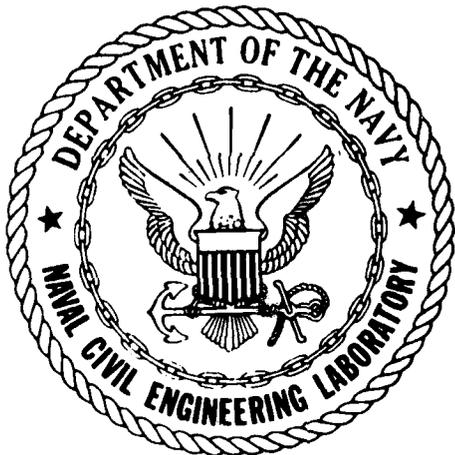


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NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

**PROBLEM DEFINITION STUDY OF REQUIREMENTS FOR VAPOR RETARDERS
IN THE BUILDING ENVELOPE**

November 1982

An Investigation Conducted by
H. R. TRECHSEL ASSOCIATES
P. O. Box 211
Germantown, Maryland

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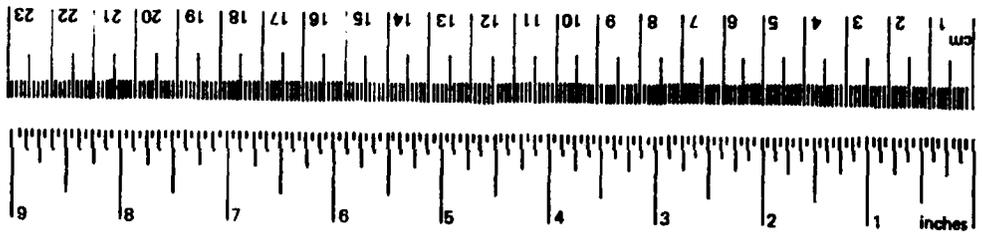
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures				Approximate Conversions from Metric Measures			
Symbol	When You Know	Multiply by	To Find	Symbol	When You Know	Multiply by	To Find
in ft yd mi	inches	2.54	centimeters	mm	millimeters	0.04	inches
	feet	30	centimeters	cm	centimeters	0.4	inches
	yards	0.9	meters	m	meters	3.3	feet
	miles	1.6	kilometers	km	kilometers	0.6	miles
in ² ft ² yd ² mi ²	square inches	6.5	square centimeters	cm ²	square centimeters	0.16	square inches
	square feet	0.09	square meters	m ²	square meters	1.2	square yards
	square yards	0.8	square meters	m ²	square kilometers	0.4	square miles
	square miles	2.6	square kilometers	km ²	hectares (10,000 m ²)	2.5	acres
oz lb	ounces	28	grams	g	grams	0.035	ounces
	pounds	0.45	kilograms	kg	kilograms	2.2	pounds
	short tons (2,000 lb)	0.9	tonnes	t	tonnes (1,000 kg)	1.1	short tons
tsp Tbsp fl oz c pt qt gal ft ³ yd ³	teaspoons	5	milliliters	ml	milliliters	0.03	fluid ounces
	tablespoons	15	milliliters	ml	liters	2.1	pints
	fluid ounces	30	milliliters	ml	liters	1.06	quarts
	cups	0.24	liters	l	liters	0.26	gallons
	pints	0.47	liters	l	cubic meters	35	cubic feet
	quarts	0.95	liters	l	cubic meters	1.3	cubic yards
	gallons	3.8	liters	l	°C	9/5 (then add 32)	Fahrenheit temperature
cubic feet	0.03	cubic meters	m ³	°C	9/5 (then add 32)	Fahrenheit temperature	
cubic yards	0.76	cubic meters	m ³	°C	9/5 (then add 32)	Fahrenheit temperature	
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature



*1 in = 2.54 (exact). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10.286.

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to prevent the types of moisture and fungus problems currently being experienced, particularly in tropical and subtropical environments.

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I. INTRODUCTION

1.1 Objective

To determine vapor retarder requirements in the insulated building envelope, by means of a problem definition study.

1.2 Scope:

Based on the current state-of-the-art, identify geographical areas where vapor retarders should or should not be used, and where they should be placed. Suggest research to resolve conflicts in current criteria. Specifically:

- o Conduct a thorough state-of-the-art study covering criteria for requirements, specification and placement for vapor retarders in the insulated building envelope. This should include a survey of pertinent literature and a documentation of current practices.
- o Define existing criteria for use of vapor retarders in the insulated building envelope. Compare these criteria with information obtained from the state-of-the-art study to determine if existing criteria are adequate in light of recent work such as the Oregon State study; i.e., determine if the omission of a vapor retarder in the insulated building envelope is a problem. Define the extent of the problem.
- o Resolve any conflicts in the literature or existing criteria where possible and/or suggest as possible areas for future research.

The scope did not include the conduct of field investigations or mail surveys but was limited to the collection and review of literature and available written reports.

1.3 Background

Lack of appropriate water vapor condensation control has in the past led to blistering and failure of paint; wetting, deterioration and loss of thermal performance of insulating materials; and rotting of wood framing and siding. [1] Such deteriorations were often attributed to the installation of thermal insulations in walls, ceilings, and floors. The conventional method for reducing such damage is to install a vapor retarder on the interior of the insulation in cold climates; on the outdoor side, on both sides, or on neither side in warm and humid climates.

* Numbers in brackets refer to references listed at the end of each chapter.

For retrofit installation or building rehabilitation, the installation of a vapor retarder according to conventional practice is often difficult and expensive. Recent field studies [2,3,4,5] have not uncovered substantial evidence of moisture-related problems in moderate and cool climates, regardless of whether a vapor retarder was used or not. Although the above studies do not cover all climate zones, and are based on relatively low numbers of houses investigated, they do bring into question the stringent vapor retarder requirements for new building construction, and the costly application of these requirements to existing buildings.

A study conducted by the National Bureau of Standards for the Department of Energy [6] developed criteria specifically for retrofit installation in moderate and cool climates. Unlike other requirements, the new criteria were not only based on climate zones, but also on indoor relative humidities, and instead of only addressing the vapor diffusion through surfaces, also considered moist indoor air leaking into cavities of the wall construction.

Analysis of the more recent studies casts some doubt on the need for vapor retarders under certain conditions. Because of this, the Naval Construction Battallion Center commissioned this study covering criteria for requirements, specification, and placement for vapor retarders in the insulated building envelope. During a meeting on October 18, 1981, with a representative of the Naval Construction Battallion Center, Dr. Robert L. Alumbaugh, the scope of the study was further defined and clarified:

- o Priority is to be given to residences, apartments, and barracks, with secondary consideration to office buildings.
- o The study should focus on both new and existing construction, with greater emphasis given to requirements for existing buildings.
- o Coastal areas of U. S. and overseas locations (including hot and humid climates) should be covered. Arctic or Antarctic regions are secondary.
- o Priorities with regard to construction types is 1) frame construction, 2) masonry, 3) metal buildings.
- o Currently, the Navy uses the DOD Construction Manual 4270.1M as basis for design. (Other relevant guidelines used are identified in 4.7.)
- o Both air-conditioned and non-air-conditioned buildings must be considered.
- o Indoor temperatures are generally maintained at 72° - 68° F in winter, 75° - 78° F in summer.
- o Energy sources for space heating are primarily gas and oil, often in the form of a central steam plant. (No combustion in the building.)

The above clarifications do not in any way limit the scope of the study, but serve to focus the effort on those areas which are of greatest concern to the Naval Construction Battallion Center.

While the task statement only mentions vapor retarders, moisture control (which is the goal for the installation of vapor retarders) cannot be adequately approached without also considering indoor relative humidity, ventilation, and air leakage, as was stated during a conference in 1972 in England: "Condensation is a physical phenomenon caused by too much water vapor in the air of a dwelling, and will not be overcome by the present emphasis on insulating cold bridges and installing vapor barriers" [7]. Accordingly, the present study did include consideration of indoor relative humidity, ventilation, and air leakage, in addition to design temperatures. However, the design and operation of air-conditioning equipment and systems, which largely determine humidity, ventilation, and room temperature, are not treated in depth in this report.

1.4 Definition and Specifications for Vapor Retarders

The American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) defines a vapor retarder (formerly barrier) as "a moisture-impervious layer applied to the surface enclosing humid space to prevent moisture travel to a point where it may condense due to lower temperature" [8]. The American Society for Testing and Materials (ASTM) defines a vapor barrier as "those materials or systems which adequately retard the transmission of water vapor under specified conditions. (For practical purposes it is assumed that the permeance of an adequate barrier will not exceed 1 perm, although at present the value may be adequate only for residential construction. For certain other types or construction, the permeance must be very low)" [9].

1 perm is a permeance unit defined as $1 \text{ gr/h. ft.}^2 \text{ in Hg}$ ($\text{PERM} = \text{ng/s.m.}^2 \text{ Pa}$). 1 perm = 57 PERM approximately.

For sheet materials not over 1/4 in. (33mm) thick, ASTM E 96-80, Standard Methods for Water Vapor Transmission of Materials [9a] are used to determine its permeance. There are two alternate methods described in E 96-80: 1) the desiccant method, also called dry cup, and 2) the water method, also called wet cup. Although both methods are considered equally valid, the results of the two tests on the same material can vary considerably (see table 1). The method selected should be that which more nearly approaches the conditions in use.

ASTM C 355-64, Standard Test Methods for Water Vapor Transmission of Thick Materials [9b] cover the determination of water vapor transmission of materials such as fiberboard, gypsum and plaster products, wood products, and plastics in thicknesses over 1/8 in (3 mm), but not more than 1 1/4 in (33 mm). There are again two methods, the desiccant (dry cup) and water (wet cup) varieties.

Except for materials less than 1/8 inch thick, the two standards can be used interchangeably. The two methods apply primarily to vapor retarders installed in walls and ceilings in conjunction with thermal insulations.

TABLE 1. PERMEANCE AND PERMEABILITY OF SELECTED MATERIALS

Extracted from ASHRAE Handbook and Product Directory, Fundamentals Volume, Atlanta, GA., 1981, pp. 21.6-21.7.

<u>MATERIAL</u>	<u>THICKNESS/WEIGHT</u>	<u>Perm</u>	<u>PERMEANCE</u>	<u>PERM</u>	<u>REMARKS</u>
Aluminum Foil	0.001 in.	0.0		0.0	Dry cup
Aluminum Foil	0.00035 in.	0.05		2.9	Dry cup
Polyethylene Sheet	0.002 in.	0.16		9.1	Dry cup
Polyethylene Sheet	0.006 in.	0.06		3.4	Dry cup
Saturated and Coated Roll Roofing	65 #/100 ft ²	0.05		2.9	Dry cup
Saturated and Coated Roll Roofing	65 #/100 ft ²	0.24		14	Wet cup
Kraft Paper, Asphalt Laminated and Reinforced	6.8 #/100 ft ²	0.3		17	Dry cup
Kraft Paper, Asphalt Laminated and Reinforced	6.8 #/100 ft ²	1.8		103	Wet cup
Blanket Insulation Backup Paper, Asphalt Coated	6.2 #/100 ft ²	0.4		23	Dry cup
Blanket Insulation Backup Paper, Asphalt Coated	6.2 #/100 ft ²	0.6-4.2		34-240	Wet cup
Asphalt-Saturated and Coated Vapor Retarder Paper	8.6 #/100 ft ²	0.2-0.3		11-17	Dry cup
Asphalt-Saturated and Coated Vapor Retarder Paper	8.6 #/100 ft ²	0.6		34	Wet cup
15-1b Tar Felt	14 #/100 ft ²	4.0		230	Dry cup
15-1b Tar Felt	14 #/100 ft ²	18.2		1040	Wet cup
Single Kraft, Double	3.2 #/100 ft ²	31		1170	Dry cup
Single Kraft, Double	3.2 #/100 ft ²	42		2400	Wet cup
Vapor Retarder Paint	0.0031 in.	0.45		26	Other
<hr/>					
		<u>Perm-in</u>	<u>PERMEABILITY</u>	<u>PERM-m</u>	
Expanded Polyurethane Board		0.4-1.6		0.58-2.3	Dry cup
Expanded Polystyrene - Extruded		1.2		1.7	Dry cup

ASTM E 398-70, Standard Recommended Practice for the Dynamic Measurement of Water Vapor Transfer [9c] is limited to sheet material. At this time the practice is not recommended for referee testing but is suitable for control testing and material comparisons.

ASTM C 755-73 [9d] outlines factors to be considered, and describes design principles and procedures for vapor retarder selection. It defines water vapor transmission values appropriate for established criteria. It covers residential and commercial buildings and industrial applications in the temperature range from -40 and +80° F (-40 to +27° C). The standard recommended practice does not establish a criterion for permeability a vapor retarder must meet, but it states that "for practical purposes it is assumed that the permeance of an adequate barrier will not exceed 1 perm (57 PERM) although at present this value may be adequate only for residential construction." For certain other types of construction the permeance must be very low. ASHRAE has published a similar statement: "The generally accepted rating of a vapor retarder is 1 perm (57 PERM) or by resistance 1 rep (0.017 REP), but in specific designs a perm rating may be needed that is well below 1 perm (57 PERM), or in resistance, well above 1 rep (0.017 REP)" [8a]. (Resistance is the reciprocal of permeance, rep = 1/perm). Despite guarded statements by both ASTM and ASHRAE, a permeance rating of 1 (57) has become accepted within the building industry as the definition of a vapor retarder. Thus with few exceptions, the issue is generally whether or not and where there should be a vapor retarder, and not what level of permeance is required at a particular location in the envelope system.

Table 1 lists the permeance for selected materials. In actual installations, the effectiveness of the retarder is substantially reduced due to joints, penetrations, tears, etc. To obtain an effective vapor retarding installation, proper application techniques need to be observed. In general, materials should be selected which can be installed with the fewest joints. The effectiveness of the vapor retarder is reduced if its installation allows passageways for the movement of air currents. It is for this reason that ASHRAE recommends that in specific designs a permeance rating of the vapor retarder material may be needed that is well below the 1 perm (57 PERM).

Vapor retarders are also used under concrete slabs and as ground covers in crawl spaces to resist vapor transmission from the moist ground up into the living areas. ASTM E 154-68 Standard Methods of Testing Materials for Use as Vapor Barriers under Concrete Slabs and as Ground Cover in Crawl Spaces [9e] should be used for determining the suitability of a specific material for its intended use. The methods include resistance to decay, resistance to puncture, resistance to deterioration from petroleum vehicle for soil poisons, and effect of low temperatures on bending.

1.5 Summary of Current Criteria for the Use of Vapor Retarders

Abstracts of major currently used criteria for vapor retarders are given in Appendices A and B, and are discussed and evaluated in Section 2. Specific recommendations for criteria based on current technology are given in Section 3.

In their most basic form, current criteria require vapor retarders on the interior of exterior walls in cold to moderate climate ($\geq 20^{\circ}\text{F}$ [7°C]) and colder winter design temperature. For ceilings in the same areas, a vapor retarder on the underside of the attic insulation is generally required, together with minimal attic ventilation. In some criteria, the barrier can be omitted if additional or more effective attic ventilation is provided. For climates warmer than $+20^{\circ}\text{F}$ (7°C) winter design temperature, no vapor retarders are generally required. The above criteria apply to new construction; in existing building retrofit, they are sometimes difficult or costly to apply. Accordingly, often retrofit insulation installations do not include any vapor retarders. In addition, vapor retarders are also called for under concrete floor slabs on grade and as a ground cover in crawl spaces. In general, the above criteria apply equally to civil as well as Navy constructions. The most significant feature of these criteria is that they are based only on climate, generally winter design temperatures, (sometimes average January temperatures) with a recognition that attic ventilation can "substitute" to some degree for a vapor retarder in the attic. No consideration is generally given to ventilation rates, relative humidity, and temperatures within the building's habitable spaces.

Several Navy design publications (see A.7) discuss HVAC equipment - related requirements to reduce moisture problems. Again, the emphasis is on moderate to cool climates, and dehumidification control appears to be permitted only in limited locations and for specific building types. The guidelines outlined in B.9 suggest changes in the Navy Design Criteria to make them applicable to warm and humid climates.

1.6 Related Activities

The subjects of moisture control and vapor retarders in buildings are currently receiving substantial attention. Below is given a brief summary of some of the broader activities undertaken by major professional and consensus standards organizations, government agencies, and others. In addition, many universities, government laboratories and private-sector organizations are engaged in specific research projects dealing with moisture control in buildings and the use of vapor retarder to reduce moisture transfer. A select group of these projects is summarized in Appendix C.

Within the broader context of moisture transfer and condensation, ASTM committee E06 and ASHRAE Section 4 are cooperating in an informal Joint Steering Committee to coordinate standards-writing activities and to identify needed guidelines and research. The Joint Steering Committee was established as a result of the ASTM symposium on "Moisture Migration in Buildings - The Need for Standards," held in Philadelphia, PA, on October 6, 1980 [10]. As a first task, the Steering Committee identified at least seven ASTM committees and subcommittees and five ASHRAE technical committees with related and sometimes overlapping scopes. Currently active in the Steering Committee are the Canadian Research Council, the USDA Forest Products Laboratory, and private industry groups.

The National Institute of Building Sciences (NIBS) is also active in this area, and on the international level, CIB W 40 has addressed this subject.

The U. S. Department of Energy, through the Oak Ridge National Laboratory, has included moisture transfer and condensation in its National Program Plan for Thermal Performance of Building Envelope Systems and Materials [11]. The Plan identifies needed studies related to air leakage, water vapor and air permeance required for indoor and outdoor finish materials to prevent internal condensation, and suggests the development of an analytical model for the dissipation of moisture generated in buildings, the preparation of guidelines for moisture control and management, the conduct of research to determine conditions under which intermittent condensation can be tolerated, and the conduct of demonstrations for evaluating moisture control guidelines.

ASHRAE has identified at least one major area of needed research, a laboratory study of the moisture flow through two wall assemblies. This study is expected to be followed up by additional research and the development of analytical tools for determining the water vapor condensation potential under given construction details, temperature and relative humidity conditions.

The U. S. Department of Housing and Urban Development (HUD) is in the process of establishing a joint building research effort with Russia. It appears that water vapor transmission and control will be one topic to be considered for joint study. The major reason for the U. S. interest is that Russia has substantial experience with very cold climates (Siberia) and with innovative prefabrication methods.

References to Section 1

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- 2 F. Glen Odell and Dr. George Tsongas, "A Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier," Final Report to the Oregon Department of Energy, Portland, Oregon, November, 1979.
- 3 John L. Weidt, Robert J. Saxler, and Walter J. Rossiter, Jr., "Field Investigation of the Performance of Residential Retrofit Insulation," NBS Technical Note 1131, September, 1980.
- 4 Ralph J. Johnson, "Residential Moisture Conditions - Facts and Experiments," presented at the 1980 ASTM Symposium on Moisture Migration in Buildings. ASTM STP 779, Philadelphia, PA, July 1982.
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- 7 D. H. Stephens and P. P. Craddock, "The Contractor and Condensation," proceedings of Conference on Condensation in Buildings, University of York, England, January 1972. Applied Sciences Publishers, Ltd., London, 1972, p. 168.
- 8 ASHRAE Handbook and Product Directory, Fundamentals Volume, Atlanta, GA 1981, p. 35.14.
- 8a Ibid, p. 21.12.
- 9 ASTM Book of Standards, Part 18, Philadelphia, PA, 1981, p. 570.
- 9a Ibid, pp 855-864.
- 9b Ibid, pp. 124-131.
- 9c Ibid, pp. 1006-1009.
- 9d Ibid, pp. 569-585.
- 9e Ibid, pp. pp. 918-923.
- 10 Moisture Migration in Buildings, ASTM STP 779, Philadelphia, PA, July 1982.
- 11 P.R. Achenbach, Editor, The National Program Plan for Thermal Performance of Building Envelope Systems and Materials, Oak Ridge National Laboratory, ORNL/Sub-7973/1, Oak Ridge, TN, March 1982.

2. EVALUATION AND DISCUSSION OF CURRENT REGULATIONS AND GUIDELINES, AND PAST RESEARCH EFFORTS

The need for vapor retarders and condensation control in buildings arises from any or all of the following moisture transfer processes that can occur under certain conditions.

- o Water vapor coming from the earth beneath a house may cause condensation and decay in the crawl space, and depending on the construction, it may flow upward through the cavity walls to the attic and cause condensation in all locations between floor and attic.
- o Moisture in liquid or vapor form may migrate through concrete slabs-on-grade, causing damp floors and decay of wood members or furnishings in contact with the floor.
- o Heat conduction at the edge of concrete slabs-on-grade may allow condensation to occur on the floor surface near the perimeter of the house during the winter.
- o The moisture generated inside a house or other building by occupant activities or by initial drying out of the construction may penetrate walls, ceiling and floor by diffusion and/or by convection, causing condensation and decay under winter conditions, as well as staining, blistering of paint, and corrosion.
- o The moisture in warm humid air in tropical or subtropical climates may penetrate walls, ceilings and floors by diffusion and/or convection, causing condensation at the exterior side of the interior wall covering in air conditioned buildings. The warm humid air may cause mold and mildew to grow on furnishings or building material inside a building that is not air conditioned or dehumidified.
- o Water leaks in roof coverings designed to be waterproof aggravate condensation control in roofs since the vapor retarder on the warm side of the roof cannot prevent such leakage and in fact tends to trap water within the insulation placed in the roof construction.

Field and laboratory research have been performed on all of these moisture transfer phenomena over the last 30 years or more. Based on the research results and the concurrent experience of builders and designers, regulations, good practice guidelines and/or recommended practices have been developed for the control of condensation, utilizing vapor retarders, ventilation and insulation in various combinations for all six of the moisture transfer processes enumerated above. In some cases the requirements are specific and quantitative; in other cases they are more general and require some professional judgment. For some moisture phenomena there is a consensus on what constitutes acceptable condensation control practices, while for others

there is a variation in opinion on the proper scope of coverage, the quantitative values to be used as reference points, the correlation of construction practice with climatic parameters, or the basic need for a particular procedure. The current state of building practice on condensation control as revealed by the codes, regulations, good practice guidelines and research recommendations summarized in Appendices A.1 to A.7, B.1 to B.10, and C.1 to C.13 is evaluated for consistency, adequacy and need, in the following pages.

2.1

Ground Cover

In 1962 a Special Advisory Group of BRAB submitted a report to the Federal Housing Administration [1], recommending that ground cover be installed in residential crawl spaces in locations where the average January temperature is 45° F or below and the average precipitation is 20 inches or more per year; and that all crawl spaces not used as heat plenums be ventilated in accordance with the current FHA Minimum Property Standards or the formula in the ASHRAE Guide. A map of the U. S. indicated the geographical areas that met the two climatic criteria.

Current HUD/MPS [2] requires cross ventilation of crawl spaces with ventilator area equal to 1/150 of the ground area, if no ground cover is used, and one tenth that amount of ventilator area if ground cover with a permeance of 1 perm is used. Ground cover shall be used where soil and moisture conditions warrant. (See Appendix A.1).

ASHRAE Handbook [3] recommends ground cover of concrete, heavy roll roofing or polyethylene film regardless of climate, but allows ground cover to be left out if crawl space ventilation meeting a certain formula is provided. (See Appendix B.1).

USDA Forest Service Information Bulletin No. 373 [4] recommends ground cover in those parts of the U. S. where the average January outdoor temperature is 35° F or lower. A map showing this isotherm is provided. (See Appendix B.2).

NAHB Insulation Manual, 1978, [5] recommends a ground cover of 4 to 6 mil polyethylene film irrespective of geographical location. (See Appendix B.3).

Manual of the League of Savings Associations [6] recommends a ground cover of 4 or 6 mil polyethylene film, 30 lb. roofing felt or roll roofing in all climates plus crawl space ventilators with a free area of 1/1500 of the crawl space area. In older buildings the ground cover can be omitted. Ventilators should be provided with a free area of 1/150 of the crawl space area. (See Appendix B.6)

The above summary shows considerable variation in the recommendations and requirements for ground cover in crawl spaces.

Except for the USDA Forest Service recommendations and the original BRAB recommendations, no geographical or climatic limitations are placed on the use of ground cover in crawl spaces. The HUD Minimum Property Standards make the mandatory use of ground cover subject to judgment on the soil and moisture conditions. The HUD/MPS, ASHRAE Handbook, and the Manual of Building and Loan Associations allow ground cover to be omitted if crawl space ventilator area is increased by a factor of 10.

A private communication from the NAHB Research Foundation [7] indicates that ground cover is widely used in current dwelling construction.

2.2 Dampproofing Slabs-on-Ground

The HUD Minimum Property Standards for One- and Two-Story Dwellings and for Multiple-Dwelling Units requires that a continuous vapor retarder membrane, tested in accordance with ASTM E 96 [8] and C 355 [8a], shall be installed below the slab for slabs-below-grade with membrane edges turned up to the top of the slab. There is a similar requirement for slabs-above-grade having ductwork or piping in or under the slab, and for slabs-above-grade without ductwork or piping except that it may be omitted in arid regions where irrigation or extensive sprinkling is not done. Vapor retarders may be placed above or below the slab for wood-block and wood-strip floor construction. (See Appendix A.1)

The ASHRAE Handbook [3a] identifies a soil membrane cover and coarse gravel fill under concrete floor slabs as a means of breaking the capillary rise of ground moisture, but does not emphasize its use.

The USDA Forest Service Information Bulletin No. 373 [4a] recommends a vapor retarder under concrete slabs-on-grade in those parts of the U.S. where the average January outdoor temperature is 35° F or lower. (See Appendix B.2)

The NAHB Insulation Manual, 1978, contains no recommendations for damp-proofing slabs-on-ground by a vapor retarder.

The Manual of the League of Savings Associations [6a] recommends a vapor retarder under concrete slabs-on-ground in all climate zones. The membrane should have a permeance less than 0.30 perms.

The above summary indicates considerable variation in the recommendations and requirements for dampproofing concrete slabs-on-grade by placing a vapor retarder underneath the slab.

The recommendations range from universal use of vapor retarders under slabs-on-grade in all climatic zones, by the Manual of the Building and Loan Associations, to no mention of this vapor control mechanism, by the NAHB Insulation Manual. The mandatory requirements in the HUD/MPS are quite comprehensive except that the vapor retarder may be omitted in arid regions under certain conditions involving judgment.

Heat Conduction at Concrete Slab Perimeters

Moisture may condense on the surface of concrete slabs-on-grade near the perimeter of the house in the winter because of high edge heat transfer to the outdoors. In climates where high summer dewpoint temperatures occur frequently, condensation may occur on the surface of an uninsulated concrete slab floor. This is primarily a condensation control problem and not a vapor retarder problem.

The HUD Minimum Property Standards [9] require thermal insulation around the perimeter of slab-on-grade floors and extending downward 24 inches from the top of the slab or downward to the bottom of the slab and horizontally beneath the floor for 24 inches. The insulation must be impervious to water. For heated slabs, the required thermal resistance is gradually increased from R-2.8 for 500 degree-day climate to R-10 for a 10,000 degree-day climate or colder. For unheated slabs, the thermal resistance is gradually increased from R-2.5 for a 2,500 degree-day climate to R-7.5 for a 10,000 or over degree-day climate.

ANSI/ASHRAE/IES Standard 90A-1980 [10] has the same requirements as the HUD/MPS for the vertical and horizontal dimensions of the insulation at the edge of a concrete slab. For heated slabs, the required thermal resistance is linearly increased from R-3 for a 500 degree-day climate to R-16.8 for a 19,000 or over degree-day climate. For unheated slabs, the thermal resistance is linearly increased from R-2.5 for a 2,500 degree-day climate to R-14.2 for a 19,600 or over degree-day climate. This Standard is widely used as the basis for State building codes.

The USDA Forest Service Information Bulletin 373 [4b] recommends perimeter insulation for concrete slabs-on-grade with vertical extension or horizontal extensions of 12 to 24 inches, depending on the severity of the climate, and also a vapor retarder to isolate the concrete and perimeter insulation from the soil. These measures are intended to reduce heat loss and to minimize condensation on the colder concrete surfaces. The thermal resistance of the insulation is not specified.

The Manual of the League of Savings Associations [6b] recommends indoor dehumidification or rigid perimeter insulation for concrete slab-on-ground construction, to control surface condensation. It does recommend 2 in. of moisture-resistant insulation under the outer edge of the slab or adhered to the foundation wall, with an R value of 5.26 to 12.5.

While there are some differences in detail between the HUD/MPS requirements and the ANSI/ASHRAE/IES requirements, they are substantially in agreement and approach a national consensus because of the wide participation of all interested groups in the values finally selected.

Dissipation of the Moisture Generated Indoors by Occupant Activities

All existing regulations and recommended guidelines reviewed in the preparation of this report, except the RCS standards for the retrofitting of existing buildings, correlate the need for vapor retarders in walls, ceilings and floors with either the design outdoor temperature or the average January outdoor temperature. A few documents recognize that other parameters may be operative, but do not include them in their criteria.

In a review of current criteria used by the Navy in the construction of Navy facilities, Moore and Spielvogel [11] point out that the requirements for a vapor retarder on the interior side of the construction is inappropriate for buildings in warm and humid climates, where the vapor barrier should be on the exterior side, since this is where the vapor pressure is higher. Koenigsberger [12] suggests the use of porous materials in hot and humid climates to absorb moisture as condensation occurs and to release it when the air is sufficiently dry.

The RCS standards [13] state that the following climatic, construction, occupancy, equipment and operational factors all affect the potential for condensation of moisture in the exterior envelope construction:

- Outdoor temperature
- Building size
- Density of occupancy
- Amount of moisture generated indoors
- Ventilation and air infiltration rate
- Type of heating system
- Slope of roof
- Attic and wall cavity ventilation

Almost all recent field studies in existing occupied houses in moderate to cool climates revealed no concealed condensation in the walls whether vapor retarders were used or not, over a wide geographical area reaching from Alabama to Winnipeg, Canada and from Portland, Oregon to New Hampshire.

Many laboratory studies indicate that condensation will form on the sheathing in insulated cavity walls under typical severe winter conditions maintained for typical periods of time.

The gap between laboratory results and field observations has not yet been satisfactorily explained. In most field tests, not enough data have been collected on the factors identified in the RCS guidelines to explain this disparity in results nor to validate the RCS standards.

The various existing regulations and guidelines, other than the RCS standards, tend to require or recommend the condensation control measures that would protect each major component of the exterior building envelope from potential condensation, without regard to whether or not the amount of moisture likely to be produced in the building could be dissipated by the furnace flue or the exhaust fans in the kitchen and bathroom, through the window and door cracks, and through the envelope without raising the moisture content of the envelope materials excessively.

The condensation control measures for floors, walls, and ceiling/roofs that are contained in the various documents reviewed in the Appendices are summarized as follows:

2.4.1 Building Envelope in General

The Navy guide specifications [14] call for a vapor retarder to be installed on the "interior (warm in winter)" side of construction. It does not address the case in warm climates where even in winter the warm side in an air-conditioned building might be the outside.

2.4.2 Floors

The HUD/MPS does not require a vapor retarder in floors over crawl spaces. Condensation control is provided by groundcover, adequate crawl space ventilation, or a combination of these measures. A vapor retarder is required under concrete slabs-on-grade.

The ASHRAE Handbook, 1981, handles condensation control in floors over crawl spaces in much the same way as the HUD/MPS, but is much less emphatic on the use of vapor retarders under concrete floor slabs.

The Residential Building Code for the State of California [15] requires that a vapor retarder with permeance of 1 perm be placed on the heated side of crawl spaces in locations where the winter design temperature is 25° F or lower.

The USDA Forest Service Information Bulletin No. 373 [4c] recommends a vapor retarder (permeance at least 1 perm, 0.25 or less preferred) on the warm side of floors over crawl spaces and under the floor of finished basements in those parts of the U. S. where the average January outdoor temperature is 35° F or lower.

The NAHB Insulation Manual [5a] recommends vapor retarders on the warm side of insulated floors over crawl spaces irrespective of climate.

The Construction Manual of the League of Savings Associations [6c] recommends a vapor retarder on the warm side of insulated floors over ventilated crawl spaces in climates where the winter design temperature is 0° F or colder.

There appear to be two different views regarding the need for vapor retarders in floors over crawl spaces. One view is that water vapor from the occupied space will move downward through the floor and could condense on the floor joist, and therefore a vapor retarder is needed in cold climates. The other view is that the air movement is upward through the floor and that if the crawl space is ventilated and there is a ground cover in place, the potential for condensation in the floor is not present and a vapor retarder is not needed in the floor itself. This difference in views is not resolved and few field studies have been carried out to explore the moisture conditions in floors. None of the field studies summarized in the Appendices explored this aspect of condensation control.

2.4.3

Walls

The HUD Minimum Property Standards (MPS) [2] requires a vapor retarder with permeance of ≤ 1 perm on the warm (winter) side of the insulated walls of all dwellings. The combination of materials on the cold side of the vapor retarder shall have a permeance greater than 1 perm or provide provision for venting moisture to the outside.

The Residential Building Code for the State of California [15] requires that a vapor retarder with a permeance of ≤ 1 perm be placed on the heated side of walls in locations where the winter design temperature is less than 25° F.

The ASHRAE Handbook, 1981, [3] recommends that the walls of every dwelling include a vapor retarder in all three condensation zones if the U-factor of the wall is < 0.25 Btu/hr. ft² F and if there are materials in the wall that would be damaged by moisture or its freezing. The vapor retarder is recommended in Zones I and II for wall U-values higher than 0.25. The ASHRAE recommendations for commercial and institutional buildings are more general. They recommend placing the structural frame inside the curtain walls to improve airtightness and recommend improving airtightness of floors and interior partitions in highrise buildings to reduce chimney effect.

The USDA Forest Service Information Bulletin No. 373 [4d] recommends a vapor retarder on the interior side of walls in all geographical locations where the average January temperature is 35° F or lower.

The NAHB Insulation Manual [5a] recommends vapor barriers on the warm side of insulated exterior walls in all geographical areas.

The Construction Manual of the League of Savings Associations [6d] states that it is essential that a material with a permeance of ≤ 1 perm be used on the inner side of all walls and that the combined permeance of all materials outside the vapor retarder should be air permeable and have a vapor permeance of ≤ 5 perms.

F. S. Wang, Dow Chemical Corp., [16] concludes from laboratory and field studies that a vapor retarder with permeance of ≤ 1 perm which also is effective as an air barrier, installed on the interior side of the wall, is the single most important factor in minimizing vapor condensation.

It will be noted that the requirements and recommendations are consistent with respect to the maximum permissible permeance of the vapor retarder. Some recommendations include a minimum permeance for the materials outside the vapor retarder, and there is considerable difference in the numerical values. There is considerable variation in the geographical coverage of the requirements and recommendations, and they are based directly or indirectly on outdoor design temperature or average January outdoor temperature. The vapor retarder requirements for walls appear conservative in light of the results of the field studies in all climatic areas of the U. S.

2.4.4

Ceilings with Attics

The HUD Minimum Property Standards [2] require a vapor retarder with a permeance of ≤ 1 perm on the warm side of the ceiling, if the attic ventilation louvre area is limited to 1/300 of the floor area. The vapor retarder can be omitted if the louvre area for attic ventilation is doubled.

The Residential Building Code of the State of California [15] recommends a vapor retarder with permeance of ≤ 1 perm on the heated side of ceilings under unvented attics in locations where the winter design temperature is 25° F.

The ASHRAE Handbook of Fundamentals, 1981 [3b] recommends a vapor retarder with permeance of ≤ 1 perm in the top-story ceiling for gabled and hip roofs for condensation Zones I and II, combined with specified natural ventilation louvre areas in all cases.

The USDA Forest Service Information Bulletin No. 373 [4e] recommends a vapor retarder of unspecified permeance in the ceilings of gabled and knee-roofs in locations where the average January outdoor temperature is 35° F or lower. Attic ventilation is specified in each case.

The NAHB Insulation Manual [5a] recommends a vapor retarder in the ceiling of gabled roofs and attic ventilation in accordance with HUD/MPS in geographical areas where the winter design temperature is $\leq 20^{\circ}$ F (essentially the same as ASHRAE Zone I).

The Construction Manual of the League of Savings Associations [6c] recommends that a ceiling vapor retarder is essential in climates with a winter design temperature of -10° F or lower combined with attic ventilation louvres having areas 1/300 of the ceiling area. In older homes without vapor retarders, the ventilator louvre area should be doubled. Likewise, a ventilator louvre area of 1/150 of the ceiling area is recommended in moderate and southern zones whether or not vapor retarders are used.

Experiments conducted in the field by NRC Canada [3c] have shown that in some houses 65% of the air exfiltration can occur through the ceiling, depending on construction details and workmanship.

This summary of requirements and recommendations relative to the need for vapor retarders in ceilings with attics reveals a rather wide range of opinion as to whether attic ventilation can adequately replace the need for a ceiling vapor retarder. Obviously design and workmanship are important factors in this process. More research is needed, both in the field and in the laboratory, to reach a consensus on good practice.

2.4.5

Flat and Low-Sloped Roofs and Cathedral Ceilings

The HUD Minimum Property Standards [2] requires a vapor retarder with permeance of $\leq \frac{1}{2}$ perm on the warm side of any roof deck construction that is integral with the ceiling. The same requirement applies to any roof deck construction installed over an unventilated space.

The ASHRAE Handbook of Fundamentals, 1981 [3b] recommends that low-sloped roofs incorporate a vapor retarder with permeance of ≤ 1 perm, combined with ventilator area equal to 1/300 of the ceiling area in all three condensation zones in the United States. Cathedral ceilings comprised only of plank decks exposed to the interior do not need vapor retarders. In more heavily insulated roof construction, a superior vapor retarder with permeance of 0.05 perm is necessary between the deck and the insulation, and a ventilation space between the insulation and the roofing is recommended.

Insulated roof membrane systems on commercial and institutional buildings are difficult to keep dry because of the prevalence of water leaks in the roof membranes. The use of inverted roof systems (with the insulation on top of the roof membrane) over a conventional insulated membrane roofing system has some advantages because the membrane roofing may be warm enough to avoid condensation on the warmer side.

The NAHB Insulation Manual [5b] recommends that a vapor retarder be installed on the warm side of flat roofs, low-pitched roofs, and cathedral ceilings, where adequate ventilation is difficult to achieve.

The USDA Forest Service Information Bulletin No. 373 [4f] recommends a vapor retarder of unspecified permeance on the warm side of insulated flat roof constructions with cross ventilation from soffitt to soffitt between the insulation and the roofing membrane in all geographical locations where the average January outdoor temperature is 35° F or lower.

The Construction Manual of the League of Savings Associations [6a] recommends that flat or shed-type roofs of single-joist construction should have an efficient vapor barrier under the insulation combined with a ventilation system that provides outlets in every joist space, either with individual vents or continuous soffitt ventilation. The Manual concludes that a vapor retarder generally is not needed in wood-plank roof/ceilings in residential construction or other occupancies where the interior winter relative humidity averages less than 40%. A vapor retarder is recommended when the interior relative humidity exceeds 40% and the average January outdoor is 35° F or lower. These higher humidities are likely to be encountered in public shower rooms, kitchens, and pool areas. If a vapor barrier is provided in exceptionally cold climates and with high relative humidities, edge venting or stack venting of the insulation should be provided.

There is wide diversity and even some apparent contradictions among the requirements and recommendations summarized above relative to condensation control in flat and low-sloped roofs and cathedral ceilings. The design and construction of an effective low-slope roofing system is an especially difficult technical problem because of the need to provide a leak-proof membrane at the roof level, a vapor retarder at the ceiling level and insulation in between which must be kept dry. Because roof leaks are so prevalent the roof insulation becomes wetted intermittently. A recent NBS report [17] states that about 2 billion dollars is spent annually for repair and replacement of waterproofing membranes on low-slope roofs. Most organizations recommend that a ventilation space be provided in low-sloped and flat roofs. However, the motive force for moving air through the ventilation space is often insufficient to dry the insulation satisfactorily in broad roof areas. Many of the techniques that have been tried for drying wet roofs have been ineffective.

Considerable research is in progress in industry on inverted roof systems utilizing water-impervious insulation on top of the membrane system. The Department of Energy has issued an interim report [18], Assessment of Roofing Research, which summarizes the present state of roofing research and contains problem statements for a number of research tasks that should be undertaken toward developing thermally efficient roofing systems.

2.4.6

Dissipation of Moisture by Ventilation

In developing the RCS Standards for retrofitting existing buildings for better thermal performance, a special task group was convened by NBS to prepare recommendations to DOE on control of condensation. The task group developed a rationale for determining the indoor relative humidity that could be maintained in dwellings in various climate zones and the number of occupants that could be accommodated in houses in a range of floor areas with an infiltration rate of $\frac{1}{2}$ air change/hour, without requiring condensation control in the form of added vapor retarders. The procedure utilized the monthly average outdoor temperature and relative humidity in selected cities, and calculated the sheathing temperature for a 7.5 mph wind in a frame wall fitted with R-14 insulation, as a basis for determining the temperature at the place of condensation. The condensation produced each month at the sheathing surface by diffusion through interior wall coverings of different permeances and by convection of 25 cfm of indoor air into the cavity was calculated. The permissible indoor relative humidity was selected at a level that would not produce a rise in moisture content of the entire sheathing and siding in excess of 26% over a 6-month winter period. Table 2 gives additional information for condensation control in Minneapolis.

TABLE 2. CONDENSATION CONTROL FOR BUILDING WALLS
 Minneapolis, Minnesota

	MONTH						
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Monthly Avg Outdoor D.B. of	50.4	33.0	19.4	14.6	18.2	30.9	46.0
Monthly Avg Outdoor D.P. of	40	25	13	6	10	20	32
Outdoor Vapor Press, in Hg	0.248	0.130	0.073	0.051	0.063	0.103	0.180
Outdoor Humidity Ratio, lb/lb	.0052	.0027	.0015	.0011	.0013	.0022	.0038
Sheathing Temp*, Inner surf. of	52.8	37.4	25.5	21.2	24.4	35.6	49.1
Sheathing Vapor Press, in Hg	0.401	0.225	0.133	0.109	0.126	0.208	0.350
Sheathing Humidity Ratio*, lb/lb	.0086	.0047	.0028	.0023	.0026	.0043	.0074
Indoor R.H. for No Condensation on Sheathing*	54	30	18	15	16	29	48
* For 7-1/2 mph Wind, Frame-Wall Construction With R-14 Insulation							
<u>25 lb/day Indoor Moisture Release. Selected R.H. Settings</u>							
Indoor R.H. Setting, %	50	35	20	20	20	30	50
Indoor Humidity Ratio, lb/lb	.0079	.0055	.0032	.0032	.0032	.0047	.0079
Indoor D.P. Temp. of	51	41.6	28.3	28.3	28.3	37.5	51
Indoor Vapor Press in Hg.	0.376	0.263	0.152	0.152	0.152	0.225	0.376
Net Cavity	0	0	0	0	0	0	0
Condensation	0	.32	.12	.49	.22	0	0
800 ft ² wall, lb/day	0	1.30	.62	1.61	.90	0	0
Infiltration/Ventilation	86	83	136	110	122	93	56
Required for R.H. Level, cfm	0	2.16	1.08	2.43	1.62	1.08	1.35
Moisture to Cavity by 25 cfm							
Convection ^a , lb/day							

1 perm interior wall covering
 5.5 perm interior wall covering
 15 perm interior wall covering

7-mo rise in sheathing and siding moisture content 26%.
 15 perm interior wall covering. 1 perm outdoors.

a/ Assumed air leakage from room to wall cavity.

This type of analysis showed that a 900 square-foot house could accommodate two occupants and a 1500-square-foot house four occupants in Minneapolis with an air infiltration rate of $\frac{1}{2}$ air change and not require the installation of vapor retarders. The corresponding occupancy in St. Louis was four for a 900-square-foot house and six for a 1500-square-foot house. The analysis indicated that about 25 cfm per person of outdoor air would be required in the Minneapolis climate and about 16 cfm per person in the St. Louis climate to dissipate the average indoor moisture produced without excessive condensation in the insulation cavity. It also showed how observations of indoor relative humidity can be used to determine whether condensation in a wall is imminent and whether the air infiltration is deficient or excessive in an occupied building.

Whereas this type of analysis incorporates a number of assumptions and has not been verified by field or laboratory experiment, it does involve most of the occupancy, climatic and construction variables that could affect the potential for condensation in wall cavities. It may suggest why almost no evidence of condensation damage has been found in field studies of occupied houses and why vapor retarders may not be needed in houses under some combinations of conditions. The report of the task group [19] is summarized in Appendix B.4.

2.5

Condensation Control in Warm and Humid Climates

The ASHRAE Handbook of Fundamentals, [3d] summarizes some of the condensation problems and mold and mildew hazards likely to occur in humid climates. Humid climates and fringe climates are defined in terms of total hours of wet-bulb temperatures at or above stated levels during the six hottest months of the year. The sections of continental United States, Hawaii and Puerto Rico that fall into these classifications are shown on a map. The Handbook recommends that in these locations the exterior surfaces of building envelopes should have a higher vapor resistance than the interior surfaces. This can best be accomplished by the use of vapor resistant paints and finishes on the exterior surfaces and lower vapor resistant materials on the inside. An air barrier should also be used to prevent excessive passage of warm humid air to the indoors, thus unnecessarily increasing the latent load on an air conditioner.

In a 200-mile-wide strip adjacent to the Gulf and Atlantic coasts from the tip of Texas at Brownsville to about the Florida-Georgia border on the Atlantic Ocean, the dewpoint temperature exceeds 70° F for the four months from June to September. In most of the large cities in this coastal section the dewpoint temperature is in the $73-75^{\circ}$ F range for the months of July and August. Thus an insulated house maintained at an indoor temperature in the range $70-72^{\circ}$ F might experience condensation on the exterior of the interior wall covering during these two months. Of course, this potential could be eliminated by operating the interior of the house at a temperature of $74-75^{\circ}$ F.

The weather data for various islands and equatorial regions indicate that the Navy undoubtedly has facilities in locations that experience more severe and prolonged humid weather than the Gulf coast of the U. S.

The information from the ASHRAE Handbook that is summarized in Appendix B.1 is not regarded as sufficiently specific and comprehensive for Navy purposes. It is probable that Navy dwellings and other buildings located in humid climates and that are continuously air-conditioned need both an air barrier and a vapor retarder of sufficient integrity to allow the interior building environment to be comfortable and that will protect the building and its furnishings from mold, mildew, odor, corrosion, staining and other deterioration.

In 1978, during field investigations in the Pacific and Southeastern United States, Moore and Spielvogel [11] found mold and mildew in virtually all buildings visited on Navy shore facilities. They also found that both design and actual comfort conditions were outside the ASHRAE comfort envelope. In review of Navy Design Criteria, Moore and Spielvogel [11a] attributed the problems primarily to the fact that the criteria do not adequately recognize the need for humidity control in warm and humid climates.

2.6

Water Leakage in Roof Coverings

Flat roofs and low-shaped roofs are probably the most difficult part of an exterior envelope in which to achieve satisfactory moisture control. In moderate and cold climates, the insulation and other construction materials may be wetted from above by roof membrane leakage, or by vapor transmission and condensation from below. Water leakage in the roof membrane essentially thwarts the purpose of the vapor retarder underneath. "The presence of water creates problems in roofing systems. Water contributes to the deterioration of organic materials; it degrades the thermal efficiency of insulations; through freeze-thaw cycles it can destroy the mechanical integrity of the weather barrier; and, because of the load of unintended accumulations, it can overstress the building structure." [18]

Ventilation of this type of roof is essential because of its potential for being wetted from either above or below. Ventilation of flat and low-sloped roofs is more difficult than a gabled roof because of limitation of space. There is little chimney effect to produce natural convection; the areas to be ventilated are often broad in both directions; and gravity drainage of water to the perimeter is often impossible. In addition, the daily solar cycle can cause movement of the moisture back and forth through the insulation each day, with a corresponding large increase in heat transfer. Dripping from a wetted roof can cause extensive damage to the construction and equipment below.

The difficulty in removing water from wetted roof insulation also stresses the importance of avoiding holes, discontinuities, and poorly sealed penetrations in the ceiling vapor retarder.

In warm and humid climates, the membrane of flat roofs constitutes a good vapor retarder on the outside of the construction where the vapor pressure is greatest. The installation of an additional vapor retarder on the inside of the construction or insulation would make it virtually impossible for any moisture in the roof insulation to escape [11b]. Such an additional vapor barrier should thus be avoided.

2.7

Extent of Moisture Problem in Navy Shore Facilities

Because of the lack of comprehensively documented moisture damage in housing, a quantitative statement regarding the extent of moisture problems in general cannot be made at this time. With regard to Navy shore facilities, it is known that a large number of family housing units in warm and humid climates experienced severe moisture problems.

The authors of this report have witnessed what they consider severe moisture problems in units in three housing developments at the Naval Air Station in Pensacola, Florida. Further studies are required to determine whether the mold, mildew, wet building materials, and weakened gypsum board are caused by capillary rise of moisture from the earth, rainwater leakage through the exterior surface, condensation within the walls, inadequate control of indoor humidity, or a combination of these phenomena.

One measure of the extent of the Navy shore facility moisture problems in warm and humid climates is the number of days required for periodic repair of moisture damage. According to Base personnel at the Pensacola Air Station, the repair of moisture problems adds approximately one day to the turn-around time between tenants in 30 to 50 percent of the two most affected housing developments. For the entire Base, this is the equivalent of approximately one housing unit permanently unoccupied. No cost for the repairs nor for the damage to furniture and other contents was made available.

Field studies at two Air Force Bases and two Navy installations on or near the South Atlantic and Gulf coasts by the National Bureau of Standards (see Appendix C.12) revealed problems of paint peeling, mold and mildew on interior surfaces, water dripping from roof above suspended ceilings, and inadequate humidity control by the air conditioning systems in housing units and bachelor enlisted quarters.

Based on three inspection trips by ARMM Consultants, Inc. (Appendix B.9) to study moisture problems in family housing, bachelor enlisted quarters, and other types of occupied buildings at Navy installations in the Pacific and in the South Atlantic and Gulf Coasts of the U. S., the moisture-related problems are extensive, although somewhat more severe in the Pacific installations. The problems included widespread incidence of mold and mildew, poor painting practices, deterioration of painted surfaces, improper use of vapor retarders, weakened and collapsed suspended ceilings, water absorption by insulation, blistering and slippage of roof membranes, and generally inadequate performance of fan-coil units in controlling indoor humidity. A rough estimate of cost for repair of the Pacific installations ranged from \$500,000 to \$1,200,000.

The extent of Navy shore facilities in the Subarctic is not known. However, the case histories described by Zarling et al. (see Appendix C.13) indicate that the formation of ice and frost in the insulation cavities of many types of buildings is widespread in the Subarctic. These case histories indicated that the moisture migration into the insulation results principally from leakage of indoor moist air through holes and discontinuities in the vapor barriers. It is also suggested that the building construction industry has not yet established improved design and construction practices that will significantly reduce this type of air leakage. Operating a building at a slightly reduced pressure relative to the outdoors will also alleviate ice and frost formation in the insulation.

Navy shore facilities constructed in the Great Lakes area at the Canadian/U.S. border might be subject to condensation or frost formation in the insulation though presumably at a lesser rate than in the Subarctic. Laboratory studies conducted at moderately cold temperatures under steady-state conditions indicate that condensation will occur in the insulation cavities in this climate zone. However, several recent field studies of occupied houses including some units located in climate zone I have not revealed detectable condensation. This lack of agreement between field and laboratory results has not been satisfactorily answered as yet. The analysis of condensation control summarized in Appendix B.4 indicates that a number of parameters other than outdoor temperature determine the likelihood of condensation in insulated walls or ceilings. Some of these are house size, occupant density, air infiltration rate, type of heating system, winter humidification, and amount of attic ventilation. The impact of variable outdoor temperatures on the accumulation of moisture in insulated walls and ceilings has not been studied to any significant degree.

In order to develop a more definitive statement on the extent of moisture problems in Navy shore facilities, it would be necessary to conduct a survey of a representative sample of facilities, as outlined in Section 4.1 below.

References to Section 2

- 1 Building Research Advisory Board (BRAB), "Ground Cover for Crawl Spaces," Report to Federal Housing Administration, Washington, D. C., May 1962, p. 3.
- 2 U. S. Department of Housing and Urban Development Minimum Property Standards (HUD/MPS), Washington, D. C.
- 3 ASHRAE Handbook and Product Directory, Fundamentals Volume, Atlanta, GA, 1981, p. 21.16.
- 3a Ibid, p. 21.13.
- 3b Ibid, Table 4, p. 21.16.
- 3c Ibid, p. 22.16.
- 3d Ibid, pp. 21.18-21.20.
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- 4b Ibid, p. 6.
- 4c Ibid, p. 5.
- 4d Ibid, pp. 5, 13, 14, 15.
- 4e Ibid, p. 23.
- 4f Ibid, p. 28.
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- 13 Residential Conservation Service Program (RCS), Federal Register, Vol. 44, No. 217, Wednesday, Nov. 7, 1979, pp. 64688, 64690, and 64691.
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- 16 F. S. Wang, "Comparative Studies of Vapor Condensation Potential in Wood-Framed Walls," ASHRAE, SP 28, 1981.
- 17 NBS Special Publication 146-3, Building Technology Project Summaries, 1979. National Bureau of Standards, Washington, D. C.
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- 19 P. R. Achenbach, "Report on Control of Condensation in the Walls and Ceilings of Retrofitted Houses," Special ad hoc Task Group, NBS, for the U. S. Department of Energy, December 29, 1978, unpublished.

3. RECOMMENDATIONS FOR NAVY PRACTICE BASED ON CURRENT KNOWLEDGE

Based on current state-of-the-art and on the above evaluation, the following criteria are suggested for use in new and retrofit shore constructions:

3.1 Ground Cover in Crawl Spaces

Ground cover of heavy roll roofing or 4- to 6-mil polyethylene film turned up 6 inches at the walls is recommended in all locations, combined with ventilator area of 1/1500 of the crawl space area located so as to produce cross ventilation. This recommendation is applicable to all new buildings, apartments, barracks and office buildings, and in retrofitting existing buildings where there is evidence that moisture from the earth is damaging the ground floor or foundation.

3.2 Dampproofing of Slabs-on-Ground

Because Navy facilities are often located in low coastal areas, dampproofing of concrete slabs-on-ground is recommended for all new Navy dwellings, apartments, barracks, and office buildings.

3.3 Edge Insulation of Concrete Slabs-on-Grade

Edge insulation of concrete slabs-on-grade in accordance with the requirements of ANSI/ASHRAE/IES Standard 90-1980 is recommended for all new dwellings, apartments, barracks and office buildings, to reduce the edge heat loss and prevent condensation on the floor surface at the perimeter of the buildings.

3.4 Condensation Control in the Walls, Floors, and Ceiling/Roofs

3.4.1 Walls

An air barrier should be provided on the warm (winter) side of the insulation in all new dwellings, apartments, barracks and office buildings, except in humid climates and fringe areas as defined in the 1981 ASHRAE Handbook of Fundamentals, Chapter 21. In humid areas and fringe areas the air barrier should be on the exterior side of the insulation. All air barriers should be secured to the structural or envelope members in a way to avoid gaps and fishmouths and should be sealed around penetrations by service systems and at the junctions with doors, windows, floor, ceiling and other walls.

A vapor retarder with a permeance not to exceed 1 perm should be provided on the warm (winter) side of the insulation in all new dwellings, apartments or barracks in condensation zones I and II, defined in ASHRAE Handbook, that are characterized by a floor area of less than 1000 sq. ft. or 300 sq. ft. per occupant. A vapor retarder of the same permeance should be provided in all dwellings, apartments, barracks and offices regardless of size or occupancy in Alaska, and in condensation zones I and II if the buildings are humidified in the

winter. A total floor area of 1200 sq. ft. or 400 sq. ft. per occupant is required before a vapor retarder may be omitted in condensation zones I and II for dwellings, apartments, or barracks that are heated by an electrical heating system, a fuel-fired system using outside air for combustion, or a central heating plant. Vapor retarders may be omitted in non-humidified office buildings if outdoor ventilating air is provided at the rate of 16 cfm per occupant in condensation zone II and at the rate of 25 cfm per occupant in zone I, in each room. A vapor retarder (paint or film) with a permeance not to exceed 1 perm should be provided on all the walls and ceiling of bathrooms and laundry rooms in dwellings, apartments, and barracks, regardless of building size or occupant density, in condensation zones I and II.

In humid climates and fringe areas, the exterior surface materials of the building envelope should have a higher vapor resistance than the interior surface materials, especially if the indoor temperature is to be maintained below 75° F.

In many cases the same film or material can serve as both an air barrier and a vapor retarder.

In the retrofit of existing buildings, vapor retarders on the inside of exterior walls can often be provided most practically and economically by the use of low permeability paints or wall paper (permeance of ≤ 1 perm). Polystyrene or other non-hygroscopic insulation board with a thermal resistance no greater than R-5.5 can be applied to outside of the exterior walls of uninsulated and non-humidified buildings in condensation zones I and II without creating a condensation problem provided the insulation board is vapor impervious at the side next to the building wall.

3.4.2 Floors

A vapor retarder with permeance of ≤ 1 perm is recommended for the warm side of insulated floors over unventilated crawl spaces in dwellings, apartments, and barracks, in condensation zones I and II and in Alaska. The vapor barrier may be omitted for condensation zones I and II when the crawl space is provided with ventilator openings equal to 1/150 of the floor area in a manner that allows cross ventilation.

3.4.3 Ceilings with Attics

The recommendations for ceilings with attics in new buildings are the same as for walls, detailed in the above paragraphs, with the following addition. Attic ventilation louvres having a free area 1/300 of the ceiling area should be provided in a manner to permit cross ventilation or with the ventilator area equally divided between soffitt ventilators and ventilators at least 3 feet above the ceiling, such as gable or ridge vents.

Low permeability paints and wall coverings are also effective in providing vapor retardancy in retrofitted ceilings. In some cases, where there is no existing insulation in the ceiling or the ceiling insulation is to be replaced, it is practical to apply new insulation with attached vapor retarders. The vapor retarder should be placed in contact with the ceiling surface in a manner that minimizes air and vapor bypass of the vapor retarder.

3.4.4 Flat and Low-Sloped Roofs

Cathedral ceilings comprised of plank decks only that are exposed to the interior do not need vapor retarders. Cathedral ceilings with insulation on top of the deck should have a vapor retarder with a permeance of 1/2 perm or less which overlaps all interior and exterior wall connections with the ceiling, as well as covering all the room space, in all geographical areas.

Insulated flat roofs and low-sloped roofs should have a vapor retarder with a permeance of 1 perm or less and should be provided with ventilation either soffitt to soffitt or soffitt to ridge, with ventilator area equal to 1/300 of the ceiling area in all geographical areas.

These guidelines apply to dwellings, apartments, barracks, and office buildings.

Low permeability paints and wall coverings can also be used as vapor retarders in retrofitting existing buildings. It is usually difficult and expensive to provide ventilation in flat and low-sloped roofs as a retrofit measure in buildings that are not so equipped originally.

4. RESEARCH NEEDED TO RESOLVE CONFLICTS AND FILL GAPS IN TECHNOLOGY

Many organizations are currently involved in conducting, or sponsoring, research in the above areas, and the Joint ASTM/ASHRAE Steering Committee could provide the mechanism for coordinating this work.

In comparing currently used regulations, guidelines, and results of laboratory studies for the use of water vapor retarders in building envelopes with the results of field studies, one major issue forces itself to the forefront: How can we explain the discrepancy between engineering calculations and laboratory studies indicating a propensity for substantial moisture damage in cool climates if effective vapor retarders are not installed on the one hand, and the lack of clearly demonstrated evidence of condensation damage in field studies of moisture problems in actual buildings on the other? Second, what is the actual extent of moisture problems, specifically in Navy shore facilities? A third major issue deals with the dynamics of water vapor condensation, accumulation, evaporation, and attendant deteriorating effects. A fourth issue revolves around the relative importance of diffusion of water vapor through surface materials, and mass transport of moisture into wall cavities through moist air leaking into wall cavities, attics, and floor spaces; i.e., the relative importance of air barriers and vapor retarders. Of particular interest to an organization constructing and maintaining buildings outside the continental United States, and generally in coastal areas, is the issue of the reversed condition, where air-conditioned buildings in warm and humid climates are subject primarily or exclusively to vapor transmission from the warm and humid outdoors to the air-conditioned indoors.

4.1 Survey of Extent of Moisture Problems in Navy Shore Facilities

While it is known that moisture problems are persistent in at least some Navy facilities in warm and humid climates, no quantified definition of the extent of moisture problems is currently available. Such a definition can be developed only through a survey of Navy shore facilities.

The survey should consist of at least two steps: (a) a broad mail survey to all major Navy facilities (world-wide) or to a representative sample, and (b) a series of site visits to selected facilities. It may be preferable to conduct two mail surveys: a short form administered to all or most facilities, and a more detailed survey administered only to a select group of facilities that reported significant moisture problems. In any case, some in-person field visits would appear to be necessary, to ascertain the results of the mail surveys, and to establish an in-depth documentation of the problems.

The survey would provide a basis for future technical work. But, more important, it would establish a rational basis for determining the level of effort justified to solve the problem.

4.2

Field Experience Versus Analytical/Laboratory Studies

Most analytical and laboratory studies considered showed a propensity for moisture damage if effective vapor retarders were not installed in cold climates. The work of the NBS task group in 1978 identified several parameters that need to be considered in evaluating the moisture problem potential in specific buildings and homes: size of home, occupant density, indoor relative humidity, tight envelope construction, amount and location of air infiltration/ventilation, home with or without combustion furnaces and flues providing positive ventilation, and homes that are humidified during the winter [1]. None of the past field studies appears to have considered the above parameters and collected or reported the necessary data to permit the evaluation of the effect any one of them may have on the moisture-related performance of the building. Most field studies may have had a built-in bias, for example, toward low occupant density/large houses. Such a bias could be expected to understate the potential for moisture problems. It is suggested that the studies outlined below be conducted to determine the effect of the above parameters on the propensity for moisture problems.

4.2.1

Collect Additional Data From Prior Moisture Studies

As a first step prior to developing a detailed work plan, the organizations that have conducted the various field studies could be requested to make available any data they may have on the several parameters identified above for the houses investigated. A review of these data could indicate the most appropriate direction for the overall study.

4.2.2

Follow-up on Recent Retrofitting Demonstration

The NBS, under sponsorship of the Community Services Administration (CSA), has conducted a nationwide weatherization demonstration experiment and collected data on size, occupancy, temperatures, relative humidity, and type of heating system. However, no data relating to moisture problems were recorded by NBS. In at least some of the sites, most likely Minneapolis, Minnesota; Denver, Colorado; Tacoma, Washington; and Portland, Maine, such data could still be gathered without the need for extensive long-term measurements. It appears that NBS would be willing to reactivate this project for the investigation of the issue of moisture control.

As summarized in Appendix C.9, Johns-Manville Sales Corp. and the Electric Power Research Institute are collaborating in determining the impact of air leakage reduction techniques in 29 houses in Denver on energy savings, and using an equal number of untreated houses as controls. This is probably the most thorough job of air leakage reduction applied in any large field experiment up to the present. The project was to be continued for several years. Investigation should be made to determine whether additional data could be taken in these houses to clarify the parameters that are operative in controlling condensation. Data should be collected on air infiltration by tracer-gas techniques, location of neutral pressure zone, indoor relative humidity, humidification, use of exhaust fans, occupant activities that generate moisture, use of vapor retarders, etc.

Additional field studies, such as the Twin Rivers retrofit experiment by Princeton University [2] may provide a useful basis for follow-up.

4.2.3 Field Survey of Buildings in Extreme Climates

A new field survey should be initiated to address specifically the effects of house size, occupant density, air infiltration rate, indoor-outdoor pressure difference, type of heating system, and winter humidification on moisture damage potential and moisture content of sheathing. To reduce the number of houses required in the survey, the study might be conducted in a cold climate in the United States with a long winter season. Preferably, the study would involve otherwise identical houses located in close proximity, and under sufficient control by the investigators so that the parameters mentioned above could be changed. Houses on a Navy or other military base could meet these requirements, probably better than civilian housing. It would be the purpose of this study to identify those parameters which most significantly affect the potential for moisture damage, and to select the more significant ones for further study in a broader range of climates.

4.2.4 Field Study in Cold and Moderate Climates

Based on the results of the survey in extreme climate, a field study should then be conducted of those parameters identified as most significantly affecting the moisture damage potential. It would be the objective of this study to determine under what conditions the specific parameter or parameters do cause moisture damage in the continental United States. The details of the study would need to be based on the results of the work described in the preceding three sections.

4.3 Systems Response to Dynamic Temperature and Humidity Changes

One reason (other than the lack of consideration for building size, occupant density, tightness of construction, type of heating system, and humidification during winter) that past analytical and experimental work is not corroborated in field studies, could be that laboratory and analytical work was generally based on steady-state conditions, whereas in actual service, temperatures, humidities, and wind effects are always dynamic in nature. Thus, if moisture does condense inside a wall structure, it may accumulate only for a relatively short period and dry out as the conditions change. By placing moisture probes designed by Forest Products Laboratory [3] in the studs, insulation, and sheathing, a dynamic pattern of moisture content in the important parts of a wall, floor, ceiling or roof could be obtained during these field studies. This would clarify wetting and drying cycles and evaluate the accumulation of moisture for the different parameters of climate, occupancy, air leakage, condensation control, etc.

4.4 Diffusion and Air Leakage

Experts in the field generally agree [1a] that moist air leakage into wall and ceiling cavities is the more significant mode of moisture transport in walls. However, in houses with furnaces not using outside air for combustion, or houses making extensive use of kitchen and bathroom fans, the air moving into

the wall cavities may in fact be the drier outside air. This air could then counteract the effects both of warm humid indoor air seeping into the cavities and of moisture entering the cavity by diffusion through interior finish materials. Past field studies of air movement in houses were generally conducted by pressurization of the house, thus eliminating the natural pressures resulting from stack effect and from the operation of furnaces. By measuring indoor-outdoor and indoor-attic pressure differences and direction, combined with tracer-gas air-change-rate measurements and air leakage studies under natural pressure differences, the pattern of moisture content in building elements could be explained and better design criteria for condensation control could be developed. Laboratory studies in a climatic chamber should be used to supplement field observations and to reduce the amount of expensive field study required.

4.5

Warm and Humid Climate

Of particular interest to the Navy, with its numerous shore facilities in warm and humid climates, is the potential for moisture problems in such climates.

The survey conducted by ARMM Consultants, Inc. (Appendix B.9) indicated substantial moisture problems in the Pacific, in the Southeastern United States, and in the Caribbean area. A preliminary survey by H. R. Trechsel Associates (see Section 2.7) at the Pensacola Naval Air Station showed substantial moisture damage, but from which of several potential causes is not known. As a result of the Pensacola study, a research plan was prepared to identify the cause or causes of the problem and to develop remedial actions. The plan has five elements:

- o A field study of rainwater penetration and capillary rise of moisture. The study is designed to ascertain whether or not rain leakage through the masonry or at the windows, or through capillary action, diffusion, or mass transport from moisture in the ground is a major cause of the observed dampness.
- o A field study of air-conditioning and condensation. This is a study to determine whether air-conditioning practices, temperature, and moisture conditions in the houses can account for some of the substantial moisture problems.
- o A survey of operational practices. This study would determine actual occupant use patterns. The results are needed to interpret the findings of the study on air-conditioning and condensation.
- o Based on the results of the preceding studies, specific corrective measures can be developed. This phase could also include the development of improved guidelines for new construction in warm and humid climates.

- o Prior to implementing the proposed remedial measures on many housing units, it is prudent to try them on a few units. If the measures are to have a broader application than in the narrow context of the specific housing units studied in Pensacola, the field trials should also be conducted at representative bases in other locations--primarily in the Pacific area. The field survey recommended under Section 2.7 on the extent of moisture problems in Navy shore facilities would provide a guide as to where such field trial installations would be most appropriate.

4.6 Additional Research

The above studies address directly the need for additional information to develop more reliable guidelines for moisture control in Navy buildings, and are most pressing. A refinement of the guidelines and advance of the technology of condensation control in buildings will require also the conduct of the following research tasks.

4.6.1 Other Studies Needed to Resolve Conflicts and Fill Information Gaps:

- o Evaluation of the relative technical and economic merits of generous crawl space ventilation without ground cover, or limited ventilation with ground cover. Either approach is considered acceptable in the HUD Minimum Property Standards.
- o Research on effective methods for quantitative control of ventilation of wall cavities with outdoor air. Some convection of outdoor air into cavity walls is considered desirable to help remove water vapor from the cavity. Increasing ventilation of the wall cavity with outdoor air is considered to be one of the more effective means for curing walls with moisture problems. On the other hand, excessive cold outside air infiltration into the wall cavity may reduce the effectiveness of the thermal insulation. The procedures now used are essentially "trial and error" methods. There is no information of a quantitative nature on the amount of ventilation attained or needed, nor on the decrease of insulation value.
- o Research on effective methods for drying flat and low-sloped roofs leading to design guidelines. A large amount of money is expended each year to repair and replace roofing membranes. Water leaks are prevalent in roofs. A variety of methods and techniques have been tried experimentally for drying out roof insulation and other materials with limited success. Continued research and new approaches to drying out flat and low-sloped roofs is very much needed.
- o A study of the relative technical effectiveness and the economics of eliminating the ceiling vapor retarder and dissipating the moisture transmitted to the attic by attic ventilation versus the use of a ceiling vapor retarder and dissipating the indoor moisture with much less ventilation of the occupied space. Some existing guidelines emphasize attic ventilation and avoid ceiling vapor retarders insofar as possible; others recommend ceiling vapor retarders in all applications, supplemented by a more limited amount of ventilation. A better evaluation of the tradeoffs and the economics of these approaches is needed.

- o A study of the need for vapor barriers in insulated floors over crawl spaces, if ground cover and ventilation are used. There is no consistency in current recommendations on the need for vapor retarders in insulated floors over crawl spaces. Some technical analysis and a well-planned field study could probably resolve this ambiguity.

The above investigations may involve analysis, laboratory, and field studies.

4.6.2

Other Research Needs to Advance the Technology of Condensation Control:

- o More comprehensive data on the permeance of paints, coatings, membranes, and building materials. There are many building materials, vapor retarders, paints, coatings and films for which handbook data are not available.
- o More comprehensive data on the effect of temperature on the permeability of vapor retarders. The equations shown in the ASHRAE Handbook [4] for making temperature corrections to permeability are limited to only a particular class of materials. It is assumed to be an approximation for other materials.
- o A portable device for measuring the permeance of interior wall coverings in the field. Retrofitting of existing buildings for energy conservation would be facilitated and more reliable from a condensation point of view if the permeability of existing interior wall coverings could be made in situ.
- o Development of more consistent guidelines for the dampproofing of concrete slabs-on-grade and more definitive guidelines on where it may be omitted. Present recommendations range from universal use of vapor retarders under concrete slabs-on-grade in all climates, to no recommendation at all, while still another group allows them to be omitted in arid regions without a quantitative guideline for this judgment.
- o A more comprehensive study is needed on the improvements in air leakage control attainable in housing by various retrofit measures and their cost and benefits. The pressurization-type approach to air leakage that is prevalent in field studies does not yield data that can be used to judge whether the air infiltration of retrofitted houses is adequate to control condensation or not. Air infiltration/ventilation serves many purposes in buildings. Field studies of retrofit techniques should be planned to collect pertinent data for evaluating the impact of the measures on all relevant environmental factors.
- o A set of guidelines for the retrofit of dwellings that include the effects on moisture control and air quality, as well as reduction in energy use. As the technology of retrofitting matures, a set of guidelines should be developed on a consensus basis to support credibility, acceptance, and economy in the process.

- o More definitive guidelines on the ratio of permeabilities (air and vapor) inside and outside the air and vapor barrier needed to prevent condensation. It is generally agreed that neither air barriers nor vapor retarders completely cut off convection and diffusion, and that successful design depending on a flow-through process for air and water vapor (without condensation and excessive heat transfer) is a more practicable approach. The relative permeabilities of the building elements inside and outside the barrier have been studied somewhat, but are not now regarded to be constant. Research is needed on both the physical principles and the workmanship factors involved to develop better design guidelines for this ratio.
- o Development of methods for draining condensed moisture or leakage water to the roof edge in low-sloped roofs and cathedral ceilings. It has been proposed that water leakage and/or condensation in low-sloped roofs and cathedral ceilings with an air space between the insulation and the roofing membrane could be drained to the soffits without wetting the insulation by a water impervious membrane laid shingle-style on top of the insulation. This concept should be explored for its practicability.
- o Test methods and procedures for determining moisture flow into, out of, and through composite wall construction under static and dynamic conditions. This project is the subject of an ASHRAE research proposal which could be implemented soon, if funds and facilities are available. It is drafted as a basic test procedure development for moisture transfer and is regarded as an initial effort for future studies of more typical building sections.

References to Section 4

- 1 P. R. Achenbach, "Report on Control of Condensation in the Walls and Ceilings of Retrofitted Houses," Special ad hoc Task Group, NBS, for the U. S. Department of Energy, December 1978, unpublished.
- 1a Ibid.
- 2 Robert H. Socolow, "The Twin Rivers Program on Energy Conservation in Housing: Highlights and Conclusions," Princeton University, prepared for the U. S. Department of Energy, August, 1978, HCP/M4288-01 UC-55d, NTIS.
- 3 J. E. Duff, "Moisture Distribution in Wood-Frame Walls in Winter," Forest Products Journal, Vol. 18, No. 1, January, 1968.
- 4 ASHRAE, Handbook and Product Directory, Fundamentals Volume, Atlanta, GA, 1981, p. 21.8.

Appendix A

SUMMARIES OF CODE AND REGULATION REQUIREMENTS
FOR VAPOR RETARDERS AND CONDENSATION CONTROL IN BUILDINGS

A.1 HUD Minimum Property Standards for One- and Two-Family Dwellings, 4900.1, 1980.

Vapor Barriers 607-2.4

a. Walls

A vapor barrier with a vapor transmission of ≤ 1 perm shall be installed on warm side (winter) of the insulated wall. The combination of materials on the cold side of the vapor barrier shall have a vapor transmission of ≥ 1 perm, or have provision for venting of vapor to outside.

b. Ceilings

When a vapor barrier is provided on the warm side of a ceiling under a ventilated roof or attic space, its vapor transmission rate shall be ≤ 1 perm.

c. Roof Deck

Any roof deck construction that is integral with the finished ceiling surface shall have a vapor barrier near the warm side having a vapor transmission of $\leq \frac{1}{2}$ perm.

Any roof deck construction installed over an unventilated space shall have the same vapor barrier requirement.

d. Slab-On-Ground

A continuous vapor barrier membrane is always required for slabs below grade with membrane edges turned up to top of slab, and a continuous vapor barrier membrane is always required for slabs above grade having ductwork or piping in or under the slab.

A continuous vapor barrier membrane is always required under slabs above grade not having ductwork or piping in or under the slab, except that it may be omitted in arid regions where irrigation and heavy sprinkling are not done. Vapor barrier may be above or below slab for wood-block and wood-strip flooring construction. Vapor barriers shall be tested in accordance with ASTM E-96 and C-355.

e. Crawl Spaces

Ground surface treatment material having a vapor transmission rate of ≤ 1 perm shall be installed where soil and moisture conditions warrant, or as a prerequisite for reducing the free ventilation area for the crawl space to 1/1500 of the ground area with cross ventilation required.

Ventilation 403-3 Table 4-3.1

a. Attics

A net ventilating area of 1/150 of the floor area shall be provided if no vapor barrier is provided on the warm side of the ceiling. The net ventilating area shall be at least 1/300 of the floor area if a vapor barrier is used on the warm side of the ceiling or if at least 50% of the required ventilating area is in the form of fixed louvres at least 3 feet above eaves. Mechanical ventilation, if used, shall provide 0.7 cfm/ft² of attic floor area plus 15% for dark roofs. The air intake shall provide 1 ft² of free opening per 300 cfm of fan capacity.

b. Caulking 607-4

A broad general requirement is stated for caulking, gasketing, or otherwise sealing around all openings in the exterior envelopes of the conditioned space, at all joints between dissimilar materials, and all junctions of major components such as wall-to-floor etc.

A.2 DOE Residential Conservation Service Program (RCS).
(Published in the Federal Register November 7, 1979*)

The provisions are mandatory for retrofit performed under RCS. The provisions for vapor retarders (barriers) depend on 1) climate zones, 2) type of room (high or low humidity spaces), 3) type of insulation, and 4) cost of installation.

In general, where an interior finish is added as part of the installation (such as where the insulation material must be covered by a fire protective finish), the provisions are similar to the HUD Minimum Property Standards.

*Rationale for individual provisions and additional background information is given in "Criteria for the Installation of Energy Conservation Measures," by H. R. Trechsel and S. J. Launey, National Bureau of Standards Special Publication 606, July, 1981.

a. Walls

For walls where no interior finish needs to be installed, such as when insulation is blown into wall cavities, a vapor retarder is required only on walls in bathrooms and unvented kitchen and laundry areas, in ASHRAE condensation zone I. In addition, in these spaces, it is also required to caulk and seal all major cracks on the interior face of exterior walls, including joints between wall and ceiling and wall and floor, and around window frames and wall penetrations of electrical and plumbing services, to reduce the leakage of warm, moist indoor air into the wall cavities. In addition, non-mandatory recommendations are included. For zone II, the same precautions as required for zone I are recommended. Also the Standard indicates that the provisions for moisture control are minimum requirements needed to prevent long-term moisture damage. For houses which are characterized by an area less than 900 ft² (75m²), less than 250 ft² (23 m²) per occupant, tight construction, electrical heating system, or a system using outside combustion air, additional precautions should be considered, such as installing vapor barriers and sealing cracks in other than high-humidity rooms and in locations other than condensation zone I.

The RCS standard also mentions the use of relative humidity indicators to monitor indoor humidity levels for determining the potential for excessive moisture accumulation. It does not provide numerical guidance on the use of the indicators (such guidance is given in NBS SP 606).

For walls insulated with organic cellular rigid-board thermal insulation on frame walls, the RCS standards provisions distinguish between installations of board with and without integral vapor retarder on frame walls with or without an insulated cavity, and board insulation inside or outside the cavity. The requirements are given in matrix form, as shown in Table A.2.1.

TABLE A.2.1 VAPOR RETARDER REQUIREMENTS FOR THE INSTALLATION OF ORGANIC CELLULAR RIGID BOARD THERMAL INSULATION ON FRAME WALLS

MATERIAL	WHERE INSTALLED	CAVITY INSULATION	REQUIREMENT
Board with vapor barrier facings (also boards which are rated by the manufacturer to have a permeance of less than 1 perm in the thickness in which the board will be installed)	Interior	Filled or Empty	No additional winter warm side vapor barrier
	Exterior	Filled	In Zones I and II of Fig. B.1.1, vapor barrier on the winter-warm side and sealing of interior cracks
	Exterior	Empty	No additional winter-warm side vapor barrier
Board without vapor barrier facings or board without integral vapor barrier characteristics	Interior	Filled or Empty	In Zones I and II of Fig. B.1.1, vapor barrier on the winter-warm side and sealing of interior cracks
	Exterior	Filled	In Zones I and II of Fig. B.1.1, vapor barriers and sealing of interior cracks only in bathrooms and other high moisture areas
	Exterior	Empty	No additional winter-warm side vapor barrier required

In addition to the above table, and in recognition of some manufacturer's special recommendation, the practice also requires that the board manufacturer's recommendations regarding the venting of wall constructions be followed.

b. Ceilings

All HUD attic ventilation criteria apply to ceiling insulations.

For buildings located in ASHRAE condensation zone I, if there is no existing insulation or if existing insulation is to be removed, provide a vapor barrier (retarder) membrane on the upper surface of the ceiling material. Never install a vapor barrier on top of existing insulation.

For buildings in zones I and II where there is existing ceiling insulation and no vapor barrier, the RCS standards recommend that a vapor barrier (such as paints and wall coverings with a permeance of less than 1 perm) be installed on the interior surface of ceilings in bathrooms and unvented kitchens and laundry areas. The Standards further recommend that cracks in the ceilings of such high moisture areas be sealed.

As for walls, the provisions for vapor barriers in ceilings are identified as minimum requirements. Additional precautions may need to be taken in small, tight, and poorly ventilated homes.

c. Floors

A vapor barrier is required on the winter warm side of mineral-fiber-batt floor insulation in condensation zones I and II.

d. Crawl Space

A ground cover vapor barrier with the cover turned up at least 6 inches (150 mm) at the walls is required. Crawl spaces are to be provided with a free ventilation area of one ft² for each 1500 ft² (1 m² for each 1500 m²) of crawl space floor area. Cross ventilation is recommended. Where crawl space walls are insulated, provisions must be made to seal off the ventilation openings in winter.

A.3

State Building Codes

Recent issues of the State Building Codes for New York, Minnesota, California and Florida were examined.

These codes contain requirements for crawl space and attic ventilation similar in form to HUD/MPS requirements.

The New York State Code contained no requirements for vapor retarders or condensation control. However, a Code Manual for the State Code, dated August 1, 1977, contains two pages of drawings showing details for the placement of vapor retarders in ceilings, walls, and knee-roofs, and between subflooring and finish flooring. It also contains details relative to ground cover and ventilation of crawl spaces, attics, and flat roofs. These drawings were very similar to the drawings shown in Agriculture Information Bulletin issued by the USDA Forest Service. (See Appendix B.2). These construction details are presented as acceptable practices and are not mandatory in the State of New York.

The Residential Building Code for the State of California, dated February 1980, requires that a vapor retarder with a vapor transmission rate of ≤ 1 perm be placed on the heated side of walls, unvented attics, and crawl spaces in locations where the winter design temperature is $\leq 25^{\circ}$ F.

The Minnesota State Building Code Commission has vapor retarder requirements under consideration.

The Florida State Building Code contains no requirements for vapor retarders.

A.4 City Building Codes

The city building codes for New York City, Los Angeles, and San Francisco were examined. They contain no requirements for vapor retarders.

A.5 ANSI/ASHRAE/IES Standard 90A-1980 (ASHRAE Standard 90-75) and NCSBCS Model Code based on these standards for Energy Conservation in New Building Construction.

These documents have been adopted in whole or with small modifications in 47 States as requirements in their State building regulations.

The only reference to vapor retarders in Standard 90A-1980 forms a part of paragraph 4.2.6. and reads as follows:

"Vapor retarders, air infiltration, and operating interior relative humidity should be considered to maintain the thermal and moisture integrity of the envelope."

A.6 Mobile Home Construction and Safety Standards, Part II: Department of Housing and Urban Development, December 18, 1975.

a. Condensation Control (vapor barriers)

Ceilings

Ceilings shall have a vapor barrier having a permeance of ≤ 1 perm (dry-cup method) on living space side.

Exterior Walls

Exterior walls shall have a vapor barrier having a dry-cup permeance of ≤ 1 perm on the living-space side. Unventilated wall cavities shall have an external covering and/or sheathing which forms a pressure envelope and which has a combined permeance of ≥ 5 perms. Wall cavities shall be provided with ventilation to dissipate condensation occurring in these cavities.

b. Air Infiltration

The opaque envelope shall be designed and constructed to limit air infiltration.

Plumbing, mechanical, and electrical penetrations of the pressure envelope shall be constructed or treated to limit air infiltration unless specifically exempted. Penetrations of the pressure envelope by electrical equipment, other than distribution panel boards and cable and conduit penetrations, are exempted. Cable penetrations through outlet boxes are exempted.

Joints between walls, wall-to-floor, or wall-to-ceiling shall be caulked or otherwise sealed unless designed to limit air infiltration.

c. Ventilation

The area in which the cooking appliances are located shall be ventilated by a metal duct, minimum cross-section area 12.5 square inches, located above the appliance and terminating outside the mobile home, or by listed mechanical equipment discharging outside the home. Installation shall be within 10 feet from the vertical front of the appliance.

Mechanical ventilation which exhausts directly to the outside shall be equipped with a separate operating control and an automatic or manual damper.

A.7 Design Criteria for Navy Shore Facilities *

Various design criteria used in the construction of shore facilities relate to moisture control. Moore, in "Moisture Problems in Buildings" (see C.11) identifies and discusses the following guidelines, criteria, and manuals:

- A. Navy Guide Specifications
- B. Economic Analysis Handbook (NAFAC P-442) June 1975
- C. Technical Guidelines and Criteria for Energy Conservation in Buildings (SOUTHDIVNAFAC 15000) July 1975
- D. Design Guidance for Bachelor Enlisted Quarters (NAFACINST 11012.114H) October 1975
- E. Construction Criteria Manual (DOD 4270.1-M) October 1972
- F. Design Manual-Mechanical Engineering (NAFAC DM-3) September 1972 with Changes 1, 2, 3, and 4

* The design criteria themselves were not made available to this contractor. Instead, we were instructed to use the summaries provided in the Moore report.

- G. A-E Guide (PACNAVFACECOM P-74) May 1975
- H. A-E Guide (SOUTHNAVFACECOM P-141) April 1975 with Change 1
- I. Various definitive drawings and project drawings
- J. Technical Guidelines for Energy Conservation in New Buildings (NAFAC) January 1975
- K. Technical Guidelines for Energy Conservation in Existing Buildings (NAFAC) January 1975
- L. Design Manual - Troop Housing (NAFAC DM-36) February 1968 with Change 1
- M. Design Manual - Architecture (NAFAC DM-1) October 1974

Moore outlines those criteria related to moisture control in warm and humid climates. Many of his comments relate to the design, selection, and operation of air-conditioning equipment. The following are his comments on those paragraphs that appear the most relevant to this study:*

Guide Specification, Section 07232 - Ceiling, Wall and Crawl Space Insulation

Paragraph 6.1 calls for vapor barrier to be installed on the "interior (warm-in-winter) side of the construction."

Comment:

The Guide Specification for ceiling, wall, and crawl space insulation was obviously written for cold climates since vapor barriers are recommended on the interior side of construction. Where vapor barriers are used in humid climates they should be on the exterior side of the construction, since that is where the vapor pressure is higher.

Guide Specification, Section 07241 - Roof Insulation

Paragraph 6 calls for vapor barrier as follows:

- 6.4 Poured Concrete Decks--Ventilating Felt
- 6.5 Precast Concrete Decks--Asphalt base sheet
- 6.6 Structural Cement-Fiber Decks--Asphalt base sheets
- 6.7 Wood Decks--Rosin-sized paper or unsaturated felt plus asphalt base sheet
- 6.8 Gypsum Decks--Ventilating Felt
- 6.9 Steel Decks--None shown

* Both content and comments of individual sections and paragraphs are reproduced verbatim. Accordingly, the comments do not necessarily reflect the opinions of this contractor.

Comment:

This paragraph calls for various types of vapor barriers in roof construction. Since the roof membrane itself is a vapor barrier and since in most all cases any additional vapor barrier would be on the room side of the insulation, a problem is created in humid climates whereby the two vapor barriers create a situation which makes it virtually impossible for any moisture in the roof insulation to escape. In climates that are variable from summer to winter, there are changes in direction of vapor flow, thus allowing any accumulation of moisture to escape during seasonal changes in weather. In humid climates where the flow of vapor is unidirectional continuously, the opportunity does not exist for any change in direction of vapor flow, so that it is essential to permit the moisture which does enter the roof insulation to escape. In this case, the escape would occur into the space. Since the roof membrane itself acts as a good vapor barrier, the magnitude of this vapor entering the space is relatively small and should not create a problem or a cooling load of any significance.

Technical Note G calls for vapor barrier except for metal decks.

Comment:

This technical note in the Guide Specification calls for vapor barriers except with metal decks. This exception should be expanded to exclude vapor barriers for all types of roof construction, for the reasons shown above.

DOD 4270.1-M - Construction Criteria Manual

Paragraph 8-5.1E calls for insulation and ventilation of spaces above ceilings, in conjunction with air conditioning of existing buildings.

Comment:

When air conditioning existing buildings in humid climates, special consideration should be given to the ventilation of spaces above ceilings. In multistory buildings, ventilation of spaces above ceilings can cause condensation on the underside of floor slabs when the dew point of the ventilation air is above the dew-point temperature of the floor slab. Since most ceilings are highly permeable, it is questionable whether ventilation with outside air above the ceiling should be utilized since the latent cooling load of the space will be increased. While vapor barriers would reduce this latent heat gain, it is usually impractical to install vapor barriers in the ceilings of existing buildings, especially when the difficulty of adequately sealing the vapor barrier is considered.

Paragraph 8-5.15B prohibits summer humidity control in priorities 6, 7, and 8, except when sensible heat factor is less than 0.65. Dehumidification control is permitted in tropical locations when the winter design temperature is higher than 65°F.

Comment:

The prohibition on summer humidity control in priorities 6, 7, and 8, except when the sensible heat factor is less than 0.65, will preclude the elimination of moisture problems in humid climates. Under design conditions, the sensible heat factor is rarely less than 0.65. However, during almost all hours of operation throughout the year in humid climates the sensible heat factor will be less than 0.65. Thus, unless humidity control is utilized, the humidity will not be controlled and moisture problems will result. One way of solving this problem would be to expand the consideration of sensible heat factor to all hours of the year. While dehumidification control is permitted in tropical locations, it does not say what types of dehumidification, nor is it suggested that it may be essential under certain conditions in certain buildings in tropical locations.

Paragraph 8-7.G discusses condensation control for cold climates.

Comment:

While this paragraph discusses condensation control for cold climates, there is no discussion of condensation control for humid climates.

A-E Guide - Pacific Division

Paragraph 3 calls for foil-backed insulation or gypsum board.

Comment:

While foil-backed insulation or gypsum board provides a good vapor barrier in itself, it is almost totally dependent upon good quality sealing of the joints in order to achieve vapor barrier performance. Since the use of these materials virtually implies that the vapor barrier would be on the inside of the construction, its location is quite improper for use in humid climates. If and when vapor barriers are necessary in humid climates, they should be placed on the exterior of the construction, not on the interior.

Design Manual - Architecture - Dm-1

Chapter 1, Section 4

Paragraph 2 suggests that climate be carefully considered before starting design.

Comment:

This paragraph suggests that a number of factors in addition to climate be carefully considered before starting design. Here it should be emphasized that when air conditioning is to be employed in buildings in humid climates, special consideration ought to be given in view of the moisture problems associated with these buildings.

Chapter 2, Section 2

Paragraph 4d discusses climate-related design criteria for tropical humid zones.

Comment:

This paragraph discusses climate-related design criteria for tropical humid zones. Consideration should be given to possibly subdividing this category into humid island climates and humid inland climates, since there are differences in temperatures, humidities and wind conditions in these two types of humid climates. Reference 30 provides a good discussion of these climates and the kinds of design approaches that are best suited in the absence of air conditioning. These approaches obviously must be tempered and reevaluated when air conditioning is employed. Since most of the discussion on design criteria for tropical humid zones is based upon non-air-conditioned buildings, consideration should be given to expanding or separating the material that applies to air-conditioned buildings from non-air-conditioned buildings.

Table 2-1 (Roofs) requires that insulation not be used over concrete slabs, that the underside of the slab be coated with an organic vapor barrier, flat roofs be avoided, cellular glass insulation is satisfactory, vegetable fiber board is unsatisfactory, insulation should be applied beneath roof slab, and that vapor barrier be used under insulation when it is above the roof slab.

Comment:

This table outlines certain suggestions and requirements for roofs in tropical zones. In air-conditioned buildings we can find no reason to preclude the use of insulation over concrete slabs provided that a built-up roof is utilized that will serve as a vapor barrier. When the vapor barrier is on the exterior of the building (as it should be in such a climate) the interior side of the roof should not be coated with a vapor barrier, since any moisture that does enter the roof

should be allowed a means for escape. While flat roofs should be avoided in both air-conditioned and non-air-conditioned buildings, it is not nearly so essential in an air-conditioned building with an insulated roof, since the insulation serves to keep the heat out of the conditioned space, whereas in a non-air-conditioned building a ventilated attic would tend to do the same thing.

Insulating materials that are not hygroscopic are preferred since in addition to not absorbing moisture they also are not subject to vermin. In modern concrete construction, it is typically difficult and impractical to apply insulation beneath the roof slab unless a suspended ceiling is utilized. With air-conditioned buildings, that approach creates other problems with ventilation and moisture flow. In air-conditioned buildings, we cannot agree that vapor barriers should be used underneath insulation when it is above the roof slab, for the reasons cited above for not coating the under side of the slab with a vapor barrier.

Table 2-2 (Walls) requires that coatings be used to reduce moisture penetration and deter algae growth, that shadow grooves not be used and that jalousies not be used for air-conditioned spaces.

Comments:

This table provides various requirements for walls. We concur that exterior coatings should be selected both to reduce moisture penetration by providing a good vapor barrier and to deter algae growth. In the search of the literature, we were unable to find any information which correlates the permeability of various finishes with their ability to resist algae growth. Since these two criteria are among the most significant of this entire study, it is suggested that an experimental study be undertaken to evaluate moisture permeability and resistance to algae growth for the various types of finishes utilized on the walls of buildings. Since buildings in humid climates must be painted much more frequently than in any other type of climate, the results of such a study should both enable a reduction in the maintenance cost of buildings in humid climates and provide improved appearance for longer periods of time.

Table 2-3 (Wall Materials and Finishes) requires that where moisture is not a problem, gypsum and cement plasters are satisfactory, portland cement plaster and cement plaster on lath should not be used in humid areas, organic fiber wallboard should not be used when subject to wetting and drying, exposed masonry is satisfactory when not subject to moisture, ferrous metal door bucks should not be used, organic fibrous insulations are subject to moisture damage and should not be used, and that cellular glass should be used rather than fibrous glass, mineral wool, and organic fiber insulation materials.

Comment:

This table should be separated for air-conditioned and non-air-conditioned buildings.

Chapter 2, Section 4, Part 5

Paragraph 6b discusses the effects of condensation.

Comment:

This paragraph discusses the effects of condensation, primarily in non-air-conditioned buildings in humid climates and in heated buildings. Additional discussion should be included on condensation problems in air-conditioned buildings in humid climates.

Chapter 3, Section 2, Part 3

Paragraph 2b covers the application and selection of insulating materials.

Comment:

This paragraph covers the application and selection of insulating materials but is somewhat inconsistent with Table 2-3 above. The discussion of vapor barriers should be expanded to include consideration of air-conditioned buildings in humid climates, in which the vapor barrier should be indicated on the exterior side of construction when necessary, and that the permeance is of much more significance in humid climates with year-round air conditioning.

Table 3-4 shows the moisture resistance of insulating materials.

Comment:

This table shows the moisture resistance of various insulating materials. It would appear that the moisture resistance capabilities were primarily considered for insulating materials used in connection with heating requirements, in which case the vapor pressure differentials are variable throughout the year and are not of large magnitude. Where the vapor pressure differential across the insulation is high and continuous, the moisture resistance of some of the insulations listed as good and excellent are not quite as good as indicated, nor are all of the materials listed as excellent equally excellent.

Chapter 3, Section 2, Part 5

Table 3-6 lists the moisture resistance properties of partition facings.

Comment:

This table lists the resistance of partition facings. See also comment on table 2-3.

Appendix B

SUMMARIES OF RECOMMENDED GOOD PRACTICE GUIDELINES FOR THE APPLICATION OF VAPOR RETARDERS AND CONDENSATION CONTROL IN BUILDINGS

B.1 ASHRAE Handbook of Fundamentals, 1981, Chapter 21 Moisture in Building Construction

The Handbook states on page 21.16 that "An exact statement showing which buildings require a vapor retarder is not readily formulated."

a. Walls (dwellings) Tentative recommendations.

The walls of every dwelling shall include a vapor retarder when the construction includes any material that would be damaged by moisture or its freezing. This applies to all three condensation zones in the U.S. (where winter design temperatures are $+20^{\circ}$ F. or lower) when the U-value is lower than $0.25 \text{ Btu/hr. ft.}^2 \text{ }^{\circ}\text{F}$ and to walls of higher U-values in condensation zones I and II (winter design temperature 0° F or lower). These three condensation zones exclude the Gulf Coast areas of Texas, Louisiana, Mississippi, and parts of Florida, and parts of the Atlantic coast of Florida and Georgia, as well as Hawaii and Alaska. Exterior vent openings and weep holes are recommended for wood-frame wall cavities.

b. Walls (commercial and institutional buildings)

Materials used in these types of buildings tend to be somewhat more moisture-tolerant and decay-resistant, and the use of vapor retarders in these types is less common. Structural frames should be inward and separate from curtain walls, to allow curtain walls to be made more airtight. The airtightness of floors and interior partitions should be improved to reduce the effect of chimney action on air leakage. Penetrations of the exterior envelope by services should be sealed.

c. Ceilings (dwellings)

Roof requirements are combined with ceiling requirements for dwellings.

A vapor retarder (permeance ≤ 1 perm) is recommended in top-story ceilings for low-sloped roofs, gabled roofs and hip roofs for condensation zones I and II, also for low-sloped roofs in zone III. Specified natural ventilation louvre areas are required for all types of roofs in all zones. Areas of the U.S. outside the three condensation zones (as described above for walls) are not specifically covered by the recommendations.

Cathedral ceilings built with plank decks exposed to the interior do not appear to need vapor retarders. In more heavily insulated roof construction, a superior vapor retarder (permeance 0.05 perm) is necessary between the deck and the insulation, and a ventilation space between insulation and roofing is recommended.

d. Roof (commercial and institutional)

The Handbook is rather ambiguous in its recommendations for the use of vapor retarders on the warm side of insulated membrane roof systems. Since most roof membrane systems are highly resistant to vapor transmission, moisture may get trapped between the vapor retarder and the membrane roof, causing the insulation to remain wet for extended periods. The decision on whether or not to use a vapor retarder may depend on relative humidity maintained in the interior space.

Since inverted roof systems (insulation on top of the roof membrane) expose the insulation to rain, the insulation must be of the closed-cell type to resist water penetration. Application of an inverted roof system over a conventional insulated membrane system has some advantages because the membrane roofing may be warm enough to avoid condensation on the warm side.

e. Crawl Spaces (dwellings)

A ground cover is recommended in the form of a concrete slab, heavy roll roofing, or 0.004 to 0.006-in-thick polyethylene film laid on a graded surface with 2-in overlap between adjacent strips.

Without ground cover, four vents, one at each corner of the crawl space, having a total area of 1/300 of the floor area plus 1/50 of the perimeter, are recommended. With ground cover, the vent area can be reduced to 1/10 of the above amount.

f. Condensation in Cooled Buildings

Condensation problems can occur in air-conditioned buildings in humid and tropical climates. A humid climate is defined as a location with wet-bulb (W.B.) temperature of 67° F or higher for 3500 or more hours during the warmest 6 consecutive months of the year, or one having a W.B. temperature of 73° F or higher for 1750 or more hours during the warmest 6 consecutive months of the year. Fringe locations are those with 3000 or more hours at 67° F W.B. or above, or 1500 hours or more at 73° F or above during the warmest consecutive 6 months of the year. These conditions are likely to occur between latitudes 30° S and 30° N in low coastal areas or islands.

In such locations, the exterior surfaces of building envelopes should have a higher vapor resistance than the interior surfaces. This can often best be accomplished by use of vapor-resistant paints and finishes on the exterior surfaces and lower vapor-resistance materials on the inside. An air barrier should also be used to prevent excessive passage of warm humid air to the indoors, which unnecessarily increases the latent load on an air conditioner.

Air leakage into walls may convey 6 to 7 times as much water vapor into a wall or roof as diffusion, even when no vapor retarder is used. This ratio could increase to 100:1 in a wall with a vapor retarder with air leaks.

The ASHRAE Handbook of Fundamentals, 1981, shows the boundaries of condensation zones I, II, and III on a U.S. map, also a map showing the zones of humid climates and fringe climates in southeastern U.S. It also contains a world map indicating humid climates between 30° N and 30° S latitudes.

Fig. B.1.1 Condensation Zones in the United States*

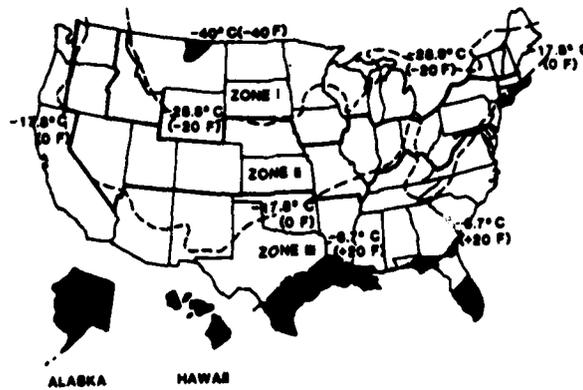
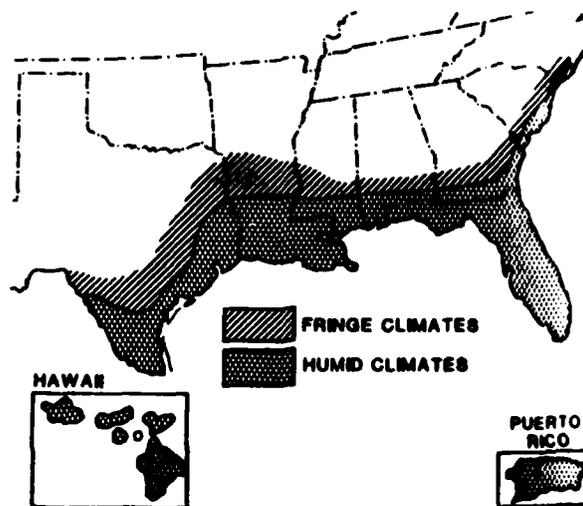


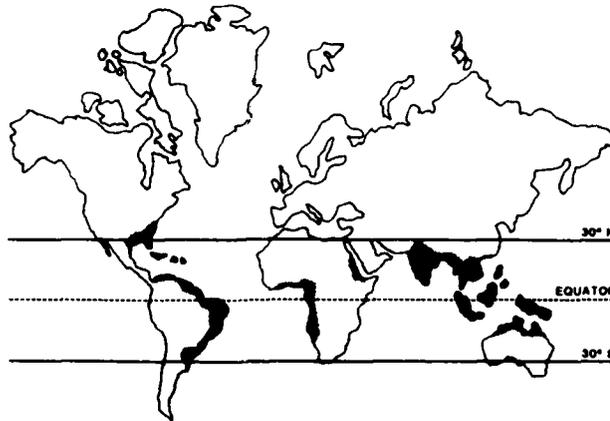
Fig. B.1.2 Humid Climates in the Continental United States**



* Extracted from p. 21.16 in ASHRAE Handbook Fundamentals, 1981.

** Extracted from p. 21.18, Ibid.

Fig. B.1.3. Humid Climates of the World* (For any specific location, the designer must consult weather records)



B.2

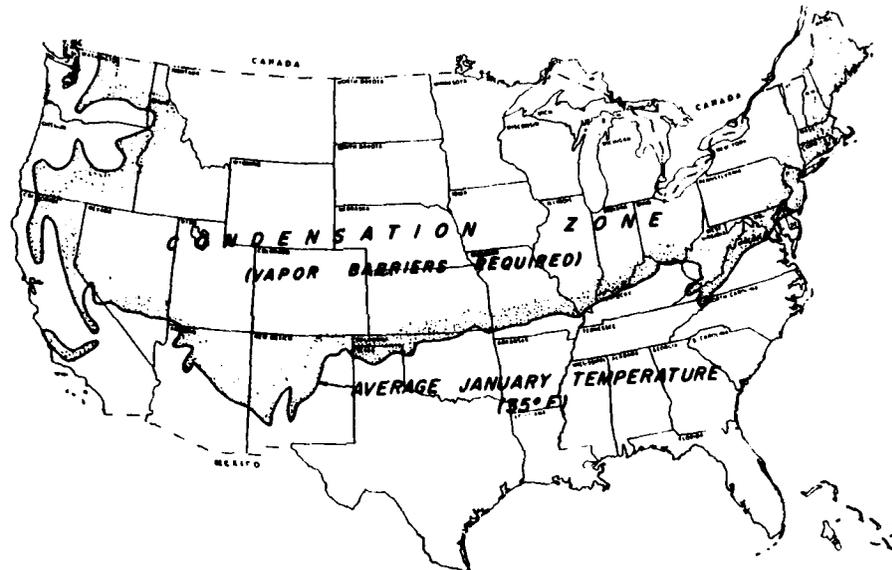
Condensation Problems in Your House: Prevention and Solution, Agriculture Bulletin No. 373, U.S.D.A. Forest Service, Sept. 1974 by L. O. Anderson and G. E. Sherwood.

- a. Shows photographs of condensation in an attic and on floor joists over a crawl space.
- b. Cites data on the moisture generated by various activities in dwellings but does not provide references.
- c. States that the typical amount of water used in placing a residential concrete floor is 240 gallons, for concrete walls 480 gallons, and in plastering the walls 300 gallons. This water is usually dissipated during the first heating season.
- d. States that winter condensation problems usually occur in those parts of the U. S. where the average January temperature is 35° F or lower. Provides a U. S. map showing the 35° F average January temperature isotherm.
- e. Provides line drawings showing recommended application of vapor retarders under concrete slabs, flatdeck roofs, crawl spaces (heated and unheated) 1½-story house with basement, full two-story house with basement, ground cover for a crawl space, walls of finished basement, knee-wall area, ceiling, and second-floor projection out from first-story wall.

* p. 21.19, Ibid.

- f. Provides line drawings showing recommended ventilation techniques for crawl spaces, gable roofs, hip roofs, flat roofs, soffitt, frieze and gable ventilators.
- g. Describes causes and cures for ice dams.
- h. Describes effects of air leakage around wall outlet boxes and methods for curing the problems associated with them.
- i. Identifies methods for correcting problems from concealed condensation.

Fig. B.2.1. U. S. Map Showing 35° F Average January Temperature Isotherm*



B.3 Insulation Manual for Homes and Apartments, NAHB Research Foundation Inc., 1978, Chapter on Vapor Barriers and Ventilation.

- a. Identifies three methods for minimizing potential water vapor problems in walls, floors and attics: 1) use vapor retarders to limit water vapor transmission, 2) ventilate dwelling with outdoor air to reduce water vapor indoors, and 3) ventilate the particular building section to dissipate water vapor to outdoor air.

* From p. 7 in Anderson/Sherwood Agriculture Bulletin 373.

- b. Recommends use of vapor retarders on warm side of insulated floors over crawl spaces and exterior walls.
- c. Recommends vapor retarders in flat roofs, low pitched roofs, and cathedral ceilings where adequate ventilation is difficult to achieve.
- d. Recommends vapor retarders in the ceiling, and adequate attic ventilation where winter design temperature is $\leq 20^{\circ}$ F.
- e. Ceiling vapor retarders are not necessary if adequate attic ventilation is provided in areas where winter design temperature is higher than -20° F.
- f. Electrically heated homes with low air infiltration and a ceiling vapor retarder may require periodic operation of a dehumidifier.
- g. A precise formula for when and where to use or not to use vapor retarders in ceilings cannot be simply stated because of the many variables involved.
- h. A ground cover of 4- to 6-mil polyethylene film turned up at the foundations walls a few inches is recommended.
- i. This manual endorses the requirements of the HUD Minimum Property Standards for the ventilation of roofs, ceilings, and crawl spaces, and the free vent areas of the ventilators.

B.4

NBS Report to DOE on Control of Condensation in the Walls and Ceilings of Retrofitted Houses, prepared by a Special Task Group of Experts, December 1978. (unpublished)

This report presents an input-output model for moisture control in houses; i.e. it states the typical amount of moisture generated in a house by a family of four and the several convection and diffusion mechanisms by which it is removed or stored in the structure.

The moisture generation for a typical family of four is on the order of 18-20 pounds per day.

The methods available for condensation control include the following:

- a. caulk and seal openings at the interior of the exterior walls and at all joints,
- b. apply low permeability paint or coatings to interior surfaces of exterior walls,
- c. maintain a low indoor humidity in cold weather with natural ventilation, an exhaust fan, or a dehumidifier,

- d. increase the air leakage in the exterior wall coverings,
- e. allow intermittent condensation to occur in amounts that do not endanger the building materials.

The features of a house and its environment that are likely to present significant potential for excessive concealed condensation are the following:

- a. Houses with less than 1200 ft² floor area,
- b. High occupant density (less than 300 ft² floor area per occupant),
- c. Absence of fuel-fired heating system in the living space,
- d. Cold climate,
- e. Winter humidification,
- f. Low-sloped roof,
- g. Unventilated attic.

Table B.4.1 shows the maximum indoor relative humidity and the minimum air infiltration or ventilation rate to control internal wall condensation to acceptable levels in houses which do not contain air barriers or vapor retarders.

Tables B.4.2 and B.4.3 show the combinations of house size, occupant density, air leakage rate, and type of heating system that do and do not require condensation control in climate zones I and II, as defined in the ASHRAE Handbook.

Three approaches to the control of condensation in retrofitted houses are described in the report.

B.5

BRAB Report to FHA, May 1962, Ground Cover for Crawl Spaces

- a. Recommends that ground cover be installed in residential crawl spaces in locations where the average January mean temperature is 45° F or below, and the average annual precipitation is 20 inches or more as reported by the nearest U. S. Weather Bureau Station.
- b. Recommends that ground cover be installed in all residential crawl spaces used as a heat plenum, regardless of location or environmental conditions.
- c. Recommends that all crawl spaces not used as heat plenums be ventilated in accordance with the current FHA Minimum Property Standards or the formula in the ASHRAE Guide.
- d. Provides a map of the U. S. showing areas meeting the criteria of paragraph a) for requiring ground cover.

TABLE B.4.1

Indoor relative humidity setting and minimum air infiltration rate for internal wall condensation control of structures which do not incorporate air and vapor barriers.

Climate Zone*	MONTH						
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
	<u>Indoor Relative Humidity, %</u>						
1	50	35	20	20	20	30	50
2	60	50	35	35	35	50	60
3.	No control needed to prevent condensation						
	<u>Air Infiltration Rate, cfm</u>						
1	69	66	109	88	98	74	45
2	64	46	71	62	66	42	47
3	Rate determined by comfort, not condensation						

*ASHRAE Handbook of Fundamentals, 1981, p. 21.16

Note: This table extracted from p. 21 of the NBS report to DoE, Dec. 1978, discussed here.

TABLES B.4.2 and B.4.3

Condensation Control Requirements for Non-Humidified Homes

B.4.2. Climate Zone I

Floor Area Ft ²	Minimum Air Leakage CFM $\frac{1}{2}$ Air Ch/hr	Occupancy, No. of Persons							
		1	2	3	4	5	6	7	8
900	60	<p>Condensation control** required for fossil-fuel heated houses. (See Guidelines)</p> <p>No* condensation control required.</p>							
1000	67								
1100	73								
1200	80								
1300	87								
1400	93								
1500	100								
1800	120								
2100	140								
2400	160								

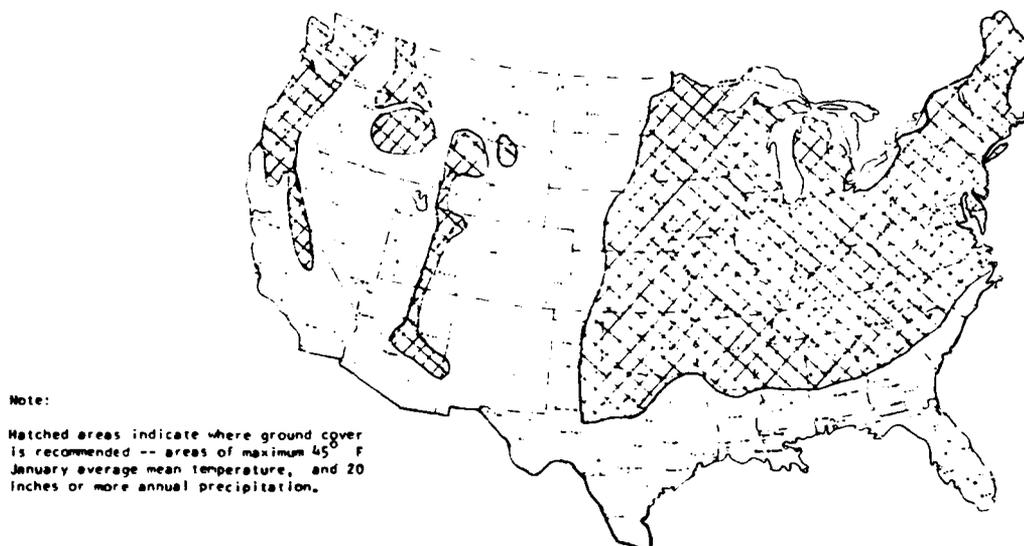
B.4.3 Climate Zone II

Floor Area Ft ²	Minimum Air Leakage CFM $\frac{1}{2}$ Air Ch/hr	Occupancy, No. of Persons							
		1	2	3	4	5	6	7	8
900	60	<p>Condensation control** required for fossil-fuel heated houses. (See Guidelines)</p> <p>No* condensation control required.</p>							
1000	67								
1100	73								
1200	80								
1300	87								
1400	93								
1500	100								
1800	120								
2100	140								
2400	160								

* Occupancy may be increased by one for each additional 16 cfm of air leakage above minimum, without condensation control

** Boundary of area requiring condensation control shall be lowered by one or two persons (see dotted line) for electrically heated houses.

Fig. B.5.1. Approximate Areas Where Ground Cover is Recommended*



B.6 Construction Principles, Materials and Methods, Harold B. Olin, John L. Schmidt, and Walter H. Lewis, The Institute of Financial Education, Chicago, IL 1980, Section 104, Moisture Control

This document is the most comprehensive and most detailed treatment of moisture control in occupied, heated buildings that was found. It covers condensation causes and remedies, design and construction recommendations for major components and smaller construction details in housing, guidelines on vapor retarder selection, and installation precautions. It covers nearly all of the details of the HUD Minimum Property Standards, the ASHRAE Handbook, the USDA Forest Service Information Bulletin and the NAHB Insulation Manual, and additional detailed information.

Exception: This document does not emphasize the need for the vapor barrier to be an air barrier at the same time; i.e. the relative importance of sealing joints and imperfections in the vapor barrier to prevent air leakage into wall and ceiling/roof construction. For example, on page 104-12 it is stated: "The installation of an adequate barrier is the most important moisture control device in exterior wall construction."

* Map extracted from p. 5 of the BRAB/FHA report discussed here.

Attic-less Joist Roofs:

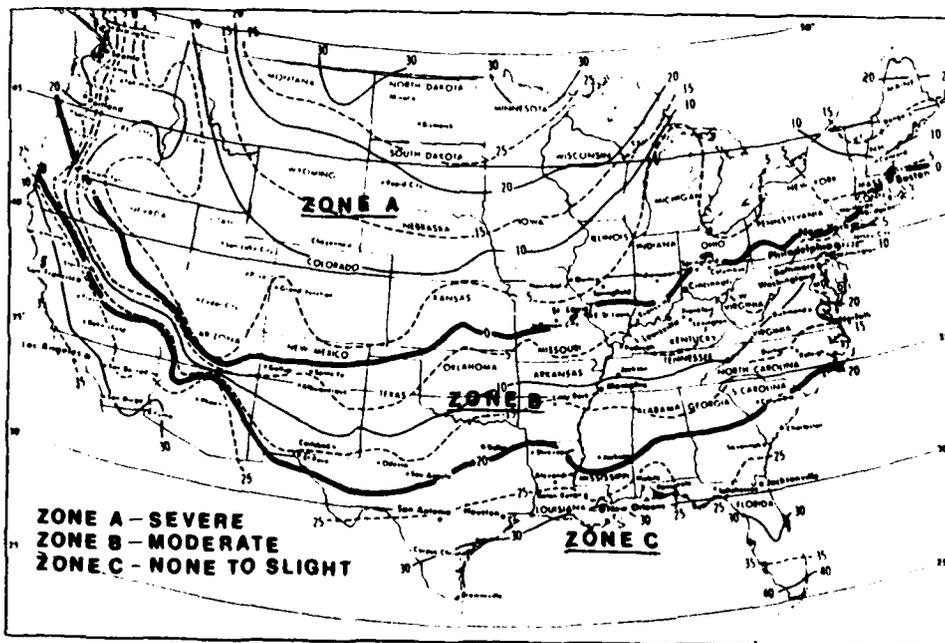
Flat or shed roofs of simple joist construction should be provided with effective ventilation, as well as an efficient vapor barrier under the insulation. Ventilation of simple joist roofs should include outlets from every joist space, either with individual vents or with continuous soffitt ventilation.

Wood Plank Roof/Ceiling

It is stated that recent nationwide study concluded that a vapor barrier generally was not needed in residential construction, nor in other occupancies where the interior winter humidity averaged less than 40%. A barrier is recommended when the interior relative humidity exceeds 40% and the average January temperature is 35° F or lower (roughly coincident with the 0° F winter design isotherm). Humidities over 40% are encountered in public shower rooms, kitchens, and pool areas. In single-family structures, only pool areas merit special consideration, since baths and kitchens are usually equipped with exhaust fans.

If a vapor barrier is provided in exceptionally cold climates and with high relative humidities, edge venting or stack venting of the insulation should be provided.

Fig. B.6.1. Condensation Hazard Zones of the U. S.*



* Map extracted from p. 104-15 of Olin/Schmidt/Lewis report here discussed.

- B.7. Principles for Protecting Wood Buildings from Decay, by T. C. Scheffer and A. F. Verrall, USDA Forest Service Research Paper FPL 190, 1973.

Water vapor is absorbed only in the walls of the wood cells. The equilibrium moisture content between wood and the atmosphere depends chiefly on the relative humidity of the atmosphere. At room temperature, the fiber saturation point is achieved at approximately 30 percent of the oven-dry weight. The fiber saturation point is the approximate lower limit for attack of wood by decay fungi.

Liquid water can be drawn into the wood by capillary action. Water generally moves into wood and wood structures much faster than it escapes through subsequent evaporation.

Decay fungi have four primary needs to sustain growth: food, air, favorable temperature, and water. Decay fungi attack most rapidly in the temperature range from 75° to 90° F. They can do little harm at temperatures near freezing or above 100° F. The rate of decay is slow at temperatures below 50° F, and falls off markedly above 90° F. The moisture content at which wood is most susceptible to decay lies in a broad range from not far above fiber saturation (about 30%) to somewhere between 60 and 100 percent, depending upon the specific gravity and the cross-sectional size of the wood.

Warm weather during many months of the year promotes decay more than hot weather for a few months and cold weather during the remainder of the year. Similarly, prolonged rains are more conducive to decay than the same amounts delivered in heavy but relatively brief showers.

A climate index was developed to relate climate to decay potential in terms of temperature and rainfall.

$$\text{Climate Index} = \sum_{\text{Jan}}^{\text{Dec}} \frac{(T - 35)(D - 3)}{30}$$

Where T is the mean monthly temperature in °F, D is the mean number of days in the month with 0.01 inches or more of precipitation, and $\sum_{\text{Jan}}^{\text{Dec}}$ is the summation of the products for each of the 12 months. The following map is derived from this formula:

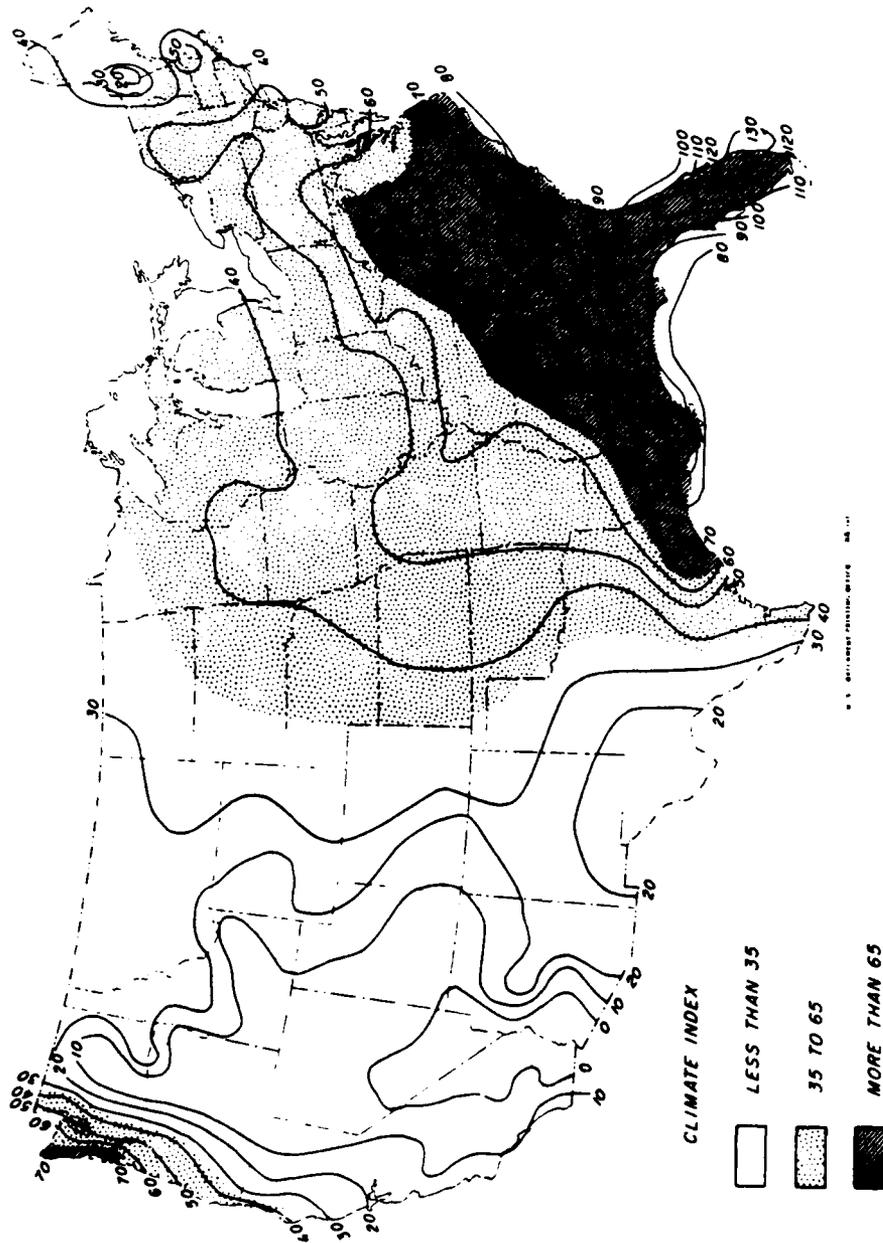


Fig. B.7.1-- Map Showing Decay Potential for Wood.

Notes: This map extracted from page 13 of the USDA Forest Service Research Paper discussed here.

Levels of decay potential for wood exposed to the weather in aboveground service based on a climate index derived from standard temperature and rainfall data: Darkest areas, wettest climates, most suitable for decay; index greater than 65. Lightest areas, driest climates, least suitable for decay; index less than 35. Gray areas, moderately wet climates, moderately suitable for decay organisms; index 35 to 65.

Water to support decay can arise from the following five sources:

- o Original moisture in unseasoned lumber. Lumber should be dried to no more than 20 percent moisture before installation. Enclosing wet lumber in building construction can prevent drying and promote decay. When wet lumber dries, it sometimes splits and warps, thus loosening joints and increasing the likelihood of rain seepage.
- o Wetting from ground moisture. Ground moisture can get to wood parts of a building by direct movement into wood in contact with the soil, and by indirect transfer from soil to wood through concrete or masonry.
- o Wetting from rain. Siding and other exterior woodwork may get wet from rain driven directly against it, from roof runoff or from water splashed from the ground. Rainwater enters largely by capillary movement.
- o Wetting from condensation. Critical wetting by condensation may occur 1) near the perimeter of crawl spaces in cold weather, 2) in floors, walls, and ceilings of cold-storage rooms, 3) in areas where sizeable amounts of steam are released, 4) in the floor below air-conditioned rooms over a damp crawl space, and 5) on slab foundations.

Condensation in floors over a crawl space can be caused by overcooling with summer air-conditioning or during cold weather in floors above a wet crawl space in an unheated building.

Where the average temperatures for January are 35° F or lower, vapor barriers should be installed in exterior walls of all new wood-frame buildings at the time of construction.

- o Wetted by Piped Water. Water leaks, if left unrepaired, can cause damage to wood components around tubs, kitchen sinks, toilets, and washtubs. Heavy lawn sprinkling can lead to moisture problems in building construction due to water leakage.

The document provides specific information on the protection of wood members in buildings, under the following major headings and subheadings.

1. Protecting Foundation and Substructure Wood
 - 1.1 Foundations with Crawl Spaces
 - 1.2 Precautions against Condensation in the Crawl Space
 - 1.3 Concrete Slab Foundations
2. Protecting Exterior Walls, Building Appendages and Associated Woodwork
 - 2.1 General Protective Measures
 - 2.2 Protecting Siding
 - 2.3 Protecting Roof Edges
 - 2.4 Protecting Building Appendages

3. Special Rooms Protecting
 - 3.1 Shower Rooms
 - 3.2 Cold-Storage Rooms
 - 3.3 Air-Conditioned Rooms
 - 3.4 Indoor Swimming Pool Areas
4. Preservative Treatments for Building Lumber
 - 4.1 Types of Preservatives
 - 4.2 On-Site Testing
5. Protecting Buildings After Construction
 - 5.1 Regular Inspections
 - 5.2 Corrective Measures Where Wetting or Decay Occurs

B.8 Rising Damp and Its Treatment by T. L. Heiman, Experimental Building Station, Australia, ASTM STP 779, 1982.

Rising-damp problems are frequently encountered in old masonry buildings where either there is no damp-proof course or the damp-proof course has broken down. Moisture in contact with the base of porous masonry walls moves upward by capillary action unless there is an effective barrier to prevent such movement. Rising damp is a common cause of deterioration in stone and brick buildings. Excessive watering of garden beds and lawns close to the building or the presence of leaking services can be contributing factors. The damage caused by capillary rise of moisture is usually restricted to the region 3 to 5 feet above the floor. The height of capillary rise of moisture depends on the size of the capillary spaces in the masonry and the rate of evaporation of moisture from the wall. The evidence of capillary rise of moisture may be efflorescence, mold growth, fretting of the stone or brick and crumbling of the mortar, a musty smell in the affected rooms, and possible rotting of skirting boards.

The dampness problem can sometimes be overcome by the insertion of a new damp-proof course in the walls or by impregnation of the masonry with chemical solutions that form moisture barriers. Other methods of treating the dampness problem, such as electro-osmosis, cementitious grouts, damp-proof mortars, and Knapen tubes, are discussed by the author. Some methods work satisfactorily in certain conditions but not in others. All of the methods described have limitations.

B.9 Air-Conditioned Buildings in Humid Climates--Guidelines for Design, Operation and Maintenance, by ARMM Consultants, Inc., April 1980.

Based on inspection trips to Pacific Naval installations in 1976, to South-eastern U.S. facilities in 1977, and again to the Pacific in 1978, at the peak of severe humidity conditions, the following problems in air-conditioned buildings were identified and evaluated. (The field studies were concerned with family housing and other types of occupied buildings.)

- o Mold and mildew on walls and other building surfaces due to thermal bridges, shading, and earth conduction.
- o Peeling, blistering, flaking, and bleeding of paint from exterior and interior surfaces.
- o Weakened and collapsed suspended ceilings, rusted metal, and other property damage from interior condensation.
- o Insulating losses due to water absorption.
- o Poor painting practices in both interior and exterior surfaces.
- o Membrane blistering and slippage on flat roofs.
- o Higher wind-uplift pressures in hurricane and typhoon belts.
- o Improper use of vapor retarders in roofs.
- o Fan-coil units typically used for air conditioning cannot control both temperature and humidity in occupied spaces.
- o Fan-coil units do not reduce the humidity sufficiently, especially at part-load conditions.
- o Fan-coil units sometimes bring in too much outside air.
- o Fan-coil units cause condensation and mildew under certain control conditions.
- o Intermittent operation of fan-coil units reevaporate condensed water on cooling surfaces.

The authors recommend changes in current design criteria and provide criteria for preventing moisture problems in new air-conditioned buildings in humid climates. The criteria are presented in two categories--architectural and mechanical (heating, ventilating and air conditioning).

The following topics are covered in the architectural category:

- 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 category includes the following topics:

- o Ventilation requirements
- o Pipe and duct insulation.

The authors recommend that the practices described for new buildings be followed to the fullest extent that is technically and economically practicable for the modification of existing buildings, but they recognize that these procedures will often alleviate but not fully solve the moisture problems. Specific recommendations are made for modification or replacement of heating, ventilating and air-conditioning systems and their controls, and for repainting surfaces to resist fungal attack.

B.10

Manual of Tropical Housing and Building, Part 1, Climatic Design.
Koenigsberger, Ingersoll, Mayhew, Szokolay, Longman Group Limited, London,
1980.

As the preface says, "The book is intended as a textbook for students and a reference book for practitioners and as an aid for their clients - investors, administrators, and politicians." It addresses primarily the needs of the urban (generally poor) population in tropical developing countries and thus emphasizes passive, that is, planning and constructional, means for creating an acceptable indoor climate.

In its discussion of "problems associated with cooling" it stresses that when a space is mechanically cooled, such cooling "must be combined with some form of mechanical ventilation system" to prevent excessive indoor relative humidity.

With regard to vapor condensation, it is mentioned that in "composite climate"* unlike the practice in cold climates, porous materials (and permeable finishes) are more appropriate since these allow the moisture to be absorbed as condensation occurs, and to be released when the air is sufficiently dry.

The book provides guidelines evaluating and classifying climates, and for comfort conditions. It outlines principles of thermal design, means of thermal control, light, and lighting, and noise and noise control. Specific design considerations for four distinct tropical climates are provided, as well as design aids. An appendix provides tables and graphs useful in applying time guidelines.

* Composite climates are defined as those which alternate between hot, dry periods and warm, humid periods.

Appendix C

SUMMARIES OF RESEARCH RESULTS APPLICABLE TO THE USE OF VAPOR BARRIERS AND CONDENSATION CONTROL IN BUILDINGS.

C.1 Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier, by Tsongas, Odell & Thompson, ASHRAE/DOE-ORNL Conference, ASHRAE SP28 1981. (Oregon Study)

Description

- a. 96 Houses were studied in the Portland, Oregon area. 71 were insulated with UF-foam, cellulose, and mineral wool; 25 were uninsulated.
- b. All insulated homes had been retrofitted for 3 to more than 10 years.
- c. 82 homes had ducted heating systems - 27 heated with gas, 52 with oil. 53% were between 20 and 40 years old; 4% were over 40 years old.
- d. No vapor barrier in any homes; 15-lb. felt was installed beneath siding in most homes.
- e. 75 homes had full or partial basements; 29 homes had heated basements. Of 37 homes with full or partial crawl spaces, 11 had ground cover.
- f. 88% had floor areas of 2200 ft² or less; 57% had areas of 1500 ft² or less; 26% had areas less than 1200 ft².
- g. Typical home had ceiling insulation, storm windows, no underfloor insulation, weatherstripping around doors but not around windows, a fireplace or wood stove in use, no air conditioning.
- h. Portland has about 4700 heating degree-days, has an average winter temperature of 46° F, and is located in ASHRAE condensation zone III.

Results

- a. Virtually no incidence of high moisture content, moisture decay or fungi was found that suggested concealed condensation.
- b. Previous moisture problems and/or damage were found in at least 46 of the 96 test houses.
- c. Examination of the wall cavities and insulation attributed essentially all of the moisture problems and/or damage to water leaks rather than to condensation.
- d. Moisture content of wood on studs, plates, and sheathings averaged 11.6%, 11.9%, and 12.1%, respectively.

- e. Air leakage tests were made in 71 homes by depressurization at 0.2-in water gage. Average air change rate (ACHR) was 16.2. For all uninsulated homes, the ACHR was 18.7, for mineral wool insulated homes 16.4, for cellulose insulated homes 13.6, and for UF-foam insulated homes 15.2.
- f. No tracer-gas air-change-rate data were taken, and no data furnished on inside wall surface covering, types of paint or permeance.

C.2 Field Investigation of the Performance of Residential Retrofit Insulation, by John Weidt, Robert Saxler and Walter Rossiter, NBS Tech Note 1137 September 1980.

- a. 39 houses were studied, located variously in Connecticut, Indiana, Kentucky, Maryland, Minnesota, Ohio, Virginia, and Washington, D. C.
- b. 25 houses were insulated with UF-foam, 8 with cellulose, and 6 with mineral fiber. All had been insulated more than 2 years. Data were collected from November 78 to January 79.
- c. No visible evidence of moisture accumulation and condensation or damage was found, except in one house. In this house, the moisture was attributed to a leak around a window frame, which caused wood rot of the framing and studs and high moisture content of the cellulose insulation.
- d. Moisture content of UF foams ranged from 3.2 to 22.0%, average value 12.1%. Moisture content of cellulose ranged from 8.8 to 13.4%, average value 11%. Moisture in loose-fill mineral wool was less than 1%.
- e. Membrane vapor barriers were found in 10 of the 39 houses; 5 had foil barriers on exterior, 4 had foil or batt-facing on interior, one had batt-facing in middle. There was no significant difference in moisture control of insulation for the various membrane locations.
- f. Not enough corollary data were taken or reported on house size, occupancy, indoor relative humidity, air infiltration, kind of heating system, weatherstripping, humidification, indoor wall covering permeability, and occupant habits to evaluate the reasons for the conditions observed.

C.3 Are Vapor Barriers the Solution to Humidity Problems?, by G. S. Dutt, Princeton University, January 1979.

Based on analytical work and data from the DOE/Princeton Twin Rivers Townhouse project, the author

- a. States that an adequate vapor barrier will not prevent condensation problems unless it is also an unbroken air barrier.

- b. Shows by calculation that moisture transport by convection through air leaks in a vapor barrier can be 5 to 20 times greater than that by diffusion, based on sulfur hexafluoride measurements in one house. The ratio was of the order of 250:1 in other houses.
- c. Suggests that the rise in observed relative humidity of the attic air during sun exposure on the roof tends to show that there was condensation on the under side of the roof.

C.4

Comparative Studies of Vapor Condensation Potential in Wood-Framed Walls, -
F. S. Wang, ASHRAE SP 28, 1981.

a. Field Tests

- o Two houses of similar exterior construction were tested simultaneously. Half of each house had no vapor retarder and half had an asphalt-coated kraft paper stapled on the interior side. One house was fitted with 1-inch extruded polystyrene plastic insulation board (R=5.4) and the other was fitted with 1/2-inch intermediate-density wood fiberboard (R=1.3) as sheathing.
- o No condensation was observed in 3 weeks with vapor retarder in place at indoor relative humidity (RH) 30-35%, temperature 70-75° F indoors, 0 to 20° F outdoors. Condensation was observed in both houses in areas with no vapor retarder.
- o Condensation was observed in both houses with and without vapor retarder with indoor RH 50-55% in 3 weeks.
- o The house with polystyrene sheathing was the last to show condensation and the first to dry out. Wall sections with polystyrene sheathing showed 9 to 13° F higher temperature in wall cavities.

b. Field Inspections

Seventy houses were inspected for concealed condensation, corrosion, and fungus growth, in Canada and the U. S. between 1974-1979. The locations were as follows:

Winnipeg and Quebec City	16 houses
Michigan	16 houses
Ohio	14 houses
Minnesota	2 houses
Illinois	2 houses
Wisconsin	5 houses
New Hampshire	1 house
Massachusetts	4 houses
New York	2 houses
South Carolina	6 houses

Age of houses - new to 10 years old. Houses represented different wall constructions, heating systems, house styles and orientation, and size.

No condensation was observed, nor water stain marks, wood decay or fungal growth. Moisture contents were in the range of 7 to 15%. Some houses had vapor barriers, others none.

c. Conclusions

- o Position of theoretical dewpoint does change with the location of the applied insulation.
- o The traditional five-to-one ratio of exterior to interior permeance was based on one single standard construction method (frame wall with insulation in the wall cavity only).
- o The dominant mode of vapor transport in a home is air convection, not vapor permeation.
- o A vapor retarder (≤ 1 perm) installed on the interior side of the wall, which also functions as an air barrier, is the single most important factor in minimizing the potential for vapor condensation.
- o The asphalt-coated kraft paper, properly installed, is an adequate vapor retarder.
- o Warmer cavity temperature reduces chance for condensation and increases chance for evaporation. Sheathings with higher insulation value raise cavity temperatures.

C.5

Annual Cycle Moisture Analysis, M. B. Stewart, ASHRAE, SP 28, 1981.

The author used the steady-state vapor diffusion model, modified by the effect of wind and solar warming, to determine hourly condensation rates for Minneapolis winter conditions, but did not include air leakage into the wall cavity. The condensation and or evaporation was integrated over the entire year to study how various construction variables would affect cumulative condensation in the cavity at the sheathing surface.

The variables studied using this model were:

Interior/Exterior permeance ratio	5:1 to 1:5
Overall permeance magnitude	3 to 30 perms
R-value in cavity	0 to R-13
Indoor relative humidity	20 to 50 %
Exposure	South and North walls

Worst condition:

Interior/exterior permeance ratio of 5:1; total permeance 30 perms, RH 50%, R-13, north exposure resulted in 7-month storage December to June, max level about 10% increase in moisture content of sheathing and siding.

In general, report seems to show that without leakage of warm, moist air from indoors into the cavity through imperfections in construction and workmanship, diffusion will not cause cavity condensation in sufficient quantities to be deleterious.

C.6 Residential Moisture Conditions - Facts and Experience, by Ralph Johnson, Proceedings ASTM Symposium, Philadelphia, October 1980, ASTM STP 779, July 1982.

Author cites a study made for NAHB by NAHB Research Foundation on relative humidity in living spaces and attic, and outdoor temperature and RH in 16 houses - in north-central Utah, southern Alabama, Ohio and central Maryland. Measurements were made during one week in summer and one week in winter. Data were recorded on size and type of house, occupancy, type of construction, type of attic ventilation, use of vapor retarders, and related information. The general conclusion from the data was that the presence of vapor barriers in the ceilings did not reduce the absolute humidities in the attics relative to the occupied spaces.

The author states that in the late 1940's and early 1950's moisture-related problems were very common in new homes. There have been almost no complaints of moisture problems from condensation in recent years.

Reasons for absence of moisture problems suggested are that today's homes are almost twice as large on the average, families are smaller, less cooking is done at home, clothes are dried in vented driers, less floor scrubbing is done, better types of exterior paints are used, most walls have vapor retarders, and air conditioning is widely used in the summer.

The author also states that concealed condensation is not a significant problem in retrofitted homes.

C.7 Assessments of Moisture Problems in Family Housing Located at Two New England Air Force Bases, by Douglas Burch and Paul Campbell, 1976.

Moisture problems in family housing at Pease AFB have been indicated by serious failure of exterior paint systems. Pease AFB is located in southern New Hampshire a few miles from the ocean.

The family housing units were two-story wood-frame row houses. Wall construction consisted of ½-inch gypsum board on 2 x 4 studs, 16" o.c., 3/8-inch sheathing and cedar wood siding (either bevel siding or shakes). Rockwool batts 1½ inches thick with asphalt-impregnated kraft paper vapor retarder on the warm side was placed in the stud space next to the interior wall. Gas-fired forced air furnaces with pan-type humidifiers heated the homes. The furnaces were in a mechanical equipment closet and a duct from the closet to the attic provided air for combustion and draft diverter. Most families operated supplementary room humidifiers.

Painting on the exterior was done on a 5-year cycle. Paint was said to be an oil-base primer and a latex top coat. Since buildings were built in the mid-1950's, several repaintings had probably occurred.

Many water blisters were observed. There were many pushed-out nails in the exterior walls. Warped and bowed siding was also observed. Vent plugs had been installed at various places, but in some cases the moisture damage appeared to be greater at those locations. Measured moisture content of sheathing was 8-13%. Insulation felt dry.

Some chalking paint surfaces did not appear to be moisture related. The paint failures appeared to be less pronounced on the cedar shake shingles.

Conclusion was that major cause of paint failure was moisture - related, aggravated by indoor humidification.

Less pronounced paint failures on exterior painted surfaces were observed at Griffiss AFB in central New York. Examination of the paint failures indicated high chalking ratings which suggests poor preparation of the surface and perhaps poor paint. Additional siding, Tedlar coated, had been installed on furring strips with the top and bottom left open for ventilation. This has reduced maintenance problems.

C.8

Air Leakage, Ventilation, and Moisture Control in Buildings, by G. O. Handegord, Proceedings ASTM Symposium, Philadelphia, October 1980, ASTM STP 779, July 1982.

- a. Considerable common knowledge was summarized. Some new or controversial statements were made.
- b. The ventilation rate afforded by a chimney in conjunction with air inlet openings will normally be sufficient to maintain relative humidity below the window condensation point.
- c. Simply lowering the indoor humidity to avoid concealed condensation is not likely to solve the problem nor satisfy the occupants.
- d. Domestic dehumidifiers can remove moisture from the room air without loss of heat energy, but their capacity is low at relative humidities below 40%.
- e. A much more significant flow of moisture (compared to diffusion) will occur through cracks, fissures, and holes owing to the pressure differences caused by wind, chimney effect, or mechanical air-handling devices.
- f. Measurements in 6 houses in Ottawa indicate that window and door leakage may constitute only about 20% of the total. As much as 70% may occur through leaks in the walls and as much as 60% can occur through the ceiling depending on the particular houses. Holes in upper plates for passage of wiring or plumbing may contribute half of the total through the ceiling. Duct and chimney penetrations can also provide large leakage areas.

- g. A chimney acts like an exhaust system and can cause a reverse of pressure across the envelope.
- h. High-rise buildings must be built to a higher standard of air-tightness because of larger chimney effects.
- i. In commercial buildings with insulated built-up roofs, the junction of the wall and roof is a critical location for air leakage. Drop ceilings are also a vulnerable location if walls are left unplastered above the ceiling.
- j. Structural frame should be inward and separate from the exterior wall system.
- k. Internal floors in high-rise buildings should be made airtight to limit cumulative chimney effect.
- l. If reasonable humidity levels are maintained indoors in winter, some concealed condensation is inevitable. Drainage by gravity through openings to the outside is the most effective practice, with drains being flashed to the vapor barrier in the wall.
- m. In flat wood-frame roofs, condensation will form immediately above the leakage opening in the vapor retarder, and the water will eventually drip through the same holes. Vapor retarders in cathedral ceilings will also leak locally, but condensation can be drained to the soffit on top of a vapor retarder that has been applied to the slope in overlapping shingle fashion.

C.9 Air Leakage Measurement and Reduction Techniques on Electrically Heated Homes, by John O. Collins Jr., ASHRAE, SP28, 1981.

Johns-Manville Sales Corporation, under sponsorship of the Electric Power Research Institute, applied air leakage reduction techniques to 29 electrically heated homes in Denver, Colorado, and identified 30 similar homes which were left untreated to use as controls in the experiment. The retrofitting was done to evaluate the effect of these procedures on energy requirements.

Depressurization air leakage tests were made in each home at pressure differences of 0.3, 0.2, and 0.1 inches W. G. before and after retrofit. Tracer-gas measurements were made in only two houses before and after retrofit.

Forty-five different leak paths required treatment. Some occurred in all houses, others in only a few houses. The leakage paths and frequency of occurrence are shown in table C.9.1. The paths treated in each house were recorded. The entire surface of all exterior walls was treated including floor/wall joint and the joints between the wall and door and window openings, with a glass mat adhesive and paint having a permeance less than 1 perm.

The cost averaged about 65¢ per square foot of floor area or about \$1050.00 per house for labor and materials. This did not include the cost of the air leakage tests. If walls in good condition had not been treated fully the cost might have been halved.

The reduction in air changes averaged 30 percent for all houses and ranged from 0 to 65 percent on individual houses. The average reduction was highest in tri-level houses (39%) and lowest in bi-level houses (13%).

The tracer-gas measurements showed a reduction from 0.70 to 0.50 air changes/hr (29%) in one house and from 0.45 to 0.29 (36%) in the second house. There was no correlation between the reductions in air leakage by the two measurement methods.

Data on reduction in energy usage are not yet available.

C.10

Air Leakage Characteristics and Weatherization Techniques for Low-Income Housing, by R. A. Grot and Roy E. Clark, ASHRAE, SP28, 1981.

Natural air infiltration tests were made in 266 houses in 14 cities using tracer-gas techniques. About 68% were frame construction, 16% masonry, and 11% masonry veneer. Age distribution was fairly uniform from 10 to 80 years. About 38% had forced-air heating systems, 37% had space heaters or floor furnaces, 20% had hydronic or steam heating systems, and 5% had gravity heating systems.

The average air infiltration rate before retrofit was 1.12 air changes per hour, the range from less than .25 for 4% to between 4.75 and 5.0 air changes per hour for about ½% of the readings taken. These data were obtained by tracer-gas techniques. Retrofit measures that affected air leakage included resetting and replacing glass, replacing threshold, sealing structural cracks, weatherstripping and caulking windows and doors, weatherstripping attic hatch, installing storm windows and doors, and installing flue vent dampers.

Fan depressurization tests at a pressure difference of 0.2 m W. G. were performed before and after retrofit on 25 homes. The induced air changes were reduced by 5% to 96% by the retrofit measures. There was no good correlation between the air infiltration rates measured by the tracer-gas technique and the depressurization method.

In the 72 houses for which energy conservation measures were applied to the exterior envelope only, the cost averaged \$1172.00 per house, the energy savings averaged 18 percent and the payback period was calculated to be 16 years.

TABLE C.9.1

FREQUENCY OF AIR LEAKAGE LOCATIONS

<u>Path or Location of Leakage</u>	<u>Percent of Houses Treated</u>
Bottom of drywall	100
Window fit including sill	86
Plumbing fixtures, inside and outside walls	79
Electric fixtures including medicine cabinet	76
Bathroom vent	59
Outside door fit	55
Access to attic space	52
Basement door fit	48
Fireplace fit	45
Stair steps and risers over unheated space	45
Garage door fit	38
Clothes dryer vent	34
Garage-house connection	31
Fireplace damper	28
Heating ducts	24
Bathtub fit	24
Kitchen fan vent	24
Closet door trim	17
In-wall air conditioner	17
Sill plate	17
Door to unheated storage	14
Door bell	14
Smoke alarm	14
Crawl space opening	14
Baseboard heater	14
Crawl space vent	14
Shower stall fit	14
Closet door runners	10
Kitchen cabinets, behind or on top	10
Philips control box	10
Sewer pipe penetration	7
Wood paneling on studs or furring	7
Intercom	7
Cellar floor drain	7
Toilet paper holder	7
Construction discontinuities	7
Telephone cord	7
Abandoned furnace flue	3
Soil pipe to basement	3
Bathroom cabinets, behind	3
Door latch	3
Sky light	3
Porous masonry	3
False ceiling beam	3
Stove damper	3

- C.11 Moisture Problems in Buildings, by Robert J. Moore, ARMM Consultants, and Lawrence G. Spielvogel, Consulting Engineer, for Southern Division of the Naval Facilities Engineering Command, Charleston, S.C., April, 1980.

Field investigations were made of moisture problems in air-conditioned buildings at various locations in the Pacific and in the Southeastern United States. Enlisted and Officers' quarters were studied in Hawaii, Guam, and the Philippines. Bachelors' quarters, a Commissary, Air Crew Training Buildings and Missile Maintenance Buildings were studied on a selective basis at the Charleston Naval Hospital, Pensacola and Jacksonville Naval Air Stations, the Naval Support Activity in New Orleans, and Corry Field.

The moisture problems found in these field studies included mold and mildew on the exterior and interior surfaces of buildings, uncomfortably high indoor humidities, condensation, drips and leaks within the buildings, and the odor, discomfort, and damage to property associated with these moisture problems. Mold and mildew were found in virtually all buildings visited in the Pacific. Of the several dozen buildings toured, the only one that exhibited satisfactory conditions was a bachelor enlisted quarters in Guam that utilized a variable air-volume system. All the other buildings used fan-coil systems, and every one had some type of moisture problem. The fan-coil units were able to control the dry-bulb temperature satisfactorily, but the humidity level was much too high for comfort.

The conditions in the Southeastern U. S. facilities were similar to those observed in the Pacific, except they were not quite as severe. This was probably due to the fact that the weather was more severe in the Pacific.

The authors made recommendations for modifying various NAVFAC specifications and guidelines for new buildings on a paragraph-by-paragraph basis on:

- a) proper locations of vapor barriers
- b) types of air-conditioning units needed to control humidity
- c) ventilation of toilets
- d) allowable indoor range of relative humidity
- e) conditions requiring reheat systems
- f) insulation of walls and roofs
- g) minimization of air leakage
- h) amount and conditioning of ventilating air, and
- i) pressurization of indoor space.

More limited recommendations were provided for modifying existing buildings to reduce moisture problems in humid climates.

- C.12 Assessment of Summer Moisture Problems in Military Buildings Located in the Southeastern United States, by D.M. Burch, P.G. Campbell, T. Kusuda, and B.A. Peavy, NBS Letter Report to Hdq. Dept. of the Air Force, April 1977.

Field trips were made during August 1976 to Myrtle Beach AFB and Keesler AFB to study moisture problems in family housing units, and to Naval installations at Charleston, S. C. and Gulfport, Mississippi to study indoor condensation problems in bachelor enlisted quarters.

The housing units at Myrtle Beach consisted of 2 x 4 studs covered on the inside with gypsum plaster on plaster board and on the outside with plywood sheathing, asphalt-impregnated building paper and plywood, brick, or wood siding. Rockwool 1½-in thick was placed between the studs. The paint failures at Myrtle Beach consisted of cracking of the exterior paint parallel to the grain on wood surfaces. Observed thicknesses of peeled paint and measured chalk ratings indicated that new paint applied on a 3-year cycle may have been applied on top of existing painted surfaces without adequate surface preparation. Measured moisture contents of exterior wood paneling was higher than the equilibrium moisture contents for wood at the prevailing dry-bulb and wet-bulb temperatures. This suggests that the paneling may have been wetted by capillary movement of rainwater into the wood.

The housing units at Keesler AFB were constructed of brick or stone, with window trim and gable ends of wood. Paint problems were confined mainly where grain cracking occurred at the gable ends. There was also moisture damage to the interior paint under some windows.

The bachelor enlisted quarters in Charleston and Gulfport were 3-story dormitories constructed over slabs-on-grade. The buildings had flat built-up roofs over rigid insulation and suspended ceilings. Space cooling was provided by fan-coil units located under the windows. (The units were equipped with integral thermostats which controlled a chilled water bypass valve.) The fans ran continuously on either high, medium, or low speed.

In the Charleston quarters most of the suspended ceiling tiles were mildewed and damp, especially in the lounge areas. The under side of the floor above the suspended ceiling tile was completely covered with drops of water. Measurements of outdoor and indoor dry-bulb and wet-bulb temperatures showed that the indoor dry-bulb temperature in several instances was below the outdoor dewpoint temperature, and the indoor relative humidity was in excess of 80 percent. The north-facing lounges revealed more severe moisture problems than the south-facing bedrooms, presumably because less sensible heat from lighting and equipment was released in the lounges.

The observed moisture conditions were less severe at the Gulfport quarters than at Charleston. The climatic conditions at Gulfport were also more favorable because the outdoor relative humidity was observed to be only 67 percent at the time of the field inspection. Ceiling panels in the Gulfport buildings were found to be free of mildew, although the mattresses in some rooms had a musty odor.

C.13

Moisture Problems in Buildings in the Sub-Arctic by J.P. Zarling, Eb Rice, and K. C. Swanson, Proceedings ASTM Symposium, Philadelphia, October 1980, ASTM STP 779, 1982.

Because of the long heating season and the extreme low temperature experienced in Arctic regions, most buildings in those regions experience some form of moisture-related problems. These problems can range from frost buildups on windows or glaciating on window sills to ice/frost formation in the insulation within the wall cavity of the structure. The formation of ice/frost in the insulation usually goes unnoticed until a warm spell or springtime, when outdoor temperature rise above the freezing point and melting water causes building damage.

The authors present nine cases of moisture migration through building materials which caused subsequent damage. Most of the examples demonstrate that the cause of the damage was not the failure of the vapor retarder itself, but the holes and discontinuities in the vapor retarder due to installation of windows, doors, vents, electrical outlets, chimneys, and structural members. Sealing these openings after the building is constructed is difficult.

The authors suggest that improved design and construction methods are needed to reduce the leakage paths for moist indoor air to enter the insulation spaces in walls and ceiling. They also suggest keeping a small negative pressure in the occupied space as a means to counteract the natural chimney effect in heated buildings. Also, the use of air-to-air heat exchangers in the ventilating air system would permit the use of more outdoor air to lower the indoor relative humidity without excessive energy use.

Appendix D
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