See Fig. 2-2.

ROOM CONDITIONS
INSTRUMENTATION RESULTS

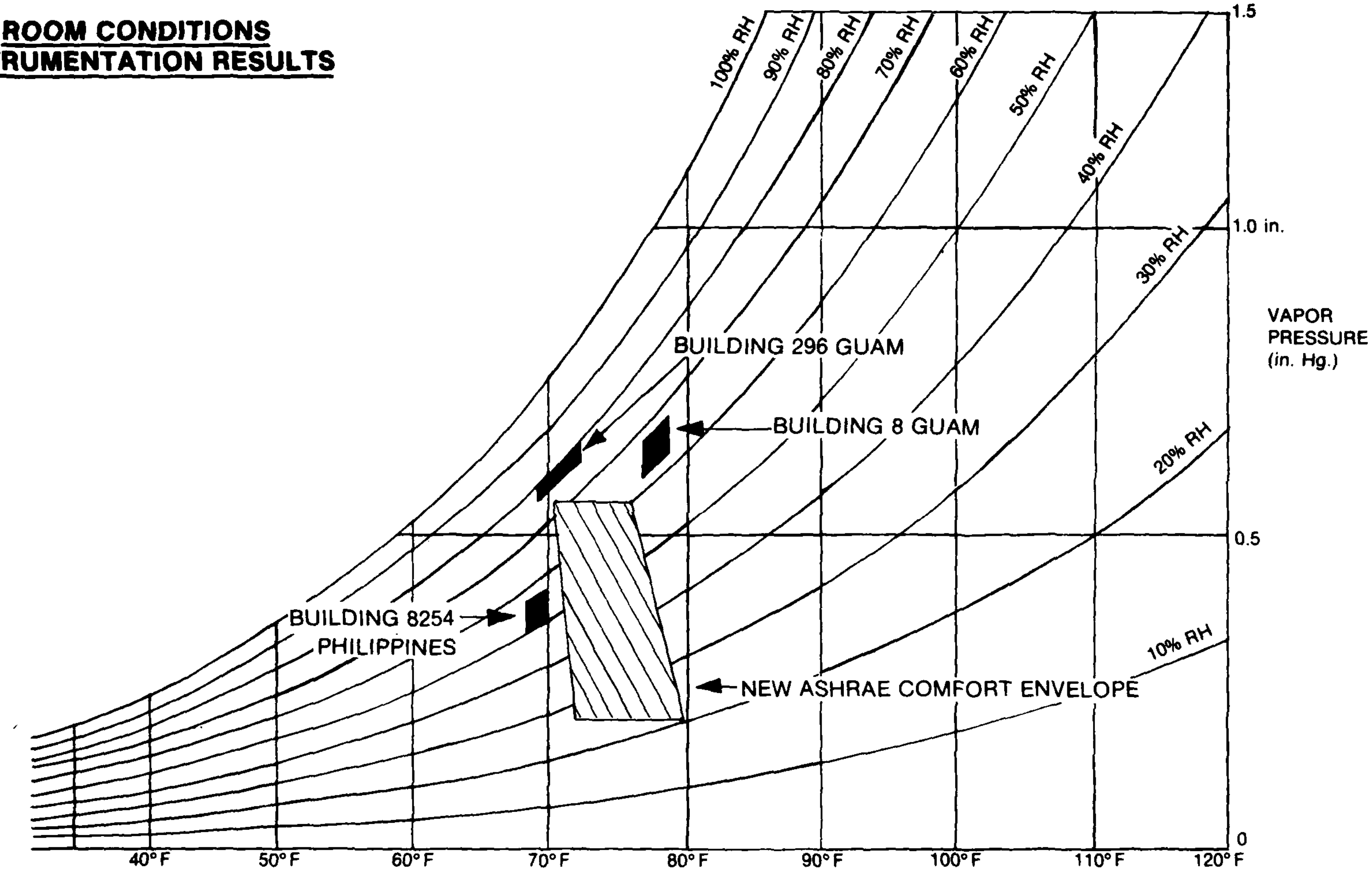


Figure 2-2 The failure of fan-coil unit HVAC systems to satisfy ASHRAE comfort criteria is illustrated by the plots on the psychrometric chart above for three instrumented rooms in multiple-unit residential projects in the Pacific (two on Guam, one in the Philippines). The two instrumented rooms on Guam failed to satisfy the RH comfort standards. In the Philippines, the instrumented room *satisfied* the RH criterion, but only because of substantial overcooling.

Explanation of HVAC Failures

There are multiple explanations for the HVAC systems' failure to maintain comfortable thermal conditions. Basically, the typical fan-coil unit is physically unable to satisfy two of the basic ASHRAE comfort criteria -- temperature and relative humidity (RH). It can satisfy one criterion, but not both. This is a general disadvantage of all-water systems. Lacking humidity control, they can only reduce RH in a humid climate by overcooling, unless the sensible cooling load is close to the unit's capacity. Achieving RH control generally requires positive means of insuring dehumidification to some predetermined level, plus a separate means of controlling temperature, such as reheat.

Fan-coil units cannot control humidity in humid climates because the fan and/or chilled-water temperature controls can respond only to sensible, not to latent cooling load. As a consequence, they can dehumidify only under a sensible cooling load. Addition of other prevalent failings observed in humid climates -- e.g., discontinuous chilled-water flow, high chilled-water temperature, excessive infiltration of humid outside air -- compounds the problems: already excessive interior RH climbs even higher.

In addition to this basic flaw in HVAC design, there are other factors aggravating the situation. These aggravating factors include faulty installation, faulty operation and maintenance, both by maintenance personnel and, as previously noted, by occupant interference with system operation.

Especially in foreign locations where the labor force lacks experience in fabricating and assembling more complex HVAC and control systems, poor field workmanship contributed to the observed HVAC problems. Despite good design, specifications, and careful supervision, inexperienced workmen can aggravate moisture problems, in general, and HVAC-system operation, in particular. Among noted flaws:

- Lack of tight construction.
- Defective vapor-sealing of pipe insulation
- Defective installation and balancing of central HVAC systems

Operation and maintenance are also worse in foreign than in domestic locations, again largely because of inexperienced local mechanics. In fact, the designer must anticipate a lower level of installation and operating and maintenance expertise in most foreign locations. Chilled-water temperatures frequently exceed design range, because the pipe insulation, wetted from the perpetual water vapor flow toward the pipe, suffers drastic losses in insulating value, and central chilled-water refrigeration plants lose reliability, both in continuity of operation (i.e., in excessive downtime) and in maintenance of chilled-water temperature.

Chilled-Water Problems

A second visit to the buildings and chilled-water plants observed two years earlier confirmed that most chilled-water plants continue operating at chilled-water temperatures above design temperature. These higher than design chilled-water temperatures may have constituted misguided attempts at energy conservation, but continue to make major contributions to moisture problems. Instruments and gauges are not calibrated, making the operator's task more difficult.

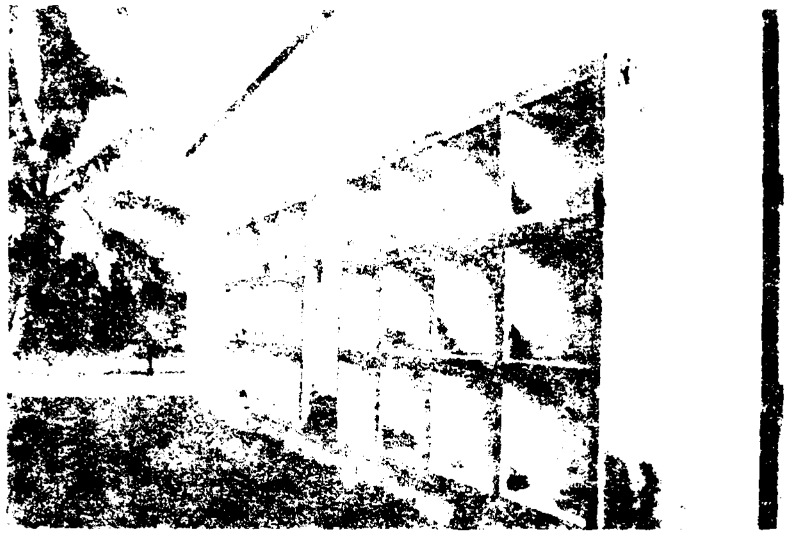
Tight operating control is especially important where a central chilled-water plant serves many buildings with long piping runs. With long runs of chilled-water piping and wet pipe insulation, chilled-water temperature can rise as much as 10°F in its trip from plant to the farthest building. Even if the plant-water temperature were correct, the insulating loss would still raise chilled-water temperature above the acceptable range at the HVAC units' cooling coils. And when the plant-water temperature is high and chilled-water temperature rises even higher at the room cooling terminals, the situation becomes even worse. Dehumidification obviously cannot occur when chilled-water temperature is higher than the design temperature for the cooling coil.

High central plant chilled-water temperatures often resulted from ill-advised departures from recommended operating procedures. Despite chillers marked 42°F - 44°F for chilled-water supply temperatures, the control panel thermostat was usually set for higher temperatures. Moreover, many large chillers have electric demand-limiting switches frequently set at 40% to 50% of full load electrical capacity. In almost all cases, there was no rational basis for these settings, and the operators were usually ignorant of the reason for installation of demand-limiting devices. These ill-advised attempts at electrical economy prevent chiller operation at sufficient capacity to achieve design chilled-water temperature.

Still another factor impairing central refrigeration plant operation was the failure to instruct operating personnel about the importance of maintaining chilled-water temperature to assure proper HVAC operation.

Another aspect of the chilled-water temperature problems concerned the difficult, continuing problem of the water distribution system's hydraulic complexity, a consequence of the large piping network, the large number of HVAC units, and the sensitivity of numerous units' latent cooling load capacity to chilled-water flow. Since most of the piping is small and pressure variations great, balancing valves must close to very small openings. These small openings promote clogging; clogging reduces chilled-water flow, and reduced chilled-water flow, in turn, impairs latent cooling performance.

Some of the situations in which design chilled-water temperatures could not be achieved may have resulted from inadequate capacity of heat rejection equipment and/or poor selection of chiller components -- i.e., inadequate compressor lift.



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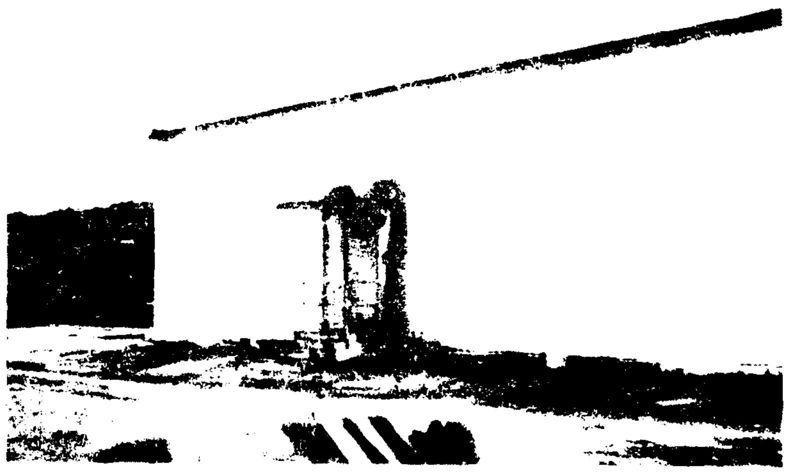
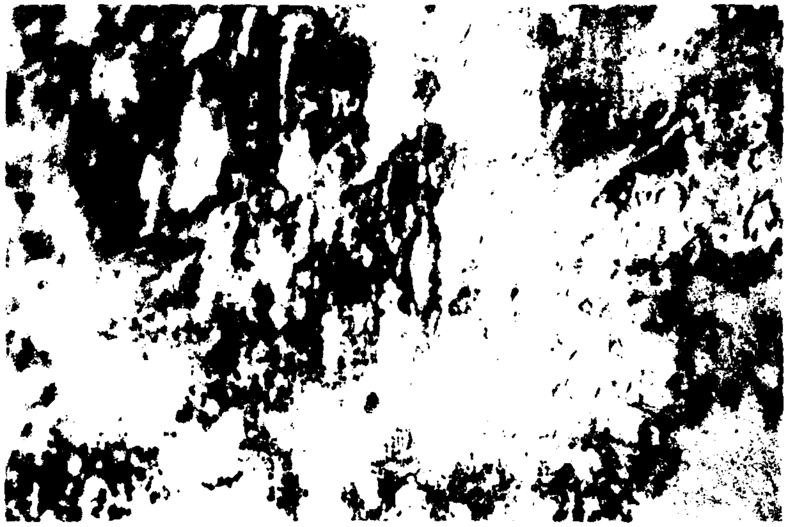


2. Lack of insulation around door frame and at foundations caused this mold growth.

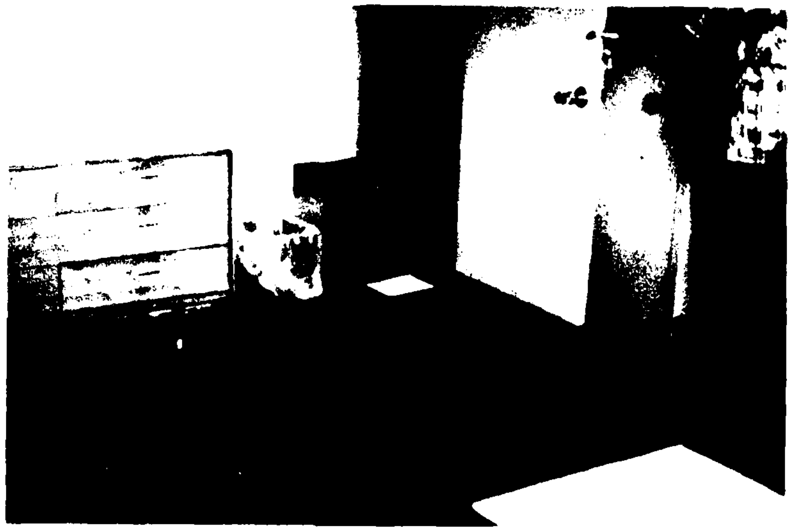
3. Note the moisture condensation on the windows and lintels of this newly renovated building. Window condensation might be reduced by double glazing and deflection of supply air from fan coil units. Lintel condensation would be reduced by insulating.

4. This cantilevered floor slab can't drain properly. Moreover, it is not thermally isolated from the conditioned space. The standing rainwater and resulting condensation combine to promote mold growth.

5. An unconditioned corridor has mold growth on the outside surface of the wall enclosing the conditioned space. These corridors frequently have the exterior doors blocked open, jalousie windows, and no control over air leakage.

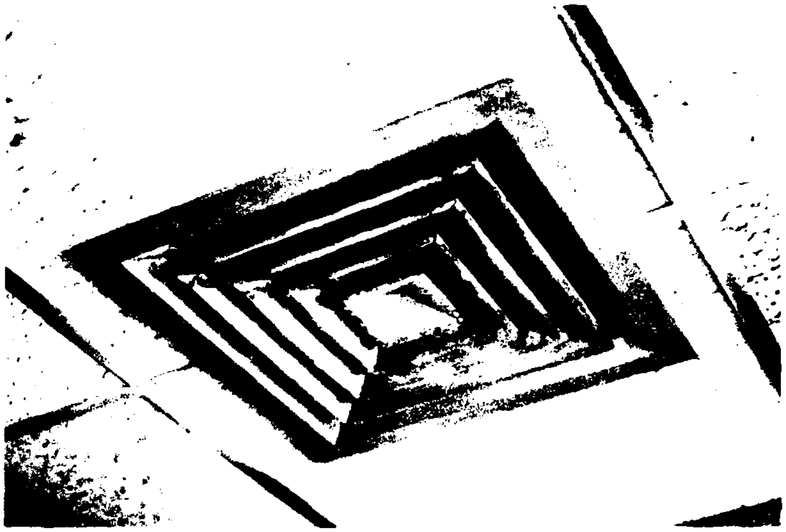


6. Closeup of corridor wall in Figure 5. Shows extent of mold growth.



7. This view shows a soaked carpet in an unoccupied hotel type room in Guam. This room has a ceiling soffit mounted fan-coil unit in which the drain pan became clogged and overflowed. Since the room was unoccupied, this condition went unnoticed for a long period of time, causing the damage shown. Note that the carpet soaked up the water, so that it was not seen in the corridor.

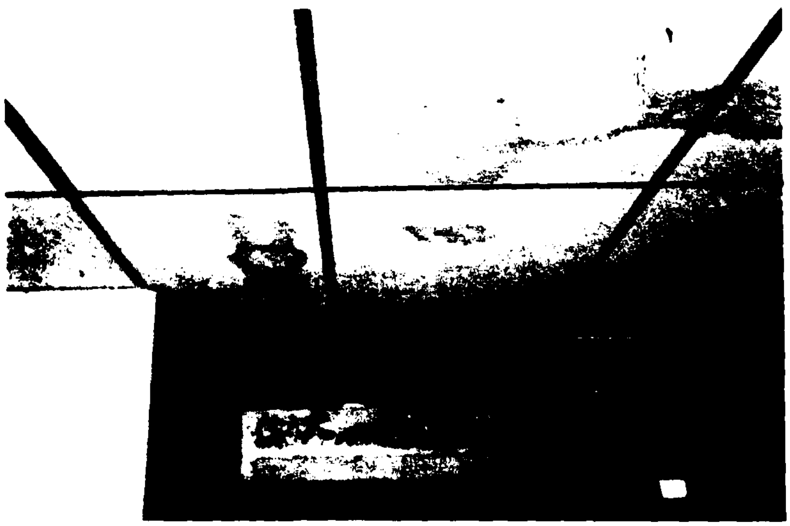
8. The top of this fan coil unit is rusting badly, due to high room dew point, and it is only one year old.



9. This view shows condensation and rusting on a ceiling diffuser, due to the low surface temperature of the diffuser and the high room dew point. Also note that the ceiling T bars are rusting, probably indicating some duct leakage above the ceiling, reducing the temperature of the T bar slightly below the dew point of the space.

10. This is the ceiling of an airconditioned room where the fan-coil unit is located in the corridor ceiling. Note how the mildew grows in the area immediately adjacent to the discharge of the fan-coil unit, due to saturated air impinging on what is probably a cold surface from the room above being cooler than this one, or due to fan cycling.

11. Pipe insulation saturated by exposure to humid air lost its thermal resistance, causing exterior condensation, dripping, and mold growth.



12. This view shows a ceiling stained from condensation dripping off chilled water piping above the ceiling. Also note the mold on the transom.

T H R E E

PRINCIPLES OF HUMID CLIMATE DESIGN, OPERATION AND MAINTENANCE

As background for the recommendations in the following chapters, this chapter discusses the principles of moisture control in airconditioned buildings in humid climates. Relationships between problems, their physical causes, and solutions appear in Table 3-1, which serves as a guide to this chapter. Since the observed moisture problems stem from readily identifiable physical causes, this chapter is organized primarily around these physical causes, and secondarily around their solutions.

Moisture problems encountered in humid climates stem from one, or more, of the following moisture-producing mechanisms:

Architectural

- o Surface condensation, both exterior and interior
- o Rainwater ponding on undrained building projections
- o Vapor flow into buildings
- o Condensation in building materials

Mechanical

- o Inadequate interior humidity control by HVAC system
- o Inadequate control of and conditioning of ventilating air

Referring to Table 3-1, as well as the foregoing list of physical mechanisms, note that the first four require predominantly architectural solutions, whereas the last two require mechanical solutions.

TABLE 3-1

GUIDE TO MOISTURE PROBLEM CAUSES AND SOLUTIONS

PROBLEM	PHYSICAL CAUSES	SOLUTIONS
1. Mildew (mold) on exterior surfaces	Condensation, high relative humidity, lack of sun and air motion, presence of fungus spores.	Warmer, more sun-exposed exterior surfaces, achieved through better roof & wall insulation, reduction of shaded, wind-sheltered surfaces.
2. Exterior paint peeling, blistering	Lack of moisture barrier, condensation, inadequate surface preparation, incompatible materials	See Solution 1, plus proper paint specification, surface cleaning, & application procedures
3. Insulating losses from condensation within wall or roof system assemblies	Vapor flow into building (from humid exterior toward cooler, drier interior)	Low vapor permeance on exterior surface (higher vapor permeance on interior surface)
4. Interior paint peeling, blistering	Condensation, inadequate preparation, incompatiible materials	HVAC humidity control, proper paint specification & application procedure
5. Property damage from drips, leaks, general condensation within buildings	Condensation, poor humidity control, equipment selection, maintenance and operation of HVAC system	a. Vapor retarder or low-permeance material on exterior surface, b. Better HVAC humidity control, plus control over the quantity of dehumidification of ventilating air
6. Uncomfortably high interior RH, (plus high latent cooling load on HVAC system)	Vapor flow into building through building envelope and infiltration	HVAC humidity control. See Solutions 3 and 5

See M0110 "Paints and Protective Coatings for Painting Practice Guidelines"

BASIC ARCHITECTURAL PROBLEMS

Exterior Surface Condensation

As indicated in Table 3-1, exterior surface condensation causes two moisture problems: mold and mildew on exterior building surfaces and peeling and blistering of paint. Discolorations -- in specks, spots, streaks, or patches of varying shade and intensity -- first appear as fuzzy, powdery surface growths, with colors ranging from predominant dark grays and black to yellowish or green tints.

Exterior mold growth occurs most frequently on walls, projecting columns, recessed wall areas, and cantilevered floor slabs. It is promoted by these factors:

- o Poor insulation
- o Thermal bridges
- o Shading
- o Stagnant air
- o Supercooling from clear-sky radiation
- o Light surface color
- o Ponding of rainwater

Poorly insulated walls are the most common sites for mold discolorations. A cooled interior produces a lower exterior wall-surface temperature in a poorly insulated wall than in a well insulated wall. See Fig. 3-1 and 3-2. In

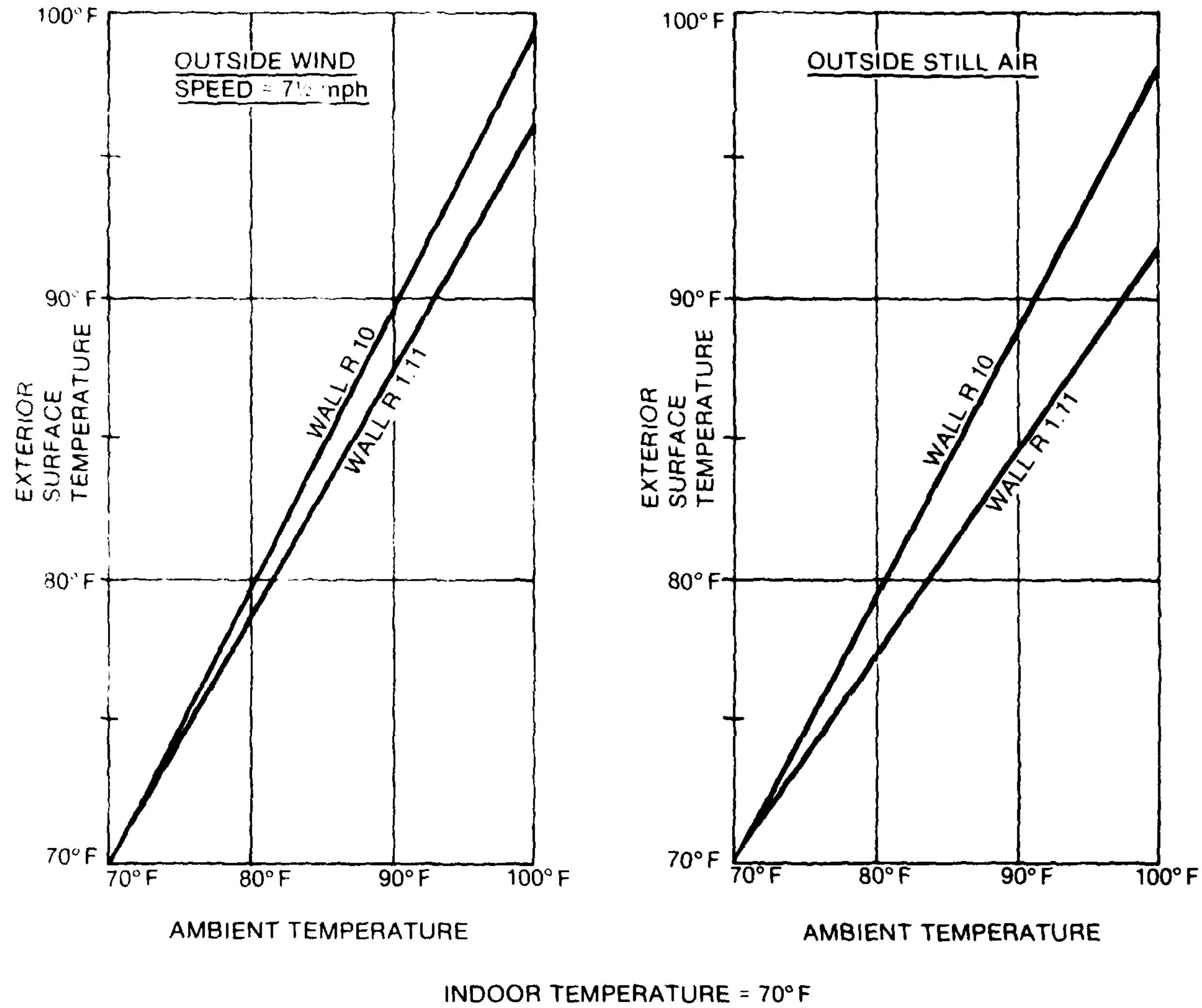


Figure 3-1 These curves show the benefits of wall insulation in raising outside surface temperature, especially with low wind speed, which raises the outside air film's thermal resistance (R value).

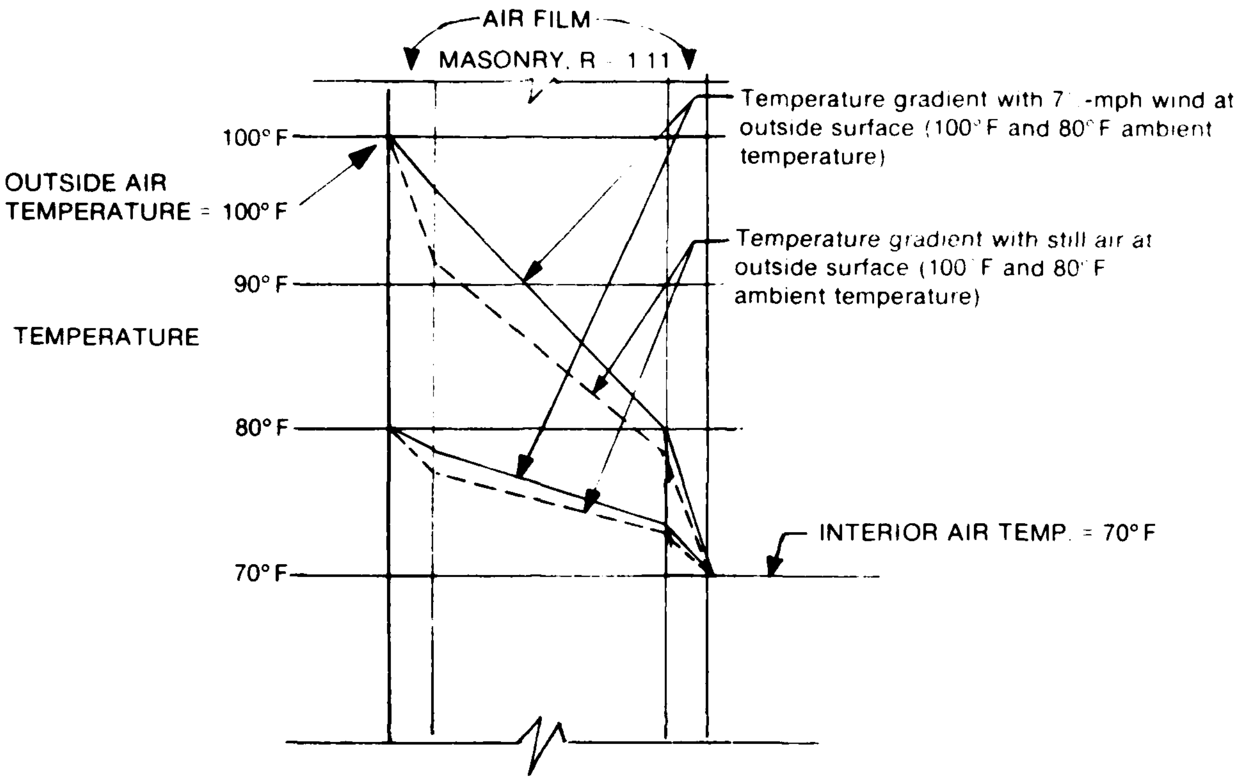


Figure 3-2 The above temperature gradients through a wall of low thermal resistance (R = 1.11, for 8-in. hollow block, sand and gravel aggregate) show the effect of outside air movement in raising outside surface temperature in humid climates, frequently above ambient dew point. Note that the thermal resistance (R value) of the outside air film decreases with increasing roughness of the outside surface. Roughness increases the surface area for conductance and for absorbing or emitting infrared radiation, thus increasing surface conductance by both these heat-transfer modes.

humid climates, ambient wet-bulb temperatures frequently approach ambient dry-bulb temperatures for hundreds, even thousands of hours annually. As a consequence, exterior wall-surface temperatures only a few degrees below ambient dry-bulb temperature can drop it below ambient dew point temperature both night and day. The consequently condensed moisture enhances fungus growth, with its resulting discoloration.

Foundation walls are especially vulnerable to mold growth, chiefly because of the uninsulated concrete's high thermal conductivity. Poured monolithically with ground floor slabs, or in direct contact with cooled, interior spaces, foundation concrete walls' exterior surface temperature often drops below dew point temperature, with resultant exterior-surface condensation for many annual hours. To raise the exterior foundation-wall surface temperature requires isolation or insulation of any foundation wall exposed to cool interior air. Insulating concrete foundation walls in humid climates departs from common construction practice in these areas. And this more complex design of foundations and slabs will normally increase construction cost. See Figure 3-3 for typical foundation wall insulation details.

Poor insulation can result from poor installation practices as well as poor design. The designer must consider not only the larger, uninterrupted wall and roof areas, but also the unusual conditions -- corners, edges,

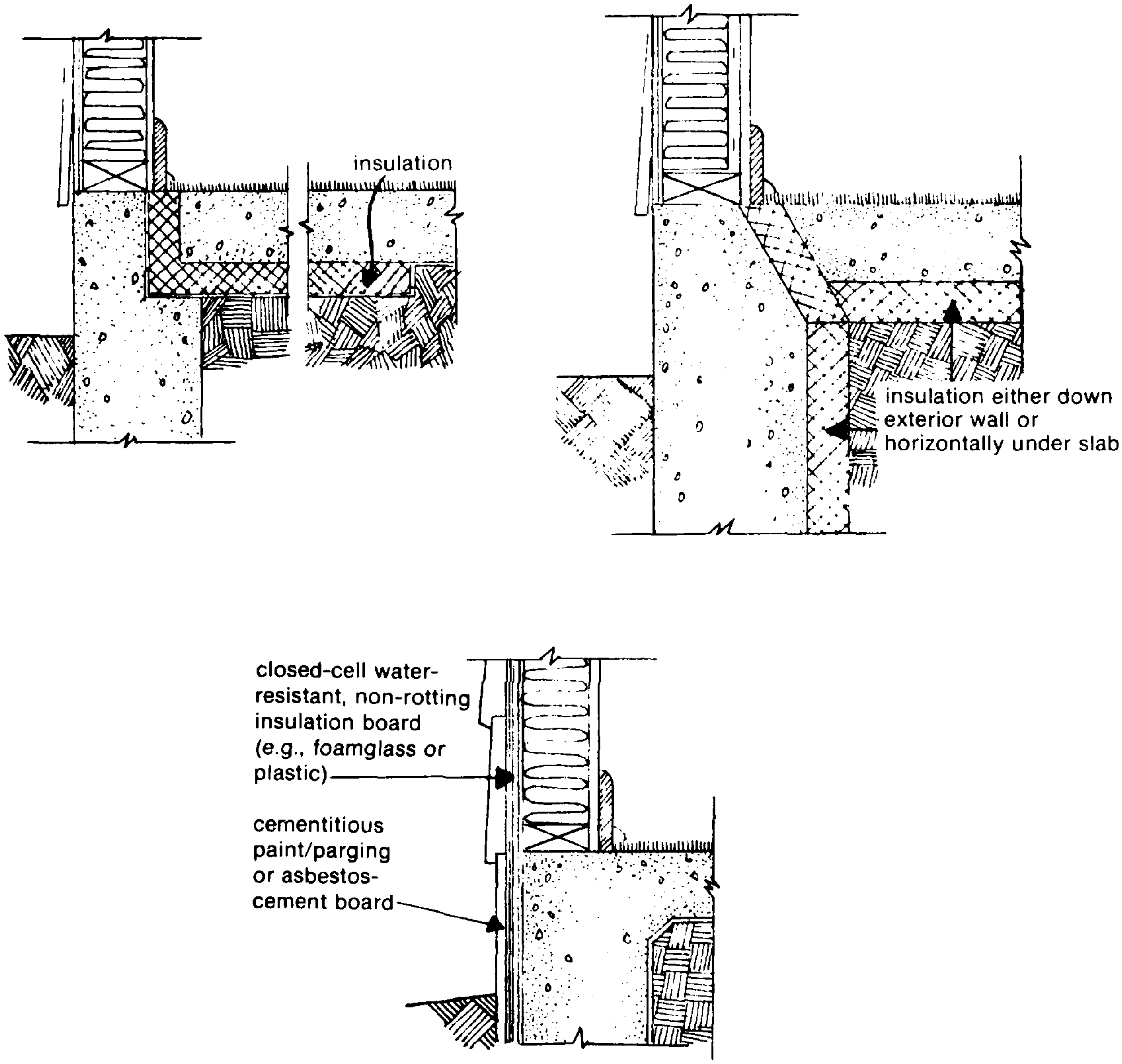


Figure 3-3 Foundation walls are more vulnerable to mold growth than superstructure walls. They also require insulation to raise outside surface temperature in airconditioned buildings located in humid climates. (The above details are based on those in the NAHB Insulation Manual.)

joints, changes in construction materials, spaces around window and door openings, louvers, piping and electrical conduit, plumbing vents, chimneys, fireplaces, flues, frames and mullions, cantilevered floor slabs, window shading projections, window and door sills, parapets, etc. Some of these items form thermal bridges.

Thermal bridges, like poor insulation, cause condensation on exterior surfaces by dropping surface temperatures close to the cooled interior temperature. A prime example of a thermal bridge is a concrete canopy or shading fins poured monolithically with the building's structural concrete frame, extending through the wall. Concrete is a notoriously poor insulator, with a thermal conductivity (k factor)= 12 Btuh/°F/ft /in.(R= .08°F/Btuh/ft /in.), about 50 times the k factor for fiberglass roof insulation board (R=4/Btuh/°F/ft /in.). See Fig. 3-4.

Studs, especially steel studs, in exterior walls also create thermal bridges between conditioned and unconditioned space. They should be avoided, if practicable.

Exterior surfaces of columns and foundation walls, other common locations for mold, act like monolithic conrete canopies and window frames as thermal bridges between inside and outside. Highly conductive heat transfer through the solid concrete keeps exterior surface temperatures close to those of the cooled building interior.

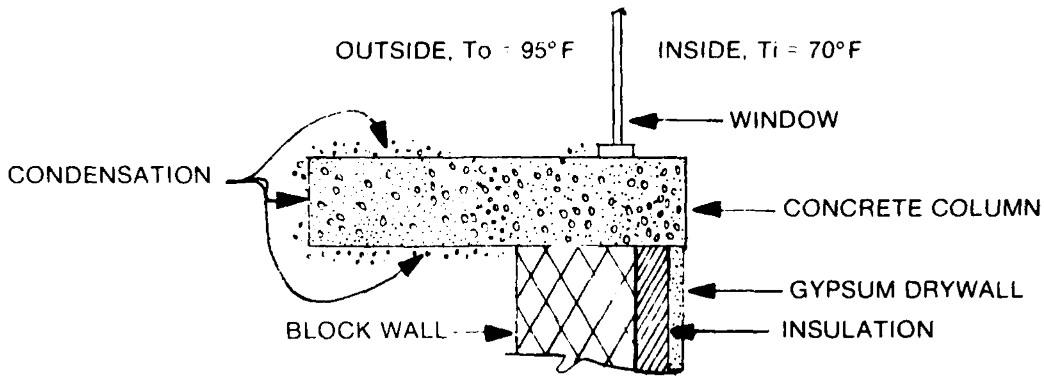
Thermal bridges should be eliminated, wherever practicable, -- for example through use of externally connected shading canopies rather than cantilevered concrete canopies. When it is impracticable to eliminate them, insulate the thermal bridges. See Fig. 3-5.

Shading -- from adjacent buildings, cantilevered canopies, horizontal projections, or mere geographic orientation -- promotes moisture-producing fungus growth, because it eliminates the solar-radiative temperature gains that evaporate moisture and dry sun-baked surfaces. Daytime temperature increases produced by solar radiation linger on into nighttime hours, inhibiting fungus growth. Conversely, fungus growth thrives in shaded locations, which remain perpetually cooler, and consequently more susceptible to moisture condensation for more hours than warmer, sun-baked locations.

Northern facades, which receive the least solar radiation in the Northern hemisphere, projecting end walls or columns, all suffer increased threat of fungus-caused discoloration from their shaded locations, as do southern facades in the Southern hemisphere.

To reduce wall-surface area favorable to mold growth, limit shaded areas to the glass portion of sun-exposed windows. See Fig. 3-6. Limiting both scope and size of shading canopies has two beneficial effects:

- o Reduction of the "cold-radiator" (i.e., thermal-bridge) effect



PLAN CROSS-SECTION
THRU CONCRETE MULLION FRAME

Figure 3-4 A thermal bridge formed by a continuous concrete mullion, column, window head, or structural member can reduce outside surface temperature by 2°F or more. Even this slight temperature drop can promote condensation, since outside surface temperature often approaches the dew point in tropical humid climates. This surface condensation can promote mold growth.

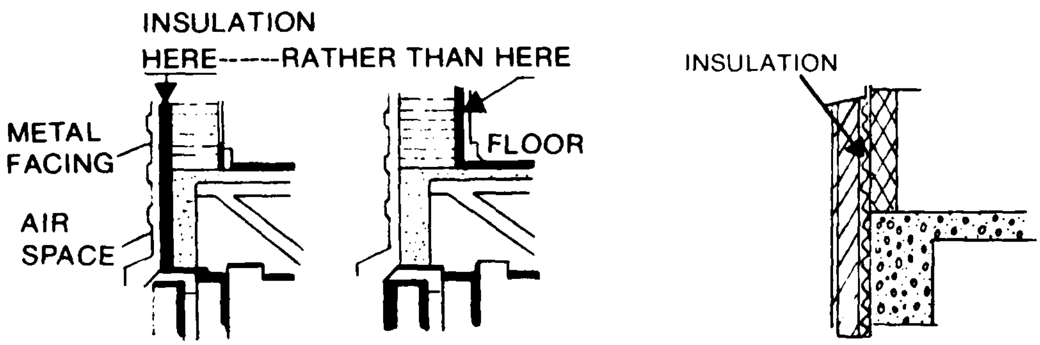
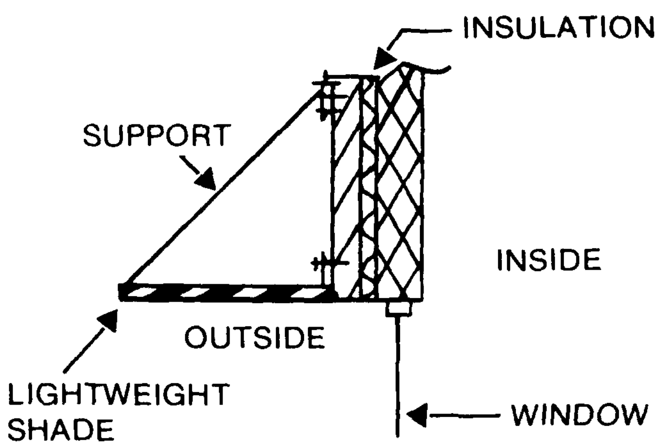
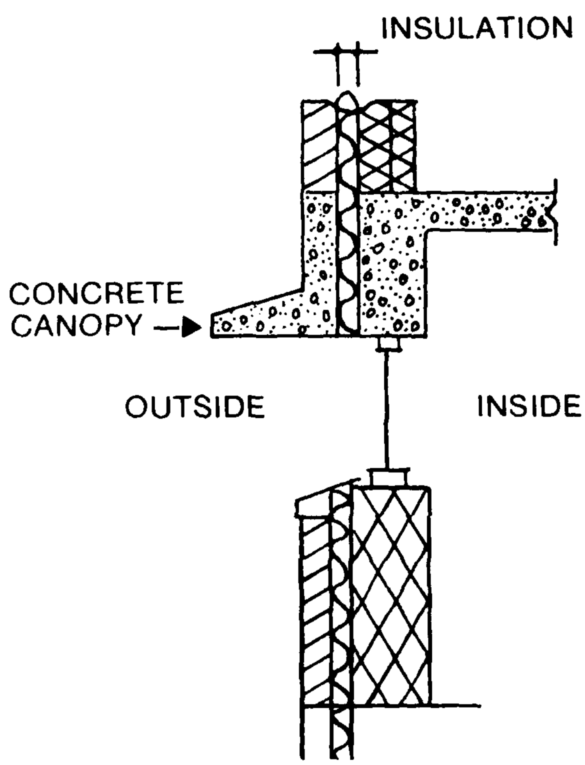


Figure 3-5 Placing continuous insulation on outside of structural framing (columns, spandrel beams, etc.) breaks thermal bridge -- i.e., rapid heat flow through highly conductive structural steel or concrete.



LIGHTWEIGHT METAL SHADE IS SUPPORTED BY EXTERIOR WALL FACING, THERMALLY ISOLATED FROM COOL INTERIOR



CONCRETE CANOPY IS SEPARATED FROM INTERIOR STRUCTURE. INSULATION CARRIED THROUGH FROM CAVITY WALL TO RAISE ITS TEMPERATURE

Figure 3-6 Window shading devices should be designed to (a) shade glass only, thus reducing shaded wall area, which is more vulnerable to condensation, moisture retention and consequent mold growth than sun-exposed wall area; (b) provide thermal breaks, thus raising the temperature of these shading surfaces for better evaporation of water, and (c) drain rainwater away from the building. The above sketches show some examples of how these goals can be accomplished.

- Increased evaporative air flow and sunlight on building surfaces

Stagnant air in wind-sheltered locations -- e.g., building projections such as columns, wing walls, and exterior stairways -- similarly promotes mold growth, because it prevents dissipation of moisture by air currents flowing over the surfaces. This phenomenon tends to aggravate mold growth on foundation walls. Wind velocity decreases as elevation decreases. Foundation surfaces near ground level thus lose the evaporative effect of higher wind velocities at higher building elevations.

Supercooling from clear-sky radiation can depress surface temperature by up to 10°F below ambient. This phenomonon occurs on clear nights with little or no cloud cover, which absorbs and re-radiates the longwave heat energy from the earth. Clear nights increase surface heat loss in earth-sky radiative exchanges and reduce building surface temperatures.

When the foregoing factors act in combination, they compound the problem of surface condensation. For example, poorly insulated wall surfaces under a cantilevered canopy and wind-sheltered by a projecting column or end wall suffer additional condensation caused by poor insulation, shading, and still or stagnant air, with possibly some deleterious effect from clear-sky radiation.

Surface color may exert some slight effect on a wall surface's vulnerability to mold growth. Most tropical building walls and roof surfaces have light-colored surfaces, designed to reflect solar radiation and reduce surface temperature and, consequently, reduce cooling load. This reduction in outside surface temperature slightly increases the risk of condensation. The risk however, is minimal, chiefly because nocturnal subcooling occurs independent of color. Surface color is even less significant than building mass in lowering or raising nighttime temperature, and, as discussed later, building mass is also a minor factor. The disadvantage of higher cooling-energy costs will almost always outweigh the slightly reduced risk of surface condensation on dark-colored building surfaces. Other techniques -- notably, improved insulation -- offer a much better solution to moisture problems than dark, heat-absorptive surfaces. Moreover, the better insulated a wall or roof is, the less significant is its color.

Ponding of rainwater on undrained building projections -- canopies, window sills, etc. -- can provide an even more abundant moisture source for mold growth than condensation. Top surfaces of all building projections should slope away from the building, to drain these surfaces and expose them to the evaporative effects of sun and wind as soon as possible after rainfall.

Building mass may be a minor factor affecting surface condensation and consequent mold growth, but it is very difficult to determine whether or not lightweight or heavyweight construction provides better defense against moisture problems. On hot, sunny days, heavyweight construction would have a slight advantage for its stable surface temperature would tend to remain above the dew point temperature, whereas lightweight construction could drop below the dew point temperature for the majority of nighttime hours. See Fig. 3-7.

Lightweight construction may however, have the advantage during the cooler, cloudier weather that predominates in some humid climates, when ambient dew point temperature is closer to ambient dry-bulb temperature. Since the exterior surface temperature of lightweight construction more closely parallels ambient dry-bulb temperature, its exterior surface temperature will tend to rise in the early morning hours with the rise in ambient temperature. Heavyweight construction will tend to remain cooler, possibly at or below dew point temperature, thus promoting condensation and mold growth.

Thus the doubtful efficacy of heavyweight construction in preventing or reducing surface condensation, plus its higher cost, effectively removes wall mass as a method of controlling exterior mold growth. Improved insulation and/ or some other dependable moisture-control technique will generally prove more effective and less costly than increasing, or lightening, wall or roof mass.

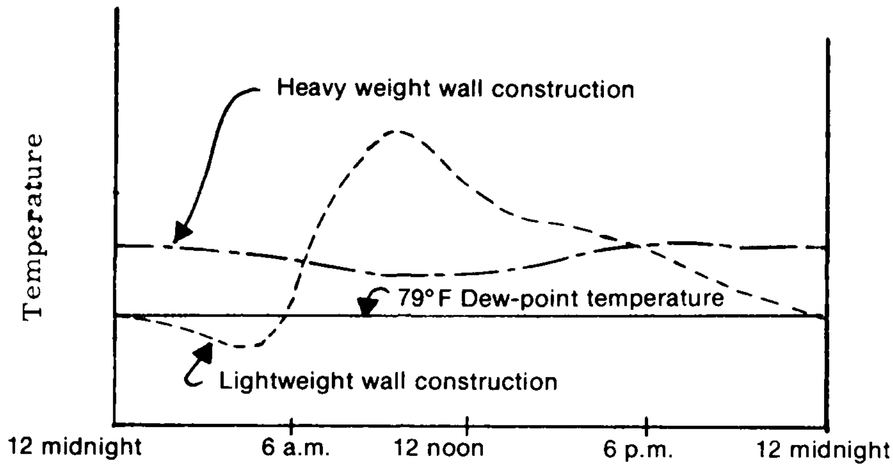


Figure 3-7 These curves show east exposure, light-colored, exterior wall-surface temperatures for one sunny day, 16°N latitude, July conditions, with constant 79°F dew point temperature maintained throughout the day. A heavy weight wall, roughly 130-psf density, maintains wall temperature above the 79°F dew point, reducing, if not eliminating, the risk of surface condensation and consequent promotion of mold growth. In contrast, the lightweight wall, roughly 10-psf density, drops below the dew point temperature during the nighttime hours. It should be recognized that there will be many combinations of ambient temperature and dew point temperature occurring throughout the year.

In addition to discoloration by mildew (mold) condensation on exterior surfaces causes paint peeling, flaking, and blistering. Blisters result from the evaporation and expansion of moisture trapped between the painted surface and the paint film.

These humid-climate painting problems can be alleviated by the following remedies:

- o Design of building surfaces by the previously discussed principles to prevent surface condensation
- o Design of building surfaces to promote quick drainage and evaporation of any accumulating or condensing moisture
- o Proper preparation of the exposed surface to assure that it is clean and dry, as required for paint or finish application
- o Use of the proper, exterior-grade paint or finish

Because of the normally perpetual vapor flow toward the inside of airconditioned buildings in humid climates, exterior wall finishes should have lower vapor permeability (higher vapor resistance) than interior finishes. Obtaining paint perm-rating data is difficult, because few paint manufacturers publish them. In fact, few manufacturers have tested their coatings for perm ratings, thereby leaving an information gap apparently attributable to designers' general failure to follow the principles of humid climate design. Paint specifiers must consequently exercise care in choosing paints for airconditioned buildings in humid climates. They should question manufacturers about general performance, specifically about paint perm ratings. Normally the higher the gloss rating, the lower the perm rating, and oil base paints have lower perm rates than latex.

Vapor Flow into Building

Water vapor flowing into a building from the warm humid exterior creates several problems:

- o Reduced thermal resistance and possible deterioration of insulating and construction materials wetted by condensed water vapor
- o Increased latent cooling load for the HVAC system
- o Reduced comfort from increased interior RH if the increased latent load is not totally dissipated by HVAC system

This humid-climate, vapor-flow problem is normally more serious than the reverse-direction vapor-flow problem in buildings in cold climates. There are two reasons:

1. The vapor-pressure differential between inside and outside is normally greater in a humid climate than in a cold, dry climate, up to 0.8 in. Hg in humid climates, rarely above 0.4 in. Hg in cold climates. See Figure 3-8 for typical vapor-pressure conditions in a humid climate.

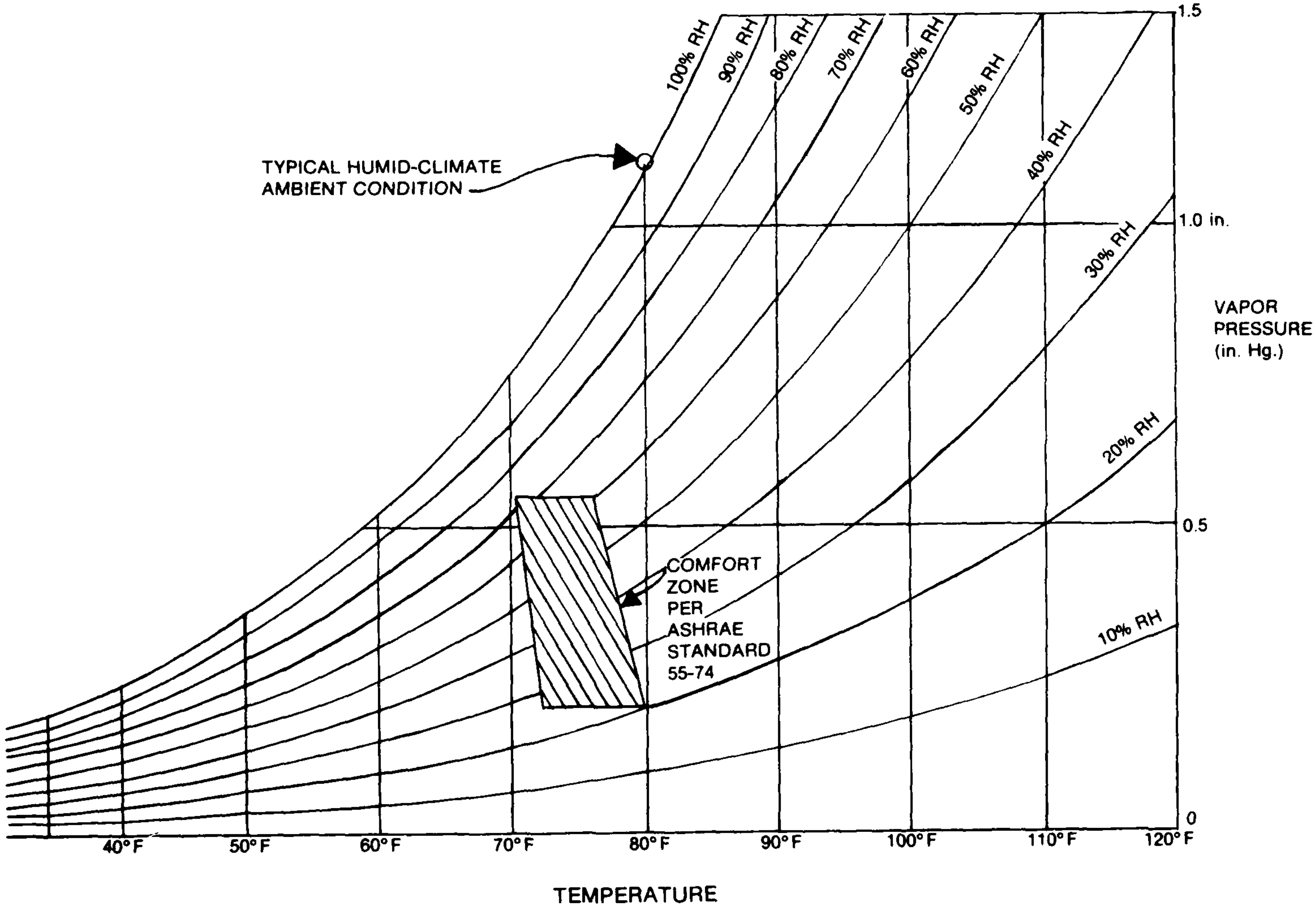


Figure 3-8 The above plot of vapor pressure vs. ambient dry-bulb temperature and relative humidity (RH) shows the high vapor-pressure differential that can exist in a humid climate, with vapor flowing from outside toward the building interior through walls and roof. In cold climates, vapor flow is outward, from the warm interior toward the cold, dry exterior -- "dry" even at 100%RH.

2. Vapor flow is normally unidirectional in humid climates, whereas in cold climates the seasonal (winter-summer) vapor-flow reversal permits self-venting, with summer dissipation of some and possibly all winter-accumulated moisture.

Since most building materials are highly vapor-permeable, paints and finishes become major determinants of vapor flow through walls and other building components lacking a vapor retarder.

Water vapor can flow through the building envelope via two mechanisms: diffusion and air leakage. Compared with heat transmission, diffusion corresponds roughly with conduction. Air leakage corresponds with infiltration. In accordance with Fick's Law of Diffusion, water vapor diffuses through the building envelope -- i.e., walls, doors, and roof -- depending on its permeance. In climates with high ambient dew point temperatures, there is a large vapor-pressure differential impelling diffusion toward the airconditioned interior. Yet despite the theoretical knowledge of basic diffusion principles, vapor flow cannot be accurately calculated.

One reason for the difficulty in calculating vapor flow is the role of air leakage, in which water vapor flows in with air following wind and atmospheric pressure changes. Air leakage is even less subject to accurate calculation than diffusion, and it can convey even larger quantities of water vapor than diffusion. Water vapor flows through open doors and windows. Exterior doors, fixed open for convenience in high-traffic areas, can load conditioned spaces with humid, outside air. Door closers may not work, and some ill-fitted doors do not close tightly. Windows may be opened by occupants seeking relief from inadequate airconditioning.

Infiltration through other building components can account for substantial quantities of interior water vapor. These vapor-admitting components include vents, louvers, stacks, flues, and joints at doors, windows, wall and roof penetrations, eaves and other wall-roof junctures.

Condensation in Building Materials

Inwardly flowing water vapor, via diffusion or air leakage, may condense within the building envelope if its flow is obstructed by a surface with high vapor resistance or containing construction materials at or below dew point temperature. In climates with dry seasons or heating seasons, reversal of the vapor-pressure gradient gives entrapped moisture an opportunity to escape. But the unidirectional vapor flow in a perpetually warm, humid climate aggravates the problem. There is seldom, if ever, an opportunity for vapor that has condensed within a wall to escape in the opposite direction.

WALL MOISTURE FLOW

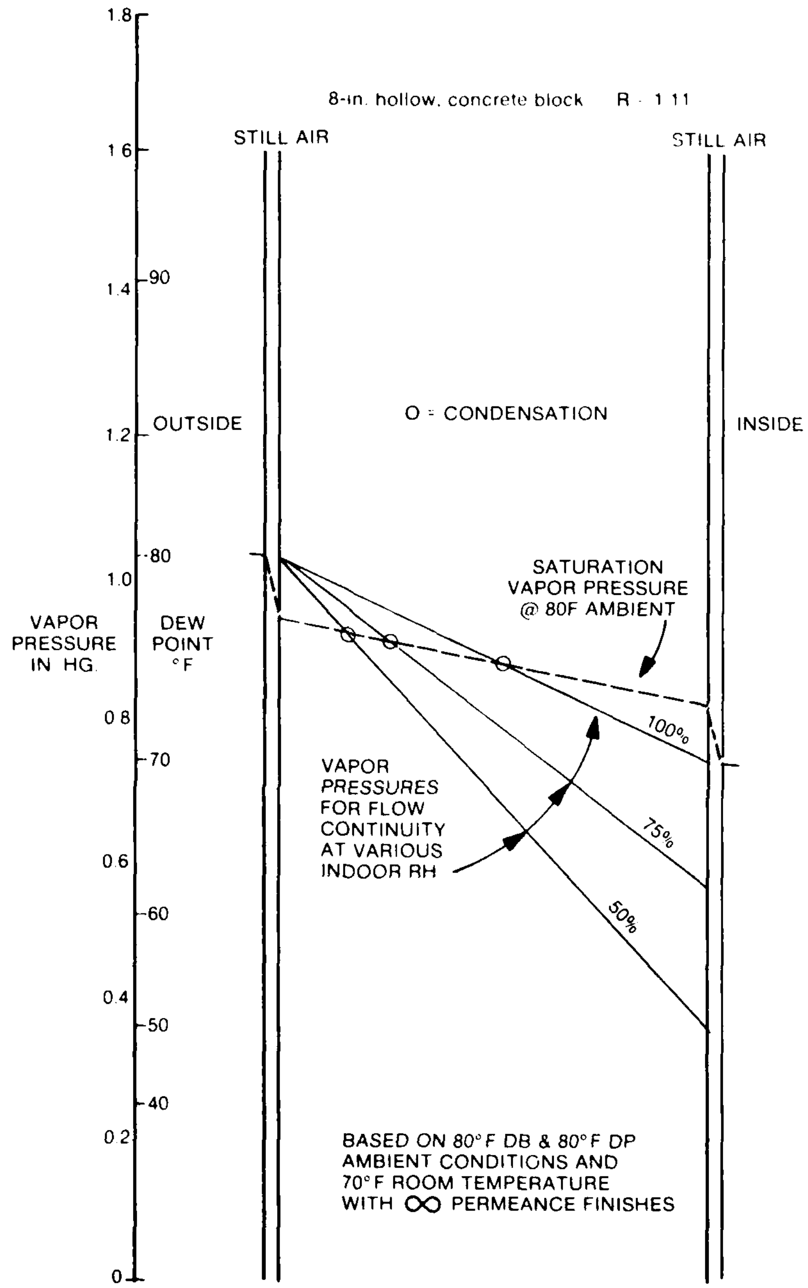


Figure 3-9 These vapor-pressure gradient lines for three different interior RH values are for totally permeable finishes, interior and exterior. To prevent condensation at the intersection of the three vapor-pressure gradient lines with the saturation-pressure gradient line, requires a low-permeance exterior surface finish to reduce vapor-flow and drop the vapor pressure below the saturation pressure line.

Condensation within the building envelope can create several problems:

- o Drastic reduction of some insulating materials' thermal resistance
- o Accelerated decay of organic materials entrapping the moisture
- o Stained, blistered, flaked or spalled finishes, a result of moisture trapped at the finish's hidden surface
- o Weakening or sagging of gypsum wall or ceiling boards with absorbed moisture
- o Ceiling collapse from increased weight and/or decreased strength of moisture-absorbing ceiling panels.

Water absorption in thermal insulation can drastically reduce its thermal resistance. Water filling an insulating material's interstices generally replaces air (thermal conductivity = 0.13 Btuh/ft /in./°F at 80°F, R=7.6/in.) with a material whose thermal conductivity is about 30 times as great at above-freezing temperatures (when k = 4 Btuh/ft /in. /°F, R=0.25/in.) Losses in thermal resistance depend upon the water-absorbing capacity of the insulating material and its degree of saturation. Some closed-cell materials lose relatively little thermal resistance -- about 2% for foamglass and 10% or so for extruded polystyrene. But fibrous materials like fiber glass, fiberboard and perlite board suffer great losses, ranging up to 40% under severe moisture conditions. (39)

An especially serious problem for HVAC system performance in humid climates springs from the loss of thermal resistance in wet insulation around chilled-water piping. This problem arises from the unidirectional water vapor flow characteristic of humid climates -- from warm, humid exterior to the cooler pipe surface. Absorbed moisture accelerates heat conduction through the pipe insulation. These pipe-insulation losses raise the temperature of the chilled water as it flows farther from the central refrigeration plant and impair the HVAC system's performance. For chilled water coils with a minimum number of rows, a 10°F higher entering chilled-water temperature can reduce dehumidification capacity by 80%.

It is the relentless unidirectional water vapor flow that creates this problem. Good workmanship when installing a well designed pipe insulation system, with highly impermeable vapor retarder and moisture-resistant insulation, can delay the inevitable saturation of the pipe insulation, thus maintaining low chilled-water temperature rise for years. Poor design and installation reduce insulation efficiency and shorten the time needed to reinsulate the piping. Fiberglass insulation may take as little as three years to become water-saturated, whereas a moisture-resistant insulation like foamglass may take 10 years or more.

But regardless how well insulated they are, chilled-water pipes should be accessible for removal of old, wet insulation and installation of new, dry insulation. The designer must concern himself with this problem of making chilled-water piping accessible. It cannot be simply buried in the ground, enclosed in a wall or partition, or run between joists in a ceiling space. Its periodic reinsulation must be anticipated, with removable panels designed specifically to provide ready access to the piping.

Wetting of airconditioning duct insulation is a less prevalent problem than wetting of chilled-water pipe insulation, for two reasons:

1. The duct is usually in conditioned space, with controlled RH and inward vapor-pressure reduced, at least to some degree.

2. The conditioned air temperature is generally 5°F to 10°F higher than chilled-water temperatures, further reducing the vapor-pressure gradient.

Ducts should not run through unconditioned space, but if this ill-advised practice is unavoidable, additional insulation is required. Insulation should be non-water-absorptive -- e.g., foamglass -- with a vapor-retarder jacket.

As discussed elsewhere in this manual, the designer should avoid unconditioned ceiling spaces, with or without outside ventilating air.

Accelerated decay of wet insulation is another problem accompanying its loss of thermal resistance. Decay stems not only from fungal attack on organic materials, but from the dissolution of phenolic binders in some inorganic materials.

Weakening of wall or ceiling boards or tiles results from the steady condensation of invading water vapor, progressively accumulating quantities of liquid moisture that can sometimes cause ceiling-panel collapse. The unidirectional vapor-flow characteristic of tropical humid climates fuels these steadily worsening material-weakening processes.

Principles of Good Painting Practice

Condensation on exterior or interior surfaces serving as substrates for paint or other coatings produces staining, blistering, flaking, and spalling. Entrapped moisture either shows through the finish or evaporates and expands, prying parts of the finish off its substrate.

In summary, painting errors generally stem from violations of the following principles of good painting practice:

1. No psychrometric vapor flow consideration given to the painting process
2. Inadequate substrate preparation

3. Paint applied over wet or mildewed surfaces

4. Use of wrong paint for exterior surface

5. Use of incompatible basic coatings

6. Incorrect mixing of batches

Inadequate substrate preparation of repainted surfaces poses an especially difficult problem: How to remove all incompatible multi-layers of existing paint to expose an acceptable surface to receive new paint.

On exteriors in the continental United States, sand blasting has been an excellent and acceptable method. In humid climates, there are some cautions:

- o The air compressor must have a water trap to remove the condensate generated by the air compressor, thus preventing its absorption by the blasting aggregate.
- o Aggregates must be carefully chosen. Favor such satisfactory materials as coke or coral. Avoid materials such as silica blasting aggregates. They may contain large quantities of water, which tends to clog the hoses.

Where sand-blasting equipment is not available, high-pressure water jets are excellent. Mounted on mobile towers, they can clean buildings as high as six to eight stories. Such a water jet system can remove all mold or mildew when sodium hypochorite is added. This jet also removes loose masonry particles. A three to four-day drying period is usually sufficient before applying the first coat of paint.

A textured, polymerized coating shows promise as a humid-climate coating. Applied to a building in Guam in 1974, this coating showed no blemishes when inspected four years later, in 1978. Available in a family of emulsion polymerized, thermoplastic solvent-soluble resins -- specifically, vinyl toluene copolymer, vinyl toluene butadiene copolymer, styrene/butadiene, and styrene acrylate -- this textured coating can be applied to a whole spectrum of substrates: masonry, wood, steel, aluminum.

Materials such as two coats of interior semi-gloss acrylic latex, exterior acrylic latex, exterior soya-alkyd resin or aluminum paint, which have performed well by test as interior vapor retarders, should be avoided as interior finishes but considered as exterior finishes, according to their published perm ratings.

BASIC HVAC PROBLEMS

Inadequate Interior Humidity Control

Excessive interior humidity, a consequence of vapor flow into buildings from a humid climate's atmosphere toward the cooler, drier interior, causes major problems -- uncomfortable high interior RH, mold growth, and property damage from interior condensation on surfaces at or below dew point temperature. The solution of many moisture-caused problems depends partially on good HVAC design -- for example, the elimination of interior condensation, which may result from a combination of excessive, uncontrolled entry of humid outside air through porous walls and air-leaking joints and the HVAC system's failure to control interior RH. Humidity control for interior comfort however, depends totally on good HVAC system design and operation. For this reason, the principles of controlling interior humidity are discussed in these final sections of this chapter, along with ventilation.

HVAC Design Criteria

The primary goal of an HVAC system in a humid climate is comfort under all cooling loads. As the means to this end, the HVAC system should:

- o Dehumidify under all loading conditions
- o Operate reliably
- o Tolerate variations in chilled-water temperature
- o Avoid installation of concealed chilled-water piping -- i.e., in partitions or above occupied space, to eliminate that source of condensation and wetting of ceiling tiles, or in partitions
- o Minimize occupants' opportunity and temptation to tamper with HVAC controls

- Provide positive continuous dehumidification of outside ventilating air under all loading conditions to avert possible increases in space humidity
- Prevent condensation in the conditioned space to the maximum practicable extent
- Allow condensed water, i.e., (coil condensate and pipe dripping) to be quickly drained.

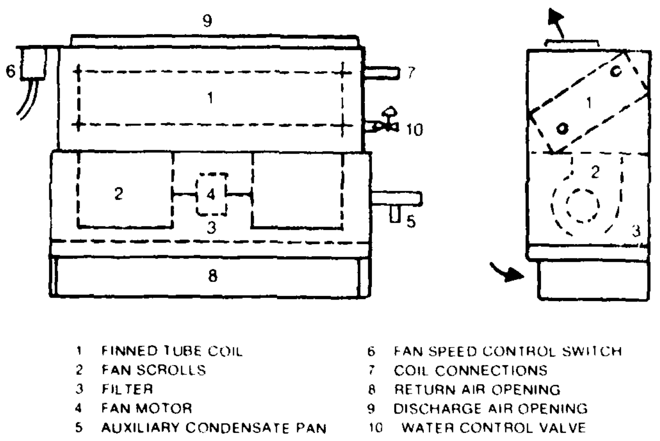
This last-noted point requires several design precautions. Cooling coils and other exposed cold surfaces should be provided with positive drainage to carry condensed water away and prevent standing water from collecting dirt, generating odor, and promoting mold growth. Air-handling units should be preferably located outside of the conditioned space, with large adequate drains, maintained in a free-flowing state, since a clogged drain is temporarily equivalent to no drainage.

Airconditioning systems employing variable supply air temperature, such as room thermostats controlling fan speed or chilled water flow, create moisture problems by allowing humidity to vary over a wide range and alternately raising and lowering surface temperatures adjacent to the supply air, thus permitting condensation to occur.

Judged by our field investigations, virtually every building with major moisture problems in humid climates has a fan-coil HVAC system. See Fig. 3-10. Buildings with other types of central airconditioning systems or unitary systems tended to have fewer or no moisture problems, primarily because of their increased dehumidification capability.

Oversizing of HVAC systems is a critical design error in humid climates. The more oversized the HVAC system, the lower its average load and the greater its tendency toward inadequate dehumidification. With a room thermostat controlling either chilled-water flow or fan operation at light sensible cooling load, there will be either: (a) inadequate chilled water flow, or (b) inadequate fan operating time to permit sufficient dehumidification for comfort control of interior RH. Humid climates, by their very nature, have high latent cooling loads and much lower sensible heat factors than any other type of climate. Moreover, sensible loads in humid climates tend to average much less than latent cooling loads, thereby aggravating the problem.

The best general solution to this problem is to provide an all-air-type airconditioning system capable of continuous dehumidification under all conditions of load. In humid climates, this virtually dictates the use of some form of reheat, since the dehumidification process will almost always require excess sensible cooling. All-air-type HVAC systems --e.g., variable air volume (VAV) and/or reheat systems --are the most suitable for this purpose.



TYPICAL FAN-COIL UNIT
(from ASHRAE 1976 Systems Handbook, P. 4.17)

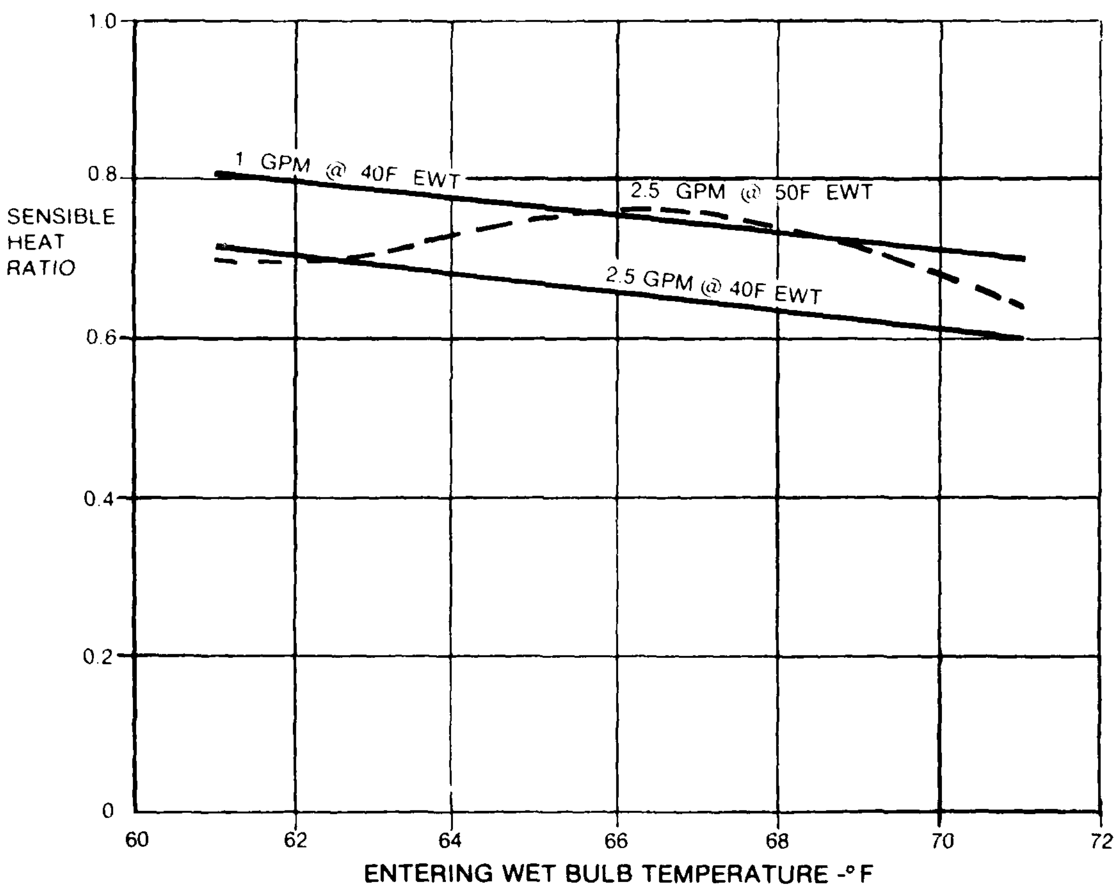
Figure 3-10 In a fan-coil unit, the fan blows recirculated room air, sometimes mixed with outside air, over coils cooled by chilled water circulated from a central refrigeration plant. In drier, colder climates, where they heat buildings in winter with hot water circulated through the coils, fan-coil units can normally satisfy ASHRAE comfort criteria. But they can't handle the high latent cooling loads of tropical humid climates without overcooling the space.

Why Fan-Coil Units Won't Work

At best, the conditions achieved by the use of fan-coil units can only approach the fringe of the ASHRAE comfort zone unless reheat is used. Under humid-climate conditions, it can satisfy a need for either temperature control or humidity control, but not both simultaneously. To maintain interior RH at 60% or less with fan-coil units, it is normally necessary to overcool the space to temperatures below 72°F, especially when the sensible cooling load is low. Conversely, when room temperature is maintained at 72°F or higher, RH generally exceeds 60%. The higher the room temperature, the lower the sensible load; less cooling is done and RH rises. This is aggravated by infiltrating humid air, plus water vapor generated by occupants, cooking, showers, storage of damp clothes, etc.

The diagram of Fig. 3-11, plotting sensible heat ratio and entering wet-bulb temperature for fan-coil units, depicts the problem. As the entering air wet-bulb temperature increases, the sensible heat ratio drops, making more latent cooling capacity available. But under normal humid-climate conditions, there is little or no sensible cooling load for many hours. Since the fan-coil unit is controlled by a thermostat rather than a humidistat, it either stops operating or, if the thermostat is set below the ASHRAE comfort range, the fan-coil unit continues operating and cools the space below the ASHRAE comfortable temperature range. Under

FAN COIL SENSIBLE HEAT RATIO VS ENTERING WET BULB



BASED ON CARRIER SERIES 42V, SIZE 2, 3 ROW COIL, 200 NOMINAL CFM

Figure 3-11 As entering wet-bulb temperature increases, sensible heat ratio decreases, providing more latent cooling capacity. To utilize this capacity however, requires a sensible cooling load, which may be so low that insufficient latent cooling is done.

most operating conditions, overcooling is the only way it can normally reduce RH below 60%.

Another problem with fan-coil units in humid climates concerns the number of cooling-coil rows. The fewer the cooling-coil rows in a fan-coil unit, the lower its latent cooling capacity. But with the relatively low sensible cooling design loads encountered in humid climates, one and two-row coils provide the required capacity. As a consequence, these coiling coils with relatively lower latent capacity are usually selected over those with three or four-row coils with higher latent cooling capacity. Thus the fan-coil units normally selected for humid climates lack sufficient latent cooling capacity, especially under light sensible loads. For a given-size fan-coil unit, additional coil rows provide significantly greater sensible and latent capacity. See Fig. 3-12, which compares three and four-row coils.

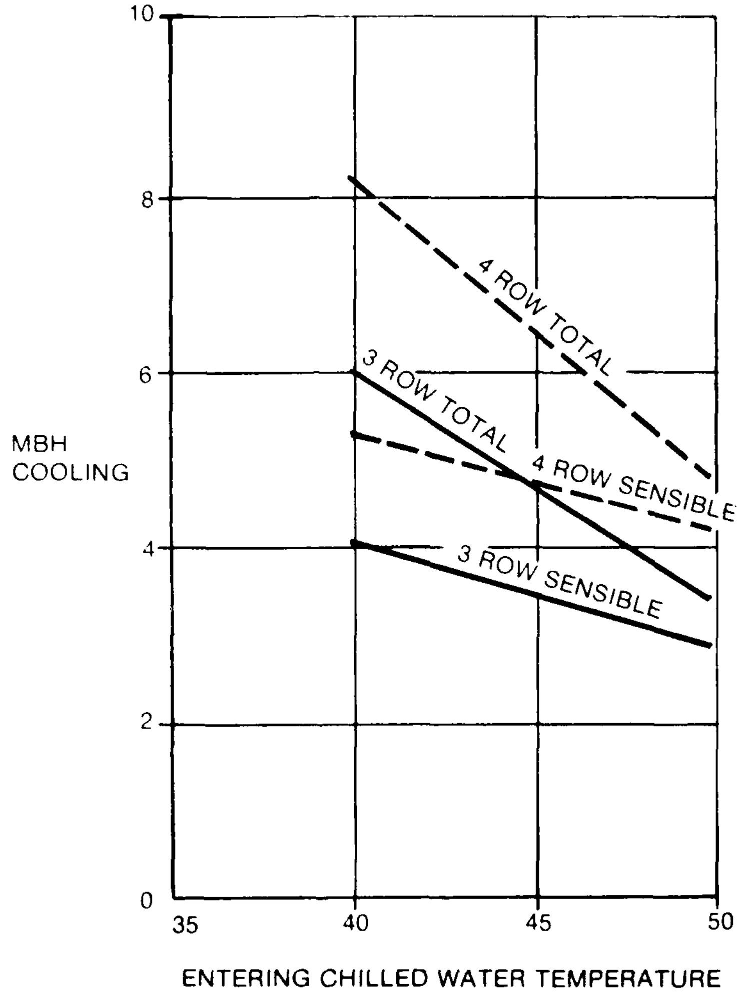
Another vital factor, often ignored in the operation of humid-climate central HVAC systems, is proper chilled-water temperature and temperature rise, which is also shown in Fig. 3-12 and 3-13. A 10°F increase in chilled-water temperature, from 40°F to 50°F, drops the latent cooling capacity by 75-80% for both three and four-row coils, while dropping the sensible cooling capacity by only 20-25%. Fig. 3-13 shows how the latent portion of the fan-coil unit capacity is reduced, both in magnitude and in percent of total capacity, as the chilled water temperature rise is increased. In order to achieve maximum latent cooling capability, chilled water temperature rise should be as low as possible.

Chilled-water flow through fan-coil units also affects latent cooling capacity. As chilled-water flow rate decreases, latent cooling capacity drops faster than sensible cooling capacity, as shown in Fig. 3-14. Humidity control thus depends more on maintaining both chilled-water temperature and adequate chilled-water flow than on the sensible or total cooling capacity.

Air flow has an opposite effect from chilled-water flow and chilled-water temperature. Reduced air flow over the cooling coils drops sensible cooling capacity faster than latent cooling capacity, as shown in Fig. 3-15. Under light sensible cooling load, reduced air flow tends to provide slightly more dehumidification.

Introducing outside air through the fan-coil unit creates additional problems. Unless the fan-coil unit operates continuously, entering outside air will not be continuously dehumidified. When exhaust systems remove more air than the fan-coil unit was designed to handle, excess outside air flows in through the air intake. As a consequence, when the thermostat-sensing element is located on the inlet side of the coil in the fan-coil unit, it may respond more to outside air temperature than to room temperature. This causes overcooling whenever the outside dry-bulb temperature is higher than room temperature, the normal

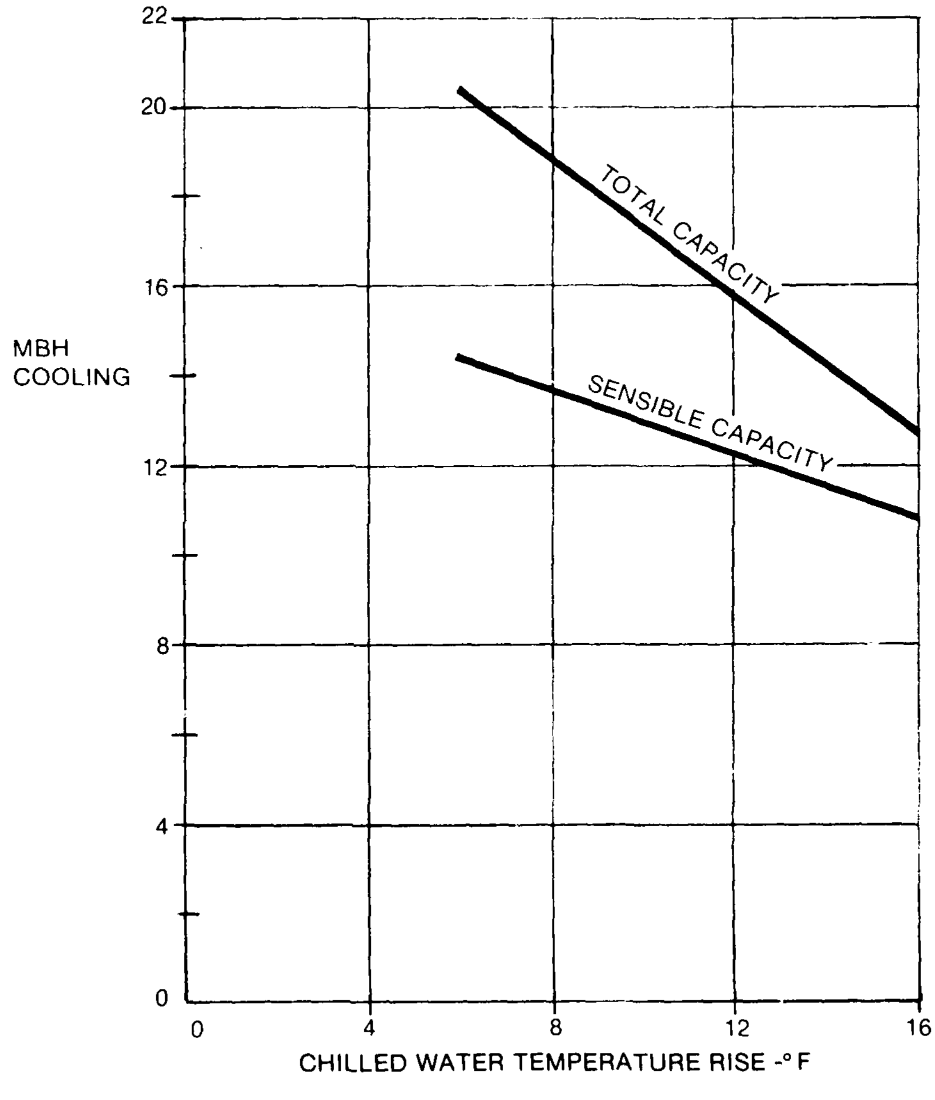
FAN COIL COOLING CAPACITY VS ROWS AND WATER TEMP.



BASED ON CARRIER SERIES 42V, SIZE 2, 200 CFM
10F WATER RISE, 80F/67F ENTERING AIR

Figure 3-12 Total cooling capacity (both sensible and latent) of given-size fan-coil unit varies with number of coil rows.

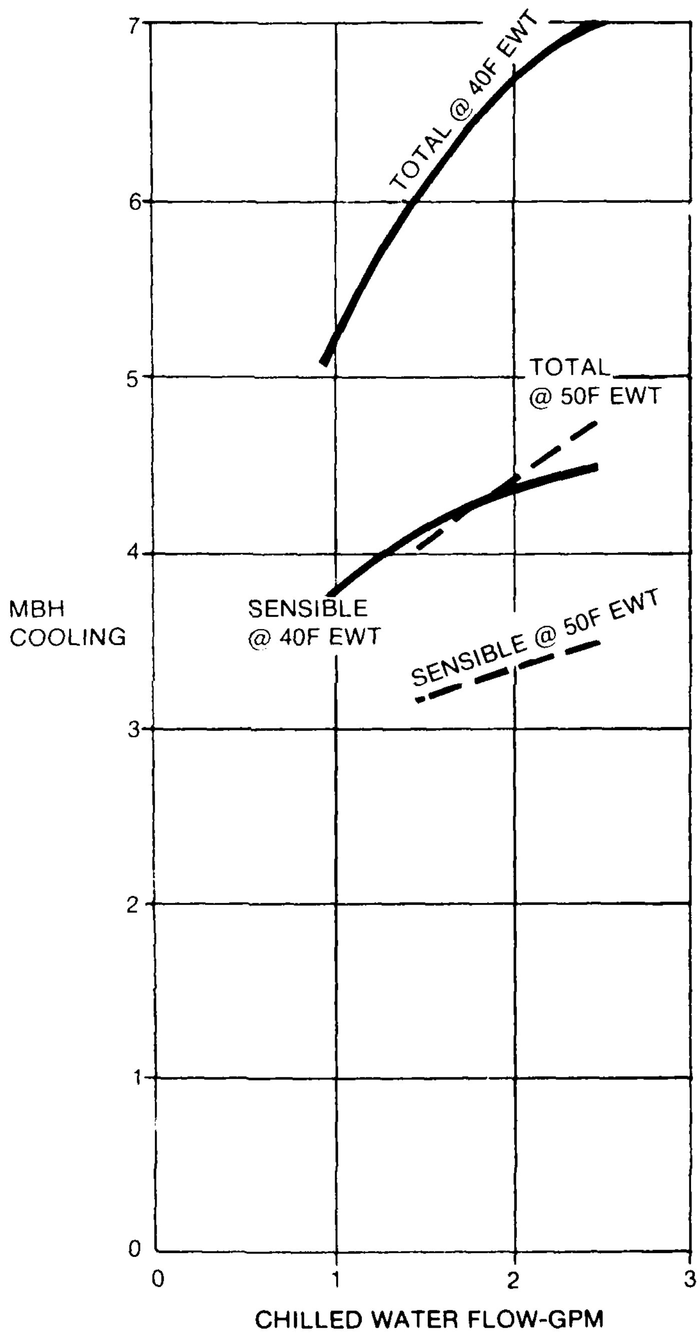
FAN COIL UNIT CAPACITY VS TEMPERATURE RISE



BASED ON CARRIER SERIES 42 FAN COIL WITH 3 ROW COIL SIZE 5
45F ENTERING WATER, 67F WET BULB, 80F DRY BULB

Figure 3-13 Latent capacity (the difference between total and sensible capacity) falls as water temperature rise increases in a three-row coil fan-coil unit with 45°F entering chilled-water temperature.[77]

FAN COIL COOLING CAPACITY VS CHILLED WATER FLOW & TEMPERATURE



BASED ON CARRIER SERIES 42V, SIZE 2, 3 ROW COIL
200 NOMINAL CFM, 80F/67F ENTERING AIR

Figure 3-14 Fan-coil unit latent cooling capacity increases faster than sensible cooling capacity with increasing chilled-water flow rate.

condition in these climates.

Supplying conditioned ventilating air through a separate ducted system in conjunction with fan-coil units will not necessarily solve the problem associated with bringing ventilating air in through the fan-coil units. With a separate conditioned ventilating air system arranged for constant dehumidification, the ventilating supply-air temperature will be lower than room temperature, thus providing some cooling capacity to the room, unless reheat is used. Under light sensible cooling load, which exists for many hours, the sensible-cooling capacity of the ventilating air system will be greater than needed, thus overcooling the room. So long as the latent heat gain in the room is not substantial and so long as there is little or no infiltration, such as from a higher quantity of exhaust air than ventilating air, it should be possible to maintain reasonable humidity control. It is, however, quite likely that there will be latent heat gain in the room and infiltration of humid outside air, thus causing high humidity. Even under these conditions, the fan-coil unit cannot dehumidify, because reduction of the sensible cooling load by the ventilating air system keeps the unit operating at close to zero sensible cooling capacity.

Variations of Fan-Coil Systems

Combined HVAC systems, complementing the fan-coil units with separate ventilating systems, are usually inefficient and uneconomical. One such alternative combines a central air-handling unit with a cooling coil that cools the air to 50°F to 55°F and reheats to a supply-air temperature of 75°F. This system is inefficient, because it wastes the sensible-cooling energy used for dehumidification and requires additional reheat energy to achieve comfortable temperatures. With this system, the fan-coil units still must handle whatever sensible cooling load exists in the space.

A second type of system employs a cooling coil only, with ventilating air supplied to the rooms at 50°F - 55°F, with a reheat coil in each room. Each room requires combined controls for the reheat coil and the fan-coil unit, to limit fan-coil operation to periods when the ventilating air supply fails to balance sensible cooling load. Because of these individual room controls, piping, and reheat coils, in addition to the fan-coil units, this more energy-efficient system will seldom recover its higher capital cost through operating savings. It is generally more economical simply to eliminate the fan-coil units and increase the ventilating units' capacity along with duct and heating-coil capacity to handle the entire load, and add return-air capability, unless odors are a problem. It then becomes the generally recommended all-air system.

Another flaw in this system concerns oversizing of the fan-coil unit. Since the sensible load capacity of a central system supplying dehumidified ventilation air can nearly equal the total design sensible load, the fan-coil unit's sensible load for a typical small room would be only a fraction of the smallest commercially available unit. Thus it is better to eliminate the fan-coil units and increase the central dehumidified air supply capacity for full cooling load, with zone or room reheat, and provide a return air system.

Another alternative system retaining fan-coil units incorporates room type dehumidifiers complementing the fan-coil units. This system would increase the fan-coil units' cooling energy consumption to offset the additional sensible heat gain from the dehumidifiers' operation. The dehumidifiers would also constitute an additional maintenance burden. And they would require an electrical distribution system in each room to supply power to the dehumidifier. Moreover, the relatively poor operating efficiency of numerous small dehumidifiers would probably result in higher energy consumption than central chilled-water dehumidification, even with reheat.

One possible option would be to use an electric heating coil controlled by a humidistat, provided the fan runs continuously, which would make the fan-coil unit system into a reheat system.

Economy Cycle

Like the room fan-coil units, the economy cycle is another HVAC concept unsuitable for use in humid climates. Even in cold climates, the economy cycle works only for a limited class of buildings -- i.e., those requiring cooling at 60°F or lower outside temperatures, low enough to permit the economy cycle to function. Residential buildings can seldom, if ever, benefit from an economy cycle even in cold climates, for they seldom require cooling when ambient temperature is below room temperature. In humid climates, an economy cycle provides even less potential benefit than in cold climates, because (a) the outside air temperature seldom ranges much below room temperature, and (b) the latent heat load introduced by outside air in a humid climate will almost always, if not always, exceed any reduction in sensible cooling load. The economy cycle will thus increase, instead of reducing the total cooling-energy consumption.

Satisfactory HVAC Solutions

Satisfactory solutions to the HVAC problem in humid climates include the following:

(1) Central air-handling systems, such as variable air volume (VAV), terminal air blending or constant volume with reheat

(2) Unitary through-wall (PTAC's) or window unit systems and packaged HVAC units, such as rooftop and typical residential central airconditioning systems.

Central HVAC offers the following advantages:

- o Centralized moisture removal eliminates fan-coil unit drain pans, thereby eliminating the problems of drain-pan overflow and re-evaporation of condensate into the space.
- o Central HVAC is less liable to equipment falure.
- o It is more tolerant of poor operation and maintenance, both in its ability to dehumidify and in its more durable physical equipment.
- o It is far less vulnerable to tampering by building occupants.

With a central HVAC system, use a "draw-through" fan, since the fan can provide some reheat. A draw-through fan adds heat on the room side of the cooling coil. Thus the supply air must be cooled several additional degrees to balance the fan-added heat. This additional cooling provides additional dehumidification. A blow-through fan adds heat on the entering side of the cooling coil. This results in less dehumidification, because the cooling-coil discharge temperature will then equal the required supply-air temperature.

Air-handling equipment should be located within the building, to eliminate the influence of weather and ambient conditions and associated losses and deterioration. Indoor location also facilitates maintenance, repair, and service.

HVAC For Specialized Buildings

Some specialized building uses -- e.g., computer facilities, laboratories, specialized maintenance in controlled environment -- require a flexible HVAC and control system, responsive to large load variations in short intervals while maintaining adequate temperature and RH control. A properly designed VAV and/or reheat system can satisfy this requirement for quick response. Designers should carefully examine the range of anticipated operating conditions and make adequate provision to assure satisfactory temperature and humidity control under all conditions.

For the more common multiple-room building, the VAV system also demonstrated its superiority over fan-coil units in a computer study described in the next section.

FAN-COIL COOLING CAPACITY VS VARIATIONS IN AIR FLOW

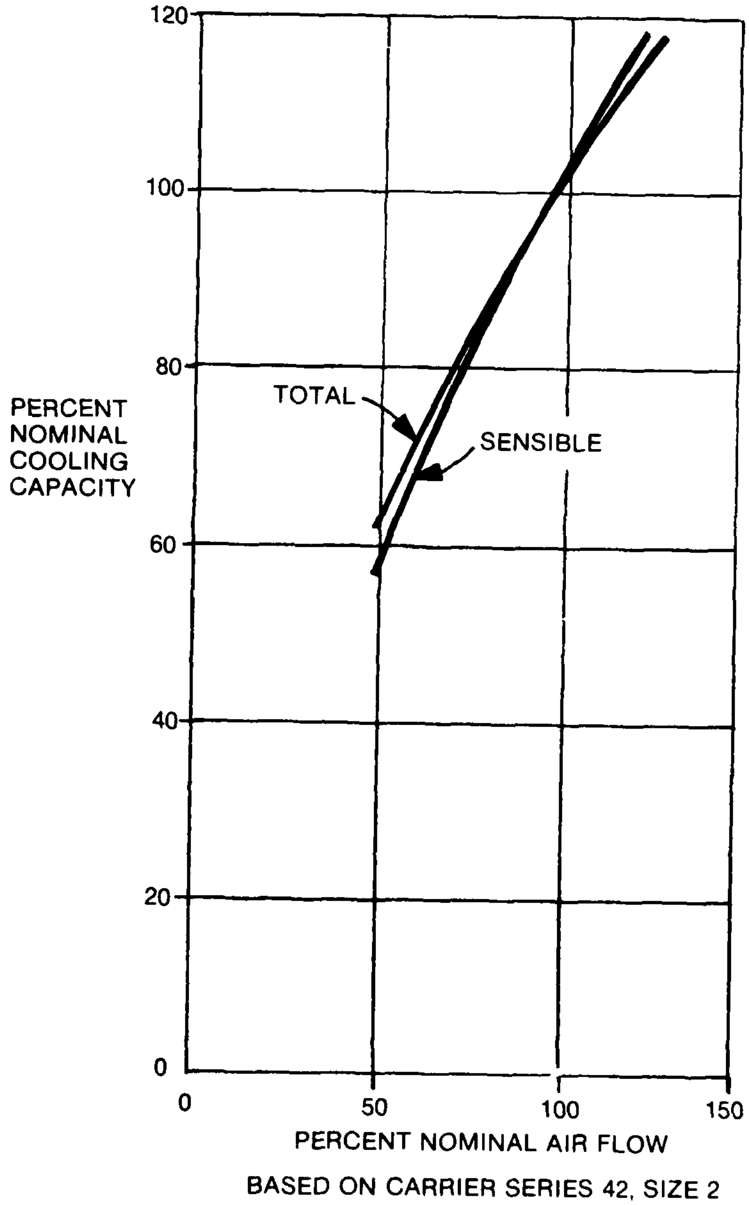


Figure 3-15 With decreasing airflow, a fan-coil unit loses only slightly more sensible than latent cooling capacity.

Computer Analysis of HVAC Performance

To evaluate the performance of an airconditioned building in a humid climate, computer analyses were run on a one-floor module simulating a typical residential occupancy located in Agana, Guam, with actual hour-by-hour weather data for 1958 input for a full-year's HVAC operation. The computer analyses investigated the impact on HVAC cooling energy consumption and space comfort of variations in the following parameters:

- Thermostat room-temperature setting of 70°F, 75°F, and 80°F
- Air changes of one, two, and three per hour
- HVAC type, both fan-coil units and variable air volume
- Building envelope permeance, both high and low

This computer analysis marks the first inclusion of building envelope permeance as a parameter in a computer simulation of building energy consumption and building comfort performance.

The analyzed module is 44 x 36 ft. in plan, located at the top floor of a building end, oriented on north-south axis, comprising four bedrooms and two bathrooms, with maximum internal heat gain of 1.2 watts/ft . The cooling system operated 24 hours per day, seven days per week. For eight of the 10 evaluated options, with varying combinations of thermostat settings, air changes, and building permeance, the HVAC system comprised five fan-coil units (one per room), with 80-watt fan motors and a total of 1,500-cfm air flow. For the other options, a Variable Air Volume (VAV) reheat system with two minimum air-flow rates was investigated as representative of all-air systems. See Table 3-2.

Variable-Volume System Outperforms Fan-Coil Units

As the key conclusion of this study, the variable-volume HVAC system, with reheat, outperformed the fan-coil units. It was, in fact, the only one of the two investigated HVAC system types that could maintain the space within the ASHRAE comfort-zone parameters. See Fig. 3-16. Compared with the basic Option 1, (fan-coil units, 75°F and one air change per hour), the simulated VAV systems used 37% and 58% more cooling energy, depending on minimum air flow rate. This additional cooling-energy consumption was required to accommodate the conditioned space's latent cooling load (i.e., to dehumidify).

Long hours at light load accounted for the disparity between the two computer-simulated VAV systems. In Option 9, with minimum air flow setting at 450 cfm, both cooling energy and reheat energy consumption exceeded the energy consumption in Option 10, with its minimum air flow of 225

OPTIONS EVALUATED

OPTION	DESCRIPTION	THERMOSTAT SETTING (°F)	AIR CHANGES/HR. (OUTSIDE AIR)	HVAC SYSTEM TYPE
1	No Permeance	75F	1	Fan Coil Units
2	No Permeance	70F	1	Fan Coil Units
3	No Permeance	80F	1	Fan Coil Units
4	No Permeance	75F	2	Fan Coil Units
5	No Permeance	75F	3	Fan Coil Units
6	Low Permeance	75F	1	Fan Coil Units
7	High Permeance	75F	1	Fan Coil Units
8	High Permeance	70F	3	Fan Coil Units
9	No Permeance	75F	1	Variable Volume (450-CFM Min.)
10	No Permeance	75F	1	Variable Volume (225-CFM Min.)

Table 3-2 A one-floor, multi-residential end module was computer-analyzed for the performance of two HVAC systems (fan-coil and variable volume) with varying thermostat settings, building envelope permeance, and air changes.

MAXIMUM ROOM HUMIDITY

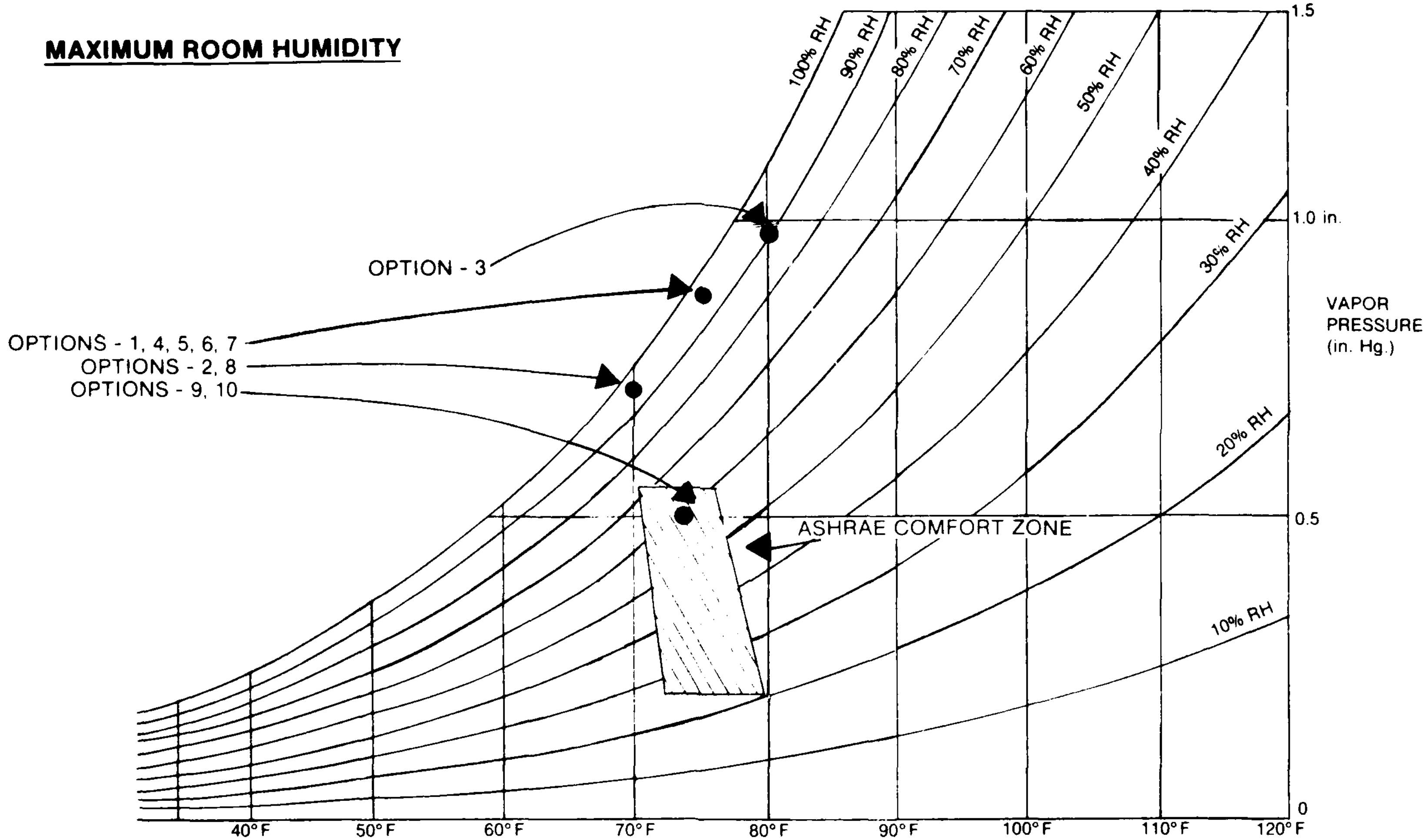


Figure 3-16 In a computer analysis of two types of HVAC systems (Fan-Coil units and Variable Volume) operating in Guam, only the Variable Volume systems (Options 9, 10) with reheat, satisfied ASHRAE comfort criteria. All the fan-coil units failed by wide margins, under varying conditions of thermostat setting, air changes per hour, and building envelope permeance (See Table 3-2).

cfm. Despite its 1,500-cfm design capacity air flow (set equal to that of the fan-coil units), the maximum requirement for both VAV systems was less than 900 cfm. See Fig. 3-17.

Further analysis of the VAV systems revealed the critical importance of part-load operation. In a climate like Guam's, the system would operate at less than half load for more than 75% of its annual operating hours, according to the computer study. See Fig. 3-17.

In practice, the VAV system would operate at half load or less even longer than 80% of the time. Precise matching of the VAV system's air-flow rate with the fan-coil system's air-flow rate, assumed in the computer analysis, results in overestimation of maximum experienced air flow due to diversity of loads among exposures. In a building operated 24 hours a day, 365 days a year, maximum experienced air flow will normally fall short of the VAV system's assumed rated capacity. On the other hand, in an office building shut down overnight and over weekends, a VAV system will operate at full-rated air flow for a higher number of hours, particularly during morning startup.

These variations with different occupancies and load patterns emphasize the need for careful investigation of minimum load conditions, to assure the HVAC system's ability to control temperature <u>and</u> humidity under all operating conditions.

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AIRCONDITIONED BUILDINGS IN HUMID CLIMATES. GUIDELINES FOR DESI--ETC(U)

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VAV SYSTEM
HOURS VS AIR FLOW

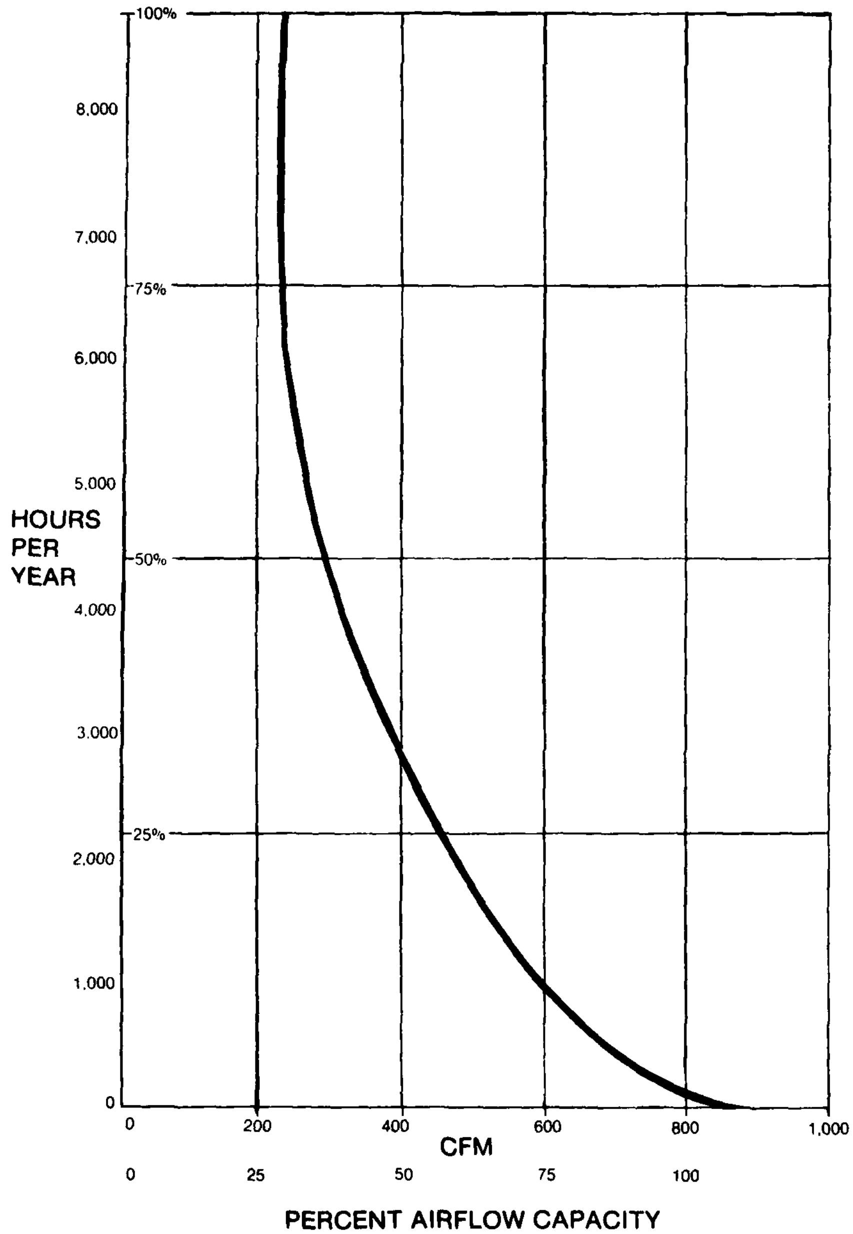


Figure 3-17 This plot of annual operating hours versus air flow (900 cfm = 100%) shows the Variable Volume (VAV) system (Options 9, 10) operating more than 50% of the time at less than about 30% air-flow capacity. It demonstrates the importance of part-load performance for any type of HVAC system in a tropical humid climate.

COOLING CONSUMPTION

OPTION	DESCRIPTION	COOLING TON HOURS/YR	% OF OPTION 1
1	NO PERM 75F 1AC FC	10,119	100
2	NO PERM 70F 1AC FC	15,611	154
3	NO PERM 80F 1AC FC	4,808	48
4	NO PERM 75F 2AC FC	12,629	125
5	NO PERM 75F 3AC FC	15,149	150
6	LO PERM 75F 1AC FC	10,128	100
7	HI PERM 75F 1AC FC	10,549	104
8	HI PERM 70F 3AC FC	26,908	266
9	NO PERM 75F 1AC VAV 30%	16,029	158
10	NO PERM 75F 1AC VAV 15%	13,834	137

LEGEND

PERM: NO = NONE; LO = LOW: HI = HIGH

AC: AIR CHANGES/HOUR EXHAUST

FC: FAN-COIL SYSTEM

VAV: VARIABLE-AIR-VOLUME SYSTEM: 30% & 15% MINIMUM AIR FLOW

Table 3-3. Cooling consumption data tabulated above are misleading, since only the Variable-Volume (VAV) system, (Options 9 and 10), satisfied the ASHRAE comfort standards (See Fig. 3-16). Additional cooling required by the VAV systems (9 and 10) provided dehumidification required to bring interior RH within the ASHRAE comfort envelope. Both Options 9 and 10 required reheat energy in addition.

Other Significant Results

The computer analysis produced a few surprises, but nothing beyond rational explanation. Here are the highlights:

- o Raising or lowering thermostat setting by 5°F to 70°F or 80°F had a tremendous impact on cooling energy consumption. Raising the thermostat setting from 75°F to 80°F cut cooling energy consumption by more than half; lowering the thermostat to 70°F increased cooling-energy consumption by more than 50% compared with that at 75°F. See Table 3-3 and Fig. 3-18.
- o Doubling or tripling the air changes from one change per hour to two or three, increased cooling consumption to a far lesser degree than lowering the 75°F thermostat setting to 70°F. Cooling-energy consumption increased by 25% for doubled air changes (from one to two per hour) and by 50% for tripled air changes (from one to three per hour). See Fig. 3-19.
- o Varying building permeance from low to high resulted in a trivial 4% increase in cooling consumption by fan-coil units because the HVAC system was unable to remove the latent load. The "low-permeance" envelope assumed painted concrete block walls with three coats of low-permeability paint and total permeance of 0.66 perms vs. 2.4 for the unpainted concrete walls

COOLING ENERGY VS ROOM TEMPERATURE AND AIR CHANGE RATE

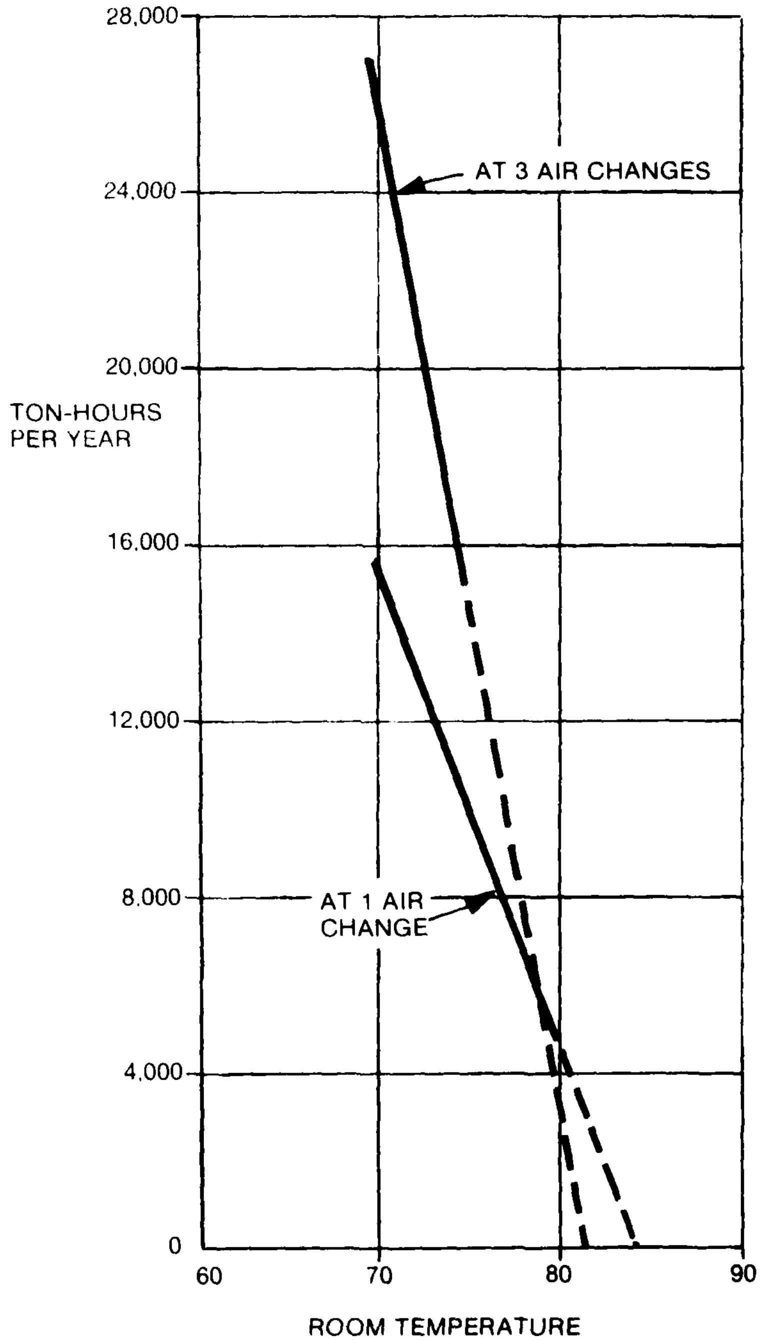


Figure 3-18 Cooling-energy consumption rises fast as thermostat setting is lowered (See Table 3-3).

COOLING ENERGY VS EXHAUST (INFILTRATION) RATE

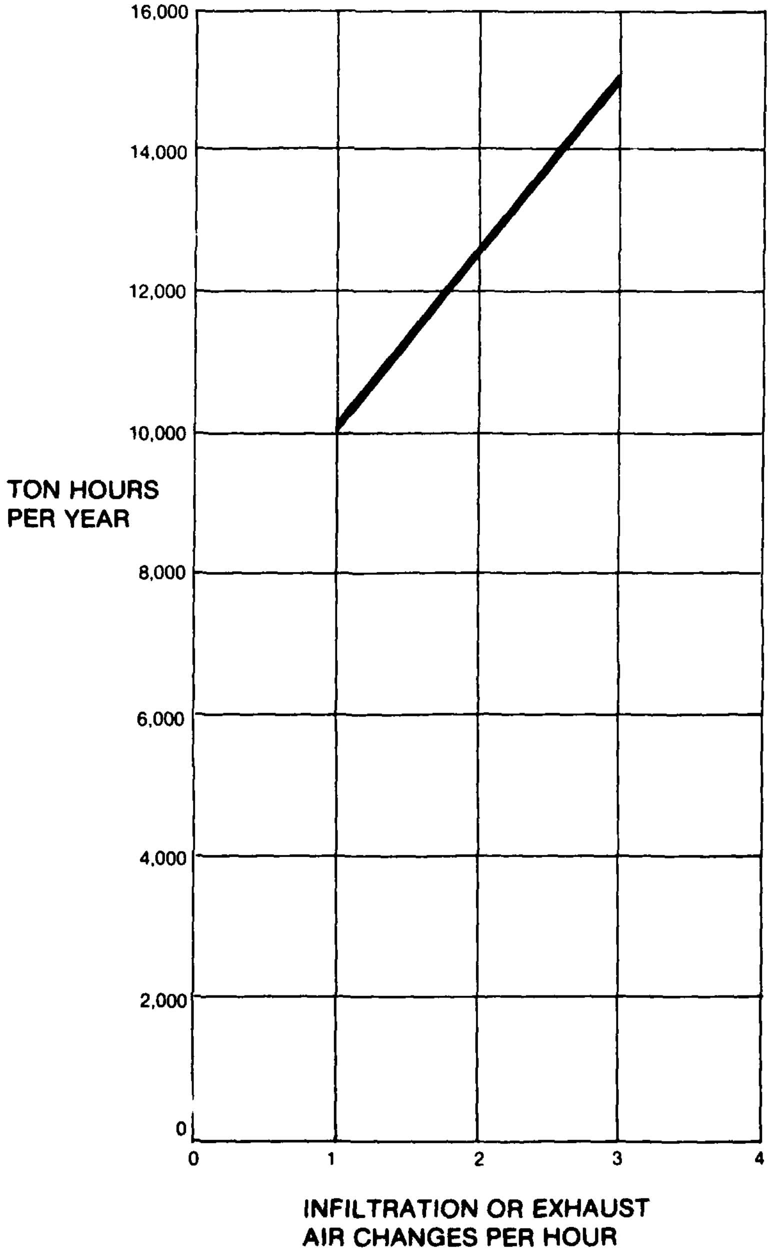


Figure 3-19 Cooling energy consumption rises 50% with a tripling of air-change rate (from one to three changes per hour) for Option 4 and Option 5 (See Table 3-3). As air-change rate rises, interior RH rises, because the fan-coil units cannot handle the additional latent cooling load imposed by increased entry of outside air.

assumed for the "high-permeance" envelope. The "low-permeance" envelope also assumed an unvented ceiling with a built-up roof system rated at 0.165 perms vs. a naturally ventilated ceiling space rated at 26.9 perms for the "high-permeance" envelope.

o Option 8 combining extremes of cooling loads (70°F thermostat setting; three air changes per hour; and high permeance construction) multiplied cooling consumption to 266% of the basic Option 1 (75°F thermostat setting, one air change per hour, permeance ignored).

The relatively slight increases in cooling consumption resulting from both increased air changes and high permeance entailed sacrificed comfort. In both instances, increased latent loads from invasion of humid outside air simply raised interior RH well above the comfort zone, because the fan-coil units could not control humidity. Any HVAC system capable of handling the latent loads (like the VAV system) would have consumed more cooling energy than the inadequate fan-coil units.

Regardless of HVAC system type, in a building with around-the-clock cooling, the HVAC system will operate at substantially less than half-rated capacity most of the time in a humid tropical climate. See Fig. 3-20. The end top-floor module assumed for the computer study had relatively high sensible cooling loads because of its high exposed surface-area-to-volume ratio. For a lower-floor, intermediate

COOLING
LOAD DURATION CURVE

FOR OPTION -1
OPERATION 24 HOURS PER DAY

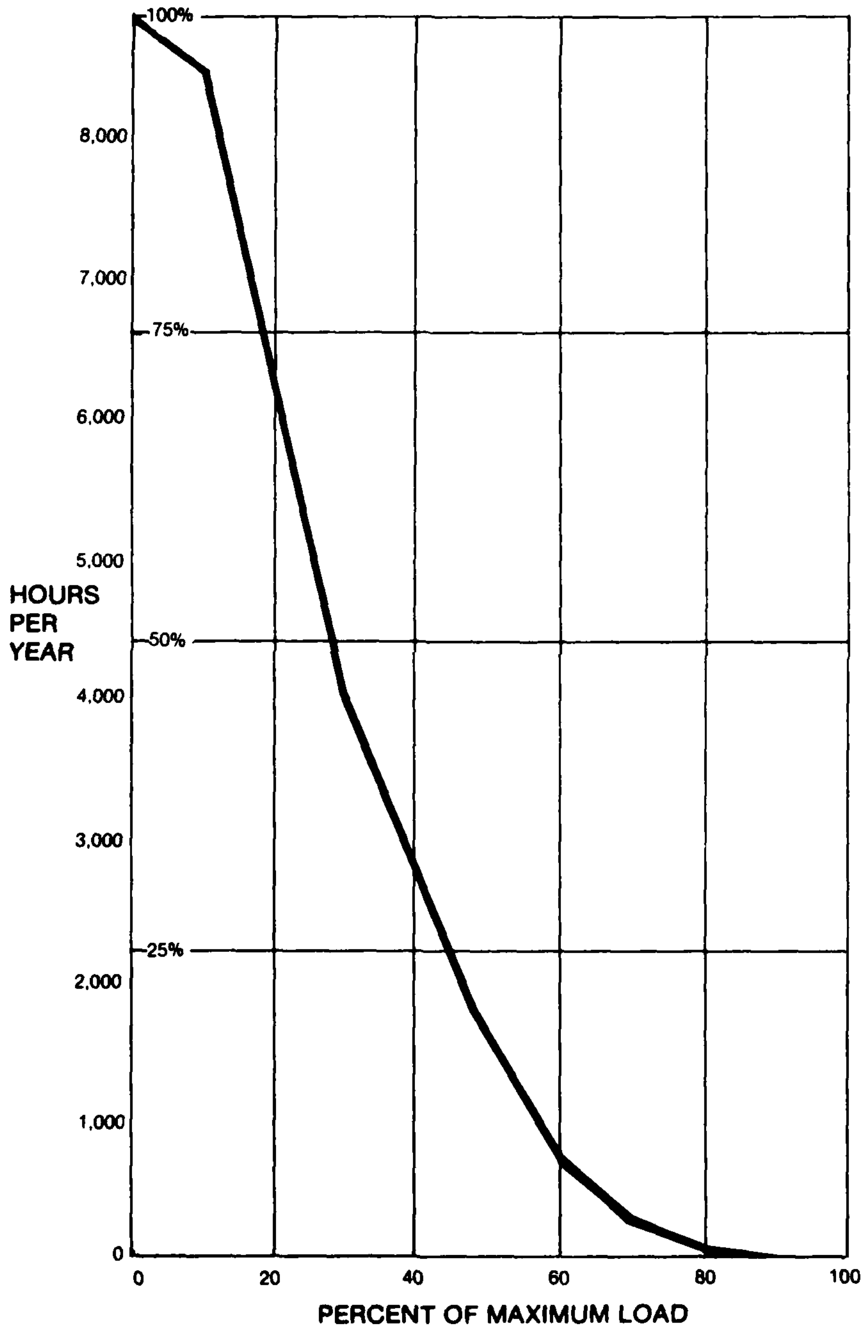


Figure 3-20 The above load duration curve for Option 1, fan-coil unit, shows that an HVAC system in a humid climate operates at less than half capacity for the majority of annual hours. Part-load dehumidification performance is critical to maintaining comfort conditions.

module, with less sensible heat gain through the envelope, the HVAC system would probably operate even longer at light load. Changes in assumed internal heat gains, somewhat higher or lower, would not change this conclusion.

Ventilating Principles

Preconditioning of outside air is generally more efficient and practical than simply allowing makeup or ventilating air to infiltrate into the conditioned space. Makeup air should enter through a continuously operating airconditioning system. It should slightly pressurize the building under most conditions of wind velocity and exhaust.

Introduction of saturated outside air at variable temperatures can cause condensation and consequent mold growth. A consequence of the HVAC system's inability to respond to a fast-rising latent load, this condensation accompanies load changes. With no reheat and cooling coils' chilled-water flow modulated, fan-coil units simply cannot handle the rising latent load. When the system is operating under high sensible cooling load, supply air cools surfaces immediately adjacent to the supply outlet. Then, when sensible load drops, and chilled-water flow is throttled, the supply-air temperature rises. It is, however, still close to being saturated, and thus at higher dew point temperature than the former supply air. Under these conditions, condensation occurs not only on grilles, registers, and diffusers, but even on surfaces on which the air impinges, such as walls and ceilings. This situation is especially common with fan-coil units and central air-handling systems lacking reheat, in which room thermostats control the cooling-coil discharge temperature, either directly or indirectly.

Ventilating the space above ceilings with outside air can cause severe problems -- e.g., condensation on surfaces within the ceiling space, dripping, and wetting of ceiling materials, with sagging and occasional collapse of ceiling tiles. This practice normally applies to single-story buildings, as an effort to keep the roof's solar heat gain out of the occupied space. But this ventilation technique is also used in multi-story buildings, where the surface above all except the top-floor ceiling is a cool floor instead of a warm roof. Since the floor and ceiling surfaces are normally below the ambient-air dew point in humid climates, water vapor will condense on surfaces within ceiling spaces, with dripping and wetting of ceiling materials.

The solution, as previously indicated by the recommendation for pre-conditioning of makeup air, is to consider the ceiling space as part of the conditioned space. An alternative solution, a vapor retarder, to prevent vapor migration from below, won't work in ceilings. It is impracticable to seal the many ceiling openings and joints.

Treat kitchens, toilet rooms, shower rooms, and closets, where moisture is generated by cooking, showering, washing, and storage of damp or wet clothing, as conditioned space. Make provision for circulation of conditioned room air, via louvered doors, even in closets. There is no need for electric heaters in closets with louvered doors and properly conditioned interior air. Louvered doors equalize vapor pressure, thereby diffusing local moisture.

Exhaust-system design in humid climates starts with this basic rule: Do not use natural ventilation. That leaves as the basic problem in exhaust-system design the choice between central exhaust or individual exhaust systems, plus the means of control. There is no universal solution.

Either system is acceptable, provided it is equipped with the following:

- Dampers to prevent air flow when exhaust fans are not running
- Intermittent (not continuous) operation, only when necessary. This enhances both operating economy and comfort.

Individual exhaust can be controlled for intermittent operation through individual switches or light switches -- e.g., in a toilet room. Central exhaust systems can be arranged to operate only in conjunction with one or more light switches. Central exhaust systems can also be programmed to operate on a 24-hour clock or a seven-day clock only during hours when exhaust is deemed necessary. Thus when the exhaust fan is shut off, the conditioned space should be pressurized to an even greater extent than when the exhaust fan is running.

FOUR

RECOMMENDATIONS FOR NEW BUILDINGS

These recommendations include (a) changes in current design criteria, plus (b) additional criteria designed to prevent moisture problems in airconditioned buildings in humid climates. These criteria appear under two basic categories: architectural and mechanical (HVAC),

The architectural category comprises the following topics:

- o Insulation of building envelope, foundation, and structural framing
- o Wall materials and finishes
- o Paints and other coatings
- o Building geometry
- o Vapor retarders
- o Joint sealing and caulking
- o Roofs

The mechanical (HVAC) category comprises:

- o HVAC equipment, controls, and duct design
- o Ventilation requirements
- o Pipe and duct insulation

RECOMMENDATIONS FOR ARCHITECTURAL DESIGN

Thermal Insulation

(1) Design wall and roof insulation to maintain exterior surface temperature above ambient dew point temperature whenever possible. See Fig. 3-1.

(2) Avoid "thermal bridges" in the structure -- e.g., cantilevered concrete canopy slabs continuous with the interior slab; projecting, uninsulated columns; or window mullions continuous with the interior structure. See Fig. 3-2. Maintain cognizance of typhoon and hurricane design criteria.

(3) Wherever structural projections -- columns, foundations, etc. -- are unavoidable, insulate them, like walls and roofs, to maintain surface temperature above ambient dew point temperature.

(4) Specify moisture-resistant insulating material -- e.g., foamglass or foamed plastics. Avoid moisture-absorbing insulation materials, fibrous glass, mineral wool, and organic fiber insulation materials. (5) Avoid metal door and window frames or specify frames with thermal breaks.

(6) Avoid organic fiber wall boards in locations subject to wetting-drying cycles.

(7) Avoid cement plaster on lath. It increases humidity during construction phase.

Paints and Coatings

(1) For airconditioned buildings in humid climates, exterior surfaces should have the lowest practicable perm-rated coating, interior surfaces should have the highest practicable perm rated paint. Before specifying paints, the designer should insist on the manufacturer furnishing in writing his material's perm rating, expressed as a perm-inch unit.

(2) Apply paint only to clean, dry substrate surfaces. Allow surface to dry after rain or fog has wet it.

(3) If practicable, let concrete surfaces age for one year before coating. Do not use paint on concrete, as this establishes a maintenance problem.

(4) Allow plaster surfaces to dry a minimum of two weeks after completion before application of any finish coating. Allow first coat to dry for a minimum 30 days before application of second coat.

(5) Plaster surfaces must also satisfy a further condition: 8% maximum moisture content (by weight), determined by moisture meter or comparable testing device, before applying first coat of paint or sealer.

(6) Some material selection suggestions can be found in Chapter 3.

Building Geometry

(1) Limit shading of exterior walls to glass portion of windows exposed to sunlight. This practice will reduce cooled, shaded surfaces vulnerable to condensation and consequent mold growth, by (a) reducing the "cold-radiator" (i.e., thermal bridge) effects, and (b) promoting evaporation of surface moisture through improved air flow and solar heat.

(2) Wherever practicable, design clear, plain surfaces, without column or wing wall projections or corners that create wind-sheltered spaces or "shadow" grooves that shade recessed spaces.

Space Limitations

(1) Provide sufficient floor-to-floor height to accommodate ceiling ducts for a central HVAC system when required to provide adequate dehumidification. When restricted floor-to-floor height precludes use of a central ducted airconditioning system, consider unitary airconditioning equipment, such as through-the-wall or window units, when life-cycle cost analysis indicates feasibility.

Building Configuration

Aircondition corridors, except when the design includes both of the following:

- o Partition between corridor and occupied space, designed as an exterior wall
- o Adequate corridor ventilation

Architectural layout -- specifically the mode of access to the occupied space -- can promote moisture problems. Eliminating corridors and vestibules, by providing direct access to living quarters (without use of lounges) from the exterior, obviously eliminates the problem of whether or not to aircondition them.

Both single-loaded exterior and double-loaded interior corridors pose the same basic problem. To protect unairconditioned corridors and the occupied space itself from moisture invasion requires the previously stated additional features:

(1) Design of partitions between corridor and occupied spaces as exterior walls

(2) Ventilation of the corridor with sufficient air motion to prevent air stagnation and consequent promotion of mold growth

The recommendation to aircondition corridors generally prevails over the alternative, since it is normally more expensive, even on a life-cycle cost basis, to provide the better quality, exterior-type corridor wall and corridor ventilation than simply to enlarge the airconditioned space.

Cooling-energy requirements for double-loaded corridors are relatively insignificant. Exterior corridors however, may require substantial quantities of cooling energy, especially with poor insulation and high solar heat gain. This high cooling-energy cost for exterior corridors may be offset by reducing infiltration and by improving the thermal quality of the exterior walls and roofs.

Entrance vestibules pose a similar problem in building configuration. The designer must balance the probable moisture-caused damage of increased air infiltration through doors opening directly into the humid exterior environment against the additional cost of the vestibule. Reasonable door openings should not overtax an HVAC system properly designed for some additional sensible and latent heat load from door openings, along with other incidental sources of air infiltration. Accordingly, there is no specific recommendation on vestibules, merely the above reminder.

Vapor Retarders

(1) Do not specify a vapor retarder for a roof in a humid climate.

(2) If a vapor retarder is specified for a wall, ceiling, or crawl space, locate it as close as possible to the exterior not the interior face. Use of an exterior finish with low vapor permeability is generally a better solution than a vapor retarder.

(3) Specify the best available vapor retarder (0.03 perms or less) for insulation on chilled-water piping.

(4) Calculate wall water-vapor permeance whenever the ambient design dew point exceeds the room design dew point by more than 15°F. Include latent load from vapor flow through the envelope in cooling-load and energy calculations when it appears to be significant.

(5) Eliminate requirement for foil-backed insulation or gypsum board. These materials are generally used on the inside, where vapor resistance can cause entrapment of condensed moisture.

(6) In cavity walls, specify a vapor retarder for the interior cavity face. See Fig. 4-1.

Joint Sealing and Caulking

(1) Minimize air infiltration by careful detailing, sealing, and caulking.

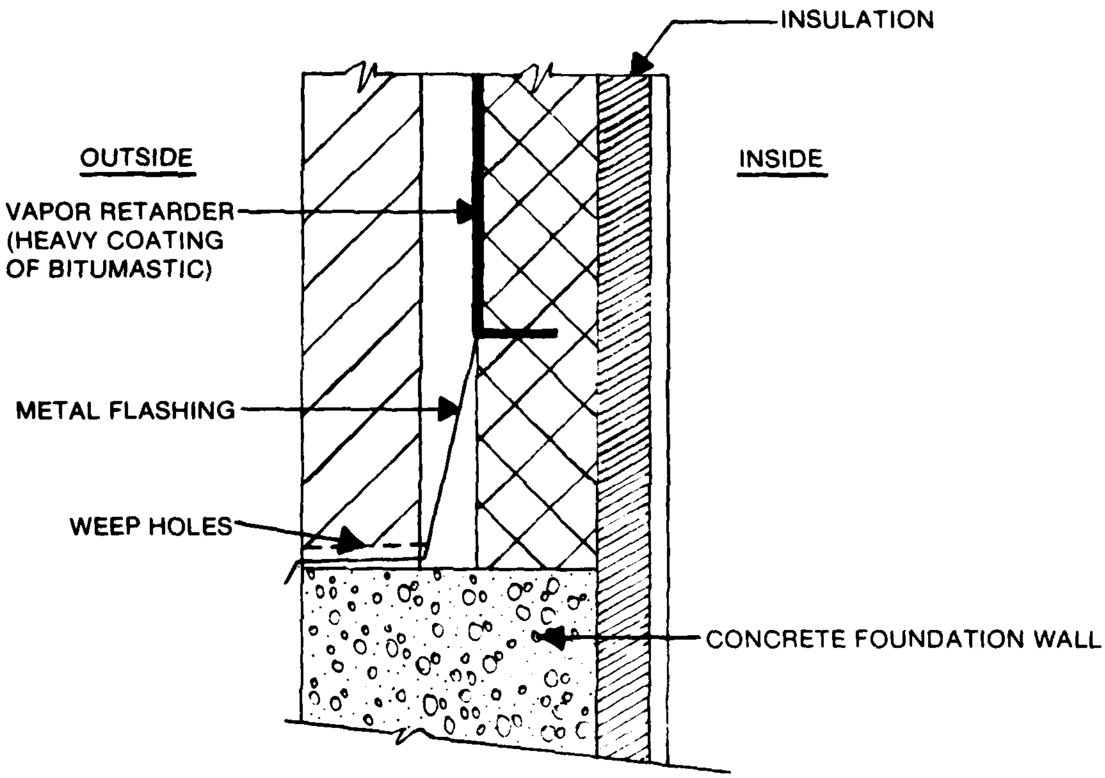
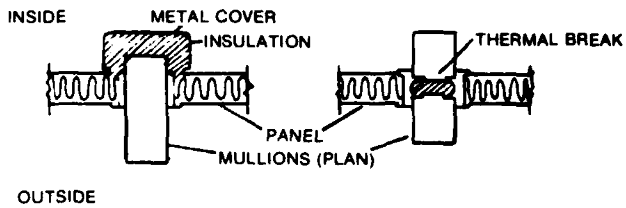


Figure 4-1 In a cavity wall, a vapor retarder can prevent water vapor flow into the interior, also aiding in directing rainwater that penetrates the outer wythe of masonry down to a flashing at the wall base, with weep holes designed to drain both condensate and rainwater as it drips and flows down through the cavity.



HORIZONTAL CROSS SECTIONS
(from ASHRAE 1977 Handbook of Fundamentals, p. 19.11)

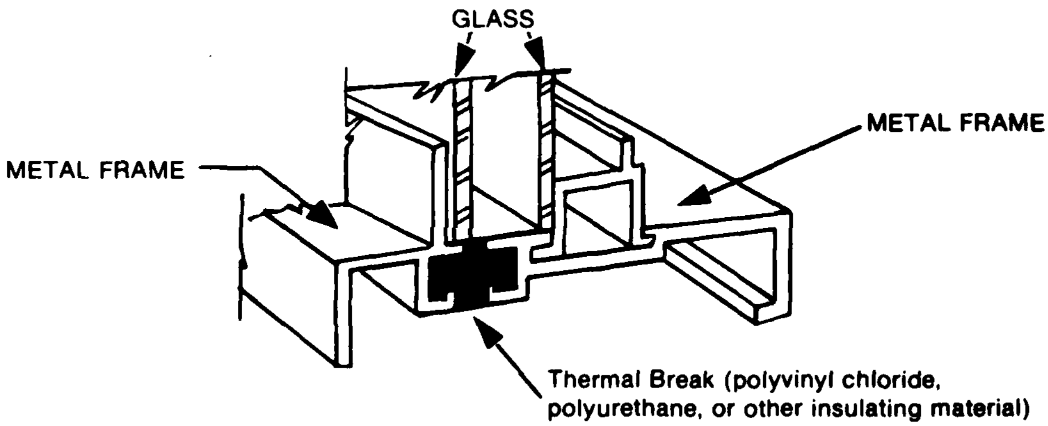


Figure 4-2 A thermal break retards heat conduction through a metal window frame or mullion by interrupting continuous heat conduction through aluminum or steel window frames, with their essentially zero thermal resistance (R value).

Windows and Doors

(1) For metal-framed doors or windows, require thermal breaks to reduce cooling-energy loss and condensation on exterior frame surfaces. See Fig. 4-2.

(2) Do not specify double glazing for the purpose of eliminating surface condensation on windows and doors in humid climates. It will reduce the frequency of condensation, but not eliminate its occurrence.

(3) Require doors and windows to satisfy the infiltration standards of ASTM E-283-73, "Standard Method Test for Rate of Air Leakage through Exterior Windows, Curtain-Walls and Doors," or ANSI #A134.1, "Specifications for Aluminum Windows," 1972.

(4) Specify interior shading devices such as shutters, Venetian blinds, window shades, or drapes, for sun-exposed windows lacking shading.

(5) Provide instructions for building administrators to instruct occupants on requirements of HVAC system, and to prevent unauthorized window and door openings that impair HVAC system operation.

Roofs

(1) Do not specify a vapor retarder for a roof in a humid climate.

(2) Specify a moisture-resistant insulation --

e.g., foamglass or plastic -- in preference to a moisture-absorptive insulation -- e.g., fiberglass, perlite board, or organic fiberboard. (3) Specify hot-mopped asphalt for slippage resistance, limited as follows:

Bitumen	Minimum slope (in./ft.)	Maximum slope* (in./ft.)
Coal tar bitumen	¼	¼
Type I asphalt	¼	½
Type II asphalt	½	3/4
Type III asphalt	½	3
Type IV asphalt	3	6

* To prevent slippage on maximum slope requires limit on interply mopping weight of 15 - 20 lb./square.

(4) Use treated, termite-resistant, wood nailers, bolted to structural framing, for membrane and flashing anchorage against wind uplift.

(5) Prime all metal surfaces with asphalt.

(6) To prevent wind-stripping of roof surfacing aggregate in areas subject to high wind velocity, specify double-coated surfacings. On Guam, these double-coated surfacings feature coral gravel aggregate, water-washed and sprayed lightly with diesel fuel primer facilitating bonding with the aggregate. Both interply moppings and double-flood coats are made with Type III asphalt, to minimize the risk of membrane slippage.

(7) Do not specify topside roof vents to relieve vapor pressure in roof systems in humid climates. Topside vents will admit more water vapor than they expel, since vapor pressure normally acts continuously downward in a humid climate. Use underside venting to facilitate water vapor flow out of the roof into the interior.

RECOMMENDATIONS FOR HVAC DESIGN

More than any other aspect of building design in humid climates, HVAC design diverges from normal design practice for colder, drier climates. Note, in the following recommendations, the many exceptions to the rules of normal airconditioning design.

General Airconditioning Design Guidelines

(1) Coordinate architectural and mechanical design throughout the HVAC design process. Good design coordination is even more important for design in humid climates than in normal climates.

(2) Consider subdivision of tropical humid climates into island and inland, where less rigorous precautions are required. Also consider division of design into airconditioned and unairconditioned buildings.

(3) Aircondition toilet rooms, corridors, stairways, and storage rooms, subject to the following exceptions:

(a) Include cooling loads from toilet rooms, closets, and similar spaces among the cooling loads for conditioned space.

(b) Unairconditioned stairways, both interior and exterior, require free air circulation. Interior stairways require, in addition, insulated, exterior-type walls separating the stairway from conditioned spaces.

(c) Provide airconditioning for storage rooms, unless stored materials can tolerate mold or mildew.

(4) Whenever practicable, locate airconditioning equipment indoors, but not in conditioned space.

(5) Locate chilled-water piping in accessible locations to permit convenient, economical investigation and replacement of insulation.

(6) Design mechanical room floors and equipment pads to drain condensate dripping from airconditioning equipment and make provision for drain pan overflows.

(7) Provide adequate air driers for pneumatic control systems.

(8) Select chillers with adequate capacity to provide the required chilled-water temperature when operating at design wet bulb conditions.

Cooling Loads and Dehumidification

(1) Use 1% design wet-bulb temperature for latent cooling load and sizing of cooling towers and evaporative condensers.

(2) Design to ASHRAE Standard 55 comfort criteria with RH no higher than 60%.

(3) Consider typical part-load conditions as well as very light load conditions for combined sensible and latent load, as well as maximum sensible and latent loads individually.

(4) Count exterior water-vapor migration into interior as part of latent-cooling load, if it appears to be significant.

(5) Whenever latent heat gain is substantial -- i.e., sensible heat factor is less than approximately 0.65 -- compute supply air volume from both latent and sensible heat gain, and use the larger.

(6) Determine minimum cooling loads to establish airconditioning system's ability to provide comfort and humidity control under these conditions.

(7) Consider both latent heat gain and dehumidification performance of airconditioning system as part of energy analysis computer program, if it appears to be significant.

(8) Provide for continuous dehumidification of outside air and supply it through airconditioning units.

(9) Do not increase the air-change rate simply to satisfy some degree of air motion under the following typical humid-climate conditions:

(a) sensible heat factor less than 0.65

(b) supply air-change rate less than six air changes per hour.

Increasing the air-flow rate for this purpose will result in excessive air flow and reduced ability to dehumidify.

System Selection

(1) Do not specify fan-coil units in buildings requiring year-round cooling. Fan-coil units, by themselves, can handle either temperature or humidity, but not both.

(2) Consider a ducted, all-air HVAC system with reheat in humid climates. Provide increased floor-to-floor height over normal limits when needed to accommodate ducts in ceiling space.

(3) Specify multiple refrigeration units (i.e., multiple compressors) for buildings with year-round cooling loads. Require special care and attention to field installation of central HVAC systems. They require more care during installation, but once operating can tolerate less maintenance than single units. They are also far less vulnerable to equipment failure.

(4) With many hours of operation at light cooling loads, use multiple chillers, so that the smallest chiller is not required to short cycle or use hot-gas bypass.

(5) In buildings with high latent cooling loads or highly variable sensible cooling loads and/or long hours of operation at light sensible cooling loads, provide reheat to maintain humidity control. When reheat is required, it is often economical to use some form of heat recovery -- e.g., reclamation of condenser heat or heat exchangers.

(6) When the designer anticipates approximately 1,000 or more annual cooling hours at a cooling load less than the minimum efficient capacity of the smallest chiller, provide a secondary or auxiliary chiller for use during those light light-load hours.

(7) Do not specify economy cycle for humid climates.

(8) Design for lowest practicable chilled-water temperature difference, consistent with economical piping and pumping costs.

(9) Where some heating is required in addition to cooling, consider air-to-air heat pumps, including through-wall and window type.

(10) Use coils with low sensible heat ratio, and/or multiple coils or circuits.

(11) Design chilled water piping systems with minimum hydraulic complexity and with balancing capability.

Cooling Towers

(1) Establish temperature of water leaving cooling tower at 7°F or so above ambient design wet-bulb temperature, or

base it on life-cycle cost analysis of fan energy vs. compressor energy. In humid climates with long operating hours at high ambient wet-bulb temperatures, cooling tower fans can consume substantial quantities of energy. It is, accordingly, more worth evaluating them for energy economy in humid climates than in drier climates.

(2) Make a life-cycle cost analysis of draw-through (induced draft) vs. blow-through (forced-draft) cooling towers, since blow-through cooling towers usually consume more fan energy.

Controls

(1) Provide alarms for high chilled-water supply temperature and high RH in typical zones.

(2) Evaluate control system for its ability to maintain comfort under all conditions of sensible cooling load, especially very light loads.

(3) Whenever humidity control is required or essential, provide reheat and a humidistat that will overcall the thermostat to lower cooling-coil discharge temperature and/or reset chilled water temperature.

(4) Don't supply variable temperature saturated air.

Outside Air Ventilation

(1) Maintain conditioned space under positive pressure with respect to ambient air for most hours of the year.

(2) If it can be shown that local wind velocity for a particular building will yield less than one air change per hour of infiltration, design for less than one air change per hour.

(3) In humid locations with mean wind speed greater than 15 mph (13 knots), design for an excess percentage of ventilating air over exhaust air as the larger of either (a) 30%, or (b) the mean wind velocity in mph. Obtain mean wind velocity from Engineering Weather Data, Departments of the Air Force, the Army, and the Navy, AFM 88-29, TM5-785, NAVFAC P89, 1 July, 1978.

(4) Design toilet room exhaust fans to maintain negative pressure with respect to adjacent rooms, and positive pressure with respect to outside air. This means that less air should be exhausted from toilet rooms than is supplied to the entire space that includes the toilet rooms.

(5) Consider toilet rooms and closets as part of the conditioned space. Provide them with louvered doors or supply conditioned air.

(6) Makeup air for toilet room and other exhaust systems should be continuously conditioned air, not infiltrating outside air or natural ventilation.

(7) Do not provide outside air ventilation above suspended ceilings. Provide for circulation of conditioned room air in ceiling plenums. Grilles or louvers can create natural circulation.

(8) Locate exhaust registers close to places where moisture is generated -- for example, at shower locations in bathrooms.

(9) Consider separate ducted ventilation systems in conjunction with fan-coil units only when the smallest fan-coil units must always operate under light sensible load conditions. Otherwise, conditioned air will require reheat under light loads.

Pipe and Duct Insulation

(1) Insulate chilled-water piping with moisture-resistant insulation -- e.g., foamglass -- and with vapor retarder of low permeability -- e.g., vinyl or aluminum-foil-backed kraft paper.

(2) Insulate airconditioning ducts where they are exposed to ambient conditions and also when they are in soffits or above suspended ceilings. Ducts exposed to ambient conditions require the same insulating materials and care required for chilled-water piping. Ducts located above ceilings and in soffits can usually be insulated with less water-resistant materials -- e.g., fiberglass -- with a vapor retarder jacket.

FIVE

RECOMMENDATIONS FOR EXISTING BUILDINGS

As a general policy, designers should follow the recommendations for new buildings in the previous chapter to the fullest extent technically and economically practicable. There are, however, obvious mandatory compromises, especially in remedial work on HVAC equipment. When, for example, existing buildings have insufficient floor-to-floor height to accommodate ceiling airconditioning ducts, installation of a new central duct system would be economically impracticable if not physically impossible. In these cases, vertical air distribution may be the solution.

Corrective measures evaluated in several locations indicate the limitations of compromised remedial action in existing buildings. They alleviate the moisture problems, but they do not solve them.

In existing buildings with moisture problems, most important is replacement of an inadequate HVAC system with a system capable of controlling humidity. Solution of the moisture problems will generally require changes in selection of paints and finishes for correct vapor permeability and their proper application. Exhaust systems in existing buildings will also normally require modification.

In existing non-residential buildings, HVAC control systems normally require the most attention, to control excessive RH.

Repainting Procedure

The problem of protecting existing building surfaces from fungus-produced mold and mildew has two vital aspects:

- o Protecting workmen from exposure to fungal infection of ears, eyes, and lungs when they are removing mildewed paints or coatings
- o Preserving the new paint or coatings from mold or mildew during its service life

Maintenance personnel should be educated about these two problems: medical protection for repainting procedures and proper paint selection and application procedures.

Solution to the potential medical problem requires disinfecting of the fungi before paint removal starts. The predominant, currently used method -- grinding of interior masonry surfaces with an electrically powered abrasive wheel -- is totally inadequate.

Workmen preparing a fungus-infected, mold-covered substrate for repainting should wear air-supplied, protective clothing. They should remove old paint as follows:

(1) Carefully break open all existing mold-covered blisters.

(2) Clean blister surface with chlorox and non-phosphate detergent to prekill mold-causing fungi before making substrate repair prior to repainting.

(3) Determine which of four or five available paint removers is suitable for the particular paint to be removed. Excellent ventilation, complete rinsing with water, and personnel protection is mandatory.

To protect new exterior acrylic emulsion paint (Type TT-C-555) from fungal attack, specify a 1% solution of 2,4, 5,6 Tetrachlorosophthalonitrile (EPA Registration No. 2204-12) in the paint formulation. This fungicide emerged as the best of nine tested fungicides from an elaborate National Bureau of Standards research program. After two years' exterior exposure, plus four weeks fungal exposure in an environmental chamber, the 2,4,5,6 Tetrachlorosophthalonitrile qualified for the highest fungal growth resistance. It scored 10 on the 0-10 fungal-growth scale of ASTM Method D3274, compared with the next highest 3.5 rating for a mercury-based fungicide.

HVAC Remedies

Tests conducted by the National Bureau of Standards on a typical fan-coil unit illustrate the limitations of corrective HVAC measures. (31)

Designed to determine performance characteristics and to establish recommendations for improving humidity control, the NBS tests yielded a minimum dew point temperature 63.5°F

(68% RH at 75°F room temperature) for a 300-cfm fan-coil unit in a room with sensible cooling load of 1,750 Btuh.

Under the lower prevailing nighttime sensible loads characteristic of many humid climates, dew point temperature would rise, producing still higher, more uncomfortable levels of room RH.

Though it is impossible to <u>control</u> space humidity with fan-coil units, it is possible to reduce it, via three NBS recommendations:

(1) Change the fan-coil unit controls from cycling chilled water valves and continuously running fans to cycling fans and continuously circulated chilled water.

(2) Reduce fan-coil air-flow rates.

(3) Replace unit-mounted with wall-mounted thermostats.

RH reductions from these recommendations depend primarily on the degree of fan-coil unit oversizing: the greater the oversizing, the greater the improvement.

Recommendation No. 1 will reduce RH, but it cannot control it with low sensible cooling loads. Recommendation No. 2 will similarly reduce RH, but at low sensible cooling loads it will not increase operating time sufficiently to drop RH to 60%. And though it will more accurately control space temperature and eliminate any influence that outside air will have on the thermostat, Recommendation 3 will not significantly change RH.

Corrective HVAC measures should, if practical, entail one of the following systems:

- o Central ducted air-handling system
- o Unitary packaged airconditioning units

With a central chilled-water system, replace the air-side (air-handling) system with a system capable of providing full-time, continuous dehumidification control. This requires reheat, which may be provided by heat recovery from the condenser or from a run-around or exhaust-heat recovery system. The airside system concept would be one of the following all-air type systems:

- o variable air volume
- o constant air volume
- o terminal air blender
- o reheat in combination with the above

Air-handling units could be located on the roof, or preferably, in fan rooms such as former storage or occupied rooms converted for the purpose. Depending on structural and architectural constraints, air-handling units can be located on a per-floor or per-wing basis, serving several floors.

Central chilled-water plants require reliably maintained design chilled-water temperature and adequate chilled water supply.

Unitary packaged systems -- e.g., through-wall units -- may provide the most economical solution where structural or architectural limitations preclude use of central chilled-water and air-handling units. This solution would usually require installation of a new electrical distribution system, since the existing system would normally lack sufficient capacity.

S I X

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