Bulletin of the
University of Minnesota

ENGINEERING EXPERIMENT STATION

Frank B. Rowley, Director

BULLETIN NO. 18

CONDENSATION OF MOISTURE AND ITS RELATION TO BUILDING CONSTRUCTION AND OPERATION

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Vol. XLIV No. 56 September 10 1941

MINNEAPOLIS

Entered at the post office in Minneapolis as second-class matter, Minneapolis, Minnesota. Accepted for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 12, 1918.

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ACKNOWLEDGMENT

The authors wish to acknowledge the support of the National Mineral Wool Association, whose generous contributions have made this program possible. The co-operation of its various offices and of its secretary, Mr. Wharton Clay, has made it possible to carry on the work without interruption for a period of four years. Special credit is due to the Technical Committee of the Association, consisting of Jan S. Irvine, chairman, W. W. Cullin, E. W. McMullen, C. L. Neumeister, and E. L. Williams. They contributed liberally of their time and technical abilities in formulating and following the research program through. We also wish to acknowledge the co-operation given by Mr. L. V. Teesdale of the Forest Products Laboratory, Department of Agriculture, Madison, Wisconsin, who has conducted extensive researches in this field.

Condensation of Moisture and Its Relation to Building Construction and Operation

PART I—INTRODUCTION

The problems brought about by the condensation of water vapor in the walls of certain types of buildings under specific conditions of operation, the most suitable types of construction to meet condensation problems, and the theory governing the transfer of moisture through walls were discussed in Bulletin 17 of the Engineering Experiment Station entitled, *Methods of Moisture Control and Their Application to Building Construction.* The experimental work reported in Bulletin 17 was conducted largely on small-scale test units. These units were built with standard types of wall construction but did not contain doors, windows, electric light fixtures, or certain other details of construction which are present in full-scale houses. While many of the laws were definitely established by the initial research program, there were still some questions as to what might be expected when these principles were applied to a practical full-scale building. For instance, there were problems in connection with electrical outlets, windows, window and door casings, joints between walls or walls and ceilings, ventilation of extended roof areas, etc., all of which could not be settled adequately by the small-scale test units.

In order to establish more firmly the conclusions and to apply the principles demonstrated by the first series of tests to a full-scale house it was decided that a test bungalow be built in the cold room and that as many different fundamental principles of construction be employed as practicable. Plans were accordingly drawn for a three-room bungalow which included thirteen different types of wall construction, a door, three windows, and several electrical outlets. The bungalow was first constructed with a flat roof, the attic space being approximately two feet high. It was later remodeled to use a gabled roof, with provisions for the construction of a second floor room. Provisions were made for supplying air of any desired temperature and humidity to the interior of the house and for cooling the exterior air to ten or more degrees below zero. The walls were constructed with removable exterior sections, and thermocouples were placed throughout in order to keep complete records of the formation of moisture or frost, together with the temperatures within the structure, during a test period. Openings were provided in the side walls of the attic space and through the top of the flat roof construction for the purpose of controlling the ventilation of the attic to the outside.

Several tests were made, and the conditions within the various parts of the structure were recorded with inside air at 70° F. and relative humidities from 20 to 40 per cent, and with outside air temperatures from +15° to −10° F. In many instances the test conditions were made severe in order to differentiate clearly among the relative merits of the various types of construction.

The test results have re-enforced the conclusions drawn from the first series of tests, and while some new facts have been brought out, none of these are contradictory to the original theories and principles established. The test conditions of 70° F. and 40 per cent relative humidity inside air with −10° F. outside air were found to give excessive moisture and frost accumulation on single and double glazed windows, on the cold surfaces of window sash weight enclosures, and on openings around the frames of doors and windows. These test conditions were used quite generally with the small test units for the purpose of accelerating test results and drawing comparisons among various types of construction. The condensation of moisture on certain types of electrical conduit installations, the passage of moisture through the ceiling openings provided for electric lighting fixtures, the temperature gradients in the air spaces of uninsulated walls, and the disagreement between the inner surface temperatures of walls as determined by tests and by calculations are some of the points which were brought out by these tests.

That part of the test equipment used in the former test program will be described only briefly, whereas the test bungalow and other features not included in the original program will be described in greater detail.

PART II—GENERAL SUMMARY

The first stage of the investigation consisted of a broad program of semi-scale and laboratory scale tests outlined to establish certain fundamental data with respect to the general problem. The second stage, the results of which are reported in this bulletin, involved the use of a full-scale structure. Since the results of the full-scale tests confirmed those previously obtained, and for the convenience of those who are particularly interested in the application of the fundamental principles which have been established, the following general conclusions are presented in order to summarize all of the information developed during both stages of the complete investigation:

1. The most likely places for moisture to condense within a structure are: (a) on the room surfaces of windows and walls; (b) within the interior parts of exposed outside walls; and (c) on the surfaces of cold attics and similar places.

2. Condensation on the inner surfaces of walls can usually be eliminated by adding sufficient insulation to raise the room surface temperature above the dew-point temperature of the room air. Window surface condensation may often be eliminated by the use of more than one thickness of glass with air space between different panes. (In many cases, the most practical solution of surface condensation problems is to reduce the relative humidity of the inside air.)

3. Condensation within the interior parts of exposed walls may be prevented by using a type of construction which will prevent water vapor from passing through the warm side of the wall to the colder portions within. (In many instances, the problems may be solved by proper control of inside air relative humidity.)

4. When condensation occurs within a frame wall insulated with loose mineral wool, it takes place on the inner or warm surface of the sheathing and not within the insulation. When it takes place in a cold attic, it is usually on the underside of sheathing boards, or on metal parts extending through the roof.

5. Condensation within cold attics may be eliminated by using a type of construction which will prevent the water vapor carried in the space below from penetrating the ceiling of the room below the attic or from passing through any channels, such as those between the studs of walls, around electric conduits, ceiling fixtures, etc. The probability of condensation in the attic will be greatly reduced by providing means for ventilation to the outside. (Attic condensation problems are caused primarily by high relative humidity of the air below the attic space and may often be entirely overcome by controlling the humidity within reasonable limits.)

6. When condensation occurs within a residence after the plaster has been thoroly dried out, one of the most common causes is that of excessive relative humidities carried within the building.

As a precautionary measure, during an extended cold period inside relative humidities should be maintained within the following limits, which were taken from Figs. 27 and 28:

Outside Air Temperatures	Inside Relative Humidities for 70° F. Air Temperature
—20° F. or below	Not over 15 per cent
—20° F. to —10° F.	Not over 20 per cent
—10° F. to 0° F.	Not over 25 per cent
0° F. to +10° F.	Not over 35 per cent
Above 10° F.	Not over 40 per cent

When single glass windows are used, condensation on the inner surface of the glass may be taken as an indicator of safe operating conditions. When condensation begins to appear on the inner surface of the lower pane near the bottom, the limits of safe operating conditions have been reached.

7. For existing construction, where walls and roof are weatherproofed, condensation within insulated walls may be prevented by controlling the relative humidities in accordance with the above table.

8. A good vapor barrier properly installed is the best insurance against condensation difficulties. It will provide protection against the moisture from wet plaster and any other conditions not anticipated. A vapor barrier should be applied as nearly as possible to the warm surface of the wall and should be applied so as to cover the complete surface and sealed properly around window and door openings and electrical outlets, etc. The full-scale house test showed that mineral wool bats and mineral wool blankets with good vapor barriers attached gave satisfactory protection against condensation, providing the materials were properly installed.

9. Moisture is generated within a house during the construction period by wet plaster. Later it may be caused by damp basements, the occupants, and the methods of housekeeping. It may also be caused by the use of humidifying equipment. The increase in relative humidity due to the moisture added by means other than the use of humidifying equipment may be controlled by ventilation with outside air. It is preferable to supply the ventilation air as near as possible to the source of the moisture.

10. In conducting the full-scale house tests, it was found that the frost and ice formation in the sash weight enclosures of the windows and in the openings next to the window and door frames was much heavier than that found in any of the walls, even without vapor barriers.

PART III—TESTING EQUIPMENT

COLD ROOM

The cold room in which the bungalow was constructed is 30 feet square and 25 feet high. The walls were constructed with 2 x 6 studs spaced 16 inches on centers and the space between was filled with mineral wool. The inside surface was finished with ½-inch fiber insulating board. The outside surface was finished with a vapor-proof paper nailed over the studs and covered with ½-inch fiber insulating board. This type of construction provided for some breathing through the inner cold surface but prevented the warm exterior air from entering the wall. It has been found satisfactory in operation and has not presented any condensation difficulties. Two doors were provided in one wall of the room—one a service door 3 feet 6 inches x 7 feet, and the other a large door 6 feet x 7 feet, used to move equipment in and out of the room.

REFRIGERATING PLANT

The air in the cold room is cooled by a 25-ton ammonia refrigerating machine. Air is taken from the top of the room, conducted through direct expansion cooling coils, and again delivered to the top of the room on the opposite side. There are two parallel sets of cooling coils each 10 rows deep, 18 inches wide, and 34½ inches high. The coils are placed in separate parallel compartments which are provided with shut-off dampers on each side so that either coil may be operated independently of the other. The purpose of this damper arrangement is to shut off one coil from the main circuit and to circulate room air through this coil for the purpose of defrosting. The room air is circulated through the coil by a 2,000 cubic feet per minute auxiliary fan. This method of defrosting has been found satisfactory and under normal conditions it has been necessary to defrost after from 2 to 4 days of operation. Defrosting requires about 20 minutes for each cooling coil. The air from the cold room is circulated through the cooling coils by means of a 6,000 cubic feet per minute fan. The cooling coils are each provided with face and by-pass dampers which are operated by thermostatically controlled motors, the thermostat being placed in the return air duct. The temperature of the air in the cold room is controlled partly by the suction pressure on the compressor, but the final control is by the face and by-pass damper arrangement.

The complete refrigerating equipment is installed in the basement underneath the cold room. Figure 1 shows a sectional view of the cold room, the cooling coils, the 6,000 cubic feet per minute fan, and the air duct which carries the air from the top of the test room through the cooling coil and back to the test room. It also shows a sectional view of the test bungalow with the flat roof construction, and a part of the air conditioning ducts which supply air to the test bungalow. Figure 2 shows in the foreground the complete assembled cooling unit exclusive of the refrigerating machine, and in the background the operator's room in which all of the testing instruments are installed.

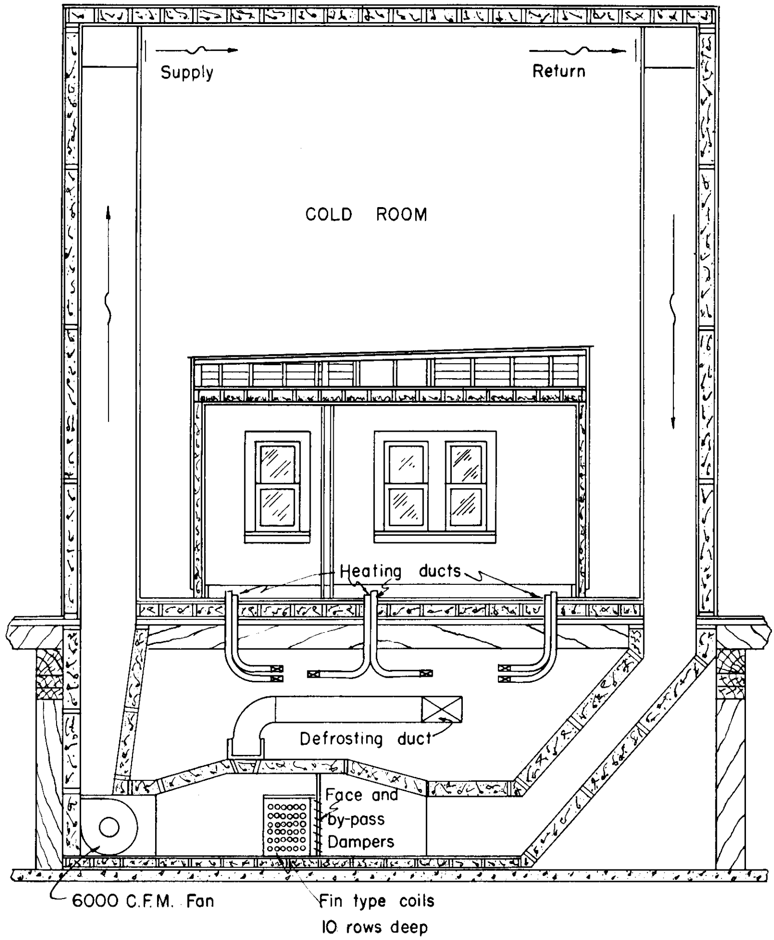

FIGURE 1. SECTIONAL VIEW THROUGH COLD ROOM, TEST BUNGALOW, AND COOLING UNIT.

AIR CONDITIONING UNIT

Conditioned air is supplied to the test bungalow from an air conditioning unit located in the basement underneath the cold room. This unit is provided with a steam heating coil, water spray head, water spray eliminator, automatic temperature and humidity control apparatus, and

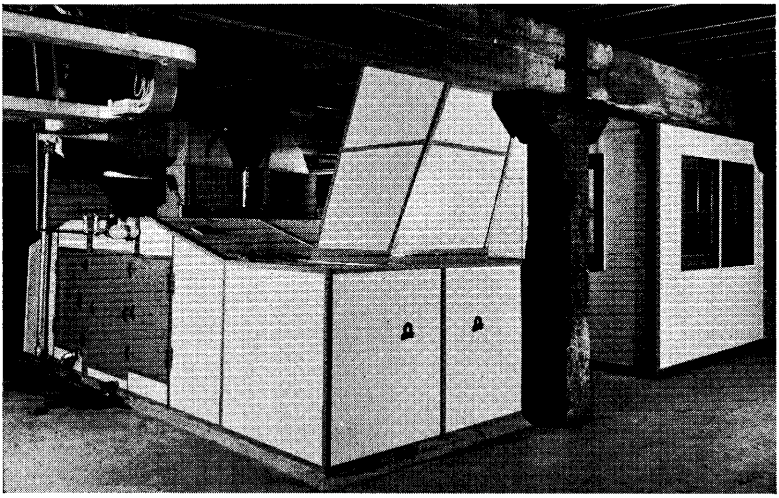

FIGURE 2. VIEW OF COMPLETED COOLING UNIT AND ONE END OF CONTROL ROOM.

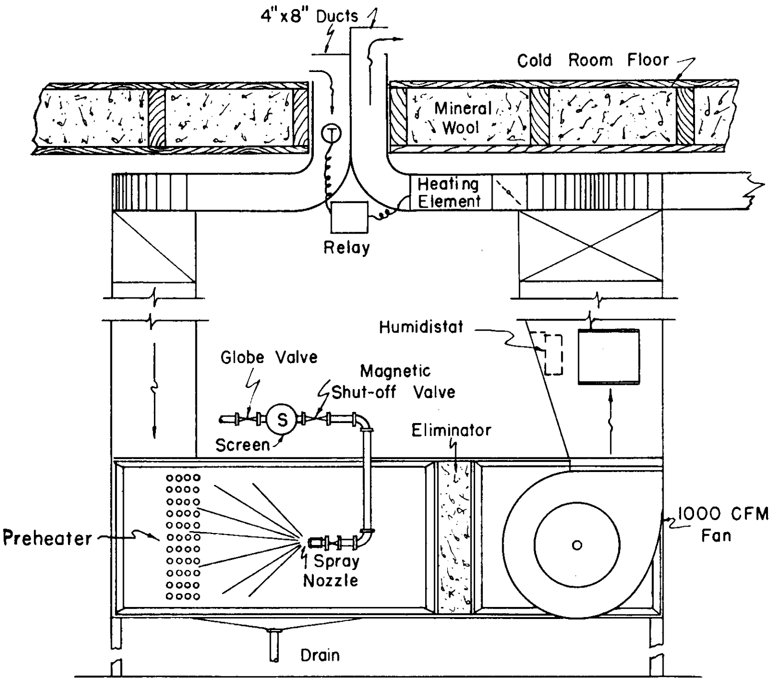

FIGURE 3. SECTIONAL VIEW OF AIR CONDITIONING UNIT WITH DISTRIBUTION DUCTS TO TEST BUNGALOW IN COLD ROOM.

fan for circulating the air from the test bungalow through the conditioning unit. In operation, air is drawn from various parts of the test house, passed through the conditioning unit, and delivered at the proper temperature and humidity to the different rooms in the test house. The humidity control is accomplished 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 is supplied by a steam heating coil built into the air conditioning unit. Final control is obtained by electric resistance heaters which are placed in each room supply duct and controlled by separate thermostats in adjacent return air ducts. This method gives an economical and satisfactory control for both the temperature and humidity in the test house. A sectional view of the temperature and humidity control apparatus, together with a part of the air distribution system, is shown in Figure 3.

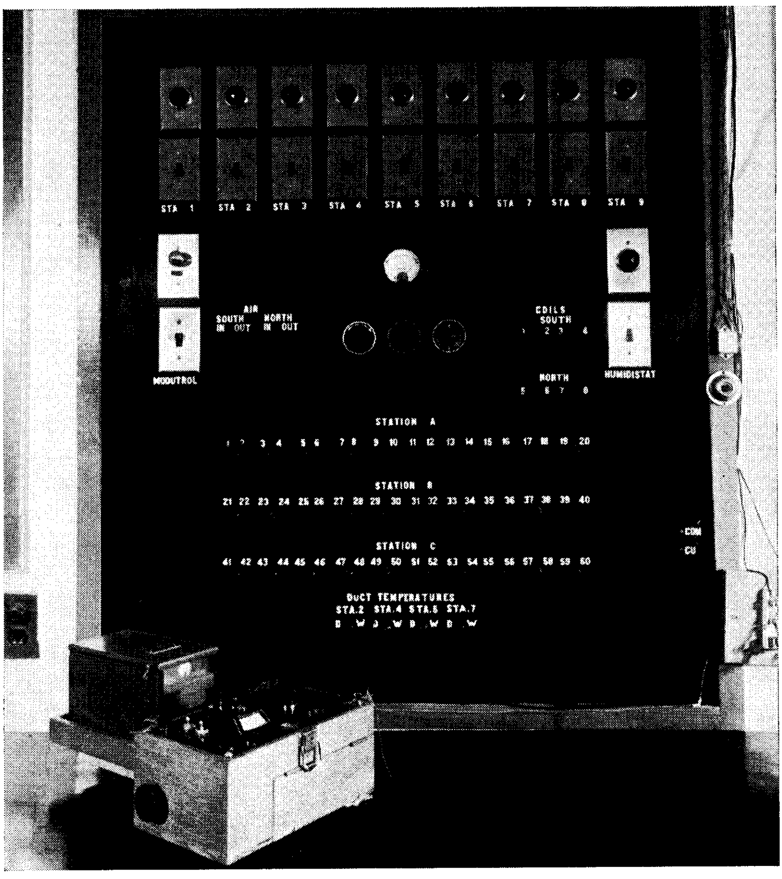

FIGURE 4. CONTROL AND THERMOCOUPLE PANEL FOR TEST EQUIPMENT.

THERMOCOUPLE EQUIPMENT

All temperatures were taken with copper constantan thermocouples and direct reading potentiometers. Permanent thermocouple leads were provided from thermocouple stations placed in the cold room to an instrument board placed in the operator's room. There were sixty pairs of thermocouple leads, and under normal operating conditions all of the temperatures were taken at the main instrument panel in the operator's room. For special surveys of wall surface temperatures, as high as two hundred thermocouples were used, and in this case the temperatures were taken by potentiometers located in the test bungalow. The temperature and humidity control instruments for the refrigerating room and also for the test bungalow were installed on the same panel as the thermocouple leads. Figure 4 shows the complete control panel with a manually operated potentiometer.

PART IV—TYPES OF CONTRUCTION TESTED

TEST BUNGALOW

The test bungalow, different views of which are shown in Figures 5, 6, and 7, has a floor area of 21 feet 0 inches x 21 feet 8 inches and a first floor ceiling height of 8 feet 6 inches. It contains three rooms, an attic space, an outside door, four double hung windows, two of which are joined with one casing, electric lights, and several electrical outlet boxes in the lower surfaces of the outside walls. Adjustable openings were

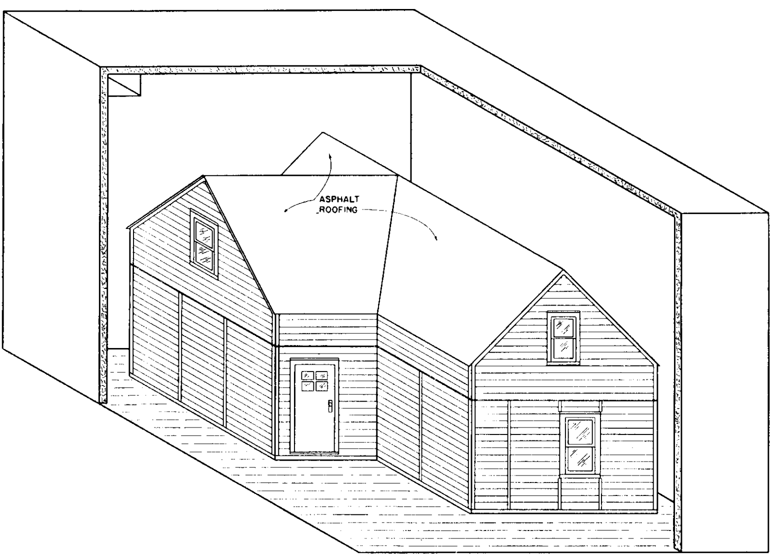

FIGURE 5. VIEW OF TEST BUNGALOW WITHIN COLD ROOM.

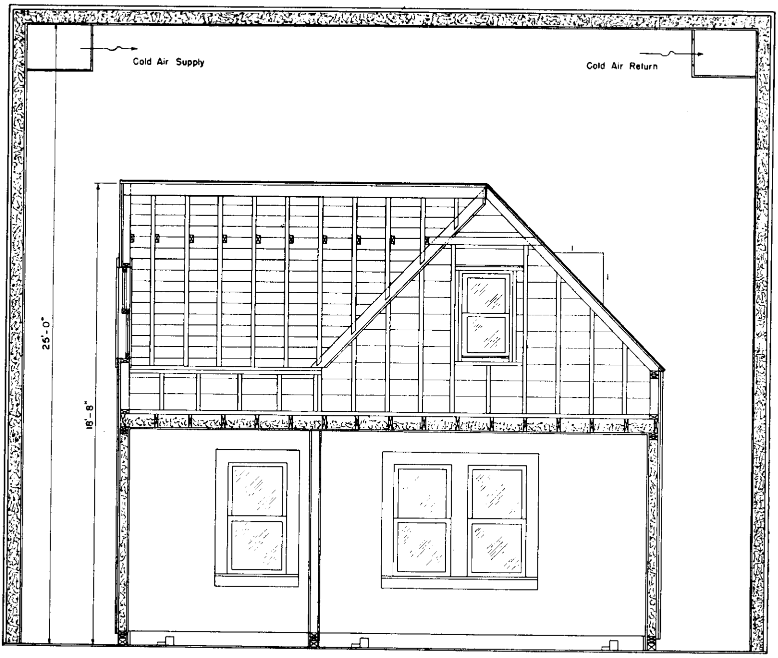

FIGURE 6. SECTIONAL VIEW OF TEST BUNGALOW WITHIN COLD ROOM.

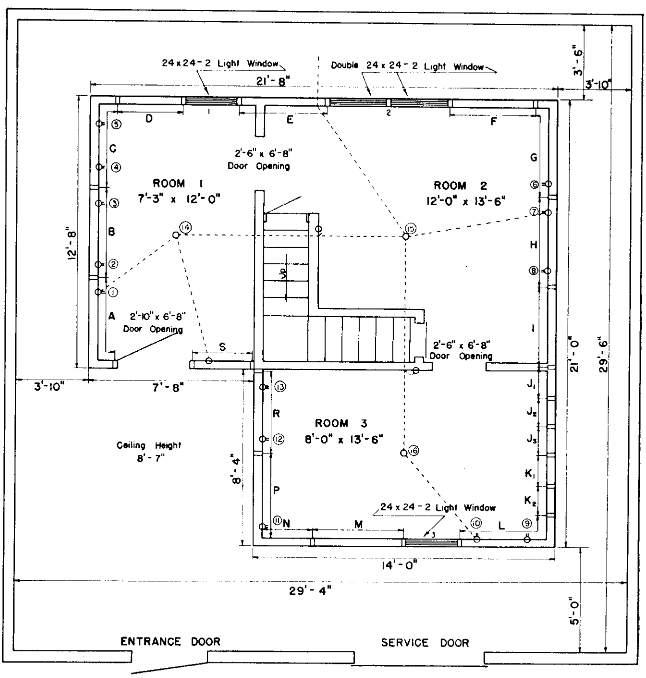

FIGURE 7. PLAN VIEW OF TEST BUNGALOW WITHIN COLD ROOM.

provided in each of the four outside attic walls and through the roof of the flat roof construction to provide different methods of attic ventilation. There is a clearance of about four feet between the walls of the bungalow and the walls of the cold room, and approximately six feet from the peak of the gabled roof to the ceiling of the cold room. The floor of the cold room serves as the floor of the test bungalow. The bungalow is of frame construction and every precaution was taken in the design to cover as wide a range of different construction methods as possible, and to make the details conform with those ordinarily met in frame buildings of this type. Thirteen different test walls were built into the structure, each four feet wide and extending for the full height of the first floor. In addition, five control panels were incorporated, each 16 inches wide and extending the full height of the first floor. These walls were built with different combinations of interior finish, insulation, and vapor barriers. The details of construction are shown in Table I. Several different arrangements of electrical outlets were provided for the purpose of showing the effect of heat conduction from the outlet boxes along connecting cables, and the vapor leakage which might occur around the joints between the outlet boxes and the vapor barrier. The construction details of outlet boxes and electric fixtures are shown in Table II. Figures 8 to 14, inclusive, show details of construction, including exterior and interior finish, insulation, vapor barriers, and electrical outlets. These will be referred to in later descriptions of the parts.

INTERIOR SURFACE FINISH

The interior surface finish of all walls consisted of either ¾-inch plaster on metal lath or ⅜-inch plaster on either wood or rock lath. For the ceiling the finish was ¾-inch plaster on metal lath. The plaster was applied in three coats on the metal lath and two coats on the rock and wood lath constructions. In each case the last coat was the finish coat and constituted the final surface finish of the walls for the test. No interior paint or paper was used.

The materials used for the different coats of plaster were as follows:

Scratch and brown coats—1 part plaster, 2½ parts sand by weight passing No. 10 sieve

Finish coat—3 parts hydrated lime, 1 part gaging lime by weight, with sufficient water added to the mixture to give required workability

The scratch coat was allowed to dry for 24 hours and the brown coat for 144 hours before the final coat was applied. Finished walls were allowed to dry for 18 days before a test period was started. Figure 11 shows an interior view of the finished bungalow. The thermocouple station at the right is located within the house, and that at the left is located on the inner surface of the cold room. Leads from these substations are carried directly to the thermocouple panel in the operator's

TABLE I

DETAILS OF WALL CONSTRUCTION

Wall Section	Mineral Wool Insulation	Vapor Barrier No.*	Vapor Barrier Description and application
			Inside Surface Finish ¾-Inch Plaster on Metal Lath
F	None	......	None
P	1-inch blanket	1	Asphalt coated on one side as integral part of blanket and lapped vertically on studs
R	2-inch blanket	1	Asphalt coated on one side as integral part of blanket and lapped vertically on studs
A	3⅝-inch bats	......	None
B	3⅝-inch bats	2	Paraffin coated bat/bak attached to bat, lapped vertically on studs with horizontal butt joints
C	3⅝-inch bats	3	Asphalt impregnated and surface glazed. Separately applied with vertical lap on studs
E	3⅝-inch bats	3	Asphalt impregnated and surface glazed. Separately applied with 2-inch horizontal lap
I	3⅝-inch bats	4	Asphalt impregnated and surface glazed. Separately applied with vertical lap on studs
S	3⅝-inch bats	3	Asphalt impregnated and surface glazed. Separately applied with vertical lap on studs
			Inside Surface Finish ⅜-Inch Plaster on Wood Lath
M	None	......	None
N	None	......	None
G	3⅝-inch bats	......	None
H	3⅝-inch bats	2	Paraffin coated bat/bak attached to bat, lapped vertically on studs with horizontal butt joints
L	3⅝-inch bats	3	Asphalt impregnated and surface glazed. Separately applied with vertical lap on studs
			Inside Surface Finish ⅜-Inch Plaster on Rock Lath
D	3⅝-inch bats	2	Paraffin coated bat/bak attached to bat, lapped vertically on studs with horizontal butt joints

*Barrier specifications:

1. Blanket insulation with an attached barrier on the warm side consisting of black kraft paper with the side facing the insulation asphalt coated and the other side unfinished. (Laboratory test 0.32 grs./sq. ft./24 hrs.)
2. Bat/bak insulation with an attached barrier on the warm side consisting of a brown kraft paper with the side facing the insulation coated with ribbed asphalt and the other side paraffin coated.
3. Asphalt impregnated and surface coated glossy paper weighing 50 lbs. per 500 sq. ft. (Laboratory test, 0.14 grs./sq. ft./24 hrs.) Paper not an integral part of insulation, applied separately on studs.
4. Asphalt impregnated and surface coated glossy paper weighing 50 lbs. per 500 sq. ft. (Laboratory test, 0.25 grs./sq. ft./24 hrs.) Paper not an integral part of insulation, applied separately on studs.

room and wires are carried from the substations to various points in the nearby wall.

EXTERIOR CONSTRUCTION OF TEST WALLS

All walls were constructed with 2 x 4 studs spaced 16 inches on centers and covered on the outside with 1-inch x 8-inch Ponderosa pine shiplap sheathing, asphalt saturated rag felt building paper, and ½-inch x 6-inch Redwood siding. The sheathing, building paper, and siding were constructed as a unit for each test section. The test sections were 4 feet wide and the full height of the first floor. Wood strips ¾ inch wide and 1¼ inches deep were spaced 16 inches apart and used as nailing strips for the sheathing. The outside surface of the studs was grooved to receive these nailing strips and the combined exterior section of the wall was fastened to the studs by long screws. By this method the outer sections of the wall could be securely fastened to the studs and yet could be easily removed for inspection during or after a test period. Removable sheathing panels 7 inches x 10 inches were provided at the top and bottom of the central stud space of all 4-foot wall sections. Removable siding sections were also provided for each test section. The

FIGURE 8. VIEW OF ENTRANCE TO BUNGALOW, WITH PART OF EXTERIOR WALL SECTIONS REMOVED SHOWING METHODS OF INSULATION AND CONSTRUCTION.

TABLE II

LOCATION OF ELECTRICAL FIXTURES AND QUALITY OF WORKMANSHIP IN APPLYING VAPOR BARRIERS AROUND ELECTRICAL OUTLETS

Fixture No.	Location	Mineral Wool Insulation	Connected	Barrier Application around Outlet	Figure	Description of Barrier
				Duplex Convenience Outlets		
	Wall					
1	A	3⅝-inch bat	Yes	None	......	None
2	B	3⅝-inch bat	No	Good	12	Paraffin coated bat/bak (No. 2*)
3	B	3⅝-inch bat	No	Fair	12	Paraffin coated bat/bak (No. 2*)
4	C	3⅝-inch bat	No	Good	12	Asphalt impregnated and surface glazed (No. 3*)
5	C	3⅝-inch bat	No	Poor	12	Asphalt impregnated and surface glazed (No. 3*)
6	G	3⅝-inch bat	No	None	......	None
7	H	3⅝-inch bat	Yes	Good	......	Paraffin coated bat/bak (No. 2*)
8	H	3⅝-inch bat	No	Fair	......	Paraffin coated bat/bak (No. 2*)
9	L	3⅝-inch bat	No	Good	......	Asphalt impregnated and surface glazed (No. 3*)
10	L	3⅝-inch bat	Yes	Poor	......	Asphalt impregnated and surface glazed (No. 3*)
11	P	1-inch blanket	No	Fair	13	Asphalt coated on one side (No. 1*)
12	R	2-inch blanket	No	Fair	13	Asphalt coated on one side (No. 1*)
13	R	2-inch blanket	No	Good	13	Asphalt coated on one side (No. 1*)
				Ceiling Lights		
	Room					
14	1	3⅝-inch bat	Yes	None	......	None
15	2	3⅝-inch bat	Yes	None	......	None
16	3	3⅝-inch bat	Yes	None	......	None

* See Table I for barrier specifications.

method of constructing the exterior wall section, the grooves in the studs to receive the nailing strips, and the removable sheathing panels are shown in Figure 10. Figure 8 shows the application of two types of insulating materials and removable siding panels with an exterior wall section removed. Figure 9 shows the same wall with the exterior walls assembled.

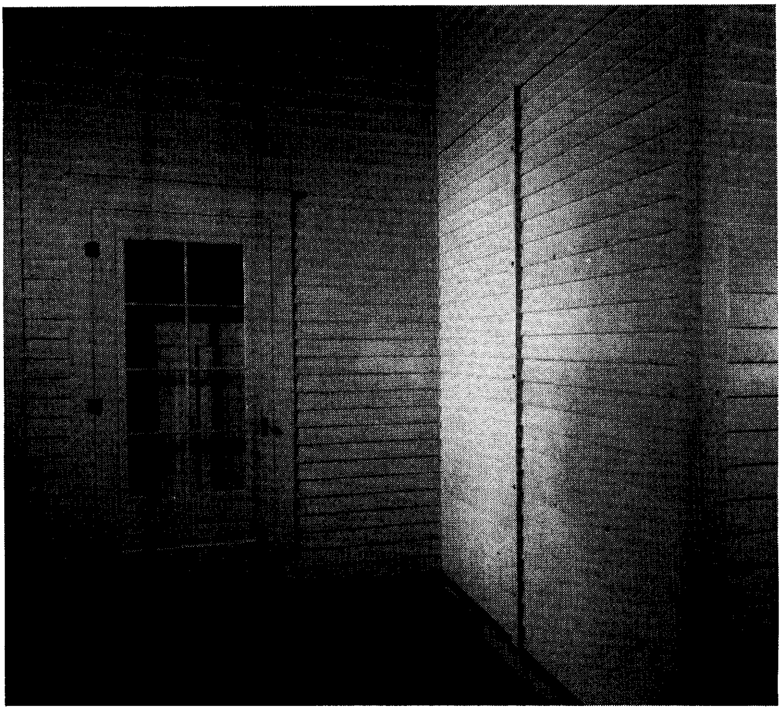

FIGURE 9. VIEW OF ENTRANCE TO BUNGALOW SHOWING THE EXTERIOR WALLS COMPLETELY ASSEMBLED.

The siding was painted with one coat of primer and one coat of outside white paint, specifications being as follows:

PRIMING COAT

Pigment by weight		64.2 per cent
Vehicle by weight		35.8 per cent
Pigment composition—titanium barium		50.0 per cent
white lead carbonate		30.0 per cent
magnesium silicate		20.0 per cent
Vehicle composition—varnish		33.0 per cent
linseed oil		40.0 per cent
dryer and thinner		27.0 per cent

OUTSIDE WHITE PAINT

Pigment by weight		66.7 per cent
Vehicle by weight		33.3 per cent
Pigment composition—	titanium barium	44.4 per cent
	white lead	25.6 per cent
	zinc oxide	30.0 per cent
Vehicle composition—	linseed oil	90.0 per cent
	dryer and thinner	10.0 per cent

NOTE.—The white lead was made up of lead carbonate, 35.7 per cent; and lead sulphite, 64.3 per cent.

FIGURE 10. VIEW OF EXTERIOR WALL WITH OUTER WALL SECTION REMOVED SHOWING DIFFERENT TYPES OF INSULATION, WINDOW INSTALLATION, AND OUTER WALL SECTION WITH REMOVABLE SHEATHING PANELS.

TYPES OF INSULATION

Mineral wool insulation was used in five different forms:

(1) 1-inch blanket with vapor barrier on warm side
(2) 2-inch blanket with vapor barrier on warm side
(3) 3⅝-inch insulating bat without vapor barrier
(4) 3⅝-inch insulating bat with vapor barrier attached to warm side
(5) 3⅝-inch insulating bat with continuous vapor barrier separately applied over surface of studs

The 1-inch and 2-inch thick insulating blankets were built with vapor barrier material on the warm side and a vapor ventilating material on the cold side. The vapor barrier material was extended ¾ of an inch on each side for the purpose of sealing the blanket to the studs. In applying the blankets they were extended for the full length of the stud space with approximately 1-inch overlap at top and bottom. The mineral wool was removed for about 1 inch at each end and the paper thus provided

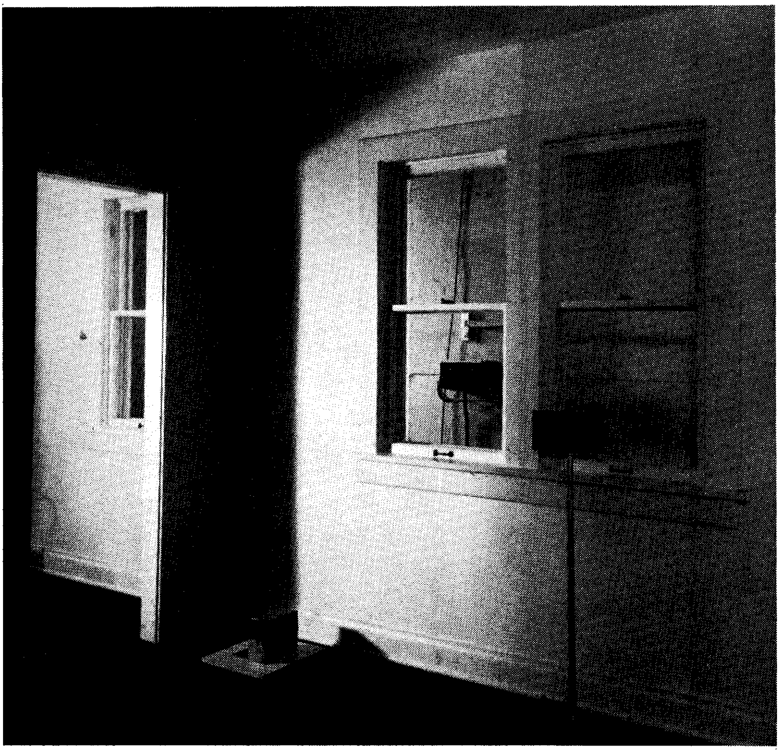

FIGURE 11. INTERIOR VIEW OF FINISHED ROOM NO. 2 SHOWING THERMOCOUPLE STATIONS, HEATING DUCTS, AND DOUBLE WINDOW.

was lapped over the surfaces of the top and bottom plates. The paper extensions at the sides and ends of the bats were then stapled onto the inner surface of the studs, thus forming a complete seal over the warm side of the insulation. The 3⅝-inch bats were placed between the studs and fitted snugly along the horizontal joints. When vapor barriers were attached to the warm surface of the bats they were extended over the inner face of the studs and fastened with staples with no lapping at the horizontal joints. When continuous barriers were used on the warm side of the insulation they were, unless otherwise specified, extended vertically over the full area of the wall with the joints lapped and stapled on the face of the studs. No special seal was provided at the joints other than the stapling. The types of insulation used in the different walls are shown in Table I. The ceiling insulation consisted of 3⅝-inch thick insulating bats without the vapor barrier.

Figure 8 shows the exterior view of the 1-inch blanket application and also the 3⅝-inch bat material applied above the doors. Figure 10 shows the exterior view of two different makes of 3⅝-inch bat insulation at right of window and below window. Figures 12, 13, and 14 show interior views of the insulated walls before plaster base was applied. Figure 12 shows the construction of Wall A with 3⅝-inch mineral wool bats without barriers; Wall B with 3⅝-inch mineral wool bats with barriers attached; and Wall C with 3⅝-inch mineral wool bats with a continuous barrier applied over the warm surface of the insulation. Figure

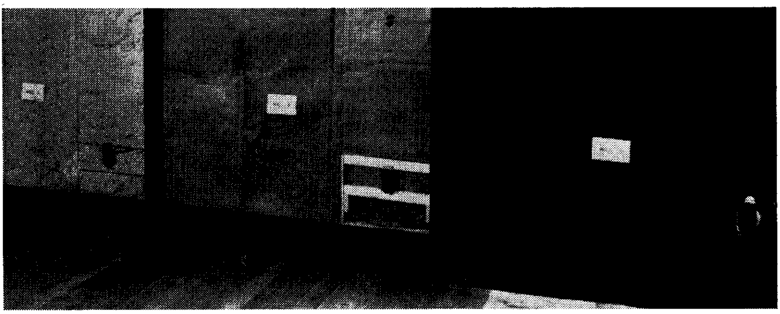

FIGURE 12. VIEW OF INTERIOR SURFACES OF WALLS A, B, AND C BEFORE LATH AND PLASTER WERE APPLIED SHOWING INSULATION, DIFFERENT TYPES OF BARRIERS, INSTALLATION OF ELECTRICAL OUTLETS, AND BARRIER SEAL AROUND OUTLETS.

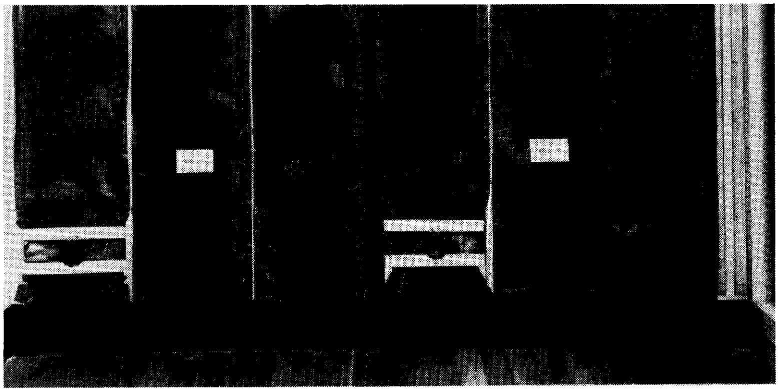

FIGURE 13. VIEW OF INTERIOR SURFACES OF WALLS P AND R BEFORE LATH AND PLASTER WERE APPLIED SHOWING METHODS OF INSTALLING BLANKET INSULATION, ELECTRICAL OUTLETS, AND BARRIER SEAL AROUND OUTLETS.

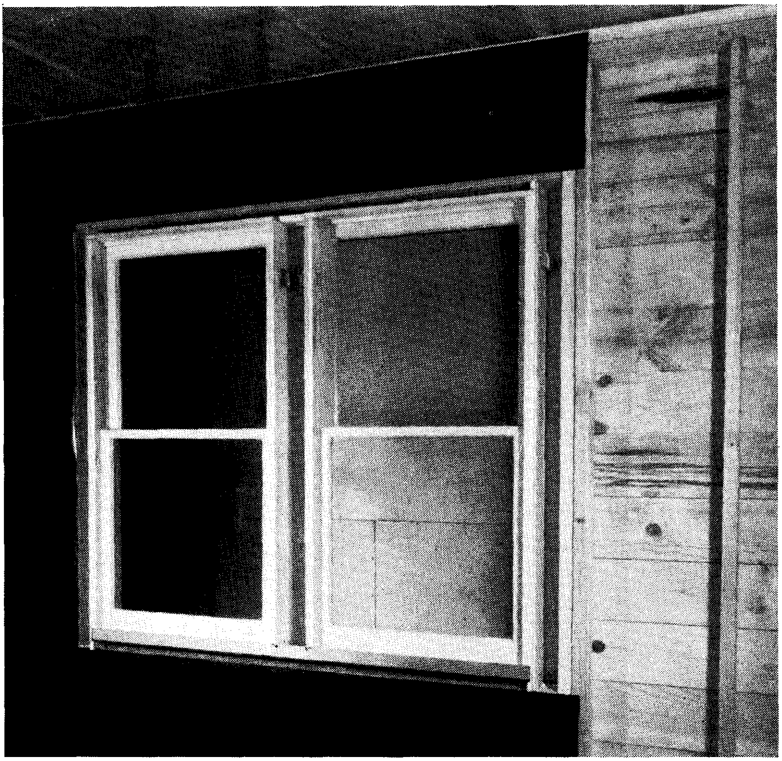

FIGURE 14. VIEW OF INTERIOR SURFACES OF WALL BEFORE LATH AND PLASTER WERE APPLIED SHOWING INSTALLATION OF CONTINUOUS BARRIER, WALL WITHOUT INSULATION, AND DOUBLE WINDOW WITH INTERIOR TRIM REMOVED.

13 shows, at the left, Wall P with 1-inch blanket insulation, and at the right, Wall R with 2-inch blanket insulation. Figure 14 shows at the left, Wall E with 3⅝-inch mineral wool insulation and a continuous barrier, and, at the right, Wall F with no insulation and no barrier. The method of attaching the barriers by lapping the edges over the studs for the blanket and bat/bak barriers will be noted in Figures 12 and 13.

VAPOR BARRIERS AND THEIR APPLICATION

The various types of vapor barriers used are indicated in Table I, which gives a description of the different walls tested. The specifications of the barriers as applied to the different walls are as follows:

Walls P, R, and J-3. An asphalt paper applied on the warm side of the blanket insulation. The surface next to the insulation was finished with a smooth coat of asphalt and the exposed surface was unfinished. The cold surface of the insulation was covered with a non-vapor-proof paper which was extended around the blanket and sealed at the edges to the vapor barrier. The barrier was extended on each side of the blanket for about ¾ of an inch for the purpose of attaching the blanket to the studs.

Walls B, D, H, and J-2. The barrier was attached to 3⅝-inch insulating bats which were cut 24 inches long and of a width to fit in between the studs. The barrier was attached to the bats with ribs of asphalt which were softened by heating as the barrier was applied to the bats. The barrier was extended for ¾ of an inch at each edge but cut flush with the bats at top and bottom.

Walls C, E, S, L, and J-1. The barrier consisted of an asphalt impregnated and surface coated glossy finished paper weighing 50 pounds per 500 square feet. The paper was applied as a continuous sheet over the inner surface of the wall with the joints lapped and stapled along the studs, excepting for Wall E where the barrier was applied horizontally with a 2-inch lap. The barrier formed a continuous lining under the plaster base and was not attached to the insulation.

Wall I. An asphalt impregnated and surface coated semi-glossy paper weighing 50 pounds per 500 square feet. The paper was applied as a continuous sheet with the joints formed by lapping the barrier over the studs.

In all cases laboratory tests on the barriers previous to their application showed them to be satisfactory vapor stops and to come within the range of acceptable barriers by the standard test as set up by the National Mineral Wool Association.

ELECTRICAL OUTLETS AND FIXTURES

The location and details covering electrical outlets and ceiling fixtures as used are shown in Figure 7 and Table II. The electrical outlets which were provided in the outside walls were fourteen inches above the floor line. The type of installation used in Walls A, B, C, P, and R are shown in Figures 12 and 13. They were all duplex outlets with the receptacle boxes fastened to a bridge construction consisting of 1-inch x 1½-inch wood strips securely fastened between the studs. The outlets were all located in the center of the stud section. One ceiling light was located in the center of each room. These lights consisted of porcelain receptacles connected to shallow outlet boxes. The installations were made in the conventional manner with the boxes fastened to a bridge construction placed midway between the joists.

The open ends of the receptacle boxes were placed flush with the finished surface of the plaster and, where vapor barriers were used, a seal was provided around the outlets to represent careless, average, and careful conditions of installation. Metal conduits were connected to the top of the ceiling outlet boxes, carried up through the ceiling insulation and over the top of the ceiling joists in the cold attic space to join the current supply. A switch for each of the lights was placed on an inside wall about five feet from the floor and connected by a metal conduit which ran up through the wall or partition and through the upper plate into the cold attic space, where it connected to the source of electric supply and to the electric light outlet in the ceiling. The locations of the switches are shown on the plan in Figure 7. The switch for Room 1 was located on the left side of the entrance door in an outside wall.

This wall was insulated with 3⅝-inch bat insulation with a continuous sheet of barrier paper over the warm surface, and a good seal around the switch box. The wall switches for ceiling lights 2 and 3 were located on inside walls, in which case no vapor barriers were used. All switches, lights, and outlets were connected by ¾-inch armored cables laid flush over the ceiling joists which were notched to keep the cables flush with the tops of the joists when passing from one space to another. When the conduit ran parallel to the joists it occasionally laid directly on the mineral wool insulation. A service pipe was placed in the center of the stud section of Wall E-4 and extended from the top of the wall through the plate with a service entrance head connected on the outside. The pipe was ¾ inch in diameter and extended the full length of the stud section. The wall was insulated with 3⅝-inch mineral wool bats with a continuous sheet of barrier lapped horizontally along the studs.

WINDOW AND DOOR CONSTRUCTION

The door and four windows were built into the outside walls of the bungalow, as shown in Figure 7. The door and one window were placed in Room 1, a double window in Room 2, and a single window in Room 3. The windows were all double hung with storm sash which were applied for the greater part of the test. The door was provided with a storm door which was used throughout the tests. The window and door casings were of standard construction, space being allowed for sash weights in the window frames and the normal space around the door and window frames. The inside trim of the door and window casings was applied with screws so that it could be removed for inspection during a test. All interior woodwork was finished with two coats of flat white paint.

PART V—TEST RESULTS

In setting up test conditions for the bungalow there were three major objectives which may be summarized as follows:

1. To study the temperatures throughout various parts of the structure under actual operating conditions, and to compare them with calculated temperatures.
2. To determine the probabilities of moisture accumulation in different parts of the structure and methods of preventing the same under different operating conditions.
3. To establish safe and practical relative humidities which may be carried within the building at a given inside air temperature, and at different outside air temperatures.

The test conditions were set up primarily for the purpose of obtaining data concerning Objectives 2 and 3. The temperature readings for Objective 1 were obtained simultaneously with other test data. In order to differentiate among different types of construction, rather severe test conditions were selected for many of the tests which were made under the second objective. The long series of tests required to study different methods of attic ventilation under constant test conditions made it possible to subject side walls and windows to very long test periods. Thus the moisture and frost conditions reported for side walls, windows, and other parts of the structure under constant air temperature and humidity conditions were the result of a sixty-nine-day test period made possible by the attic ventilation study. It was during this period that a greater part of the temperature data throughout various parts of the structure were taken.

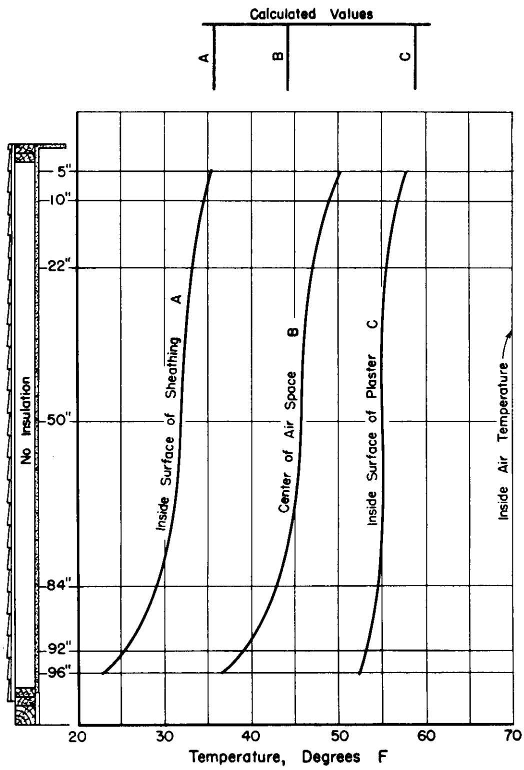

FIGURE 15. TEMPERATURES IN DIFFERENT SECTIONS OF UNINSULATED WALLS.

There were thirty-three separate tests made—twenty-eight of them under constant outside air temperature conditions and five of them under variable outside air temperature conditions. The general test conditions which include length of test, air conditions, and type of attic ventilation are shown in Table III.

The results of the tests will be discussed under the following major headings:

1. Temperatures throughout Structure
2. Moisture Conditions within Structure at Constant Outside Air Temperature
3. Moisture Conditions within Structure at Variable Outside Air Temperatures
4. Moisture Conditions within Attic
5. Limiting Operating Conditions

TEMPERATURES THROUGHOUT STRUCTURE

AIR SPACE TEMPERATURES

The heat transmitted across an air space may be divided into two parts—that transmitted by direct radiation and that transmitted by conduction and convection. That part transmitted by radiation is independent of air space orientation, but that portion transmitted by conduction and convection is affected by the position of the air space and the direction of heat flow. In a vertical air space such as found in the side walls of a house there will be normal convection currents which will pass upward on the warm side and downward on the cold side of the air space. These convection currents will increase the rate of heat transmitted by convection. The conductance coefficients which are usually used for vertical air spaces in a wall have been determined experimentally for air spaces varying in height from 6 inches to 5 feet, and within these limits there are but small differences in the coefficients. There are, however, differences in temperatures between air at the bottom and top of the air space due to the convection currents. While these differences in temperatures may not affect the average air space conductance coefficient, they do enter into condensation problems. The upward flow of air on the warm side and the downward flow on the cold side of the air space result in higher air temperatures and also higher vapor concentrations in the upper parts of the air space. The higher air temperatures at the top of the air space will also maintain warmer exterior surface temperatures and thus reduce the possibilities of condensation at the top of the space. Most of the test results for the uninsulated frame walls have shown that this combination of conditions yields higher rates of condensation on the inner surface of the sheathing at the bottom than at the top of the air space. For the walls with fill insulation there is a small amount of air circulation within the insulation, thus giving a slightly higher temperature at the top than at the bottom of the insulated space, but when condensation has occurred in this type of wall it has usually been slightly greater at the top than at the bottom of the insulated space. This is probably due to the fact that the rise in dew-point temperature in the upper part of the air space has exceeded the rise in the inner surface temperature of the sheathing.

TABLE III

RECORD OF TEST CONDITIONS

Test No.	No. of Hours	Outside Air, Degrees F.	Inside Air Degrees F.	Inside Air Rel. humid., per cent	Attic Ventilation
		Constant Outside Air Temperature			
40-1	276	0	70	25	None
40-2	126	0	70	30	None
40-3	159	+15	70	53	None
40-4	158	−15	70	17	None
40-5	154	−10	70	30	¼ square inch, *4 sides
40-6-1	32	−10	70	40	⅛ square inch, 4 sides
40-6-2	126	−10	70	40	¼ square inch, 4 sides
40-7-1	194	−10	70	40	¼ square inch, 3 sides
40-7-2	118	−10	70	40	All vents open
40-7-3	72	−10	70	40	½ square inch, 2 sides
40-7-4	120	−10	70	40	All vents open
40-7-5	99	−10	70	40	1¾ square inches, 3 roof openings
40-7-6	117	−10	70	40	½ square inch, 3 roof openings
40-8-1	168	−10	70	40	¼ square inch, 3 roof openings
40-8-2	48	−10	70	40	All vents open
40-8-3	168	−10	70	40	¼ square inch, 3 duct openings
40-8-4	168	−10	70	40	⅛ square inch, 3 duct openings
40-8-5	44	−10	70	40	All vents open
40-9-1	191	− 5.2	70	40	¼ square inch, 3 windows
40-9-2	49	− 7.9	70	40	½ square inch, 3 windows
40-9-3	144	− 4.8	70	40	½ square inch, 3 windows
40-9-4	120	− 5.8	70	40	None
40-9-5	116	− 6.2	70	40	¼ square inch, 3 windows
40-9-6	172	− 5.9	70	40	Mechanical
40-9-7	92	− 6.2	70	40	Mechanical
40-9-8	72	− 8.5	70	40	¼ square inch, 2 windows
40-9-9	72	− 9.8	70	40	½ square inch, 2 windows
40-9-10	360	− 9.4	70	40	1 square inch, 2 windows
		Variable Outside Air Temperature			
40-10	168	−15 to 0	70	20	None
40-11	168	−15 to 0	70	25	None
40-12	168	−15 to 0	70	30	⅛ square inch, 3 windows
40-13	168	−15 to 0	70	40	¼ square inch, 3 windows
40-14	168	− 5 to +10	70	40	¼ square inch, 3 windows

* Figure indicates area of ventilation opening in square inches per square foot of ceiling area.

In this series of tests, surface temperatures and also air temperatures at the center of the air space were taken at various elevations in an 8-foot outside wall. The average results of these tests for two walls are shown in Figure 15. The vertical scale indicates the distances below the ceiling at which temperatures were taken, and the horizontal scale gives the temperatures recorded. The inside air temperatures were 70° F. and the outside −10° F. The short lines with corresponding letters at the top of diagram give the calculated temperatures for the corresponding walls. These calculations were made on the basis of inside surface conductance coefficient, f_i=1.65, and for an outside surface conductance coefficient, $f_o=2.00$, which was assumed to be the average for the tests. The over-all conductance coefficient, U, for the walls was calculated to correspond to the type of construction and the known values of the materials. The surface temperatures were all taken at points midway between the studs and at the elevations indicated. As will be noted from the figure, there is a variation in the temperature of the air from 36° to 50° F. between bottom and top of air space. The inner surface temperature of the sheathing varies from 23° F. at the bottom to 36° F. at the top, while the inner surface temperature of the plaster varies from approximately 52° F. at the bottom to 58° F. at the top. These variations are not straight lines, and it should be pointed out that the temperatures are affected at the extreme top and bottom by the ceiling and floor connections. For instance, at the top, the wall joins with a cold attic wall and with an insulated ceiling which is exposed to attic air on one side. At the floor line it joins with a floor which is warmed on top and bottom, although the final measurements were taken about 7½ inches above the floor line. These values are typical of what may be expected in the air space of an ordinary outside frame wall.

INSIDE SURFACE TEMPERATURES OF PLASTER

The inside surface temperature of a wall will depend upon many factors. Among these are inside and outside air temperatures, velocity of the air over the surface of the wall, particularly the inside surface; the thermal conductance of the wall, the type of construction, and the particular point at which the surface temperature is taken. For a given type of wall for which the thermal conductance coefficient is known and for given conditions of air temperature and velocity, it has been assumed possible to calculate inside surface temperatures with a fair degree of accuracy. The method of calculation has been based upon the fact that the temperature drop between two points along the path of heat flow is directly proportional to the heat resistance between those two points. In other words, if the over-all conductance coefficient, U, of a wall is known and a reasonable inside surface conductance coefficient, f_i, can be assumed, then the ratio between the temperature drop from inside air to inside surface of wall to that between inside and outside air is the same as the ratio of the heat resistances between inside air and surface and inside and outside air, or it is equal to the ratios of $1/f_i$ to $1/U$, where f_i and U are the inside surface and over-all conductance coefficients for the wall. Some variations are to be expected, depending upon whether the point for which temperature is calculated is over an air space or over a stud, and, to some extent, as to its elevation from the floor. But for average conditions these variations are not sufficient to seriously invalidate the calculated temperatures.

In these tests a very complete survey was made of the inner surface temperatures at various elevations from the floor and at various positions horizontally for each type of wall tested. The temperatures were also calculated for many of these points. The results of tests and of calculations for inside and outside air temperatures of 70° and −10° F., respectively, are shown by the curves of Figure 16. The ordinates show the distances below the ceiling at which the temperatures were taken, and the abscissa show the recorded temperatures. The curved lines were plotted from temperatures taken from actual test walls with

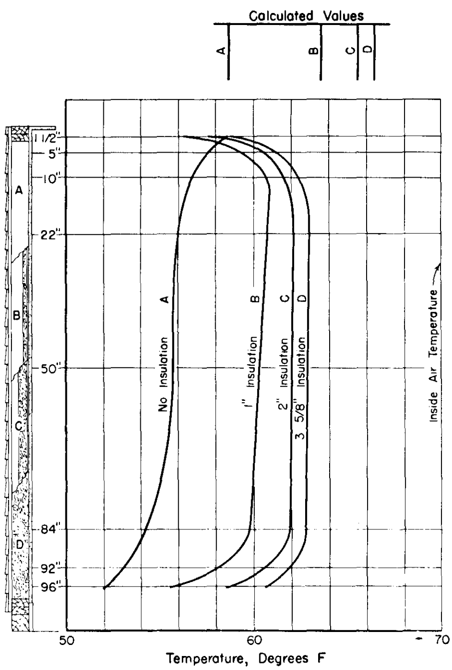

FIGURE 16. INSIDE SURFACE TEMPERATURES OF PLASTER FOR DIFFERENT TYPES OF INSULATION.

insulation as indicated on the individual curves. The short lines with corresponding letters at the top of the diagram give the calculated surface temperatures for the corresponding walls.

As will be noted, the surface temperatures throughout the central section of the wall are substantially uniform, altho slightly higher at the top than at the bottom. Extending upward from a point approximately 12 inches below the ceiling the curves for the insulated walls show a decided drop in temperature with a minimum temperature at the top of the wall. Likewise, when extending downward from a point approximately 18 inches from the floor line the curves show a rapid drop in surface temperature. This drop in temperature at top and at bottom for the surfaces of the insulated walls can probably be attributed to the type of construction. As indicated in the cross section of the wall at the left of the diagram, there are two 2 x 4 plates at the top of the side wall beyond which it joins a cold attic wall, and in addition to this there is a cold attic above the ceiling. These construction features would give higher rates of heat conductance from the upper part than from the central part of the inner wall surface. Likewise, at the bottom there is a 4 x 4 foundation timber with two 2 x 4 plates which will give a higher thermal conductance than that of the insulated parts of the wall. These structural differences seem to be sufficient to cause the lower surface temperatures as recorded for the extreme upper and lower surfaces as compared to the central section of the insulated walls. For the uninsulated wall the surface temperatures drop off at the bottom but rise at the top. In this case the temperature differences are not due so much to structural differences as they are to the effect of the air space convection currents. The thermal conductance through the 2 x 4 plates at top and bottom of the insulated wall would be less than that through the air space. As shown previously, there will be a variation of from 11 to 12 degrees between the air temperatures at top and at bottom of the air space due to convection currents. The warm currents rising on the inner surface of the air space create a high air temperature at the top, and the cold air currents dropping on the outside, or cold surface, result in lower temperatures at the bottom of the air space. This accounts for the different characteristics of the curve at top and at bottom.

One of the most interesting facts brought out by the curves is the difference which exists in every case between the measured and calculated wall surface temperatures. An investigation showed that this difference was due to the fact that the inner surface conductance coefficients, f_i, were much less for the different walls than the 1.65 which was assumed in making the calculations. This difference may be explained as follows: The surface conductance coefficients for walls were originally determined and are usually applied under conditions in which the temperature of objects surrounding the wall surface are the same as that of the surrounding air. Under these conditions the heat is transferred to or from the surface partly by conduction and convection and partly by radiation, the temperature difference being the same for both, and substantially half of the heat is transferred by radiation for a normal wall. In these tests the inner surfaces of the walls were exposed to the surfaces of other outside walls whose temperatures were much lower than those of the surrounding air, and in some instances even lower than the wall surface temperatures under consideration. Thus the amount of heat transferred to the surface of the wall by radiation was greatly reduced and the temperature drop between the air and the surface of the wall must have been correspondingly increased to keep up the normal heat flow through the wall. Due to the fact that some of the walls were insulated and others were not, the relative effect on the insulated walls was greater than that on the uninsulated wall. This can readily be seen by considering two walls—one insulated and the other uninsulated—and so arranged that they are facing each other. In both cases the radiation of heat to the wall will be reduced, but the uninsulated wall, having the lower surface temperature, will receive some radiant heat from the insulated wall with its higher surface temperature. Thus the percentage reduction in radiant heat, and therefore the percentage increase in temperature drop between air and wall surface temperatures, would be greater for the insulated than for the uninsulated wall. If all the walls of a house were facing walls of equal insulation and surface temperatures there would theoretically be no heat transmitted to the wall surface by radiation. Under normal conditions walls are facing interior walls and furniture as well as exterior walls, and thus the effect on the surface conductance coefficients is not as great as that shown in these tests. It is a factor, however, which makes it impossible to calculate with accuracy the surface temperatures of walls on the basis of standard surface conductance coefficients. In constructing the ceiling under the attic 2 x 6-inch joists were used and their ends were extended over the 2 x 4-inch top plates of the side walls as far as the inner surface of the sheathing. The outside joists were placed with their outer surfaces in the same plane as the inner surface of the studs below. Thus, when the insulation was placed between the floor joists, it was extended over the 2 x 4-inch plates at the ends of the joists, but not over the plate of the wall at the sides of the joists. The effect of this difference in insulation over the top plates of the side walls was shown by a difference in surface temperatures of a similar wall in different locations. The inside surface temperatures were about 2 degrees lower at the top of those walls which ended at the uninsulated space than for those which ended at the insulated spaces.

An interesting point, not shown in the curves, is that the surface temperatures of the plaster were higher for wood lath than for metal lath plaster base, other construction details being the same. For instance, the surface temperature at mid-height of an insulated wall having metal lath as plaster base was 54.7° and for the same wall with wood lath it was 56.8° F. With 3⅝-inch mineral wool bat the average surface temperatures were 62.1° and 63.3° F. for walls with the metal lath and wood lath plaster bases, respectively. This same difference shows up throughout the temperatures of comparative walls. There is a difference between the surface temperatures of walls over the studs and between the studs, depending upon the type of insulation used between the studs. For walls without any insulation, with −10° F. outside air and 70° F. inside air, the surface temperatures between the studs average .5° F. colder than those directly over the studs. For walls which were finished with ¾-inch plaster on metal lath and 1-inch blanket insulation, the surface temperature between the studs was .3° F. warmer than that over the studs. For the same wall with the 2-inch blanket insulation the temperature was .4° F. higher, and for the same wall with 3⅝-inch bat insulation it was .5 of a degree higher between the studs than directly over the studs. For a wall finished with ⅜-inch plaster on wood lath and insulated with 3⅝-inch bat insulation, the surface over the central section was 1.6 degrees warmer than that over the studs. The fact that the difference is 1.6 degrees for the wood lath plaster base as compared to .5 degree for the metal lath plaster base is probably due to the higher conductance value of the metal lath plaster base.

For an uninsulated ceiling in which metal lath was used as a plaster base, the surface temperature between the studs was 41.9° F. as compared with 44.9° F. over the studs, with an attic air temperature of 7.5° F. For the same ceiling insulated with 3⅝-inch mineral wool bats, the surface temperature of the plaster between the studs was 64.3° F. as compared with 62.8° F. over the studs. A comparison between the temperatures of 44.9° F. for the uninsulated ceiling and 64.3° F. for the insulated ceiling shows why it is important to apply insulation to the upper floor ceiling. The temperature of the insulated ceiling is slightly higher than that of the surface of the insulated side wall, but the temperature of the uninsulated ceiling is approximately 13° F. lower than the corresponding temperature of uninsulated side walls.

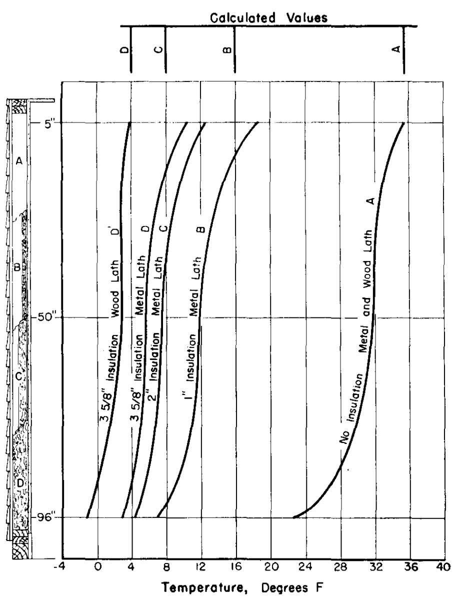

FIGURE 17. INNER SURFACE SHEATHING TEMPERATURES FOR DIFFERENT TYPES OF INSULATION.

INSIDE SURFACE TEMPERATURES OF SHEATHING

The inside surface temperatures of sheathing are important when considering the probability of condensation in walls without vapor barriers. Test values for walls having different thicknesses of insulation and for inside air temperatures of 70° F. and outside air of −10° F. are shown in the curves of Figure 17. In these curves the ordinate shows the distance from the ceiling at which the temperatures were taken, and the abscissa, the actual temperatures for the various heights. The short lines at the top of the diagram show the calculated values for sheathing temperatures of corresponding walls.

OUTSIDE SURFACE TEMPERATURES OF WALLS

The outside surface temperatures were taken for several walls, both between the studs and over the surfaces of the studs. The results are shown in Table IV.

TABLE IV

OUTSIDE SURFACE TEMPERATURES OF WALLS

Wall No.	Plaster Base	Insulation	Surface Temperatures	
			Between studs	Over studs
F	Metal lath	None	0.6	−0.5
M	Wood lath	None	0.1	−0.7
P	Metal lath	1-inch blanket	−3.5	−3.9
R	Metal lath	2-inch blanket	−4.8	−4.5
B	Metal lath	3⅝-inch bat	−4.7	−3.9
H	Wood lath	3⅝-inch bat	−5.9	−4.8

These results show that for the uninsulated wall the space between the studs is about 1 degree warmer than that over the studs. For the 1-inch blanket it is .4 of a degree warmer; for the 2-inch blanket, .3 of a degree colder; and for the 3⅝-inch bat with metal lath or wood lath, it averages about 1 degree colder between the studs. This difference is comparatively small and does not seem sufficient to explain the stud marks which sometimes appear on insulated walls.

SURFACE TEMPERATURES AT ELECTRICAL OUTLET PLATES

When electrical outlets are placed in an outside wall and connected with armored cable running through the wall, there is apt to be a difference in temperature between the exposed surface of the outlet cover plate and the adjacent surface of the wall, due to the fact that heat will be conducted from the surface of the outlet plate along the connecting cable. The difference in temperature will depend upon the type of construction and the location of the cable in the wall. It may or may not be a serious factor in so far as surface condensation is concerned.

Duplex outlets were placed in three of the outside walls and connected with armored cables which passed up through the vertical sections to the attic space above. In each case the wall was insulated with 3⅝ inches of mineral wool and the connecting cable was placed substantially in the center plane of the wool. The results of the tests are given in Table V. The average difference in surface temperatures is 7.3° F. and should not result in any condensation problem. However, if the cables were placed next to the sheathing the drop in temperature between the surface of the outlet box and the plaster would have been greater, and under these conditions condensation might take place.

TABLE V

COMPARISON OF SURFACE TEMPERATURES FOR ELECTRICAL DUPLEX OUTLET COVER PLATES AND SURFACE OF ADJOINING PLASTER

Inside Air, 70° F. Outside Air, −10° F.

Wall No.	Description of Wall		Surface Temperature, Degrees F.	
	Inside finish	Insulation	Plaster	Cover plate
A	¾-inch plaster on metal lath	3⅝-inch mineral wool	62.0	54.8
H	⅜-inch plaster on wood lath	3⅝-inch mineral wool	62.0	54.9
L	⅜-inch plaster on wood lath	3⅝-inch mineral wool	64.3	56.7

WINDOW SURFACE TEMPERATURES

The inside surface temperatures of window glass are usually lower than other surfaces which are exposed to the room air, and serve as good indicators of excessive relative humidity. In these tests inner surface temperatures were taken at various elevations of both the upper and lower window panes, with and without storm sash. The results of these tests are shown in Table VI. There is a considerable drop in temperature from top to bottom for both the upper and lower window panes.

TABLE VI

SURFACE TEMPERATURES OF WINDOW GLASS

Inside Air, 70° F. Outside Air, −10° F.

	Location	Upper Pane	Lower Pane	Calculated Value
Room surface without storm sash	2 inches from top rail	34.8	33.2	....
	Center of pane	29.7	30.8	30.2
	2 inches from bottom rail	18.0	27.6	....
Room surface with storm sash	2 inches from top rail	52.5	52.3	....
	Center of pane	48.0	47.5	47.5
	2 inches from bottom rail	40.4	38.3	....
Inside surface of glass in storm sash	Center of pane	10.5	8.9	12.8

For the single glass window the coldest surface was found near the bottom of the upper pane, the temperature being about 10 degrees lower than for a corresponding point on the lower pane. For the windows with storm sash the room surface temperature of the lower pane was slightly less than that for the upper pane for points which were 2 inches from the bottom of each. The great difference between room air and surface temperatures for the lower portion of the upper pane with single glass, double hung windows is probably due to the greater exposed surface area near the bottom of the upper pane due to the construction of the meeting rail. In all cases where condensation occurred it started first in the colder sections of the glass and gradually built out into the warmer surfaces.

The calculated values given in Table VI were calculated on the basis of inside surface conductance coefficient $f_o=1.65$, and outside coefficient equal to 2.0. As will be noted, these calculated values check very closely with the measured values for the central section of the window pane. The differences between calculated and test values for the lower surfaces of both upper and lower panes, with or without storm sash, show the fallacy of basing the probability of condensation on calculated values. For instance, with 70° F. inside and −10° F. outside air, calculations show that inside relative humidities of 22.6 and 44.7 could be carried for single and double glass windows, respectively, but the test values indicate that condensation would start at relative humidities of 12.6 and 31.5.

TEMPERATURES IN AND AROUND WINDOW FRAMES

Window sash weight enclosures, the openings above and below average window frames, and the openings around door frames, if left without insulation, constitute cold spaces where condensation may occur. The temperatures of the room surfaces of various parts of the window casings and also of the air in the open uninsulated spaces are given in Table VII.

TABLE VII

TEMPERATURES IN AND AROUND WINDOW FRAMES

Inside Air, 70° F. Outside Air, −10° F.

Location	Position		
	2 inches from top	Center	2 inches from bottom
Room surface of right trim	....	58.1	....
Air space right sash weight enclosures	53.2	30.7	21.2
Room surface of mullion trim	....	60.9	....
Air space mullion sash weight enclosures	56.5	42.0	26.0
Room surface of left trim	....	59.2	....
Air space left sash weight enclosures	49.5	27.5	6.3
Air space in frame above window	....	50.1	....
Air space in frame below window	....	16.8	....

The significant points in these results are the variations in air temperatures from top to bottom of the window sash weight enclosures with the corresponding low temperatures at the bottom of the air space. In one instance there is a variation of 43 degrees with a low temperature of 6.3° F. in the window sash weight enclosure. In all cases there was, however, very heavy frost formation on the outside surfaces of the air space for the window sash weight enclosures. This will be discussed under the heading *"Condensation within Structures."*

MOISTURE CONDITIONS WITHIN STRUCTURE AT CONSTANT OUTSIDE AIR TEMPERATURE

One of the purposes of these tests was to determine the points at which objectionable condensation might take place in different types of construction when operating a building under severe temperature and humidity conditions. To accomplish this, inside air conditions were established at 70° F. and 40 per cent relative humidity and outside air at −10° F. The test bungalow was operated under these conditions for a sufficient length of time to indicate definitely those parts which were most vulnerable to the penetration of moisture. In making the tests to determine the minimum amount of attic ventilation it was necessary to operate at constant air conditions but with different ventilation openings into the attic. This made it feasible to run a prolonged test on the side walls under constant and severe temperature and humidity conditions. The results of tests Nos. 40-9-1 to 40-9-10, inclusive, covering a sixty-nine-day period, are described here for the purpose of showing comparisons in so far as probabilities of condensation are concerned for the interior parts of various types of walls, the openings around door and window frames, the surfaces of single and double glass windows, electrical outlets and fixtures, and special features of construction such as required at joints between side walls or side walls and ceiling. The descriptions of the test walls are given in Table I, and their locations in the building are shown in Figure 7. The results described here are relative and show the comparative merits of different types of construction. The fact that condensation occurs may not mean that the wall or type of construction would be condemned. Safe operating conditions for the various types of construction are discussed in the last section of this bulletin, and in that section limiting temperatures and humidities for inside and outside air are recommended for different types of construction.

CONDITIONS WITHIN EXPOSED WALLS AFTER SIXTY-NINE-DAY TEST

Wall F.—¾-inch metal lath and plaster, no insulation and no vapor barrier.

A small amount of frost had accumulated on the inner surface of the sheathing at the bottom plate. The cracks between the sheathing boards appeared to be slightly less than normal width, indicating that a small amount of moisture had been absorbed by the sheathing during the test.

Wall P.—¾-inch metal lath and plaster, 1-inch mineral wool blanket insulation with vapor barrier attached to warm side of insulation.

Surface of sheathing over test section was clear of frost excepting in upper right-hand corner where there was a slight amount, apparently due to a vapor leak through the joints between the barrier and the plate. Conditions were considered satisfactory.

Wall R.—¾-inch metal lath and plaster, 2-inch mineral wool blanket insulation with vapor barrier attached to warm side of insulation.

The inner surface of the sheathing was clear excepting in upper right-hand corner where a small amount of frost had accumulated, due possibly to an imperfect seal between upper end of barrier and top plate. Conditions within this wall were considered satisfactory.

Wall A.—¾-inch metal lath and plaster, 3⅝-inch mineral wool bats without vapor barrier.

There was a heavy accumulation of frost over the entire inner surface of the sheathing with the exception of a narrow line opposite an electric cable which extended from top to bottom of wall. The surface of the sheathing back of the cable was clear of frost, evidently due to the heat conducted through the cable. The cracks between the sheathing boards were completely closed, indicating that a considerable amount of moisture had been absorbed by the sheathing. No frost was found between the sheathing and building paper excepting at one or two points where there were knot holes in the sheathing.

Wall B.—¾-inch metal lath and plaster, 3⅝-inch mineral wool bats with vapor barriers attached to warm side of insulation.

There was some frost on the sheathing, particularly along the horizontal joints between the bats. The width of cracks between the sheathing boards was less than normal, indicating that some moisture had been absorbed by the sheathing boards. While there was some frost formation on the sheathing, the conditions were considered satisfactory.

Wall C.—¾-inch metal lath and plaster, 3⅝-inch mineral wool bats with a continuous vapor barrier applied to the studs on the warm side of the insulation.

The inner surface of the sheathing was entirely clear of frost. The cracks between the sheathing boards appeared to be normal width and there was no indication that additional moisture had been absorbed by the sheathing. The wall was in excellent condition.

Wall E.—¾-inch metal lath and plaster, 3⅝-inch mineral wool bats with a continuous vapor barrier applied over the surface of the studs on the warm side of the insulation. There were 2-inch horizontal lapped joints between barrier sheets.

The inner surface of the sheathing was clear of frost, the cracks between the sheathing boards appeared to be of normal width, and there was no indication of any moisture having been absorbed by the sheathing. The wall was in excellent condition.

Wall I.—¾-inch metal lath and plaster, 3⅝-inch mineral wool bats with a continuous vapor barrier applied over warm surface of insulation on face of studs.

The inner surface of the sheathing was clear of frost and the width of the cracks between the sheathing boards appeared to be normal. The wall was in excellent condition.

Wall M.—⅜-inch plaster on wood lath, no insulation or vapor barrier.

The inner surface of the sheathing was covered with frost for about 3 inches at the bottom. There was also heavy frost on the inner surface of the building paper at two points where there were knot holes in the sheathing. The width of cracks between the sheathing boards was less than normal, indicating that moisture had been absorbed by the sheathing.

Wall N.—⅜-inch plaster on wood lath, no insulation or vapor barrier. This wall was the same as Wall M except that it was at the corner of the building.

There was a heavy accumulation of frost on the inner surface of the sheathing along the corner studs. There was also frost on the side surfaces of the corner studs, particularly at the bottom. There was a heavy formation of frost on the inner surface of the sheathing over the spots where nails had been driven in from the outside, even tho they did not extend through the sheathing. This wall is unsatisfactory under these operating conditions. The reason that it showed more condensation than Wall M was probably due to the fact that it was located at the cold corner.

Wall G.—⅜-inch plaster on wood lath, 3⅝-inch mineral wool bats without vapor barrier.

There was a heavy accumulation of frost over the entire inner surface of the sheathing. The cracks between sheathing boards were closed, indicating that a considerable amount of moisture had been absorbed by the sheathing boards. No frost was found between sheathing and building paper.

Wall H.—⅜-inch plaster on wood lath, 3⅝-inch mineral wool bats with vapor barrier attached.

A small amount of frost had accumulated at center of central stud section and also at top of side stud section. The frost was somewhat heavier opposite the cracks between the insulating bats. The cracks between the sheathing boards appeared to be of normal width, indicating that no great amount of moisture had been absorbed by the sheathing boards. The construction would be rated as satisfactory.

Wall L.—⅜-inch plaster on wood lath, 3⅝-inch mineral wool bats with a continuous vapor barrier.

No frost had formed on the inner surface of sheathing excepting at the extreme upper right-hand corner where a small amount had accumulated, apparently due to a poor joint between barrier and surface of studs. The cracks between sheathing boards appeared to be normal, indicating that no moisture was absorbed by sheathing. The general conditions of the wall were good.

Wall D.—⅜-inch plaster on ⅜-inch Gypsum lath, 3⅝-inch mineral wool bats with barrier attached.

A slightly greater amount of frost had accumulated on the inner surface of the sheathing of this wall than for other bat/bak insulated walls in which metal or wood lath was used. The cracks between the sheathing boards were rather tight, indicating that moisture had been absorbed by the surface of the sheathing. While the conditions for this wall were not as good as for those walls in which metal lath or wood lath was used as a plaster base they were not serious and should not cause any difficulty under normal operating conditions.

From an inspection of the walls after the sixty-nine-day test period the following general conclusions were drawn:

1. Walls with continuous vapor barriers over the warm side of the insulation are satisfactory for very severe operating conditions. It is important that the barriers be properly sealed at top and bottom plates and over the surfaces of the studs. If the barrier is installed so that there is an appreciable space between the plaster base and the barrier, it is particularly necessary to seal it at top and bottom to prevent the transfer of vapor by convection currents which may be set up by the temperature differences of the air on the two sides of the barrier.

2. Vapor barriers having horizontal joints should be applied with care to prevent the possibility of excessive leakage through the joints.

3. Insulated walls without vapor barriers on the warm side are unsatisfactory for severe operating conditions.

4. Condensation may occur in uninsulated walls under severe operating conditions. Any special features of construction which may tend to lower the temperature of the condensing surface or to accelerate the passage of vapor through the warm surface of any wall may increase the probability of condensation. The reason that condensation may occur in an insulated wall, whereas it will not occur in the same type of wall without insulation, is that insulation prevents the flow of heat through the wall and thus lowers the temperature of the normal condensing surface.

The remedies are to place a vapor barrier on the warm side of the insulation or to reduce the relative humidity carried within the building.

MOISTURE ABSORBED BY 2 X 3-INCH PINE ABSORPTION BLOCKS

The amount of moisture absorbed by a hygroscopic material depends more upon the relative humidity than upon the absolute humidity of the air with which the material is in contact. Thus, for a wood frame wall the amount of moisture which may be taken up by the sheathing, where there is no evidence of condensation, may be governed by any change in the construction which will tend to change the temperature or the density of the vapor in contact with the inner surface of the sheathing. The vapor density may be changed by controlling either the amount which enters the wall from the warm side or that which may leave it from the cold side, and the temperature may be changed by the application of insulation to the wall. For the walls used in these tests the vapor density was changed by the application of vapor resisting materials on the warm side of the insulation and the temperature was changed by the application of various thicknesses of insulation. The probable effect of the moisture conditions within the wall on the absorption of moisture by the sheathing was determined by the gain in weight of moisture absorption blocks which were placed at various elevations and at various planes within the test walls. The location within the various walls and the final moisture content of the test blocks after the sixty-nine-day test are shown in Table VIII. The results of these tests are not absolute but do show relative conditions within the test walls. The gain in moisture content for the test blocks was entirely due to the hygroscopic action of the wood, as no frost accumulated on the blocks.

Referring to Table VIII, it will be noted that the figures for final average moisture absorption are substantially the same for either the walls with metal lath or with wood lath as a plaster base when other conditions were equal. Referring to Walls F and A, it will be noted first, that the average moisture absorption for the block in the center plane of the stud space was slightly higher for Wall F without insulation than for Wall A with insulation. This same thing is true when comparing Walls M and G, and may be due to the fact that for the insulated wall the temperature at the inner surface of the sheathing is

TABLE VIII

FINAL MOISTURE CONTENT IN PER CENT FOR 2-INCH BY 3-INCH WOOD BLOCKS PLACED AT DIFFERENT POSITIONS IN THE STUD SPACES OF TEST WALLS

Test Conditions—Inside Air, 70° F. and 40 Per Cent Relative Humidity. Outside Air, 10° F., Continuous for 69 Days

Wall No.	Insulation	Type of Barrier	Test Blocks: Horizontal Position	Vertical position and final moisture content, per cent: Top	Center	Bottom	Average
			¾-Inch Plaster on Metal Lath				
F	None	None	Next to plaster	4.82	5.55	6.72	5.70
			Center of stud space	6.23	6.94	8.20	7.12
			Next to sheathing	8.06	7.29	8.85	8.07
A	3⅝-inch bats	None	Next to plaster	4.83	4.79	3.94	4.52
			Center of stud space	4.49	5.52	6.77	5.59
			Next to sheathing	13.52	17.97	16.55	16.01
B	3⅝-inch bats	Attached with one side paraffin coated	Next to plaster	3.32	4.03	2.41	3.25
			Center of stud space	4.89	5.86	4.02	4.92
			Next to sheathing	12.65	13.45	12.12	12.74
C	3⅝-inch bats	Separate surface glazed asphalt sheet	Next to plaster	1.07	1.23	0.92	1.07
			Center of stud space	3.43	2.88	2.60	2.97
			Next to sheathing	5.61	6.30	5.25	5.72
			⅜-Inch Plaster on Wood Lath				
M	None	None	Next to plaster	5.96	6.51	8.56	7.01
			Center of stud space	6.91	6.22	10.44	7.86
			Next to sheathing	6.89	7.91	14.53	9.78
G	3⅝-inch bats	None	Next to plaster	4.13	3.76	3.40	3.76
			Center of stud space	5.13	5.00	5.30	5.14
			Next to sheathing	15.85	12.74	13.54	14.04
H	3⅝-inch bats	Attached with one side paraffin coated	Next to plaster	3.21	3.60	1.50	2.77
			Center of stud space	5.51	5.54	3.67	4.91
			Next to sheathing	12.81	16.30	5.84	13.65
L	3⅝-inch bats	Separate surface glazed asphalt sheet	Next to plaster	1.71	1.79	1.35	1.62
			Center of stud space	4.11	4.11	3.58	3.93
			Next to sheathing	7.15	5.92	4.60	5.89

lower than for the uninsulated walls, and this tends to lower the absolute humidity of the air within the space and therefore lowers the relative humidity along the central plane of the wall. For the insulated wall the blocks on the warm side of the insulation absorbed a lesser amount, and those on the cold side absorbed a greater amount, of moisture than corresponding blocks within the uninsulated wall. This is due to the fact that the application of insulation increases the temperature gradient between the warm and the cold surfaces of the space between the studs and thus lowers the relative humidity on the warm side and raises it on the cold side of the space. Referring to Walls C and L, each having good vapor barriers on the warm side of the insulation, it will be noted that the percentage of moisture absorbed by the blocks in the center line of the insulation is much less than that for corresponding blocks in the insulated Walls A and G which do not have barriers. This shows the effect of the vapor barriers in reducing the vapor density within the space between plaster base and sheathing. For Walls B and H, which are insulated with 3⅝ inches of mineral wool and which have vapor barriers attached to the warm side of the insulation, the amount of moisture absorbed by the center line blocks is somewhat less than the percentage absorbed by corresponding blocks in Walls A and G which are insulated without barriers, but it is greater than that absorbed by corresponding blocks in the insulated Walls C and L which have continuous barriers. The inspection after the test showed that there was not a large amount of condensation on the surface of the sheathing for Walls B and H as compared with that on the surface of the sheathing for Walls A and G. In other words, the results from the absorption blocks indicate that the conditions in Walls B and H were more similar to those found in Walls A and G than to those found in Walls C and L, whereas the examination of the sheathing after the test showed the reverse condition to be true.

An explanation of this apparent difference might be as follows: The vapor density or relative humidity within the insulated space is controlled first, by the ratios of the vapor transmittance of the warm side to that of the cold side, and second, by the temperature of the sheathing. As the ratio between the vapor transmittance increases, the vapor density increases until its dew-point temperature reaches the temperature of the sheathing. After this point is reached any further increase in the ratio will only mean more condensation, and, to a large extent, the relative humidity will remain constant and will be governed by the sheathing temperature. From this it is apparent that the absorption blocks will serve as indicators of vapor densities in the wall up to the point of condensation, but that the inspection method is necessary to determine the complete results.

The variation in relative humidity from the bottom to the top of the space in a given plane depends upon the temperature gradient from bottom to top, and also upon the absolute humidity gradient. For the open-spaced walls there is a considerable amount of circulation by convection due to the difference in temperatures between the warm and the cold side of the air space. The temperature difference is shown in Figure 15 to be as much as 14 degrees for the center of the air space. At the same time vapor may be passing through the warm surface of the wall. Thus the absolute humidity may be increasing from the bottom to the top, but due to the temperature rise, the relative humidity may be decreasing. Referring to Walls F and M, the absorption blocks show greater percentages of absorption at the bottom than at the top. The absolute moisture content would logically be greater at the top than at the bottom of the space, but the gain in temperature from bottom to top is sufficient to cause a reduction in relative humidity. The same condition exists in Wall M. For the cold side of Wall F there is a slightly greater absorption for the test block at the bottom than at the top of the air space, but in Wall M there is a considerably greater percentage of absorption for the bottom than for the top blocks. For Wall A, in which the space was filled with insulation, the absorption blocks next to the plaster show a higher absorption at the top than at the bottom of the air space. This same condition exists in Wall G. In these walls there is very little change in temperature from bottom to top due to lack of free air circulation, but there is an increase in moisture near the top. Thus the relative humidity in these is greater at the top than at the bottom of the space next to the plaster. Walls C and L show very low moisture absorption for all of the test blocks, indicating a very dry wall.

CONDITIONS WITHIN WINDOW AND DOOR FRAMES AFTER TEST

Window No. 1.—A heavy ice formation was found over the inside face of the blind stop in the sash weight enclosure on the left side of the window. The accumulation of ice was approximately one half the depth of the enclosure near the bottom, and gradually decreased in depth toward the top of the blind stop. A typical condition of ice formation is shown in Figure 18 for the right sash weight enclosure with the inside trim removed. The accumulation of ice in this section was approximately the same as that for the left sash weight enclosure.

Window No. 2.—A small amount of frost and ice was formed at the bottom of the left sash weight enclosure and extended up for a short distance on the inside surface of the blind stop. There was about ¾ inch of ice at the bottom of the right sash weight enclosure which covered the entire inner surface of the blind stop and tapered off about three fourths of the way up. The center sash weight enclosure was substantially half full of ice and frost at the bottom and tapered off about half way up as shown in Figure 19. Heavy ice was formed in the space underneath the sill and also in the space above the head jam.

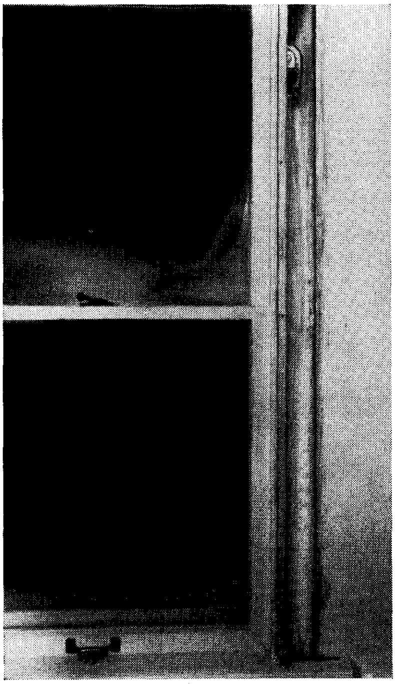

FIGURE 18. ICE FORMATION WITHIN LEFT SASH WEIGHT ENCLOSURE, AND CONDENSATION ON WARM SURFACES OF GLASS FOR WINDOW NO. 1.

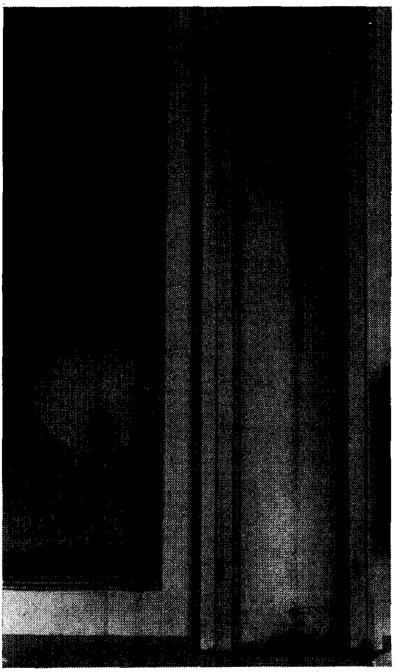

FIGURE 19. ICE FORMATION WITHIN MULLION ENCLOSURE OF WINDOW NO. 2, AND CONDENSATION ON WARM SURFACES OF GLASS.

Window No. 3.—The sash weight enclosure on the right-hand side at the bottom was half full of frost and ice which extended substantially half way up on the inside surface of the blind stop. The sash weight enclosure on the left side showed heavy frost at the bottom which tapered off about 18 inches from the bottom. There was solid ice about 1 inch thick on the inner surface of the outer head casing in the space above the head jam.

OUTSIDE DOOR FRAME

Very heavy frost and ice had formed in the upper part of the space on the right side of the door frame between the side jam and stud. This extended nearly to the bottom of the space. There was practically no ice in the space at the left side of the door casing. There were, however, indications of air leakage between this space and the outside air. The space over the top of the door head jam was filled with frost which was approximately ¾ inch thick on the inner surface of the outer trim.

The frost and ice formation in the sash weight enclosures of the windows and around the openings next to the window and door frames was very much heavier than that found in any of the walls. This indicates that the spaces around the window and door frames may present more serious condensation problems than those found in outside walls either with or without insulation. Figures 18 and 19 show the ice conditions as found in the sash weight enclosures for Windows 1 and 2, and are typical of other similar spaces.

ROOM SURFACES OF WINDOW GLASS DURING TEST

The room surfaces of the windows were very badly frosted during and after the sixty-nine-day test. There was a heavy frost and ice formation on the lower portions of both the upper and the lower panes, and also on the inner surfaces of the storm sash where used. As shown by Table VI, the room surface temperatures for both the upper and the

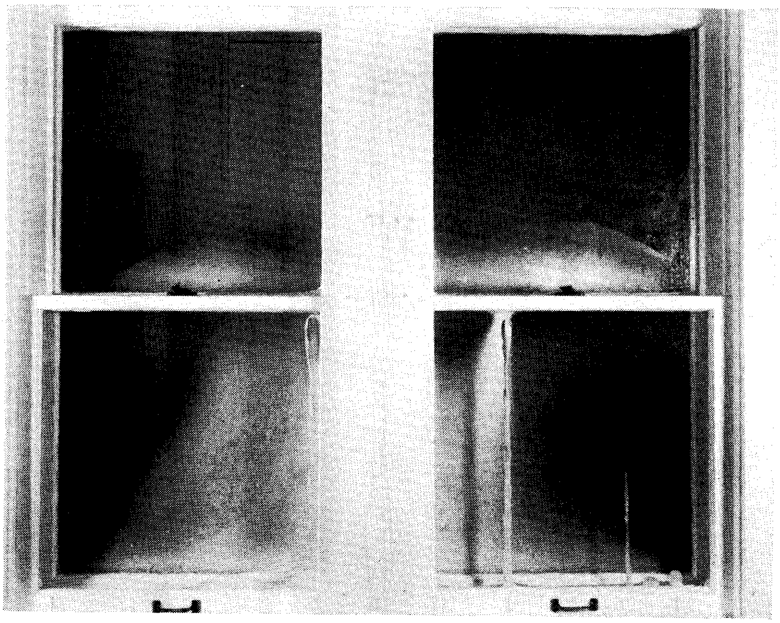

FIGURE 20. CONDENSATION ON WARM SURFACES OF GLASS FOR DOUBLE WINDOW NO. 2 WITH STALAGMITES FORMING BETWEEN INSIDE WINDOW AND STORM SASH.

lower window panes were lower at the bottom than at the top. The moisture which formed on the inner surfaces ran down from the upper area and formed heavy ice near the bottom of each pane. From the top sash some of the water ran down and dripped through the crack at the parting rail, forming stalagmites between the inner and the outer sash. The heavy ice formation at the lower part of the sash and also the stalagmites between the lower sash are shown in Figure 20. The heavy frost and ice formation on the windows on which storm sash were used indicated that the test conditions were too severe for practical operation with double glass windows. From Table VI the room surface temperature of the lower pane 2 inches from the bottom rail was 38.3° F. and that for a corresponding point on the upper pane was 40.4° F. The dew-point temperature ot the air within the room was slightly above 44° F., thus condensation was inevitable. For windows without storm sash the corresponding temperatures were 18° and 27.6° F. for the upper and lower panes, respectively. In order to avoid condensation upon the room surfaces of the windows it would have been necessary to maintain an inside relative humidity of 31 per cent when using storm sash, and from 13 to 15 per cent when operating without storm sash.

CONDITIONS WITHIN ATTIC

During the greater part of the test period, ventilation was provided for the attic space by openings in the three gable windows in the attic. The conditions of ventilation and the results for different tests will be discussed under the heading "Moisture Conditions within Attic."

MOISTURE CONDITIONS WITHIN STRUCTURE AT VARIABLE OUTSIDE AIR TEMPERATURES

In the first series of tests on the bungalow, inside and outside air conditions were held constant throughout each test period. In practice, buildings are subjected to variable outside temperatures, and part of the exterior surfaces may be exposed to radiant heat from the sun at certain periods throughout the day. The operating conditions for Tests Nos. 40-10 to 40-14, inclusive, were planned to simulate the effects of these variables on the building.

During the months of January and February, 1936, exceptionally low temperatures were experienced throughout the northern sections of the United States, and condensation problems developed for the first time in many buildings. An examination of the Minneapolis Weather Bureau records showed that for the periods of lowest temperatures, from January 18 to February 20, 1936, the average of the mean daily temperatures was —8.3° F. The records also showed that the average of the mean daily temperatures for January and February for the twenty-year period between 1891 and 1910, inclusive, was +14.3° F. The curves of Figure 21, giving the average hourly temperatures for the two periods, show a difference of approximately 22° F. throughout the day. The 1936 period was considered as representing the most severe conditions which would be exepected.

TEST CONDITIONS

An outside temperature cycle was selected which ranged between 0° and —15° F. This conformed very closely to, and equaled in severity, the Weather Bureau records for 1936. As it was difficult to control the cooling cycle to conform exactly with predetermined temperature range, it was impossible to avoid some differences between the various tests. A typical operating curve, as used in this series of tests, is superimposed on the mean daily temperature curve for 1936 in Figure 21.

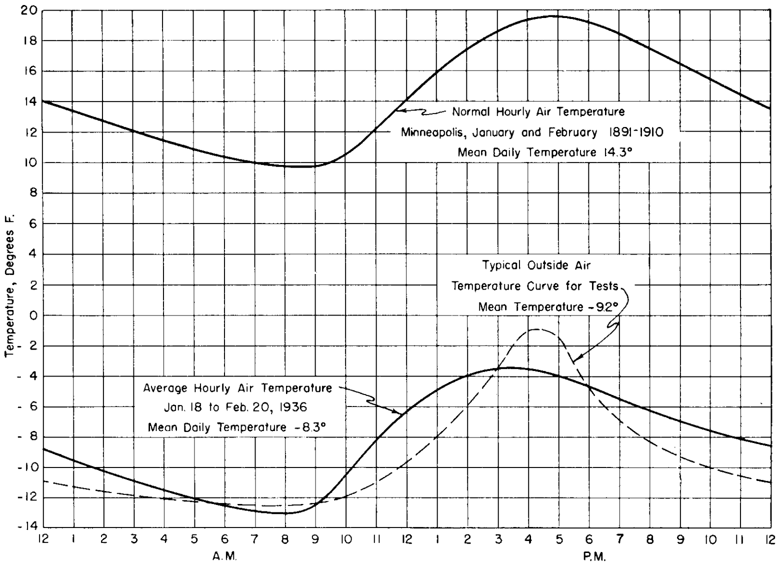

FIGURE 21. CURVES SHOWING OUTSIDE AIR TEMPERATURES FOR TWO DIFFERENT PERIODS, AS OBTAINED FROM WEATHER BUREAU RECORDS, AND TYPICAL OUTSIDE AIR TEMPERATURES FOR TESTS.

In order to simulate the effect of sunshine on the exterior of the walls a heat radiating device was constructed and radiant heat was applied to a part of the wall for a predetermined time during each twenty-four-hour cycle. The radiating device consisted of an open-face box 4 feet wide, 8 feet high, and 10 inches deep. Two inches of insulation was used on the side walls, and the inner surfaces were lined with bright metallic foil. Eighteen electric light bulbs were uniformly distributed on the inside over the 4 x 8-foot area. In applying heat to the walls the open face of the radiant heat box was clamped by special hooks which were easily removed, and the box was sealed against the exterior surface of the test wall by means of a rubber gasket. The heat was then turned on and adjusted to give, as nearly as possible, a uniform temperature rise to the inner surface of the sheathing, and to reach 35° F. at the end of approximately two hours. At the end of the two-hour period the heat was turned off and the wall allowed to cool until the end of a second two-hour period, after which the radiant heat device was removed. Temperatures of the interior surface of the sheathing were recorded at twenty-minute intervals throughout the four-hour test cycle.

A second heat radiating box, 39 inches wide, 61 inches high, and 10 inches deep, was constructed in the same manner as the one previously described, and was used to apply radiant heat to one half of double window No. 2, as shown in Figure 6. The cycle used in this test was the same as that for the side walls with the exception that temperatures were taken of the air space within the sash weight enclosure.

The curves of Figure 22 show the average outside air temperatures for the tests, the inner surface temperatures of the sheathing for Wall A

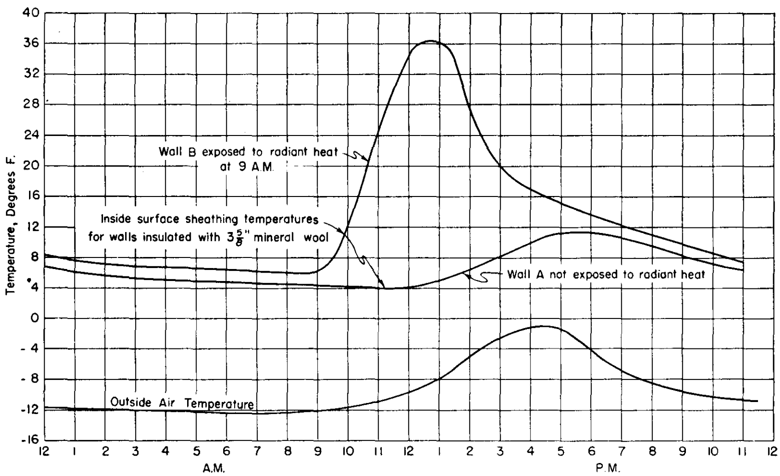

FIGURE 22. CURVES SHOWING THE OUTSIDE AIR TEMPERATURES AND INSIDE SURFACE TEMPERATURES OF SHEATHING EXPOSED AND NOT EXPOSED TO RADIANT HEAT.

without radiant heat, and the inner surface temperatures of the sheathing for Wall B with radiant heat applied. The curves for the inner surface temperatures of the sheathing represent temperatures taken in Test 40-12. As will be noted, the inner surface of the sheathing was raised to a temperature above 32° F., and as will be shown by results of tests, there was evidence that frost was melted and that the water soaked into the inner surface of the sheathing as the result of the application of radiant heat to certain of the walls.

DESCRIPTION OF WALLS TESTED

The construction of the thirteen walls tested is given in Table IX. They represent five conditions in so far as the application of insulation is concerned:

1. Wall F—no insulation and no vapor barrier.
2. Walls C, E, and L—3⅝-inch bat insulation with continuous vapor barriers over the warm surface of the insulation.

3. Walls P and R—one-inch and two-inch blanket insulation, respectively, with a vapor barrier lining on the warm side of the blanket.

4. Walls B, D, and H—3⅝-inch bat insulation with vapor barriers attached to warm side of the bats.

5. Walls A, I, G, and M—3⅝-inch bat insulation without vapor barriers.

There are some differences between the individual walls of certain groups as to the type of plaster base used, and for Walls P and R of Group 3 different thicknesses of blankets were used. Four of the walls were exposed to the four-hour cycle of radiant heat as indicated in Table IX.

TABLE IX

DESCRIPTION OF WALLS WITH AND WITHOUT SUN EFFECT FOR VARIABLE TEST CYCLES

Wall No.	Inside Finish		Mineral Wool Insulation	Description of Vapor Barrier
	Lath	Plaster		
F	Metal	¾-inch	None	None
C	Metal	¾-inch	3⅝-inch bats	Asphalt impregnated and glossy surface coated
E	Metal	¾-inch	3⅝-inch bats	Asphalt impregnated and glossy surface coated
L	Wood	⅜-inch	3⅝-inch bats	Asphalt impregnated and glossy surface coated
P*	Metal	¾-inch	1-inch blanket	Black Kraft, one side asphalt coated
R	Metal	¾-inch	2-inch blanket	Black Kraft, one side asphalt coated
D	⅜-inch Gypsum	⅜-inch	3⅝-inch bats	Paraffin coated on one side and ribbed asphalt on opposite side
B*	Metal	¾-inch	3⅝-inch bats	Paraffin coated on one side and ribbed asphalt on opposite side
H	Wood	⅜-inch	3⅝-inch bats	Paraffin coated on one side and ribbed asphalt on opposite side
A	Metal	¾-inch	3⅝-inch bats	None
I*	Metal	¾-inch	3⅝-inch bats	None
G	Wood	⅜-inch	3⅝-inch bats	None
M*	Wood	⅜-inch	3⅝-inch bats	None

* Indicates walls exposed to four-hour cycle of radiant heat.

RESULTS OF TESTS ON SIDE WALLS

There were five tests in this series, each run under the conditions as shown in Table X. In all of the tests the inside air was maintained at 70° F. and the inside relative humidity was maintained constant throughout each test period but was varied from 20 to 40 per cent for the different tests. It was the intention to maintain outside air temperatures at a variable cycle from 0° to −15° F. for the first four tests, and from +10° to −5° F. for the fifth test. The actual temperature ranges varied from these figures as shown in Table X. A test period of seven days was selected as a reasonable length of time for each test of the series. This gave seven complete cycles, and was a sufficient length of time to indicate differences in results for the various types of wall construction.

At the end of each seven-day test period the exterior sections of the walls were removed and the results noted by a visual inspection. The results will be considered for each type of construction under the different test conditions.

Wall F—without insulation or vapor barrier.

No frost was found on the interior surface of the sheathing for any of the tests. For Test 40-13, with 40 per cent inside relative humidity, the cracks between the sheathing boards appeared to be slightly narrower at the end of the test than at the beginning, thus indicating some moisture absorption by the sheathing. For practical purposes it may be said that the wall was not affected by the tests.

Walls C, E, and L—all having 3⅝-inch insulation with a good type of vapor barrier applied in a continuous sheet over the warm surface of the studs.

All walls appeared to be in the same condition at the end as at the beginning of each test.

TABLE X

RECORD OF TEST CONDITIONS MADE AT VARIABLE OUTSIDE AIR TEMPERATURES

Test No.	Duration in Hrs.	Inside Air, Degrees F.		Outside Air, Degrees F.	
		Dry bulb temp., degrees F.	Rel. humid., per cent	Variation*	Average
40-10	168	70	20	−0.4 to −14.3	−10.0
40-11	168	70	25	−0.3 to −12.9	− 9.5
40-12	168	70	30	−1.2 to −12.6	− 8.6
40-13	168	70	40	−0.6 to −11.1	− 8.4
40-14	168	70	40	+9.8 to − 4.6	+ 2.4

* Variable outside temperature cycle consisted of lowering the temperature in 16 hours and raising the temperature in 8 hours.

Walls P and R—each having blanket insulation but of different thicknesses as shown in Table IX. Radiant heat was applied to Wall P but not to Wall R.

Wall P appeared to be the same at the end as at the beginning of each test, while for Wall R there was a slight amount of frost which accumulated in the upper part of one stud section during Test 40-13, with 40 per cent relative humidity, but this was not considered enough to cause any condensation problem.

Walls B, D, and H—all insulated with 3⅝-inch bats with barrier attached to warm side.

Different types of plaster base were used on each of the walls, and Wall B was subjected to the radiant heat. For tests 40-10 and 40-11 with 20 to 25 per cent relative humidity, respectively, and an outside temperature of 0° to −15° F., there was no frost formation on the sheathing of any of the walls and they all appeared to be in the same condition after as before the tests. In Test 40-14, where the inside relative humidity was 40 per cent and the outside air temperature varied from +10° to −5° F., the conditions of the walls were substantially the same as in Tests 40-10 and 40-11. For Test 40-12, with 30 per cent relative humidity, there was some frost on the sheathing at the joints between the insulating bats. For Test 40-13, with 40 per cent relative humidity, the frost accumulation was heavier at the joints, but not sufficient to cause any serious condensation problem. Wall B, to which radiant heat had been applied, showed slightly less frost than either of the other two, due to the surface temperature of the sheathing being above the melting point of the frost during part of the tests.

Walls A and I—insulated with 3⅝-inch bats without vapor barrier. Radiant heat was applied to the exterior surface of Wall I.

For Test 40-10, at 20 per cent relative humidity, light traces of frost were found on the sheathing of Wall A, while Wall I showed no frost. For Test 40-11, with 25 per cent relative humidity and an outside air temperature of 0° to −15° F., there was some frost on the sheathing, and in some cases the insulation was frozen to the surface of the sheathing. The heaviest accumulation of frost was at the line of joints between the bats. For Wall I the insulation was not frozen to the sheathing but the cracks between the sheathing boards appeared to have been reduced in size, indicating that more of the moisture had entered the sheathing boards. Conditions similar to those in Test 40-11 were found in Test 40-14 where the inside relative humidity was 40 per cent and the outside air temperature varied from +10° to −5° F. For Test 40-12, with 30 per cent relative humidity and an outside temperature of 0° to −15° F., there was about 1/16 inch of frost distributed over the inner surface of the sheathing for Wall A with the insulation frozen to the sheathing over approximately 50 per cent of the area of the wall. For Wall I with radiant heat applied there was very little frost on the surface of the sheathing, but the sheathing boards were warped and the cracks between them were narrower than for Wall A. For Test 40-13, with 40 per cent relative humidity and an outside temperature of 0° to −15° F., the frost formation was very much heavier over the surface of the sheathing for both walls.

Walls G and M—the same construction as Walls A and I with the exception that wood lath was used as a plaster base instead of metal lath.

The results were substantially the same as those for Walls A and I, and the discussion for Walls A and I will apply to Walls G and M, respectively.

The results of the tests on these four walls with 3⅝-inch insulating bats and no barrier indicate that 25 per cent relative humidity at an outside temperature cycle of 0° to −15° F. is about the maximum that can be carried without danger of condensation. For an outside temperature cycle of +10° to −5° F., 40 per cent relative humidity is about the maximum. The effect of radiant heat is to melt the frost, the water being absorbed by the sheathing boards causing them to warp.

CONCLUSIONS FROM TEST RESULTS ON WALLS

1. In so far as could be determined by a visual inspection, the test results for the variable outside temperature cycle of 0° to −15° F. used in this series were substantially the same as those obtained for a constant outside temperature of −10° F. as used in previous tests for comparable inside relative humidities.

2. The application of radiant heat has a tendency to melt the frost, the water from which is absorbed by the sheathing boards causing them to warp. It tends to alleviate one condition by reducing the quantity of frost accumulation, and to aggravate another condition by increasing the swelling and warping of the sheathing.

3. At 20 per cent relative humidity for the inside air, all walls were entirely satisfactory. At 25 per cent relative humidity for the inside air and an outside temperature cycle of 0° to −15° F., walls without vapor barriers, and exposed to these conditions for short periods, may be con-

sidered satisfactory. The same conditions may exist for these walls when the inside humidity is increased to 40 per cent with a corresponding increase in outside temperature cycle of +10° to —5° F. At 30 per cent relative humidity and an outside air temperature of 0° to —15° F., the walls which were insulated and did not have a vapor barrier showed no accumulation of frost on the surface of the sheathing. This humidity is not recommended for walls without vapor barriers at these outside air conditions.

4. The insulated walls with continuous barriers over the warm side of the studs showed no accumulation of frost for any of the tests and are therefore satisfactory.

5. Walls which were insulated with bats with barriers attached and horizontal butt joints between the bats did show a frost accumulation on the surface of the sheathing opposite the joints in several instances. It was not sufficient in these tests, however, to cause any serious condensation troubles.

RESULTS OF TESTS ON WINDOW AND DOOR CASINGS

The conditions found within the window and door casings after the first four tests were very similar to those found in previous tests at a constant outside temperature condition of —10° F. and similar inside conditions. These results have in all cases been somewhat erratic. This has probably been due to the fact that the inner casings were removed after each test, and in replacing them there was some variation in the tightness of fit, which affected the amount of vapor which could pass through the cracks.

The effect of radiant heat was to melt the frost from the cold surface of the window casings. A part of the water thus formed soaked into the casing and a part ran down, forming heavier frost or ice at the lower part.

From the results of these tests it is safe to say that no frost difficulties would occur in the casings at anything up to 20 per cent relative humidity in combination with an outside temperature cycle of 0° to —15° F. and probably there would be no difficulty with humidities up to 25 per cent. At 30 per cent humidity, ice and frost formed which might cause serious difficulty. At humidities above 30 per cent the formation was not consistent, but there was sufficient to make it inadvisable to run humidities above 30 per cent with this type of construction, and for outside temperatures of —10° F. Probably 25 per cent should be a maximum safe operating condition.

MOISTURE CONDITIONS WITHIN ATTIC

One of the purposes of the tests on the bungalow was to determine the practical limits to which attic ventilation could be applied to reduce or eliminate condensation. The attic ventilation studies were made concurrently with those on side wall construction. Two different types of roofs—a flat and a gabled—were used over the attic space studied. The original bungalow was constructed with a flat roof, and after the tests on this were completed, it was removed and a gabled roof applied. For convenience in making the necessary inspection during tests the side walls for the flat roof construction were made 24 inches high. The side walls for the gabled roof construction were also approximately 24 inches high, and sufficient space was provided for a second floor room, but this was not used for the tests.

ATTIC WITH FLAT ROOF

Figure 1 shows the cross-sectional view and Figure 7 the floor plan of the bungalow having a flat roof. The roof was constructed with 2 x 4 rafters spaced 16 inches on center and covered with 1 x 8-inch pine shiplap and asphalt roofing material weighing 50 pounds per 100 square feet. The side walls, which were approximately 2 feet in height, were constructed with 2 x 4 studs spaced 16 inches on center and covered with 1 x 8-inch pine shiplap sheathing, building paper, and lap siding. The attic floor, or ceiling of room below, was constructed with 2 x 6 joists spaced 16 inches on center with ¾-inch metal lath and plaster applied to the under side, and 3⅝-inch mineral wool bats placed between the joists. Electric lights were located in the ceilings of each of the rooms

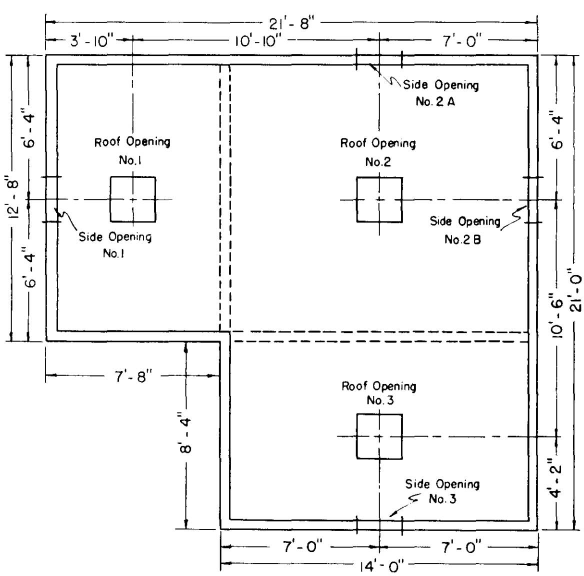

FIGURE 23. LOCATION OF SIDEWALL AND ROOF OPENINGS FOR FLAT ROOF CONSTRUCTION USED IN TEST SERIES 40-1 TO 40-8, INCLUSIVE.

below and armored cables were carried from the side wall switches up through the partitions and over the attic floor to the lights as shown in Figure 7.

Adjustable ventilation openings were placed in the attic side walls and in the roof as shown in Figure 23. Only one set—either side wall or roof openings—was used for a particular test. For a part of the tests in which the roof openings were used ventilation was provided through plain openings in the flat roof, and for the remainder of the tests it was provided by special roof ventilators, the design of which is shown in Figure 24. These ventilators were designed to introduce and exhaust ventilation air through adjacent openings in the roof without interference between the two streams of air. Outside air was taken from just above the outer surface of the roof and carried down by a ventilation flue to within 6 inches of the attic floor. Exhaust air was taken from the under side of the roof boards and carried up through a ventilation flue for a distance of two feet above the roof. By this method ventilation air could be applied to any given area independent of side wall opening. All openings in the roof and side walls were provided with shutters and could be closed tight during any test period.

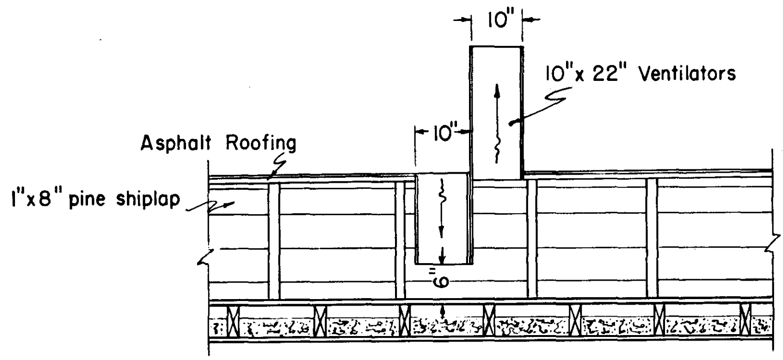

FIGURE 24. SECTION THROUGH ROOF CONSTRUCTION SHOWING SPECIAL ATTIC VENTILATORS.

ATTIC WITH GABLED ROOF

After the tests on the flat roof construction were completed the roof was removed and a gabled roof installed as shown in Figures 5 and 6. The side walls were 24 inches from top of plate to top of floor joists, and the roof was pitched with a ratio of 1 to 1. The side walls and roof were of the same design as for the flat roof construction. The attic floor remained the same as for the flat roof construction excepting that an attic stair well and stairs were installed. The attic stairs were installed without insulation in the side walls for the stair well and without special precautions to prevent air leakage around the attic door. After the first tests were made it became evident that a large amount of air leakage was taking place through the walls of the attic stair well and through the cracks around the attic door. The walls were then insulated and the cracks between the plaster board sheets, which were used for the wall surfaces, were carefully taped. The warm surfaces of these walls were also painted with two coats of interior paint. A rubber gasket was used around the attic door to prevent excessive air leakage. Adjustable ventilation openings were provided in three of the side walls, as shown in Figure 25. These consisted of 18 x 18-inch two-light double-hung windows placed in each gable at a distance of 38 inches above the attic floor. No vapor barriers were used except that the walls of the stair well were sealed as previously described.

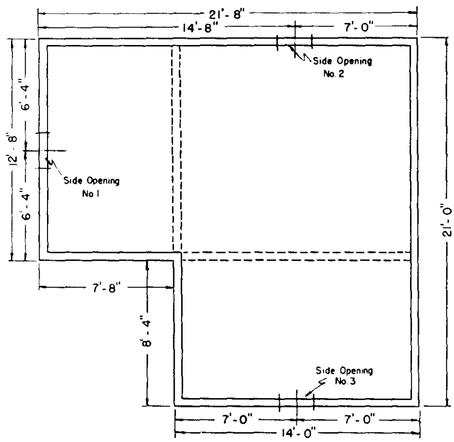

FIGURE 25. DIAGRAM SHOWING LOCATION OF SIDE WALL OPENINGS USED IN GABLES TO VENTILATE ATTIC FOR TEST SERIES 40-9 TO 40-14, INCLUSIVE.

RESULTS OF TESTS USING FLAT ROOF

Fourteen tests were made with the attic having a flat roof. The results of these tests are summarized in Tables XI, XII, and XIII. The inside and outside air conditions shown for each test were maintained constant throughout the test period.

In evaluating the results of a given test, the surfaces upon which frost accumulated, such as the under side of roof boards, inner surfaces of side walls, exposed surfaces of insulation around electrical boxes and cables, and cold surfaces of ceiling joists next to insulation, etc., were examined and an estimate was made of the amount of frost accumulated during the test period. Consideration was given to the duration of the test in hours, and the results were recorded as "none," "trace," "light," "medium," "heavy" frost accumulation. Conditions reported as "trace," or "light," were not such as to be considered serious or apt to give any

TABLE XI

CONDITIONS IN ATTIC WITH FLAT ROOF FOR DIFFERENT TYPES OF VENTILATION AND DIFFERENT OPERATING CONDITIONS

Test No.	Duration in Hours	Inside Air		Outside Air, Degrees F.	Ventilating Opening			Frost Accumulation during Test	
		Degrees F.	Rel. humid., per cent		Side wall[a]	Roof[a]	Size, sq. in.[b]	Inner surfaces of roof boards and side walls	Around electrical boxes, cables, and joists
40-1	276	70	25	0	None	None	....	None except on nailheads and trace in cold corner	None
40-2	126	70	30	0	None	None	....	Trace	Trace
40-3	159	70	53	+15	None	None	....	Trace	Trace
40-4	158	70	17	−15	None	None	....	Trace	Trace
40-5	154	70	30	−10	1, 2a, 2b, 3	None	1/4	None	Medium
40-6-1	32	70	40	−10	1, 2a, 2b, 3	None	1/8	Heavy	Heavy
40-6-2	126	70	40	−10	1, 2a, 2b, 3	None	1/4	Light accumulation near openings 2a and 3	Heavy
40-7-1	194	70	40	−10	1, 2b, 3	None	1/4	Light with medium accumulation near opening 3	Heavy
40-7-3	72	70	40	−10	1, 2b	None	1/2	Light to medium over Rooms 1 and 2, heavy over Room 3	Heavy
40-7-5	99	70	40	−10	None	1, 2, 3*	1 3/4	Light	Heavy
40-7-6	117	70	40	−10	None	1, 2, 3*	1/2	Light over Room 2, heavy in corners and over Room 3	Heavy
40-8-1	168	70	40	−10	None	1, 2, 3*	1/4	Light to medium over Rooms 1 and 2, heavy in corners and over Room 3	Heavy
40-8-3	168	70	40	−10	None	1, 2, 3†	1/4	Light over Room 2, heavy over Room 3, medium accumulation on inner surfaces of exhaust duct and outer surfaces of supply duct extending into attic space	Heavy
40-8-4	168	70	40	−10	None	1, 2, 3†	1/8	Same as in Test 40-8-3, except heavier	Heavy

[a] Refer to Figure 23 for location of roof and side wall openings.
[b] Size refers to area of each opening in square inches per square foot of total ceiling area.
* Square openings cut through roof.
† Special ventilators used, see Figure 24.

condensation trouble. The results of the visual inspection are reported in Table XI. The temperatures recorded in Table XII and the air circulation data in Table XIII were taken at various periods throughout the test.

The first four tests were made without any attic ventilation. The three tests, 40-2-3 and 4 were made under temperature and humidity conditions which were more severe than those for Test 40-1, and which, from a curve to be explained later, all showed equal probabilities of condensation. As will be noted from the results recorded in Table XI, these conditions may be considered safe, and probably the limiting conditions which could be used for continuous operation without encountering frost.

For the five tests, 40-5 to 40-7-3, inclusive, ventilation openings were provided in the side walls as indicated. For the remainder of the tests they were provided in the roof, three of them having plain openings through the roof and two having special ventilators as indicated.

The general conclusions covering attic ventilation will be discussed at the end of this section. Those which are particularly apparent from the tests on the flat roof construction are:

1. Attic ventilation will reduce the rate of frost accumulation on the under side of roof boards and, if conditions are not too severe, it may eliminate the frost altogether.

2. It is difficult to prevent condensation in areas around electrical cables, over ceiling lights, and similar places by the use of ventilation alone. This applies to any specific points where vapor may be entering and where it is not easily diffused with the air supplied by ventilation before coming in contact with cold surfaces.

3. The ventilation air cools the attic space and thus increases the heat loss through the ceiling. This loss is, however, not great, and should not exceed 5 per cent of the initial heat loss through an insulated ceiling if the amount of ventilation air is kept within reasonable limits.

4. If roof ventilators are to be used the air is more effectively distributed with the special design shown in Figure 24 than when plain openings are used.

5. When a ventilator duct as shown in Figure 24 extends through the roof, the inner surface of the duct above the roof line may become very cold, thus causing more condensation on the inner lining of the exhaust duct than would ordinarily be encountered in the ventilated space.

6. If excessive attic ventilation is used it may transfer attic condensation problems from under side of roof boards to the upper surfaces of insulating materials or electrical conduits, and perhaps the surfaces of floor joists. This was indicated by the fact that when all of the side wall and roof vents were opened to clear out the frost which had accumulated over previous test periods, the under surfaces of the roof and the inner surfaces of side walls were readily cleared of frost, but there was a much heavier frost accumulation on the top surface of insulation over electrical outlets and ceiling lights, and over certain of the partitions where electric cables passed up into the attic space. Under these conditions the attic air was cooled down to substantially outside air temperatures.

7. With the type of construction used and without attic insulation, no serious difficulty should be encountered when operating at 70° F. and 30 per cent relative humidity inside air with zero degrees outside air.

8. For the same inside air and —10° F. outside air no difficulty should be experienced with ventilation as shown in Test 40-5. From these tests, however, trouble may be encountered even if ventilation is resorted to under more severe conditions of operation.

TABLE XII

TEMPERATURES IN ATTIC WITH FLAT ROOF FOR DIFFERENT TYPES OF VENTILATION AND DIFFERENT OPERATING CONDITIONS

Test No.	Inside Air		Outside Air, Degrees F.	Ventilating Opening			Attic Air Temperature				Inside Roof Surface Temperature			
	Degrees F.	Rel. humid., per cent		Side wall[a]	Roof[a]	Size, sq. in.[b]	R-1[c]	R-2[c]	R-3[c]	Average	R-1	R-2	R-3	Average
40-1	70	25	0	None	None	....	12.1	12.0	11.5	11.9	9.4	9.7	8.6	9.2
40-2	70	30	0	None	None	....	12.5	12.4	11.8	12.2	10.1	9.8	9.0	9.6
40-3	70	53	+15	None	None	....	24.9	24.8	24.6	24.8	22.7	23.0	22.5	22.7
40-4	70	17	−15	None	None	....	0.8	0.7	−0.1	0.5	−2.8	−2.3	−3.5	−2.9
See footnote [d]	70	......	−10	None	None	....	4.9	4.8	4.0	4.6	1.6	2.0	0.9	1.5
40-5	70	30	−10	1, 2a, 2b, 3	None	¼	−0.4	0.0	1.3	0.3	−2.8	−1.9	−1.2	−1.7
40-6-1	70	40	−10	1, 2a, 2b, 3	None	⅛	1.1	1.5	2.8	1.8	−1.6	−0.8	0.2	−0.7
40-6-2	70	40	−10	1, 2a, 2b, 3	None	¼	−0.6	0.0	1.4	0.3	−2.8	−1.8	1.0	−1.2
40-7-1	70	40	−10	1, 2b, 3	None	¼	0.6	0.8	1.6	1.0	−1.9	−1.3	0.8	−1.3
40-7-3	70	40	−10	1, 2b	None	½	0.9	−0.6	2.5	0.9	−1.7	−2.3	0.2	−1.2
40-7-5	70	40	−10	None	1, 2, 3*	1¾	−5.8	−4.8	−2.8	−4.5	−5.9	−4.9	−4.2	−5.0
40-7-6	70	40	−10	None	1, 2, 3*	½	−1.5	−0.5	1.2	−0.3	−3.9	−2.3	−1.1	−2.4
40-8-1	70	40	−10	None	1, 2, 3*	¼	0.2	1.6	2.9	1.6	−2.3	−0.8	0.3	−0.9
40-8-3	70	40	−10	None	1, 2, 3†	¼	−2.6	−1.8	−1.1	−1.8	−4.1	−3.8	−2.9	−3.6
40-8-4	70	40	−10	None	1, 2, 3†	⅛	−1.3	−0.6	1.4	−0.2	−3.6	−2.7	−0.8	−2.4

[a] Refer to Figure 23 for location of roof and side openings.
[b] Size refers to area of each opening in square inches per square foot of total ceiling area.
[c] R-1 indicates location, in inches, above centers of Room 1, R-2 above Room 2, etc.
[d] Calculated from temperatures in Test 40-4.
* Square openings cut through roof.
† Special ventilators used, see Figure 24.

TABLE XIII

VELOCITY AND DIRECTION OF AIR FLOW THROUGH VENTILATING OPENINGS IN ATTIC WITH FLAT ROOF FOR DIFFERENT TYPES OF VENTILATION AND DIFFERENT OPERATING CONDITIONS

Test No.	Inside Air		Outside Air, Degrees F.	Ventilating Opening			Air Flow in Ft./Min. and Direction			
	Degrees F.	Rel. humid., per cent		Side wall[a]	Roof[a]	Size[b]	Opening 1	Opening 2, or 2a	Opening 2b	Opening 3
40-5	70	30	−10	1, 2a, 2b, 3	None	1/4	50-in	50-in	Slight	100-out
40-6-1	70	40	−10	1, 2a, 2b, 3	None	1/8	....	....	....	....
40-6-2	70	40	−10	1, 2a, 2b, 3	None	1/4	50-in	50-in	Slight	100-out
40-7-1	70	40	−10	1, 2b, 3	None	1/4	Slight	60-in	Closed	100-out
40-7-3	70	40	−10	1, 2b	None	1/2	50-in, 50-out	30-in, 100-out	Closed	Closed
40-7-5	70	40	−10	None	1, 2, 3*	1 3/4	75-in	40-out	....	40-out
40-7-6	70	40	−10	None	1, 2, 3*	1/2	80-in	100-out	....	100-out
40-8-1	70	40	−10	None	1, 2, 3*	1/4	30-in	50-in	....	90-out

Test No.	Degrees F.	Rel. humid., per cent	Outside Air, Degrees F.	Side wall	Roof	Size	Opening 1		Opening 2		Opening 3	
							Supply	Exhaust	Supply	Exhaust	Supply	Exhaust
40-8-3	70	40	−10	None	1, 2, 3†	1/4	90	110	110	130	50-out	120
40-8-4	70	40	−10	None	1, 2, 3†	1/8	120	100	100	110	50-out	130

[a] Refer to Figure 23 for location of roof and side openings.
[b] Size refers to area of each opening in square inches per square foot of total ceiling area.
* Square openings cut through roof.
† Special ventilators used, see Figure 24.

TABLE XIV

CONDITIONS IN ATTIC WITH GABLED ROOF FOR DIFFERENT TYPES OF VENTILATION AND DIFFERENT OPERATING CONDITIONS

Test No.	Duration in Hours	Inside Air		Outside Air, Degrees F.	Ventilating Opening		Frost Accumulation during Test			
							Inner surfaces of roof boards and side walls			Around electrical boxes, cables, and joists
		Degrees F.	Rel. humid., per cent		Number[a]	Size[b]	Above Room 1	Above Room 2	Above Room 3	
				Stairway and Door Not Sealed						
40-9-1	191	70	40	−5.2	1, 2, 3	¼	Heavy	Heavy	Very heavy	Heavy
40-9-2	49	70	40	−7.9	1, 2, 3	½	Heavy (3.74) *	Heavy (7.15)	Very heavy (9.79)	Heavy
				Stairway and Door Sealed						
40-9-3	144	70	40	−4.8	1, 2, 3	½	Trace (0.14)	Light (1.01)	Light (2.26)	Heavy
40-9-4	120	70	40	−5.8	None	......	Medium (3.92)	Heavy (4.81)	Heavy (5.69)	Heavy
40-9-5	116	70	40	−6.2	1, 2, 3	¼	Light (1.79)	Light (2.40)	Medium (3.88)	Heavy
40-9-8	72	70	40	−8.5	2, 3	¼	Light (3.06)	Medium (4.30)	Heavy (4.62)	Heavy
40-9-9	72	70	40	−9.8	2, 3	½	Light (2.31)	Light (3.24)	Medium (3.95)	Heavy
40-9-10	360	70	40	−9.4	2, 3	1.0	Trace (1.24)	Light (1.96)	Light (2.31)	Heavy
				Mechanical Ventilation						
40-9-6	172	70	40	−5.9	1, 3	35[c]	Light (1.07)	Light (1.69)	Light (2.56)	Heavy
40-9-7	92	70	40	−6.2	1, 3	105[c]	None (0.0)	None (0.0)	None (0.09)	Heavy
				Variable Outside Temperatures[d]						
40-10	168	70	20	−0.4 to −14.3	None	......	None	None	None	None
40-11	168	70	25	−0.3 to −12.9	None	......	Light	Light	Light	Medium
40-12	168	70	30	−1.2 to −12.6	1, 2, 3	⅛	Trace	Light	Light	Heavy
40-13	168	70	40	−0.6 to −11.1	1, 2, 3	¼	Trace	Light	Medium	Heavy
40-14	168	70	40	+9.8 to − 4.6	1, 2, 3	¼	Trace	Trace	Trace	Heavy

[a] Refer to Figure 25 for location of openings obtained by lowering attic windows from the top.
[b] Size refers to area of each opening in square inches per square foot of total ceiling area.
[c] Figures give total cubic feet per minute supplied through opening No. 3.
[d] Temperature lowered in 16 hours, followed by temperature rise in 8 hours.
* Figures in parentheses are the condensation rates in grams per square foot of ceiling area per 24 hours obtained by weighing the frost accumulation on aluminum panels placed on under surface of roof boards.

TABLE XV

TEMPERATURES IN ATTIC WITH GABLED ROOF FOR DIFFERENT TYPES OF VENTILATION AND DIFFERENT OPERATING CONDITIONS

Room Air Temperature 70 Degrees F.

Test No.	Outside Air, Degrees F.	Ventilating Opening		Attic Air Temperature							Temperature under Surface of Roof Boards				
				Above Room 1	Above Room 2			Above Room 3	Average mid-height	Variation at mid-height					
		Number[a]	Size[b]	Mid-height	Bottom	Mid-height	Top	Mid-height			Above Room 1	Above Room 2	Above Room 3	Average	Variation
								Stairway and Door Not Sealed							
40-9-1	−5.2	1, 2, 3	¼	10.3	9.6	10.6	11.1	9.9	10.3	0.7	7.0	6.7		6.8	0.3
40-9-2	−7.9	1, 2, 3	½	7.1	6.4	7.5	7.8	6.8	7.1	0.7	4.1	4.3		4.2	0.2
								Stairway and Door Sealed							
40-9-3	−4.8	1, 2, 3	½	8.0	7.8	8.0	8.3	7.6	7.9	0.4	5.5	5.3		5.4	0.2
40-9-4	−5.8	None		9.5	9.7	9.5	9.9	9.5	9.6	0.0	6.3	5.5		5.9	0.8
40-9-5	−6.2	1, 2, 3	¼	7.7	7.3	7.7	8.1	7.2	7.6	0.5	5.1	4.8	4.3	4.7	0.8
40-9-8	−8.5	2, 3	¼	6.5	6.0	6.3	6.8	5.8	6.3	0.7	3.2	2.9	2.5	2.9	0.7
40-9-9	−9.8	2, 3	½	5.0	4.3	4.9	5.4	4.3	4.8	0.7	1.8	1.4	1.0	1.4	0.8
40-9-10	−9.4	2, 3	1.0	3.7	2.5	3.6	4.1	3.0	3.4	0.7	0.9	0.5	0.2	0.5	0.7
								Mechanical Ventilation							
40-9-6	−5.9	1, 3	35[c]	7.5	7.2	7.3	7.8	7.1	7.4	0.4	4.9	4.6	4.1	4.5	0.8
40-9-7	−6.2	1, 3	105[c]	5.0	4.2	4.4	5.1	3.2	4.5	1.8	2.8	2.3	1.7	2.3	1.1

[a] Refer to Figure 25 for location of openings obtained by lowering windows from the top.
[b] Size refers to area of each opening in square inches per square foot of total ceiling area.
[c] Figure gives total cubic feet per minute supplied through opening No. 3.

TABLE XVI

VELOCITY AND DIRECTION OF AIR FLOW THROUGH VENTILATING OPENINGS, AND RELATIVE RATES OF CONDENSATION AT DIFFERENT LOCATIONS IN ATTIC WITH GABLED ROOF FOR DIFFERENT TYPES OF VENTILATION AND DIFFERENT OPERATING CONDITIONS

Test No.	Inside Air		Outside Air, Degrees F.	Ventilating Opening		Air Velocity in Feet per Minute and Direction			Condensation[d] Grs./Sq. Ft./24 Hrs.			
	Degrees F.	Rel. humid., per cent		Number[a]	Size[b]	Opening 1	Opening 2	Opening 3	Above Room 1	Above Room 2	Above Room 3	Average
						Stairway and Door Not Sealed						
40-9-1	70	40	−5.2	1, 2, 3	¼	75-in	Breathing	50-out	....	....	....	....
40-9-2	70	40	−7.9	1, 2, 3	½	70-out	Breathing	60-out	3.74	7.15	9.79	6.94
						Stairway and Door Sealed						
40-9-3	70	40	−4.8	1, 2, 3	½	60-out	Breathing	50-out	0.14	1.01	2.26	1.14
40-9-4	70	40	−5.8	None	......	Closed	Closed	Closed	3.92	4.81	5.69	4.81
40-9-5	70	40	−6.2	1, 2, 3	¼	80-out	Breathing	80-out	1.79	2.40	3.88	2.66
40-9-8	70	40	−8.5	2, 3	¼	Closed	Breathing	70-out	3.06	4.30	4.62	4.09
40-9-9	70	40	−9.8	2, 3	½	Closed	40-in and out	70-out	2.31	3.24	3.95	3.20
40-9-10	70	40	−9.4	2, 3	1.0	Closed	80-in and out	80-out 30-in	1.24	1.96	2.31	1.78
						Mechanical Ventilation						
40-9-6	70	40	−5.9	1, 3	35[c]	Out	Closed	In	1.07	1.69	2.56	1.78
40-9-7	70	40	−6.2	1, 3	105[c]	Out	Closed	In	0.0	0.0	.09	.03

[a] Refer to Figure 25 for location of openings obtained by lowering windows from top.
[b] Size refers to area of each opening in square inches per square foot of total ceiling area.
[c] Figures give total cubic feet per minute supplied through opening No. 3.
[d] Condensation rate in grams per square foot of ceiling area per 24 hours obtained by weighing frost accumulation on aluminum panels placed on under surface of roof boards.

RESULTS OF TESTS FOR ATTIC WITH GABLED ROOF

The results for fifteen tests, Nos. 40-9-1 to 40-14, inclusive, are given in Tables XIV, XV, and XVI. The first two tests, 40-9-1 and 40-9-2, were made before the attic stair well walls were insulated and sealed or the attic door sealed with a rubber gasket. Tests 40-9-3 to 40-9-10, inclusive, were made at constant air conditions throughout each test. Tests 40-9-6 and 40-9-7 were made at constant air conditions but with mechanical ventilation. The five tests, 40-10 to 40-14, inclusive, were made at constant inside air conditions and variable outside air temperatures for each test, and either without or with ventilation as shown. The frost accumulation was determined by visual inspection of the various parts after each test period. The scale used in describing the intensity of frost accumulation was "none," "trace," "light," "medium," "heavy," and "very heavy." In some of the tests the actual rate of frost accumulation in grams per square foot per 24 hours was determined by the use of aluminum condensation panels which were placed on the under side of the roof boards. These figures are shown in parentheses after the descriptive ratings of each test in Table XIV.

The importance of sealing the cracks around the attic door and of applying a vapor-proof covering over the warm surface of the attic stair-well walls is shown by a comparison of the results for Tests 40-9-2 and 40-9-3. The average rate of condensation before the door and stair well were sealed was 6.94 grams, whereas after these parts were reasonably well sealed, the rate was 1.14 grams per square foot per 24 hours. The sealing of these openings did not, however, appear to make any difference in the rate of condensation around the cables leading to electrical outlet boxes and switches, or to those areas over partitioned walls through which vapor was apparently leaking and condensing in the upper surface of the insulation.

In the majority of tests in which natural ventilation was used there was a heavier accumulation of frost on the under side of the roof boards over Room No. 3 than over Room No. 1. There was, likewise, a general tendency for the air to flow in through the opening over Room No. 1 and out through the opening above Room No. 3. In order to reverse the direction of air flow a small propeller exhaust fan was placed in the ventilation opening above Room No. 1. This was set to discharge at the rate of 35 cubic feet per minute for Test 40-9-6, and 105 cubic feet per minute for Test 40-9-7. The net results of these tests were that with 35 cubic feet per minute the relative condensation rates above Rooms Nos. 1 and 3 were substantially the same as for gravity ventilation. At 105 cubic feet per minute exhaust there was no condensation on the roof boards above either room. The ventilation did not, however, affect the accumulation of frost around electrical cables, etc.

Of the five tests, 40-10 to 40-14, inclusive, the first four were run with outside air temperatures varying from 0° to −15° F., and the fifth at temperatures varying from +10° to −5° F. An explanation of these cycles and the reasons for selecting them will be found under the section headed "Moisture Conditions within Structure at Variable Outside Air Temperature."

By comparing the results for Test 40-13 having a variable outside air temperature averaging −8.4° F. with the results for 40-9-5 having a constant outside temperature of −6.2° F., all other conditions being the same, it will be noted that the results obtained by visual inspection were the same, except that the roof boards above Room No. 1 showed a trace for the variable cycle and light frost for the constant air temperature cycle. For all practical purposes the results of these two tests may be considered as equal. Theoretical calculations and also previous test data have shown that the rate of condensation is slightly less for the variable temperature cycle. The difference between the results for the two different cycles is small in any event, and it is probable that the method of recording the results for these tests would not differentiate between the two rates of condensation.

Additional heat loss through the ceiling due to attic ventilation may be calculated from the average attic air temperatures as recorded for different ventilation openings. For Test 40-9-4, without ventilation, the average attic air temperature was 9.6° F. For Test 40-9-5, with three openings each equal to ¼ square inch per square foot of total ceiling area, the average temperature was 7.2° F. With 70° F. in the rooms below, the increased rate of heat loss through ceiling would be

$$\frac{70 - 7.6}{70 - 9.6} = 1.032$$

or 3.2 per cent. For test 40-9-3, with three ½-inch openings, the loss was slightly less, but in this case the outside air temperature was 1 degree higher than for the test without attic ventilation. This loss was somewhat less than that shown for the flat roof construction.

In general, the conclusions drawn from test data taken with gabled roof construction substantiate those drawn from test data taken with the flat roof construction. There are, however, some specific conditions which apply only to the gabled roof construction which may be summarized as follows:

1. The accumulation of frost on the inner surface of attic windows was in all cases as great as that on the under surface of the roof boards, and in many instances where there was no accumulation of frost on the roof boards there was a rather heavy accumulation on the inner surface of the glass. It would be possible for the moisture on the inner surface of the glass to melt and cause a problem even tho there was no moisture problem caused by condensation on the under surface of sheathing or other points about the attic.

2. In several cases heavy beads of frost and ice formed on the under side of the roof boards at points where nails were driven through from above. Often these frost spots occurred when there was no visible frost on any other surface of the sheathing or under side of roof boards.

3. In one case heavy frost accumulated on the under side of the 2 x 4 plate which was placed along the top of 2 x 6 joists to form the base for attic side walls. The side wall below did not have any vapor barrier on the warm side and the vapor apparently entered from the warm side, passed up to the plates, and condensed.

4. After the first four tests, covering a twenty-eight-day period, the cold room was allowed to warm up and the surface of attic walls and other places subjected to condensation were examined for moisture and water marks. Inspection showed that the frost which had accumulated above electric fixtures had melted and run down over the fixtures. While this was not in sufficient quantities to cause any damage it did emphasize the necessity of sealing as carefully as possible the openings around ceiling electric lights.

5. From the test data the following recommendations may be made for attics where no vapor barrier is used in the ceiling:

a. With 70° F. and 20 per cent relative humidity inside air in combination with —10° F. outside air, no condensation troubles would be expected even without attic ventilation.

b. With 70° F. and 25 per cent relative humidity inside air in combination with —10° F. outside air, light frost will accumulate in the attic but probably will not cause any damage unless the building is operated under these conditions for more than one week.

c. 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 ¼ square inch area per square foot of ceiling area on each exposed wall will be sufficient and will be the maximum that will be effective. If all of the above conditions are maintained constant with the exception that the inside relative humidity is increased to 30 per cent, condensation difficulties may develop.

THE EFFECT OF RADIANT HEAT FROM THE SUN ON ATTIC CONDENSATION

In order to determine the effect of radiant heat from the sun on the accumulation of frost in the various parts of an attic a heat radiating device at variable outside air temperatures, similar to that described under the heading of "Moisture Conditions with Structures," was applied first to one side of the roof of a small test house, and later to an area of the roof of the test bungalow. The area covered by the radiation box was 38 x 66 inches and it was designed for easy application to the roof, and also for variable application of heat.

The ceiling of the small test house was constructed with ¾-inch metal lath and plaster and 3⅝ inches of mineral wool without vapor barrier. The gabled roof was constructed with 2 x 4 studs spaced 16 inches on center, covered with 1 x 8-inch pine shiplap and asphalt roofing material weighing 50 pounds per 100 square feet. Removable roof board 7 x 12-inch panels were centrally located in each roof slope, and in addition to this 6 x 10-inch removable aluminum panels were similarly located.

Two tests were made with inside air maintained constant at 70° F., 60 per cent relative humidity, and outside air at —10° F. These tests were made without attic ventilation. In running a test the test conditions were maintained for a sufficient length of time to accumulate heavy frost on the under side of the roof boards. The heat radiating device was then applied to one slope of the roof and the heat adjusted to give a gradual rise in temperature of the under surface of the roof boards until the temperature reached 40° F. This required approximately three hours. The temperature was then maintained constant for a period of one hour, after which the heating device was removed. Weights of the removable wood and aluminum test panels were taken to determine the weight of frost accumulation during both the cold and warm cycle of the tests.

For the first test the rate of frost accumulation as determined by weighing the aluminum panels during the cold period was 5.55 and 6.04 grams per square foot of ceiling area per 24 hours for Slopes 1 and 2, respectively, giving an average of 5.8 grams. When heat was applied to Slope No. 1 the frost entirely disappeared from the aluminum panel under the heat radiating device, but accumulated on the panel under Slope No. 2 at the rate of 26.8 grams per square foot per 24 hours.

In the second test, where the wood panels were used, the rate of frost accumulation for the periods without heat was 2.1 and 4.61 grams per square foot per 24 hours for Slopes 1 and 2, respectively, giving an average of 3.35 grams per square foot per 24 hours. The low rate of frost accumulation for Slope No. 1 may have been due to the fact that this slope was subjected to the heat cycle in the previous test and had not completely cooled off. At the end of the cold cycle the heat radiating device was applied to Slope No. 2 and the temperature built up and held as in the test with the aluminum panel. During this four-hour heating period the rate of frost accumulation on Slope No. 1 was 38.1 grams, whereas for Slope No. 2 with heat applied there was a loss of 87.9 grams per square foot per 24 hours. This high rate of loss as compared with the first test was due to the fact that there was a heavy frost accumulation on the inner side of Slope No. 2 which had melted off, a part of it evaporating and the remainder running down the slope of the roof.

During the cold period for both tests there was a uniform rate of frost accumulation on all of the exposed surfaces within the attic. During the heating period there was an increased rate of frost accumulation on the cold surfaces due to the fact that moisture was evaporated from the warm surfaces by the radiating device.

Tests were made on one section of the roof of the large test bungalow by using the heat radiating device and repeating the test cycle as used with the small test house, with the exception that the high inside relative humidities were not used. These tests were run in parallel with some of the attic ventilation tests.

The results for the tests on the bungalow were not taken quantitatively as the section of the roof covered by the radiating device was relatively small. The results, however, substantiated those obtained on the small test house, and indicate that the heat of the sun may have a vital effect upon the attic condensation problem.

SUMMARY OF RESULTS ON ATTIC VENTILATION

The principles which are involved in attic condensation and the results which may be expected from ventilation may be summed up as follows:

1. Attic condensation is caused by the accumulation of vapor in the attic space until the dew-point temperature of the vapor is above the temperatures of the surrounding objects with which the vapor comes in contact.

2. The source of vapor is usually from the rooms below the attic. It is transmitted from these rooms to the attic space directly through the ceiling, through openings around electric fixtures, through side walls and up between the studs, through partition walls, through cracks around attic doors, and, in fact, through any place in the structure which may not be vapor proof and which is subjected to vapor pressure differences.

3. The vapor density in the attic space is reduced by the interchange between attic and outside air. This may be brought about by natural leakage or by artificial ventilation.

4. Natural leakage takes place through the roof, through the side walls, through any cracks around windows, or in any other part of the structures. It will be facilitated by omitting any building paper under the shingles, and any vapor-proof paper in the side walls.

5. If openings are provided for gravity ventilation they should be well distributed in order to get diffusion between the entering air and that within the attic space. It is important to reduce the vapor densities of attic air before it comes in contact with cold surfaces.

6. The quantity of ventilation air required varies with the amount of vapor which may enter the attic and the temperature of the cold surfaces. The area of the openings required to furnish this air will depend upon their location and the exposure of the building, together with the wind velocities to be expected. Good air distribution is essential and the location of ventilation openings must be carefully considered.

7. The admission of cold air will lower attic air temperature and therefore increase the heat loss through the ceiling of the upper floor. It is possible, however, to obtain good ventilation without increasing this loss by more than 5 per cent.

8. Excessive attic ventilation will cool the top surfaces of the insulation, the surfaces of the floor joists, and similar surfaces with which the entering vapor from below comes in contact before it is diffused with the ventilation air, and thus increase the condensation problem in these parts.

9. The first signs of attic condensation are usually on the under surfaces of roof boards, inner surfaces of side walls, and inner surface of glass windows. Under more severe conditions they may occur on the upper surfaces of the insulation, over partitions, and similar places from where the vapor enters. Ventilation is more effective in clearing up condensation on roof, wall, and window surfaces than in other parts of the structure. This is due to the fact that it is difficult to diffuse ventilation air with the vapors leaving the channels through which they enter. Ventilation may actually aggravate condensation in the latter cases.

10. If a direct ventilator shaft is used to carry air from the attic space to the outside it is desirable to so design the shaft that the surfaces with which the leaving air comes in contact will be as warm as possible. The direct unprotected ventilator flue leading out of an attic space may accumulate frost and ice on its inner surface during cold periods, which will cause serious condensation difficulties when the shaft warms up.

11. Some of the channels through which vapor may enter the attic are:
    a. Directly through the ceiling if no vapor barrier is used.
    b. Poorly sealed openings around electric fixtures, particularly those in the ceiling.
    c. Unprotected side walls and partitions through which vapor may pass and then vent up through into the attic space.
    d. Outside walls in which the vapor barrier is some distance from the plaster and in which the space between back of plaster and vapor barrier is not well sealed at top and bottom.

12. If condensation takes place in an attic which has no ventilation and does not have insulation in the roof proper, it will usually take place first on the under surface of the roof boards, on attic side walls, on windows, on sewer or vent pipes passing through the attic, and on similar cold surfaces.

13. Sunshine on the surface of a roof may entirely change the condensation problem. It will cause the frost which may have accumulated on the under side of the exposed surface to vaporize and pass over to other cold surfaces, where it may condense and serve to concentrate the total frost in confined areas. Thus the north slope of a roof and the north-exposed walls of a building may show much higher rates of condensation than those surfaces of a roof or walls which are exposed to the heat from the sun.

14. Natural ventilation through properly designed openings into the attic space is controlled by temperatures, outside wind velocity, building exposure, and size and location of vent openings. It is impossible to lay down any specific rules to fit all conditions. The recommendations, however, given for flat and gabled roofed attics will serve as a guide. Other measures which are more positive for preventing condensation are: first, to provide vapor barriers in the proper location, and second, to operate the building under safe conditions, as will be explained under the heading "Limiting Operating Conditions."

15. The condensation rates for the under surface of roof boards and inside surfaces of attic walls were found to be substantially the same as those for the inner surface of the sheathing for insulated walls operated under similar test conditions.

LIMITING OPERATING CONDITIONS

According to generally accepted laws, the rate of vapor transmittance through a given non-hygroscopic permeable material is directly proportional to the difference between the vapor pressures on the two sides of the material. There are wide variations in the permeability of different materials, and thus for a given pressure drop the rate of vapor transfer will be entirely different, due to different types of materials or different combinations of materials.

Since the walls of most buildings are made up of several materials, it follows that the resistance to the passage of vapor will vary throughout the different sections of the wall, and that for a uniform continuous rate of vapor flow through the wall, the vapor pressure gradient throughout the various sections will vary accordingly. If the materials are so arranged that there is a relatively high vapor resistance within the high vapor pressure side of the wall as compared to the low vapor pressure side, there will be a low vapor pressure or vapor density within the wall, whereas, if the reverse conditions are true, there will be a relatively high vapor pressure within the wall. If the temperatures of the materials throughout the wall are sufficiently high to prevent condensation of the vapor in contact with them the vapor pressure throughout the wall will seek the level required to give a uniform rate of vapor flow throughout all parts of the wall, and the rate of flow will be the same for either arrangement of materials so long as the same materials are used in the wall. If, on the other hand, the temperatures of the materials in any part of the wall are below the dew-point temperatures of the vapor in contact with them, these temperatures will determine the maximum vapor pressures which may be established, and there may be condensation within the wall. This condition will be more apt to occur with the second, than with the first, arrangement of materials since, in this case, higher vapor pressures, and therefore higher dew-point temperatures, are required within the wall for continuous uniform rates of flow through the wall.

CONDITIONS CAUSING CONDENSATION

In order to illustrate the above theory the three walls of Figure 26 may be considered. Each wall is built up of two homogeneous materials, one having twice the vapor resistance of the other, and designated as A and B, respectively. The individual materials are identical for each wall, the only difference being in the arrangement relative to the high and low vapor pressure sides of the wall. In each case the vapor pressure on the left-hand side of the wall has been taken as .5 inch of mercury, and that on the right-hand side as .2 inch of mercury. The material of the high vapor resistance, *A,* is placed on the left-hand side of the wall for Case 1, and on the right-hand side for Cases 2 and 3. The broken diagonal line which passes from the left side downward toward the right side for each wall represents the vapor pressure gradient which would be established within that wall by the surrounding vapor pressure conditions and the assumed temperature within the wall. The scale at the left of the walls represents the vapor pressure in inches of mercury and is the scale used in plotting the vapor pressure gradient line through each wall. The temperatures corresponding to .3 and .4 inch of mercury pressure as required along the dividing line *a-b* for the three conditions are 45° and 52.6° F., respectively. It is assumed that the temperature conditions surrounding the walls are such that in Cases 1 and 2 the temperatures along the line *a-b* are above 45° and 52.6° F., respectively, and that the normal vapor pressure gradient may therefore be automatically established. In Case 3, however, the temperature conditions surrounding the walls are such that the temperature along the line *a-b* is only 45° F., and thus the vapor pressure gradient cannot be established as normally required for uniform flow.

In Cases 1 and 2 there will be a uniform and equal rate of vapor flow throughout each material in both walls, and the arrangement of materials will make no difference in the final results excepting that the vapor pressure will be higher along the line *a-b* for Case 2 than for Case 1. In Case 3, which has the same arrangement of materials as

Case 2, the temperature along the line *a-b* corresponds to a vapor pressure of .3 inch of mercury, whereas the normal vapor pressure for uniform vapor flow should be .4 inch of mercury. The vapor pressure gradient across material *B* is therefore increased and that across material *A* is decreased, or in other words, there will be more vapor flowing into the wall than can flow out, and therefore condensation will occur along the line *a-b*.

VAPOR TRANSMITTANCE EQUATIONS

For each of the above cases equations may be written giving the rate of vapor transmittance in terms of vapor transmittance coefficients and vapor pressure drop through each material. From these equations the conditions to be expected within the wall could be calculated. To use them it would be necessary to have vapor transmittance coefficients for the different materials and to be able to determine the vapor pressure drop across each section of the wall.

A vapor transmittance coefficient may be expressed in any system of units. For the purpose of this discussion it will be defined as the amount of vapor in grams transmitted through 1 square foot of wall area in 24 hours, at a vapor pressure difference of 1 inch of mercury between the two sides of the material. In the equations the following nomenclature will be used:

V_A=vapor transmittance coefficient for material A
V_B=vapor transmittance coefficient for material B
P_A=vapor pressure drop in inches of mercury across material A
P_B=vapor pressure drop in inches of mercury across material B
C =moisture condensed in grams per square foot of area per 24 hours

1. (Case 1) $P_A V_A = P_B V_B$
2. (Case 2) $P_B V_B = P_A V_A$
3. (Case 3) $P_B V_B = P_A V_A + C$

If the vapor transmittance coefficient for the materials were known it would be possible to determine the rate of vapor transmittance through any part of the wall for any set of vapor pressure and temperature conditions, and also the probability of condensation occurring within the wall. Since these coefficients are as yet not known, the most practical method is to determine the conditions for a given wall by tests.

LIMITING CONDITIONS FOR CONDENSATION IN A WALL

From the discussion of the three cases in Figure 26 it is evident that condensation at any plane within a wall may take place when the vapor pressure conditions on the two sides of the wall are such that they tend to establish a vapor pressure at that plane which is higher than that corresponding to the temperatures at the plane. The vapor pressures are established by one set of conditions and the temperatures by another, and there are many combinations of vapor pressures and temperatures which may cause the same results.

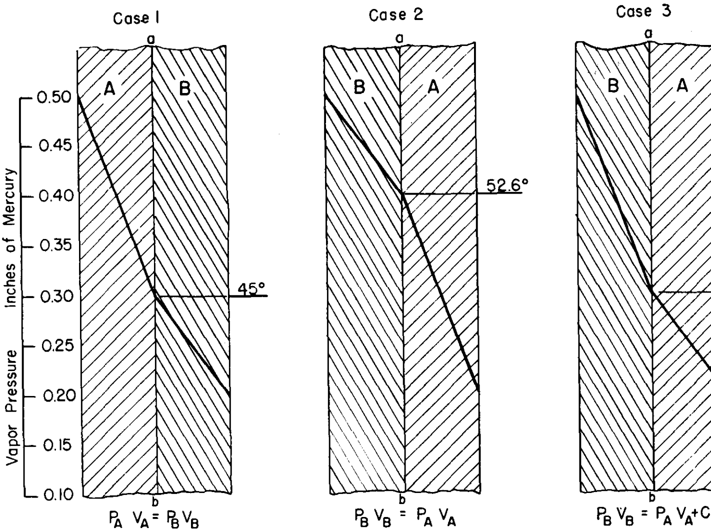

FIGURE 26. EFFECT OF TEMPERATURE AND ARRANGEMENT OF MATERIALS ON CONDENSATION WITHIN A WALL.

The analysis of the three cases of Figure 26 suggests a method by which one set of conditions which will just start condensation may be readily converted to any other set of equivalent conditions and thus obviate the necessity of testing a wall under the large variety of conditions which would otherwise be necessary to establish safe operating temperatures and humidities to be used with the wall. From equations 1 or 2, $\frac{P_A}{P_B}=\frac{V_B}{V_A}$. If the ratios, $\frac{V_B}{V_A}$ were known it would be possible to calculate data for a set of curves from which one set of safe operating conditions could be converted into another set of equivalent safe operating conditions. Since the transmittance coefficients V_B and V_A are not known the ratio may be established from the pressure drop P_A and P_B. The only obstacle in determining the pressure drop P_B and P_A is that the vapor pressure along the line *a-b* is not known for Cases 1 and 2 where condensation is not taking place, and that for Case 3 where it is known condensation is taking place, and the ratio of $\frac{P_A}{P_B}=\frac{V_B}{V_A}$ does not hold. If, however, any wall as of Cases 1, 2, or 3, is put under test with constant vapor pressures on each side of the wall, and if the temperature conditions are controlled so that the temperature at the line *a-b* is gradually lowered until condensation just starts to take place, then the above ratio will hold and the vapor pressure at the line *a-b* will be known. There will be a uniform flow of vapor throughout all parts of the wall, and the vapor pressure at the line *a-b* will correspond to the temperature, and the ratio between the vapor transmittance coefficient for the two parts of the wall will be the same as the ratio of the vapor pressure drops through the corresponding parts. These conditions may be translated from those used in the test to another corresponding set of conditions by the use of a properly constructed set of curves for a given type of construction.

LIMITING OPERATING CONDITIONS FOR AN INSULATED FRAME WALL WITHOUT VAPOR BARRIERS

The above analysis, which may be applied to any type of wall in which there is a plane where condensation normally takes place, has been applied to a frame wall, and the results have been checked by tests on a full-scale wall construction. The wall was built of 2 x 4 studs spaced 16 inches on center with ¾-inch metal lath and plaster applied to the inner surface, 1-inch sheathing, building paper, and pine lap siding to the outer surface, and with the space between the studs filled with 3⅝ inches of mineral wool insulation. No vapor barrier was used in the wall. The wall was 4 feet wide and 8 feet high, and was tested as a wall of the bungalow under different operating conditions.

The curves representing equal operating conditions for this wall are shown in Figure 27. They have been drawn for inside air temperatures of 70° F. with relative humidities varying from 10 to 60 per cent in combination with outside air temperatures varying from —20° to +35° F. The ordinates represent the ratios of vapor pressure drops, $\frac{P_1}{P_2}$. P_1 is the vapor pressure drop from that of the air on the warm side to a vapor

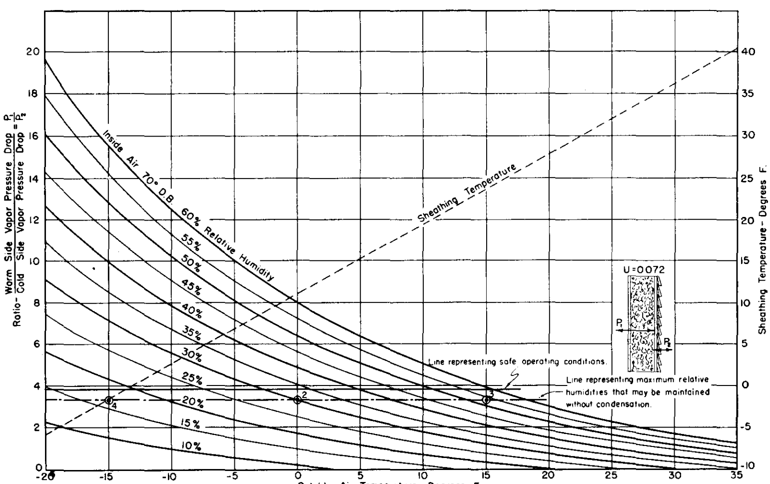

FIGURE 27. CURVES FOR DETERMINING EQUIVALENT LIMITING OPERATING CONDITIONS FOR FRAME WALL WITH 3⅝-INCH MINERAL WOOL INSULATION. NO VAPOR BARRIER ON WARM SIDE OF WALL.

pressure corresponding to the inside surface temperature of sheathing, and P_2 is the vapor pressure drop from that corresponding to the surface temperature of the sheathing to that corresponding to the temperature of outside air. The diagonal line represents the inner surface sheathing temperature of the wall for the various outside temperatures indicated by the abscissa. The curved lines represent the inside relative humidities that may be carried for 70° F. inside air temperature in combination with any of the given outside air temperatures.

The horizontal lines on the chart represent ratios between P_1 and P_2 which will give equivalent condensation conditions for various outside air temperatures. Since the vapor pressure drops P_1 and P_2 have been calculated on the basis that condensation was just about to take place on the inner surface of the sheathing, and since the ratio $\frac{P_1}{P_2}$ is constant only when no condensation is taking place, it follows that, strictly speaking, there is only one horizontal line which will represent equal conditions of condensation. This will be the line representing different combinations of conditions at which condensation is just about to start. Any horizontal line above this will represent conditions of condensation but not in equal quantities, and any horizontal line below it will represent conditions of no condensation.

In order to establish the correctness of these curves a wall corresponding to the specifications was built up and tested with inside and outside air temperatures of 70° and 0° F., respectively. The relative humidity of the inside air was gradually increased until condensation just started to take place on the inner surface of the sheathing. From these tests 30 per cent relative humidity with 70° F. inside air was established as the initial condensation point for zero outside air. A horizontal line was then drawn through this point and corresponding conditions were selected from the chart for +15° and −15° F. outside air temperatures. These combinations were, 70° F. and 53 per cent relative humidity, 70° F. and 17 per cent relative humidity in combination with +15° and −15° F. outside air temperatures, respectively. Prolonged tests under these combinations of air temperatures and humidities showed that the conditions were equivalent for the three sets as established, and that the line drawn on the system of curves represents equivalent operating conditions at which condensation would be just about to take place. Tests 40-2, 40-3, and 40-4 of Table III give the test results as obtained for the three equivalent conditions.

In practice, conditions are not maintained continuously for any given outside air temperature. There are variations throughout the day, and there are sunshine effects which may change the results. For this reason, a line has been selected and drawn on the system of curves which is somewhat above that established by the tests. This line has been designated on the chart as the limiting operating condition. It is to be interpreted as a more practical condition which may be used for the given wall without any danger of condensation.

The curves of Figure 27 are based on an inside air temperature of 70° F. If other inside air temperatures are used the vapor pressures will be different for a given relative humidity, and, further, the temperature of the sheathing will be changed for a given outside air temperature. The curves of Figure 28 have been drawn to give on the ordinates equivalent relative humidities to be used with any inside air temperature from 65° to 85° F. in combination with outside air temperatures between −20° and +20° F. Thus for 0° F. outside air temperature, 70° F. inside air temperature at 33 per cent relative humidity would be equivalent to 85° F. and 20 per cent relative humidity in so far as probabilities of condensation are concerned. The curves of Figure 28 were based on the line designated as "Line Representing Safe Operating Conditions" in Figure 27.

The curves of Figures 27 and 28 may be applied to an unventilated attic, providing the ceiling is constructed the same as the warm section of the wall from inside air to sheathing line, and the roof is constructed similar to the wall from sheathing to outside surface for the wall upon which these curves were based. Tests have shown that the rate of condensation on the under side of roof boards corresponds very closely to that on the inner surface of sheathing if there is no attic ventilation, and if the combination of ceiling and roof corresponds to similar parts of the side walls.

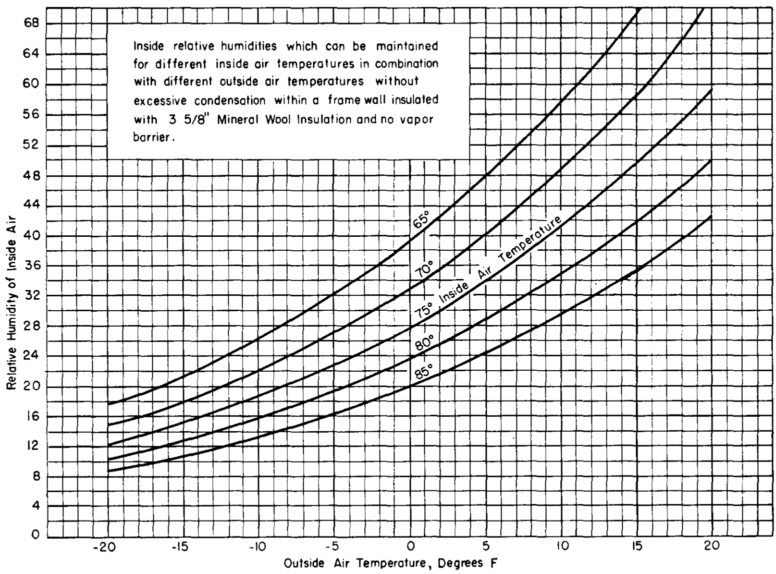

FIGURE 28. EQUIVALENT RELATIVE HUMIDITIES FOR DIFFERENT INSIDE AIR TEMPERATURES IN COMBINATION WITH VARIOUS OUTSIDE AIR TEMPERATURES.