NATIONAL BUREAU OF STANDARDS REPORT

2929

THE HEATING AND VENTILATING SYSTEM AT REFLECTION POINT

by

P. R. Achenbach
S. D. Cole

Report to

Division of Housing Research
Housing and Home Finance Agency

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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P. R. Achenbach
S. D. Cole
Heating and Air Conditioning Section
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ABSTRACT

An unconventional heating and ventilating system in a prototype house, known as Reflection Point, in Cincinnati, Ohio, was investigated during a field test to study the methods of heat transfer from the heat source to the room surfaces and to determine whether the use of reflective materials on walls and ceiling resulted in any decrease in heat requirements. The heating system employed electric heaters in coves near the ceiling, reflective paper on walls and ceilings, reflective draperies, and special floor coverings. Forced ventilation was used with an electrostatic precipitator for air cleaning. A continuous test of 20 hours duration at low outdoor temperatures indicated that inadequate heating capacity was provided for design conditions, that this house had practically the same heat loss for a given indoor-outdoor temperature difference as it would have with non-reflective furnishings and a conventional heating system, and that wall and roof constructions of lower heat transmittance should be used for economy in heating. The tests further indicated that this heating system would satisfactorily heat a house of moderate heat loss, that it produced a greater radiant heat flux in the living space than a plastered ceiling heating panel, and that it had the characteristics of a multidirectional source of radiant energy and would probably warm the floor of a house and the lower extremities of the occupants better than a plastered ceiling heating panel. The forced ventilation eliminated much of the random infiltration of outdoor air except during very windy weather.

I. INTRODUCTION

At the request of the Housing and Home Finance Agency field tests were made of an experimental heating and ventilating system at Reflection Point in Cincinnati, Ohio. The system in this house was unconventional in that electric heating elements in coves near the ceiling were employed, walls and ceilings were covered with reflective wallpaper, special reflective drapery materials were used at the windows, portions of the floor were covered with aluminum foil and an embossed rubber pad beneath the rugs, and a ventilating blower pressurized the house by introducing unheated outdoor air through the perforated ceiling of a central hall.

The tests were made to provide information as follows in regard to this heating and ventilating system:

(1) Evaluate the emissivities of the wall coverings and draperies.

(2) Evaluate the heating element temperatures.

(3) Determine whether or not less heat was required to produce a given air temperature in this house than for houses with conventional wall coverings of higher emissivity and with conventional heating systems.

(4) Determine whether or not the reflective drapery materials reduced the heat loss through the windows.

(5) Evaluate the relation between surface and air temperature at exterior walls, interior walls, floor, furniture, etc.

(6) Determine whether or not comfort was attainable at appreciably lower air temperatures than for conventional heating methods.

(7) Evaluate the amount of forced ventilation and its effect on house temperatures and comfort.

II. DESCRIPTION OF HOUSE

The prototype house was a one-story structure built on a bluff overlooking the city of Cincinnati, Ohio. The living room, dining room, kitchen, and entrance foyer were built on a concrete floor slab on grade whereas the bedrooms and study were built over a small basement and double garage. The gross floor area of the house was about 2000 sq. ft. and the ceiling height was 9 feet except in the kitchen, interior hall, and bath adjoining the study. The significant areas and volumes of the various rooms are summarized in Table 1.

TABLE 1 - ROOM SIZES AND VOLUMES AT REFLECTION POINT

Room	Length of Cold Wall, ft	Ceiling Height, ft	Gross Cold Wall Area, ft²	Window Area, ft²	Door Area, ft²	Net Cold Wall Area, ft²	Other Heat Transmitting Partitions, ft²	Ceiling Area, ft²	Floor Area, ft²	Crack Length, ft	Room Volume ft³
Living Room	39.6	9	356	100	0	256	0	377	377	0	3393
Dining Room	27.8	9	250	78	0	172	0	189	189	21	1701
Kitchen and Utility	29.0	8	232	68	18	146	0	254	254	51	2032
Foyer	11.2	9	101	51	20	30	0	176	175	19	1534
Interior Hall	5.5	7.9	43	8	20[c]	15	113[a]	0[b]	233	37[c]	1841
North Bedroom	26.2	9	236	58	0	178	0	160	160	56	1440
South Bedroom	28.9	9	260	68	0	192	0	238	238	56	2142
Study	14.6	9	131	53	0	78	0	129	129	43	1161
Large Bath	7.0	8	56	6	0	50	49[c]	57	57	11	456
Small Bath	0.0	10	21	[illegible]	0	12[c]	0	23	24	0	240
Whole House	189.8	-	1636	493	58	1135	162	1608	1837[d]	294	15990

[a] Partitions adjacent to basement stairwell

[b] Fresh air inlet

[c] Walls for skylight

[d] Total enclosed floor area for whole house was 1966 ft²

Several special construction features were incorporated in the house which were related primarily to the heating, ventilating, and air conditioning of the structure. The more important of these features are summarized below:

1. Coves extending about one foot downward from the ceiling and one foot from the sidewalls were used to support, partly enclose, and conceal from view sheathed electric heating elements and copper tube refrigerant circuits, used to heat and cool six rooms of the house, respectively. The hallway, bathrooms, and part of the kitchen were heated by high temperature sheathed electric heaters mounted on the walls near the ceiling. The cove heaters totalled about 60% of the installed heating capacity.

2. Embossed aluminum foil paper in various colors was used for interior coverings on most of the wall and ceiling area.

3. Fabrics with moderate reflective properties were used for draperies at many of the large windows.

4. The concrete floors were covered with aluminum foil with the reflective surface upward, a waffle-design foam rubber mat and wall-to-wall nylon carpeting in the living room, dining room, den, and one bedroom. Cork floor covering was used under the aluminum foil for the portion of the floor over the basement and garage.

5. Forced ventilation with filtered outdoor air was provided using a blower and electrostatic precipitator to reduce random infiltration at doors and windows. The ventilating air was introduced through a perforated ceiling in the hall without special means for preheating it.

6. Large picture windows were used in every room of the house, totalling about one third of the gross exterior wall area. Most of the windows were of fixed plate glass with no provision for opening them.

7. The electric heaters in each room were divided into several circuits. Four thermostats with stepped settings were used to add increments of heating capacity in each room as the air temperature decreased.

Inspection of the house construction during the tests and published descriptions of the house indicate that the following materials were used:

Walls: Embossed aluminum foil wallpaper on 3/8 in. gypsum board on 2x4-in. studs with 3/8 in. plywood sheathing and 25/32 in. redwood vertical tongue-and-groove siding.

No insulation in the stud spaces.

Roof: 7x12-in. wooden beams spaced 8 ft. on centers, carrying 1/4 in. plywood ceiling, 2x6 in. tongue-and-groove planking covered with 6 layers of roofing felt. The ceiling was covered with embossed aluminum foil paper. (There was a layer of about 1/2-in. of ice frozen on the roof surface during the tests).

Floor: On grade, there was a layer of gravel, a concrete slab with aluminum foil covering, waffle-design sponge rubber mat, and nylon carpeting. Over the basement and garage there was a 5/16-in. layer of cork tile between the concrete slab and the aluminum foil.

III. TEST PROCEDURE

Two and one-half days were spent in the house studying the performance of the heating system. The first twenty-four hours were used to become acquainted with the electric heating circuits in the house, installing thermocouples, and preparing for specific measurements of temperature and heat consumption. This period of preparation was followed by a continuous test of 20 hours duration from 4:00 P.M. on February 7 until noon of the following day during which the outdoor temperature decreased to 2.5°F and the wind velocity attained 14 mph for one minute intervals at various times.

Shielded thermocouples were installed at the 30-in. level in the center of each room. Thermocouples were also placed on three wall surfaces of the living room at the 30-in. level; in the air one inch from the wall-surface thermocouples in the living room; at the fresh-air inlet in the hall; on the rug, rubber mat, and aluminum foil on the floor of the study, respectively; on the rug at the center of the living room; on the window surface in the living room; and on the sheath of the electric heating elements at two places. In addition an unheated 8-inch black globe was used at the center of the living room to obtain a radiation-convection temperature, and an ordinary mercury-in-glass thermometer was installed at the same station. Outdoor temperatures were measured with a mercury thermometer and wind velocities were observed with a vane anemometer for one minute intervals each hour. Hourly readings were taken of all watthour meters used to integrate electrical energy consumption.

Because the outdoor temperature was low, all of the installed electric heaters were energized during the entire 20-hour continuous test. During the seven-hour period from 5:00 P.M. to midnight all of the Venetian blinds were raised and all of the draperies were drawn away from over the windows. During the next four hours all of the blinds were in the lowered positions and all drapes were drawn over the windows. From 4:00 A.M. to 8:00 A.M. all of the windows remained covered and the ventilating air blower was stopped.

During the course of the test the ceiling surface temperatures and interior and exterior wall surface temperatures in the living room were observed at small distance intervals by means of a taped thermocouple. The air delivery of the ventilating blower was also measured with an anemometer.

Samples of all the different reflective wallpapers and fabrics were secured from surplus rolls stored in the house for measurement of emissivity.

IV. TEST RESULTS

Emissivity of the Wall Coverings and Draperies

The total thermal radiation emissivity was measured for samples of each of the kinds and colors of reflective wallpaper and for the milium fabric and the woven nylon with foil yarn used as drapery materials. The total emissivities at a temperature of 212°F and the thicknesses of the wall coverings and drapery materials are summarized in Table 2. Because the thicknesses of the materials affect the surface temperatures of the specimens during the tests the true values of emissivity at 212°F are probably about one percent higher than the tabulated values for the wallpapers and from 3 to 5 percent higher than the tabulated value for specimen 10, the nylon fabric.

The table shows that the emissivity of the wallpaper varied somewhat with color, ranging from a low value of 0.26 for the bronze color to a high value of 0.40 for the red color. The average of the values for the eight specimens was 0.32. An emissivity of 0.05 was measured for a specimen of the red wallpaper with the red paint removed which is in the range expected for polished aluminum.

The emissivities of the drapery fabrics were in the range from 0.58 to 0.69 which is lower than for most fabrics in common use for this purpose.

Table 2

EMISSIVITY AND THICKNESS OF WALL COVERINGS AND DRAPERIES

Specimen	Thickness	Emissivity
#1 - Red Daisy	.0056	.40
#2 - Gray Poinsettia	.0053	.31
#3 - Bronze Daisy	.0056	.26
#4 - Green Poinsettia	.0036	.34
#5 - Blue Daisy	.0053	.30
#6 - Gray Daisy	.0060	.32
#6 - Gray Daisy reversed, white paper side out	.0060	.78
#7 - Gray Stipple	.0063	.30
#8 - Yellow Daisy	.0060	.35
#9 - Gray Cloth (Milium fabric)	.0061	.58
#9 - Gray Cloth Reversed (Milium fabric)	.0061	.65
#10 - Aluminum Cloth (Nylon with foil yarn)	.0170	.69
#6 - Gray Daisy (Paper removed)	.0015	.31
#1 - Red Daisy (Red paint removed, surface bright)		.05

Heating Element Temperatures

Measurements were made of the heating element temperatures at two locations, one on the south side of the living room and the other on the west side of the south bedroom by securing fine wire thermocouples to the metallic sheath of the electric elements. For constant heating at full capacity the living room heater element had an average temperature of 430°F whereas that in the south bedroom averaged 500°F. There were small deviations of ±10°F from the above averages caused by voltage variations and changes in average room temperature.

At these temperatures the sheathed electric heating elements would act very much like black body radiators emitting energy in all wave lengths with a maximum intensity at a wave length of about 5.6 microns.

Heat Loss

Because of the low outdoor temperature prevailing during the 20-hour continuous test all of the installed electric heater capacity was energized continuously throughout the test. Thus the heat input was uniform at a rate of 27.9 KW, equivalent to 95,300 Btu/hr.

The temperatures observed in the house during the tests are summarized in Table 3 for three time periods, namely, (a) from 8 P.M. to midnight when all windows were uncovered, (b) from midnight to 4 A.M. when all windows were covered with drapes or Venetian blinds, and (c) from 4 A.M. to 8 A.M. when all the windows were covered but the ventilating blower was not running. The indoor air temperature at the room centers, the outdoor temperature and wind velocity and the indoor-outdoor temperature difference are shown graphically in Fig. 1 for the 20 hours of the test.

The computed heat transmission coefficients for the several building elements are listed in Table 4 with adjustments having been made to the outside surface coefficient in accordance with the observed average wind velocity during the three time periods previously mentioned. The computed heat loss of the house for each of the three test conditions and for the design conditions of 70 degree indoor-outdoor temperature difference and 15 mph wind has been summarized in Table 4.

Table 3

OBSERVATIONS IN HOUSE AT REFLECTION POINT DURING FIELD TEST

	Time Period		
	8 PM to 12 M	12 M to 4 AM	4 AM to 8 AM
Average Outdoor Temp., °F	8.3	6.5	3.4
Average Wind Velocity, mph	7.5	5.4	3.9
Indoor-Outdoor Temp. Diff., deg. F	45.9	46.1	50.6
Temp. at Room Centers, 30-in. level			
Living Room, Unheated Globe, °F	57.0	56.8	57.7
Living Room, Shielded Thermocouple, °F	53.1	52.6	54.0
Dining Room, " " °F	51.4	50.8	51.7
Kitchen, " " °F	54.8	52.8	54.4
Foyer, " " °F	52.3	50.6	53.1
N. Bedroom, " " °F	54.4	52.7	53.6
S. Bedroom, " " °F	56.2	54.5	55.5
Large Bath, " " °F	57.0	54.1	55.8
Study, " " °F	73.6	77.3	77.6
Average,[a] " " °F	54.2	52.6	54.0
Exterior Wall Surface, Living Room, °F	46.4	44.8	44.5
Air 1-in. from Wall " " °F	51.1	49.6	50.3
Interior Wall Surface, " " °F	57.2	55.8	56.2
Air 1-in. from Wall, " " °F	55.7	54.7	55.4
Fresh Air at Hall Ceiling, °F	33.1	31.3	-
Window Surface, Living Room, °F	29.5	22.8	24.3
Rug Surface, Living Room Center, °F	61.0	59.9	60.0
Rug Surface, Study, °F	69.6	69.7	69.7
Upper Rubber Mat Surface, Study, °F	65.7	65.6	66.3
Aluminum Foil Surface, Study, °F	57.8	57.9	58.4
Heating Element Temp., Living Room, °F	438	425	425
Heating Element Temp., S. Bedroom, °F	508	495	494
Heat Input Rate, Btu/hr	95,300	95,300	95,300

[a] Study not included.

TEMPERATURE, °F

WIND VELOCITY. MILES PER HOURS

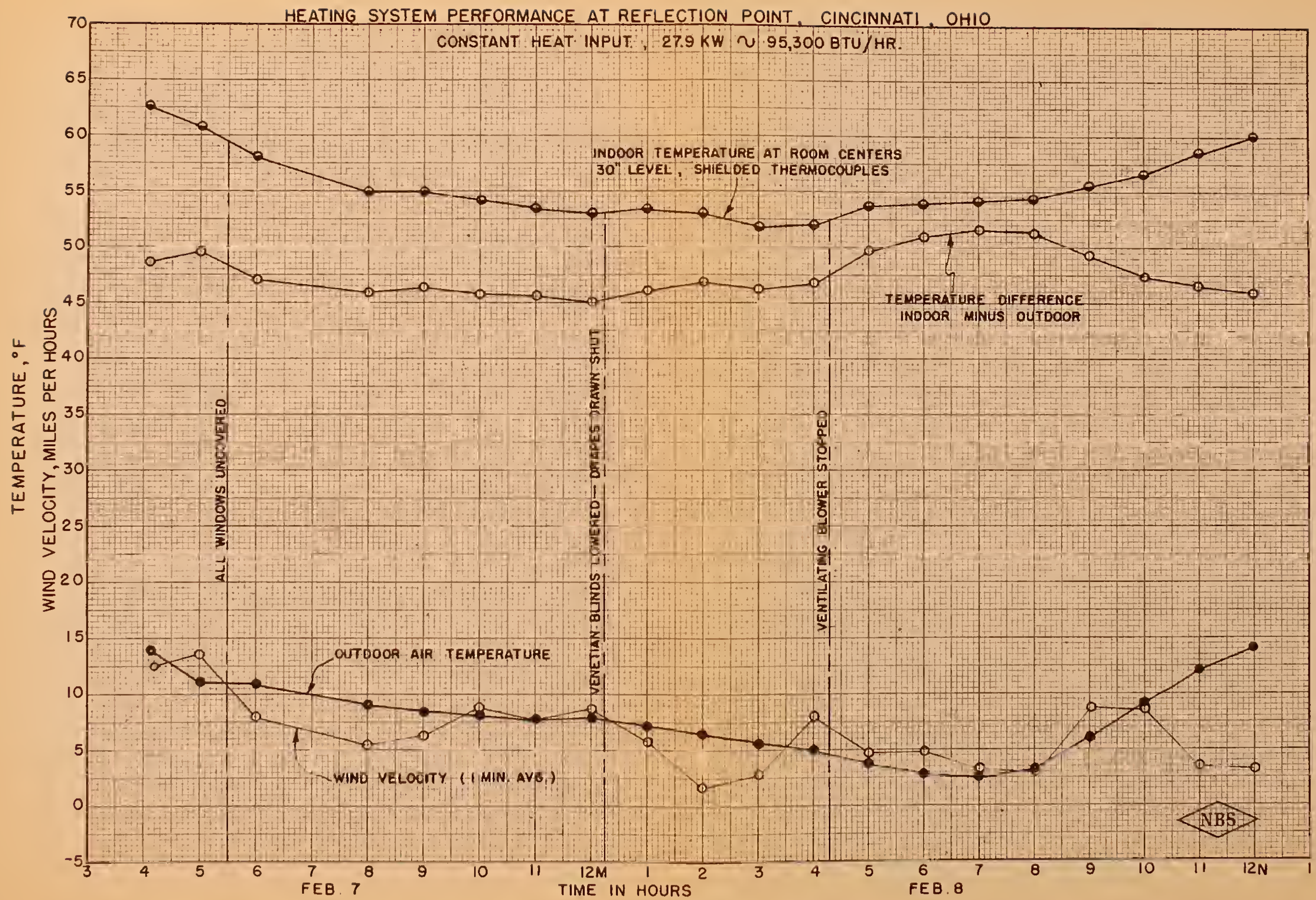

HEATING SYSTEM PERFORMANCE AT REFLECTION POINT, CINCINNATI, OHIO
CONSTANT HEAT INPUT, 27.9 KW ∿ 95,300 BTU/HR.
INDOOR TEMPERATURE AT ROOM CENTERS
30" LEVEL, SHIELDED THERMOCOUPLES
TEMPERATURE DIFFERENCE
INDOOR MINUS OUTDOOR
ALL WINDOWS UNCOVERED
VENETIAN BLINDS LOWERED — DRAPES DRAWN SHUT
VENTILATING BLOWER STOPPED
OUTDOOR AIR TEMPERATURE
WIND VELOCITY (1 MIN. AVG.)
TEMPERATURE, °F
WIND VELOCITY, MILES PER HOURS
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-5
3
4
5
6
7
8
9
10
11
12M
1
2
3
4
5
6
7
8
9
10
11
12N
1
FEB. 7
TIME IN HOURS
FEB. 8
NBS

FIG. 1

Table 4

COMPUTED TRANSMISSION COEFFICIENTS
AND HEAT LOSSES AT REFLECTION POINT

COMPUTED TRANSMISSION COEFFICIENTS, BTU/HR $(FT^2)(°F)$

	Wind Velocity, mph			
	15	7.5	5.4	3.9
Ceiling	0.326	0.315	0.310	0.306
Outside Walls	0.312	0.303	0.298	0.294
Windows and Doors	1.13	1.02	0.96	0.92
Floor over Basement	0.33	0.33	0.33	0.33
Inside Partitions	0.37	0.37	0.37	0.37

COMPUTED HEAT LOSS OF LIVING SPACE, BTU/HR

Indoor-Outdoor Temp. Diff. °F	70	45.9	46.1	50.6
Wind Velocity, mph	15	7.5	5.4	3.9
Outside Walls	24,800	15,750	15,720	17,150
Windows and Doors	42,300	24,820	23,730	25,100
Inside Partitions	1,350	880	900	990
Ceiling	52,400[a]	38,350	39,600	40,600
Floor over Basement	8,360	4,180	3,920	3,920
Slab on Ground	4,470	2,920	2,970	3,280
Infiltration[b]	20,160	13,220	13,280	14,580
Total	153,840	100,120	100,120	105,620

[a]Based on 100 Deg. F. Temperature difference between ceiling surface and outdoor air

[b]Based on one air change per hour

A comparison of the data in Tables 3 and 4 shows that a heat input rate of 95,300 Btu/hr produced an average indoor-outdoor temperature difference of 45.9°F for the period from 8 P.M. to midnight whereas the computed heat loss using conventional methods was 100,120 Btu/hr. That is, the observed heat loss was 95.1% of the computed value. This is considered good agreement in view of several uncertainties in the heat loss calculations such as the reverse heat loss from the heated coves, the two kinds of foundation construction, the variable ceiling temperatures, the effect of radiant heat on the window losses, and the infiltration rate.

An agreement between observed and computed heat losses with less than 5% disparity is not to be expected with any kind of heating system. This comparison between observed and computed heat loss indicates that a heat loss calculation made by conventional methods would be a good guide in selecting the heating capacity required for the type of heating system and construction used since the heat is introduced into the living space without significant losses.

The computed heat loss of the structure was 77.5 Btu/hr per sq. ft. of enclosed floor area at design outdoor weather conditions which is a higher heat loss rate than for most present-day dwelling constructions. It will be noted in Table 4 that the ceiling heat loss accounts for 34 to 39 percent of the total computed loss of the house. This is an unreasonably high percentage considering the relative ease with which a ceiling can be insulated. These percentages indicate that more heat was lost through the ceiling than was probably absorbed by the ceiling surface from the direct radiation of the electric heaters.

In the six rooms of the house heated from coves at the ceiling the gross heat input was 56,500 Btu/hr or 44.5 Btu/hr per sq. ft. of ceiling area under the test conditions. Assuming that about 38 percent of the total heat input was lost through the roof, the net heat transfer downward from the ceiling was approximately 28 Btu/hr per sq. ft. of ceiling area.

Effect of Window Draperies

When the Venetian blinds were lowered and the drapes drawn over the windows for the period from midnight to 4 A.M., there was practically no change in the indoor-outdoor temperature difference for the same heat input rate. During this

period the heat input rate of 95,300 Btu/hr produced an indoor-outdoor temperature difference of 46.1°F. The computed heat loss was the same for this period because both the average wind velocity and temperature decreased. As compared to the first four-hour period of the test, the indoor temperature decreased 1.6°F and the outdoor temperature decreased 1.8°F during the second four-hour period. The infiltration heat loss computation during both periods was based on one air change per hour and the observed temperature difference between room air and outdoor air.

Table 3 shows that the window surface temperature in the living room decreased 6.7°F after covering the windows whereas the outdoor temperature decreased only 1.8°F. This decrease in window temperature indicates a lower window heat loss at the thermocouple location but may not be indicative of the average change for all windows. A drapery in front of a window produces a chimney effect that probably increases air circulation adjacent to the window pane as compared to an undraped window. The decreased window heat loss, if it existed, was partly or wholly counterbalanced by the greater loss through that portion of the wall that was covered by the drapes when they were drawn back since there was no appreciable increase in indoor-outdoor temperature difference caused by covering the windows.

Wall, Floor, and Ceiling Temperatures

The temperatures observed on the exterior wall surface and one inch from the wall surface, as summarized in Table 3, indicate that the wall surface was 4.8°F colder than the air for the period from midnight to 4 A.M. For the same wall construction and indoor-outdoor air temperature difference, but with non-reflective wallpaper on all interior surfaces and a convection heating system the wall surfaces would be about 8°F colder than the room air. This comparison indicates that enough radiant heat was incident upon and absorbed by the reflective wallpaper to raise its temperature about 3°F above that expected with non-reflective wallpaper in a convection-heated house.

The actual rise of the reflective wallpaper temperature may not have been quite as great as 3°F because the cellulose tape used to secure the thermocouple to the wall may have absorbed enough additional radiation to locally warm the thermocouple. However, a similar thermocouple on an interior wall averaged only 1.1°F warmer than the air one inch from the wall so this represents an approximate upper limit to the error caused by the tape on the outside wall. This rise in exterior wall surface temperature caused by the absorption of radiant

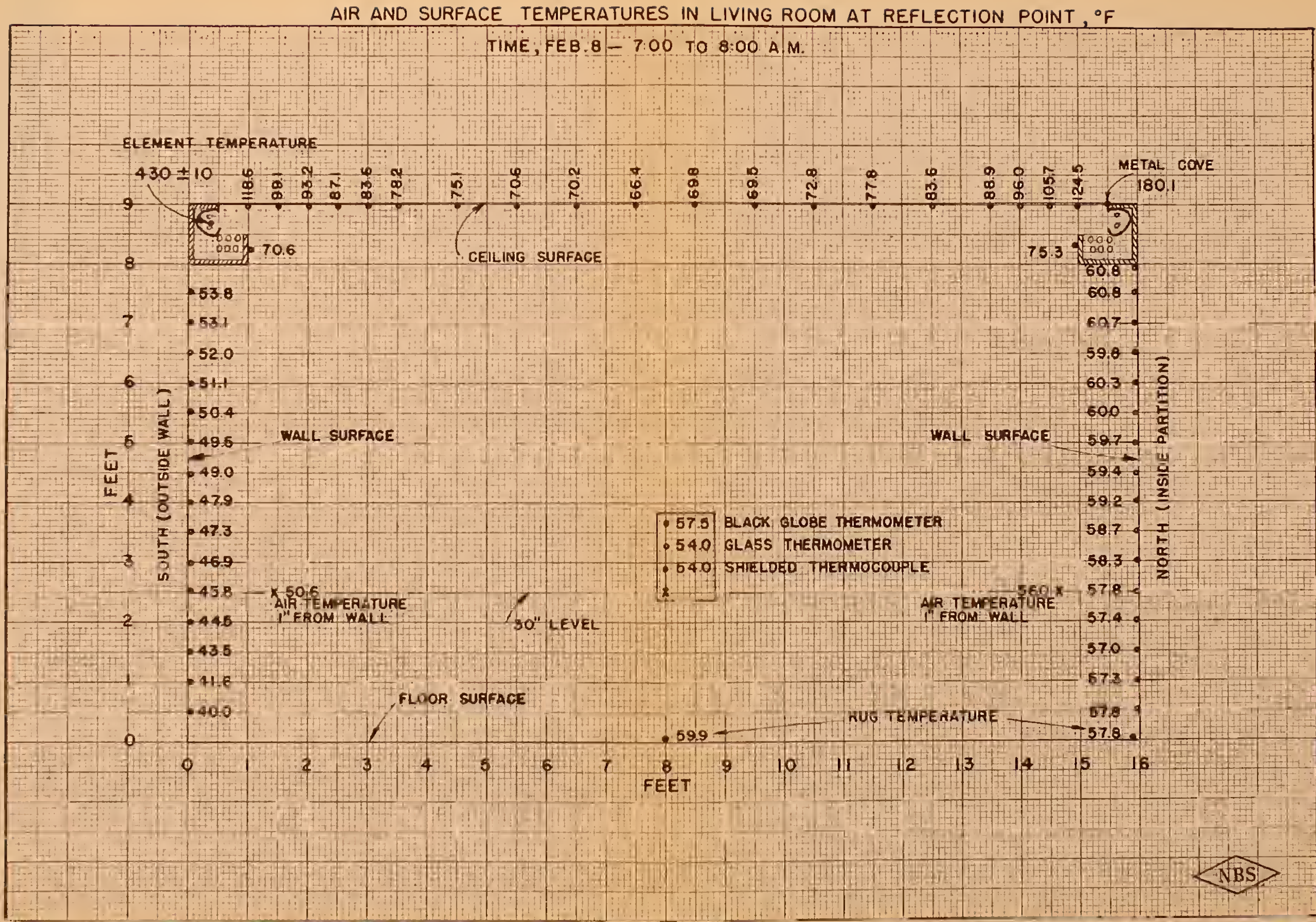
energy would cause a greater loss of heat through the exterior wall for the same indoor-outdoor air temperature difference than for a non-reflective wall without radiant sources in the room. For the conditions existing during the test the increase of the wall heat loss from this cause would be about 5%, for a 2 degree warmer wall surface temperature.

The rug surface at the center of the living room averaged 7 to 8°F warmer than the air at the 30 in. level. The rug, being a good absorber, received radiant heat from the ceiling and walls and served as a source of convection heating for the air in the room.

The temperatures of an interior and exterior wall and the ceiling of the living room were observed at 6-inch and one-foot intervals between 7 and 8 A.M. when the ventilating blower was not running. These temperatures are indicated on an outline vertical section of the room in Fig. 2. The rug surface temperature and air temperature at the 30-in. level are also shown. A vertical gradient in exterior wall surface temperature of 13 to 14°F was observed.

The pattern of ceiling surface temperature shown in Fig. 2 is plotted against distance in Fig. 3 to indicate the shape of the temperature curve. The arithmetical average of the ceiling temperatures shown in Fig. 3 is about 86°F. for the ceiling surface between the edges of the coves. The heat input rate in the living room was 17,065 Btu/hr during this period of the test and the temperature of the unheated globe at the center of the living room was 57.7°F. Thus an average of 45.3 Btu/hr per sq. ft. of ceiling area was transmitted from the electric heating elements in the living room for a difference of 28.3°F between the average ceiling temperature and that of the unheated globe.

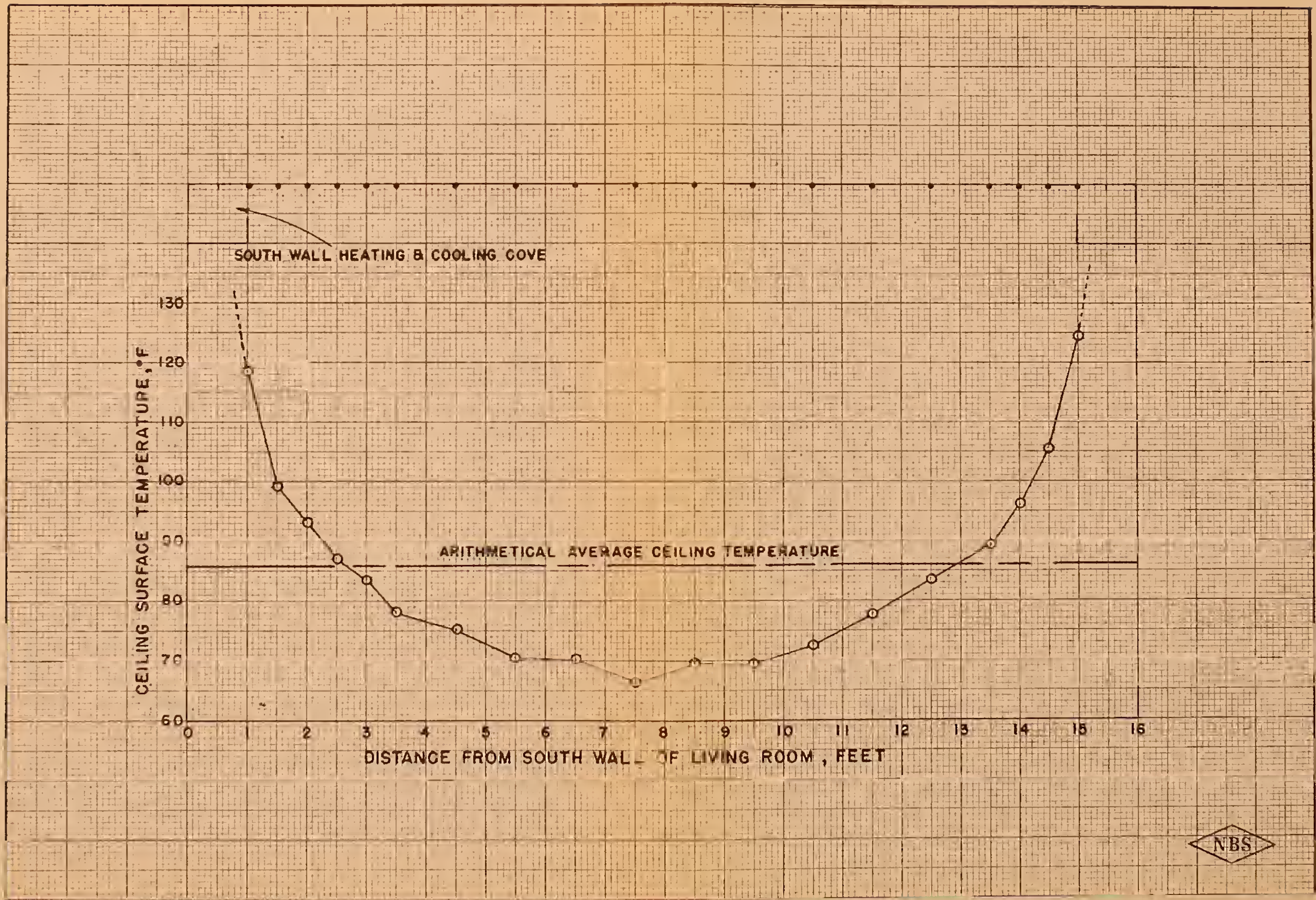
Computation indicates that the heat loss of the ceiling in the living room was about 8,700 Btu/hr or just about half of the heat input into the living room. Thus, about half of the energy transferred from the heating elements in the living room was lost through the roof and a substantial portion of this upward heat loss represents heat that was not available for reflection or radiation to the room from the ceiling surface. Therefore, the average heat emission and reflection of the ceiling surface to the room may have been as low as 22.6 Btu/hr per sq. ft. under the conditions described above. It is probable, however, that the heat radiated from the ceiling was greater than this value because some of the 8,700 Btu/hr heat loss of the roof must have been provided by warm air in contact with



AIR AND SURFACE TEMPERATURES IN LIVING ROOM AT REFLECTION POINT, °F
TIME, FEB. 8 — 7:00 TO 8:00 A.M.
ELEMENT TEMPERATURE
430 ± 10
118.6
99.1
93.2
87.1
83.6
78.2
75.1
70.6
70.2
66.4
69.8
69.5
72.8
77.8
83.6
88.9
96.0
105.7
124.5
METAL COVE
180.1
70.6
CEILING SURFACE
75.3
53.8
53.1
52.0
51.1
50.4
49.5
WALL SURFACE
49.0
47.9
47.3
46.9
45.8
X 50.6
AIR TEMPERATURE 1" FROM WALL
44.5
43.5
41.6
40.0
30" LEVEL
FLOOR SURFACE
57.5 BLACK GLOBE THERMOMETER
54.0 GLASS THERMOMETER
54.0 SHIELDED THERMOCOUPLE
60.8
60.8
60.7
59.8
60.3
60.0
WALL SURFACE
59.7
59.4
59.2
58.7
58.3
56.0 X
57.8
AIR TEMPERATURE 1" FROM WALL
57.4
57.0
57.3
57.8
RUG TEMPERATURE
59.9
57.8
SOUTH (OUTSIDE WALL)
NORTH (INSIDE PARTITION)
FEET
FEET
NBS

FIG. 2

PATTERN OF CEILING SURFACE TEMPERATURE IN LIVING ROOM



the cooler central area of the living room ceiling or by reflected energy from the walls. The measured heat output of a plastered ceiling heating panel containing embedded copper tubes, for the same difference between average ceiling temperature and an unheated globe temperature at the 30-in. level, were found during other studies to range from 27.5 to 32 Btu/hr per sq. ft. of panel area depending on the tube spacing. Thus, it would appear that the coves and reflective ceiling surface at Reflection Point and a non-reflective ceiling panel heating surface might be about equally effective per unit area in transmitting heat to a living space for the same temperature difference between ceiling surface and an unheated globe. If the roof had been better insulated, thus decreasing the upward heat loss, the effectiveness of the cove and reflective ceiling system would have been proportionately increased.

Comfort

It was impossible to make any precise observations regarding what constituted comfort conditions in the test house during a brief field trip. However, during the day preceding the 20-hour test summarized in Table 3 and Fig. 1, outdoor temperatures were considerably higher and the interior of the house was warmer. Specific note was taken by the observers during this first day that an air temperature of about 67 or 68°F was required for comfort while they were moving about in the house and clothed in ordinary business suits. Of course, it is possible that other individuals would be comfortable at lower air temperatures.

At no time during the 20-hour test from 4 P.M. on February 7 to 12 N on February 8 was the house comfortably warm when the air temperatures ranged from a high value of 63°F in the living room at 4 P.M. down to 50°F in the dining room and foyer at 4 A.M. A portable electric heater was used to warm the study to a higher temperature during the test to provide a comfortable location for the observers when data were not being taken. However, the electric energy used by this portable heater was not included in the heat input used for computation purposes and the air temperature in the study was not included in the average for the house.

Obviously, portable electric heaters could be used to make any small area in the house comfortable during severe weather even though the general level of temperature in the house was uncomfortably low. However, resort to "spot heating" with a resultant saving in overall heat usage is a possibility with any heating system and should not be considered as one of the special features of this particular house.

The data in Table 3 show that the radiation-convection temperature measured with the unheated globe was 4.2°F higher than that indicated by a shielded thermocouple at the same station. For the conditions of the test and an 8 in. globe, the mean radiant temperature was computed to be 2.5°F above the globe temperature. The difference between air temperature and mean radiant temperature would probably increase at greater heat input rates and decrease at lower heat input rates. For equal comfort, the mean radiant temperature in a convection-heated room will always be a little lower than the air temperature whereas for this system the mean radiant temperature would always be expected to be higher than the air temperature. Thus, comfort would probably be attained with the heating system used in this house at an air temperature several degrees lower than for a convection heating system with no high temperature sources of radiation present. This difference in air temperature might approach 10% of the indoor-outdoor temperature difference at design conditions. However, it was impossible to deduce from the data taken that the reduction in heat loss resulting from lower air temperature would not be offset by the greater heat loss to the walls and windows due to the greater radiant flux in the rooms. It is concluded, therefore, that the saving of heat would probably be less than 10% for the heating method employed as compared to a convection heating system entirely enclosed in the living space.

In the Test Bungalow a ceiling panel heating system produced a radiation-convection temperature in an 8-in. unheated globe 2.1°F above the air temperature at the same station with non-reflective surfaces on walls and ceiling when the outdoor temperature was 32°F and the average heat transfer rate from the ceiling was about 28 Btu/hr per sq. ft. of panel area. If it is assumed that the heat transfer rate from the reflective ceiling at Reflection Point was also of the order of 28 Btu/sq. ft. of ceiling area during the 20-hr test heretofore described, then it is concluded that the radiant heat flux intercepted by the unheated globe was about twice as great at Reflection Point as in the Test Bungalow because the temperature difference between globe and air was about twice as great at Reflection Point.

In the Test Bungalow using a plastered ceiling panel heating system comfort was experienced by most observers with summer weight clothing at an air temperature of 67°F to 68°F except for some coolness around the feet and lower part of the legs after several hours exposure. The floor surface temperature at the center of the room was equal to the air temperature at the 30-in. level ±1°F in most cases. At Reflection Point the rug surface temperature was 7 to 8 degrees warmer than

the air at the 30-in. level. This indicates that appreciably greater radiant heat flux reached the floor at Reflection Point. The comparison is not ideal because the Test Bungalow had an unheated basement whereas the living room floor at Reflection Point was on grade. However, the comparison is believed to be significant because sub-floor temperatures have been shown to have only a small effect on floor surface temperatures in buildings with uninsulated walls. These comparisons suggest that comfort might be obtained in a room with a plastered ceiling heating panel at about the same air temperature as in a room with reflective walls and ceiling of the type used in the house at Reflection Point except that the former would approach more nearly a unidirectional heat source and would not radiate as much heat to the lower parts of the occupants of the room as the latter.

Forced Ventilation

The volume of air delivered by the ventilating blower was measured near the outlet of the electrostatic precipitator. The observed air delivery after being corrected to the density of the house air was 370 cfm. This represents about 1.4 air changes per hour for the house.

During the period of the test from midnight to 4 A.M. when the outdoor temperature averaged 6.5°F the ventilating air entered the living space at the perforated ceiling in the hall at an average temperature of 31.3°F. This caused the hall to feel undesirably cold. It is believed that the hall would still have felt too cold if the remainder of the house had been at a comfortable temperature and the ventilating air were brought in without tempering.

When the ventilating air blower was stopped the temperature difference between indoors and utdoors increased about 5 degrees indicating that the natural ventilation with an average wind velocity of 4 mph was less than the forced ventilation rate. During the period from midnight to 4 A.M. about 14,600 Btu/hr were required to warm the ventilating air from the temperature at the precipitator outlet to the average room temperature. The remaining 80,700 Btu/hr of the gross electric heat input were available for heat transmission loss corresponding to an average of 1750 Btu/hr per degree indoor-outdoor temperature difference. Since the indoor-outdoor temperature difference increased 5°F when the blower was stopped an additional 8,750 Btu/hr was used to offset heat transmission loss and the remaining 5,850 Btu/hr represents the heat required to warm the natural air leakage. This represents about 115 cfm or 0.43 air change per hour.

It was observed during the early part of the test when the wind velocity was higher that outdoor air leaked into the house around the doors on the windward side of the house even when the ventilating blower was running.

IV. DISCUSSION AND CONCLUSIONS

The experience gained during the field test at Reflection Point and analysis of the data obtained indicates the following conclusions:

(1) Disregarding the cost for electric heating, a house of moderate heat loss can be comfortably heated by using radiant heat sources in coves at the ceiling and reflective papers on the walls and ceiling such as were used at Reflection Point. However, the test house was inadequately heated by the electric heating units used. All of the installed capacity produced an indoor-outdoor temperature difference of about 46°F.

(2) Reflective ceiling and wall surfaces used with a source of radiant heat in coves at the ceiling, appeared to increase the radiant heat flux in the living space as compared to most other heating methods; had the characteristics of a multi-directional source of radiant energy; and appeared to warm the floor of the house and the lower extremities of the occupants better than an ordinary ceiling heating panel would do, even though the surfaces had emissivities no lower than 0.3.

(3) In the opinion of the observers an air temperature of about 67°F to 68°F was required in this house for comfort when the observers were engaged in light activity and clothed in conventional business suits. The mean radiant temperature of the living room in the house was about 7°F higher than the air temperature during the test.

(4) The test results did not indicate positively that any saving in heat resulted from the use of reflective ceiling and wall coverings. It is reasonably certain that the saving, if any, would be less than 10% as compared to some other convection and radiant heating systems entirely contained in the living space. It is believed that the greater savings claimed by the owner are dependent partly on

maintaining lower air temperatures than were considered comfortable by the observers; partly on the saving of heat possible during sunny weather in any house with large window areas on the east, south and west exposures because of solar heating; and possibly by some use of spot heating with portable heaters.

(5) Because the heating system used at Reflection Point did not significantly reduce the heat loss of the house as compared to a conventional system, it is just as important to provide low heat transmission values in the roof and exterior wall construction with this type of heating system as with any other. The heat transmission coefficients of the roof and exterior walls were considered to be undesirably high.

(6) With radiant heaters in a cove near the ceiling, a reflective ceiling would have lower ceiling surface temperatures and lower ceiling heat loss than a non-reflective ceiling. It is probable that a non-reflective ceiling surface would be adversely affected by the high temperature near the coves if it were made of plaster or wood. However, a house with a reflective ceiling could probably be warmed satisfactorily with either reflective or non-reflective wall coverings by means of radiant heaters in coves near the ceiling of the type used at Reflection Point.

(7) Ceiling surface temperatures were higher near the perimeter of the rooms than near the center. While this pattern of temperature is desirable near the exterior walls from a comfort standpoint, excessive ceiling temperatures tend to make the ceiling paper brittle and might adversely affect wood or plaster surfaces if these materials were used as a base for the reflective paper on the ceiling. These considerations might dictate a limiting heat loss which this type of distribution system could accommodate. There was some evidence of brittleness of the paper on the ceiling of the test house even though the heating system had not been in operation one full heating season at the time of the tests. Ceiling surfaces temperatures of 125°F were observed near the coves during the test even when the heat input rate was inadequate for the house.

(8) The special drapery materials had emissivity coefficients in the range from 0.58 to 0.69 and their use over the large windows did not significantly change the heat loss of the house. The temperature difference between the air and an unheated globe at the center of the living room was increased only 0.3°F as a result of drawing drapes and blinds over all the windows. This does not represent any considerable change in the comfort in the living room.

(9) The nylon rugs, foam rubber mats, aluminum foil and cork tile were considered to be adequate floor coverings. As used, the aluminum foil was only partially effective as reflective insulation because about half of the surface was in contact with the rubber mat. In our opinion, other satisfactory floor coverings could be found for houses using this type of heating system.

(10) Consideration of the importance of radiant heat transfer in the heating system at Reflection Point indicates the necessity for the type of step-control or modulating control of the heat sources that was used to avoid uncomfortable periods that would occur with an on-off type of control.

(11) Forced ventilation of the test house presumably eliminated much of the random air leakage except on the windward side and promoted interior cleanliness although the latter feature was not directly observed during the field test. The natural ventilation rate of the house was quite low when the blower was not running. The introduction of untempered ventilating air through the hall ceiling caused coolness in local areas nearby. Tempering of the ventilating air before introduction would eliminate such discomfort and would not add to the cost of heating the house.

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