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AN EVALUATION OF SOLAR HEAT GAIN ON SUMMER COMFORT CONDITIONS IN THE MORTIMER E. COOLEY MEMORIAL LABORATORY

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PREFACE

This report is presented as a result of an investigation and evaluation of solar heat gain on summer comfort conditions in the Mortimer E. Cooley Memorial Laboratory, located on the North Campus of the University of Michigan, Ann Arbor, Michigan.

The period studied intensively was from approximately May until September, 1955 since this period was anticipated to reveal some of the most serious solar heating effects. A forthcoming report will reveal results of a similar study undertaken for the period September, 1955 to May, 1956. The latter study was undertaken to explore effects of a seasonal nature upon solar heating problems in the Cooley Laboratory.

The work upon which this report is based was undertaken at the request of Dr. R. G. Folsom, Director, Engineering Research Institute, University of Michigan, and of Dr. G. G. Brown, Dean of the College of Engineering, University of Michigan.

The authors wish to acknowledge gratefully the advice and suggestions of Dr. E. W. Hewson, Professor of Meteorology, Department of Civil Engineering, the University of Michigan; the cooperation of the U. S. Weather Bureau, Willow Run Station, and the assistance of the Department of Mechanical and Industrial Engineering, University of Michigan, in lending certain measuring equipment for use on this project. The authors also wish to acknowledge the assistance of the results of earlier work by Dr. L. W. Orr, Research Engineer, Engineering Research Institute, in the installation and testing of a small group of aluminum shade screens on the Mortimer E. Cooley Memorial Laboratory.

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ABSTRACT

In this report an evaluation is presented of the results of measurements of temperature, humidity, and of other physical variables upon summer comfort conditions in the Mortimer E. Cooley Laboratory, University of Michigan.

Records were kept of sensations of comfort or discomfort, together with the physical variables studied, for three rooms in the Cooley Laboratory. These rooms were: 1) one unshaded room on the south side of the building, 2) one shaded room on the south side of the building, and 3) one unshaded room on the north side of the building.

It is concluded in this report that the use of aluminum shade screens on the south side of the building has greatly increased the percentage of days during which workers on the south side of the building feel comfortable. The increase in the percentage of comfortable days is attributed to the reduction of glare and of direct radiant solar heating of the rooms.

Our observations have led us to agree for the most part with the upper limits of the "summer comfort zone" set forth by the American Society of Heating and Air-Conditioning Engineers, when the effects of radiant heating are neglected. These upper limits have been estimated by the American Society of Heating and Air-Conditioning Engineers at 66° minimum and 75° maximum for effective temperature and at 30% minimum and 70% maximum for relative humidity. Our conclusions are that a third coordinate should be considered when radiant heating is of importance. These conclusions may be summarized by our tentative definition of a "comfort volume." This volume would be defined in two dimensions by the limiting values of effective temperature and of humidity, mentioned above, for the condition of no radiant heating. A third dimension for this "comfort volume" would be described by the locus of limiting values of (mean radiant temperature minus dry bulb temperature) at which a feeling of discomfort is experienced. The subject whose comfort is under study is understood to be in an environment which is under conditions for which the American Society of Heating and Air-Conditioning Engineers' comfort chart would predict comfortable reactions when radiant effects between subject and environment are negligible. Analysis of the data obtained indicates that roughly one additional degree of mean radiant temperature less dry bulb temperature may be tolerated without discomfort for each degree of effective temperature less than the maximum of 75°. This relationship appears to be substantially independent of relative humidity between the limits of 30% and 70% studied. The limits of effective temperature studied were 68° to 78° and the limits of mean radiant temperature less dry bulb temperature studied were 0 to 7°F.

I. OBJECTIVES

The objectives of this study are two-fold:

1) To evaluate the effect of aluminum shade screens placed outside large windows with southern exposure in the Mortimer E. Cooley Memorial Laboratory in reducing personnel discomfort caused by radiant solar heating of work areas.

2) To extend the understanding of conditions required for human comfort in interior work areas by considering the simultaneous effects of radiant solar heating, humidity, and effective temperature.

II. INTRODUCTION

The Mortimer E. Cooley Memorial Laboratory, located at the North Campus of the University of Michigan, has been occupied for over a year and a half, and during this period the personnel using the building have become cognizant of many of the practical features which are inherent in the building design. A salient feature of the design is the extensive use of plate glass in the north and south exterior walls. The majority of the rooms have one wall which is essentially of glass. The glass used has a blue tint which reduces the direct transmission of sunlight to some degree.

The use of extensive areas of glass in the building design has provided a desirable impression of space in the rooms and is regarded with favor from this point of view. However, the use of glass as an exterior wall has caused the building to be unusually responsive to exterior weather conditions as compared with a building of conventional construction. One undesirable effect of the rapid response of building conditions to weather conditions has been that some of the laboratories and offices on the south side of the building are uncomfortably hot on sunny days during the autumn season. This condition is caused by radiant heating of the work area by sunlight, and by secondary radiation from the window glass heated by the absorption of that part of the sunlight not reflected or transmitted.

As a preliminary step toward investigation and possible alleviation of overheating on the south side of the building, aluminum shade screens were installed on six windows of Room 232 of the Cooley Laboratory in October, 1954. While the installation of the shade screens was in progress, Dr. L. W. Orr, of the Engineering Research Institute, recorded preliminary data which indicated a definite increase in comfort in the room on which the shade screen installation was proceeding. Specifically, the data reported were room temperature, inside surface temperature of the shaded glass and inside surface temperature of the unshaded glass.

The more comprehensive study reported herein was designed to yield sufficient data for evaluation of comfort conditions in rooms of southern exposure with, and without, shade screens and in one unshaded room with a northern exposure. It was initially anticipated that a correlation of human comfort with radiant heating effects might be derived from the experimental data necessary for the desired evaluation of shade screen performance, and such has been the case. Accordingly, an opinion of the shade screen performance and a preliminary correlation of the subjective feeling of "comfort" with the measurable physical variables of mean radiant temperature, wet bulb temperature, and dry bulb temperature are presented.

III. EXPERIMENTAL PROGRAM

A. General

An experimental program was developed for this study in such a manner as to insure that necessary data were taken which would relate measurements of physical variables to sensations of comfort or discomfort of the workers in the Mortimer E. Cooley Laboratory. It was desired to obtain records of physical measurements and personnel reactions within the building and also to obtain a record of available weather data external to the building. A general outline is given here of the measurements taken and the methods of measurement used in this study. The pertinent experimental data required and the manner in which they were obtained are listed below.

B. Exterior Measurements

The exterior weather data were obtained from the Willow Run Weather Bureau, which is located less than ten miles from the Cooley Laboratory and in a similar environment. Values for the following measurements were recorded:

1. Outside air temperature
2. Wind velocity and direction
3. Sky coverage by clouds

C. Interior Measurements

Wet and dry bulb temperatures were taken daily from April through August, 1955 with a standard sling psychrometer. A recording hygrothermograph was located in the control room, but the data from this instrument are omitted because they offer no basis of comparison with conditions in the test rooms. Globe, room air, glass pane and screen temperatures were recorded at intervals of twenty-four minutes on the temperature recorder.

The accompanying plan of the second floor of the Cooley Laboratory (Figure 1) and the elevations of the test rooms (Figure 2) illustrate the locations of the thermocouples in the test areas. The globe position was fixed at the same level as the upper portion of the bodies of human beings occupying the test areas. The inside air temperature was measured at a point six inches removed from the globe in order to avoid the possible influence of convection currents induced by the thermal convection of the globe. The glass pane temperatures were recorded by thermocouples cemented to interior surfaces at the geometric centers of the panes. The screen temperatures were measured by a thermocouple cemented to the screen.

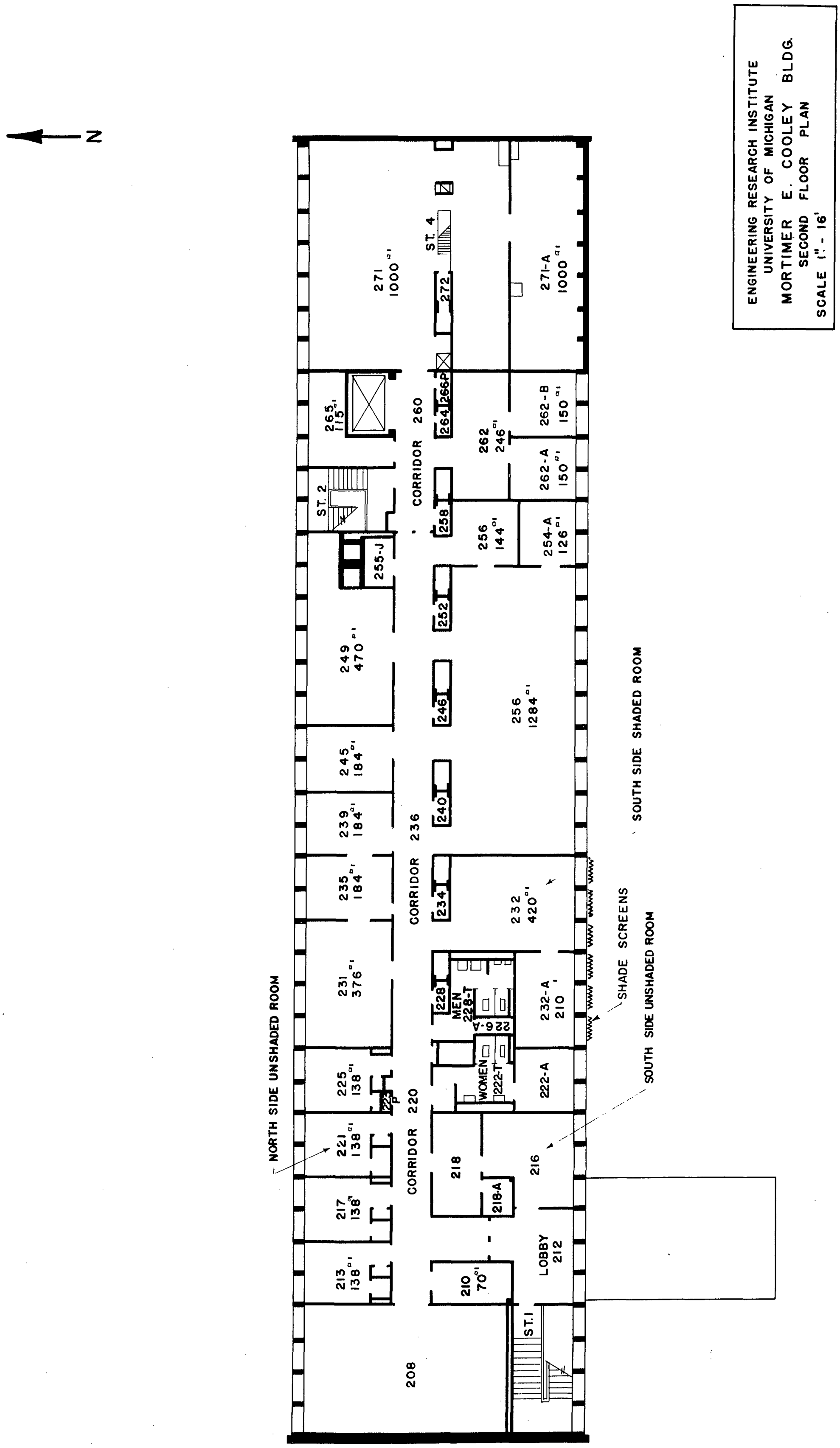


FIG. 1 - PLAN OF THE SECOND FLOOR OF THE COOLEY LABORATORY

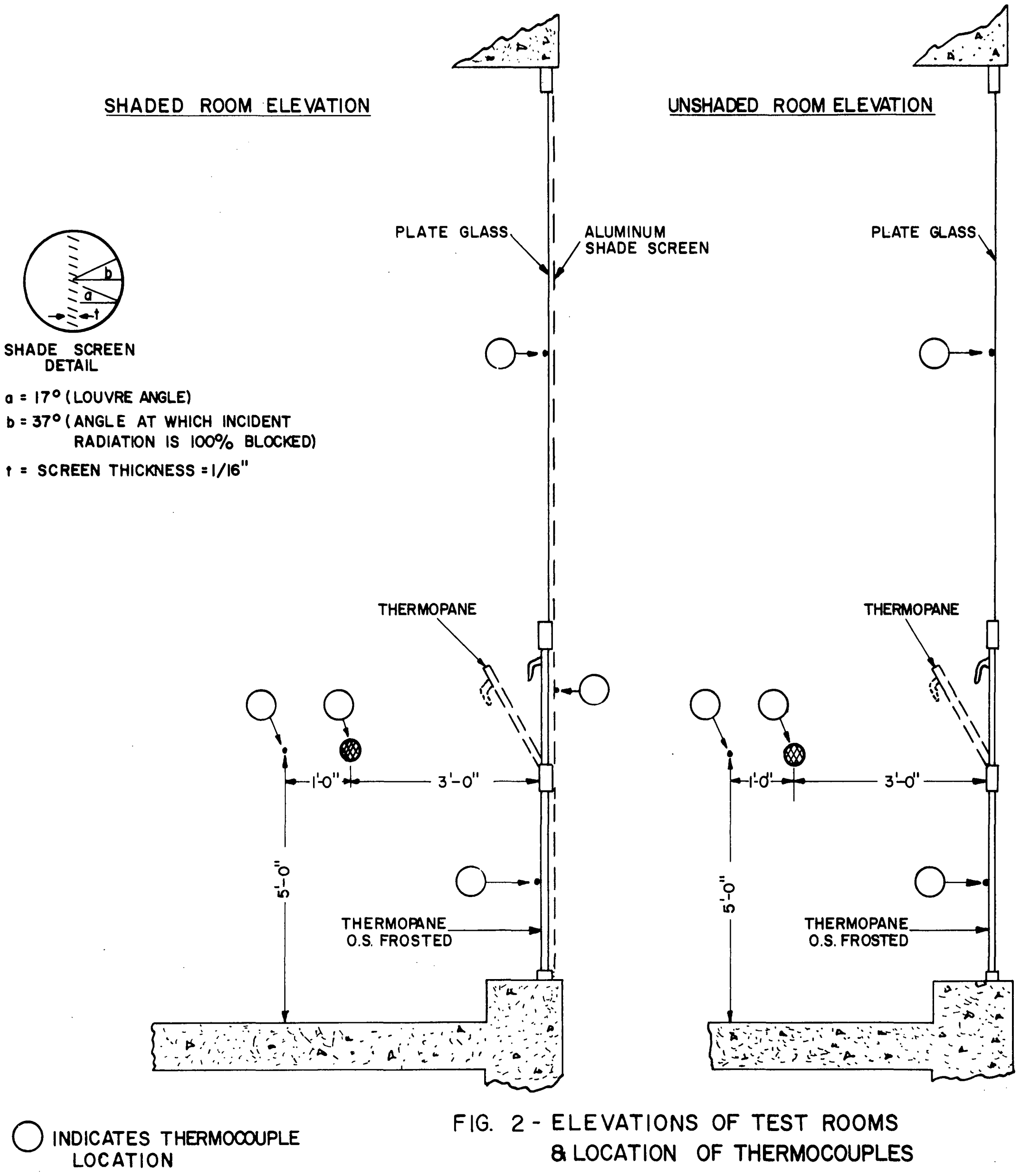


FIG. 2 - ELEVATIONS OF TEST ROOMS & LOCATION OF THERMOCOUPLES

The data recorded were as follows:

1. Shaded Room - Southern Exposure

    a. Screen temperature
    b. Inside glass temperature (glass pane, frosted thermopane)
    c. Globe temperature
    d. Air temperature
    e. Window position, inside shade position and thermostat setting
    f. Relative humidity

2. Unshaded Room - Southern Exposure

    a. Inside glass temperature (glass pane frosted thermopane)
    b. Globe temperature
    c. Air temperature
    d. Relative humidity
    e. Window, inside shade position and thermostat setting

3. Unshaded Room - Northern Exposure

    a. Inside glass temperature (glass pane)
    b. Globe temperature
    c. Air temperature
    d. Relative humidity
    e. Window, inside shade position and thermostat setting

IV. DESCRIPTION OF BUILDING

A. Description of the Rooms Selected for Experimentation

The Cooley Laboratory has two exterior walls consisting essentially of glass. These walls face either north or south. In order to evaluate the effect of the aluminum shade screens, two rooms on the south side of the building were selected, one of which had screens and the other of which had none. The room without screens is referred to as the "unshaded room," while the one with screens is referred to as the "shaded room." The "control room" has no screens and faces north. The unshaded "control room" receives very little direct solar radiation during the year, except in the summer months when it does receive solar radiation in the early mornings and late afternoons.

B. Description of Windows in the Cooley Laboratory

Figure 2 shows typical elevations of the windows in the Cooley Laboratory. The entire wall consists of three sections of windows. "AKlo" glass is used in all three sections. In the upper two sections the "AKlo" glass is clear and in the lowest section it is frosted. In the lower two sections the "AKlo" glass is used in combination with clear plate glass to form "Thermopane" panels. In the lower two sections the "AKlo" glass is mounted on the outside. The "AKlo" glass is 1/4-inch thick, tinted blue, and is described more fully as "Blue Ridge AKlo Heat Absorbing Clear" glass.

The "Thermopane" panels consist of two sheets of 1/4-inch thick plate glass mounted in the same frame and separated by an air space. Figure 3 illustrates the performance of the above glass as advertised by the manufacturer (4).

C. Heating and Ventilating Systems in the Rooms

In the normal heating season, the rooms of the Cooley Laboratory are heated by a forced circulation warm air central system. Auxiliary heat is provided by finned tube convectors located horizontally below the windows at floor level. In the summer the forced circulation system is used to distribute air cooled by washing with 65°F city water. With the windows closed, about 3.7 air changes per hour are provided by the air circulating system. The circulating fan has a capacity of 28,000 cfm under the conditions of use. In the summer the dampers on the room air inlet ducts are maintained in the open position and hence the mean air velocity in a particular room might be considered constant if the windows are left closed. However, to avoid imposing arbitrary and perhaps difficult-to-maintain restrictions on the personnel working in the test rooms, it was decided that window position would be left to the discretion of the occupants, on the assumption

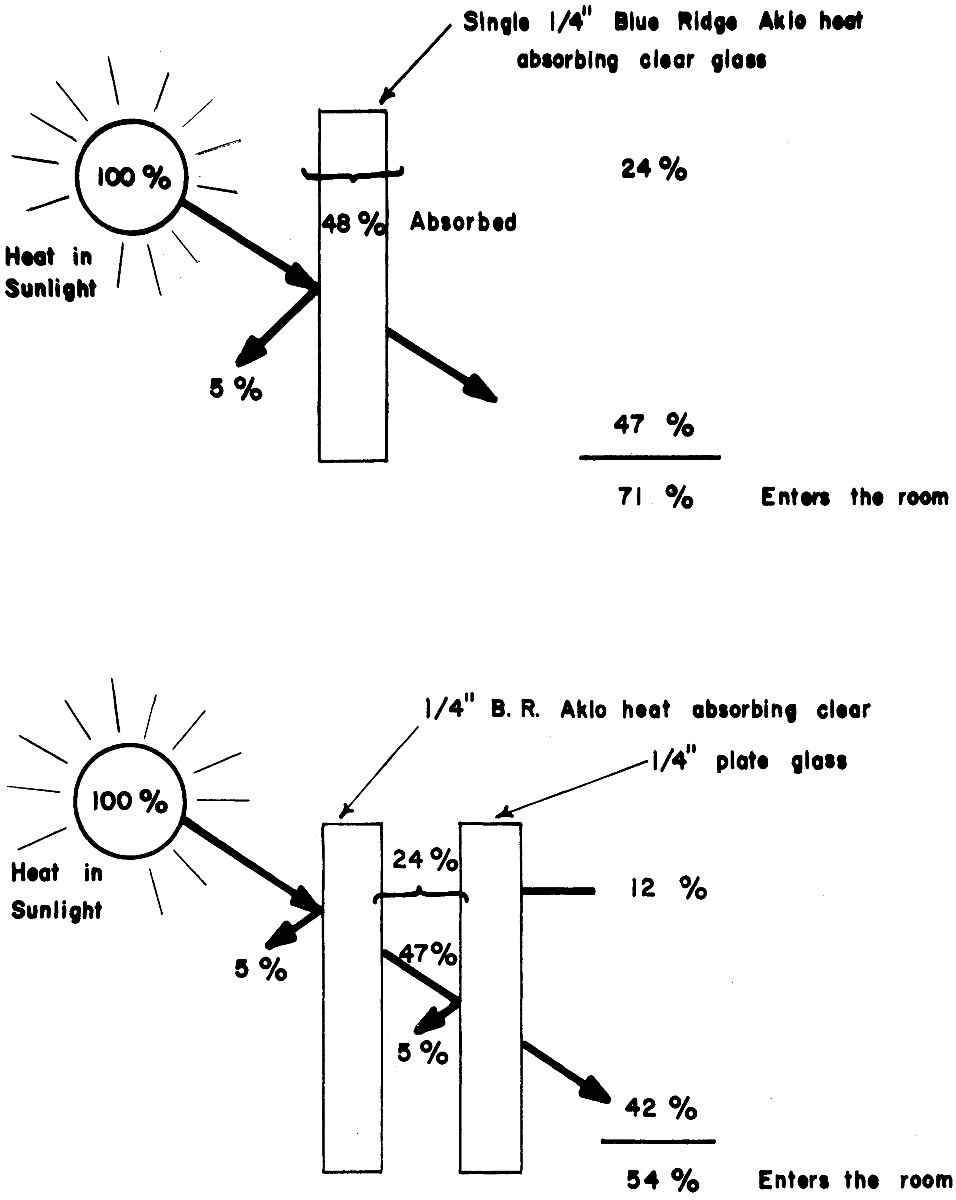


FIG. 3 - ENERGY TRANSMITTED BY SINGLE AND DOUBLE GLASS PANES

INFORMATION FROM REFERENCE (4)

that windows and doors would be adjusted to give the optimum room comfort under the prevailing weather conditions. Spot checking with an anemomenter at normal wind conditions of 5 to 15 mph, indicated that the room air velocity in the vicinities of the globes was in the 25-30 fpm range with the windows closed, and in 50-60 fpm range with the windows open. By using the data only for the days when the wind velocity is 5-15 mph the constancy of room air velocity is justified if window position is specified. Experimentally it was found that a wind velocity of 10 to 15 mph gave a room air velocity of 50-60 fpm in the vicinity of the globe thermometers located in the test rooms.

D. Solar Radiation to the Rooms During the Year

Figure 4 illustrates the duration of direct solar radiation to the south side of the building and the solar altitudes during the different months of the year at the latitude of Ann Arbor, which is very nearly 42°N. Using the American Nautical Almanac (2), and Tables of Computed Altitudes and Azimuths (8), the altitude of the sun was calculated for the first of each month at the time of day when the sun was at the zenith.

The duration and altitude of solar radiation affects solar heating of rooms with windows facing south. The severity of this effect varies with the seasons. In the summer atmospheric temperatures are high, partly because of the high altitude of the sun. However, the duration of direct solar radiation to the south side of the building is only 8 to 9 hours. In the fall the sun is at lower altitudes than in the summer. Neglecting atmospheric absorption changes, the sun radiates more energy to vertical surfaces in the fall than in the summer because of the more nearly perpendicular impingement and the greater duration of direct solar radiation to the south side of the building. A maximum of more than 11 hours of solar exposure to the south side is reached in the fall. In addition, the mean outside temperature is higher in the fall than on days of comparable solar exposure in the spring. These observations assist in explaining the qualitative observation that the period of greatest discomfort caused by solar heating of the south side of the building occurs in the fall of the year. This study was set up to study the spring and summer periods, to observe also the cumulative effect of higher air temperatures and solar heat gain. A further study will be undertaken to observe similar situations during the fall and winter seasons.

The altitudes of the sun when it is at the meridian are plotted in Figures 5 and 6.

Figure 7 shows the path of the sun as seen from a point at the latitude of Ann Arbor. The figure is a view of the "sky" with Ann Arbor as center. The observer is looking down and sees the path which the sun traces on the "sky." A more satisfying picture is obtained if one can assume that he is, for example, 50 miles

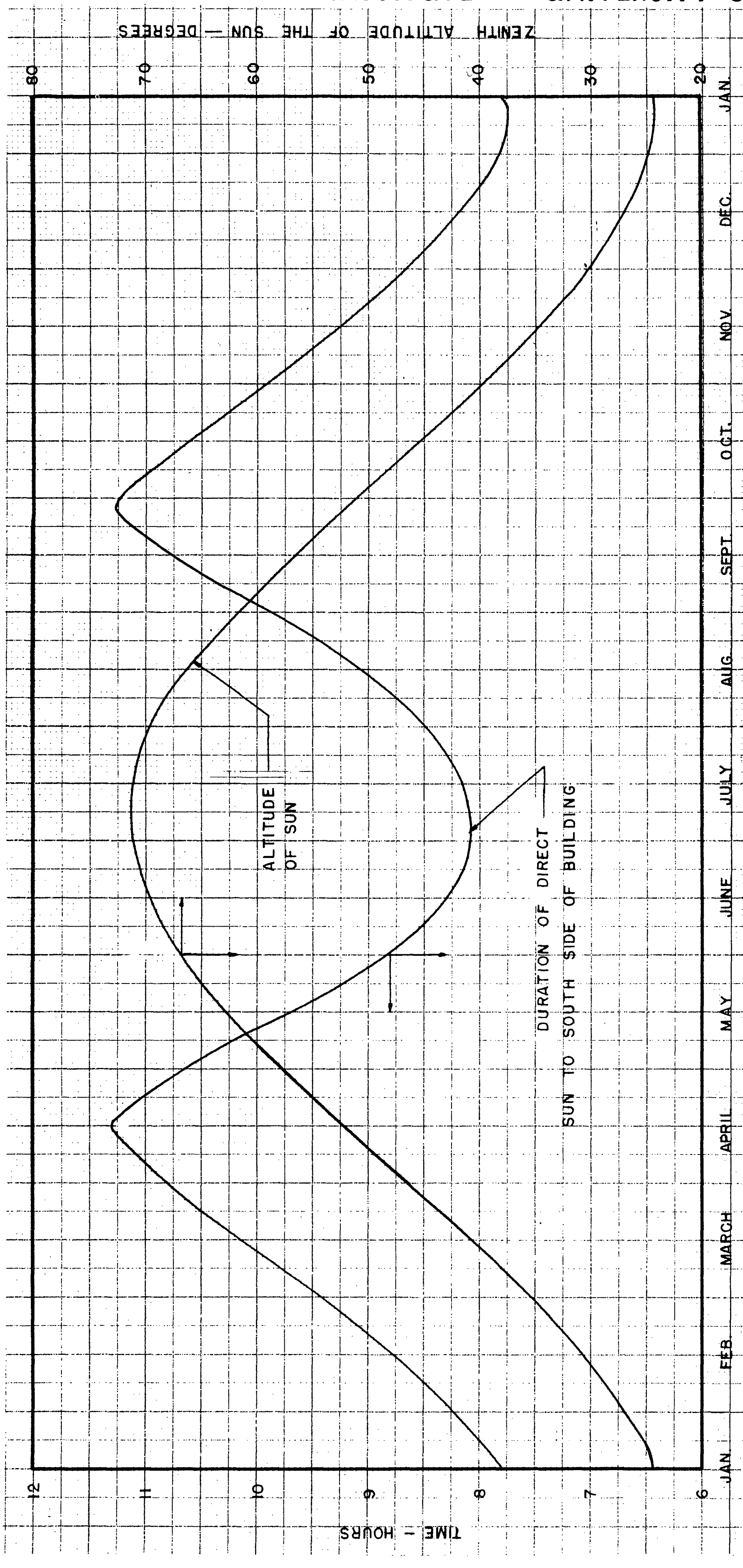


FIG. 4 DURATION OF DIRECT SOLAR RADIATION TO THE SOUTH SIDE OF COOLEY BLDG.

REF.: AMERICAN NAUTICAL ALMANAC, U.S. Govt. Pt. Off. (1954)
TABLES OF COMPUTED ALTITUDES AND AZIMUTHS, U.S. Navy Dept. Bull. 214 (1940)

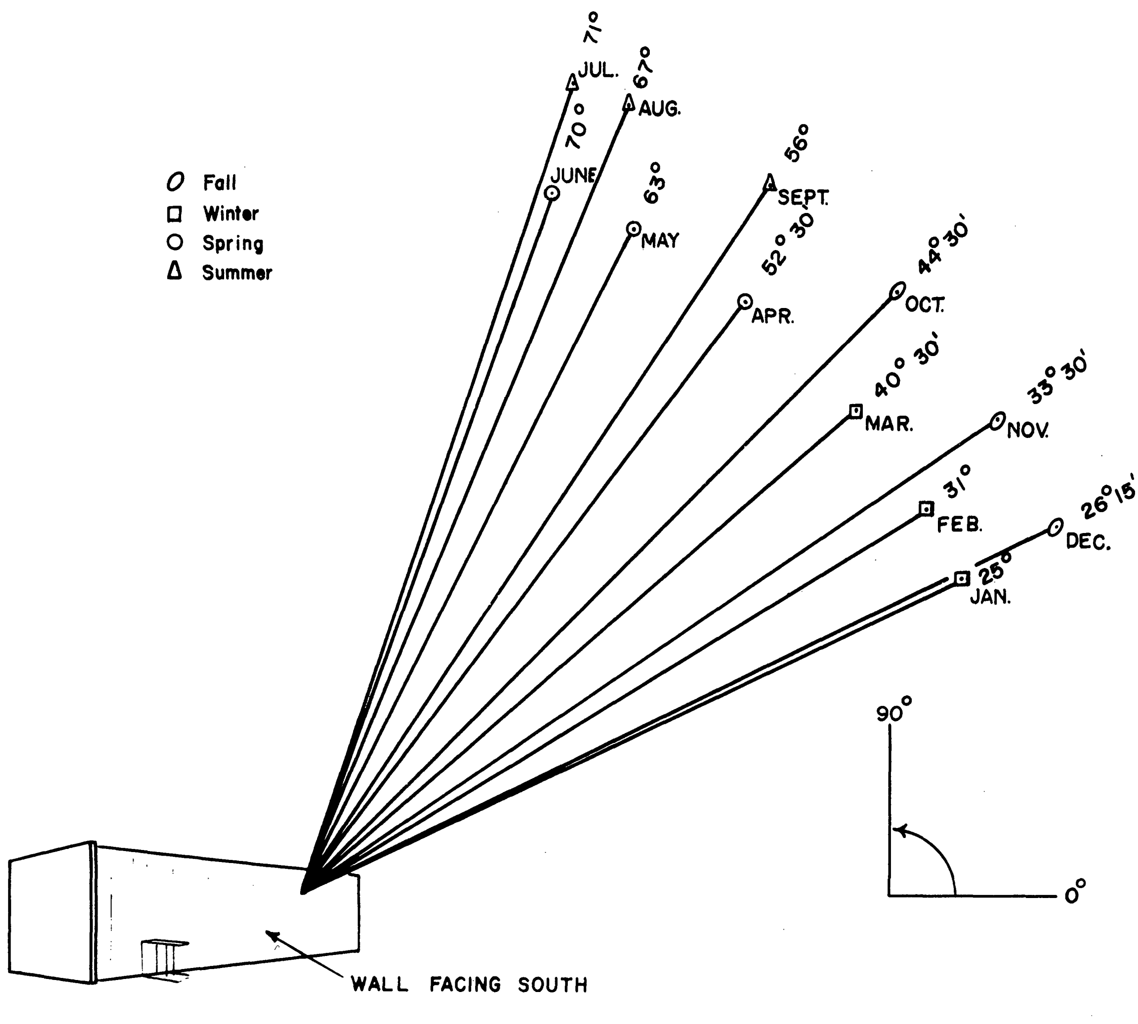


FIG. 5 - ALTITUDES OF THE SUN (1st of the month) AT THE ZENITH

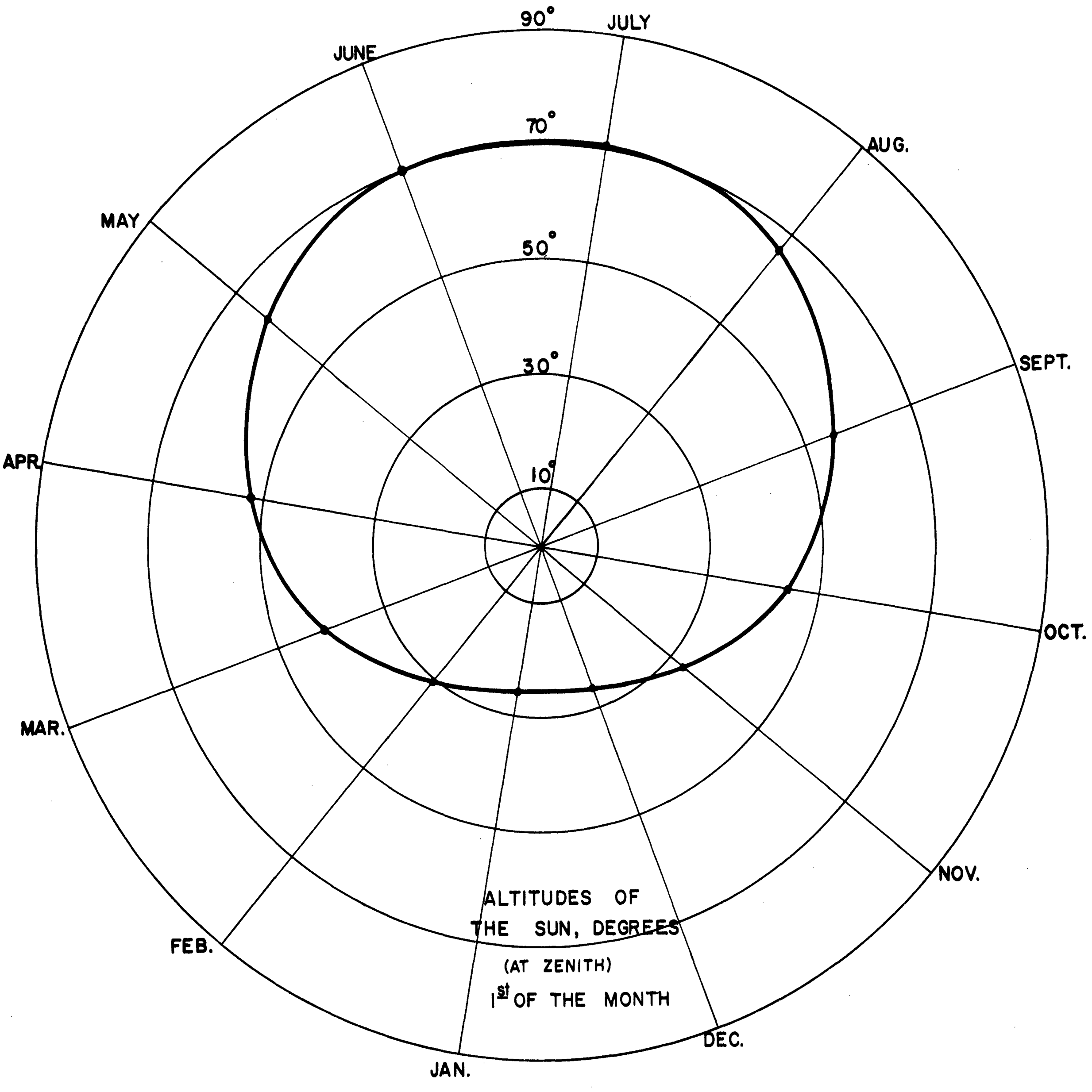

90°
70°
50°
30°
10°
JUNE
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
ALTITUDES OF
THE SUN, DEGREES
(AT ZENITH)
1st OF THE MONTH

FIG. 6

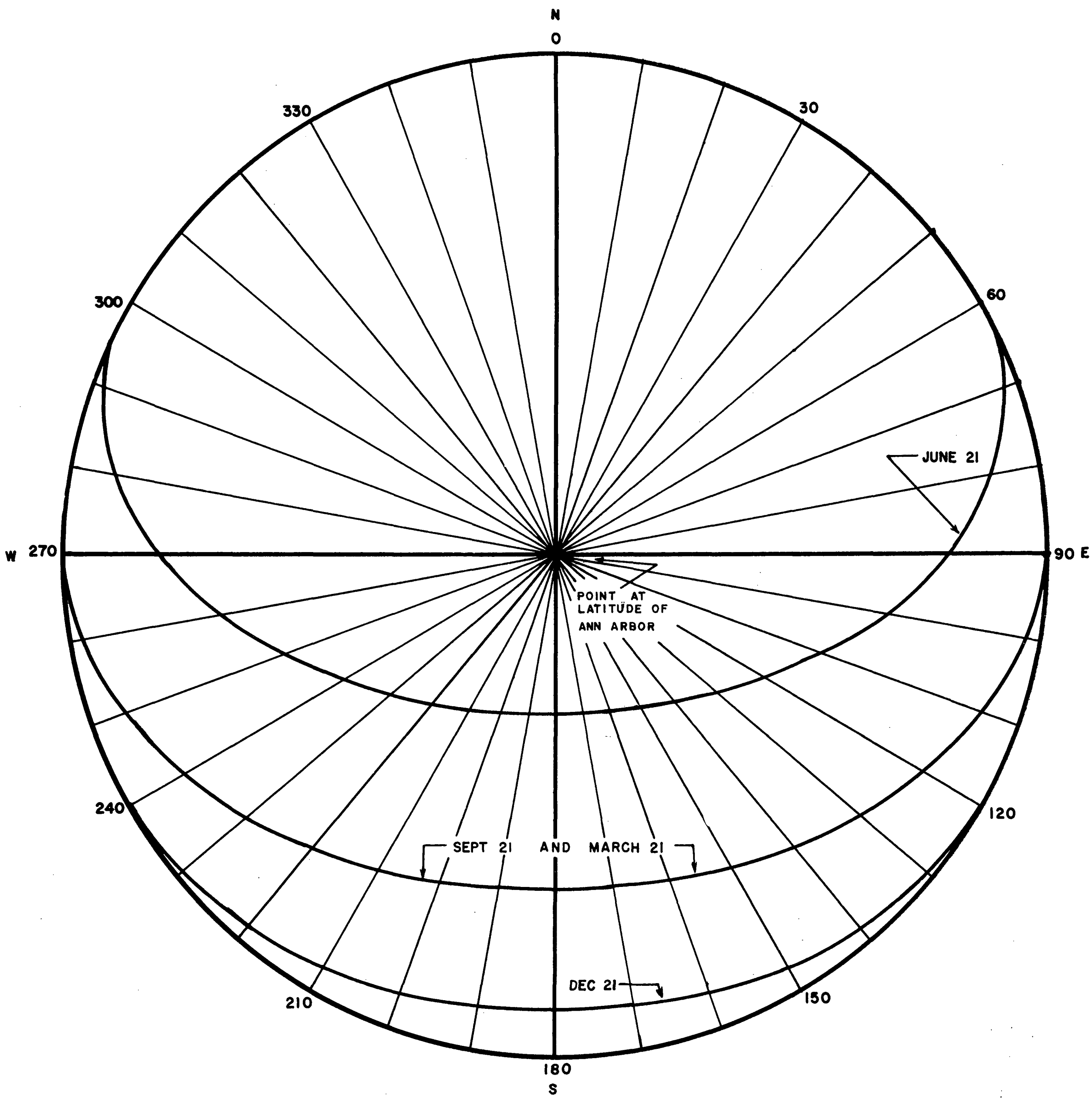


FIG. 7 PLAN VIEW OF TRACE OF LINE TO SUN ON SPHERE OF LARGE DIAMETER WITH CENTER AT ANN ARBOR, MICHIGAN

in the air at a point directly over Ann Arbor. He looks down and views the trace made by a line joining Ann Arbor and the sun as this line "cuts" a plastic hemisphere, say 10 miles in diameter with its center at Ann Arbor. The altitudes and azimuths of the sun from sunrise to sunset are plotted for both solstices and for both equinoxes. It way be noticed from the figure that during the summer, the sun rises in the northeast sky and sets in the northwest sky. Thus, even though the length of the day is long, the sun remains in the south sky for a comparatively short time. On both solar equinoxes, the solar path is the same, viz., March 21 and September 21. It is in these seasons that the sun remains in the south sky for a relatively long time. In winter, as may be noticed for the December 21 solar path, the solar altitude is lowest and the length of the day is the shortest.

The low duration of solar exposure in the winter would alone result in a small amount of solar heating compared with that to be anticipated during the spring, summer, or fall. At Ann Arbor, the sky is often cloudy in the winter, thus reducing the probable duration of solar heating to the lowest value expected for the entire year.

TABLE I

DURATION OF DIRECT SOLAR RADIATION TO THE SOUTH SIDE OF THE COOLEY MEMORIAL LABORATORY (1954)

DATE	TIME IN HOURS
January 1	7.8
February 1	8.8
March 1	10.1
March 21	11.1
April 1	11.3
May 1	9.7
June 1	8.4
June 21	8.1
July 1	8.1
August 1	9.1
September 1	10.7
September 21	11.1
October 1	10.7
November 1	9.2
December 1	8.2
December 21	7.7

TABLE II

ALTITUDES OF THE SUN AT THE ZENITH
ON THE FIRST DAY OF EACH MONTH (1954)

MONTH	ALTITUDE
January	25° 00'
February	31° 00'
March	40° 30'
April	52° 30'
May	63° 00'
June	70° 00'
July	71° 00'
August	67° 00'
September	56° 30'
October	44° 30'
November	33° 30'
December	26° 15'

V. DESCRIPTION OF EQUIPMENT

A. The Globe Thermomenter

The globe thermometer provides a convenient and simple means of evaluating the combined effects of convection and radiation as they influence human comfort. It consists of a hollow 6-inch diameter copper shpere coated with matte black paint and containing a thermometer with its bulb at the center. The thermometer may be replaced by a thermocouple in order to measure the temperature without disturbing the equilibrium of the globe. The globe is sensitive to radiation, air temperature, and air movement. If it is placed in an environment in which the walls or other surroundings are warmer than the air, the radiation received by the sphere in this environment will raise the temperature of the globe to a point above that of the surrounding air. Conversely with the surroundings cooler than the air, the globe temperature will be below the air temperature.

The difference between the globe temperature and the air temperature is a function of the radiation received from all surfaces in view of the globe. However, in order that this temperature difference may be used to evaluate the magnitude of the radiation, the air velocity near the globe must be measured and appropriate allowance made to correct the observed difference of globe and air temperatures.

1. Mean Radiant Temperature

A globe must be placed in a location with constant air velocity and temperatures for about 15 minutes before the globe thermometer reaches a constant reading. The rates of heat transfer to and from the globe are then equal. Consider the case in which the surroundings of the globe are warmer than the air in which the globe is placed. Then at equilibrium the globe is receiving heat by radiation from the surroundings just as rapidly as it is losing heat by convection to the air.

The mean radiant temperature of the surroundings may be inferred from the temperatures of the air, the temperature in the globe, and the properties of the globe, as described below.

Application of the Stefan-Boltzmann equation results in Equation (1) for the rate of radiant heat transfer H_R to the globe, assuming an emissivity of 0.95,

$$H_R = (0.95)\ (1.73 \times 10^{-9})\ (T_S^{\,4} - T_G^{\,4}) \qquad (1)$$

and Equation (2) expresses the rate of convective heat transfer H_C from the globe as studied by Bedford and Warner (3)

$$H_C = 0.169 \sqrt{v}\ (tg - ta) \qquad (2)$$

Combining Equations (1) and (2) results in Equation (3).

$$T_S = 100 \sqrt[4]{\left(\frac{T_G}{100}\right)^4 + 1.028\sqrt{v}\,(tg - ta)} \qquad (3)$$

In equations (1), (2), and (3) the following definitions are employed:

H_R = rate of radiant heat transfer to the globe, $BTU/HR \times FT^2$

H_C = rate of convective heat transfer from the globe, $BTU/HR \times FT^2$

T_S = temperature of surroundings, degrees Rankine

T_G = temperature of globe, degrees Rankine

v = air velocity, feet per minute

tg = temperature of globe, degrees Fahrenheit

ta = temperature of air, degrees Fahrenheit

Figure 8, taken from the work of Bedford and Warner(3) permits graphical solution of Equation (3) for T_S. The temperature T_S is the absolute temperature of the surroundings of the globe and may be called "Mean Radiant Temperature" or "Mean Black Body Temperature."

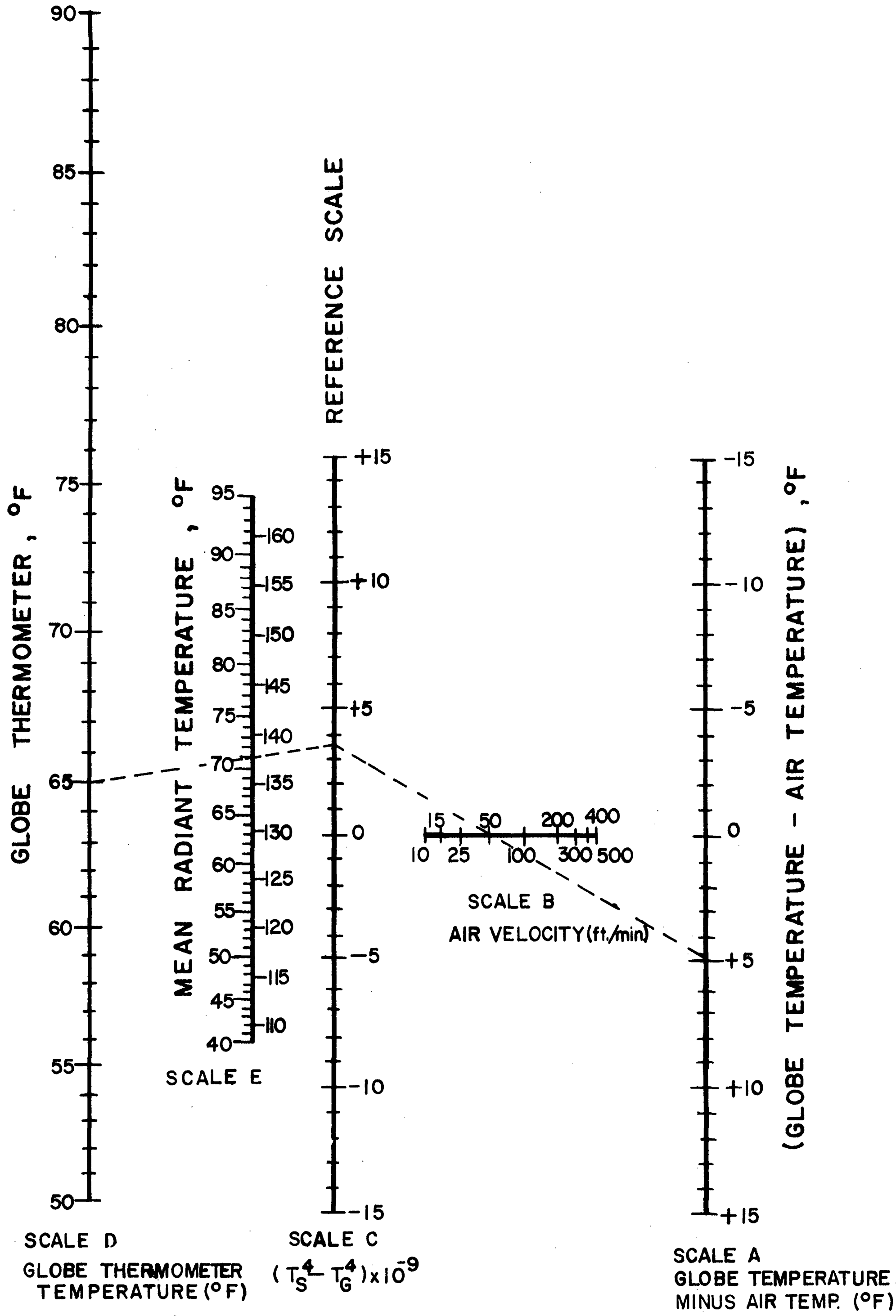
The mean radiant temperature T_S is meant to be that uniform temperature to which all surfaces in view of the globe must be heated in order to give the globe temperature obtained in an actual environment. The feeling of warmth or cold for human beings is directly related to the mean radiant temperature of the surroundings.

B. Temperature Recording Equipment and Procedure

Thermocouple temperatures were recorded by an electronic null-balance 12 record strip-chart recorder. This instrument employed '38 copper constantan calibration, with a scale of 0-200°F. A chart speed of one inch per hour was used. A balancing time of one second and a printing interval of two minutes provided a record which was nearly free from over-printing. The rapid balancing time was specified solely to permit subsequent use of the instrument in applications requiring more rapid printing.

1. Calibration of the Recorder

Thermocouples were connected to the recorder described above, and the system comprising recorder and thermocouples was calibrated against an external standard of temperature. The



SCALE E - LEFT SIDE - MEAN BLACK BODY TEMP. (°F)
RIGHT SIDE - MEAN RADIATION INTENSITY (B.T.U./sq. ft., hr.)

FIG. 8 - CHART FOR ESTIMATION OF MEAN RADIANT TEMPERATURE FROM GLOBE THERMOMETER READINGS

(based on the nomograph of BEDFORD & WARNER JOURNAL of HYGIENE 16, p 458 (1934)) technique employed was to place the thermocouples in a water bath together with a standardized mercury thermometer and to compare the recorded thermocouple temperatures with the temperature read by the thermometer.

The mercury thermometer used was a Princo, number 271726, with a range of -3°C. to +60°C. This thermometer bore the designation NBS52 and had previously been determined to have a maximum error of ±0.2°F.

The thermocouple temperatures recorded during calibration of the instrument-thermocouple system were in all cases within ±0.5°F. of the calibrated thermometer readings.

2. Temperature Recorder

Outside air temperature was continuously recorded by a bi-metallic helix, clockwind recorder located in a shaded area on the roof of the Cooley Laboratory. Spot-checking revealed that the temperatures recorded by this instrument deviated less than 1°F. from temperatures indicated by the standard mercury thermometer used in 1., above.

3. Humidity Recorder

A sling psychrometer was used to obtain wet and dry bulb temperature data once each day in each of the test rooms. Calibration of the thermomenters mounted on the sling psychrometer against a National Bureau of Standards mercury thermometer indicated the maximum deviation to be 0.2°F. A recording hygro-thermograph was located in the control room to record variations of relative humidity directly. The hygro-thermograph measurements were not considered primary data, but a check on daily humidity trends in the building.

C. Thermocouple Settings

Copper constantan thermocouples were used to measure temperatures recorded by the temperature recorder. The glass surface temperatures were measured by fixing the thermocouple to the glass surface with Canada balsam. The screen temperatures were measured by sealing the thermocouple bead with Canada balsam between two fins of the screen. Globe temperatures were measured by thermocouples located at the geometric center of the globe, and room air temperatures were measured by thermocouples located at the same level as the globe, but removed from the globe a sufficient distance to be outside the influence of the thermal condition at the globe.

VI. EVALUATION OF RESULTS

A. General

This study of comfort conditions in the Mortimer E. Cooley Memorial Laboratory was authorized during the overall period of November, 1954 to September 1, 1955. Requirements of time necessary to establish agreement upon an experimental program and the procurement of instruments resulted in a delay before actual measurements were taken until about February 15, 1955. A temperature recorder of the desired range could not be obtained until about May 1, 1955. Preliminary familiarization runs using a 20 point recorder measuring from 0 to 1000°F. were conducted from about February 15, 1955 to May 1, 1955. However, poor definition of temperature differences resulted from using the recorder with extremely wide range. Consequently, temperature readings of significance were not taken prior to about May 1, 1955. Further work refining the measuring circuits and conducting calibrations resulted in a further consumption of the month of May, 1955 before fully significant data could be obtained.

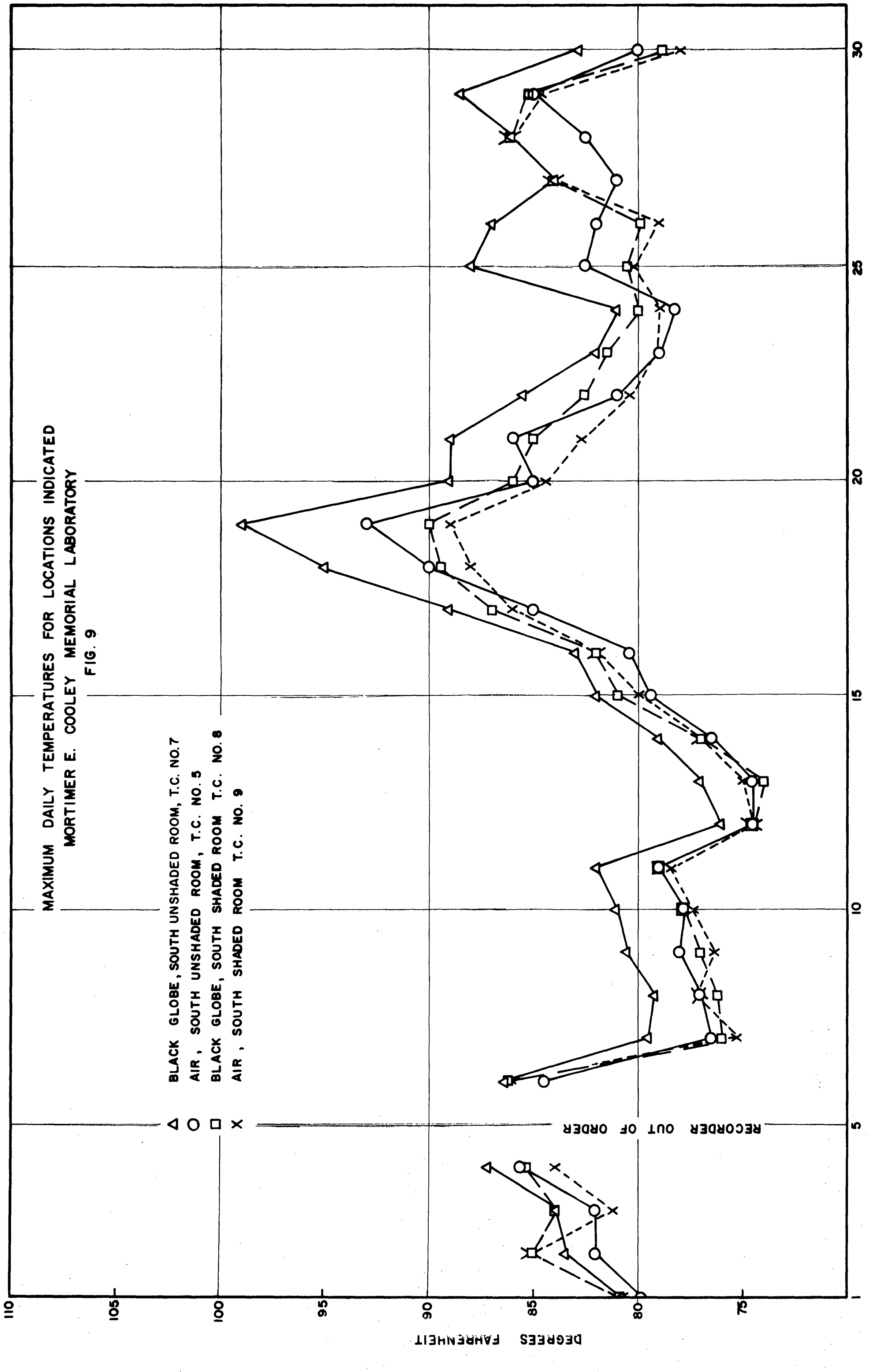
The results reported in this study have necessarily stressed the measurements of physical conditions which prevailed within specified portions of the Cooley Building during the period of the study. It has been stressed above that no attempt has been made to control the conditions within the rooms under study in order to find the effects of the conditions upon human comfort. Consequently, the evaluations of comfort impressions reported are to be interpreted as qualitative only. A more reliable assessment of conditions of comfort would require the reporting of data at closely spaced intervals by a group of people who are trained in the reporting of comfort conditions. Such a group would necessarily have to be sufficiently large and sufficiently representative of persons who might use the particular type of work area involved in order that a statistical sampling of the comfort impressions could be obtained. Most of the comfort impressions reported are those of a small group of one to three persons who were doing office work, drafting, and electronics laboratory work in the rooms under study. As a consequence of the recognized weakness in the evaluation of comfort, the correlation of sensations of comfort to the physical variables mentioned cannot be regarded as definitive. However, the comfort impressions are set forth for what they are worth.

Temperatures were recorded in 12 locations in the three rooms under study during the periods reported herein. Humidity measurements were taken daily with a sling psychrometer and were recorded on a seven day strip chart in certain rooms. Some additional readings of temperature were taken in the exterior air. It can be seen therefore that the measurements of the physical variables are probably much more reliable than the correlation of these variables to comfort sensations of working personnel.

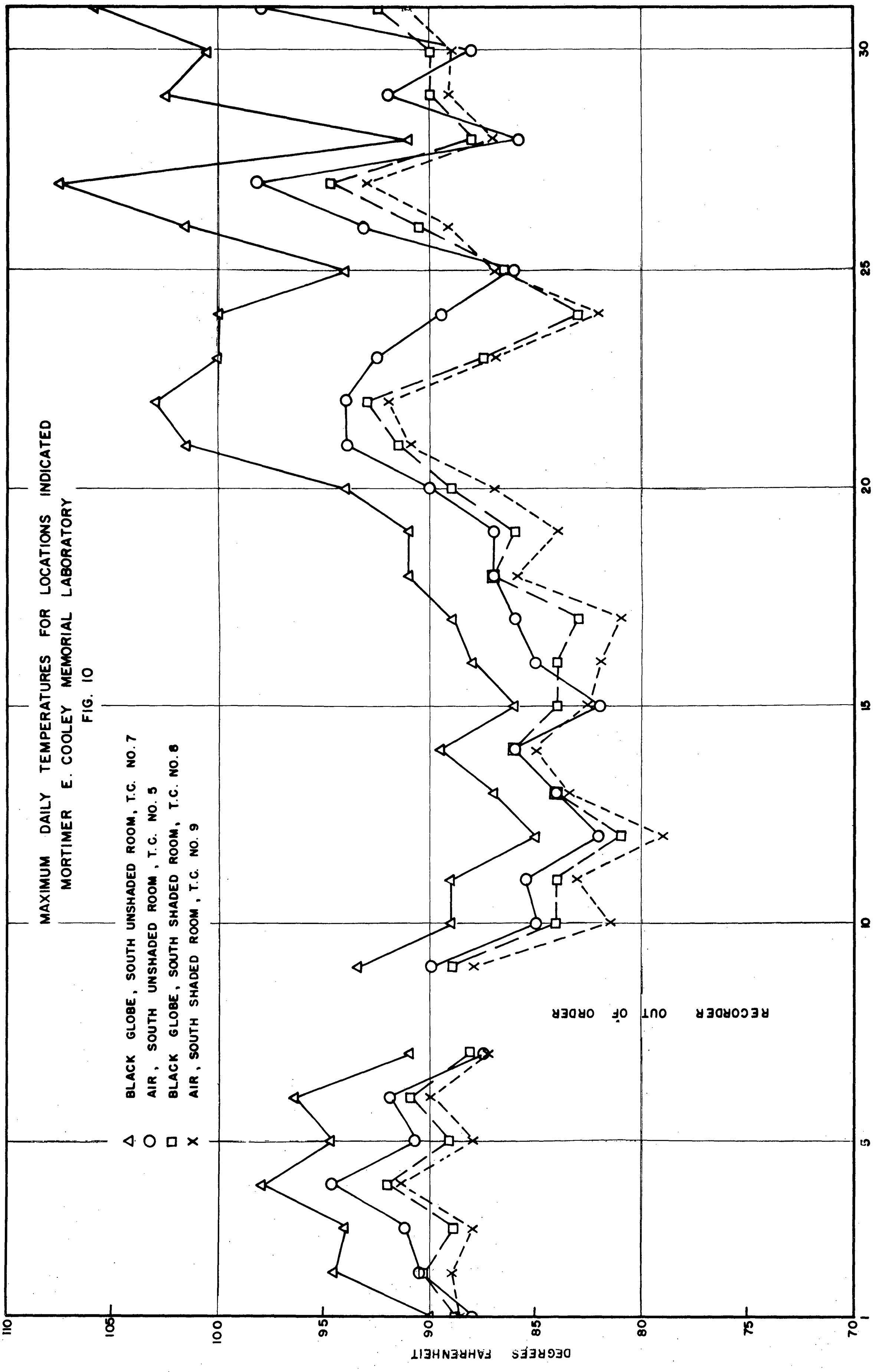
Therefore, probably the most reliable and significant of the results reported for this study are the measurements of temperatures in the working area.

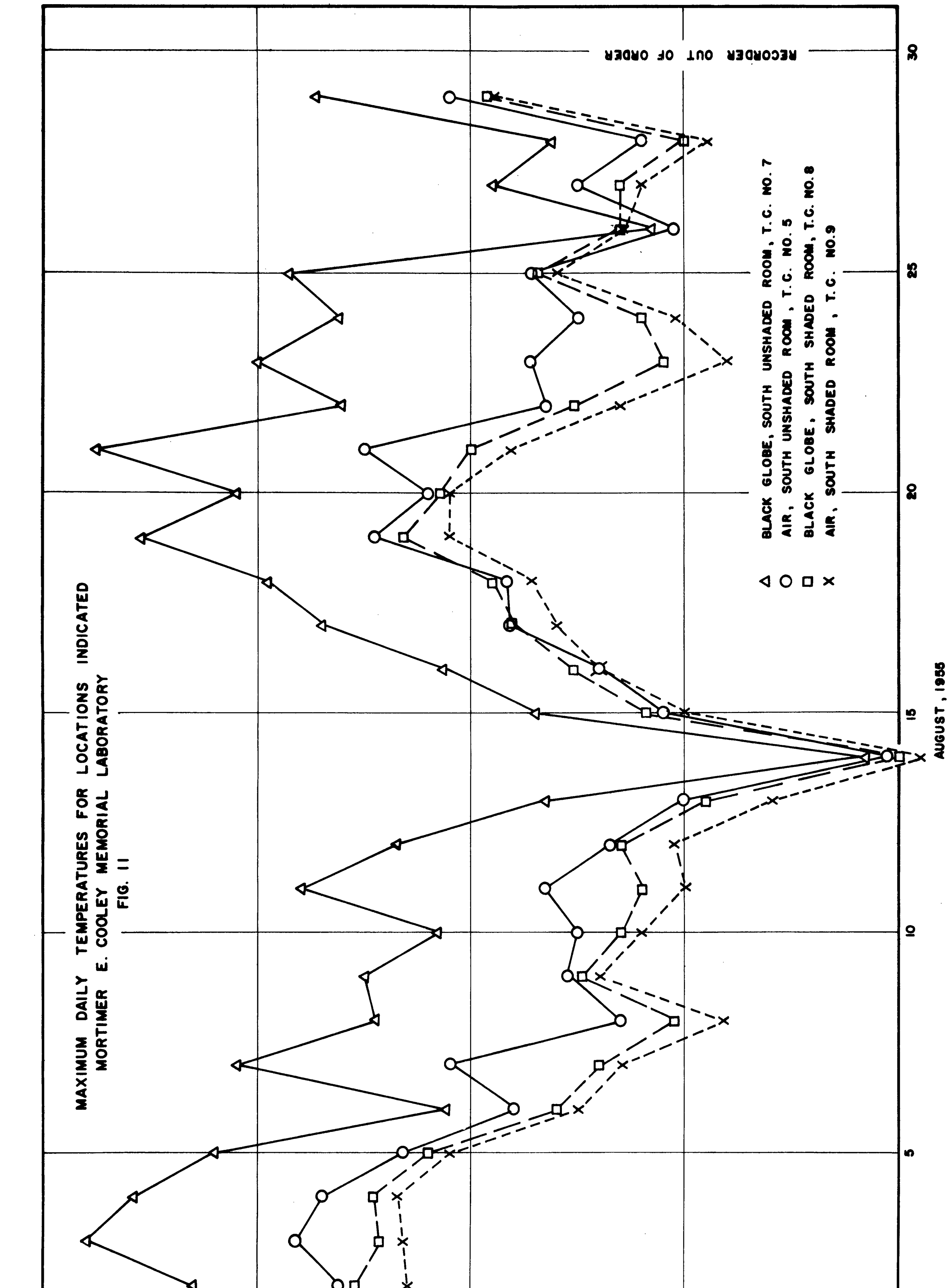
One of the questions for which an answer was most desired was that of the probable degree of discomfort resulting to personnel in the working area of the Mortimer E. Cooley Memorial Laboratory because of the large areas of glass enclosing the south side of the building during periods of exposure of the south side of the building to direct sunlight. The impressions of comfort concerning exposure to the south side of the building to direct solar radiation are covered later in this report. A condensed summary of the results of temperature measurements from the south side of the building is presented in Figures 9, 10, and 11. These figures cover certain selected locations for the months of June, July, and August, respectively in 1955. The temperatures reported are those of a black globe hanging in the center of the room and of the stagnant air near this globe in each of the two rooms both on the south side of the building. One room had aluminum shade screens on the windows and the other had no shade screens on the windows nor any draperies or blinds of any kind on the interior. The temperature inside the black globe in intended to represent an approximation to the feeling of radiant heat which an individual would sense within such a room, and the air temperature is of course self-explanatory. The principal feeling of discomfort in entering a room under direct solar radiation with a south wall of glass is one of radiant heat. One feels a burning or prickling sensation much as he would upon opening the door of a furnace. The black globe measures the radiant temperature of all surroundings including the walls of the room and hence give something of an average radiant temperature of all parts of the room. However, the glass panes making up the south wall of the room generally were at quite elevated temperatures. The mean radiant temperature due to a high radiant temperature on one side and a relatively low radiant temperature on the other side of an individual in a room may not fully represent the potentialities for discomfort in such a situation.

Figures 9, 10, and 11 present four temperature points for each day in June, July, and August, 1955. Temperatures were recorded in twelve locations, each location being recorded once each 24 minutes. Consequently, a temperature recording was taken once each two minutes of the entire 24 hour day for the entire 3 month period mentioned above in the summer, 1955. The points chosen therefore are selected from a total of 720 points taken each day. These 4 points represent the maximum temperatures for each point of each day. The maximum temperature did not occur necessarily at the same time for all points. Generally the maximum temperature for the two points in a given room occurred at the same time, within 20 to 30 minutes of each other and maxima were recorded as being



MAXIMUM DAILY TEMPERATURES FOR LOCATIONS INDICATED
MORTIMER E. COOLEY MEMORIAL LABORATORY
FIG. 9


MAXIMUM DAILY TEMPERATURES FOR LOCATIONS INDICATED
MORTIMER E. COOLEY MEMORIAL LABORATORY
FIG. 10
△ BLACK GLOBE, SOUTH UNSHADED ROOM, T.C. NO. 7
○ AIR, SOUTH UNSHADED ROOM, T.C. NO. 5
□ BLACK GLOBE, SOUTH SHADED ROOM, T.C. NO. 8
× AIR, SOUTH SHADED ROOM, T.C. NO. 9
RECORDER OUT OF ORDER
DEGREES FAHRENHEIT
110
105
100
95
90
85
80
75
70
JULY, 1955
1
5
10
15
20
25
30



MAXIMUM DAILY TEMPERATURES FOR LOCATIONS INDICATED
MORTIMER E. COOLEY MEMORIAL LABORATORY
FIG. 11

at the same time. Consequently, the difference between the black globe temperature and the air temperature can be regarded as taken at the same time and therefore representing the maximum elevation of radiant temperature over air temperature for the day indicated. The maximum temperature for the shaded room generally occurred several hours later than for the unshaded room. Quite often the maximum temperatures for both the black globe and the air in the shaded room occurred at about 5 p.m., whereas those for the unshaded room occurred generally in the region of 12 noon to 2 p.m.

Examination of Figures 9, 10, and 11 indicates that for all but one or two days reported the black globe temperature in the unshaded room exceeded by a significant margin the black globe temperature in the shaded room. For a large number of the days the temperatures of the black globe and the air in the shaded room approximated the air temperature in the unshaded room. However, on extremely hot days as indicated in Figures10, and 11 for approximately the latter two weeks of July and August respectively, the air temperature as well as the black globe was significantly higher in the unshaded than in the shaded room.

Even without reporting the complete summary of comfort impressions for each day involved in these figures one can surmise that the temperatures shown for July and August indicate a marked improvement in comfort conditions due to the presence of shade screens in the shaded room as compared with the unshaded room.

B. Analysis of the Data for a Single Day

As indicated above, the temperature points recorded in Figures 9, 10, and 11 represent for each day only 4 points selected out of a total of 720. In order to show the manner in which the individual temperatures which were recorded varied with the time of day, a typical day has been selected for a more complete analysis.

Figure 12 is a photograph of the temperature record registered on the temperature recorder for June 16, 1955. Points 5 and 11 did not reproduce in the photographic process. Figures 14, 15, and 16 have been plotted from these recorded data.

Figure 14 shows the globe temperatures and air temperatures in the shaded and unshaded rooms as they vary during the day. The day chosen was clear and relatively hot with a wind velocity of 10 miles per hour. The weather data on this day were as follows:

Day - June 16, 1955 (Thursday)
Sky Coverage - 0.1 (clear)
Wind - 10 mph; northwest
Temperature - maximum 94°F. (Figure 10)
minimum 58°F
Barometer - 29.30" high
29.23" low
Humidity - maximum 80% 5:30 a.m. and 27% at 5:30 p.m.

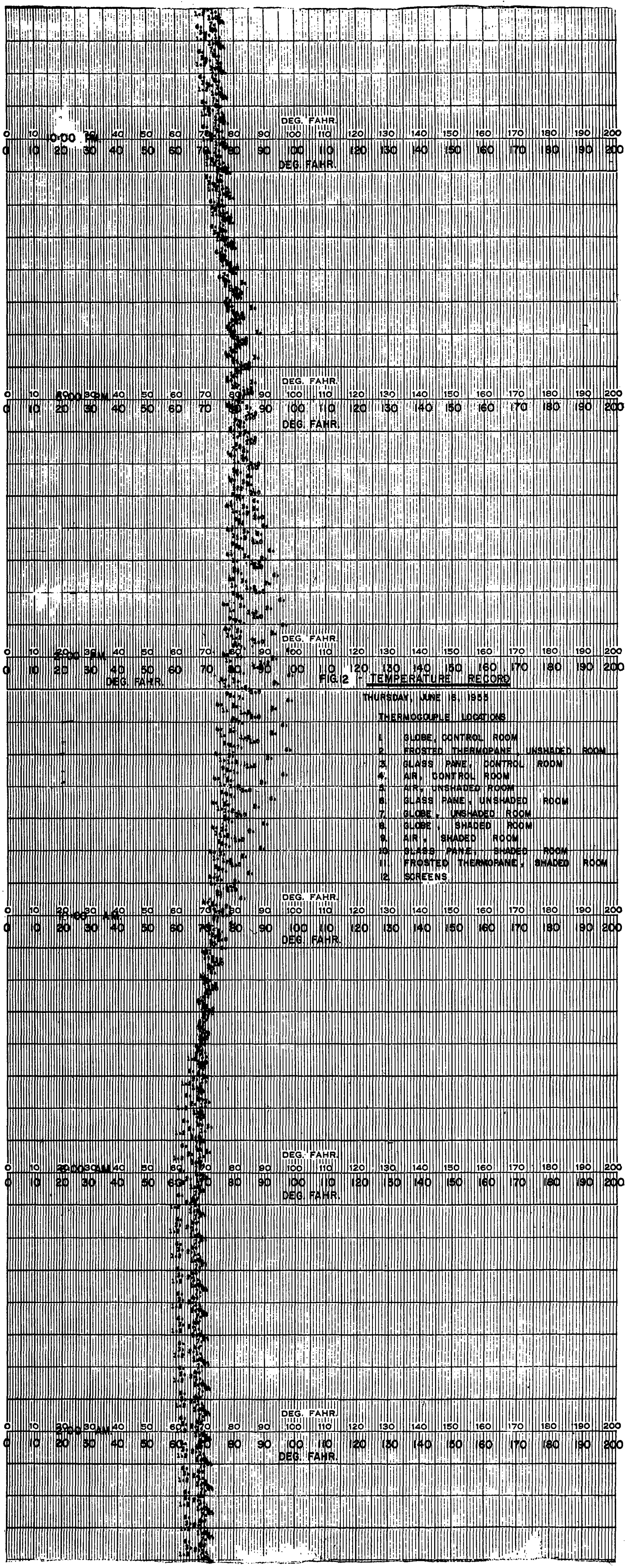


FIG. 2 - TEMPERATURE RECORD

THURSDAY, JUNE 16, 1955

THERMOCOUPLE LOCATIONS

1. GLOBE, CONTROL ROOM
2. FROSTED THERMOPANE, UNSHADED ROOM
3. GLASS PANE, CONTROL ROOM
4. AIR, CONTROL ROOM
5. AIR, UNSHADED ROOM
6. GLASS PANE, UNSHADED ROOM
7. GLOBE, UNSHADED ROOM
8. GLOBE, SHADED ROOM
9. AIR, SHADED ROOM
10. GLASS PANE, SHADED ROOM
11. FROSTED THERMOPANE, SHADED ROOM
12. SCREENS

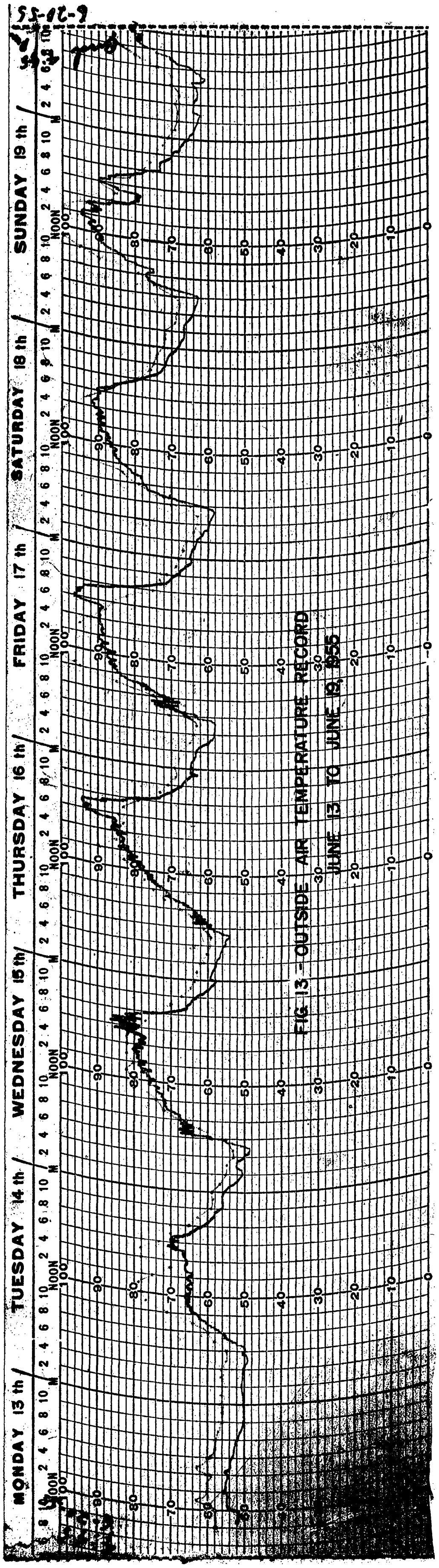


FIG. 13 - OUTSIDE AIR TEMPERATURE RECORD
JUNE 13 TO JUNE 19, 1955

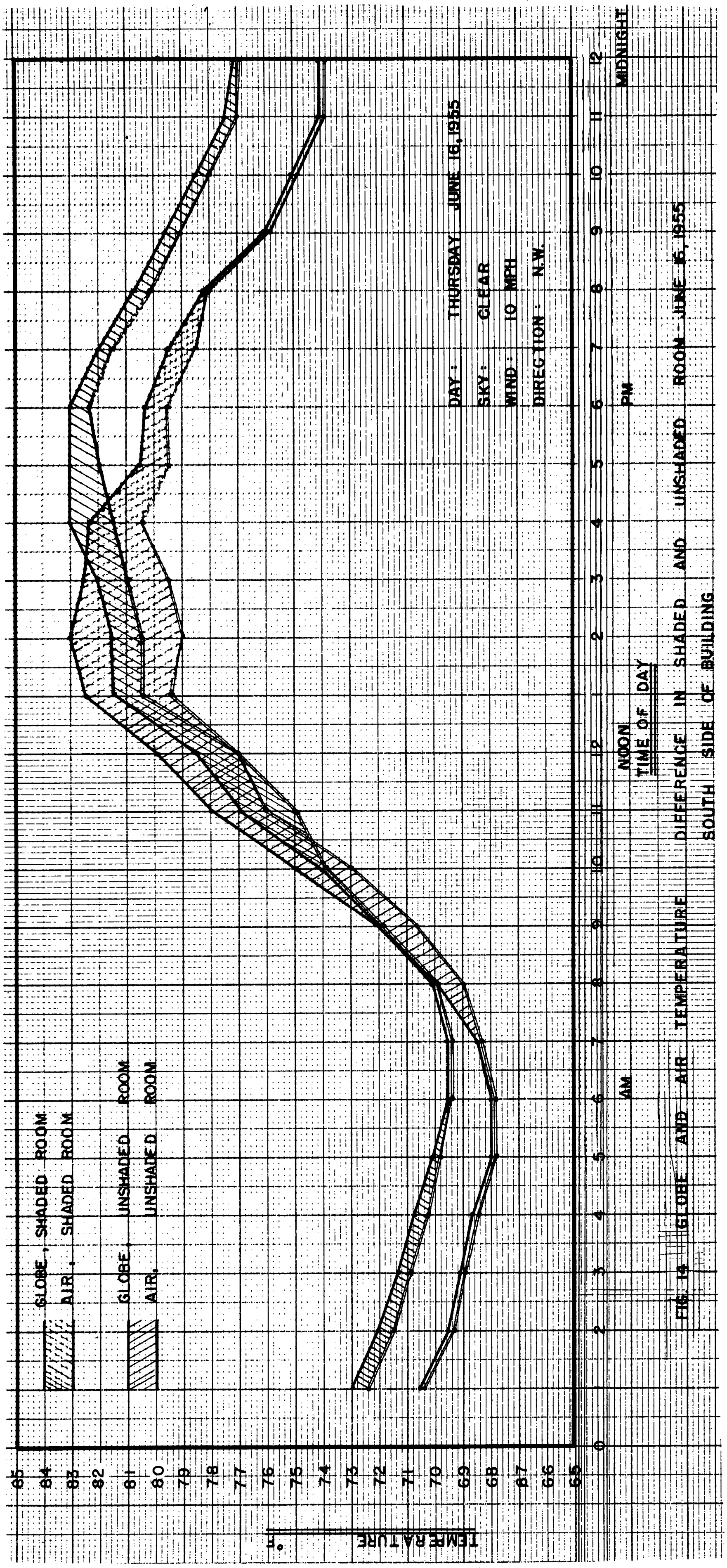


FIG. 14 GLOBE AND AIR TEMPERATURE DIFFERENCE IN SHADED AND UNSHADED ROOM - JUNE 16, 1955 SOUTH SIDE OF BUILDING

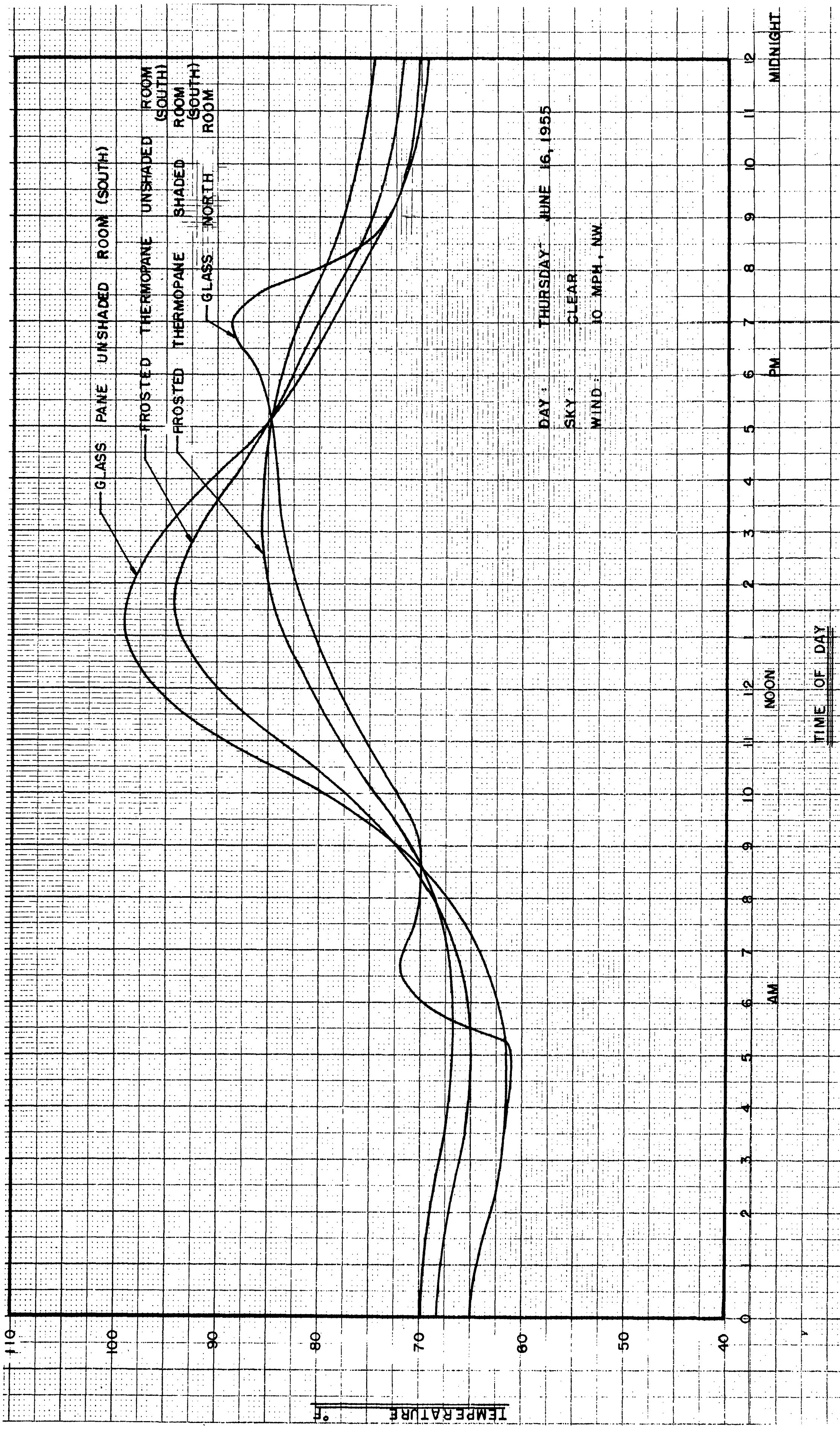


FIG. 15 - INSIDE SURFACE TEMPERATURE OF THE GLASS PANES - JUNE 16, 1955

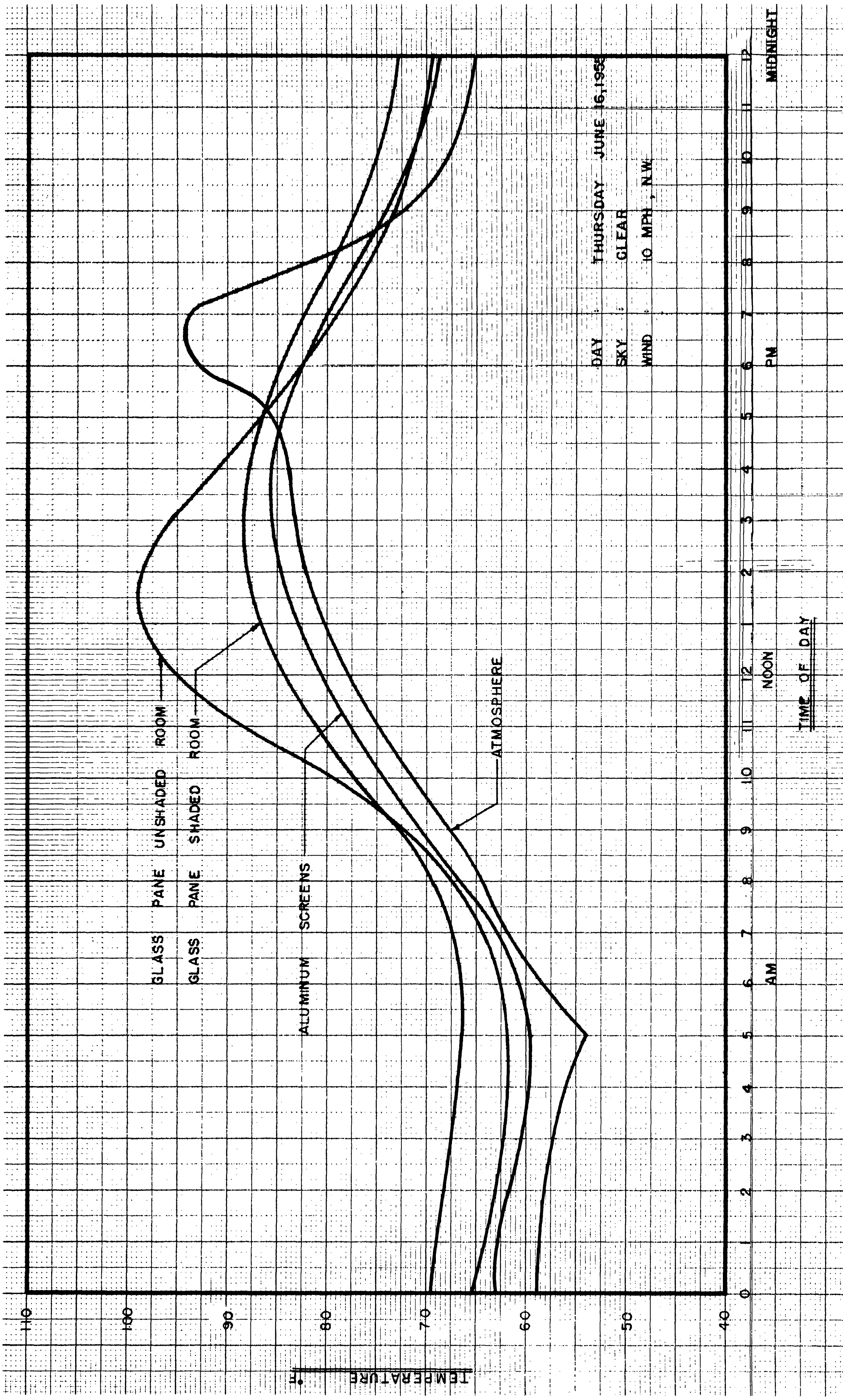


FIG. 16 - COMPARISON OF TEMPERATURES OF ATMOSPHERE, SCREENS AND GLASS PANES - JUNE 16, 1955

The day selected was not the most uncomfortable experienced in the Cooley Building for the summer as implied by the temperatures indicated on Figures 9, 10, and 11. However the variation of temperatures throughout the day follows much the same pattern in all days studied in this investigation. The chief qualification to this arises from the differing apparent paths of the sun on the celestial sphere with the change in seasons. As may be inferred by inspection of Figure 15, periodic maxima occurred for the glass pane on the control room located on the north side of the building, an unshaded room, at about 7 a.m. and 7 p.m. for the 16th of June. A similar fact can be noted in Figure 16 at about 7 p.m., where the temperature of the atmosphere apparently arose to a sharp maximum. This same effect can also be noted on the one week strip chart of Figure 13, indicating the outside air temperatures during the week June 13 to June 19, 1955. It is believed that these maxima in a windowpane on the north side of the building and on the outside air temperature early and late in the day resulted from the fact that the sun was north of the east west orientation of the building at these periods. Consequently, the north side was being subjected to direct solar radiation during the early morning and late afternoon. The maximum of the outside air temperature in the late afternoon can be interpreted by noting that the recording thermometer was suspended from the underside of an overhang on the north side of a cupola on the roof of the Cooley Building. It was shaded from direct solar radiation from all directions except the northwest. Consequently, the apparent maximum in air temperature at about 7 p.m. was probably not a real maximum, since radiation as well as local air temperature was affecting the recorder.

It may be noticed from Figure 14 that in the shaded room the difference between the globe and air temperature varies between much smaller limits than the corresponding difference in the unshaded room. However, between sundown and sunrise there still remains a small difference between the globe temperature and air temperature in the shaded room, whereas there is practically no difference between these temperatures in the unshaded room. This observation means that the surroundings in the shaded room, that is the walls and the windows, usually remain warmer than the air inside. However, at night the average temperature of the surroundings in the unshaded room is about the same as the air temperature inside the room. This behavior apparently means that it takes the shaded room longer to get warm but also longer to cool once the sun goes down. However, the maximum in air temperatures and globe temperatures in the shaded room usually occurred late in the afternoon from about 4 to 5 p.m. Consequently, this room had all night to cool off before the workers came in the next morning.

On June 16, 1955, the maximum intensity of radiation received by the globe in unshaded room occurred at 2 p.m. The difference between the globe and air temperature was 4°F, in the unshaded room and 1°F in the shaded room. Assuming the same air velocity in the two rooms, the net radiant energy received by the globe in the unshaded room was 3.56 BTU/hr/sq.ft., while that received by the globe in the shaded room was 0.9 BTU/hr/sq.ft. In other words the net radiant energy received by the globe in the shaded room was about 25% of that received by the globe in the unshaded room.

Figures 15 and 16 illustrate the variation of temperature of the glass panes and the air and shade temperatures. The glass pane in the unshaded room is cooler at night than the one in the shaded room due to the larger radiation losses to the sky. However, this pane heats up very rapidly when sunlight strikes the south side of the building, reaching a maximum of 100°F. on June 16, 1955, compared to the corresponding 85°F. in the shaded room. In other words, the temperature of the glass pane in the unshaded room responds very quickly to the variations in solar radiation, whereas the shade screens retard the heating and cooling effects of solar radiation and atmospheric convection on the glass pane in the shaded room.

It is interesting to note that the screen temperatures are sometimes lower than the glass temperatures during the periods of solar exposure. The temperature difference referred to is mainly caused by convective cooling if the wind is blowing from certain directions. On days when wind blows northward, the screen temperatures are low due to convective heat transfer effects. If the wind blows southward, the screen temperature remains at a higher value than if the wind is blowing northward. The screens remain warmer than the outside air at night, probably because of heat transfer from the rooms. The screens also cool faster than the glass, a consequence of their large surface area, exposed position, and small thermal capacity.

Figure 15 compares variation of the inside surface temperatures of the frosted thermopanes with those of the single glass panes. The temperature of the glass pane in the control room (facing north) is seen to rise abruptly in the mornings and late afternoons when the windows of this room receive direct solar radiation, but remain relatively cool the remainder of the day. This curve indicates a rapid rate of response to the variation of the incident radiation to be inherent in the glass pane.

C. Comfort and Variables Influencing Comfort

Before proceeding to the other results and their interpretation, it may be pertinent to clarify some of the technical terms and the factors affecting human comfort. The most important of these terms are discussed below.

Effective Temperature - Effective temperature is an empirically determined index of the degree of warmth or cold felt by the human body in response to temperature, humidity, and air movement. The use of the concept of effective temperature has been described by Yaglou, et al., (9). Effective temperature is a scale of thermo-equivalent conditions indicating the sensation of warmth, and to a degree determining the physiological effects on the human body induced by heat or cold.

The numerical value of the effective temperature index for any given air condition is equal to the temperature of saturated air, which at an air velocity or turbulence of 15 to 25 feet per minute (representing practically still air) induces a sensation of warmth or cold equivalent to that of the given condition. Thus an air condition has an effective temperature of 65° when it induces a sensation of warmth like that experienced in practically still air at 65°F. saturated with moisture.

Effective temperature alone does not serve as an index of comfort. Moist air at a comparatively low temperature and dry air at a higher temperature may both feel as warm as air at an intermediate temperature and humidity. However, the sensations of comfort experienced in these three conditions of air would be different, although the effective temperature might be the same. Consequently, humidity must be considered in addition to effective temperature in setting up an index of probable comfort in the absence of large radiation effects.

Yaglou, et al., (9) indicated that air with relative humidities above 70% is uncomfortably humid, while air with relative humidities below 30% is too dry for comfort. The American Society of Heating and Air-Conditioning Engineers (5) developed a definition of a comfort zone which embodies the probable effects of effective temperature and humidity. The average summer comfort zone is between 66° to 75° effective temperature, the optimum being 71°. The relative humidity limits are placed between 70% and 30%. The winter comfort zone has boundaries which indicate the comfortable conditions to be at slightly lower temperatures. It should be emphasized that these zones are not very rigidly defined, but only indicate the conditions under which a large percentage of the subjects participating in the American Society of Heating and Air-Conditioning Engineers' investigation were comfortable.

<u>Mean Radiant Temperature</u> - Mean radiant temperature is that uniform temperature to which all the surfaces in view of a globe thermometer must be heated in order to give the same globe temperature as the actual surroundings give, even though different parts of the surroundings may be at different temperatures.

<u>Limitations of the Comfort Chart</u> - The application of the summer comfort zone of the A.S.H.A.E.,(5), is restricted to situations in which the human body has reached thermal equilibrium with the environment. Equilibrium is usually reached after 1-1/2 to 3 hours exposure. The comfort zone is further not applicable to conditions where there is appreciable radiant heating, but only where the heating is of convective nature. The chart is thus meant to be applicable to homes, offices, etc. in which radiant energy interchange plays a minor part in the heating or cooling mechanism.

A considerable volume of work has been reported by the American Society of Heating and Air-Conditioning Engineers (5) describing some effects of radiation upon the limits of human comfort and endurance. However, this information has apparently not been incorporated into the definition of the "comfort zone," referred to above.

In addition to being influenced by effective temperature and relative humidity, comfort is also a function of the physiological and psychological response of the human eyes to light and glare. Thus a person standing in the sun may feel a different degree of comfort than one standing in the shade, even though both subjects may be the same effective temperature, humidity, and mean radiant temperature. Glare is pronounced on clear days in modern buildings which make widespread use of glass windows as an exterior wall. Hence light, or the glare from outside of a building, is an important variable to be dealt with when one considers human comfort within a building.

The Cooley Laboratory has north and south walls consisting essentially of glass. The use of large areas of window glass gives an impression of space, but also admits a large amount of light and glare from the sky. Therefore the study of comfort conditions in the Cooley Laboratory requires consideration of lighting conditions in addition to effective temperature, humidity, and mean radiant temperature. However, no attempt has been made in this investigation to measure or to evaluate the effect of glare.

D. Comparison of the Shaded and Unshaded Rooms with Respect to Comfort

1. Dry Bulb

The dry bulb temperatures in the shaded and the unshaded rooms were not appreciably different during working hours. This observation is partly the result of the personnel at work in adjusting the windows and doors, but is also due to the release of heat from electronic equipment operating in the shaded room. The amount of heat liberated by the equipment in the shaded room studied was observed to be between 1000 to 1500 watts. The heat release in the unshaded room was negligible, the overhead electric lights being the only connected electrical load.

2. Relative Humidity

The relative humidities in the two rooms were not appreciably different.

3. Difference between Globe Temperature and Air Temperature

The significance of any difference between globe temperature and air temperature has already been discussed in a previous section (VII - A). The elevation of globe temperature above dry bulb temperature was observed to be much larger in the unshaded room than in the shaded room during the working hours. At the time of maximum dry bulb air temperature in the unshaded room on June 16, 1955, the increment of the globe temperature over the dry bulb air temperature was 4°F. This difference is to be compared with an increment of 1°F in the shaded room. Part of this temperature difference of 1°F in the shaded room can be attributed to heat generated in the electronic equipment operating there at that time. However, an estimate of the effect of the presence of this equipment is difficult to formulate and, since the total effect is small, it is assumed that radiation and air heating effects essentially cancel each other when interpreted in terms of globe and air temperatures.

4. Comfort Conditions

On the following two charts (Figures 17 and 18) are plotted some of the effective temperature and humidity data observed in the shaded and unshaded rooms studied. The method of presentation adopted in these figures is based on that of the comfort chart developed by the American Society of Heating and Air-Conditioning Engineers (5). That the comfort zone defined by the American Society of Heating and Air-Conditioning Engineers' chart is not applicable to conditions in the Cooley Laboratory may be seen by noting the uncomfortable points lying within the "comfort zone." Though scanty, these data are indicative of the relative number of uncomfortable days experience in the shaded room and in the unshaded room on normal working days in June. On very hot days, as experienced in the last week of June, both of the rooms were uncomfortable, although to a different degree. It may be concluded that subjects in the shaded room experience fewer uncomfortably hot days than those in the unshaded room. This conclusion is supported by the data on the glass temperatures and globe and air temperature differences, which are the measurable variables which contribute to human comfort.

E. Relationship of Effective Temperature and Mean Radiant Temperature

It has been mentioned that the American Society of Heating and Air-Conditioning Engineers' comfort chart is not applicable to rooms where there is an appreciable radiant energy effect. The mean radiant temperature, as defined earlier and as measured by the globe temperature, is probably the best expression of the overall effect of radiation at a given point. With the data for the three variables, globe temperature, effective temperature and relative humidity available, the possibility of extending the concept of the comfort zone to include radiant effects presents itself.

The following tables and curves represent an attempt at correlating the data obtained in this investigation in terms of simultaneous effects of effective temperature, humidity, and mean radiant

TABLE III

COMPARISON OF SHADED AND UNSHADED ROOMS
JUNE 7 TO JUNE 30, 1955

SHADED ROOM

DATE	W.B., °F	D.B., °F	E.T.°	R.H.%	FEELING
7	67	72	69	72	uncomfortable
8	65.5	74	70.5	63	comfortable
9	63	74.5	70	52.5	comfortable
10	65	75.5	71	56.5	chilly
13	61	73	68.5	50	chilly
14	61	73	68.5	50	chilly
15	60.5	73	68.5	46.5	chilly
16	65	76	71	55	comfortable
17	66.5	79	73.5	51.5	uncomfortable
20	69.5	84.8	76.5	46.5	uncomfortable
21	63	82.5	73	35	comfortable
22	64	80.5	73.5	41	uncomfortable
23	62.5	78	71.5	41	uncomfortable
24	63.5	76.5	70.5	46.5	comfortable
27	64	81	73	38.5	uncomfortable
28	65.3	82.7	74.5	40	uncomfortable
29	65.5	83	73.5	39.5	comfortable
30	71	77	74	74	uncomfortable

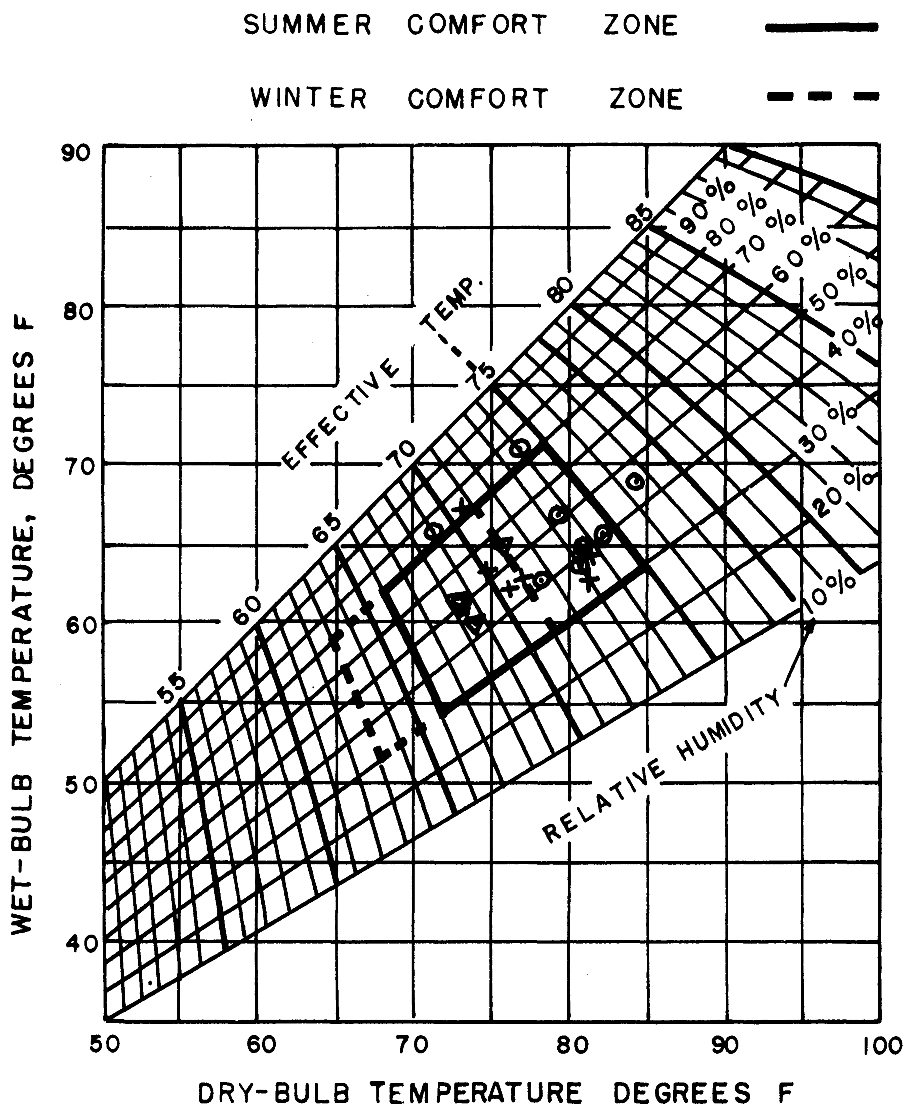


FIG. 17 - COMFORT CONDITIONS IN SHADED ROOM
JUNE 7 TO JUNE 30, 1955

+ COMFORTABLE

⊙ UNCOMFORTABLE

▽ CHILLY

TABLE IV

COMPARISON OF SHADED AND UNSHADED ROOMS
JUNE 7 TO JUNE 30, 1955

UNSHADED ROOM

DATE	W.B., °F.	D.B., °F.	E.T.°	R.H.%	FEELING
7	69	77.5	73.5	65	uncomfortable
8	65.5	74	70	63	comfortable
9	63.5	76	71	49.5	comfortable
10	66	76.5	72	57.5	comfortable
13	61	73	68.5	50	comfortable
14	61.5	74	69	48.5	comfortable
15	61.5	74	69	48.5	comfortable
16	65.5	76	71.5	57	uncomfortable
17	66.5	80	73.5	49	uncomfortable
20	70.5	85	77.5	50	uncomfortable
21	65	84	75	34.5	uncomfortable
22	63.5	80	72.5	39	uncomfortable
23	62.5	78	71.5	41	uncomfortable
24	63	76.5	71	46.5	comfortable
27	63	78.5	71.7	39	comfortable
28	66	79.9	73.5	47	uncomfortable
29	69	83.5	75	46	uncomfortable
30	71.5	77.5	74	74	uncomfortable

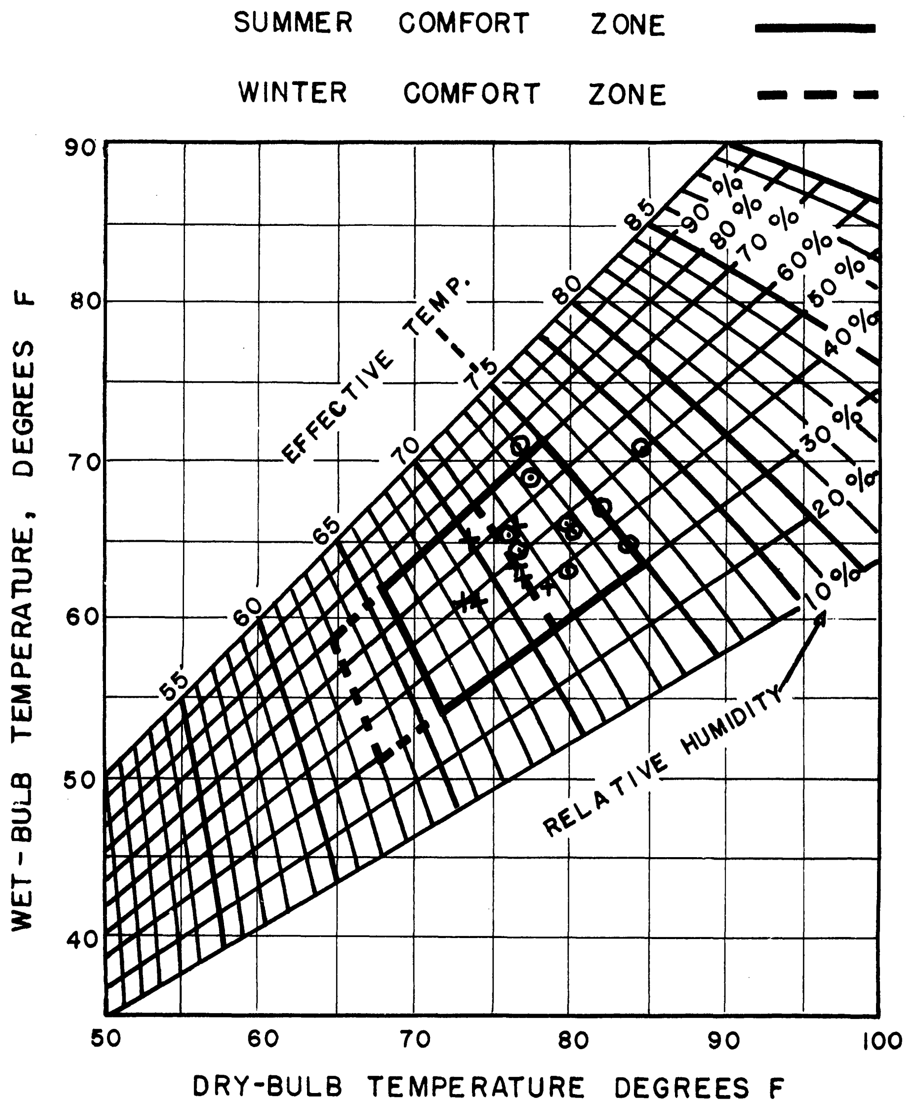


FIG. 18 - COMFORT CONDITIONS IN UNSHADED ROOM
JUNE 7 TO JUNE 30, 1955

\+ COMFORTABLE

⊙ UNCOMFORTABLE

temperatures upon comfort. A correlation is presented which is applicable only for the summer and is intended to determine the upper limits of the comfort zone when radiant energy effects were considered. Tables V, VI, and VII present data plotted in Figures 19, 20, and 21, respectively. In Figures 20 and 21 the elevation of mean radiant temperature over the dry bulb temperature has been plotted aginst the effective temperature at selected values of relative humidity range, and a straight line has been drawn separating the comfortable and the uncomfortable points. The points on such a line are hence points representing limiting values of comfort. Figure 19, and condition of 75° effective temperature and zero evaluation of MRT over dry bulb temperature is equivalent in terms of comfort to a condition of 71° effective temperature and a 4° elevation of MRT over dry bulb temperature. Any point lying on the upper side of this line would be considered uncomfortable, while one lying on the lower side would be comfortable. In other words, this line is similar to the boundary line of 75° effective temperature on the comfort chart in that it separates an uncomfortable zone from a comfortable one. However, the comfort chart correlation applies to the case in which the parameter representing the radiant energy effects, i.e., mean radiant temperature minus dry bulb temperature, is maintained constant at 0°F. while Figures 20 and 21 represent the data for the case of essentially constant relative humidity and variable mean radiant minus dry bulb temperature.

Figure 20 shows a plot of MRT minus dry bulb temperature as a function of effective temperature for the points selected from the high humidity range (60-70%). The slope of this line shows that 1.2°F elevation of the MRT over the dry bulb is equivalent to 1° increase of the effective temperature. In Figure 21 are plotted points in the low humidity range, showing that 0.75°F. elevation of the MRT-D.B. is equivalent to 1° increase in the effective temperature. In Figure 19 is plotted the MRT-D.B. in the effective temperature range of 70-75° and for the intermediate humidity range. This plot shows that a 1°F elevation of MRT over the dry bulb temperature in this range is equivalent to a 1°F. elevation of the effective temperatures in approaching the limits of the comfort zone.

The data plotted in Figures 19, 20, and 21 represent the actual conditions in the selected rooms during working hours without any impositions or restrictions being placed by the experimenters. The data are found to be widely scattered, and the correlations are open to further experimentation with controlled variables. The curves indicate a 1.2 to 1, 0.75 to 1, and a 1 to 1 ratio of the elevation of MRT over the dry bulb temperature to the effective temperature in the three figures shown. However, an average value of one degree elevation of MRT over the dry bulb temperature is taken as equivalent to a 1° increase in the effective temperature in the environment under investigation.

These results may be compared to those of Houghten, Gunst, and Suciu (6), who made a similar study for winter conditions and found that for 75° E.T. and 50% relative humidity, a 1.5° change in the MRT

TABLE V

MEAN RADIANT TEMPERATURE - EFFECTIVE TEMPERATURE RELATIONSHIP IN AN INTERMEDIATE HUMIDITY RANGE

M.R.T.,°F.	D.B. TEMPERATURE,°F.	E.T.°	RELATIVE HUMIDITY,%	MRT-D.B.,°F.	FEELING
90	83.5	75	46	6.5	uncomfortable
79	77	73.5	65	2	uncomfortable
81	76	71.5	49.5	5	uncomfortable
85	80	73.5	49.0	5	uncomfortable
83	80	72.5	39	3	uncomfortable
79	79	74.5	69	0	uncomfortable
80.5	79	74	62	1.5	uncomfortable
85.5	82	75.5	49	3.5	uncomfortable
79.5	79.5	73.5	51.5	0	uncomfortable
84	82	73.5	41	2	uncomfortable
84	81	71.5	41	3	uncomfortable
84.5	83	73.5	39.5	1.5	uncomfortable
88.5	83	74.5	40	5.5	uncomfortable
85	81	73	38.5	4	uncomfortable
88	82	73.5	43.7	6	uncomfortable
82	79	72.5	65.5	3	comfortable
84	83	73	35	1	comfortable
78.5	76.5	71	56.5	2	comfortable
80	76.5	71	55	3.5	comfortable
83	80	71.5	52	3	comfortable
76	74	70.5	63	2	comfortable
81.5	78	70.5	43.5	3.5	comfortable
79	79	70.5	42.5	0	comfortable
84.5	77	71.5	52	7.5	uncomfortable

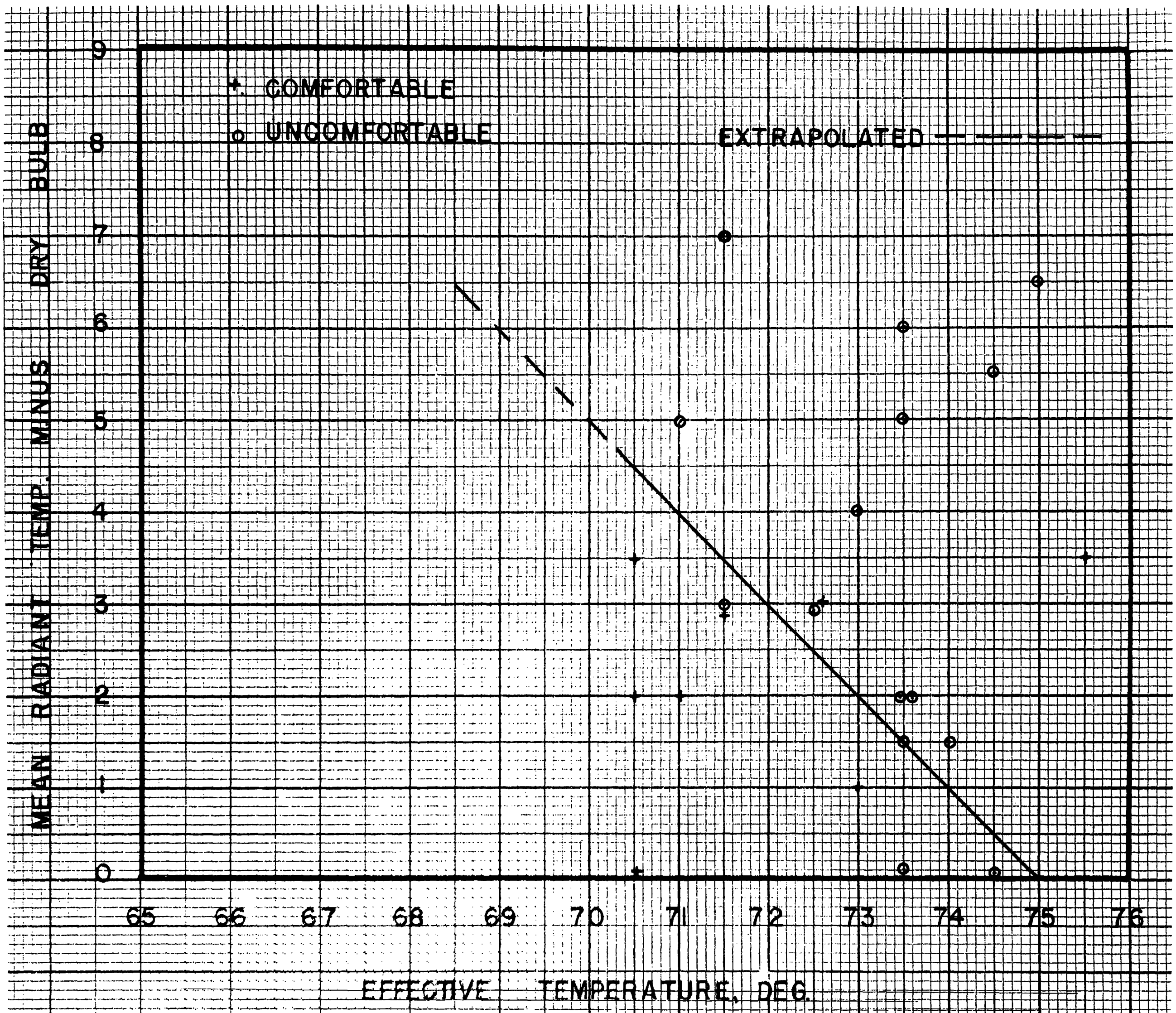


FIG. 19

EFFECT OF MEAN RADIANT TEMPERATURE ON COMFORT

INTERMEDIATE HUMIDITY ZONE

TABLE VI

MEAN RADIANT TEMPERATURE - EFFECTIVE
TEMPERATURE RELATIONSHIP
IN A
HIGH HUMIDITY RANGE

M.R.T., °F.	D.B. TEMPERATURE, °F	E.T.°	RELATIVE HUMIDITY,%	MRT-D.B., °F.	FEELING
82	79	72.5	65.5	3	comfortable
78.5	74	70.5	63	4.5	comfortable
79.5	75.5	72.2	64.5	4	uncomfortable
76	74	70.5	63	2	comfortable
75	73	69.5	61	2	comfortable
79	79	74.5	69	0	uncomfortable
80.5	79	74	62	1.5	uncomfortable
72	69.5	68	66	2.5	comfortable
79	77	73.5	65	2	uncomfortable
74	72.5	70	63	1.5	comfortable
82	76	71.5	57	6	uncomfortable
83	77.5	72	57.5	5.5	comfortable
84.5	77	71.5	52	7.5	uncomfortable
83	80	71.5	52	3	uncomfortable
80	75.5	70	59.5	4.5	comfortable
83.5	79	75	75	4.5	uncomfortable
83.7	77.5	74	74	6.2	uncomfortable

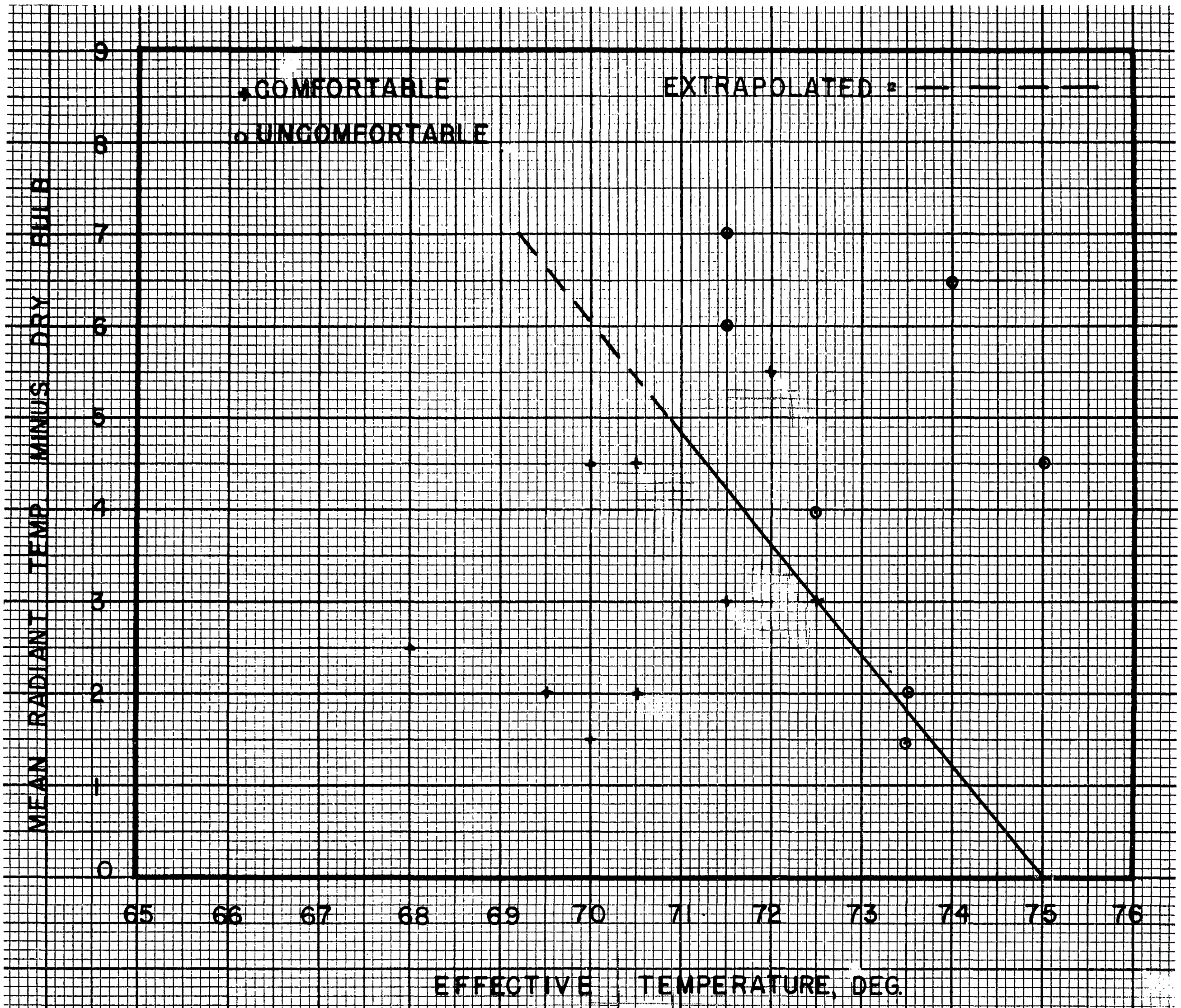


FIG. 20

EFFECT OF MEAN RADIANT TEMPERATURE ON COMFORT

HIGH HUMIDITY RANGE (60% TO 70%)

TABLE VII

MEAN RADIANT TEMPERATURE - EFFECTIVE
TEMPERATURE RELATIONSHIP
IN A
LOW HUMIDITY RANGE

M.R.T., °F	D.B. TEMPERATURE, °F.	E.T.°	RELATIVE HUMIDITY, %	MRT-D.B., °F.	FEELING
89	85	75	34.5	4	uncomfortable
83	80	72.5	39.0	3	uncomfortable
83	78	71.5	41	5	uncomfortable
84.5	79	71.7	39	5.5	comfortable
76	71	66	39	5	comfortable
76.5	72	67	37	4.5	uncomfortable
70	70	68.5	34	0	uncomfortable
82	77	69	34	5	uncomfortable
78.5	78.5	70.5	31.5	0	uncomfortable
89.5	83.5	72	27	6	comfortable
82.5	79	70	36	3.5	comfortable
77	75	68.2	38	2	comfortable
83	80	70.5	39	3	comfortable
84.5	83	73.5	39.5	1.5	uncomfortable
88.5	83	74.5	40	5.5	uncomfortable
85	81	73	38.5	4	uncomfortable

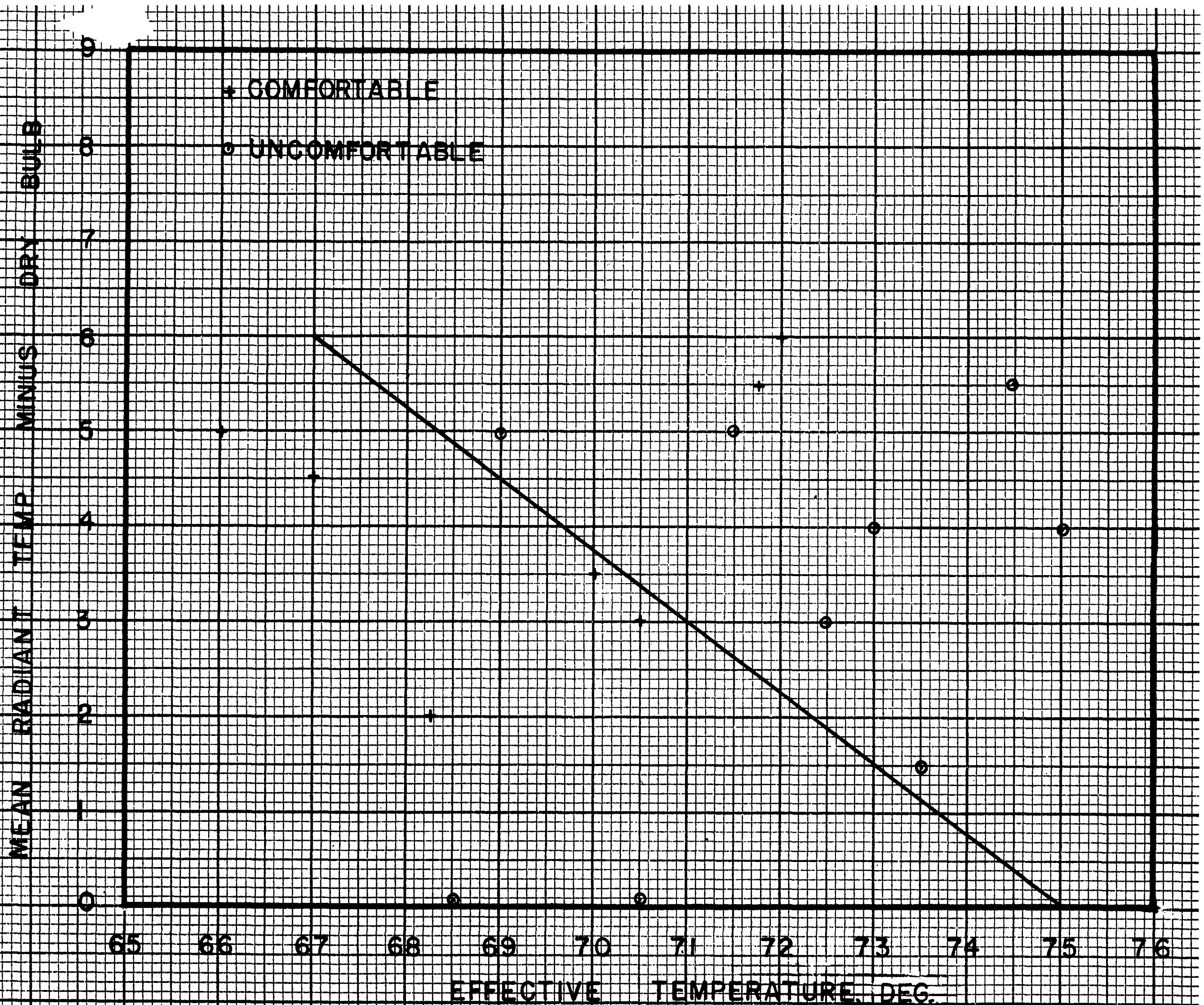


FIG. 21

EFFECT OF MEAN RADIANT TEMPERATURE ON COMFORT

LOW HUMIDITY RANGE (30% TO 40%)

was equivalent to 1° change in the effective temperature in approaching the limits of the comfort zone. Houghten's experiments were done in winter and in absence of any appreciable sky glare.

The above results were summarized in Figure 22, where a dimension of MRT minus D.B. on the vertical coordinate is added to the usual two dimensions of effective temperature and relative humidity of the comfort chart. The use of this modified comfort chart can perhaps be best illustrated by an example. For instance, assume that the data are as follows:

Effective temperature - 68°

Relative humidity - 50%

Mean radiant temperature minus dry bulb temperature - 5°F.

Point A is located in the plane of the figure by values of the relative humidity and the effective temperature. It should be noted that this point could also be located from the wet and dry bulb temperatures at constant low air velocity. Point B in space is located by first moving from point A horizontally to the left to the 45° line (which corresponds to MRT-D.B. = 0° line), then vertically to MRT-D.B. = 5°F. line and then horizontally to the right to point B directly above point A. It is seen that point B is inside the surface of the comfort volume (solid zone). Hence this air condition would be comfortable. If, however, for the same point A, the MRT minus dry bulb temperature were 8°F, the corresponding point would lie outside the boundaries of the comfort zone defined by the planes LMPQ, LMN, MNOP, and OPQ.

It would be possible to display the relationship for limiting conditions of comfort among mean radiant temperature less dry bulb temperature, wet bulb temperature, and dry bulb temperature by means of an alternative method of plotting. In this alternative method a two-dimensional plot would be used. Contour lines of constant limiting values of mean radiant less dry bulb temperature could be superimposed upon the usual American Society of Heating and Air-Conditioning Engineers' comfort chart. Such a method of plotting would avoid reference to a projection of a three-dimensional figure and would probably be more convenient in a practical work. A contour plot was not used to present the results of this study since contours of mean radiant less dry bulb temperature were parallel to lines of constant effective temperature. This is a result of the assumption of the equivalence of one degree of (MRT-D.B.) to one degree of effective temperature, regardless of humidity. The use of the contour plot should not be overlooked, however, if future work indicates that there is a marked dependance upon relative humidity of comfortable tolerance to mean radiant temperature less dry bulb temperature.

It would be of interest to extend the correlation discussed above to determining the limits of the conditions which could be called

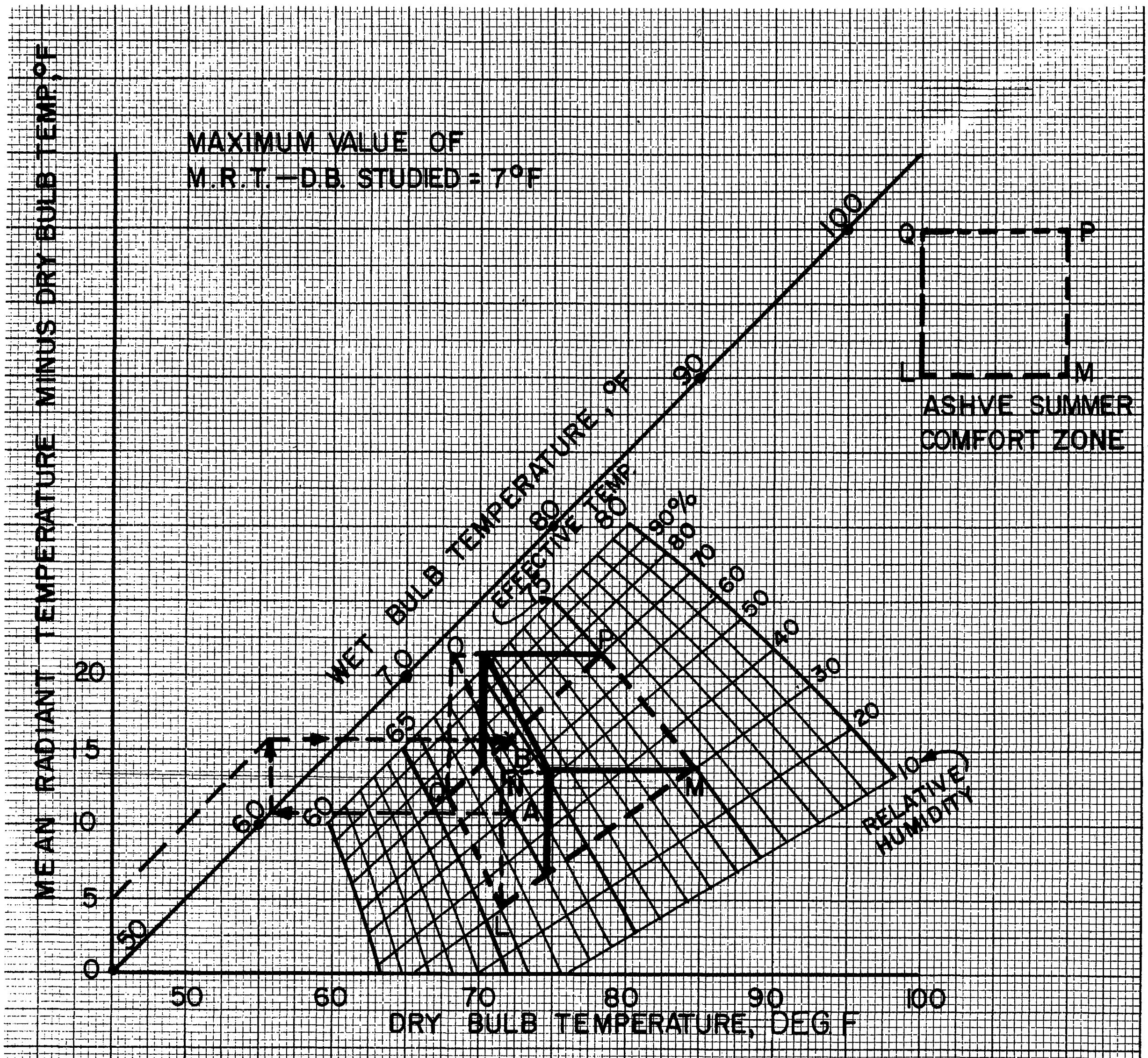


FIG. 22 - SCHEMATIC DIAGRAM SUMMARIZING THE EFFECT OF MEAN RADIANT TEMPERATURE ON SUMMER COMFORT

comfortable. Interesting speculations are possible as to the maximum depression or elevation of effective temperature which might be counteracted comfortably by means of radiant heating or cooling, respectively.

A speculation upon further application of the correlation of mean radiant, dry bulb, and wet bulb temperatures to human comfort is that of correlating the limits of human endurance to extremes of temperature and humidity. The authors make no attempt to explore this subject in this report, but merely suggest that the application of the method of correlation discussed above relative to comfort conditions might be extended to studies of human endurance in environments in which the factors of air temperature, humidity and radiant temperature are variables subject to measurement or control.

VII. LIMITATIONS OF RESULTS

The present program of investigations was designed primarily to evaluate the performance of the aluminum shade screens on the south side of the Cooley Laboratory, and to obtain comfort data from the personnel during the usual period of occupancy, 8:00 a.m. to 5:00 p.m. The data have been obtained by imposing the minimum of restrictions or inconveniences on the personnel. Thus, for example, the windows, the thermostat settings, etc., have been left entirely to the discretion of the personnel. These uncontrolled variables have made the correlations subject to random scatter of data.

The globe thermometer has certain limitations in that it does not take into account the direction of radiation, but indicates the overall amount of radiation, whereas the human being is sensitive to the distribution of radiation, as well as the rate of radiant heat transfer.

It should also be mentioned that no attempt was made to estimate a possible effect from the presence of screens on the windows of the areas surrounding the unshaded room. Such an effect might cause the data from the shaded room to be influenced by the heating of the unshaded room. Conversely, the presence of the warmer unshaded room adjacent to the shaded room would influence data taken in adjacent shaded rooms. Although the effect may be small, it should be noted that such an interaction existed and was beyond the control of the experimenters. The building functioned as an integrated whole, and the rooms studied were not truly isolated from their surroundings.

The data, as mentioned above, were scattered. The observers were not numerous nor were they selected or trained to evaluate comfort objectively. Since the subjects were performing their normal duties of office work, drafting, and electronics laboratory work, it was not possible to establish equilibrium between the subject and surroundings in all cases. Hence the correlations and conclusions are considered an attempt to utilize the data collected, but are not considered by the authors to be definitive. It is expected that a statistical study of extensive data would define a "comfort volume" not by rigid boundaries, but by bounds within which a given percentage of a cross section of subjects would experience a feeling of comfort.

VIII. CONCLUSIONS

A. The screen installation on the south side of the Cooley Laboratory, is helpful in increasing personnel comfort in the building. Typically the net incident radiation entering the shaded room is about one-fourth that entering the unshaded room. Further, the shades appreciably reduce the glare from the sky.

B. The screens reduce the radiation from the shaded room to the sky at night as compared to that from the unshaded room. This situation might be advantageous in the winter time, in that the heating load might be lower and the occupants of the building might feel warmer because of an increase in the temperature of the windows to which they are exposed.

C. The inside surface temperature of the double-walled glass panes are lower than those of the single panes. The possibility of installing the double-walled thermopanes in place of the single panes might be considered. The thermopane would be of advantage in the winter by reducing or perhaps eliminating condensation of moisture on the inside glass surfaces. Double panes would also reduce the winter heating load.

D. The maintenance of comfortable conditions in the building may become more difficult in the fall than in the summer because of the longer duration of direct solar radiation to the south side, because of the lower solar altitudes, and because of a relatively high outside temperature in early fall.

E. The mean radiant temperature is an important variable in human comfort. In the rooms studied in this investigation receiving considerable radiation and glare, 1°F. elevation of the mean radiant temperature over the dry bulb is approximately equivalent to 1° elevation of the effective temperature.

F. A study of solar azimuths and altitudes indicates that, of the direct solar radiation incident upon the building studied, most of the radiation is received by the south side of the building. A more detailed study of the solar azimuths and altitudes might be helpful in determining the optimum orientation of future buildings of similar nature.

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