

SPACE HEATING
WITH
ELECTRIC RADIANT PANELS

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1949

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ACKNOWLEDGMENT

The author wishes to express his appreciation to L. Slegel, Professor of Mechanical Engineering, and to S. H. Graf, Head of the Department of Mechanical Engineering, for their help and suggestions; and to Mrs. James F. Culbertson, wife of the author, for her stenographic work and help in plotting the performance data.

ADVANCE BOND

W. L. BROWN

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I. INTRODUCTION

In any discussion of radiant heating, the term "radiation," is often misused and, therefore, should be properly defined. Correctly applied, the term "radiation," means the heat which is transferred by what are presumed to be ether waves, traveling in straight lines at the speed of light, 186,000 miles per second. These waves set up in the ether are actually energy and on meeting the surface of a body, they are transformed into heat, which may raise the temperature of the receiving body.

All objects radiate energy, the amount of energy radiated depending on the temperatures of the objects and their emissivities. The amount of energy radiated is directly proportional to the fourth power of the absolute temperature of the radiating object. Thus the energy interchanged by radiation between two bodies is proportional to the difference between the fourth powers of their absolute temperatures. Of course, the radiant interchange also depends on the position of the bodies relative to each other, and the equation for this interchange must include a shape or configuration factor to account for this.

The general radiant interchange equation then

becomes $Q_{1-2} = C(T_1^4 - T_2^4)F_e F_a A_1,$

where Q is the total net energy interchanged by radiation between Bodies 1 and 2, in Btu per hour. C is the Stefan-Boltzmann constant or proportionality factor; its value is $0.174(10^{-8})$ Btu per hour per square foot of area per degree Fahrenheit absolute.

T_1 is the temperature of Body 1, degrees Fahrenheit, absolute.

T_2 is the temperature of Body 2, degrees Fahrenheit, absolute.

F_e is the emissivity factor of the two bodies.

F_a is the shape factor of the two bodies.

A_1 is the area of Body 1 in square feet. (3, p.31)*

When radiant energy impinges on a body, a part of the energy is reflected, a part is absorbed, and a part passes through the body. The rate at which a body absorbs radiant energy which it intercepts is proportional to the rate at which the body radiates energy. If a body absorbs all radiant energy which it intercepts, it is a perfect absorber. Such a body is also a perfect radiator, as the two functions are reciprocal. There is no perfect radiator in nature. Since a perfect radiator is a perfect absorber, it would absorb all radiation impinging on it and

*Numbers in parentheses refer to bibliography.

would reflect non-light radiation as well as heat radiation; it would, therefore, appear black to the human eye, and, for that reason, a perfect radiator is generally called a "black body," and its radiation, black radiation. All other radiation is called gray radiation.

The ratio of the rate at which the surface of an actual body radiates energy to the rate at which a "black" body would radiate energy is called the "radiation factor," or the "emissivity" of that surface. Numerous tests of emissivity have been made on many various materials to determine this particular characteristic. Below is shown a table of various emissivities of some of the more common materials now used. (1, p.20-8, 20-9)

EMISSIONS OF VARIOUS MATERIALS
AT A TEMPERATURE OF 70 F

Material	(e)	Material	(e)
"Black" body	1.00	Oak	0.90
Aluminum, Dull	0.22	Oil Paint	0.94
Aluminum, Polished	0.04	Paper	0.93
Asbestos Board	0.94	Plaster	0.91
Brass, Dull	0.22	Roofing Paper	0.91
Brass, Polished	0.03	Rubber, Hard	0.95
Brickwork	0.95	Rubber, Soft	0.86
Concrete	0.90	Stonework	0.93
Glass	0.92	Tile	0.90
Glazed Earthenware	0.90	Water	0.95
Iron and Steel, Dull	0.82	White Marble	0.84
Lead, Dull	0.28	Woodwork, (painted)	0.92
Linoleum, (unpolished)	0.90	Woodwork, (rough)	0.94
Marble, Polished	0.93	Woodwork, (waxed)	0.90

In order that the presentation of radiant heating be more complete, the physiological aspects of the problem must be taken into account.

It is generally known that the human body requires no heat from without (provided we do not lose too much heat to surrounding objects), because heat is generated inside the body by a chemical and physical process known as metabolism, which provides more heat than we require. The normal rate of heat production in the average human individual is about 400 Btu per hour, which is given off to the surroundings by various means. Depending upon the conditions, possibly 300 Btu per hour of this heat may be given off by radiation and convection, and the remainder by evaporation and respiration. Therefore, no heating system has to serve the purpose of adding heat to the individual; its only function is to control the net rate at which the body loses heat by these various means.

The radiation loss is that amount of heat given off from the human body by radiant energy when the surface of the body is warmer than the surfaces of the surrounding walls, windows, ceilings, furniture, etc. Convection loss is the amount of heat given off from the body to the cooler ambient air which passes over the surface of the body and carries away the heat. The heat loss by evaporation is that amount of heat taken from the body as perspiration

passes through the pores of the skin and is evaporated, and the heat dissipated by respiration is the amount of heat given to the air we breathe.

While it is somewhat difficult to differentiate exactly between the radiation loss and convection loss, it is found that conditions of comfort for the human body depend principally on the temperature of the ambient air and the MRT or mean radiant temperature of the room and, to a lesser extent, on the relative humidity and velocity of the air in the enclosure. The term, "mean radiant temperature," is the average temperature of all of the surfaces by which the room is enclosed. This is not necessarily the same as the arithmetic average of the various surface temperatures, but rather the radiant temperature which corresponds to the average of the several rates of heat emission (Btu per square foot) from the several surfaces. Ordinarily these surfaces include the floor, ceiling, walls, windows, and doors.

The temperature of the surrounding air is usually the most important factor that determines the proportion of heat given off by the human body by convection and the temperature of the surroundings determines the proportion dissipated by radiation. Disregarding the velocity and relative humidity of the air, the same degree of comfort may be obtained through a wide range of air temperatures

and MRT. For example, when the MRT is low, the air temperature must be high; when the MRT is high, the air temperature must be low. The comfort temperature, which is a function of both the air temperature and the MRT, may be the same for both of these conditions. (3, p.32-33)

This fact constitutes one of the principal advantages of radiant heating; that is, that the air temperature in a room may remain fairly low and, with the proper MRT maintained, the comfort temperature will remain high.

"When a room is heated by means of a panel, air convection currents are developed in the room similar to those which are developed when the room is heated by means of a free-standing radiator. Consequently, the heating panel delivers heat to the room partly by radiation and partly by convection. The proportion of the total heat flow delivered by convection varies with the location of the heating panel, with the height of the ceiling, and with the size, number, and location of pieces of furniture and other articles which interfere with the free flow of air along the floor and along the walls. It is generally sufficiently accurate to assume that a ceiling panel will deliver 70 per cent of its heat by radiation and 30 per cent by convection; a floor panel 55 per cent by radiation and 45 per cent by convection; and a wall panel 65 per cent by radiation and 35 per cent by convection." (2, p.571)

II. PURPOSE OF THIS INVESTIGATION

There has been much discussion and controversy over the performance of radiant panel heating, such as the temperature variation throughout the heated space, lag in heat response, method of controls, operating costs, and preferable type of radiant panel heating system.

It was the purpose of this paper, therefore, to determine some of these characteristics using one particular type of radiant heating system; namely, electric radiant panels located in the floor of the space to be heated.

III. TEST EQUIPMENT

Test Room

The test room used in this investigation was of wood construction 12 feet square, with an 8-foot ceiling. Floor joists were of 2 x 6's placed on sixteen-inch centers, while the wall studs and ceiling joists were of 2 x 4's also placed on sixteen-inch centers.

Insulation and covering of the test room proceeding from the inside to the outside, were as follows: fibreboard of 1/2-inch thickness completely covered the four walls, followed by a 2-inch thickness of cotton blanket insulation between the studs, with the paper backing toward the warm side of the wall; next was a tar paper covering nailed on the outside of the wall studs and then plywood of 1/4-inch thickness covered the tar paper. The inside ceiling was covered with the same material as the walls, namely, 1/2-inch thick fibreboard. Kimsul blanket-type insulation of 3-inch thickness was placed between the ceiling joists, which were covered either with plywood or fibreboard, both of 1/2-inch thickness. Construction of the floor consisted of 1/2-inch thickness of plywood, with a 2-inch thickness of cotton fill between the joists. Tar paper was nailed to the outside, or underneath side, of the floor joists, but was not covered with plywood. Slats of wood placed at

various locations held the tar paper firmly in position against the joist.

The electric panels, which consisted of eight separate panels, were placed on the flooring of 1/2-inch thick plywood and covered completely with another plywood flooring of the same thickness. Large screws were used to fasten the flooring tightly to the floor joists so that air spaces around each panel would be minimized.

The test room itself, which will be designated the warm room, was completely enclosed in a large room, which will be designated the cold room. The dimensions of the cold room were 20 feet by 20 feet, with a 16-foot ceiling. With respect to the cold room, the warm room was placed in the center of the cold room, making the distance to each warm room wall the same. This total distance was four feet. In order to have the same distance both above and below the warm room, it was built four feet up from the floor of the cold room. A picture on the following page shows part of the enclosing cold room and the stairway leading to the raised warm room.

In order to minimize the heat loss from the cold room to the outside, the cold room was insulated in the same manner as the warm room. This insulation included fibreboard on the inside, cotton fill between the wall studs, tar paper on the outside of the studs and followed with plywood covering.



Figure 1. Interior View of the Cold Room showing the space beneath the warm room and stairway leading to the entrance.

Refrigeration Unit

In order to maintain a temperature in the cold room as nearly constant as possible and, hence, a heat loss from the warm room also as nearly constant as possible, a refrigeration unit was installed. It was located outside of the cold room and connected to a finned-tube heat exchanger which was placed about one foot below the ceiling in one corner of the cold room. Cool air was circulated in the cold room by means of two fans built as an integral part of the heat exchanger. The refrigeration unit had a capacity of two tons and was powered by a three horsepower electric motor. Pressure controls were installed on the compressor so that only intermittent operation was necessary between the pressure limits as set.

Electric Radiant Panels

The electric radiant panels which were used in this test were made by Professor Louis Slegel, Mechanical Engineering Department, Oregon State College, for use in previous experimentation. They were of a fabricated type, built in the following manner: a 4 by 8 foot asbestos-cement board of 1/4-inch thickness was routed with an electric saw to a depth of about 3/32 of an inch. The routed grooves were made on two-inch centers across the

board and run lengthwise on the board, leaving a space of two inches at both ends. Each set of two grooves at each end was connected so that a continuous wire could be placed in the groove. High strength, bare, copperweld wire of gage number 18 was placed in the groove with the two ends extending out at the same end of the panel. This wire had a resistance of 21.70 ohms per thousand feet and was used primarily because it had almost exactly the conductivity which was calculated as being required. Another sheet of 1/4-inch asbestos-cement board of the same dimensions as the first panel was placed on the grooved panel, with the joining surfaces coated with an adhesive compound. Three-sixteenths inch bolts were then used to bolt the panels together. A junction box was placed on the top surface of the panel and the two wire ends from the grooves were connected to this junction box.

An exception to this construction was that in four of the panels, one layer of 1/4-inch fir plywood was substituted for one of the layers of asbestos-cement board. A sheet of asbestos paper was glued to the entire grooved side of the asbestos-cement board; the plywood board was then bolted to the grooved board and the asbestos paper served to insulate the resistance wire from the plywood. In Figure 2, on page 13, is shown the typical construction of these panels as previously described.

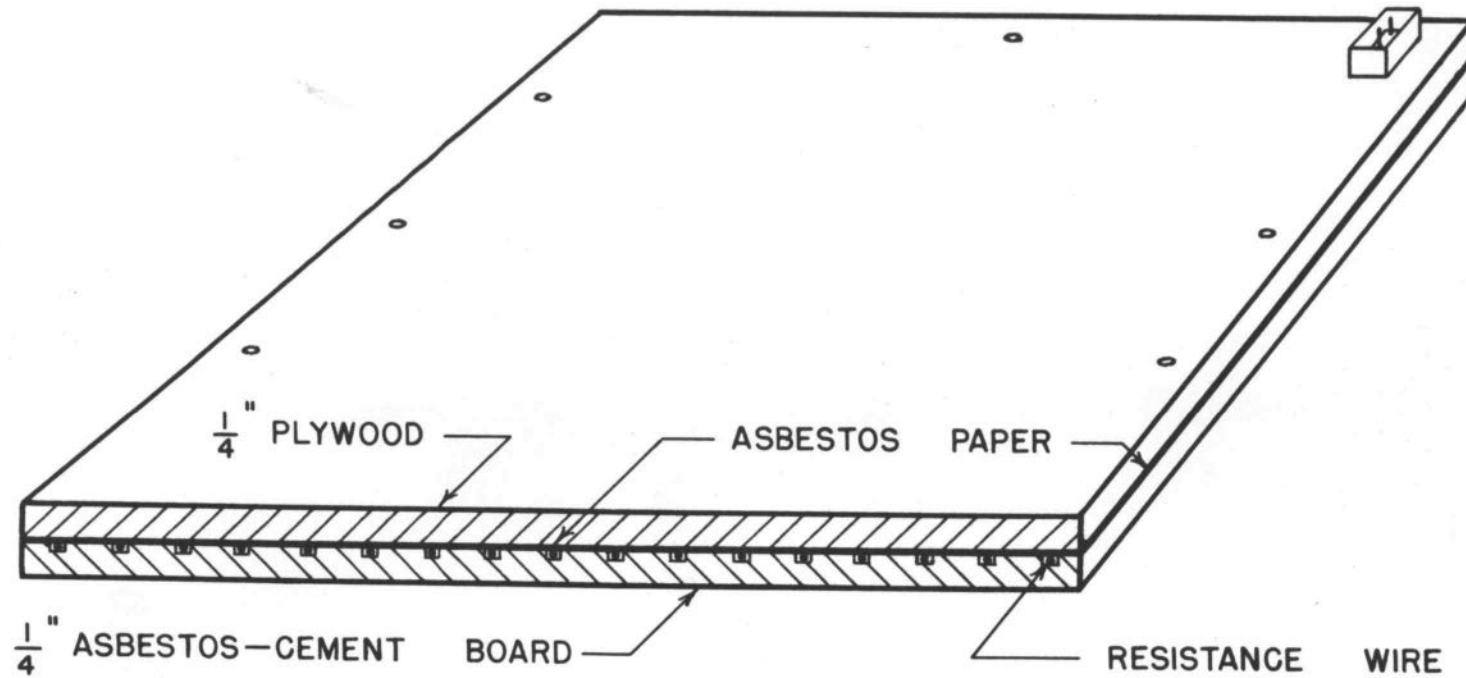


Figure 2. SECTIONAL VIEW SHOWING CONSTRUCTION DETAILS OF ELECTRIC RADIANT PANELS

Altogether, eight panels of the construction shown were made. Two were 4 by 8 feet; two were 2 by 8 feet, and the remaining four were 2 by 6 feet in dimension. The electrical resistance of each panel, of course, depended on the length of resistance wire in it. A 4 by 8 foot panel contained approximately 180 feet of resistance wire, giving it a total resistance of about 3.90 ohms. The total resistance of all eight panels was 17.60 ohms.

Thermocouples

Copper-constantan thermocouples of wire gage number 25 were used throughout the warm room for obtaining the various temperatures. They were made by twisting together the two bare wires for a length of about $1/4$ inch. These were then fused together at the tip by short-circuiting across the terminals of a 110 volt circuit with a transformer adjustment.

Locations of the thermocouples in the warm room were chosen with the purpose of obtaining the temperatures over a definite area and at a definite height level. Several grooves were cut in the plywood floor to a depth of approximately $1/8$ inch, and a number 14-gage copper wire was peened into these grooves; at the same time a special glue preparation was put around the wire to eliminate any possible air entrapment in the grooves.

Altogether, there were 62 thermocouples placed in the floor, each of which was soldered to the embedded copper wire on the particular section of flooring above each electric radiant panel. Reference is made to Figures 3 and 4, pages 16 and 17, for the number designation of each panel, with the location of the thermocouples on the floor surface and the thermocouples located in the panel itself.

In panels number 1, 2, 4, and 5, six couples of three each were soldered onto the two short embedded copper wires of 1 1/2 feet in length, placed 2 1/2 feet apart. Each of the six couples was wired in parallel so that one average temperature for the particular panel was obtained. Three embedded copper wires of 1 1/2 feet in length were peened into each of the floor panels, numbers 3 and 6. Two of the copper wires were spaced at a distance of two feet from either end of the panel, and the third wire was located exactly in the middle of the panel. Nine couples were soldered onto these wires, with three on each wire. Again the wiring was made in parallel so that an average temperature of each panel was obtained. Panels 7 and 8 had two embedded wires of slightly less than four feet in length, placed 2 1/2 feet from either end of the panel. Five couples were soldered onto each wire for both panels, making a total of ten couples; again a parallel circuit was

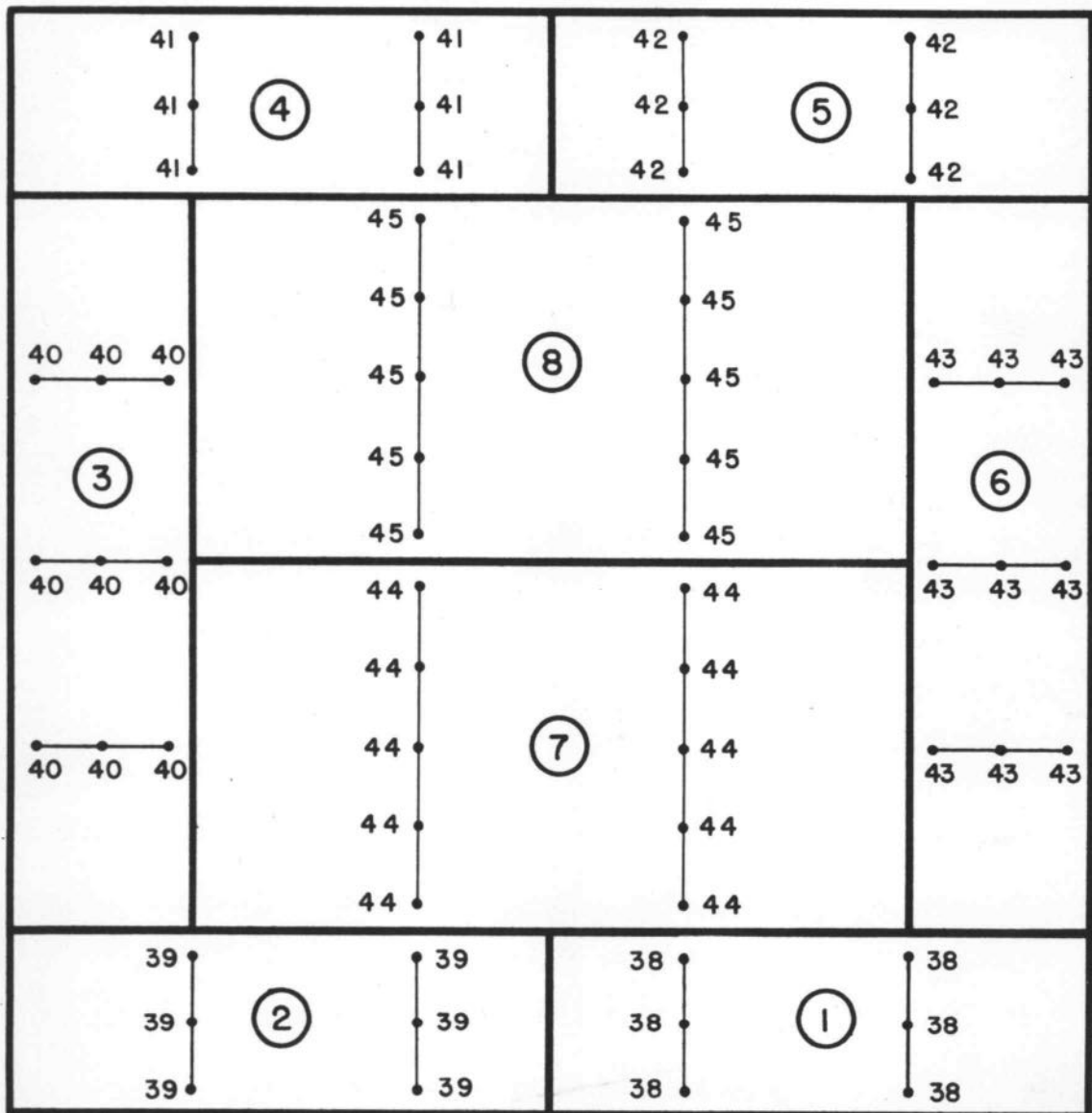


Figure 3. FLOOR SURFACE THERMOCOUPLE LOCATIONS

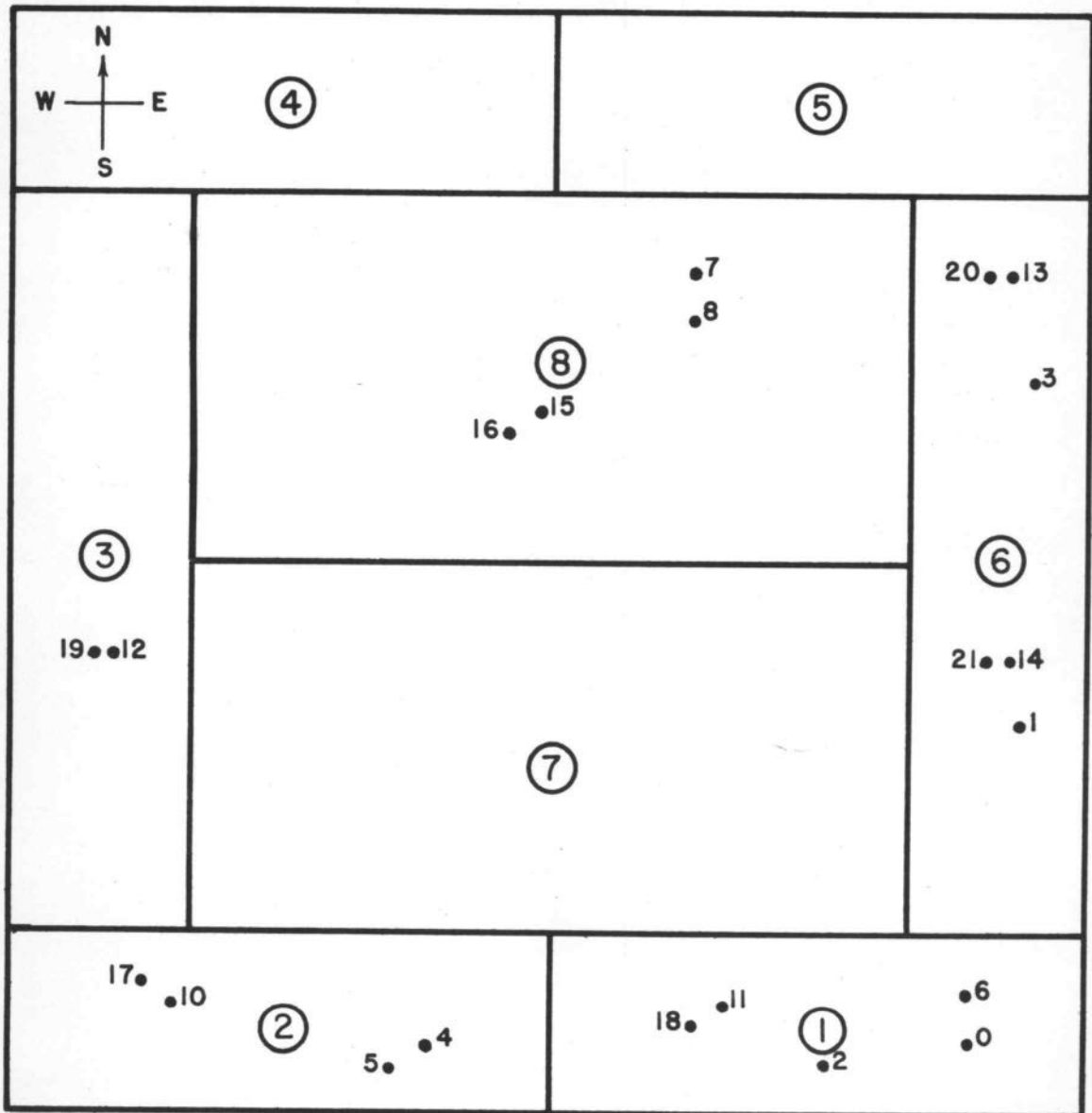


Figure 4. RADIANT PANEL AND THERMOCOUPLE LOCATIONS

used. After all the couples had been properly secured to the embedded wire, it was painted a dull green so that there would be no reflective surface. The thermocouple leads from each panel were connected to a main selector switch in the recording room.

Thermocouples on the walls were located both on the north and south walls, with three rows placed on the north wall and a single row on the south wall. The rows on the north wall were located at levels of $1 \frac{1}{3}$ feet from the floor, midway between the floor and ceiling, and $1 \frac{1}{3}$ feet from the ceiling. On the south wall the row was placed $1 \frac{1}{3}$ feet from the ceiling. Each row consisted of five couples which were embedded into the surface of the fibre-board and glued with a special preparation. As with the previous couples, each row was wired in parallel to give an average temperature of the wall at the particular level.

Ceiling thermocouple locations were determined by dividing the 12 by 12 foot ceiling into approximately three equal areas. The center area had only two couples, while the two outer areas had eight couples each. The couples of each area were wired in parallel, as were the others.

Three couples were located in approximately the center of the warm room, with one placed six inches from the ceiling, another midway between the floor and ceiling, and the last one six inches from the floor. All of these

couples were shielded with aluminum foil, so as to give the actual room temperature and to prevent a higher temperature reading due to receiving of radiant energy from the radiant panels.

Eight additional thermocouples were also located near the center of the warm room. Four were placed on a black ball suspended from the ceiling at a position midway between the ceiling and floor, while the other four were placed on a horizontal wire ring surrounding the black ball. Each set of four couples was wired in parallel, in the same manner as were all the previous couples.

In Figure 5 on the following page is shown a partial view of the interior of the warm room, with the location of the black ball and the shielded couple midway between the floor and ceiling.

During the construction of the electric radiant panels, several thermocouples were placed in the panels at various locations in order to determine the temperatures at these locations during operation. When couples were placed in the wire grooves for determining the temperatures of the resistance wires, they were insulated electrically from the resistance wires by means of small porcelain insulators, into which the couples were inserted.

The final two thermocouples were located in the cold room; one was placed approximately seven feet from the

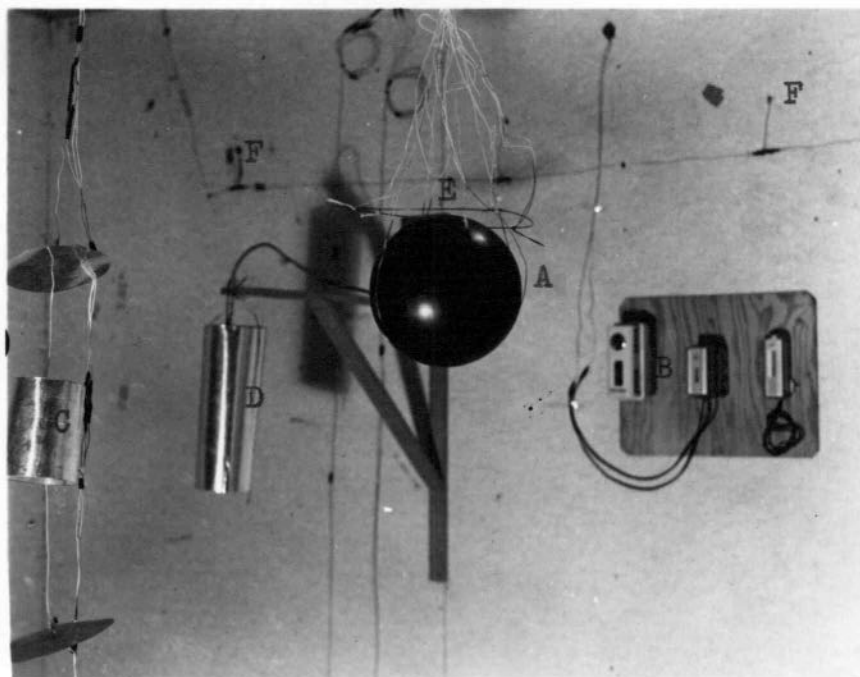


Figure 5. Partial View of the Interior of the Warm Room.

- A -- Black Ball
- B -- Thermostat Control
- C -- Shielded Thermocouple midway between floor and ceiling
- D -- Shielded Thermometer connected to recording instrument
- E -- Thermocouples surrounding the black ball
- F -- Embedded Wall Thermocouples

floor on the north, outside wall of the warm room approximately six feet from the ceiling of the cold room. The complete listing of all the thermocouples and locations of them used in this test are shown on the following page.

Controls and Equipment

With the exception of the thermostat control, all of the recording instruments and electrical equipment used were located in an instrument room which adjoins the cold room.

The thermostat used in all tests was of the low capacity type and required a relay to open or close the power circuits. The temperature-sensitive element of this control was bi-metallic. This thermostat also had an adjustable temperature differential which was set at approximately $1/2$ degree for this complete test. A mercury-type relay was used with this particular thermostat and was placed in the circuit between the power source and the variable transformer.

A potentiometer was used in this test to determine the millivolt reading of each thermocouple. As previously mentioned, a main selector switch was used to connect the thermocouple from any particular location into the circuit. Fifty different poles were on the selector switch altogether.

LOCATION AND IDENTIFICATION OF THERMOCOUPLES

Couple No.	Location
0	Top surface of Panel 1, over wire
1	Top surface of Panel 6, over wire
2	Top surface of Panel 1, over midpoint
3	Top surface of Panel 6, over midpoint
4	Buried couple of Panel 2, at midpoint
5	Buried couple of Panel 2, at wire
6	Buried couple of Panel 1, at wire
8	Buried couple of Panel 8, at wire, filled groove
10	Bottom surface of Panel 2, at wire
11	Bottom surface of Panel 1, at wire
12	Bottom surface of Panel 3, at wire
13	Bottom surface of Panel 6, at wire (north)
14	Bottom surface of Panel 6, at wire (south)
15	Bottom surface of Panel 8, at wire
16	Bottom surface of Panel 8, at midpoint
17	Bottom surface of Panel 2, at midpoint
18	Bottom surface of Panel 1, at midpoint
19	Bottom surface of Panel 3, at midpoint
20	Bottom surface of Panel 6, at midpoint (north)
21	Bottom surface of Panel 6, at midpoint (south)
22	Ceiling surface, outside area; average of 8 couples
23	Ceiling surface, middle area; average of 8 couples
24	Ceiling surface, center area; average of 2 couples
25	North wall, 1 ft, 4 in. from ceiling; average of 5 couples
26	North wall, center of wall; average of 5 couples
27	North wall, 1 ft, 4 in. from floor; average of 5 couples
28	South wall, 1 ft, 4 in. from ceiling; average of 5 couples
29	Globe temperature; average of 4 couples
30	Air temperature at globe; average of 4 couples
33	Air temperature of room 6 in. from ceiling
34	Air temperature of room midway
35	Air temperature of room 6 in. from floor
36	Cold room
37	North wall, outside of warm room; average of 5 couples
38	Panel 1, floor surface; average of 6 couples
39	Panel 2, floor surface; average of 6 couples
40	Panel 3, floor surface; average of 9 couples
41	Panel 4, floor surface; average of 6 couples
42	Panel 5, floor surface; average of 6 couples
43	Panel 6, floor surface; average of 9 couples
44	Panel 7, floor surface; average of 10 couples
45	Panel 8, floor surface; average of 10 couples

Both voltage and wattage in the heating circuit were continuously recorded by means of a recording voltmeter and recording wattmeter. An integrating wattmeter was also used. Both the recording meters and integrating meter were in the circuit between the variac and the heating elements in order to not include losses in the variac. The variac mentioned was used in the power circuit for varying the voltage for different tests.

Also used in the instrument room were two recording thermometers, one giving the temperature in the cold room, and the other giving the temperature in the warm room at the level midway between the floor and ceiling.

In Figure 6, on the following page, is shown a picture of the various recording instruments used in this test.

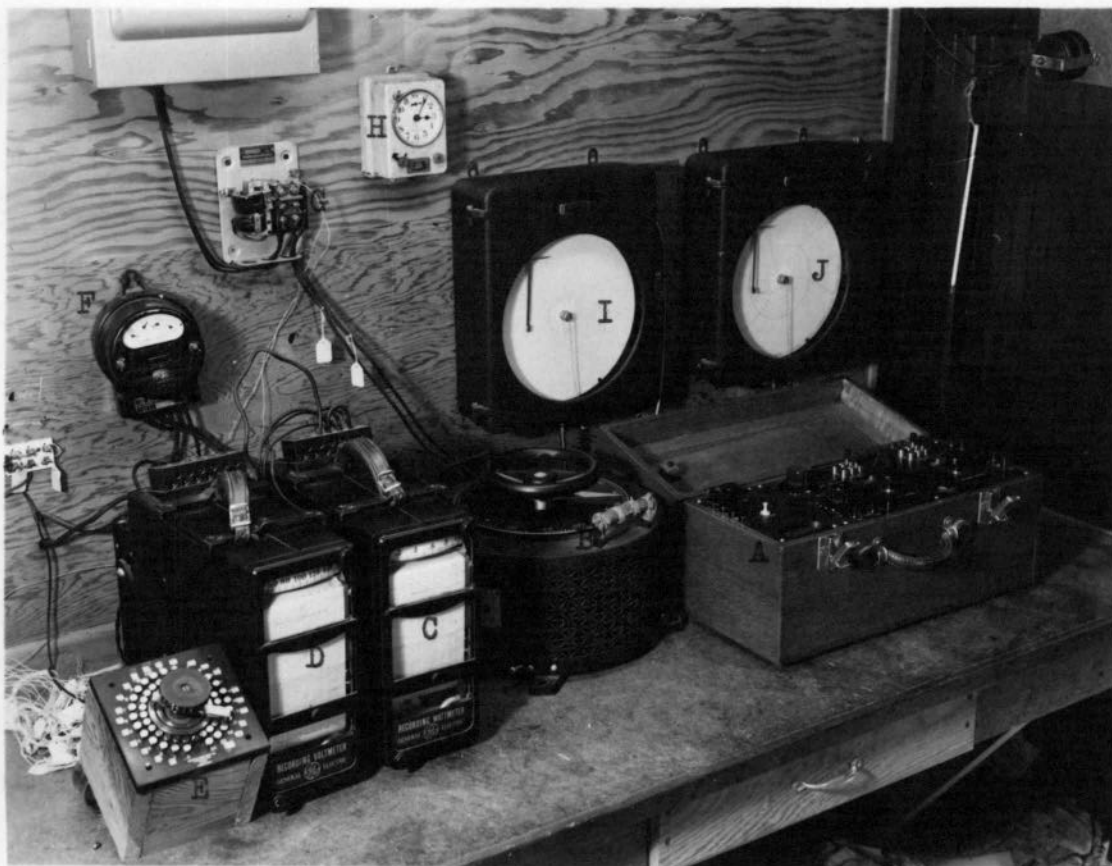


Figure 6. Recording Instruments

- A -- Potentiometer
- B -- Variac
- C -- Recording Wattmeter
- D -- Recording Voltmeter
- E -- Selector Switch
- F -- Integrating Kilowatt-hour Meter
- G -- Relay Switch
- H -- Clock
- I -- Recording Thermometer for the
Warm Room
- J -- Recording Thermometer for the
Cold Room

IV. TESTING PROCEDURE

Approximately 24 hours before the test was begun, the refrigeration unit was turned on and run continuously, so that the cold room temperature was as nearly constant as possible. With the pressure limits as set on the compressor, the cold room temperature was approximately 35 F. After the cold room temperature of 35 F was once reached, only intermittent operation of the compressor was necessary to maintain this temperature.

The test itself consisted of making a number of different runs, with the operating conditions changed for each run.

The first run was made by operating all eight panels starting from a cold condition; that is, with the beginning temperature of the warm room at approximately 35 F. The warm room thermostat was set at 69 F and the power was thrown on. In this first case, the variac was set at 220 volts. Thermocouple readings were taken by means of a potentiometer. These data were taken and recorded almost continuously throughout each particular testing period. Approximately fifteen minutes were required to obtain a complete set of thermocouple readings, which meant that the time interval from one reading to another on any one couple was fifteen minutes. At each power on and power off

period, as controlled by the thermostat, readings were made as frequently as possible in order to determine the maximum and minimum temperatures of the various thermocouple locations. In this first run, 12 hours were required to complete the test.

During the complete run, the recording wattmeter and voltmeter were in operation. In addition, an integrating watt-hour meter was also in the circuit and at the completion of each fifteen-minute period, it was read and recorded.

Another 12 hours elapsed before additional data were again taken with the same conditions as previously mentioned. Of course, in this case, the panels had been in continuous operation, and therefore, more consistent temperatures and cycling periods prevailed.

For the remaining runs, each was conducted in the same manner as was the first. One run had only the border panels operating and the variac set at 177 volts. The other had only the center panels operating with the variac set at 157 volts. After the warm-up and continuous operation runs had been made for both the border and center panels, a fan was set on the floor and allowed to run for at least 12 hours before any thermocouple readings were taken. The fan was tilted upward at an angle of about 30 degrees from the horizontal, so that the air passing

through the fan swept the east wall and then passed over the ceiling surface to some extent. With the fan running for both the border and center panels operating, thermocouple readings were made.

From all the data obtained, operating curves were later plotted for each condition of panel operation.

V. RESULTS AND DISCUSSION

As shown by the curves, the operation periods and temperature variations of the room surface, the room air, and also the temperature variation at or near the panel resistance wire, have been plotted for three distinct conditions of panel operation. These conditions were with all panels operating, border panels only operating, with fan on and off, and center panels only, with fan on and off. For these particular panels, it is felt that these conditions represent the various ways in which they might be used as floor panels in any installation.

The temperatures at each particular location in the room were plotted together, so that any variation which occurred between them may be readily seen. Beginning at the top of each graph, and reading downward, the temperatures which were plotted for each set of curves are as follows: panel temperature, ceiling temperature, wall temperature, room temperature, floor surface temperature, and cold room temperature.

Each test for one particular condition of operation was designated a letter. The designations were as follows: Run D is with all panels operating at 220 volts. Actually it is shown in two parts; the first time period (PM) preceding the second time period (AM) by 24 hours. Runs K and M are with border panels operating at 177 volts, with

fan on and off; Runs H and L are with center panels only operating at 157 volts, with fan on and off.

The numbers placed on both ends of each plotted curve for every run, correspond to the various thermocouple locations as listed on the identification sheet.

In order to maintain the same power input for all panel operating conditions, the voltages, as previously mentioned, were 220 volts, 177 volts, and 157 volts. The resulting power loads on the heating circuits were approximately 2560, 2620, and 2570 watts respectively. Because of external power loads on the same power lines which served the laboratory, and due to some extent to fluctuations in voltage from the power source, it was impossible to maintain constant voltages for any condition of panel operation. However, since these fluctuations occurred during every testing period, the over-all performance would not be greatly effected.

Warm-Up Period Requirements

Since the warm-up period for each test condition followed the same trend, these data were not plotted. However, the warm-up requirements can be briefly summarized as follows: with all panels operating at 220 volts and a total resistance of 17.60 ohms in the circuit, the time required to heat the room from 35 F to the temperature

which satisfied the thermostat, was $4 \frac{1}{4}$ hours. The thermostat was set for 69 F, but the room air temperature when the power went off was 74 F. This meant that the thermostat had a control lag of five degrees at this time. It was noted that a similar condition occurred for the warm-up period for both the border and center panels only, in operation. For these cases, however, the room starting temperature was 41 F and at the power off time, the room temperature was $73 \frac{1}{2}$ F. The time required to bring the room temperature from 41 F to $73 \frac{1}{2}$ F was 3.78 hours with the border panels and 3.82 hours for the center panels. Even though the power requirements for the warm-up period at first seem greater with all panels operating, than with the other panel conditions, such was not the case. The room air temperature with all panels operating was 35 F at the start, and not 41 F as were the other two conditions. The data show the time required to bring the room air temperature from 41 to 74 F with all panels operating was only 3.46 hours. Air temperature outside of the warm room was approximately 36 F during each warm-up period.

During the warm-up period, the power required was 2600 watts for all panels operating, 2670 watts for border panels operating, and 2520 watts for center panels operating. These values were taken from the recording wattmeter data. However, the integrating watt-hour meter showed a

slightly higher wattage, which was approximately 50 watts higher for each panel operating. This slight discrepancy showed a small error existing probably in the integrating watt-hour meter.

ALL PANELS OPERATING

The plotted curves for this test period are somewhat different from other conditions of operation. Shown by the graph is the period just preceding and following the first power off point, after the panels had started from the cold condition. In addition, a four-hour operating period which followed 24 hours later, is shown. These curves were assembled in this manner to show the more steady condition which exists after continuous operation.

Surface Floor Temperatures

Beginning with the floor surface temperatures, Couple 40 which was over Panel 3, varied from a maximum of 82 F to a minimum of 74 F and remained within those limits during all remaining test periods. Couple 42, located over Panel 5, also had a maximum of 82 F but a slightly higher minimum of 75 F, even after more than 12 hours of continuous operation of the panels. Over Panels 1 and 6, which are shown by Couples 38 and 43 respectively, the tempera-

tures were identical ranging from a maximum of 81 F to a minimum of 73 F for all periods which followed.

Although not plotted, floor temperatures over Panels 2, 4, 7, and 8 were within less than a half degree of those over Panels 1 and 6. During the continuous operation period shown on the right side of the graph, the temperature of Panels 5, 6, 7, and 8 were identical and Panel 2 and 3 were identical. As previously mentioned, the maximum temperature for Panels 5, 6, 7, and 8 was 82 F and the minimum was 75 F while the maximum for Panels 2 and 3 was 81 F and the minimum was 74 F. This one degree difference over the panels shows how consistent the floor temperatures were for all panels operating.

Room Air Temperatures

During the first period, (designated PM period) the temperature six inches from the ceiling varied from 68 to 75 F and slowly leveled to a more even differential of 69 to 71 F during further periods. Midway in the room and at the black ball, the temperatures were alike, varying from 69 F to 76 F. During constant operation, this differential was only 69 to 72 F. Couple 35, located six inches from the floor was one degree higher than any other room air temperature, reaching 76 F maximum and a more consistent 72.5 F maximum during the time following. The

minimum temperature, at Couple 35 during both the PM and AM periods, was a consistent 70 F. The curves for the AM period following, shows all the room temperatures to be alike except at the location six inches from the ceiling. The temperature differential existing between the location six inches from the ceiling and six inches from the floor was only one to two degrees.

Wall Temperatures

The wall surface temperatures at the center of the north wall and at the point one foot, four inches from the ceiling on the south wall, are alike. These temperatures were quite consistent and varied for continuous operation from 67 1/2 to 70 F. The surface temperature closer to the floor, or one foot, four inches from the floor on the north wall, was slightly higher and varied from 68 to 71 F. As would be expected, at the point one foot, four inches from the ceiling on the north wall, the temperature was two degrees less than the point one foot, four inches from the floor on the same wall.

Ceiling Temperatures

The ceiling temperatures were even more consistent than those in other points of the room. It was found that the temperature at the outside area was slightly lower

than those at the middle and center areas. However, the difference was very slight and in some cases was only one degree, while in other times, it varied within two degrees. For continuous operation, the temperature variation was from 68 to 70 F at the outside area and from 69 to 71 F for the middle and center areas.

Panel Surface Temperatures

Although not shown by the other test curves, the temperatures at Couples 11 and 12 on the bottom surface over the wire of Panels 1 and 3 and Couples 16 and 20 located on the bottom surface at the wire midpoint of Panels 8 and 6 were plotted. The temperature at the bottom surface of Panel 1 was consistently higher than those for the other panels mentioned. It varied from a minimum of approximately 85 F to a maximum of 114 F. Of course, at the initial power off point, the temperature was much higher and was found to be 141 F. The bottom surface at the midpoint of Panel 3 had the next highest maximum temperature. It ranged from a maximum of about 104 F to a minimum of approximately 83 F. Once again, at the initial power off point, the temperature was higher and was 124 F. The bottom surface at the wire of Panel 3 was just slightly more than Panel 8 at the midpoint. This temperature varied from a minimum of approximately 82 F to a maximum of about

99 F. The maximum obtained at the initial power off point was 121 F. The bottom surface at the midpoint of Panel 6 varied from a minimum of 81 F to a maximum of approximately 95 F. The maximum obtained, which was again at the initial power off point, was 111 F. Attention should be called to the fact that the curves of Panels 3 and 8 cross, and that Couple 12 reaches a higher maximum and a lower minimum than that of Panel 8. This condition was caused because Couple 12 was located at the wire, while Couple 16 was located at the midpoint.

Panel Temperatures for Buried Couples

The temperature of Couple 6, which was located at the wire of Panel 1, has the greatest maximum temperature of any of the others in these locations. The maximum reached following the first power off point, was 146 F. However, following this time for continuous operation, the maximum was only approximately 119 F. The minimum at this location was approximately 84 F. Couple 8, which was located at the wire of Panel 8, had the next highest temperature. The maximum occurred at the initial power off point and was 136 F. After continuous operation, the maximum was quite consistent at only 113 F. A minimum recorded was approximately 83 F. Couple 5, at the wire of Panel 2, showed only a slightly higher temperature than

that at the midpoint for this same panel. The maximum obtained was 108 F for Couple 5, and 106 F for Couple 4. This occurred, of course, at the initial power off point. For continuous operation, Couple 5 was consistently higher, having a maximum of approximately 94 F and a minimum of 81 F. Couple 4 had a maximum of approximately 91 F and a minimum of approximately 80 F. It should be noted that for more continuous operation, the temperature difference between these two couples existed only during the power on period and for just several minutes after it went off.

CENTER PANELS ONLY OPERATING

The plotted curves of Run L, fan off, and Run H, fan on, show the same relative trends as those which existed for both the conditions of all panels operating and border panels operating. However, there are some very noticeable temperature differences which existed.

Floor Surface Temperatures

For the fan off condition, the floor temperatures over the operating Panels 7 and 8 varied from 82 F to 91 F during the test period. With the fan on, these same surface temperatures varied from 78 F to 95 F. This difference can be explained by the fact that the actual power on

time was approximately 24 minutes, with fan off and approximately 42 minutes with the fan on. Also, the power off period was only one hour with the fan off, while with the fan on, the power off period was one hour 49 minutes. Consequently with a longer power on and off time, greater maximum and lower minimum temperatures would occur.

Room Air Temperatures

The room air temperature at the globe and midway between the floor and ceiling showed a slight difference with the fan on, and with it off. At this location with fan off, the temperature varied from 69 to 71 F, but with fan on, those same temperatures varied from 69 to 73 F. Undoubtedly undisturbed air would probably show a smaller temperature differential in the center of a space than agitated air. However, at the ceiling and floor locations where effects of circulating air would be more pronounced, the same would not hold true. Such was the case. With the fan off, the temperature differential existing between points six inches from the floor and six inches from the ceiling was four degrees, while with the fan on the temperature differential was only 1 1/2 to two degrees. For the fan off, Couple 33 varied from 68 to 70 F and Couple 35 varied from 70 to 72 1/2 F. With fan on, Couple 33 varied from 69 to 72 F and Couple 35 varied from 71 to

74 F.

Wall Temperatures

There were two noticeable differences in wall temperatures for fan on and off operation. First, with fan off, all the wall temperatures were alike, both on the north and south walls. This included those 1 1/3 feet from the floor and 1 1/3 feet from the ceiling. With the fan on, the south wall temperature was one degree greater than those on the north wall, which were all alike. The second difference was that the wall temperatures were lower but had a variation from only 67 1/2 F to 69 F with fan off, while these same temperatures were higher but had a variation from 68 F to 71 F with fan on. Apparently, circulating the room air caused various surfaces to have higher temperatures, but on the other hand, caused a greater variation in temperature to exist.

Ceiling Surface Temperatures

For both cases of fan on and off operation, the ceiling surface temperature of the outside area was about one to 1 1/2 degrees lower than those in the middle and center areas. Of course, the middle and inside areas were more directly over the operating panels, so this fact could

account for such a condition. However, as was mentioned previously, the circulating air caused the surface temperatures to be consistently higher than with the fan off. With the fan on, the temperature ranged from approximately 69 F to 71 F, while with fan off, the temperature variation was only 67 1/2 F to 69 F.

Panel Temperatures

At Couple 8, which was a buried couple on the resistance wire in Panel 8, the temperature ranged from 102 to 154 F with fan off and from 97 to 160 F with fan on. Likewise, Couple 15, located on the bottom surface of Panel 8 over the wire, ranged from 107 to 148 F with fan off and 98 F to 156 F with fan on. Couple 16, located on the bottom surface of Panel 8 at the wire midpoint, varied from approximately 105 to 129 F with fan off and from 97 to 135 F with fan on. The reason that these temperatures with the fan were greater and had a lower minimum, was due to longer power on and off time, as previously noted. Naturally, the locations of the couples themselves caused such a discrepancy between maximum and minimum temperatures.

BORDER PANELS OPERATING

Referring to Runs K and M, this series of curves

with border panels operating, both fan on and off, follow very closely to the same general trend as do those with all panels and center panels only operating.

Floor Surface Temperatures

For this test condition, the floor surface temperature over those panels operating, shows almost identical temperature variation for both fan on and off. The maximum reached was 90 F and the minimum was 78 F. The floor surface temperature over any one particular panel does not differ by more than two to three degrees from any other panel during any of the testing period. Since the power on time was approximately 35 minutes and the power off time was approximately one hour 44 minutes for both fan on and off, it would account for these temperatures being so alike.

Room Air Temperatures

As was noted for other runs, there was a slight temperature difference at Couples 29, 30, 33, 34, and 35. However, in this case, the difference in temperature at these locations was very small, being from 1/2 to one degree. The temperatures at Couples 35 and 33 show that the differential between the point six inches from the

floor and six inches from the ceiling was within one degree F. Following the same high and low trends during the power on and off periods, the maximum and minimum temperatures ranged from 68 1/2 to 72 F.

Wall Temperatures

Wall surface temperatures show the same trend as previously noted. The temperatures at the designated points on the wall all are within one to two degrees of each other. With the fan operating, this variation is consistently only one degree apart. Temperatures range from 68 to 71 F.

Ceiling Temperatures

A noticeable difference for this condition of border panels operating was that the ceiling surface temperature of the outside area was just one degree less than those in the middle and center areas, even though the outside area was more nearly above the operating panel. One possible explanation of this might be that the heat traveling to the cooler walls would cause the temperature of the ceiling area closer to these walls to be slightly colder than those areas which were further away.

Panel Temperatures

The temperatures of Couples 4, 5, and 6 are almost identical for both fan on and off operation. Couple 6, located at the wire in Panel 1, varies slightly only at the maximum which was 155 F with fan on and 153 F with fan off. Couple 4 varies from 88 to 105 F and Couple 5 from 89 to 110 F, with very little change for either fan on or off. It should be noted that after Couple 4 reaches a maximum temperature, it follows exactly the same path as Couple 5 during the off period. Of course, since these couples are located at the midpoint and at the wire, this condition could easily occur. Naturally, Couple 5 at the wire would show greater response to power on, but during the power off, it shows no difference to exist between Couples 4 and 5.

VI. DISCUSSION SUMMARY

Panel Temperatures

It was noted that the maximum consistent temperature of the resistance wire occurred in Panel 8 during the operation with center panels only. This maximum temperature was approximately 160 F. Since the power input was very close to being the same for each different condition of panel operation, this maximum temperature would be expected, because with center panels only operating, these panels were furnishing as much heat to the room as were those with all panels and border panels operating. This means, of course, that the temperature of the radiant panels when only part are operating must be higher than when they are all operating.

Floor Surface Temperatures

The floor surface temperatures were very similar for both center panels only and border panels operating. The maximum temperature reached was approximately 90 F. However, with all panels operating, the maximum was consistently only about 82 F. As mentioned previously, the resistance wires were at a higher temperature with border panels and center panels only operating, and consequently, higher floor temperatures would naturally result. For a

lower desirable floor temperature than, all panels operating would be the system to use. In addition, one authority, (1, p.21-7) states that the maximum permissible floor temperature is 90 F., while 85 F is the maximum recommended temperature for floors in offices and in residences.

Room Air Temperatures

For any condition of panel operation, the room air temperatures varied only slightly. The variation was just a little less with all panels operating than with the others in operation. The minimum was 69 F and the maximum 72 F midway in the room. The largest temperature differential, which was approximately $4 \frac{1}{2}$ degrees, between the point six inches from the floor and six inches from the ceiling, was noted with center panels only operating. However, in any case, such a small gradient would be considerably less than usually found with any convection type of heating system.

Wall and Ceiling Temperatures

In general these temperatures were slightly less than the room air temperatures, but followed the same relative trend. The effect of the fan showed the wall and ceiling temperatures to be a little higher with than

without the fan, for center panels only. There was no noticeable effect using the fan with border panels operating.

Temperature Lag

Except for those couples located at the wire, there existed a definite time lag at each power on and off point. As might be expected, the further the distance from the heating panels, the greater the lag to heat response. At the floor, the lag varied from three to six minutes following on and off periods. The lag in the air temperature in the room was slightly longer, being from ten to twenty minutes, and on the wall and ceiling, the temperature lag proved to be fifteen to twenty-five minutes. Since this condition of lag exists in almost every radiant heating system, it is important to control the temperature limits as closely as possible.

VII. CONCLUSIONS

Cycle Periods and Fan Effects

Most cycling periods were alike for all conditions, with the power on 35 to 40 minutes, and the power off one hour 40 minutes. However, there were two noticeable exceptions to these conditions. With the center panels only operating, and fan off, the power on was only 24 minutes, but the power off time was shorter also, being only one hour in length. If the power on time had been longer, undoubtedly the power off time would have been lengthened. The other exception was with border panels operating and fan off, which showed the power on period to be 30 minutes long and the power off time one hour 30 minutes.

In general, the effect of the fan on, caused a greater variation of air temperature midway in the room than with the fan off, but caused a smaller temperature gradient between the points six inches from the floor and six inches from the ceiling. Also, with the fan on, slightly higher room surface temperatures were noted, but longer periods of power on and off were required. An explanation for this fact is that since all room surface temperatures were very close to the same, more heat would be required to accomplish this condition. Likewise, these various temperatures would require a longer time to

decrease in temperature. The conclusion might be then, that for more even surface temperatures to exist in a heated space, at least some convection currents would be necessary. In an average home, this condition is more prevalent, due to infiltrating air, persons living in the room, and also opening and closing of doors.

Thermostat Control

Although only one particular thermostat was used for all runs, and the results using it were all quite satisfactory, the differential for which it was set and that which actually occurred should be mentioned. This type of thermostat, which was described more in detail in the equipment section, was set for only a half degree differential. However, the actual differential was higher than this, varying from one to two degrees. Generally, the temperature of the room air did not go below 69 F, but for almost all cases, a temperature of 71 F was reached before the thermostat was satisfied and turned the power off. In addition, when bringing the room initially from a cold start, a temperature of almost 74 F was reached before the thermostat turned off the power. The reason for this initial greater over-heating before satisfying the thermostat and the lower over-heating which followed for continuous operation might be caused by the peculiarities of a

bi-metallic control. After being used for a length of time in a temperature range close to the differential set on the thermostat, it would operate much more accurately. At least, this happened to be the case. Undoubtedly, for this type of heating, a thermostat control of the type used would be definitely satisfactory.

Power Requirements

Comparing power requirements showed that with center panels only operating, 64 square feet of panel were transmitting 2540 watts of electricity in the form of heat, making about 40 watts per square foot of panel. At this rate, with all panels operating, and with border panels operating, about 9600 watts and 5000 watts respectively, would be utilized. With all panels operating, 144 square feet of panel were transmitting about 67 watts per square foot and with border panels operating, 80 square feet of panel were transmitting 62.5 watts per square foot.

The rates of electricity, shown previously, indicate that they are probably considerably more than would be required in a normally constructed home.

Even with a higher capacity than probably needed, the maximum resistance wire temperature was about 160 F. This temperature occurred with center panels only operating, while the others varied from five to 40 degrees less.

These indicated temperatures show that from the standpoint of operating temperatures, panels of this type are safe and satisfactory.

Although the cycling periods varied slightly, except as noted previously for the center panels only, and fan off, the typical cycle consisted of a phase which was averaging about 37 minutes with power on and about one hour and 40 minutes with the power off. The slight individual time intervals varied partly because of the line voltage fluctuation.

Based on these above data, a load of about 730 watts would be required to maintain the same temperature conditions within the room if this load were continuously applied. On this basis, a load of approximately 0.625 watt per cubic foot of room space would be required. For intermittent operation, a power rate of about 2.31 watts per cubic foot was used to heat the room under the conditions of this test.

Of course, this rate would vary with the type of construction and size of the space to be heated. For making any predictions with this rate, for any other structure, would require a correction corresponding to the actual conditions under which the proposed structure would operate.

Performance Properties

Two desirable properties of any panel are low thermal capacity and good thermal conductivities, which would result in panels having quick response and little lag. These conditions would control the time of response from the heated panel and also the tendency to overheat or underheat the room. The panels operating in this experiment had both reasonably low thermal capacity and good thermal conductivity. However, as noted previously, some overheating occurred, while lag to heat response was more pronounced. It is felt that these panels showed a performance which would be very satisfactory in any similar typical house construction.

Panel Locations

All the plotted performance data show that these panels, located as they were in the floor, would be very definitely satisfactory in this position. However, in any typical home, special precaution should be exercised in laying them. The reason is that since these panels were of the fabricated type, any attempt to nail them to floor joists could easily result in a broken resistance wire, and hence, an inoperative panel. It is suggested that by properly marking on the panel surface, the locations of

the resistance wires in the panel, these panels could be secured in place without damage.

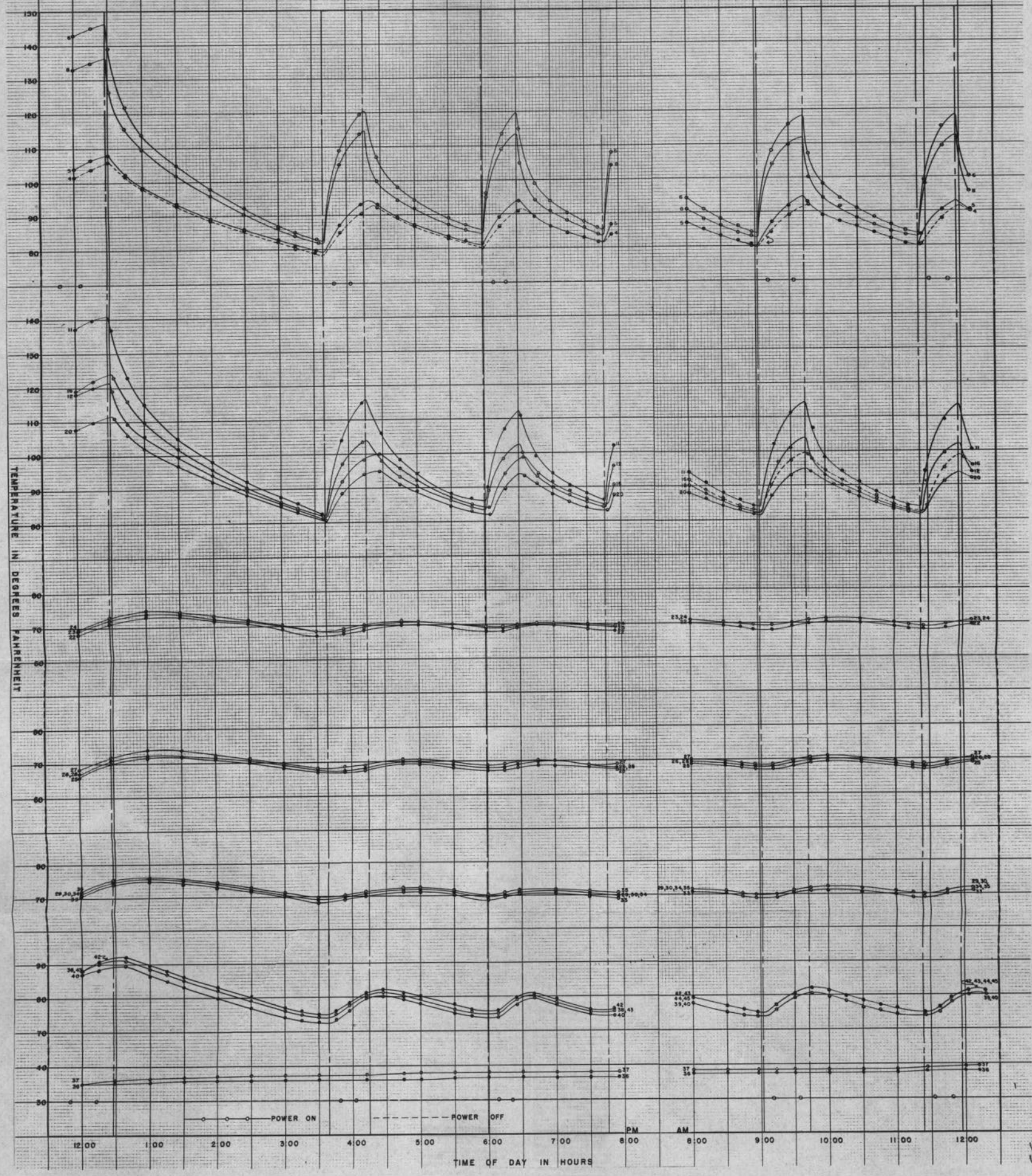
Comparison Suggestion

A similar performance test of these panels has been made with the panels located in the ceiling of the space to be heated (4, p.1-45). The results of the investigation are given in the Oregon State College Engineering Experiment Station Bulletin 24. For those interested, it is suggested that a comparison of the operating results be made for these panels, located in the floor and in the ceiling.

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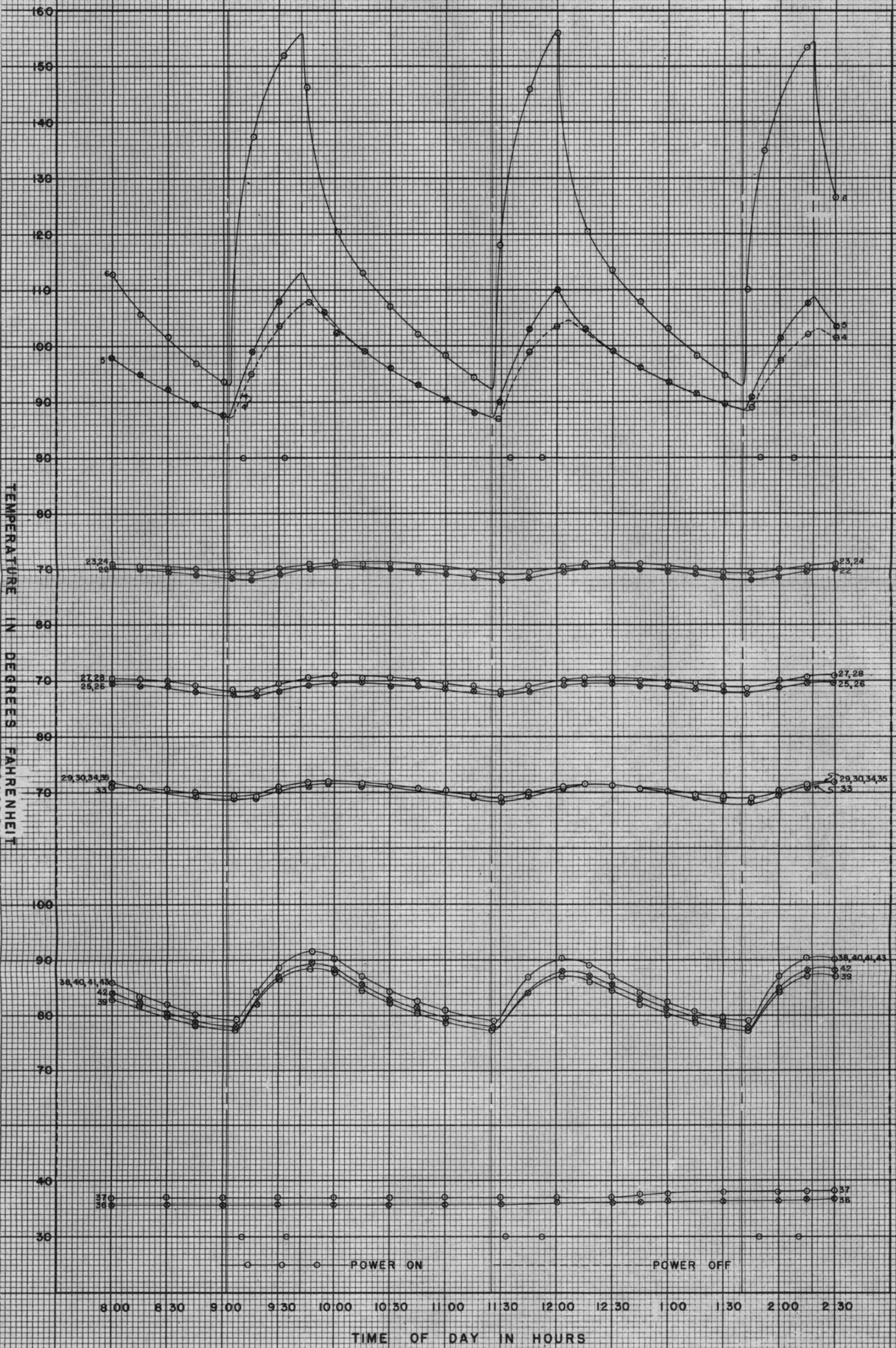
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2. Heating, Ventilating, Air Conditioning Guide. The Society, New York, 1948, Vol. 26, 1280 p.
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TEMPERATURE VARIATIONS
 RUN "D"
 ALL PANELS OPERATING 220 VOLTS AC FAN OFF
 THERMOSTAT SET AT 69° F.



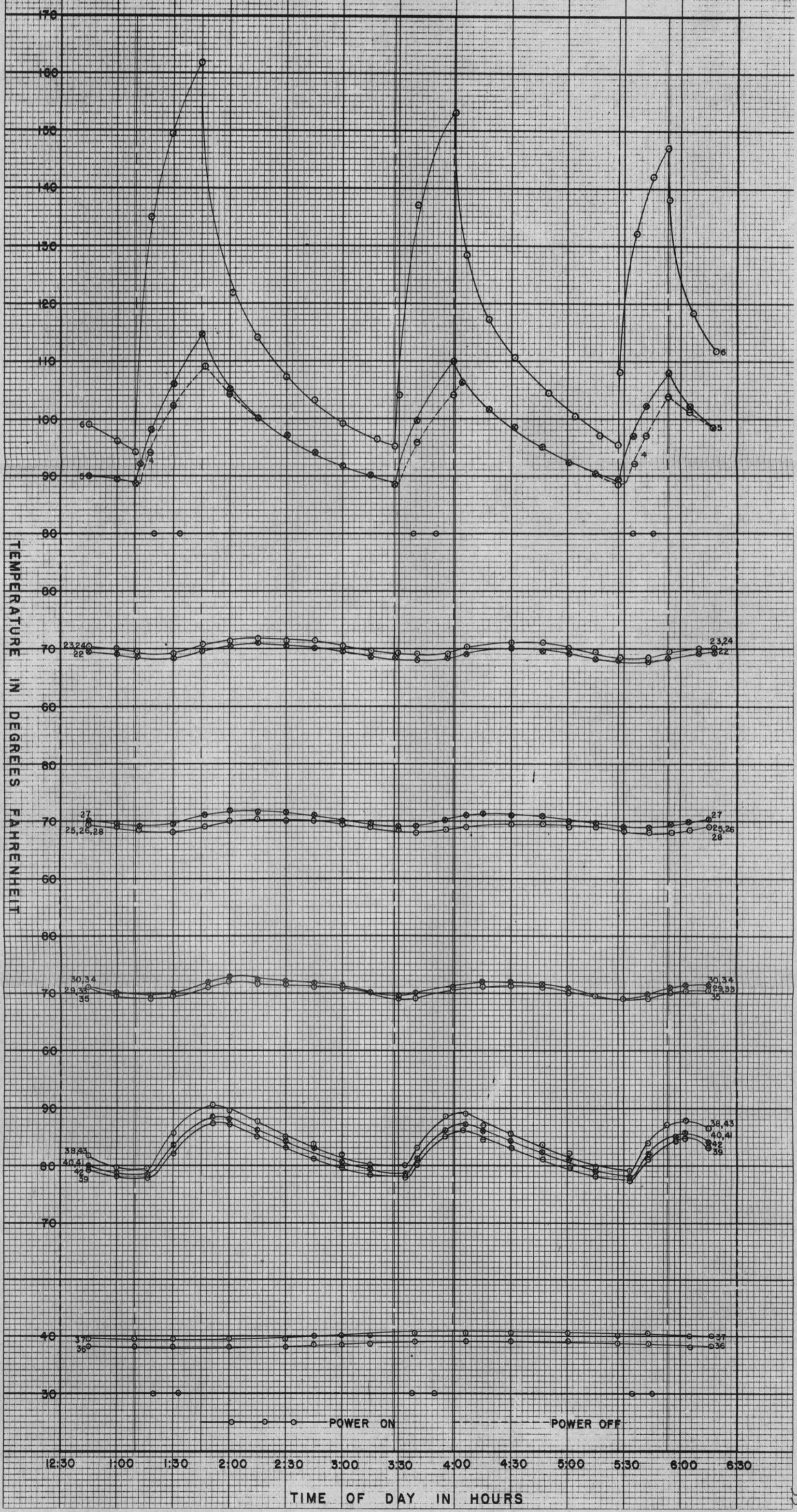
TEMPERATURE VARIATIONS
RUN "K"

BORDER PANELS OPERATING—177 VOLTS AC FAN ON
THERMOSTAT SET AT 69° F.



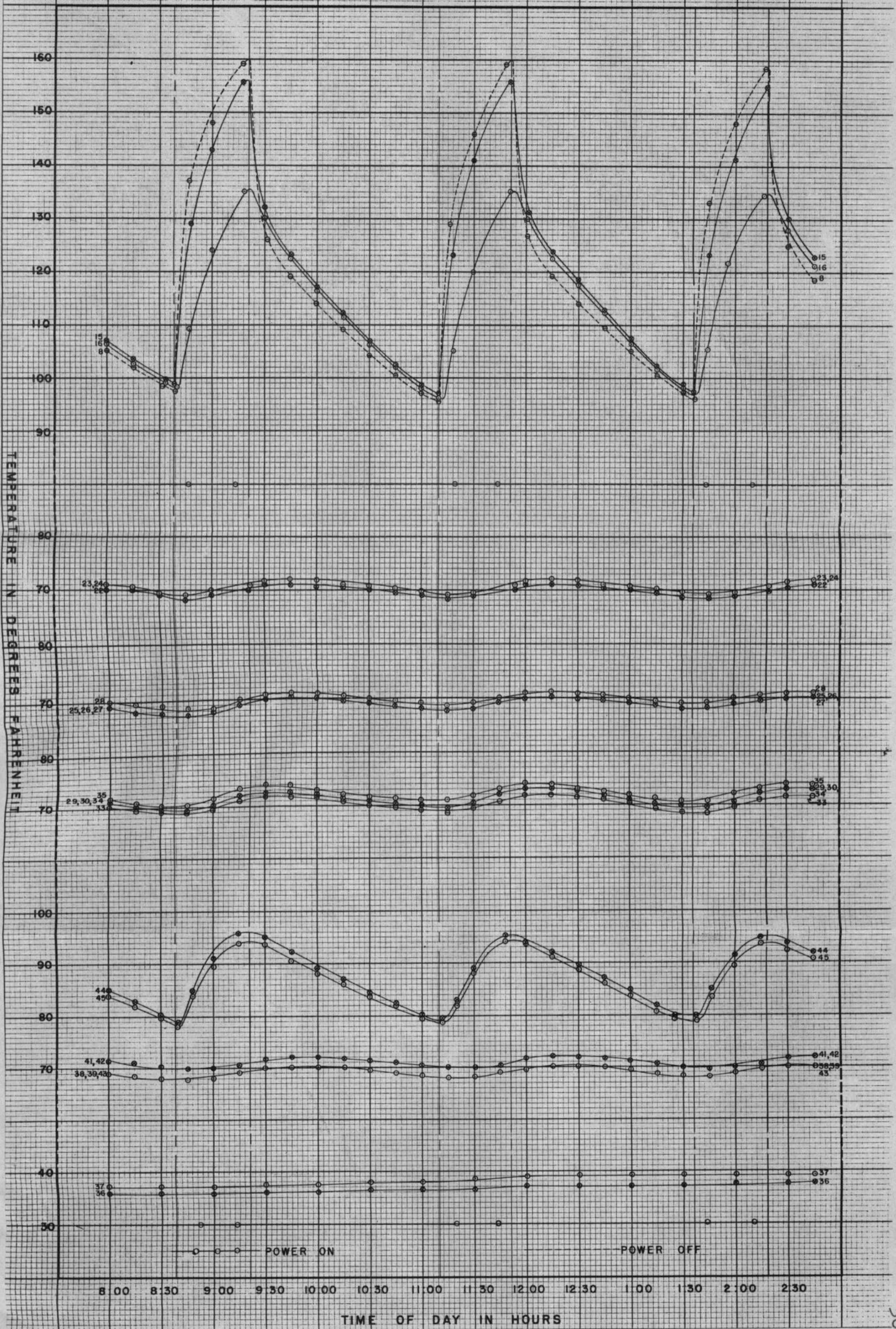
TEMPERATURE VARIATIONS RUN "M"

BORDER PANELS OPERATING—177 VOLTS AC FAN OFF
THERMOSTAT SET AT 69° F.



TEMPERATURE VARIATIONS
RUN "H"

CENTER PANELS OPERATING — 157 VOLTS AC FAN ON
THERMOSTAT SET AT 69° F.



TEMPERATURE VARIATIONS RUN "L"

CENTER PANELS OPERATING—157 VOLTS AC FAN OFF
THERMOSTAT SET AT 69° F.

