Moisture and Temperature Control in Buildings Utilizing Structural Insulating Board

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INTRODUCTION

The occurrence of condensation within the walls and attics of conventional residential structures has been under intensive study in various laboratories throughout the country and by members of the building industry during the past decade. The methods of construction which will maintain a home substantially free of any condensation problems have been fairly well established. With respect to condensation within the walls, three common precautions are: (1) to reduce the relative humidity of the inside air; (2) to use sufficient insulation in the cold walls; and (3) to use a vapor resistant interior surface construction. Condensation problems in the attic may be controlled with the use of vapor resistant materials located on the warm side of the ceiling and with vapor seals around the attic door and fixture outlets. As an added precaution in unheated attics, provision should be made for supplying ventilation in order to remove any vapors that might accumulate in the attic because of slow transmission through the vapor resistant ceiling, through the attic door, or through any openings around the door and electric outlets.

Plan of Investigation

This investigation, the third in a series undertaken for the Insulation Board Institute, was conducted in a full-scale test bungalow to observe the occurrence of moisture condensation and the distribution of temperatures in various building constructions utilizing structural insulating board. Previous tests with these materials had been conducted on small test panels only. By duplicating, as nearly as possible, the variables in standard residential constructions, it was thought that the resulting conditions observed during operation of the test bungalow would be more conclusive than data gained heretofore from the small test panels.

Four main objectives were included in this investigation, as follows:

1. To establish more firmly the conclusion that an interior finish possessing a permeability rate of 1.25 grains per square foot per hour per inch of mercury vapor pressure difference is a safe material to recommend in the field. Under normal conditions previous investigations on individual test panels in a special vapor transmission test apparatus[1] had shown that the rate of 1.25 was safe regardless of the type of exterior finish used.

[1] F. B. Rowley and C. E. Lund, *Vapor Transmission Analysis of Structural Insulating Board* (University of Minnesota Engineering Experiment Station Bulletin No. 22, 1944) pp. 10-16.

2. To determine what effect different rates of vapor permeability in interior and exterior surface constructions have on moisture condensation within the walls of standard residential structures. Seven different types of wall construction were included. Insulating board lath having low, medium-low, and high permeability rates were tested in combination with structural insulating board sheathing having low, medium, and high permeability rates.
3. To provide experimental data on the volume of ventilating air required to prevent the formation of frost in the attic for different ceiling constructions. Variations in attic construction included a weather-stripped attic door, a paint vapor barrier, and added insulation.
4. To obtain more definite data on attic air temperatures, with and without ventilation, as related to outdoor temperatures which, in turn, could be used to determine with greater accuracy heat losses through the ceiling area.

Previous Investigations

In 1940 and 1941, the University of Minnesota Engineering Experiment Station published two extensive studies on moisture and condensation control in building construction and operation.[2] In 1941, the Insulation Board Institute entered upon a cooperative research program with the Station to study more specifically moisture control in buildings constructed with structural insulating board.

Two studies have been published under the IBI cooperative program. The first investigation[3] was concerned with the vapor transmission analysis of structural insulating board. In this investigation tests were conducted to determine the vapor permeability of various structural insulating boards: small test panels constructed with this material were tested for vapor permeability; interior paints and wall coverings applied to structural insulating board were tested for effectiveness as vapor barriers—all under temperature and humidity conditions commonly prevailing in residential buildings.

The primary purpose of the second investigation[4] was to find vapor resistant coatings for structural insulating board which would maintain their effectiveness under conditions of high humidities—conditions which are prevalent in vegetable storage warehouses where it is necessary to protect both the structure and the stored product from the damages resulting from moisture condensation.

[2] F. B. Rowley, A. B. Algren, and C. E. Lund, *Methods of Moisture Control and Their Application to Building Construction* (University of Minnesota Engineering Experiment Station Bulletin No. 17, 1940).
F. B. Rowley, A. B. Algren, and C. E. Lund, *Condensation of Moisture and Its Relation to Building Construction and Operation* (University of Minnesota Engineering Experiment Station Bulletin No. 18, 1941).

[3] F. B. Rowley and C. E. Lund, *Vapor Transmission Analysis of Structural Insulating Board* (University of Minnesota Engineering Experiment Station Bulletin No. 22, 1944).

[4] F. B. Rowley, M. H. LaJoy, and E. Erickson, *Vapor Resistant Coatings for Structural Insulating Board* (University of Minnesota Engineering Experiment Station Bulletin No. 25, 1946).

TYPES OF CONSTRUCTION TESTED

Test Bungalow

The full-scale test bungalow in which the different wall and attic constructions were incorporated is shown within the large cold room in Figure 1. A view of the entrance to the completed bungalow is shown in Figure 2, while Figure 3 represents a plan view of the structure. The bungalow had a floor area of 21 feet by 21 feet 8 inches and a first floor ceiling height of 8 feet 6 inches. It was identical to the one used in a previous investigation described in detail in Bulletin No. 18.[5] The test bungalow was of standard frame construction and was so designed that several different types of interior and exterior construction could be incorporated in the walls and studied at the same time. In the present investigation 15 test wall sections were built into the structure, each of which was 4 feet wide and extended the full height of the first floor. These walls were constructed with different combinations of vapor resistant materials on the interior and exterior sides of the studding. All walls were substantially the same in the over-all coefficient of heat transmission.

The bungalow contained three rooms with four double-hung windows and one exterior door fitted with a storm door. The attic door opened to an attic stairway. In the attic there were three gable ends with a window fitted into each. The attic window at the rear of the bungalow was used for supplying ventilating air, while the opposite

[5] Rowley, Algren, and Lund, *Condensation of Moisture and Its Relation to Building Construction and Operation.*

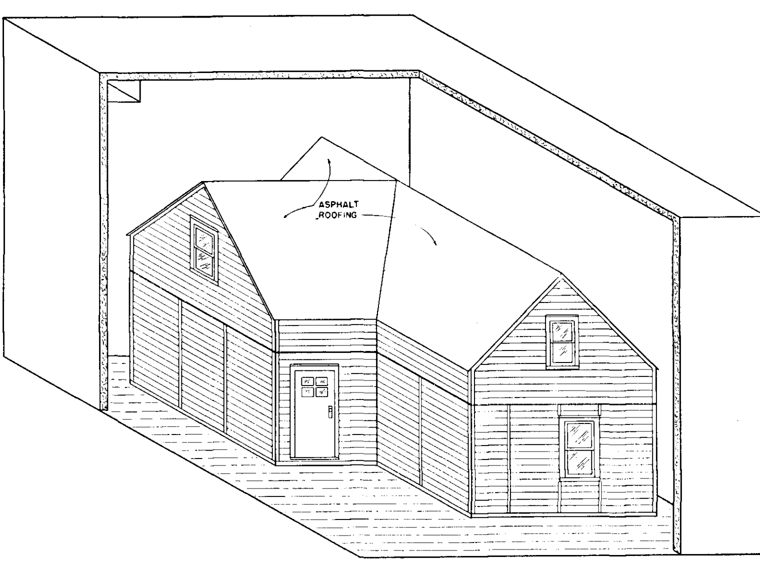

Figure 1. View of test bungalow within cold room

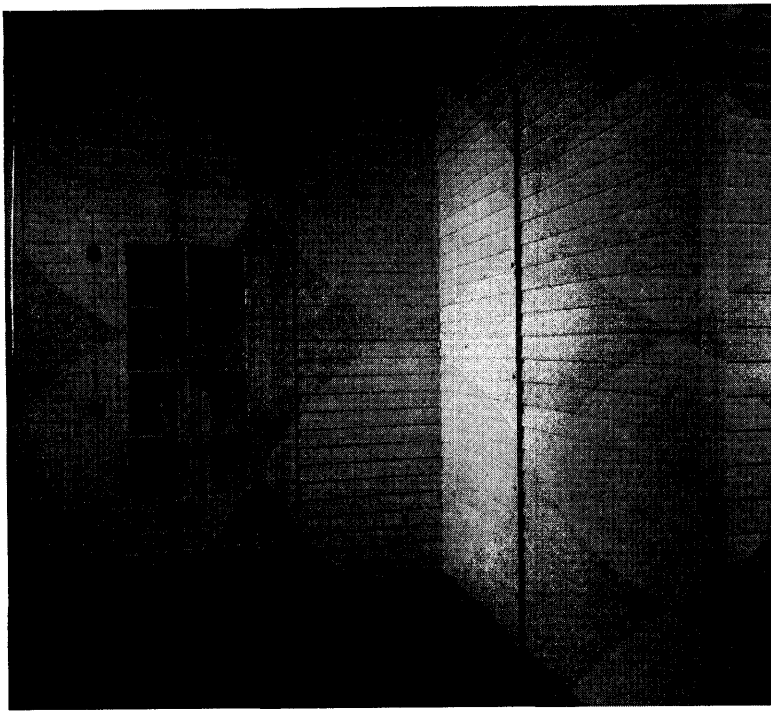

Figure 2. View of entrance to completed bungalow

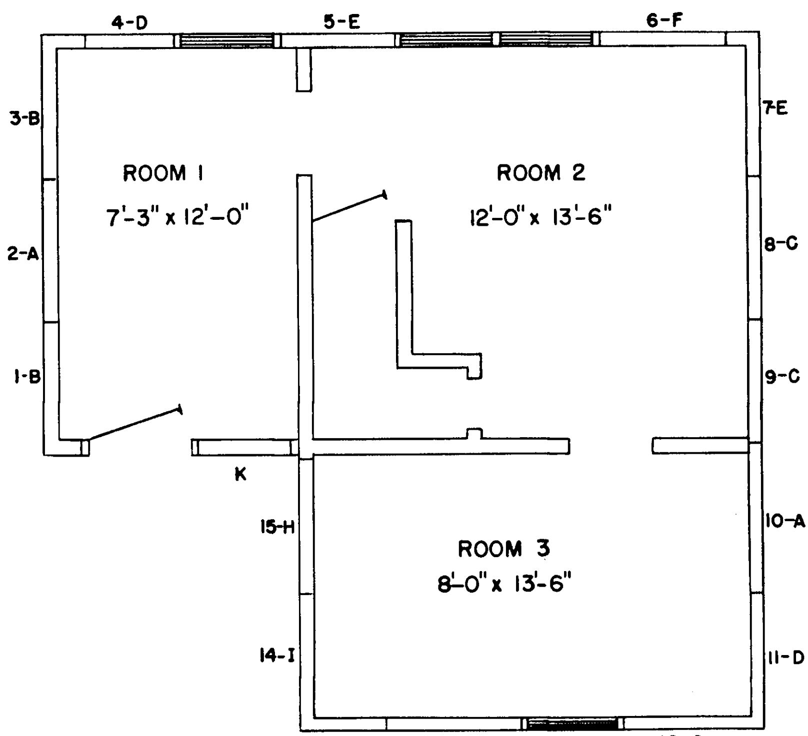

Figure 3. Plan view of test bungalow showing position of test walls

window was opened a slight degree for the discharge of air into the low temperature room.

Interior Construction

The interior finish of all walls consisted of ½-inch plaster applied to ½-inch insulating board lath, and the ceiling was finished with ½-inch plaster applied to 1-inch insulating board lath. Two coats of plaster were used: the first, a brown coat, consisted of two and one-half parts sand to one part plaster by volume; the finish coat consisted of three parts gaging plaster to one part finishing lime. The first coat was allowed to dry for five days and then was followed by the application of the finish coat which was allowed to dry for 30 days before the start of the test. After the first few weeks of preliminary tests, the ceiling was painted with two coats of paint to serve as a vapor barrier. The composition of this coating was as follows:

1. Composition of primer (A-21)[6] by weight: pigment, 58 per cent, and vehicle, 42 per cent. Composition of the pigment consisted of: titanium dioxide, 10 per cent; silica, 20 per cent; metro-nite, 70 per cent. Composition of the vehicle consisted of: vegetable oils, 84.8 per cent; drier and thinner, 15.2 per cent.
2. Composition of flat white paint (C-20)[6] by weight: pigment, 59 per cent, and vehicle, 41 per cent. Composition of the pigment consisted of: titanium calcium, 72.2 per cent, and magnesium silicate, 27.8 per cent. Composition of the vehicle consisted of: vegetable oils, 22.1 per cent; resins, 7.9 per cent; drier, 3.2 per cent; turpentine, 2.7 per cent; mineral spirits, 64.1 per cent.

On the basis of previous tests this paint coating was selected as one which would provide a reasonably good vapor barrier. Actual tests of this coating when applied to ½-inch plaster on ½-inch insulating board resulted in a permeability rate of 1.61 grains per square foot per hour per inch of mercury vapor pressure difference. Since a 1-inch insulating board lath was used, the permeability rate of the ceiling of the test bungalow would be slightly lower than this value because of the added resistance of the thicker lath. This treatment was taken in accordance with the permeability rate of from 1.00 to 1.50 which was originally planned for use as the ceiling barrier.

The application of the insulating board lath to all of the 4-foot wide exterior wall sections as well as to the ceiling surface was done by methods used in actual practice. Figure 4 shows the lath application. The lath boards used were commercially fabricated to give a well-fitted shiplap, or V-joint. The vertical and horizontal joints of a standard wall section were duplicated because joints have always been a questionable source of vapor leakage. In any typical construction the average face dimensions of a solid wall are longer than those used in the test wall. Thus, approximately 10 per cent more joints were

[6] Composition, code numbers, and test results of paint finishes given by Rowley and Lund, *Vapor Transmission Analysis of Structural Insulating Board,* Bulletin No. 22, pp. 56-62.

used in the test panels in this investigation than would be found in an average construction.

Exterior Construction

All exterior wall panels were constructed on studs spaced 16 inches on centers with structural insulating board as the sheathing and ¾-inch by 8-inch cedar as the siding. As shown in Figure 5, wood strips, ¾-inch wide and 1⅛-inch deep, were used as nail strips for the sheathing. The outside surfaces of the fixed studs were grooved to receive these nailing strips. Figure 4 shows the stud grooves, while Figures 5 and 6 show the sheathing applied to the nailing strips which fit into the grooves. Figure 7 shows the two sections fitted together. The combined exterior section of the wall was attached to the studs by long wood screws. By this method the outer section of the wall could be fastened securely to the studs and yet could be removed easily for inspection during or after the test period. The siding was applied over the sheathing and nailed to the nailing strips with the exception of the top, center, and bottom siding boards which were applied with wood screws to facilitate removal for inspection. The exterior siding was painted with two coats of pure white lead and linseed oil paint.

Application of insulating board sheathing was in accordance with standard practice. Where the schedule called for 4-foot by 8-foot sheathing, one board alone was taken to cover the complete wall panel as shown in Figure 5. Where the schedule called for 2-foot by 8-foot sheathing, these were applied as shown in Figure 6. Thus, the horizontal and vertical joints found in actual construction were included.

Above the first floor ceiling line the construction consisted of wood sheathing, roof boards of ponderosa pine shiplap, and siding of ½-inch by 6-inch redwood which was painted with both one coat of primer and one coat of outside white paint.

Ceiling and Attic Construction

In the study of frost accumulation in the attic, five different ceiling and attic constructions were used. These are shown in Figure 8.

The variations in these constructions included the effects of using or not using a rubber gasket around the attic door, a vapor barrier on the ceiling plaster, and added insulation. Construction 1 consisted of ½-inch plaster over 1-inch lath with no vapor barrier or additional insulation and with a loose-fitting attic door. Construction 2 was identical to Construction 1 with the addition of a rubber gasket fitted around the attic door. Construction 3 was the same as Construction 2, plus two coats of paint applied to the ceiling plaster as a vapor barrier. The description of this paint is covered above under the section entitled **Interior Construction.** Construction 4 was identical to Construction 3 with the addition of ½-inch insulating board applied to the tops of the ceiling or attic floor joists as added insulation. Construction

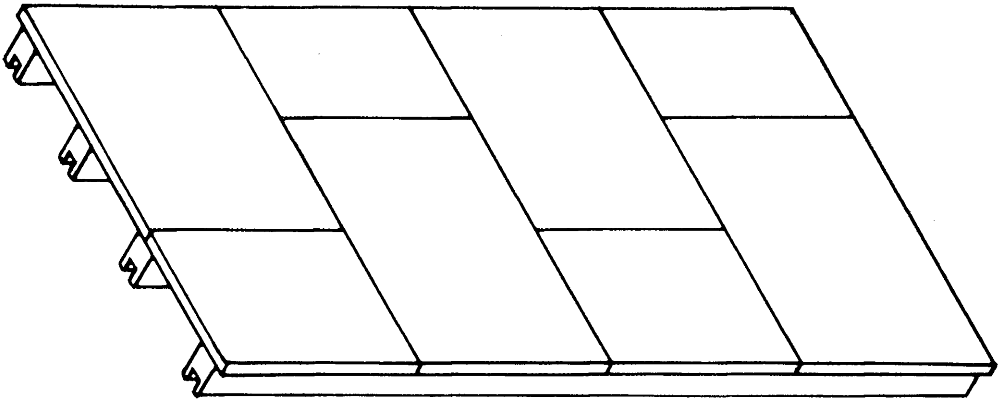

Figure 4. Typical wall construction showing horizontal and vertical joints in application of insulating board lath

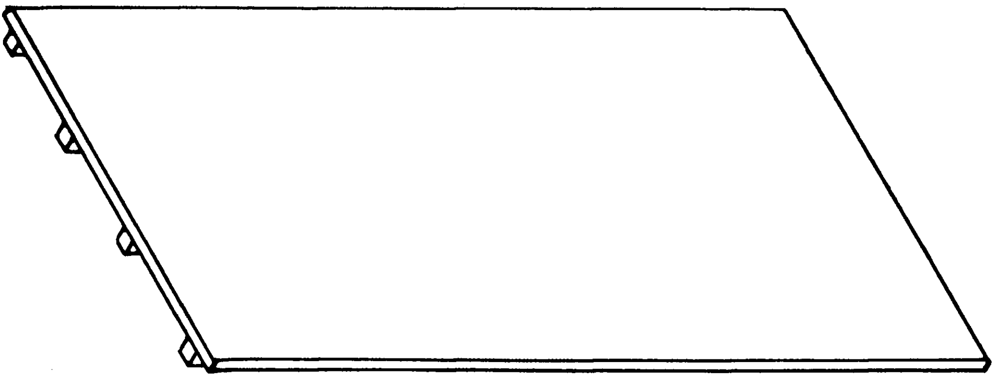

Figure 5. Typical wall construction for application of 4-foot by 8-foot insulating board sheathing with no vertical or horizontal joints

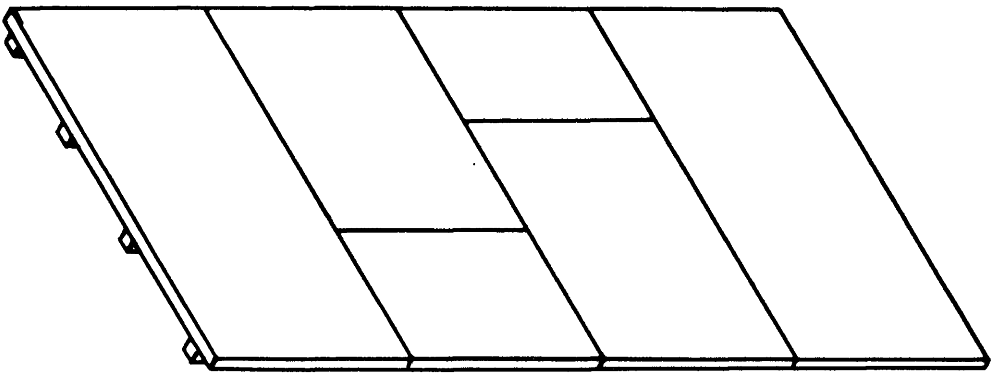

Figure 6. Typical wall construction showing horizontal and vertical joints in application of 2-foot by 8-foot insulating board sheathing

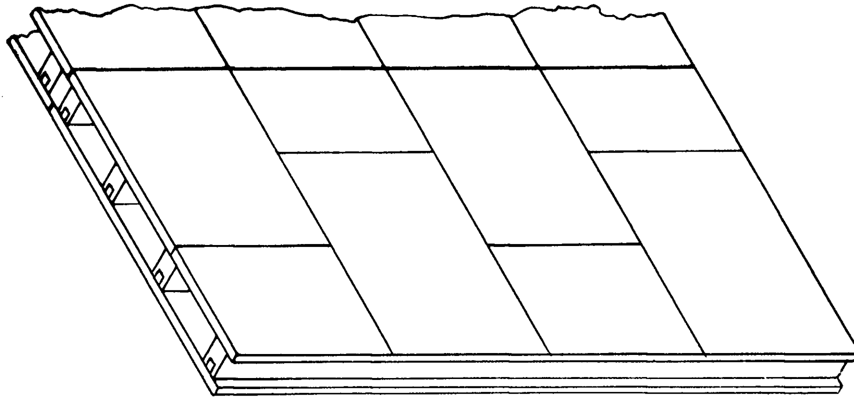

Figure 7. Exterior wall panel fitted to grooved studs

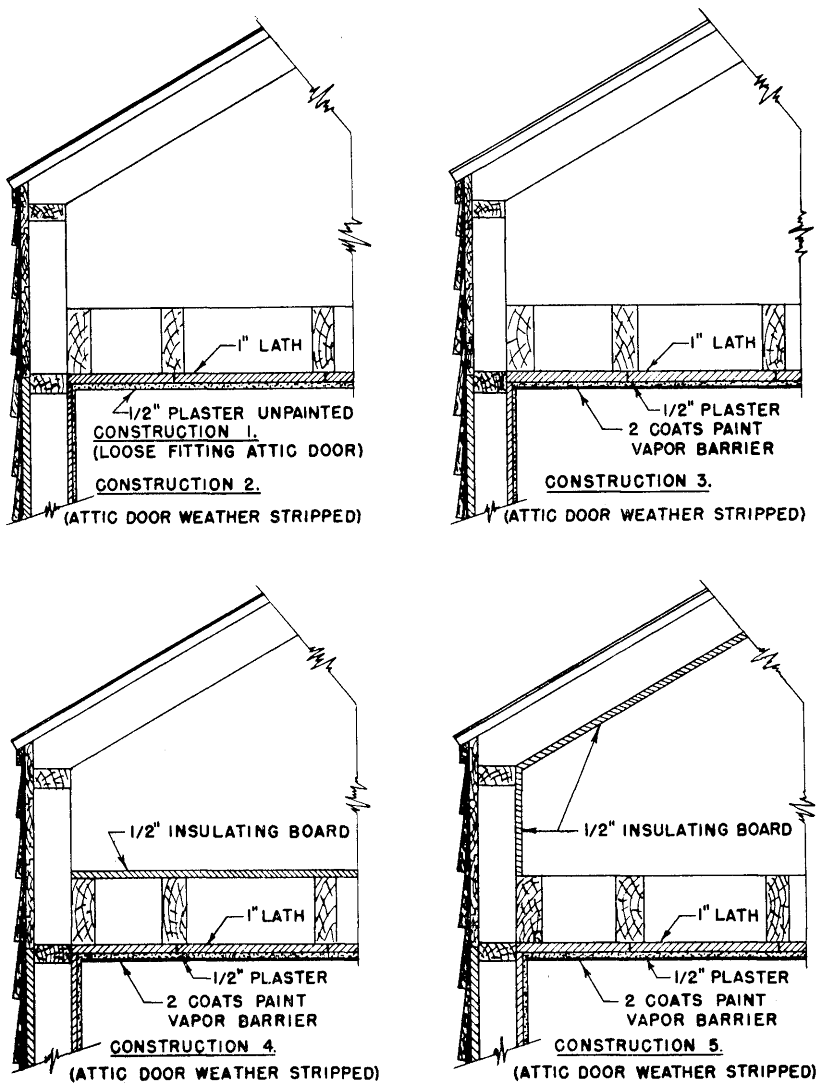

Figure 8. Ceiling and attic constructions

5 was the same as Construction 3 but for the addition of ½-inch insulating board applied to the under side of the roof rafters and to the wall area extending above the first floor line.

Interior and Exterior Construction of Test Wall Panels

The materials selected for interior and exterior construction of the test wall panels possessed different rates of vapor permeability. As many combinations as were possible within the size limitation of the test bungalow were incorporated in nine different panels. Figure 9

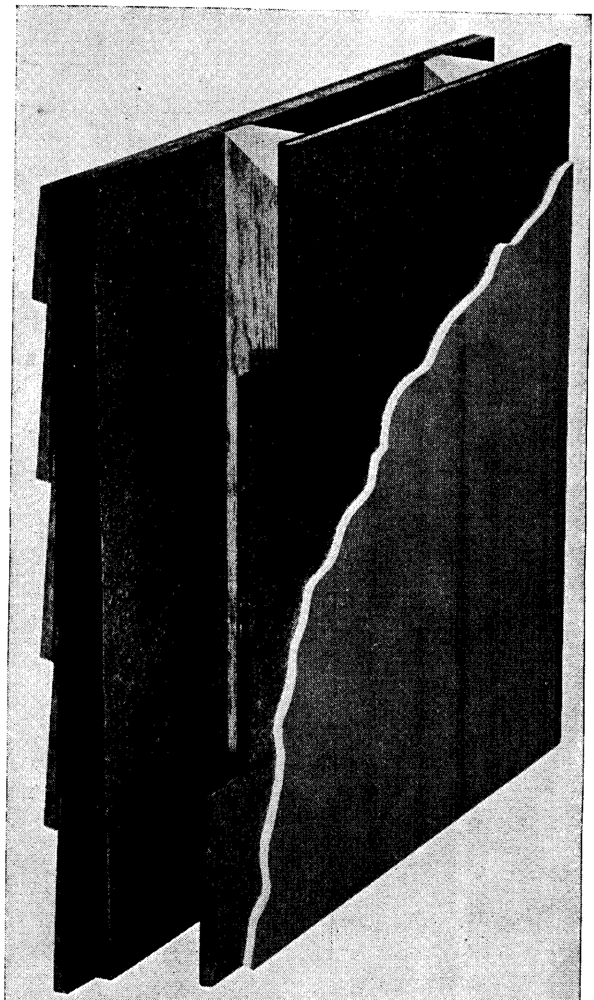

Figure 9. General construction of test walls

shows the general construction of all the test walls. Figure 10, a cross section of each wall panel, describes the materials used in their construction. All of the exterior walls were constructed with 4-foot by 8-foot sheathing, except Walls A and C, in which 2-foot by 8-foot sheathing was used in order to investigate the effect of horizontal and vertical joints on test results.

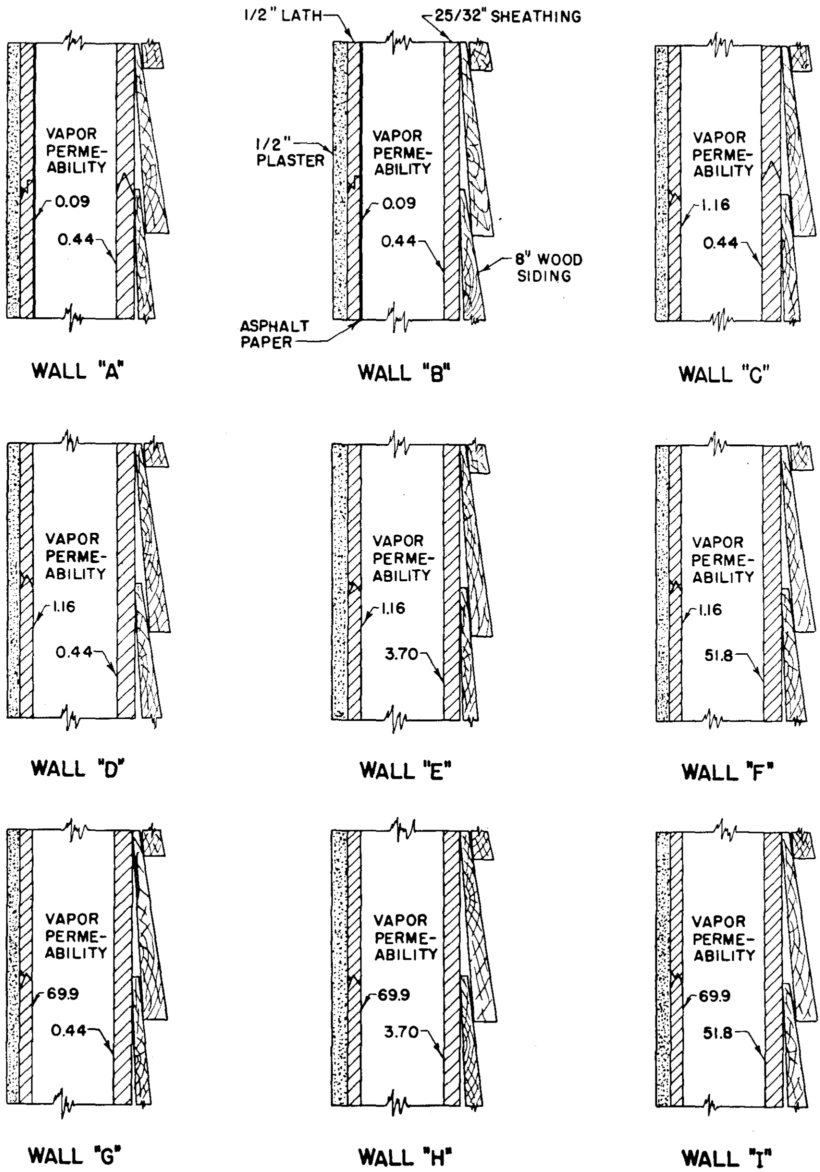

Figure 10. Construction of test wall panels

Representative vapor permeability rates selected to conform to the various classifications were as follows:

Low permeability rate—below 0.50 grains per square foot per hour per inch of mercury vapor pressure difference

Medium-low permeability rate—between 1.00 and 1.25 grains per square foot per hour per inch of mercury vapor pressure difference

Medium permeability rate—between 3.0 to 5.0 grains per square foot per hour per inch of mercury vapor pressure difference

High permeability rate—above 30.0 grains per square foot per hour per inch of mercury vapor pressure difference

Table I represents a summary of the selection of vapor resistant materials. In Group 1, Walls A and B were constructed with vapor resistant asphalt paper in conjunction with plain untreated insulating board lath in order to meet the requirement of a low permeability lath. The permeability rate of 0.09 for the asphalt paper was based on actual tests in the special vapor transmission test apparatus.

For the walls in Groups 2, 3, and 4 which required a lath possessing a medium-low permeability rate, it was necessary to select and try out various coatings on a plain board. A plain lath, code No. P-6,[7] was selected to be coated with various vapor resistant paints. Results of these tests are shown in Table II. Four different coatings were tested. Specimen P-6-5 with one coat of A-21 primer, plus one coat of C-20 flat white paint, gave a permeability rate of 1.14, which was within the requirements. To establish more firmly the results of this treatment,

[7] Rowley and Lund, *op. cit.*, pp. 22-25.

Table I. Selection of Vapor Resistant Materials for Wall Panels in Test Bungalow—Permeability Rates Expressed in Grains per Square Foot per Hour per Inch of Mercury Vapor Pressure Difference

Group No.	Wall Designation (Figs. 2 and 10)	Insulating Board Lath		Insulating Board Sheathing	
		Permeability rate	Code No.	Permeability rate	Code No.
1	2-A and 10-A	0.09*	P-2	0.44	R-1
	1-B and 3-B	0.09*	P-2	0.44	R-1
2	8-C and 9-C	1.16†	P-6	0.44	R-1
	4-D and 11-D	1.16†	P-6	0.44	R-1
3	5-E and 7-E	1.16†	P-6	3.70	R-6
4	6-F and 13-F	1.16†	P-6	51.80	S-5
5	12-G	69.9	P-3	0.44	R-1
6	15-H	69.9	P-3	3.70	R-6
7	14-I	69.9	P-3	51.80	S-5

* Asphalt paper barrier.
† Surface treated.

Table II. Selection of Insulating Board Lath Coating—Vapor Transmission Test Results for Selection of Insulating Board Lath Coating with a Permeability Rate between 1.00 to 1.25 Grains per Square Foot per Hour per Inch of Mercury Vapor Pressure Difference

Specimen No.	Coating	Permeability Rate Grains per sq ft per hr per in. Hg
P-6-1	1 coat A-21 primer 1 coat A-2 asphalt paint	0.55
P-6-2	1 coat A-21 primer 1 coat A-2 asphalt paint	0.59
P-6-3	1 coat A-21 primer	1.74
P-6-4	2 coats A-21 primer	1.04
P-6-5*	1 coat A-21 primer 1 coat C-20 flat white paint	1.14
P-6-6*	1 coat A-21 primer 1 coat C-20 flat white paint	1.17

* Surface coverages:
A-21 Primer .... 650 square feet per gallon
C-20 Paint .... 572 square feet per gallon

a duplicate test was conducted as shown by sample P-6-6. The permeability rate of this sample amounted to 1.17. The average of P-6-5 and P-6-6 was 1.16. This was used for all lath requiring a medium-low permeability rate.

An interior finish construction having a high permeability rate was planned for the walls in Groups 5, 6, and 7. For this purpose ½-inch plaster without additional vapor resistant material was applied to plain ½-inch insulating board. A plain insulating board lath, code No. P-3, with a permeability rate of 69.9 was used as a plaster base.

With respect to the sheathings it was possible to select from the regular run of commercial insulating boards those which possessed low, medium, and high permeability rates. As shown in the last two columns of Table I, commercial sheathing R-1 having a permeability rate of 0.44 was used for all walls of high vapor resistant exterior construction. This included the walls in Groups 1, 2, and 5. Sheathing R-6 with a medium permeability rate of 3.70 was selected for the walls in Groups 3 and 6. Plain sheathing S-5 with a high permeability rate of 51.8 was used for the walls in Groups 4 and 7.

Location of Test Walls in Bungalow

Figure 3 indicates the location of the 15 test walls around the test bungalow. Beginning at the left foreground of Room 1, the walls are numbered from 1 to 15, consecutively. Types of wall are designated by letter; for example, Walls 1-B and 3-B were identical in construction. There were duplicate walls for all those in Groups A through F. Single tests were conducted on Walls G, H, and I. These 15 walls utilized all space available for 4-foot by 8-foot panels. Two small areas

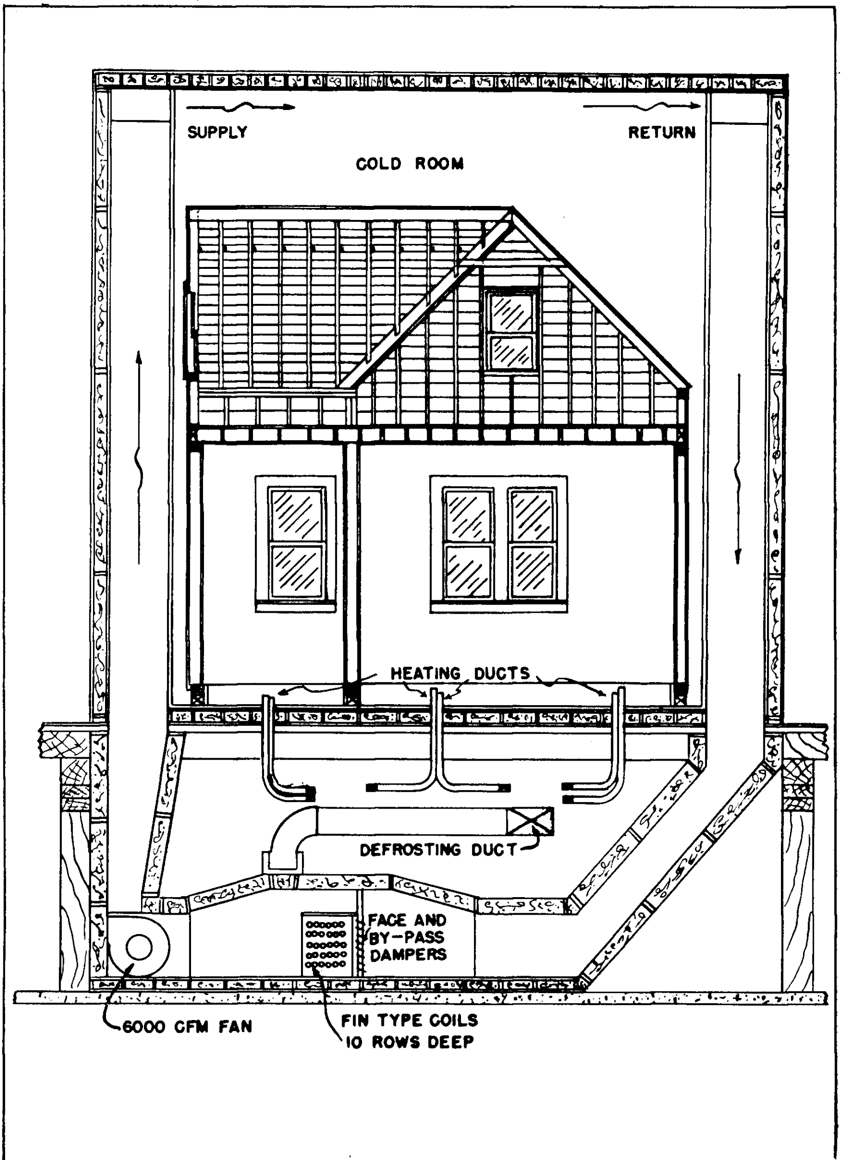

Figure 11. Cross-sectional view of test bungalow within cold room

remained, as indicated by sections J and K, which were constructed similarly to Walls I and F, respectively. These were used as control panels and were removed occasionally for inspection to indicate the time at which the main test walls should be removed for final examination.

Equipment and Instruments

Test apparatus—The cold room which housed the test bungalow was 30 feet square and 25 feet high with walls constructed of 2-inch by 6-inch studs spaced 16 inches on centers and covered with ½-inch fiber insulating board on inside and outside wall surfaces. The stud space was insulated with mineral wool 6 inches thick, and a vapor resistant paper was nailed to the studs next to the outside surface of the wall to prevent the vapor in the warm exterior air from entering the wall. The paper was omitted from the inner or cold surface of the wall so as to allow some breathing through the cold inner surfaces. This method of construction proved satisfactory in operation and did not present any condensation problems.

The room was cooled by circulating the cold room air over direct expansion coils supplied by a 25-ton ammonia compressor. By means of a 6,000-cubic foot per minute fan, the air was circulated from return duct openings at the top of the cold room through the coils into the supply duct and delivered again to the cold room by a vent directly opposite the return duct vent. The cooling coils were separated in compartments by an arrangement that allowed one coil to be defrosted while the other was in operation.

A cross-sectional view of the test bungalow, cold room, and cooling unit is shown in Figure 11.

Conditioned air was supplied to the test bungalow from an air conditioning unit located in the basement below the cold room. The unit consisted of a steam heating coil with thermostatic controls, a water spray head and eliminator, an automatic temperature and humidity control aparatus, and a 1,000-cubic foot per minute fan. A sectional view of the system appears in Figure 12. In operation, air was drawn from the test bungalow, passed through the conditioning unit, and delivered at the proper temperature and humidity to the rooms of the bungalow. The humidity control was maintained by a humidistat placed in a room of the test bungalow and connected to a solenoid water valve in the spray water line. The major part of the heat was supplied by a steam heating coil built into the air conditioning unit. This was supplemented by electric resistance heaters which were placed in the supply air ducts and controlled by thermostats in adjacent return air ducts. This method resulted in economical and satisfactory control of both temperature and humidity in the test bungalow.

The attic ventilation was supplied by the ventilator shown in Figure 13. The motor and 700-cubic foot per minute fan were attached to the cold room wall, and a 4-inch duct carried the air to the plenum chamber fitted over the north or rear attic window. To assure uniform delivery of the air through the open window into the attic, a baffle was placed over the supply duct vent. A bell-shaped orifice with static and impact tubes connected to a manometer in the test bungalow determined the volume of air supplied. The air was carried from the cold room through the supply duct to the plenum chamber into the attic space and out through the opposite window which was open.

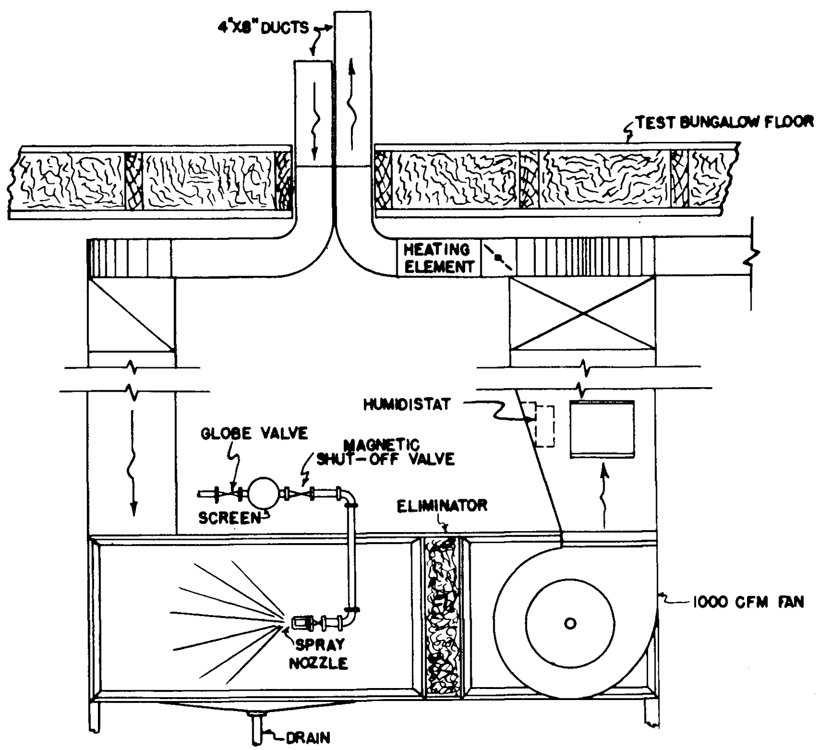

Figure 12. Sectional view of air conditioning unit and distribution ducts

Instruments—The measurement and control of temperatures and relative humidities were considered very important throughout this research project.

All temperatures were taken with copper-constantan thermocouples. Thermocouples were placed in the cold room, in the attic,

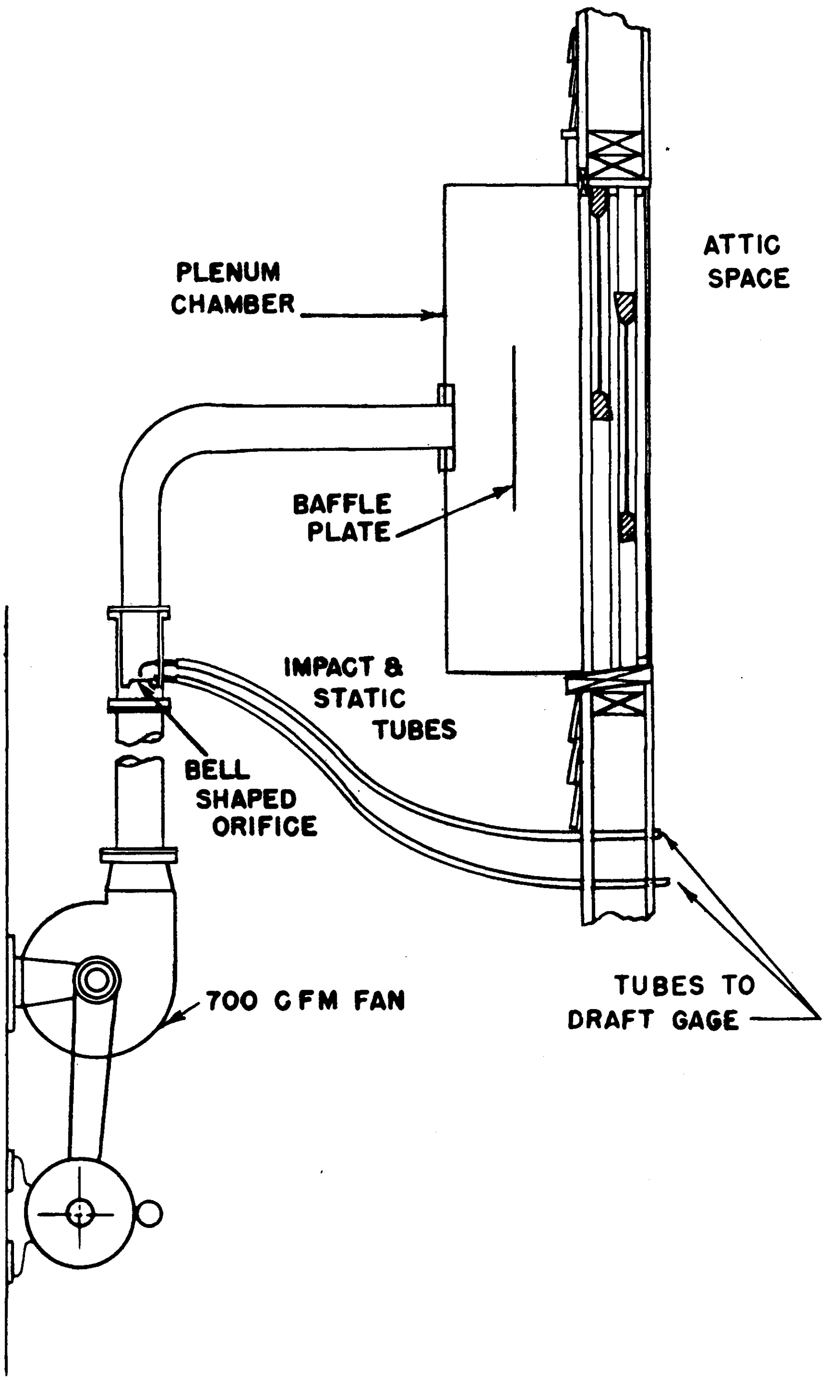

Figure 13. Sectional view of attic ventilator

in the bungalow rooms, and in the test walls. Figure 14 shows the thermocouple stations within Room 2 of the test bungalow. Four thermocouples were located in each test wall, as follows: one on the interior surface of the plaster, one on the cold side of the insulating board lath, one on the warm side of the sheathing, and one on the cold side of the sheathing. They were placed midway between the studs at approximately one-half the wall height.

Permanent leads for 60 thermocouples were connected between stations and an instrument panel in the operator's room. By an arrangement of switches 48 of these could be connected to automatic recorders; thus, all temperatures could be taken by a manually-operated potentiometer.

To measure the relative humidities of the air within the bungalow and attic, a wet- and dry-bulb apparatus was used. It was comprised of two thermocouples, each mounted in a glass tube with the beaded end extending into a solid brass tip of the same diameter as the glass tube. The brass tip of the wet-bulb thermometer served to give a good

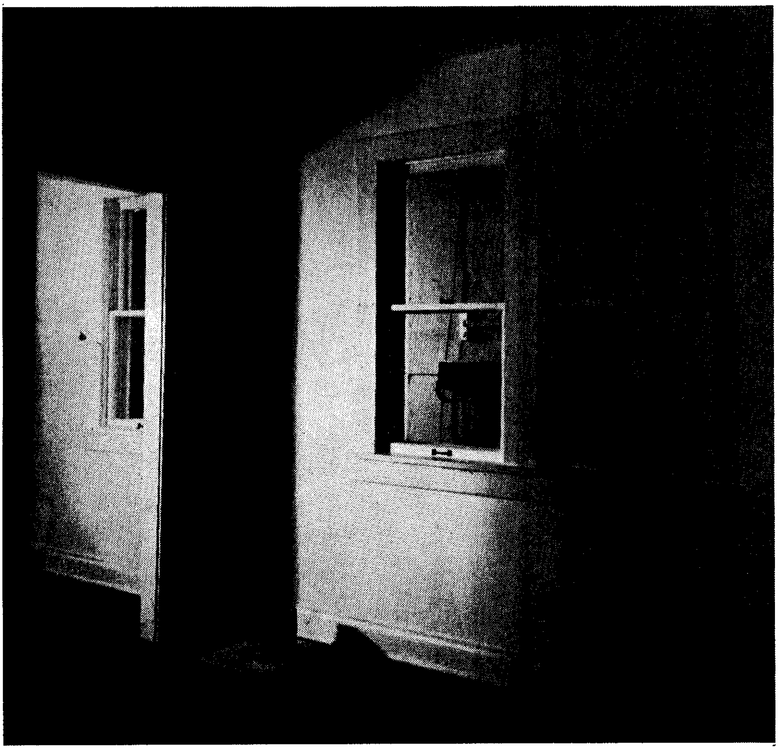

Figure 14. Interior view of finished Room 2 within test bungalow showing thermocouple stations, heating duct, and double windows

thermal contact between the thermocouple and wicking material. Water was fed to the wick of the wet-bulb thermometer from a constant level water reservoir. An electric fan was placed behind the apparatus to obtain sufficient air velocity for accurate wet-bulb temperatures.

The moisture content of the test wall sections and other parts of the bungalow was obtained by the use of a commercial type of electric moisture meter which measured the comparative electrical conductivity of a wood or fiber material, which is an index of moisture content. The instrument was calibrated for use on insulating board.

The rate of air flow was determined by a calibrated orifice with the aid of a standard Pitot tube and draft gage.

TEST RESULTS

All of the test results will be discussed under three separate divisions, as follows: (1) results pertaining to moisture conditions within the walls; (2) results pertaining to attic ventilation required to prevent condensation of moisture on the attic roof boards; and (3) results pertaining to attic air temperatures as related to outdoor temperatures.

Test results of the first two studies included in this section were obtained during the 66-day period of operation. During this time the test bungalow was subjected to continuous operation under the following conditions: outside air was maintained between 0 F and —10 F; inside air was maintained at 70 F and 40 per cent relative humidity. Results of the third study in this section, as mentioned above, were obtained from the conductance of a special series of tests.

Wall Moisture Study

Two general methods were used to determine the amount of moisture accumulated throughout the various parts of the structures. (1) Exposed surfaces and interior sections were inspected visually to note the accumulation of frost and ice; (2) the gain in moisture content by different members of the structure was taken with an electric moisture gage.

Results after 66-day test period—After continuous operation for a period of 66 days all exterior walls were removed from the test bungalow and examined. No changes in operating air temperatures either inside or outside the test bungalow were made during this inspection period. A comprehensive summary covering results of tests on moisture content of the various materials in each wall and notations on frost accumulation on the siding is contained in Table III. In this table column 1 refers to the group and code numbers of the wall panels. The letters identify the type of wall as shown in Figure 10, and the number prefix refers to its location in the test bungalow as shown in Figure 3. The moisture contents given in columns 2 through

Table III. Wall Moisture Study—Moisture Content and Frost Conditions at End of 66-Day Test Period—Continued

Wall No.	Moisture Content (Per Cent by Weight-Moisture Meter Reading)						Frost Accumulation on Siding Inner Surface
	Lath	Sheathing		Siding			
	Cold side	Cold side	Warm side	Top board	Middle board	Bottom board	
Group 4	Walls with treated lath having a MEDIUM-LOW permeability rate of 1.16 and sheathing having a HIGH permeability rate of 51.8						
6-F	13.3	6.5	5.4	9.6	9.5	8.8	No frost accumulation
13-F	14.9	....	5.4	8.4	8.9	8.2	No frost accumulation
Group 5	Wall with plain lath having a HIGH permeability rate of 69.9 and sheathing having a LOW permeability rate of 0.44						
12-G	6.6	6.6	7.6	10.1	6.4	7.5	Heavy frost accumulation on top board along joint at top of wall section. Middle and bottom boards clear
Group 6	Wall with plain lath having a HIGH permeability rate of 69.9 and sheathing having a MEDIUM permeability rate of 3.70						
15-H	5.9	9.2	6.9	16.5	8.9	6.4	Heavy frost accumulation on upper surface of top board. Middle and bottom boards clear
Group 7	Wall with plain lath having a HIGH permeability rate of 69.9 and sheathing having a HIGH permeability rate of 51.8						
14-I	6.4	12.3	7.9	17.0	20.0	16.1	Heavy frost accumulation of approximately 3/32-inch thickness on surface of top board. Only slight frost accumulation on middle and bottom boards

Table III. Wall Moisture Study—Moisture Content and Frost Conditions at End of 66-Day Test Period

Wall No.	Moisture Content (Per Cent by Weight-Moisture Meter Reading): Lath, Cold side	Sheathing, Cold side	Sheathing, Warm side	Siding, Top board	Siding, Middle board	Siding, Bottom board	Frost Accumulation on Siding Inner Surface
Group 1	Walls with plain lath and paper barrier having a LOW permeability rate of 0.09 and with sheathing having a LOW permeability rate of 0.44						
2-A	12.6	....	5.4	7.9	8.1	7.9	No frost accumulation
10-A	....	6.1	....	9.0	8.0	6.7	No frost accumulation
1-B	13.9	6.2	5.4	7.9	8.5	6.4	No frost accumulation
3-B	16.1	....	5.4	8.2	7.4	8.4	No frost accumulation
Group 2	Walls with treated lath having a MEDIUM-LOW permeability rate of 1.16 and sheathing having a LOW permeability rate of 0.44						
8-C	14.9	7.2	5.4	9.6	9.5	7.1	No frost accumulation
9-C	16.2	6.5	5.4	10.2	7.9	7.2	No frost accumulation
4-D	11.4	6.7	5.7	10.6	8.3	7.0	Slight frost accumulation on top board for half of length. Middle and bottom boards clear
11-D	15.9	6.0	5.6	9.5	6.7	6.6	No frost accumulation
Group 3	Walls with treated lath having a MEDIUM-LOW permeability rate of 1.16 and sheathing having a MEDIUM permeability rate of 3.70						
5-E	17.9	6.4	5.4	8.3	7.8	7.9	No frost accumulation
7-E	13.5	7.0	6.5	13.0	11.6	9.5	Slight frost accumulation on top board along joint at top of wall section. Middle and bottom boards clear

7 were obtained with an electric moisture gage. The figures in column 3 represent an average of these readings taken from top to bottom on the cold side of the sheathing. The moisture content readings of the cold side of the lath and the warm side of the sheathing were taken at the mid-height level of the wall section. The last column consists of notes based on visual inspection of frost accumulation on the inner surface of the siding. These notations on frost were limited to the inner surface of the siding because the temperature gradient throughout all of the walls in the test bungalow was such that the surfaces in the inner stud space were at temperatures above freezing. The lath and sheathing facing this inner stud space were examined for moisture content as shown in the table in columns 2 and 4, respectively.

The walls listed in Table III are divided into seven groups in accordance with the different combinations of wall construction used.

Group 1 included four walls (2-A, 10-A, 1-B, and 3-B) containing interior and exterior materials both of low permeability rates. With respect to these four walls there was no frost accumulation on the inner surface of the siding boards. The moisture content of the siding ranged from 6 to 9 per cent which is safe for this type of exterior construction. The moisture content of the lath ranged from 12.6 to 16.1 per cent, a condition which would be expected in these walls inasmuch as a very high vapor resistant material in the form of an asphalt coated paper was located on the cold side of the lath. Moisture from the inside passed through the lath and was stopped by this barrier, which tended to build up a high equilibrium moisture content within the lath.

Walls constructed with lath having a medium-low vapor permeability rate of 1.16 and sheathing having a low permeability rate of 0.44 are shown in Group 2 of Table III. These included Walls 8-C, 9-C, 4-D, and 11-D. The vapor barrier on the lath consisted of one coat of A-21 primer, plus one coat of C-20 flat white paint. As is apparent from the results, there was no frost accumulation on the inner surface of the siding for three of these four walls. Wall 4-D showed a slight frost accumulation on the top siding board for a small portion of its length, while all other boards were clear. However, this frost accumulation was not appreciable and should not result in any serious condensation problem.

Group 3 consisted of two walls, 5-E and 7-E. These were constructed with treated lath having a medium-low permeability rate of 1.16 and sheathing having a medium permeability rate of 3.70. It should be noted that there was no evidence of frost accumulation on the inner surface of the siding of Wall 5-E and only a slight line of frost appeared on the top siding board of Wall 7-E. The moisture content of the siding was comparatively low, whereas the moisture content of the lath was high as would be expected when a good vapor barrier is located on the cold side of the lath.

Group 4 included Walls 6-F and 13-F constructed with treated lath having a medium-low permeability rate of 1.16 and sheathing having a high permeability rate of 51.8. These walls were constructed in accordance with the principle of a medium-low vapor permeability interior finish and a vapor porous exterior finish. As noted in Table III, no frost accumulation appeared on the inner surface of the siding of either of the two walls, which indicated that the moisture was effectively retarded by the interior vapor barrier.

Walls 12-G in Group 5, 15-H in Group 6, and 14-I in Group 7 were all constructed with lath having a high permeability rate of 69.9 and with sheathing having permeability rates varying as follows: 0.44 for Wall 12-G, 3.70 for Wall 15-H, and 51.8 for Wall 14-I. For all walls of these last three groups there was a heavy accumulation of frost on the top siding board. This occurred along the joint at the top of the wall section and was independent of the type of sheathing used. The effect of the type of sheathing in combination with a vapor porous lath is indicated by the results on moisture content shown in columns 5, 6, and 7 of Table III. For Wall 12-G in which a sheathing of high vapor resistance was used, the siding moisture content ranged from a low of 6.4 to a high of 10.1 per cent. Using a sheathing of medium permeability, such as for Wall 15-H in Group 6, the moisture content of the top siding board increased to 16.5 per cent. When a vapor porous sheathing was used, as for Wall 14-I in Group 7, the siding took on moisture ranging to a high of 20 per cent. For the walls in these last three groups the amount of moisture entering into the inner stud space was the same in each case. With a vapor resistant sheathing the moisture was retarded in passing through and was in part absorbed by the structural members themselves, or it passed through any openings occurring at the joints of the structure. In walls in which the sheathing was less vapor resistant, there was the opportunity for the vapor to flow through the material until it reached a cold surface where frost and condensation occurred. Irrespective of whether the moisture is taken up by the structural members, such as the studdings and plates, or by the exterior facing, such as the siding, both may be considered serious conditions, and construction methods should be such as to reduce the chance of vapor entering into the stud space.

Conclusions from wall moisture study—Results have shown that when the vapor resistant lath on the inside surface of a wall possesses a permeability rate of 1.16 grains or less, the vapor passage is sufficiently reduced so that no serious condensation problem may be expected within the wall. This is true for exterior wall constructions having either high or low permeability as used in this investigation and is in accordance with conclusions reached from smaller scale tests which were reported previously in Bulletin No. 22.[8] On the basis of

[8] Rowley and Lund, *Vapor Transmission Analysis of Structural Insulating Board.*

the results of these tests, together with previous experience, the vapor permeability of an acceptable interior barrier to be used in standard residential construction should be 1.25 grains, or lower, per square foot per hour per inch of mercury vapor pressure difference.

Attic Ventilating Requirements

Simultaneous with the wall moisture study, investigations were conducted in the attic to determine the volume of ventilating air required to prevent the formation of frost on the cold attic surfaces. Outside air was metered through a calibrated orifice, supplied through one of the attic windows, and exhausted by gravity through an open window located in the opposite gable. These studies were conducted under five different attic constructions. The principal objective was to determine the volume of ventilating air in cubic feet per hour required to prevent any serious accumulation of moisture or frost on the various building materials used in the attic construction.

The results of this study over the extended 66-day test period are summarized in Table IV. Column 1 contains brief descriptions of the five different ceiling and attic constructions investigated. Columns 2 through 7 show the test operating conditions regarding attic ventilation and inside and outside air temperatures, while the last column contains the principal results of the test; namely, notations concerning visual observations of frost accumulation on the various materials used in ceiling and roof constructions.

Construction 1 consisted of a ceiling finish of ½-inch plaster over 1-inch structural insulating board lath with no vapor resistant treatment, a loose-fitting attic door, and a conventional uninsulated roof. This and the four other constructions are shown in Figure 8. Two different operating conditions were involved in tests under this construction. The first consisted of no ventilation being supplied to the attic. Under this condition frost accumulated on the roof board as would be expected with such a construction and an unventilated attic. The second operating condition consisted of supplying ventilation at the rate of 4,130 cubic feet per hour, which was equivalent to approximately 1¾ air changes per hour. This was considered a comparatively high rate of ventilation and of a magnitude which would be difficult to attain in actual structures where the ventilation is obtained entirely by natural means through louvres located in the gable ends of the attic. At this ventilating rate it was found that the frost accumulation from the previous run remained on the roof boards. Although selected areas were scraped free of frost at the start of each test run, observations revealed that frost continued to accumulate on these areas. It was not possible to establish a safe operating ventilating rate under this construction. The capacity of the ventilating unit was limited to 1¾ air changes per hour; however, this was considered high and constituted a value which in actual practice would be difficult to attain

Table IV. Attic Ventilating Requirements To Prevent Frost Accumulation for Different Types of Ceiling and Attic Construction

Type of Construction	Attic Ventilation			Inside Air Temperature		Outside Air Temperature (Deg F)	Notations on Frost Accumulation
	Cubic feet per hour	Air changes per hour	Cubic feet per hour per sq ft attic floor area	Dry-bulb	Dew-point		
Construction 1—No vapor barrier, no added insulation, loose-fitting attic door	0	0.00	0.0	66.0	45.4	0.0	Frost accumulation on roof boards
	4,130	1.72	10.6	68.5	45.7	—8.0	Frost accumulation remained on roof boards after a 9-day run at this ventilating rate
							Necessary ventilating rate to prevent frost accumulation was not established
Construction 2—No vapor barrier, no added insulation, rubber gasket around attic door	4,090	1.70	10.4	69.0	44.2	—9.0	No frost accumulation on observed knots, nails, or roof boards*
	3,720	1.54	9.6	68.0	44.6	—7.0	No frost accumulation
	3,570	1.48	9.0	69.0	45.2	—5.0	No frost accumulation
	3,450	1.44	8.8	68.5	46.7	—8.0	No frost accumulation
	2,700	1.12	6.9	68.0	45.1	—8.0	Frost accumulation on knots and nails
							Necessary ventilating rate is between 2,700 and 3,450 cfh
Construction 3—Two coats of paint on ceiling plaster as vapor barrier, no added insulation, rubber gasket around attic door	2,615	1.09	6.2	68.5	45.4	—5.5	No frost accumulation on knots, nails, or roof boards
	2,090	0.87	5.1	69.0	42.5	—4.0	No frost accumulation
	1,565	0.65	3.8	69.0	42.8	—5.5	Frost accumulation on nails only
							Necessary ventilating rate is between 1,565 and 2,090 cfh

* Selected areas in roof boards, including knots and nail shanks extending through roof boards, were scraped clear of frost after each test. These specific areas were used for observation.

Table IV. Attic Ventilating Requirements To Prevent Frost Accumulation for Different Types of Ceiling and Attic Construction—Continued

Type of Construction	Attic Ventilation			Inside Air Temperature		Outside Air Temperature (Deg F)	Notations on Frost Accumulation
	Cubic feet per hour	Air changes per hour	Cubic feet per hour per sq ft attic floor area	Dry-bulb	Dew-point		
Construction 4—Two coats of paint on ceiling plaster as vapor barrier, ½-inch insulating board on floor joists, rubber gasket around attic door	1,610	0.67	4.5	69.0	45.4	—7.0	Frost accumulation on nails only
	1,790	0.75	4.6	69.0	44.3	—6.0	Frost accumulation on nails only
	2,090	0.87	5.4	69.0	44.9	—5.5	No frost accumulation
							Necessary ventilating rate is between 1,790 and 2,090 cfh
Construction 5—Two coats of paint on ceiling plaster as vapor barrier, ½-inch insulating board on under side of roof rafters, rubber gasket around attic door	1,220	0.51	3.1	68.0	44.4	—4.0	Frost accumulation on roof boards at eaves
	1,945	0.81	4.9	68.0	46.6	—5.0	Frost accumulation on roof boards at eaves
	3,020	1.26	7.7	68.0	46.4	—4.0	No frost accumulation at eaves
							Necessary ventilating rate is between 1,945 and 3,020 cfh

by natural ventilation. Consequently, if a particular construction were found to require such a high ventilating rate, then corrections in the construction should be recommended as a more practical and economical means of reducing vapor problems in the attic. Construction 1, therefore, was not considered a satisfactory type from the standpoint of vapor transmission into the attic, and condensation problems could be expected in a home having this type of construction even though precautions had been taken to provide louvres in the gable ends of the attic for ventilating purposes.

Construction 2 was identical to Construction 1, except that a rubber gasket was provided around the attic door in order to reduce the passage of vapor through the cracks. Observations were made on selected areas in the roof boards, such as on the knots and nail shanks extending through the boards, the particular areas of which were colder than the other surfaces in the attic construction. As shown under Construction 2 in Table IV, the ventilation was gradually reduced from the high rate attained under Construction 1 until the rate of 2,700 cfh was reached. At this rate frost began to accumulate on the knots and nail shanks. However, the next higher rate of 3,450 cfh was sufficient to prevent the formation of frost. No attempts were made to obtain an exact limiting rate but merely to obtain, by this trial and error method, an approximate value. Under this construction the desirable ventilating rate was found to be between 2,700 and 3,450 cfh or, in nominal figures, approximately 1¼ air changes per hour.

Construction 3 was the same as Construction 2, except that two coats of paint were applied to the ceiling plaster. Under this construction it was possible to reduce further the ventilating requirements to a point where the ventilating rate required to prevent frost was established between 1,565 and 2,090 cfh. No frost accumulated at 2,090 cfh, but it began to accumulate when the rate was reduced to 1,565 cfh. Thus, by applying a vapor barrier in the form of an oil paint to the ceiling plaster, a ventilating requirement of approximately three-fourths air changes per hour resulted.

Construction 4 was identical to Construction 3 but for the application of ½-inch insulating board to the tops of the ceiling joists; i.e., providing an attic floor of insulating boards. This application did not appreciably increase the vapor resistance of the ceiling, but had the effect of lowering the coefficient of heat transmission through the ceiling. This, in effect, tended to result in lower temperatures within the attic. Under this construction there was very little difference in the ventilating requirements compared to Construction 3.

Construction 5 differed from Construction 4 only in the location of the added insulation within the attic. Under this last construction the ½-inch insulating board was removed from the tops of the ceiling or attic floor joists and applied to the under side of the roof rafters. In cases where the attic space is planned for future living quarters, a construction of this type would be used. The ventilating requirement under this last construction was established within the range of from ¾ to 1¼ air changes per hour.

Conclusions from attic ventilation study—A summary of the amount of attic ventilation required to prevent the accumulation of frost under the five different attic constructions investigated is presented in Table V. The method of measurement was that of visual observation of frost accumulation within the attic at the different trial

Table V. Summary of Attic Ventilating Requirements To Prevent Frost Accumulation for Five Different Attic Constructions—Inside Air 70 F and 40 Per Cent Relative Humidity; Outside Air –5 F

Attic and Ceiling Construction	Safe Ventilating Rate		
	Cubic feet per hour	Attic air changes (No. per hour)	Cubic feet per hour per sq ft of ceiling area
Construction 1—No vapor barrier, no added insulation, loose-fitting attic door	Rates not established		
Construction 2—No vapor barrier, no added insulation, rubber gasket around attic door	2,700 to 3,450	1.12 to 1.44	6.9 to 8.8
Construction 3—Two coats of paint on ceiling plaster as vapor barrier, no added insulation, rubber gasket around attic door	1,565 to 2,090	0.65 to 0.87	3.8 to 5.1
Construction 4—Two coats of paint on ceiling plaster as vapor barrier, ½-inch insulating board on floor joists, rubber gasket around attic door	1,790 to 2,090	0.75 to 0.87	4.6 to 5.4
Construction 5—Two coats of paint on ceiling plaster as vapor barrier, ½-inch insulating board on under side of roof rafters, rubber gasket around attic door	1,945 to 3,020	0.81 to 1.26	4.9 to 7.7

rates of attic ventilation specified. Inasmuch as this essentially was a trial and error method, it should again be noted that no exact limiting values were found. The results are shown in the form of two figures, both approximate, the lower being the ventilating rate at which frost accumulation did appear and the higher being the ventilating rate which resulted in the elimination of frost accumulation.

With respect to a construction similar to Construction 1 in which the ceiling was untreated and the attic door loose-fitting, it was concluded that it would be difficult to prevent moisture condensation and frost accumulation by ventilation alone. From the results of the tests it was shown that a ventilating rate of 1¾ changes of air per hour was not sufficient for such purposes.

A loose-fitting attic door was found to be a serious source of vapor leakage into the attic. When the attic door was fitted with a rubber gasket to form a tight seal against vapor leakage, it was then possible to determine the necessary rate of attic ventilation of approximately 1¼ air changes per hour as a value which did prevent frost accumulation. This applied as well to a construction, such as that of Construction 2, in which no vapor resistant treatment was applied to the ceiling plaster.

If the construction consisted of a ceiling painted with some type of a vapor resistant coating, such as a standard interior finish oil paint, and if the attic door were weather stripped (i.e., fitted with a rubber gasket) as in Constructions 3, 4, and 5, it was concluded that a ventilating range of from approximately three-fourths to one air change per hour should be sufficient to prevent any frost from accumulating within the attic during extended cold periods.

Attic Air Temperatures

The last principal factor of this investigation was concerned with the relationship between attic ventilation and attic temperatures. In structures where the attic is ventilated with outside air, the question has arisen as to what method should be used in calculating heat loss through the ceiling area. The methods of calculation for unventilated attics have been well established, but such is not the case with respect to ventilated attics. Most residential structures being built today in the northern temperature zone are supplied with louvres in the gable ends of the attic to obtain ventilation. This is generally regarded as good construction and serves as a precaution against problems of moisture condensation within the attic. For these structures it is important to know what method of heat loss calculation can be applied to determine the transfer of heat through the ceiling.

Some investigators have suggested that in cases where the attic is ventilated, the attic air temperature may be assumed to be equal to the outside air temperature. The ceiling heat loss would then be calculated by multiplying the ceiling area by the coefficient of heat transmission through the ceiling and by the temperature difference between the inside and the outside air. This method would not give credit for any insulating value of the roof. Consequently, the results of such a calculation would show a heat loss value which would be higher than the actual case. But, the argument has been advanced that it is more accurate to use this method than to use the standard method of calculation for an unventilated attic where full credit is allowed for the roof construction. Very little is yet known of the relationship between attic air temperatures and outside air temperatures at specific rates of attic ventilation. It is hoped that this investigation will contribute experimental data on this point.

A special series of tests were conducted for both Construction 4 and Construction 5, which have been previously described and are shown in Figure 8. In these tests the inside air temperature was maintained at approximately 70 F with relative humidity at 40 per cent, while the outside air temperature was maintained at approximately —6.5 F. Tests were conducted at no ventilation, 1,500, 3,000, and 4,200 cubic feet of air per hour.

Thermocouples were located within the cold room at levels of 2 feet above the bungalow roof and 5 feet above the floor at the east and west sides of the bungalow. In the open attic space three thermocouples were located at different elevations above each of the three rooms. One was located 2 inches above the attic floor joists, one at mid-height, and one at 7 feet above the attic floor. One thermocouple station was also provided in the northwest corner of the attic at a level of 1 foot above the floor joists, which with the others resulted in a total of 10 set thermocouple stations for temperature measurements within the attic. In addition, two thermocouples were provided for exploring different parts of the attic in order to determine the temperature variations that might occur at points other than the set thermocouple stations. Thermocouples were also established in each of the three rooms below.

A detailed record of these tests is shown in Table VI for Construction 4 and in Table VII for Construction 5, respectively. The test for each different ventilating rate was continued for a sufficient length of time to insure equilibrium temperature conditions.

In Construction 4 the temperature variation from room to room at corresponding elevations was not considered great. At the mid-height level the temperatures were found to be substantially the same throughout the attic. The greatest variation occurred at the stations located 2 inches above the attic floor joists where a maximum variation of approximately 4.5 F between Rooms 1 and 2 was obtained.

In Construction 5 the attic temperatures were approximately 12 F higher than those in Construction 4, due to the location of the added insulation. At the mid-height level a maximum variation of approximately 2.5 F occurred between the three rooms. Again, the greatest variation appeared at the stations located 2 inches above the attic floor joists where a maximum variation of approximately 8 F between Rooms 1 and 2 was obtained. This large variation was due mostly to the fact that the thermocouple station above Room 2 was located near the entrance of outside ventilating air. Results shown in column 9 of Table VII represent the temperatures at the low point in the attic directly in the path of this ventilating air.

Exploration at other points within the attic, such as in the corner areas and near the eaves, did not reveal any greater temperature differences than existed from room to room as measured at the set thermocouple stations.

To show clearly the attic air temperatures as affected by different rates of attic ventilation, the results of the detailed tables previously shown (Tables VI and VII) have been averaged at equilibrium conditions, and the results of these averages have been plotted in the form of curves which are presented in Figures 15 and 16 for Constructions 4 and 5, respectively. In Figure 15 for Construction 4 the inside air temperature was maintained at 70 F, with maximum fluctuations of 0.5 F, for the four different ventilating conditions. Likewise, for these

Table VI. Detailed Record of Tests Showing Relationship between Attic Air Temperatures and Inside and Outside Air Temperatures at Different Rates of Ventilation for Construction 4 (Rubber Gasket around Attic Door, Ceiling Plaster Painted, ½-Inch Insulating Board on Attic Floor Joists)

Time	Cold Room Air Temperature, Deg F			Attic Air Temperature, Deg F										Inside Air Temperature, Deg F		
				Room 1				Room 2			Room 3					
Hours of Test	2 ft above roof	5-ft level, west side	5-ft level, east side	1-ft level, northwest corner	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	Room 1	Room 2	Room 3
							No Ventilation									
1	−3.0	−4.0	−3.5	14.5	15.5	14.0	15.0	14.5	14.0	14.5	15.0	13.5	13.5	70.5	70.5	70.5
2	−4.0	−4.0	−4.0	14.0	15.0	13.5	14.0	13.5	13.5	14.0	14.5	13.5	13.5	70.0	70.0	70.5
3	−4.0	−5.0	−4.0	13.0	15.0	13.5	14.0	13.5	13.5	13.5	13.5	12.5	13.0	70.0	71.0	70.5
4	−5.0	−5.0	−5.0	12.5	14.0	12.5	13.5	13.5	13.0	13.5	13.5	13.0	13.0	70.0	70.0	70.5
5	−5.0	−5.5	−5.5	13.0	13.5	12.5	13.0	13.0	12.5	13.0	13.0	12.0	12.0	71.0	70.0	70.5
6	−5.0	−6.0	−5.0	13.0	13.5	12.5	13.0	12.5	12.5	13.0	13.0	12.0	12.5	69.0	70.0	70.5
7	−5.0	−6.0	−5.0	13.0	13.0	12.0	13.0	12.0	12.0	12.5	13.0	12.0	12.0	69.0	70.0	70.5
8	−6.0	−6.0	−6.0	12.0	12.5	11.5	12.5	12.0	12.0	12.5	12.0	11.0	11.5	69.0	70.0	70.0
9	−6.0	−6.0	−6.5	12.0	13.0	12.0	12.5	12.0	12.0	12.5	12.0	11.0	12.0	71.0	72.0	70.5
10	−6.0	−6.0	−5.5	12.0	13.0	12.0	12.5	12.0	12.0	12.5	12.5	11.5	11.5	69.0	70.0	69.0
11	−6.0	−6.5	−5.5	12.0	13.0	12.0	12.0	12.0	12.0	12.0	12.5	11.5	12.0	69.5	70.0	69.0
							1,500 cfh Attic Ventilation									
1	−6.0	−6.5	−5.5	12.0	13.5	11.0	12.5	10.0	11.5	12.0	12.5	11.0	11.5	69.5	70.0	69.5
2	−6.0	−6.0	−6.0	11.0	13.0	11.0	11.0	9.5	11.5	11.5	12.0	10.5	11.0	70.5	70.5	69.0
3	−6.0	−6.0	−6.0	11.0	12.5	11.0	11.0	9.0	10.5	11.5	10.5	10.0	10.5	70.0	70.0	69.0
4	−6.0	−6.0	−6.0	10.5	12.5	10.5	10.5	8.5	10.5	11.5	10.5	9.5	10.0	69.5	70.5	69.0
5	−6.0	−6.5	−6.0	10.0	12.0	10.0	11.0	9.0	10.0	11.0	10.0	10.0	10.0	70.0	70.0	70.0
6	−5.0	−6.0	−6.0	10.5	12.0	10.0	10.5	8.0	10.5	10.5	10.0	10.0	10.0	70.5	69.0	70.5
7	−5.5	−6.5	−5.5	11.0	12.0	11.0	11.0	9.5	11.5	11.0	10.5	10.5	11.0	69.0	70.0	70.0
8	−6.0	−6.5	−6.0	11.0	12.5	10.0	10.5	8.0	10.5	11.0	10.0	10.0	10.0	70.5	70.5	69.5

Table VI. Detailed Record of Tests Showing Relationship between Attic Air Temperatures and Inside and Outside Air Temperatures at Different Rates of Ventilation for Construction 4 (Rubber Gasket around Attic Door, Ceiling Plaster Painted, ½-Inch Insulating Board on Attic Floor Joists)—Continued

Time	Cold Room Air Temperature, Deg F			Attic Air Temperature, Deg F										Inside Air Temperature, Deg F		
				Room 1				Room 2			Room 3					
Hours of Test	2 ft above roof	5-ft level, west side	5-ft level, east side	1-ft level, northwest corner	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	Room 1	Room 2	Room 3
							1,500 cfh Attic Ventilation—Continued									
9	—6.0	—7.0	—6.0	10.5	12.0	9.5	10.0	8.0	9.5	10.0	10.5	9.5	9.5	69.5	70.0	70.5
10	—6.0	—7.0	—6.0	10.0	12.0	9.0	10.0	8.0	9.5	10.5	9.5	9.0	9.0	70.0	69.5	70.0
11	—6.0	—7.0	—6.0	10.0	11.0	9.5	10.0	8.0	10.0	10.5	10.5	9.5	9.5	70.0	70.0	70.0
12	—6.5	—7.0	—6.0	9.5	11.5	10.0	10.0	8.0	10.0	10.0	10.0	9.5	10.0	69.5	70.0	70.5
							3,000 cfh Attic Ventilation									
1	—6.5	—7.0	—6.0	9.0	12.0	9.0	9.5	6.5	9.0	10.0	10.5	9.5	9.0	71.0	70.0	70.0
2	—6.5	—7.5	—6.0	9.5	10.5	9.0	9.5	6.0	9.0	10.0	10.0	9.0	9.0	69.5	70.0	70.0
3	—6.0	—7.5	—6.0	9.0	11.0	9.0	9.0	6.0	9.0	9.5	9.5	9.0	8.5	70.0	70.0	70.5
4	—6.5	—8.0	—6.5	8.5	10.0	8.5	9.0	6.0	9.0	9.0	10.0	9.0	9.0	69.5	70.0	70.5
5	—6.0	—7.5	—6.0	9.0	10.0	9.0	9.0	6.0	9.0	10.0	10.0	9.0	9.5	69.5	70.0	71.0
6	—6.5	—7.5	—6.0	9.0	10.5	9.0	9.0	6.0	9.0	9.5	10.5	9.5	9.0	70.0	69.0	70.0
7	—6.0	—8.0	—6.0	9.0	10.5	9.0	9.0	6.0	9.0	9.5	10.0	9.0	9.0	69.0	69.5	69.5
8	—6.0	—7.5	—5.5	9.0	10.5	8.5	9.0	7.0	9.5	10.0	10.0	9.0	9.5	69.0	69.5	70.0
							4,200 cfh Attic Ventilation									
1	—5.5	—7.0	—6.0	9.0	11.0	8.5	9.0	5.0	9.0	9.0	8.5	9.0	9.0	70.5	70.0	70.0
2	—5.0	—7.0	—6.0	8.5	10.0	9.0	9.0	5.5	9.0	9.5	9.0	9.0	9.0	70.0	71.0	70.0
3	—5.5	—7.0	—5.5	9.0	9.5	8.5	9.0	5.0	9.0	9.0	9.0	9.0	9.0	70.0	70.0	70.5
4	—5.5	—7.0	—5.5	8.5	10.5	9.0	9.0	6.0	8.5	9.0	9.0	8.5	9.0	70.5	70.5	70.5
5	—5.5	—7.0	—5.5	9.0	10.0	9.0	9.0	5.5	9.0	9.5	8.5	9.0	9.0	69.0	70.5	70.0
6	—6.0	—7.0	—5.5	9.5	11.0	9.0	10.0	9.5	9.5	10.5	10.0	9.0	9.5	70.0	69.5	69.5

Table VII. Detailed Record of Tests Showing Relationship between Attic Air Temperatures and Inside and Outside Air Temperatures at Different Rates of Ventilation for Construction 5 (Rubber Gasket around Attic Door, Ceiling Plaster Painted, ½-Inch Insulating Board on Under Side of Roof Rafters)

Time	Cold Room Air Temperature, Deg F			Attic Air Temperature, Deg F										Inside Air Temperature, Deg F		
				Room 1				Room 2			Room 3					
Hours of Test	2 ft above roof	5-ft level, west side	5-ft level, east side	1-ft level, northwest corner	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	Room 1	Room 2	Room 3
							No Ventilation									
1	—1.5	—3.0	—2.0	30.5	31.0	30.0	31.0	28.5	30.0	31.0	29.5	30.0	30.0	70.0	72.0	73.0
2	—2.5	—3.0	—3.0	29.0	31.0	29.5	30.0	28.5	29.5	30.5	29.0	29.5	29.5	71.0	72.0	71.0
3	—3.0	—4.0	—3.0	28.5	31.0	29.0	29.5	28.0	29.0	29.5	28.5	29.0	29.0	69.0	71.0	71.0
4	—3.5	—4.5	—3.5	28.0	29.5	28.0	29.0	27.0	28.0	29.0	27.0	29.0	28.0	69.0	70.5	70.0
5	—3.5	—5.0	—4.0	27.5	29.5	29.0	28.5	26.5	27.5	28.5	27.5	28.0	28.0	70.0	70.5	71.0
6	—4.5	—5.0	—5.0	27.0	29.0	28.0	28.0	26.0	27.0	28.0	27.0	28.0	27.0	70.0	70.0	70.0
7	—5.0	—5.5	—5.0	26.5	28.0	27.0	27.5	26.0	27.0	27.5	26.0	27.0	27.0	70.0	70.0	70.0
8	—5.5	—6.0	—5.5	26.0	28.0	26.5	27.0	25.0	26.0	27.0	25.0	27.0	26.0	70.0	69.0	69.0
9	—5.5	—6.5	—6.0	25.0	28.0	26.0	27.0	25.0	26.0	27.0	28.0	26.0	27.0	70.0	69.0	69.0
10	—4.5	—5.0	—5.0	26.0	27.0	26.0	26.5	25.0	26.0	26.5	25.0	26.0	26.0	69.0	70.0	70.0
11	—5.5	—6.0	—5.5	25.0	28.0	26.0	26.5	25.0	26.0	26.5	25.0	27.0	26.0	70.0	70.0	70.0
12	—6.0	—7.0	—6.0	25.0	28.0	26.0	26.0	24.0	25.0	26.0	25.0	27.0	25.5	69.5	70.0	70.0
13	—7.0	—7.0	—7.0	25.0	27.0	25.5	26.0	24.0	25.0	26.0	24.0	27.0	25.0	70.0	70.0	70.0
14	—7.0	—7.5	—6.5	24.5	27.0	25.0	25.5	24.0	25.0	25.5	24.0	27.0	25.0	70.0	70.0	70.5
15	—7.0	—7.0	—6.5	24.5	27.0	25.0	25.5	23.0	25.0	25.5	24.5	27.0	25.0	69.5	69.5	70.0
							1,500 cfh Attic Ventilation									
1	—6.0	—7.0	—6.0	20.0	22.0	20.0	21.0	16.5	20.0	20.5	19.0	22.5	20.0	69.0	70.0	71.0
2	—6.0	—7.5	—6.0	20.5	22.5	21.0	21.5	17.0	20.5	21.0	19.0	22.0	20.5	69.5	70.0	70.5
3	—5.5	—7.0	—6.0	20.5	23.0	21.5	21.5	17.5	21.0	21.5	19.0	22.5	21.0	69.0	69.0	70.0
4	—6.0	—8.0	—6.0	20.5	23.0	21.0	21.5	17.0	21.0	21.5	19.0	22.0	21.0	69.0	69.0	70.0

Table VII. Detailed Record of Tests Showing Relationship between Attic Air Temperatures and Inside and Outside Air Temperatures at Different Rates of Ventilation for Construction 5 (Rubber Gasket around Attic Door, Ceiling Plaster Painted, ½-Inch Insulating Board on Under Side of Roof Rafters)—Continued

Time	Cold Room Air Temperature, Deg F			Attic Air Temperature, Deg F										Inside Air Temperature, Deg F		
				Room 1				Room 2			Room 3					
Hours of Test	2 ft above roof	5-ft level, west side	5-ft level, east side	1-ft level, northwest corner	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	2 in. from floor joists	Mid-height level	7-ft level	Room 1	Room 2	Room 3
							3,000 cfh Attic Ventilation									
1	—6.5	—8.0	—6.5	19.0	22.0	19.0	19.5	14.0	18.5	19.0	19.0	21.5	19.0	70.0	70.0	70.0
2	—6.0	—7.5	—6.5	19.0	21.5	20.0	20.0	14.5	19.0	20.0	19.0	22.0	19.5	70.0	70.0	70.5
3	—6.0	—7.5	—6.0	19.0	21.5	20.0	20.5	15.0	19.5	20.0	19.0	22.5	19.5	70.0	70.0	70.5
4	—6.0	—7.5	—6.0	19.0	23.0	20.5	20.0	15.0	19.5	20.0	19.0	22.5	19.5	70.0	70.5	70.5
							4,200 cfh Attic Ventilation									
1	—6.0	—6.5	—6.0	24.0	27.0	25.0	25.0	17.0	23.0	23.0	22.0	27.0	24.0	69.5	70.0	70.0
2	—6.0	—6.5	—6.0	21.0	24.5	22.0	22.0	16.5	21.5	22.0	21.0	25.0	21.0	70.0	69.5	70.0
3	—5.0	—6.0	—5.0	21.0	24.0	22.0	22.0	16.0	21.0	21.0	21.0	24.5	21.0	69.5	70.0	70.0
4	—5.5	—6.5	—6.0	21.0	24.0	21.0	22.0	15.5	21.0	21.0	21.0	24.0	21.0	69.5	70.0	69.5
5	—5.0	—6.0	—5.5	20.0	23.0	20.0	21.0	15.0	20.0	20.5	20.0	23.0	20.0	70.0	70.0	70.0
6	—5.5	—6.0	—5.5	20.0	23.0	20.0	21.0	15.0	20.0	20.5	20.0	23.0	20.0	70.0	70.5	70.0
7	—5.5	—6.5	—5.5	20.0	23.0	20.0	20.5	15.0	20.0	20.0	20.0	23.0	19.0	70.0	70.0	70.0
8	—5.5	—6.5	—6.0	19.0	23.0	20.0	20.0	14.0	19.5	20.0	20.0	23.0	19.0	70.0	70.0	70.0
9	—6.0	—7.0	—6.0	19.0	22.0	20.0	20.0	14.0	19.0	19.0	20.0	22.0	19.0	69.5	69.5	69.0
10	—5.5	—7.0	—6.0	19.0	22.0	20.0	20.0	14.0	19.0	19.0	19.0	22.0	19.0	70.0	70.0	70.0
11	—5.5	—7.0	—5.5	19.0	22.0	20.0	20.0	14.0	19.0	19.0	19.0	23.0	19.0	70.0	70.0	70.0
12	—6.0	—7.0	—6.0	19.0	22.0	19.0	20.0	14.0	19.0	19.0	19.0	22.0	19.0	70.0	70.5	70.5
13	—6.0	—7.5	—6.0	19.0	22.0	19.0	20.0	14.0	19.0	19.0	19.0	22.0	18.0	70.0	69.5	69.5
14	—7.0	—8.0	—7.0	18.0	20.0	19.0	19.0	14.0	18.0	18.0	18.0	21.0	18.0	69.5	69.5	70.5
15	—6.0	—7.5	—6.0	18.5	21.0	19.0	19.5	14.0	19.0	19.0	19.0	22.0	18.5	70.0	70.0	70.0
16	—5.5	—8.0	—6.5	18.5	21.5	19.0	20.0	13.5	18.0	18.0	18.5	21.0	18.0	69.0	69.5	69.0
17	—6.0	—7.5	—6.0	18.5	21.5	19.0	20.0	14.0	19.0	19.0	19.0	21.5	18.5	69.5	70.5	70.0

same four test runs the cold room temperature was maintained at -6.5 F, with maximum fluctuations of 0.5 F. Since the inside air and the outside air temperatures were substantially constant during all of the test runs, the curve shows directly the effect of ventilation upon the attic air temperatures. At zero or no ventilation the attic air temperature was 12.1 F. When the ventilating rate was set at 1,500 cfh, the attic air temperature dropped to 9.8 F. This drop of 2.3 F was encountered because of the amount of ventilation supplied. A further increase in the ventilating rate to 3,000 cfh resulted in a lower attic air temperature of 9.1 F, which was equivalent to an over-all drop of 3 F. When the ventilating rate was increased again to 4,200 cfh, the resulting drop in attic air temperature was only 3.1 F.

In Construction 4 an interior finish of ½-inch plaster over 1-inch insulating board lath was applied to the ceiling, and the tops of the ceiling or attic floor joists were covered with ½-inch insulating board. The effect of ventilation upon reducing attic air temperatures was considered small. It was found that the roof remained effective in providing thermal resistance against heat loss; hence, it would be an error not to allow some value for the roof in heat loss calculations with respect to this type of construction.

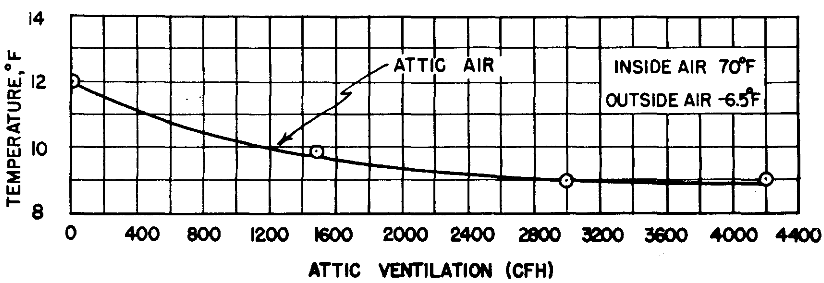

Figure 15. Effect of ventilation on attic air temperatures for Construction 4

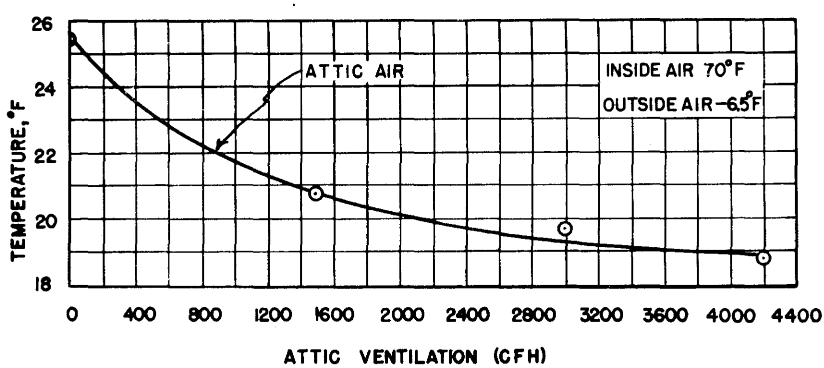

Figure 16. Effect of ventilation on attic air temperatures for Construction 5

Figure 16 shows similar results concerning Construction 5. For the four different ventilating conditions in this test the inside air was maintained at 70 F, with maximum fluctuations of 0.5 F, and the outside air was maintained at —6.5 F, likewise, with maximum fluctuations of 0.5 F. Inasmuch as the inside and outside air temperatures were substantially constant during all of the test runs, the curve may again be used to show directly the effect of ventilation upon the attic air temperature. In this construction the insulating board was removed from the tops of the ceiling or attic floor joists and applied to the under side of the roof rafters. This resulted in the ceiling having lower thermal resistance than in Construction 4, but with the roof having a comparatively high thermal resistance. As would be expected, the attic air temperatures in Construction 5 were found to be considerably higher than those in Construction 4. For the no-ventilation-condition the attic air temperature was 25.3 F. When the ventilating rate was set at 1,500 cfh, the attic air temperature was found to be 20.8 F, which was equivalent to a drop of 4.5 F. When the ventilation was increased further to 3,000 cfh, the attic air temperature dropped to 19.7 F. Compared to the no-ventilation temperature, this represented a decrease of 5.6 F. At the highest ventilating rate of 4,200 cfh, the attic air temperature was 18.8 F, or 6.5 F lower than that for no ventilation. Even at this high ventilating rate of 4,200 cfh, which is equivalent to approximately 1¾ air changes per hour, the attic air temperature was considerably higher than the outside air temperatures. Again, for this type of construction it would be a serious error not to allow some value for the roof in heat loss calculations.

Conclusions from attic air temperature study—The principal significance of these experimental data on attic air temperatures lies in their use in calculating heat loss through the ceiling of a ventilated attic. Therefore, Table VIII has been prepared to show the comparison of actual attic air temperatures with outside air temperatures when used in such calculations. Since the heat transfer by conduction through a given construction is directly proportional to the design temperature difference, the ratio between temperature differences would be equivalent to the ratios between actual heat losses. In this table the last column shows the ratio between temperature differences as obtained from columns 5 and 6. Column 5 shows the design temperature difference under actual conditions, while Column 6 shows the design temperature difference between inside air and outside air, which has been proposed by some investigators as the temperature difference to be used in calculations on heat loss through the ceiling of a ventilated attic.

Under Construction 4, in terms of percentage, it can be seen that if the attic air temperature is assumed to be equivalent to the outside air temperature, the heat loss calculations would be approximately

25 per cent too high in an attic ventilated at the rate of 1¾ air changes per hour.

Under Construction 5 this error would be considerably greater, amounting to approximately 50 per cent at the corresponding ventilating rate. It was recognized that a construction such as Construction 5 may not be used where louvres will provide attic ventilation. However, many structures similar to this type are built with the thought of planning future living quarters within the attic. In these structures windows usually replace the louvres, and there may be some reluctance on the part of the residents to open the windows for ventilating purposes for fear of causing serious heat loss. A significant fact apparent from these results is that with constructions of this type and with a large amount of ventilation in the attic, the roof still offers substantial thermal resistance.

It was concluded that if the full insulating value for the roof were allowed in the calculations in the case of a ventilated attic, the magnitude of the error would be relatively small and would depend upon the type of construction and the amount of ventilation provided. In a construction like that of Construction 4 of this investigation, this error would be small. For example, at a ventilating rate of 1¾ air changes per hour, the calculations, allowing full value for the roof, would be approximately 5 per cent too low. However, if no value were allowed for the roof, the calculations would result in being approximately 25 per cent too high. In the case of Construction 5, the error would be somewhat larger. At a ventilating rate of 1¾ air

Table VIII. Summary of Relationship between Attic Air Temperatures and Outside Air Temperatures at Different Rates of Ventilation for Constructions 4 and 5—Comparison of Attic Air Temperatures with Outside Air Temperatures When Used in Calculations on Heat Loss through the Ceiling Area

Ventilating Rate (cfh)	Inside Air Temperature	Outside Air Temperature	Actual Attic Air Temperature	Design Temperature Difference for Heat Loss Calculation through Ceiling: Inside air minus attic air (A)	Design Temperature Difference for Heat Loss Calculation through Ceiling: Inside air minus outside air (B)	Ratio B to A
Construction 4—½-Inch Insulating Board on Floor Joists						
0	70.0	−6.0	12.1	57.9	....	....
1,500	69.9	−6.4	9.8	60.1	76.3	1.27
3,000	69.5	−6.6	9.1	60.4	76.1	1.26
4,200	69.5	−6.0	9.0	60.5	75.5	1.25
Construction 5—½-Inch Insulating Board on Under Side of Roof Rafters						
0	69.9	−6.9	25.3	44.6	....	....
1,500	69.3	−6.4	20.8	48.5	75.7	1.56
3,000	70.2	−6.5	19.7	50.5	76.7	1.52
4,200	69.7	−6.6	18.8	50.9	76.3	1.50

changes per hour, the calculations, again allowing full value for the roof, would be approximately 14 per cent too low. If no value were allowed for the roof, the resulting calculations would be approximately 50 per cent too high. Thus, for the above two constructions it would be considerably more accurate to allow full value for the roof in the heat loss calculations than to neglect it entirely.

SUMMARY

This investigation was conducted on a full scale test bungalow of conventional frame construction under simulated winter conditions. The inside air temperature was maintained at 70 F and 40 per cent relative humidity, while the outside air temperature was maintained between 0 F and −10 F. As previously noted, the four objectives of this research program were: (1) to establish more firmly whether an interior surface construction of 1.25 grains per square foot per hour per inch of mercury vapor pressure difference possessed sufficiently low vapor permeability to safeguard a home against wall condensation problems; (2) to determine the effect of different combinations of vapor resistant interior and exterior surface constructions upon moisture condensation within the walls of a standard residential structure; (3) to obtain experimental data on the volume of ventilating air required to prevent the formation of frost within the attic, utilizing different ceiling constructions; and (4) to determine the relationship between attic air temperatures and outside air temperatures at different rates of attic ventilation.

Based on the results obtained over an extended test period and on the specific constructions, operating temperatures, and humidity involved, the following may be concluded:

1. Conventional frame walls constructed with an interior finish having a vapor permeability rate equal to, or lower than, 1.25 grains per square foot per hour per inch of mercury vapor pressure difference may be considered safe with respect to effectively reducing moisture condensation in residential structures.

2. The degree of vapor resistance of the exterior finish of an exposed wall in a residential construction is not as critical a factor as the vapor resistance of the interior finish. If the interior finish is of sufficiently high vapor resistance, the exterior construction may possess either a high or low permeability rate.

3. To minimize effectively the formation of frost within the attic, the ventilating requirements amount to approximately one air change per hour, provided the attic door is made to fit tightly with the aid of a gasket and the ceiling is made substantially vapor resistant, such as by the application of two coats of an interior oil paint. The ventilation may be provided mechanically or by natural circulation through sufficient louvre area. "For

inside air conditions of 70 F and relative humidities of more than 25 per cent in combination with —10 F outside air, attic ventilation should be used. For these conditions and with a building 25 feet square, openings of 1/4 square inch per square foot of ceiling area on each exposed wall will be sufficient." (Bulletin No. 18)

4. Attic air temperatures were found to be substantially higher than the outside air temperatures, even during operation under the high ventilating rates. In calculating the heat loss through the ceiling where the attic space above is ventilated in an amount sufficient to safeguard against condensation, the heat loss due to such ventilation may be neglected without serious error.