# SUMMERTIME HEAT GAIN ANALYSES FOR A TEMPERATURE-CONTROLLED DAIRY CATTLE SHELTER

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## PREFACE

The experimental work described in this thesis was carried out under the Oklahoma Agricultural Experiment Station Project "Summer Temperature Control in Dairy Cattle Loafing Barns." One of the objectives set forth in the project outline is: "To obtain data indicating wherein temperature control in dairy cattle loafing barns can be achieved through: (a) low heat gain construction, (b) operation of ventilating equipment, (c) operation of cooling equipment." The study and analyses made in this thesis are in furtherance of this objective and deal with summertime heat gain through certain parts of an experimental, temperature-controlled livestock shelter; and with indoor temperature variations occurring in the shelter.

Helpful contributions to this study were made by Mr. Thomas Maher, who made temperature readings in the experimental shelter; Miss Ruth Reder, of the Agricultural Chemistry Department, who made available pyrheliometer data collected by that department; Mr. William Hardy, of the Flight School, who made available weather data collected by The Weather Service; and Mr. E. W. Schroeder, who was the writer's adviser for this thesis.

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# SUMMERTIME HEAT GAIN ANALYSES FOR A TEMPERATURE-CONTROLLED DAIRY CATTLE SHELTER

## I. INTRODUCTION

Studies by animal physiologists indicate that environmental temperatures approaching the body temperature of a dairy cow cause changes in her body regulatory mechanisms that result in depressed milk production, sluggish appetite, and other undesirable effects. For example, experiments[1] in the animal psychroenergetic laboratory at Columbia, Missouri indicate that the optimum environmental temperature for Jersey and Holstein cows is close to 50 degrees Fahrenheit; and that undesirable effects on the cows are much more pronounced when the temperature is raised above 50 F than when it is lowered below 50 F. These experiments also show that 80 F is a critical temperature for dairy cows; and that the cows had difficulty in adjusting themselves to higher temperatures.

The long pasture seasons and mild winters in Oklahoma compared to states in northern dairy areas are favorable for economical dairy production; but Oklahoma's long, hot summers are a handicap to dairymen who wish to maintain a high level of milk production during summer months. Five year records[2] of the U. S. Weather Bureau show that all of Central Oklahoma, or roughly one-half of the state, has at least 1,000 hours yearly when temperatures are above 85 F.

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[1] A. C. Ragsdale, et al, University of Missouri Research Bulletin 449 (September, 1949), p. 17.

[2] Anonymous, "Number of Hours Per Year of High Dry Bulb Temperatures," Heating and Ventilating, 36 (March, 1939), 35-38.

Evidently, possibilities exist for increasing the productivity of dairy cattle in Oklahoma by providing comfortable shelters for them during hot summer weather. Shades and open shelters can at best protect the cattle from hot sunshine only; and it is common experience that many open shelters have higher temperatures within the shelter than outdoors. Shelters which can keep indoor temperatures below the critical temperature of about 80 F need to be enclosed, insulated if necessary, and equipped for mechanical cooling.

The Oklahoma Agricultural Experiment Station has initiated a project entitled "Summer Temperature Control in Dairy Cattle Loafing Barns". Results from this project are expected to provide data on performance under summertime conditions of a mechanically cooled, enclosed shelter and an open front shelter for dairy cattle. These performance data are to include indoor temperature variations, heat gain through components of the mechanically cooled shelter, effectiveness of cooling and ventilating equipment, and other data. Such data need to be available to help farm building specialists estimate heat gain to hot weather shelters for livestock, select cooling equipment, and take other necessary measures to reduce heat gain.

## II. OBJECTIVES

The general aim of this study was to develop information that would be helpful in predicting indoor temperature variations and heat gain through certain components in a temperature-controlled dairy cattle shelter. Specific objectives were:

1. To obtain data that would show the probable pattern of indoor temperature variations throughout the day in a temperature-controlled dairy cattle shelter under summertime conditions.
2. To obtain summertime heat gain data for six kinds of west-facing masonry walls and analyze these data to determine:
    (1) Lag between time of maximum heat gain to outdoor surface and time of maximum heat gain from indoor surface to indoor air.
    (2) Decrement in heat gain from indoor surface to indoor air caused by thermal capacity and other effects in the masonry walls.
    (3) A simple method for estimating heat gain through masonry walls under summertime conditions.
3. To obtain data on summertime attic space temperatures above a temperature-controlled shelter; and analyze these data to arrive at a method for predicting attic temperatures under summertime conditions.

## III. REVIEW OF LITERATURE

The 1948 Guide[1] presents a method for estimating instantaneous heat gain through a wall of given construction and orientation. This method requires that data be at hand on heat gain decrement and time lag for materials in the wall; and is based on the expression:

$$(q/A)_i = U(t_m - t_i) + \lambda U(t_e^* - t_m),$$

where:

$(q/A)_i$ = Instantaneous rate of heat gain to indoor air, btu per hr.-sq. ft.

$U$ = Overall air-to-air heat transfer coefficient for the wall, btu per hr.-Fahrenheit degree-sq. ft.

$t_m$ = 24 hr. average sol-air temperature, Fahrenheit degrees.

$t_i$ = Constant temperature of indoor air, Fahrenheit degrees.

$\lambda$ = Heat gain decrement factor, dimensionless.

$t_e^*$ = Sol-air temperature, degrees Fahrenheit, at a time earlier than the instant for which heat gain is being computed by the amount of time lag for the material in the wall or roof.

A simplified procedure is suggested for computing summertime heat gain by the equation:

$$(q/A)_i = U(t_p - t_i),$$

where:

$$t_p = t_m + \lambda(t_e^* - t_m).$$

It is suggested that design tables will be available in due time to list values of $t_p$.

In these expressions, values of $U$, $t_m$, $\lambda$, and $t_e$ are experimentally determined or estimated on the basis of experimental data for comparable

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[1] Guide Publication Committee, Heating Ventilating Air Conditioning Guide 1948, pp. 269-274.

walls or roofs. Values are listed for a few materials such as stone, solid concrete, brick, wood, and insulating board. No values are given for hollow masonry units of concrete or clay tile. The sol-air temperature, $t_e$, is a computed air temperature which, in the absence of solar and sky radiation would give a rate of heat entry into the outdoor surface of the wall equal to the rate that actually occurs under existing conditions of solar and sky radiation and outdoor air temperature. Sol-air temperature is defined by the expression:

$$t_e = (b/f_o)I_t + t_o,$$

where:

$t_e$ = Sol-air temperature, degrees Fahrenheit.

b = Absorptivity of the surface for solar and sky radiation, dimensionless.

$f_o$ = Outdoor wall surface film conductance, btu per hr.-sq. ft.-deg. F temperature difference.

$t_o$ = Outdoor dry-bulb temperature, deg. F.

Mackey and Wright[2] have developed an instrument which they have named the sol-air thermometer. It consists of an 8 inch cube of cork covered with several layers of aluminum foil alternated with 1/4 inch air spaces so that each face of the assembly is well insulated from other faces. A thin slice of the material for which sol-air temperatures are to be measured is cemented to the center of each face. When the sol-air thermometer is exposed to solar and sky radiation, temperatures of the slices of material will give a close approximation to the actual sol-air temperature for that material and the orientation corresponding to the

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[2] C. O. Mackey and L. T. Wright, Jr., "The Sol-Air Thermometer - A New Instrument," Transactions American Society of Heating and Ventilating Engineers, 52:271-280, June, 1946.

particular face of the thermometer.

Measurement of heat transfer through walls or roofs of buildings in service calls for determination of temperatures on the wall or roof surfaces, or at points within the material. This is usually done by means of thermocouple junctions affixed to the surfaces or buried in the material at the spot where temperature data are desired. Kelley[3] recommends that the wires from which the junctions are formed be of as small diameter as is feasible. He suggests that, when measuring surface temperatures, the junction be slightly embedded in the wall by first grooving it to a depth of one-half the wire diameter, then taping the junction into the groove.

A heat meter, which apparently operates on the principle of the Nicholls heat flow meter, has been developed by Gier and Dunkle[4]. It employs a set of thermopiles on either side of a thin bakelite wafer. When the wafer is in contact with a wall through which heat is being transmitted, a temperature differential occurs across the wafer and is measured by the thermopiles in combination with a potentiometer or millivoltmeter.

Heat gain from attic spaces to a temperature-controlled shelter could be a major part of the cooling load for the shelter. It is common experience that temperatures in poorly ventilated attics become uncom-

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[3] C. F. Kelley, T. E. Bond, and C. Lorenzen, Jr., "Instrumentation For Animal Shelter Research," Agricultural Engineering, 30:297-300, 302, 304, June, 1949.

[4] Anonymous, "New Heat Meter Has Many Applications In Refrigeration Industry," Ice and Refrigeration, (October, 1948), pp. 23-24, 66.

fortably high during the heat of the day. Goodman[5] states that attic temperatures under summertime conditions can be kept down to approximately 20 Fahrenheit degrees above outdoor temperatures if the attic is well ventilated. Simons and Lanham[6] found that attic ventilation with small louvers of less than 2 sq. ft. have negligible effect on temperatures in rooms below.

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[5] William Goodman, "Figuring Solar Heat Gains of Buildings," _Heating, Piping, and Air Conditioning_, 10 (June, 1938), p. 394.

[6] Joseph W. Simons and Frank B. Lanham, _Factors Affecting Temperatures In Southern Farmhouses_, p. 75.

# IV. EXPERIMENTAL EQUIPMENT AND PROCEDURES

## Temperature-Controlled Shelter

The temperature-controlled shelter used for this study was built during the spring and early summer of 1950 for the Oklahoma Agricultural Experiment Station project "Summer Temperature Control in Dairy Cattle Loafing Barns." It is a single story, gable-roof building 26 ft. by 50 ft. The shelter is located on high ground approximately 1/4 mile south of the New Dairy Center west of the A. and M. College campus. The site is unshaded and well exposed to prevailing southerly winds.

The shelter is depicted in Fig. 1 and shown in plan, Fig. 2, and cross-section, Fig. 3. The first story walls were built with 8 by 8 by 16 in. hollow masonry units manufactured from portland cement and a lightweight aggregate obtained from expanded shale. The cores of the units were filled one course at a time during wall construction with the shale aggregate poured into the cores of the units after they had been placed in the wall. The aggregate was rodded to obtain thorough filling of the cores. Exceptions to this type of wall construction were 18 special wall panels which were incorporated into the west and south walls. These special panels in the west wall are shown and dimensioned in Figs. 4 and 5. Panels numbered (7), (8), and (9), Fig. 4, were built with pumice aggregate block, sand and gravel aggregate block, and expanded shale aggregate block, respectively. The cores in this upper set of panels were not filled. Panels numbered (10), (11), and (12), Fig. 4, were built with pumice aggregate block, sand and gravel aggregate block, and expanded shale aggregate block, respectively. The cores of the block in panels (10) and (11) were filled one course at a time with pumice aggregate. The cores of the block in panel (12) were similarly filled with

Fig. 1 - South and East Sides of Experimental Temperature-Controlled Shelter For Dairy Cattle.

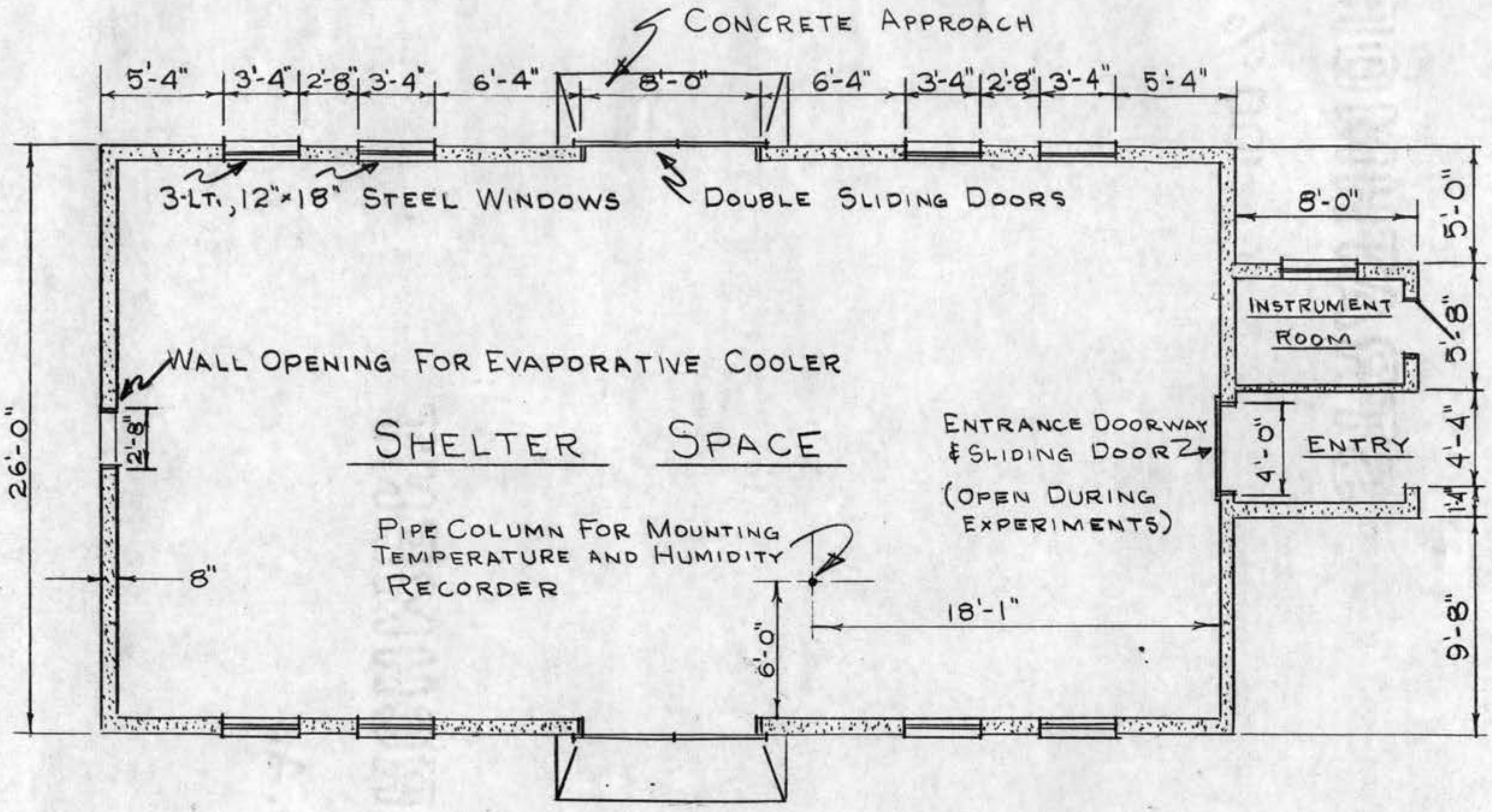

FIG. 2 - FLOOR PLAN OF TEMPERATURE-CONTROLLED SHELTER FOR DAIRY CATTLE

Scale: $\frac{1}{8}$" = 1'-0"

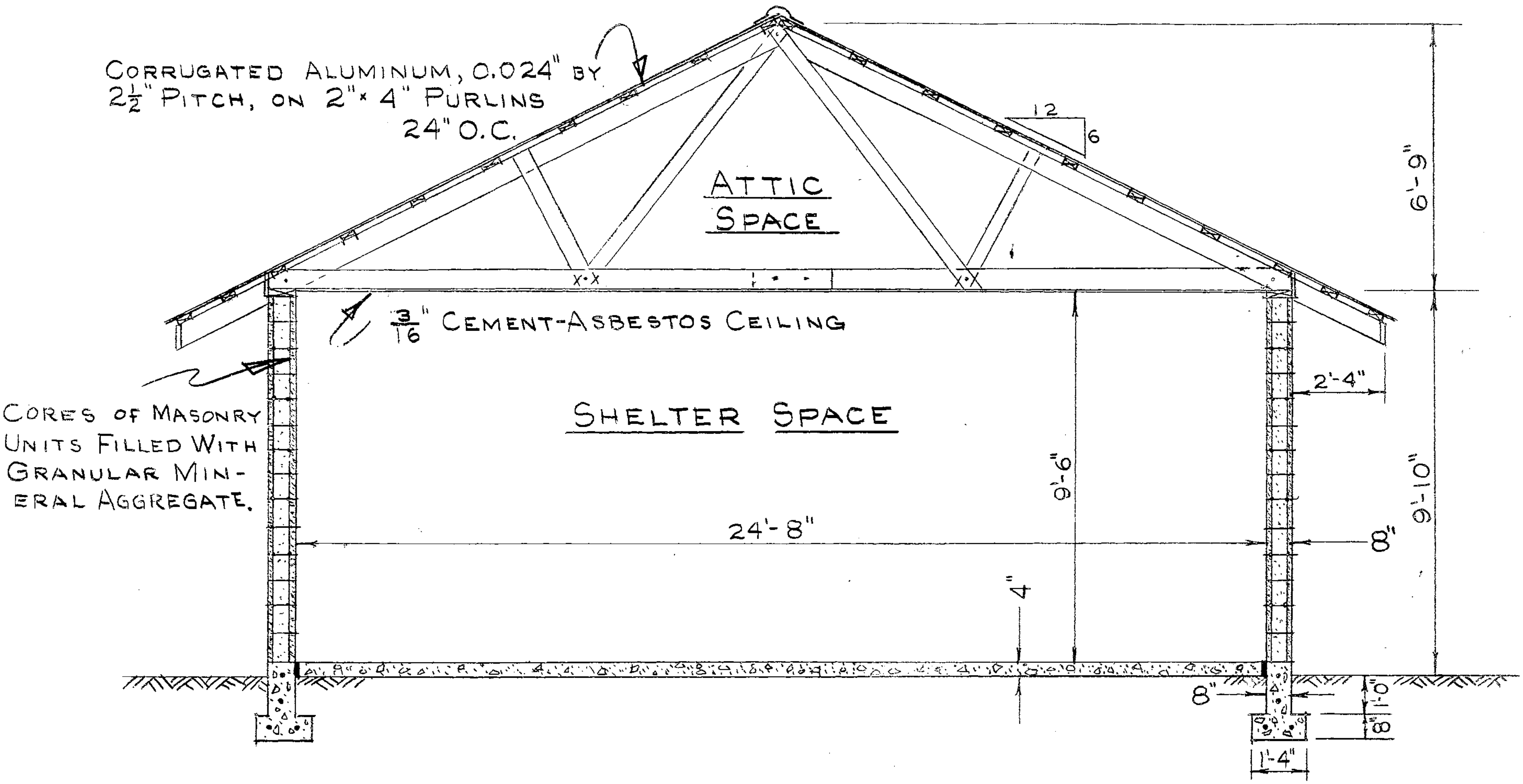

FIG. 3 – TYPICAL CROSS-SECTION OF TEMPERATURE CONTROLLED SHELTER FOR DAIRY CATTLE
Scale: $\frac{1}{4}$" = 1'-0"

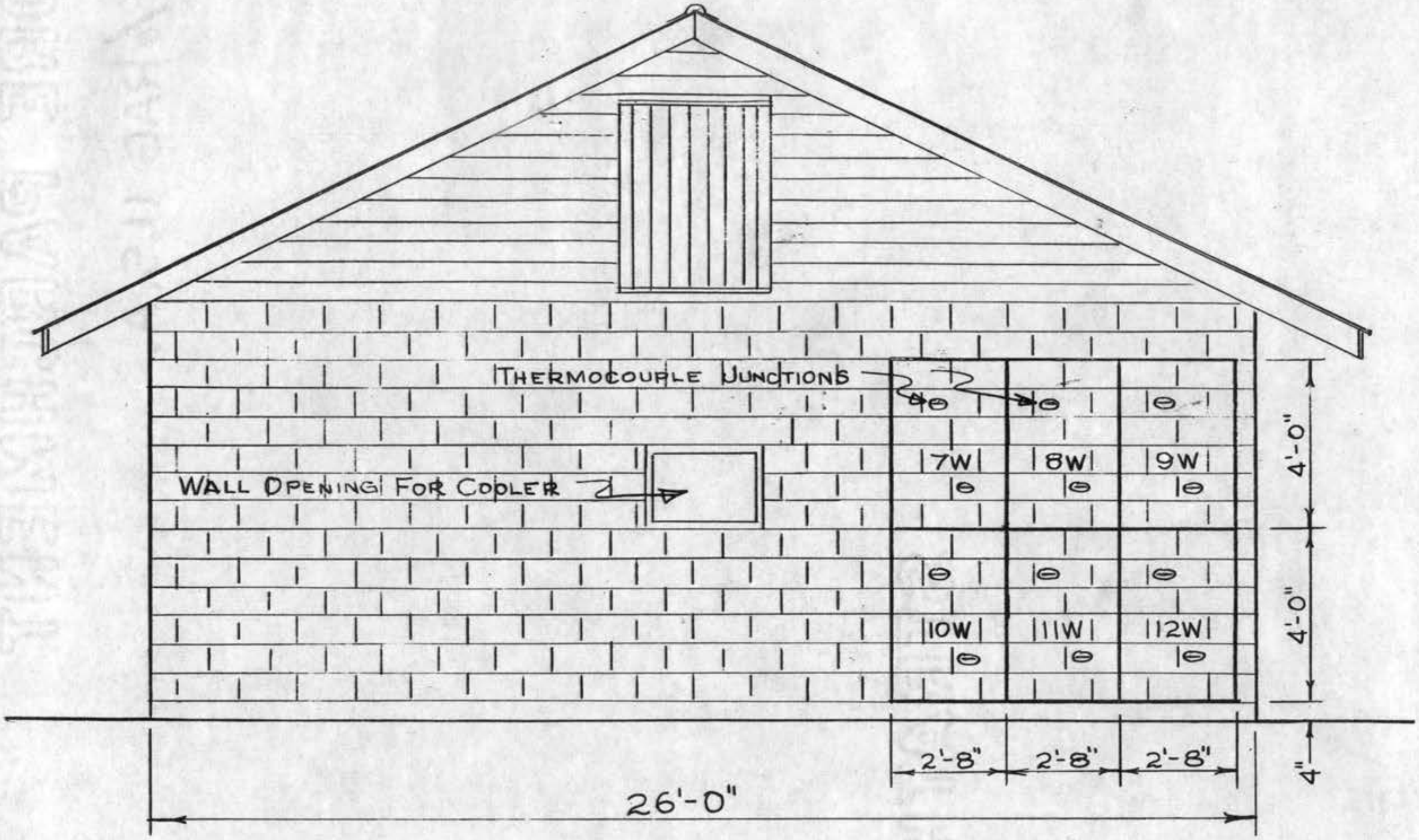

FIG. 4 - WEST END ELEVATION OF TEMPERATURE-CONTROLLED SHELTER FOR DAIRY CATTLE

Scale: $\frac{1}{4}$" = 1'-0"

Fig. 5 - West Wall of Temperature-Controlled Shelter With Thermocouple Junctions Installed.

expanded shale aggregate. The other special wall panels were not used in this study, and therefore will not be described.

Certain physical properties of the three kinds of masonry units used in the walls and special panels are listed in Table I. The bulk density of the aggregates and the weights of the block were determined after the materials had been held in dry, covered storage for more than 30 days. The bulk density was determined by the rodding method. The weights of the units with cores filled were obtained by weighing each unit after each of its cores had been filled, rodded ten times, and struck off to remove surplus aggregate. The samples used in these weighings were random selections from stockpiles at the building site. Kluge, Sparks, and Tuma[1] have measured the thermal conductivity of several kinds of lightweight aggregate concrete by the guarded hot-plate method. The average thermal conductivities in btu per hr.-sq. ft.-degree Fahrenheit temperature difference-in. of thickness were 2.02 for pumice aggregate concrete, 3.83 for expanded shale aggregate concrete, and 7.62 for sand and gravel aggregate concrete. These data were obtained for concrete of plastic consistency when mixed, and therefore may not represent the conductivities of "dry" concrete such as is used in mokding concrete block. However, the values of these conductivities relative to each other are probably representative of either plastic or "dry" mixed concrete.

The shapes of the three kinds of block used in the wall panels are shown in Figs. 6, 7, and 8. The relative textures and shades of the block are illustrated in Fig. 9.

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[1] Ralph W. Kluge, Morris M. Sparks, and Edward C. Tuma, "Lightweight Aggregate Concrete," Journal of the American Concrete Institute, 20, (May, 1949), p. 633.

## TABLE I

### WEIGHTS AND CORE VOLUMES FOR MASONRY UNITS IN WALLS OF TEMPERATURE CONTROLLED SHELTER

| Kind of Concrete In Unit | Specimen Number | Kind of Core Filling | Weight of Unit, Lb. | | Weight of Core Filling, Lb. | Core* Volume, Cu.Ft. |
|---|---|---|---|---|---|---|
| | | | Cores Empty | Cores Filled | | |
| Sand and Gravel | 1 | Pumice Agg. | 42.5 | 49.1 | 6.6 | 0.167 |
| " | 2 | " | 42.4 | 48.5 | 6.1 | 0.154 |
| " | 3 | " | 42.5 | 49.6 | 7.1 | 0.180 |
| " | Ave.of 1,2,3 | " | 42.8 | 49.1 | 6.6 | 0.167 |
| Pumice | 1 | Pumice Agg. | 24.6 | 33.0 | 8.4 | 0.213 |
| " | 2 | " | 22.6 | 31.3 | 8.7 | 0.220 |
| " | 3 | " | 26.1 | 34.8 | 8.7 | 0.220 |
| " | Ave.of 1,2,3 | " | 24.4 | 33.0 | 8.6 | 0.218 |
| Expanded Shale | 1 | Expanded Shale Agg. | 26.1 | 38.2 | 12.1 | 0.202 |
| " | 2 | " | 27.5 | 39.3 | 11.8 | 0.198 |
| " | 3 | " | 25.6 | 38.3 | 12.7 | 0.212 |
| " | Ave.of 1,2,3 | " | 26.4 | 38.6 | 12.2 | 0.204 |

* Core volumes were computed from the observed weight of the core filling and a bulk density of 59.8 lb. per cu. ft. for expanded shale aggregate and 39.5 lb. per cu. ft. for pumice aggregate.

The double sliding doors on the South and North walls of the shelter were built with two thicknesses of 1 inch matched lumber between which was sandwiched a 25/32 inch sheet of rigid insulation board.

The roof was framed with trussed rafters and covered with 0.024 in. gage by 2 1/2 in. pitch corrugated aluminum roofing on 2 by 4 inch purlins spaced 24 inches on centers. Ceiling material consisted of 3/16 in. cement asbestos board applied to 1 by 3 1/2 in. nailing strips on the under side of the ceiling joists.

Gable end openings for ventilation of the attic space included a screened and louvered opening with a net free opening area of approximately 11 1/2 sq. ft. in the east gable end and an attic access door with a free opening area of approximately 7 1/2 sq. ft. in the west gable end. The louver and access door remained open at all times during the period covered by this study.

The shelter space was cooled by an 8,000 cfm evaporative type cooler mounted at the west end of the shelter as shown in Fig. 5. The wall opening through which the cooler discharged was equipped with a set of adjustable fins to provide uniform distribution of cool air throughout the shelter space. Air was exhausted from the shelter through the entrance door at the east end of the building.

### Instrumentation

Dry bulb temperatures within the shelter were measured with a dry bulb temperature and relative humidity circular chart recorder manufactured by the Brown Instrument Company. It provided a continuous trace of dry bulb temperature on a 7 1/2 inch diameter chart graduated from 0 to 100 F at 2 degree intervals. The instrument was mounted in the location shown in the floor plan, Fig. 2, on a pipe column approximately

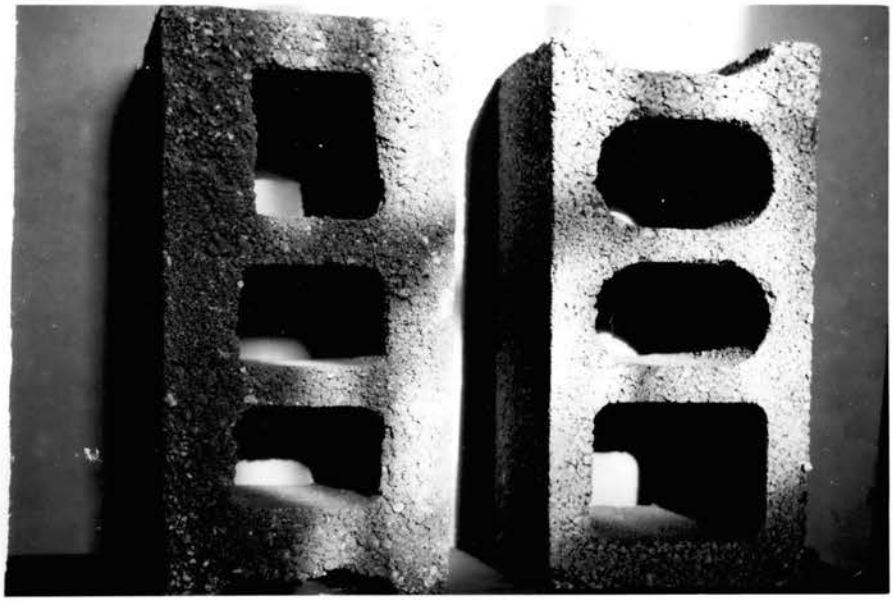

Fig. 6 - Opposite Core Ends of Pumice Aggregate Concrete Used in Walls of Temperature - Controlled Shelter.

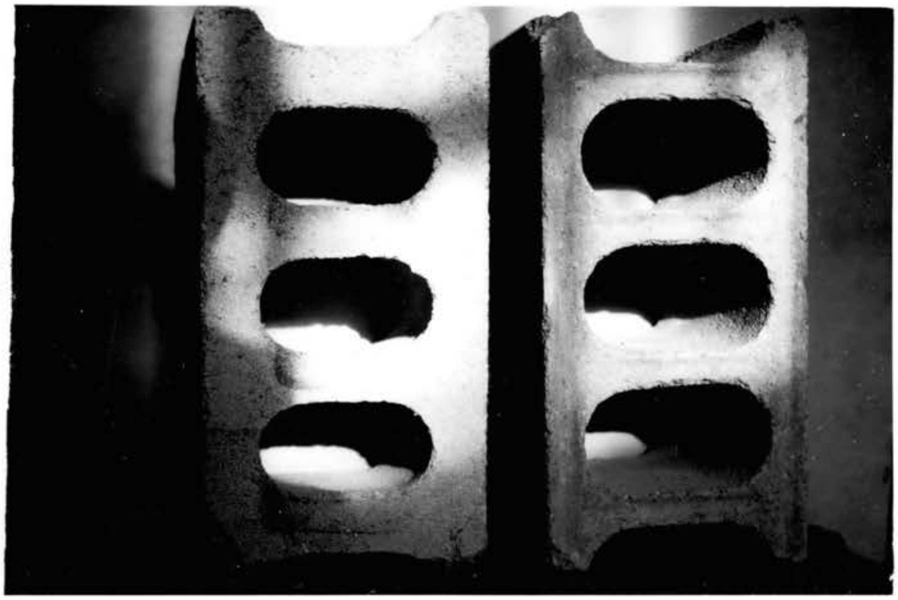

Fig. 7 - Opposite Core Ends of Sand and Gravel Aggregate Concrete Block Used in Walls of Temperature-Controlled Shelter.

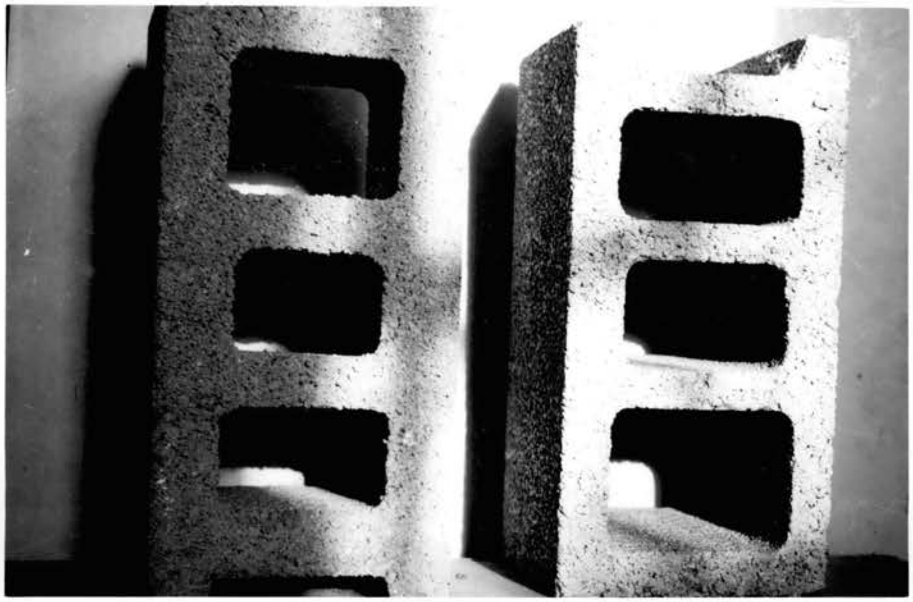

Fig. 8 - Opposite Core Ends of Expanded Shale Aggregate Concrete Block Used in Temperature Controlled Shelter.

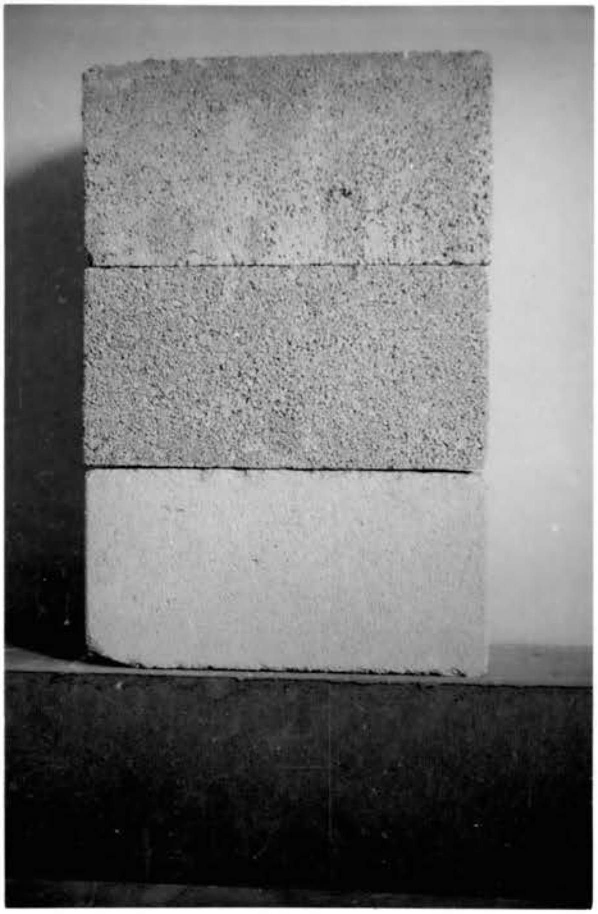

Fig. 9 - Comparative Surface Textures and Shades of Pumice Aggregate Concrete Block, Top, Expanded Shale Aggregate Concrete Block, Middle, and Sand and Gravel Aggregate Concrete Block, Bottom.

3 ft. above the floor. The instrument was protected from damage by the cattle by a steel cage as shown in Fig. 10 which could be swung open for access to the instrument. Calibration of the instrument was checked daily against a Bendix-Friez hand aspirated psychrometer. The temperature obtained with this recorder apparently provided a true indication of temperatures throughout the shelter. Temperatures measured during several explorations of the shelter space with a mercury thermometer showed no appreciable or consistent differences from those on the dry bulb temperature trace of the recorder.

Temperatures on outdoor and indoor wall surfaces were measured with 20 gauge iron-constantan thermocouple junctions and an electronically-balanced potentiometer manufactured by the Brown Instrument Company. This potentiometer is equipped with a switching panel which permits as many as 48 separate thermocouple circuits to be brought into the potentiometer. Temperatures are read on a circular chart with a full scale graduation of 300 F by one-half degree intervals.

Thermocouple junctions were made by twisting and soldering together approximately 1 1/2 inches of iron and constantan wire ends. The circuit to the potentiometer was completed with continuations of the iron and constantan wires. The junctions were installed in the wall surfaces in shallow grooves chiselled in the masonry block. These grooves had a depth equal to the thickness of the junctions and a length of approximately two inches. Each junction and one-half inch of the lead wires to the instrument were placed in the groove and covered with mortar. The mortar was then struck off so that the junction remained embedded in the groove covered with a thin "skin" of mortar as shown in Fig. 11. Two junctions in the outdoor surface and two in the indoor surface were in-

Fig. 10 - Dry Bulb Temperature and Relative Humidity Recorder Used in Temperature Controlled Shelter.

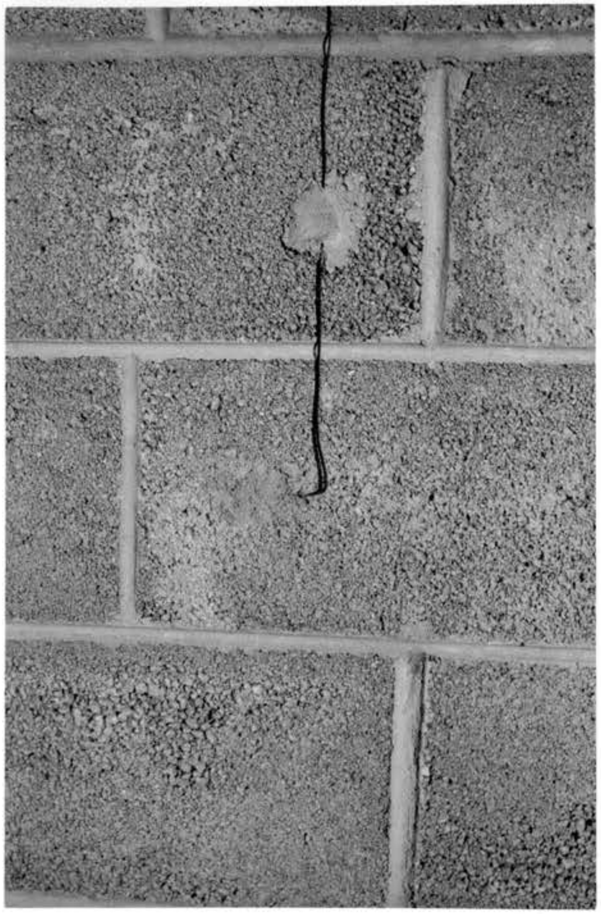

Fig. 11 - Thermocouple Junction Installation in Surface of Concrete Masonry Wall.

stalled in each panel at the points marked in Fig. 4. Surface temperature readings were taken half-hourly from 10:00 a.m. to 12:00 noon, and from 1:00 p.m. to 6:00 p.m.

Attic temperatures were measured by a thermocouple junction prepared in the same manner as described for surface temperature junctions. The junction was installed 16 ft. from the East end of the attic and 5 ft. 8 in. south of the attic center by securing the lead wires to a trussed rafter diagonal so that the junction was suspended in the attic air midway between the roof sheets and attic floor. Attic temperatures were observed at half-hourly intervals from 10:00 a.m. to 12:00 noon and 1:00 p.m. to 6:00 p.m. Temperatures obtained with the attic thermocouple junctions were checked frequently throughout the attic space with a mercury thermometer.

Outdoor dry bulb temperatures were obtained from the trace of a recording dry bulb thermometer maintained by the college Meteorology Department. The instrument was mounted in a standard Weather Bureau instrument shelter on the roof of the Meteorology Department Weather Office located on the A. and M. campus.

Instantaneous solar and sky radiation intensities were obtained from the trace of a recording pyrheliometer maintained by the A. and M. College Agricultural Chemistry Department. The recording pyrheliometer included an Eppley horizontal disc sensing element and a Leeds and Northrup recording potentiometer. The sensing element was mounted on the roof of the Dairy Building on the college campus. The completed installation had been inspected and approved as suitable for obtaining U. S. Weather Bureau records by a representative of the U. S. Weather Bureau. The instrument was calibrated for charts recording radiation intensity in gram-calories per sq. cm.-minute. Charted values were converted to btu per sq. ft.-hr. by the multiplication factor 221.21.

Wind velocities were obtained from records of the campus Meteorology Department. These records gave the wind velocity at 5:00 p.m. daily measured 30 ft. above ground at the Meteorology Department Weather Office on the campus.

## V. PRESENTATION AND ANALYSIS OF DATA

The data presented in the following pages are from temperature observations and records for Aug. 8, Aug. 9, Aug. 19, Aug. 24, Aug. 25, Aug. 26, and Sept. 1. These seven days were selected because throughout each of them, the pyrheliometer traces were not seriously broken due to cloudiness. Cloudiness causes extreme fluctuations in the pyrheliometer trace which makes analysis of the data very difficult.

All temperatures shown in the data that follows are on the Fahrenheit scale; and this specification will be omitted in continuous references to temperature data in order to avoid needless repetition.

### Shelter Temperature Variations

The indoor dry bulb temperatures for each of the seven days are listed in Table II and plotted in Fig. 12. The average of indoor temperatures is plotted in Fig. 13. These show that indoor temperatures rose steadily throughout the morning, but, in general, did not reach the control temperature of 80 F until the afternoon, between 1:00 p.m. and 2:00 p.m. Afterwards, the average temperature remained at 80 F, but with daily variations of as much as 4 degrees higher.

Outdoor dry bulb temperatures for each of the seven days are listed in Table III and plotted in Fig. 15. The averages of these temperatures are plotted in Fig. 13. It is shown that the maximum outdoor temperature on any of the seven days was 97 F, which is probably not representative of hottest Oklahoma summer weather.

The differences of the outdoor and indoor temperature are plotted in Fig. 14. The maximum difference of about 11 degrees occured between 12:00 noon and 4:00 p.m.

## TABLE II

## OUTDOOR DRY BULB TEMPERATURES, DEGREES FAHRENHEIT
## STILLWATER, OKLAHOMA. 1950

| CST | Aug. 8 | Aug. 9 | Aug.19 | Aug.24 | Aug.25 | Aug.26 | Sept.1 |
|---|---|---|---|---|---|---|---|
| 8:00 a.m. | 84.0 | 80.0 | 75.5 | 76.0 | 85.5 | 85.0 | 76.0 |
| 8:30 | 85.0 | 81.0 | 78.0 | 78.0 | 86.0 | 86.5 | 78.0 |
| 9:00 | 86.0 | 82.0 | 78.5 | 80.0 | 87.5 | 87.5 | 79.0 |
| 9:30 | 86.5 | 83.0 | 80.0 | 81.0 | 88.0 | 89.0 | 79.5 |
| 10:00 | 87.0 | 84.0 | 81.5 | 82.5 | 89.0 | 90.5 | 81.0 |
| 10:30 | 88.5 | 86.0 | 82.5 | 84.5 | 89.5 | 91.5 | 82.0 |
| 11:00 | 89.0 | 86.5 | 83.5 | 85.5 | 90.0 | 93.0 | 83.0 |
| 11:30 | 89.5 | 87.0 | 84.0 | 86.5 | 91.5 | 93.5 | 84.0 |
| 12:00 | 90.0 | 87.5 | 85.0 | 88.5 | 92.0 | 95.0 | 85.0 |
| 12:30 p.m. | 90.2 | 88.0 | 86.0 | 89.5 | 92.5 | 95.0 | 85.5 |
| 1:00 | 90.5 | 88.5 | 86.0 | 92.0 | 93.5 | 96.0 | 86.0 |
| 1:30 | 90.5 | 88.5 | 87.0 | 92.5 | 94.0 | 96.0 | 86.5 |
| 2:00 | 90.5 | 88.5 | 87.0 | 94.0 | 94.5 | 97.0 | 86.5 |
| 2:30 | 90.5 | 88.5 | 87.5 | 94.0 | 94.5 | 97.0 | 86.5 |
| 3:00 | 90.7 | 88.5 | 88.0 | 94.0 | 96.0 | 97.0 | 86.5 |
| 3:30 | 90.5 | 88.5 | 88.0 | 94.0 | 96.5 | 96.0 | 86.5 |
| 4:00 | 90.3 | 88.0 | 87.5 | 93.5 | 97.0 | 96.0 | 86.0 |
| 4:30 | 89.5 | 87.8 | 86.5 | 93.5 | 96.0 | 96.0 | 86.0 |
| 5:00 | 89.0 | 87.0 | 86.0 | 93.0 | 94.5 | 95.5 | 85.0 |
| 5:30 | 87.5 | 86.5 | 85.0 | 92.5 | 93.0 | 95.0 | 82.0 |
| 6:00 | 86.0 | 84.0 | 83.0 | 90.5 | 90.5 | 92.5 | 79.0 |
| 6:30 | 83.0 | 82.5 | 80.0 | 88.5 | 89.0 | 89.5 | 77.0 |
| 7:00 | 81.0 | 81.0 | 77.0 | 88.0 | 87.0 | 88.5 | 76.0 |
| 7:30 | 80.0 | —— | —— | —— | —— | —— | —— |
| 8:00 | 79.5 | —— | —— | —— | —— | —— | —— |
| 8:30 | 79.0 | —— | —— | —— | —— | —— | —— |
| 9:00 | 78.0 | —— | —— | —— | —— | —— | —— |
| 9:30 | 77.5 | —— | —— | —— | —— | —— | —— |
| 10:00 | 76.5 | —— | —— | —— | —— | —— | —— |

## TABLE III

## TEMPERATURE CONTROLLED SHELTER INDOOR TEMPERATURES

## DEGREES FAHRENHEIT. 1950

| CST | Aug. 8 | Aug. 9 | Aug.19 | Aug.24 | Aug.25 | Aug.26 | Sept.1 |
|---|---|---|---|---|---|---|---|
| 8:00 a.m. | 80.0 | 74.5 | 63.0 | 72.5 | 76.5 | 77.5 | 66.0 |
| 8:30 | 79.0 | 75.0 | 65.5 | 73.5 | 77.0 | 78.0 | 67.0 |
| 9:00 | 80.0 | 76.5 | 68.0 | 74.0 | 78.0 | 76.5 | 68.5 |
| 9:30 | 78.0 | 77.5 | 70.5 | 75.0 | 77.0 | 76.5 | 69.5 |
| 10:00 | 78.0 | 78.5 | 71.0 | 76.0 | 76.0 | 77.0 | 71.0 |
| 10:30 | 78.5 | 79.0 | 72.5 | 77.0 | 76.5 | 78.0 | 72.0 |
| 11:00 | 79.0 | 79.5 | 73.5 | 78.0 | 78.0 | 78.0 | 73.5 |
| 11:30 | 79.5 | 80.0 | 76.0 | 79.0 | 78.0 | 78.5 | 74.5 |
| 12:00 | 80.0 | 76.5 | 76.0 | 79.0 | 79.0 | 79.0 | 76.0 |
| 12:30 p.m. | 80.0 | 76.5 | 77.0 | 79.5 | 80.0 | 80.0 | 77.0 |
| 1:00 | 80.0 | 77.5 | 78.5 | 80.0 | 80.5 | 80.0 | 78.0 |
| 1:30 | 80.5 | 77.0 | 79.5 | 80.5 | 81.5 | 81.0 | 79.0 |
| 2:00 | 81.0 | 77.5 | 80.0 | 81.0 | 82.0 | 82.0 | 77.0 |
| 2:30 | 80.5 | 76.5 | 78.0 | 82.0 | 82.0 | 82.0 | 76.0 |
| 3:00 | 80.5 | 78.0 | 77.0 | 82.0 | 82.5 | 82.5 | 79.0 |
| 3:30 | 81.0 | 77.5 | 75.0 | 82.0 | 84.0 | 84.0 | 79.0 |
| 4:00 | 80.0 | 77.5 | 75.0 | 82.0 | 83.0 | 83.0 | 77.0 |
| 4:30 | 80.5 | 77.0 | 75.0 | 83.0 | 83.0 | 83.0 | 75.0 |
| 5:00 | 81.5 | 80.5 | 78.5 | 83.0 | 83.0 | 83.0 | 75.0 |
| 5:30 | 82.0 | 80.5 | 75.0 | 83.0 | 82.5 | 82.5 | 74.5 |
| 6:00 | 82.0 | 80.0 | 74.0 | 82.0 | 83.0 | 83.0 | 74.5 |
| 6:30 | 82.0 | —— | —— | —— | —— | —— | —— |
| 7:00 | 79.5 | —— | —— | —— | —— | —— | —— |
| 7:30 | 78.0 | —— | —— | —— | —— | —— | —— |
| 8:00 | 79.0 | —— | —— | —— | —— | —— | —— |
| 8:30 | 77.5 | —— | —— | —— | —— | —— | —— |
| 9:00 | 77.0 | —— | —— | —— | —— | —— | —— |
| 9:30 | 76.0 | —— | —— | —— | —— | —— | —— |
| 10:00 | 76.0 | —— | —— | —— | —— | —— | —— |

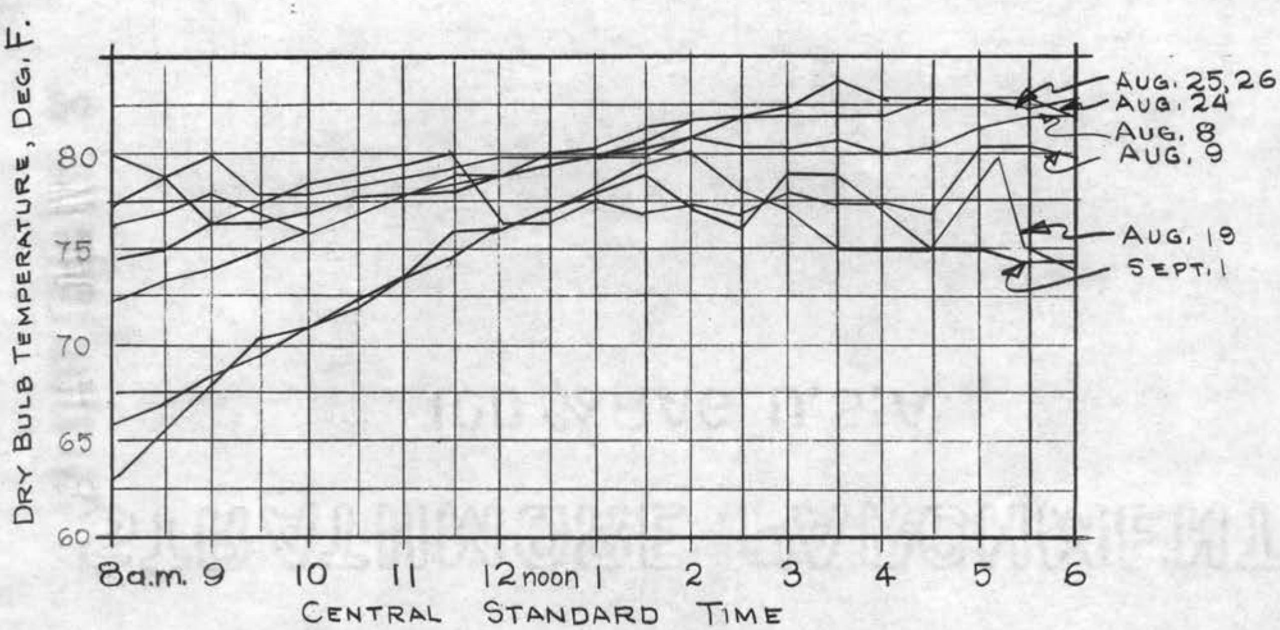

Fig. 12 - Dry Bulb Temperatures In Temperature-Controlled Dairy Cattle Shelter, 1950.

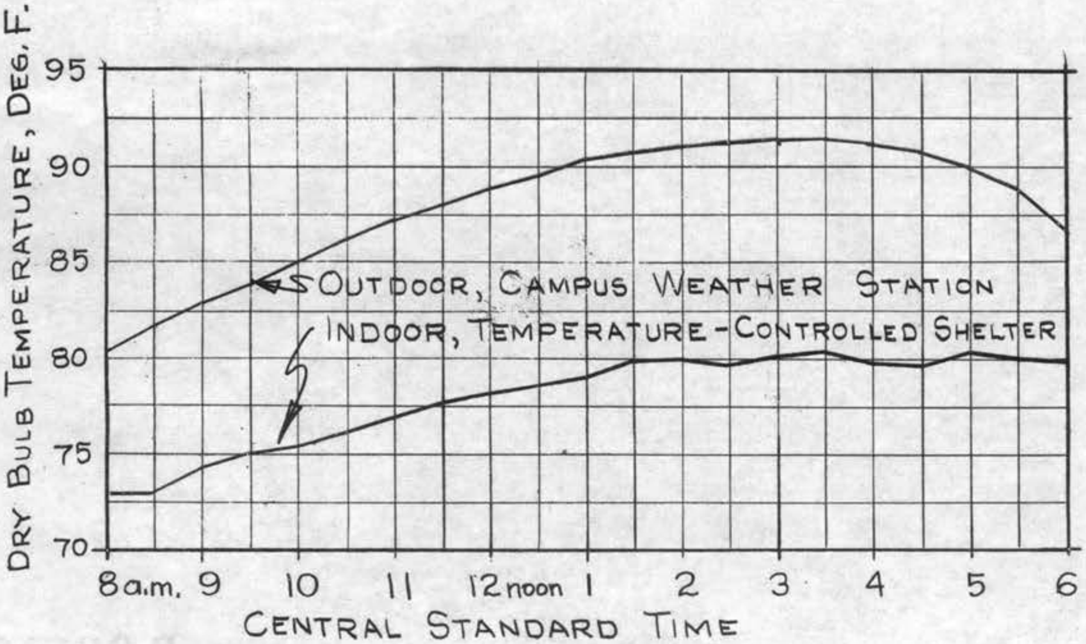

Fig. 13 - Average Temperatures For Seven Selected Days, Stillwater, Summer, 1950.

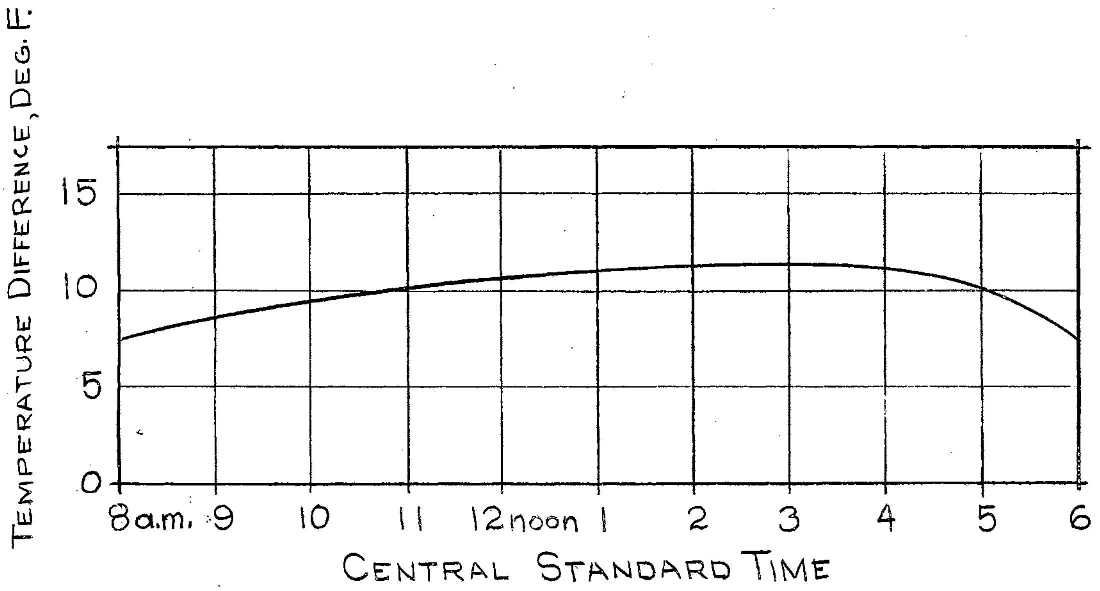

Fig. 14 - Average Outdoor-Indoor Temperature Difference, Deg. F. D.B., Temperature-Controlled Shelter, Seven Selected Days, Summer, 1950.

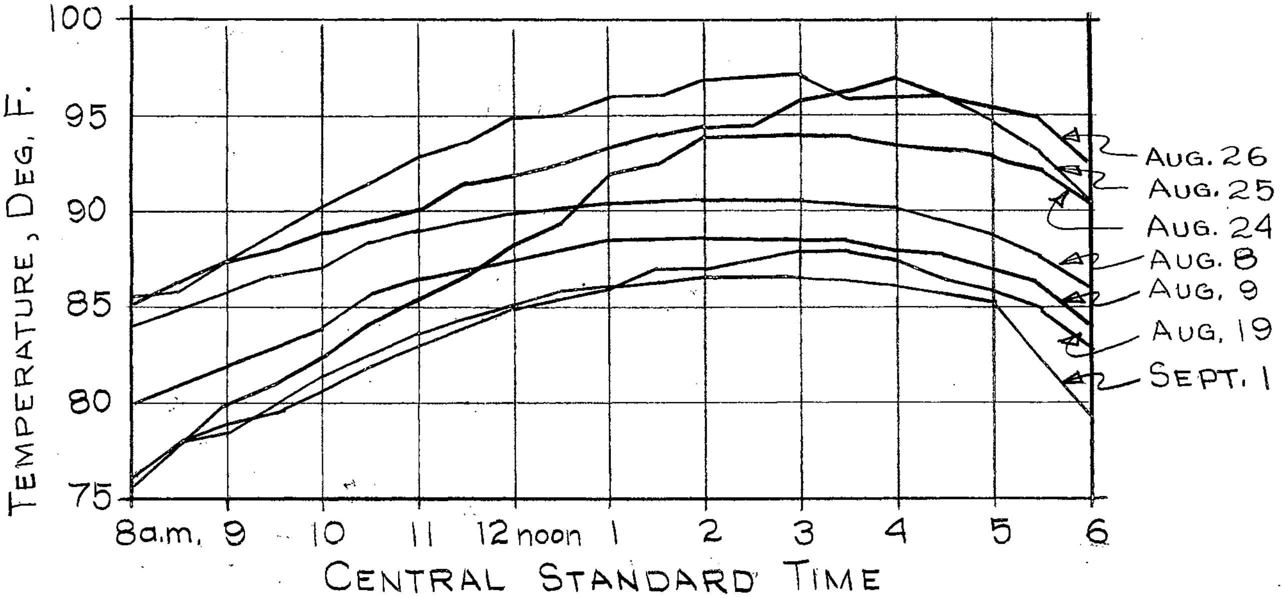

Fig. 15 - Outdoor Dry-Bulb Temperatures Stillwater, 1950

These data indicate that the cooling equipment and shelter construction are adequate to maintain indoor temperatures of 80 F during a comparatively cool summer. If indoor temperatures as high as 85 F could not be tolerated for brief periods during hot days when outdoor temperatures would be above 100 F, the ceiling could be insulated to obtain considerable reduction in cooling load. Heat gain estimates on a comparable structure have shown that about one-half of the heat gain through the structure occurs through the ceiling.

## Heat Gain Through West Wall Panels

Instantaneous heat gain to the outdoor surface of each of the six west-facing panels was computed at half-hourly intervals from 10:00 a.m. to 12:00 noon and 1:00 p.m. to 6:00 p.m. by the expression:

$$q/A_L = f_o(t_e - t_L),$$

where:

$q/A_L$ = Instantaneous rate of heat gain to outdoor surface of wall, btu per sq.ft.-hr.

$f_o$ = Coefficient of conductive heat transfer for air film at outdoor wall surface, btu per hr.-deg. F-sq.ft.

$t_e$ = Sol-air temperature.

$t_L$ = Outdoor wall surface temperature.

Values for $t_L$ were obtained by direct observation at half-hour intervals of temperatures at the thermocouple junctions embedded in the outdoor panel surfaces. The temperatures used in computing $q/A_L$ were the arithmetic average of the observed temperatures at each of the two junctions in the outdoor surface of each panel.

A value for $f_o$ was selected on the basis of experimental data published in the 1948 Heating, Ventilating, Air Conditioning Guide. These data list a value of $f_o = 3.5$ for concrete and an air velocity of 5 m.p.h.; and $f_o = 5.2$ for an air velocity of 10 m.p.h. No measurements were made of air velocities at the west wall. Wind velocities observed at the campus weather station at 5:00 p.m. and 30 ft. above ground, on each of the seven chosen dates are given in Table IV. It will be noted that these velocities were generally lower than 10 m.p.h., and that in most instances the wind direction was such that a west-facing surface would be sheltered from the direct effect of the wind. Therefore, a value of $f_o = 3.5$ was considered to be reasonable and was used for all computations of $q/A_L$.

TABLE IV

WIND VELOCITIES AT OKLAHOMA A. & M. CAMPUS WEATHER STATION, 5:00 P.M., 1950

| Date | Wind Velocity, m.p.h. | Wind Direction |
|---|---|---|
| Aug. 8 | 9 | East |
| Aug. 9 | 6 | East |
| Aug. 19 | 10 | Northeast |
| Aug. 24 | 8 | South |
| Aug. 25 | 8 | Southwest |
| Aug. 26 | 12 | South |
| Sept. 1 | 7 (Gusts to 15) | North |

Table V lists sol-air temperatures, $t_e$, for a west-facing wall computed at each half-hourly interval by the expression:

$$t_e = \frac{b}{f_o} I_t + t_o,$$

where:

$b$ = Absorptivity of the wall surface for incident solar and sky radiation, dimensionless.

$I_t$ = Incident solar and sky radiation, btu per hr.-sq.ft.

$t_o$ = Outdoor air temperature, dry bulb.

Heating And Air Conditioning by Allen, Walker, and Jones recommends a value of $b = 0.7$ for a medium dark surface, including dark-colored cement, asbestos shingles, stucco, and other similar materials. Then, the value of $b/f_o = 0.7/3.5 = 0.20$. This value, 0.20, was used for all computations of sol-air temperatures of the west wall surface. It should be noted that, so far as the outdoor film coefficients and solar absorptivity are concerned, it is the ratio of these two quantities rather than their individual values which affect sol-air temperature computations.

Total incident solar and sky radiation intensities, $I_t$, for a vertical, west-facing, unshaded surface were computed at half-hour intervals on the basis of measured total solar and sky radiation intensity on a horizontal surface. Solar radiation intensity at normal incidence, $I_n$, is related to $I_t$ and $I_{sv}$, sky radiation on a vertical surface by the expression:

$$I_t = I_n \text{Cos}\ (270 - \alpha)\ \text{Cos}\,\beta + I_{sv},$$

where:

$\alpha$ = Azimuth angle of the sun.

$\beta$ = Altitude angle of the sun.

It is apparent that $I_n$ and $I_{sv}$ must each be known before $I_t$ can be computed. However, the pyrheliometric measurements gave a single value for total solar and sky radiation intensity, I, on a horizontal surface. Therefore a supplementary analysis was needed to compute $I_n$ and $I_{sv}$ from the pyrheliometer data. This analysis was based on the ratio:

$$e = I_n \sin\beta\ / I_{sh}$$

where $I_{sh}$ is the instantaneous sky radiation intensity on a horizontal surface. The 1948 Heating, Ventilating, Air Conditioning Guide lists values for "e" as a function of $\beta$, and states: "For rough estimates, assume that the sky radiation on a vertical surface is one-half of that

## TABLE V

## SOL-AIR TEMPERATURES FOR WEST-FACING WALL, DEGREES FAHRENHEIT

$b/f_o = 0.20$

STILLWATER, OKLAHOMA. 1950

| CST | Aug. 8 | Aug. 9 | Aug.19 | Aug.24 | Aug.25 | Aug.26 | Sept.1 |
|---|---|---|---|---|---|---|---|
| 10:00 a.m. | 94.3 | 84.3 | —— | 86.7 | 93.3 | 94.8 | 85.3 |
| 10:30 | 95.8 | 90.3 | —— | 88.9 | 93.8 | 95.9 | 86.5 |
| 11:00 | 96.4 | 90.9 | —— | 89.8 | 94.4 | 97.3 | 87.4 |
| 11:30 | 97.1 | 91.4 | —— | 90.8 | 95.9 | 97.9 | 88.5 |
| 12:00 | 97.6 | 92.1 | —— | 92.8 | 96.5 | 99.4 | 89.5 |
| 1:00 p.m. | 105.4 | 100.3 | 98.2 | 103.3 | 105.1 | 107.7 | 98.2 |
| 1:30 | 111.1 | 107.4 | 106.2 | 110.5 | 111.8 | 114.1 | 105.5 |
| 2:00 | 116.7 | 113.9 | 113.8 | 117.7 | 122.9 | 122.7 | 101.8 |
| 2:30 | 119.1 | 119.6 | 120.0 | 122.8 | 123.4 | 126.4 | 118.2 |
| 3:00 | 126.5 | 124.6 | 127.6 | 127.7 | 129.2 | 131.5 | 123.5 |
| 3:30 | 133.8 | 130.1 | 125.2 | 130.7 | 132.7 | 133.7 | 128.3 |
| 4:00 | 141.2 | 133.1 | 132.8 | 131.9 | 134.3 | 136.3 | 127.1 |
| 4:30 | 144.8 | 138.4 | 136.1 | 131.8 | 141.2 | 136.3 | 131.3 |
| 5:00 | 148.3 | 139.6 | 138.2 | 128.4 | 131.4 | 134.2 | 129.1 |
| 5:30 | 139.1 | —— | —— | 122.3 | 124.4 | 127.2 | 121.4 |
| 6:00 | 138.6 | —— | —— | 112.1 | 113.3 | 106.3 | 110.5 |
| 6:30 | 128.7 | —— | —— | —— | —— | —— | —— |
| 7:00 | 114.8 | —— | —— | —— | —— | —— | —— |
| 7:30 | 80.0 | —— | —— | —— | —— | —— | —— |
| 8:00 | 79.5 | —— | —— | —— | —— | —— | —— |
| 8:30 | 79.0 | —— | —— | —— | —— | —— | —— |
| 9:00 | 78.0 | —— | —— | —— | —— | —— | —— |
| 9:30 | 77.5 | —— | —— | —— | —— | —— | —— |
| 10:00 | 76.5 | —— | —— | —— | —— | —— | —— |

on a horizontal surface. Sky radiation may be assumed independent of vertical surface orientation."

Total solar and sky radiation intensity I on a horizontal surface can be expressed by:

$$I = I_{sh} + I_n \sin\beta ,$$

or $I_n = (I - I_{sh}) / \sin\beta$ .

Substituting for $I_n$ in the expression defining "e".

$$e = (I - I_{sh})/I_{sh},$$

or $I_{sh} = I/(e+1)$.

and $I_{sv} = 0.5\ I/(e+1)$.

$$I_n = I_{sh} \times e/\sin\beta .$$

In order to apply these expressions, the azimuth and altitude of the sun must be known for all times during each of the chosen days. These were interpolated for half-hourly intervals from navigation tables[1] and the 1950 American Nautical Almanac, and are listed in Table VI. Table VII lists computed values for $I_{sh}$ and $I_n$.

An example showing how the sol-air temperature was computed for 3:00 p.m., August 25, 1950 and a west-facing wall will make the foregoing analysis clear. First compute $I_{sh}$:

$$I_{sh} = I/(e+1).$$

$I = 212.2$ btu per hr.-sq.ft. (pyrheliometer measurement)

$e = 4.36$ at $\beta = 47.4°$. (1948 Guide, p. 263 and Table VI)

$I_{sh} = 212.2/(4.36+1) = 39.6$ btu per hr.-sq.ft.

Compute $I_n = I_{sh}\ (e/\sin\beta\ )$.

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[1] U. S. Navy Department Hydrographic Office, Astronomical Navigation Tables Volume H.

# TABLE VI

## ALTITUDES, $\beta$ , AND AZIMUTHS, $\alpha$ , OF THE SUN
## STILLWATER, OKLAHOMA, 1950

| C S T | Aug. 8 | | Aug. 9 | | Aug. 19 | | Aug. 24 | | Aug. 25 | | Aug. 26 | | Sept. 1 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ |
| | ° ' | ° | ° ' | ° | ° ' | ° | ° ' | ° | ° ' | ° | ° ' | ° | ° ' | ° |
| 8:00 a.m. | 27-55 | 90.0 | 27-46 | 90.0 | 26-04 | 93.0 | 25-07 | 94.0 | 24-56 | 94.0 | 24-44 | 94.5 | 23-30 | 96.5 |
| 8:30 | 33-58 | 94.5 | 33-48 | 94.5 | 32-06 | 97.5 | 31-08 | 99.5 | 30-56 | 99.5 | 30-44 | 100.0 | 29-28 | 102.0 |
| 9:00 | 39-59 | 99.0 | 39-49 | 99.0 | 38-03 | 103.0 | 37-04 | 105.0 | 36-52 | 105.0 | 36-39 | 105.5 | 35-20 | 107.0 |
| 9:30 | 45-55 | 104.5 | 45-44 | 105.0 | 43-54 | 108.5 | 42-51 | 110.5 | 42-38 | 110.5 | 42-25 | 111.0 | 41-02 | 113.0 |
| 10:00 | 51-40 | 112.0 | 51-29 | 112.0 | 49-31 | 115.0 | 48-23 | 117.0 | 48-09 | 117.0 | 47-55 | 117.5 | 46-26 | 120.5 |
| 10:30 | 57-10 | 119.5 | 56-59 | 119.5 | 54-47 | 123.5 | 53-35 | 125.5 | 53-19 | 125.0 | 53-04 | 126.0 | 51-26 | 128.5 |
| 11:00 | 62-09 | 129.5 | 61-56 | 130.0 | 59-01 | 134.0 | 58-10 | 136.0 | 57-53 | 136.0 | 57-36 | 136.5 | 55-50 | 138.5 |
| 11:30 | 66-20 | 143.0 | 66-06 | 143.0 | 63-23 | 147.0 | 61-55 | 149.0 | 61-35 | 149.0 | 61-17 | 149.5 | 59-19 | 151.0 |
| 12:00 | 69-13 | 161.0 | 68-56 | 161.0 | 65-58 | 163.0 | 64-21 | 164.0 | 64-00 | 164.0 | 63-40 | 164.5 | 61-35 | 165.0 |
| 12:30 p.m. | 70-09 | 181.5 | 69-52 | 181.5 | 66-47 | 181.0 | 65-06 | 181.0 | 64-46 | 181.0 | 64-25 | 181.0 | 62-18 | 181.0 |
| 1:00 | 68-55 | 202.0 | 68-38 | 202.0 | 65-42 | 199.0 | 64-06 | 198.0 | 63-45 | 198.0 | 63-25 | 198.0 | 61-21 | 197.0 |
| 1:30 | 65-50 | 219.0 | 65-36 | 219.0 | 62-55 | 215.0 | 61-26 | 213.0 | 61-07 | 213.0 | 60-48 | 212.5 | 58-53 | 210.5 |
| 2:00 | 61-31 | 232.0 | 61-17 | 232.0 | 58-54 | 228.0 | 57-34 | 226.0 | 55-17 | 225.5 | 55-00 | 225.0 | 55-15 | 222.5 |
| 2:30 | 56-25 | 241.5 | 56-14 | 241.5 | 54-06 | 237.5 | 52-50 | 235.5 | 52-36 | 235.0 | 52-21 | 234.5 | 50-45 | 233.0 |
| 3:00 | 50-53 | 249.5 | 50-42 | 249.0 | 48-46 | 246.0 | 47-37 | 244.0 | 47-23 | 243.5 | 47-09 | 243.0 | 45-41 | 240.5 |
| 3:30 | 45-04 | 255.5 | 44-54 | 255.5 | 43-05 | 252.5 | 42-02 | 251.5 | 41-49 | 250.0 | 41-36 | 250.0 | 40-13 | 250.0 |
| 4:00 | 39-08 | 261.0 | 38-59 | 261.0 | 37-13 | 257.5 | 36-13 | 256.0 | 36-01 | 255.5 | 35-49 | 255.5 | 34-30 | 253.0 |
| 4:30 | 33-06 | 265.5 | 32-57 | 266.5 | 31-14 | 263.0 | 30-16 | 261.5 | 30-04 | 261.0 | 29-52 | 261.0 | 28-36 | 258.5 |
| 5:00 | 27-02 | 271.0 | 26-53 | 271.0 | 25-11 | 267.5 | 24-15 | 266.0 | 24-03 | 265.5 | 23-51 | 265.5 | 22-37 | 263.0 |
| 5:30 | 20-59 | 274.5 | 20-50 | 275.0 | 19-07 | 272.0 | 18-11 | 270.5 | 17-59 | 270.0 | 17-47 | 270.0 | 16-34 | 268.0 |
| 6:00 | 14-59 | 279.0 | 14-50 | 279.0 | 13-05 | 276.5 | 12-09 | 275.0 | 11-57 | 274.5 | 11-45 | 274.5 | 10-32 | 272.0 |

## TABLE VII

### DIRECT SOLAR RADIATION INTENSITY, $I_n$, AT NORMAL INCIDENCE AND SKY RADIATION INTENSITY, $I_{sh}$, ON A HORIZONTAL SURFACE STILLWATER, OKLAHOMA. 1950

| C S T | Aug. 8 | | Aug. 9 | | Aug. 19 | | Aug. 24 | | Aug. 25 | | Aug. 26 | | Sept. 1 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $I_n$ | $I_{sh}$ | $I_n$ | $I_{sh}$ | $I_n$ | $I_{sh}$ | $I_n$ | $I_{sh}$ | $I_n$ | $I_{sh}$ | $I_n$ | $I_{sh}$ | $I_n$ | $I_{sh}$ |
| 8:00 a.m. | 186.6 | 29.8 | 198.3 | 31.5 | 181.5 | 28.5 | 133.3 | 20.8 | 180.5 | 28.1 | 200.0 | 31.3 | 191.5 | 29.6 |
| 8:30 | 211.0 | 34.7 | 209.0 | 34.2 | 204.5 | 33.3 | 216.5 | 34.9 | 166.7 | 27.1 | 227.0 | 36.7 | 224.0 | 35.9 |
| 9:00 | 231.5 | 38.8 | 241.0 | 40.3 | 226.0 | 37.6 | 241.0 | 40.1 | 237.0 | 39.3 | 245.5 | 40.8 | 243.0 | 40.2 |
| 9:30 | 244.0 | 41.2 | 247.5 | 41.8 | 239.0 | 40.2 | 229.0 | 38.7 | 243.0 | 41.9 | 249.0 | 41.9 | 255.0 | 42.7 |
| 10:00 | 255.0 | 43.2 | 255.0 | 43.1 | 252.7 | 42.7 | 251.0 | 42.4 | 251.5 | 42.6 | 255.0 | 43.0 | 258.0 | 43.4 |
| 10:30 | 256.0 | 43.1 | 257.0 | 43.1 | 255.0 | 43.1 | 259.0 | 43.6 | 250.7 | 42.1 | 258.7 | 43.5 | 265.0 | 44.8 |
| 11:00 | 263.0 | 43.7 | 261.0 | 43.5 | 261.0 | 43.7 | 264.0 | 43.2 | 253.4 | 42.3 | 259.0 | 43.2 | 264.5 | 44.3 |
| 11:30 | 267.5 | 44.6 | 266.0 | 44.3 | 267.0 | 44.4 | 259.0 | 43.3 | 253.0 | 42.2 | 263.0 | 43.8 | 269.0 | 44.9 |
| 12:00 | 269.0 | 44.9 | 273.0 | 45.8 | 270.0 | 45.1 | 261.0 | 43.4 | 255.0 | 42.5 | 263.0 | 43.8 | 270.0 | 45.1 |
| 12:30 p.m. | 274.0 | 45.8 | 274.0 | 45.8 | 275.0 | 45.7 | 262.0 | 43.6 | 256.0 | 42.5 | 263.0 | 43.8 | 275.0 | 45.8 |
| 1:00 | 269.0 | 44.9 | 272.0 | 45.3 | 280.0 | 46.6 | 259.0 | 43.1 | 255.0 | 46.2 | 263.0 | 43.8 | 273.0 | 45.6 |
| 1:30 | 258.5 | 43.1 | 275.0 | 45.8 | 278.5 | 46.3 | 261.0 | 43.3 | 252.8 | 42.1 | 262.0 | 43.6 | 275.0 | 45.4 |
| 2:00 | 253.5 | 42.2 | 275.0 | 45.8 | 287.5 | 46.7 | 254.5 | 42.5 | 252.5 | 42.3 | 262.0 | 44.1 | 270.5 | 45.3 |
| 2:30 | 243.5 | 40.7 | 272.0 | 45.7 | 280.0 | 48.2 | 247.0 | 41.7 | 243.0 | 41.1 | 253.0 | 42.7 | 269.2 | 45.7 |
| 3:00 | 243.5 | 41.1 | 267.0 | 45.3 | 288.0 | 48.6 | 244.0 | 41.2 | 235.0 | 39.6 | 250.0 | 42.1 | 268.0 | 45.2 |
| 3:30 | 262.5 | 44.3 | 271.0 | 45.8 | 238.6 | 40.2 | 232.5 | 39.1 | 230.7 | 38.7 | 239.5 | 40.2 | 261.0 | 43.8 |
| 4:00 | 280.0 | 46.9 | 265.0 | 44.6 | 263.0 | 43.8 | 222.0 | 36.8 | 211.0 | 35.0 | 232.5 | 38.5 | 236.5 | 38.8 |
| 4:30 | 283.5 | 46.4 | 275.0 | 45.0 | 267.0 | 43.3 | 205.0 | 33.2 | 240.0 | 38.8 | 214.7 | 34.5 | 241.0 | 38.8 |
| 5:00 | 289.0 | 45.9 | 271.0 | 43.0 | 265.0 | 41.6 | 179.5 | 27.9 | 180.4 | 28.0 | 197.0 | 28.4 | 222.0 | 34.0 |
| 5:30 | 244.0 | 36.6 | 263.0 | 39.2 | 251.0 | 37.1 | 145.5 | 21.1 | 146.0 | 21.2 | 157.5 | 22.6 | 191.5 | 27.1 |
| 6:00 | 245.0 | 33.9 | 230.0 | 33.2 | 184.0 | 24.5 | 103.7 | 13.5 | 104.7 | 13.6 | 66.1 | 8.6 | 150.5 | 18.9 |

Note: All values of $I_n$ and $I_{sh}$ are in units of btu per hr.-sq.ft.

$\sin \beta = \sin 47.4° = 0.736.$

$I_n = 39.6 \times 4.36/0.736 = 235.0$ btu per hr.-sq.ft.

Compute $I_{sv} = 0.5\ I_{sh}$.

$I_{sv} = 0.5 \times 39.6 = 19.8$ btu per hr.-sq.ft.

Compute $I_t = I_n \cos (270 - \alpha) \cos \beta + I_{sv}$.

$\alpha = 243.5°$ (Table VI).

$\beta = 47.4°$ (Table VI).

$I_t = 234.5 \cos (270 - 243.5) \cos 47.4 + 19.8.$

$I_t = 166.1$ btu per sq.ft.-hr.

Compute $t_e = (b/f_o)\ I_t + t_o$.

$b/f_o = 0.2$ (cf. preceding discussion).

$t_o = 96.0$ (Table III).

$t_e = 0.2 \times 166.1 + 96.0 = 129.2°.$

Compute $q/A_L = f_o\ (t_e - t_L\ )$.

$t_L = 111.0°$ (surface temperature measurement).

$q/A_L = 3.5\ (129.2 - 111.0) = 63.6$ btu per hr.-sq.ft.

Computations for $q/A_L$ at half-hour intervals during each of the seven days and for each of the six panels were made according to the analysis. The resulting data for each panel were then compared and the three highest values out of the possible seven at each half-hour time interval were averaged to obtain an average $q/A_L$. These average values of $q/A_L$ were then plotted and are shown in Figs. 16 through 18.

Instantaneous heat gain, $q/A_i$, from the indoor surface of the panels to indoor air was computed at half-hour intervals during each of the seven days by the expression:

$q/A_i = f_i\ (t_{is} - t_i)$, btu per sq.ft.-hr., where:

$f_i$ = Indoor surface film conductance, btu per sq.ft.-deg.-hr.

$t_{is}$ = Indoor panel surface temperature.

$t_i$ = Indoor air dry bulb temperature.

The value of $f_i$ was assumed constant at 2.0 btu per hr.-sq.ft.-deg. This the value recommended in the <u>1948 Heating Ventilating Air Conditioning Guide</u> for still air and a concrete surface. Indoor panel surface temperature, $t_i$, was taken as the average of the two temperature measurements at the thermocouple junctions embedded in the indoor surface of each panel. The indoor air dry bulb temperature, $t_i$, was taken as the temperature measured by the recording dry bulb and relative humidity indicator at the location shown in the floor plan, Fig. 2. Of the seven possible values for $t_{is}$ and $t_i$, respectively, at each half-hour interval for each panel, only three were chosen so that the computed $q/A_i$ was based on the same data at each half-hour interval as the computed $q/A_L$. This resulted in three values for $q/A_i$ at each half-hour interval. These were averaged and are plotted in Figs. 16 through 18.

Table VIII summarizes the data of Figs. 16 through 18. The "Time Lag" listed in Table VIII is the time elapsed between time of maximum heat gain to the outdoor wall surface for each panel and the time of maximum heat gain to indoor air. The "Decrement Factor" listed in Table VIII is the quotient of maximum heat gain to indoor air divided by maximum heat gain from outdoor air to outdoor surface. It is shown that, for all six west-facing panels, maximum heat gain to indoor air occurs in the period 7:30 p.m. to 9:00 p.m.; and that maximum indoor heat gain is from 23 percent to 45 percent of maximum heat gain to the outdoor surfaces. It appears that the most effective of the six kinds of masonry walls in obtaining low heat gain, compared on the basis of maximum heat gain is the pumice concrete block with cores filled with pumice aggregate. It is shown that maximum heat gain through the wall panel built with expanded shale concrete block with the cores filled with expanded shale aggregate was 2 btu per hr.-sq.ft. higher than maximum heat gain through the same kind of concrete block but with empty cores. This was contrary to expectations.

The time lag characteristics of all six kinds of masonry wall studied are such that maximum heat gain through west-facing walls to indoor air in a temperature-controlled shelter is delayed until late in the evening, when attic fan circulation of cool night air might be used in lieu of mechanical cooling.

In order to find a simplified procedure for computing instantaneous heat gain for design purposes through the six kinds of masonry walls investigated, the relationship existing between $(t_e - t_i)$ and $(q/A)_i$ was investigated. If $(q/A)_i$ is divided by $(t_e - t_i)$, a quantity which has the same dimensions as an overall coefficient of heat transfer for a wall is obtained. This quantity could be named an effective overall coefficient of heat transfer and defined by:

$$U_e = \frac{(q/A)_i}{t_e - t_i} ,$$

where:

$U_e$ = Effective overall (air to air) coefficient of heat transfer under summertime conditions of periodic heat flow, btu per hr.-sq.ft.-deg. F.

$(q/A)_i$ = Instantaneous rate of heat gain to indoor air, btu per hr.-sq.ft.

$t_e$ = Sol-air temperature.

$t_i$ = Indoor air temperature

Values for $U_e$ are plotted for hours from 10:00 a.m. through 6:00 p.m.

for each of the six kinds of walls, Figs. 19 through 21. Each set of plotted values is based on the same selection of data as used for plotting instantaneous heat gain rates to outdoor and from indoor surfaces, respectively.

It is seen that the graphs of $U_e$ vs. time follow a similar pattern for all six kinds of wall; but that appreciable differences in $U_e$ occur during the latter part of the afternoon. For example, at 5:00 p.m., $U_e$ for sand and gravel aggregate concrete block, cores empty, is 0.45; $U_e$ for pumice aggregate concrete block, cores empty, is 0.31; and $U_e$ for processed shale aggregate concrete block, cores empty, is 0.11.

These graphs could be used for estimating heat gain through west-facing walls, by computing $t_e$ for successive hours during the hot part of the day; then computing $q/A_i$ by selecting the appropriate value of $U_e$ and multiplying by $t_e - t_i$. They would not necessarily be usable for locations which have a different pattern of sol-air temperature variation, because it is obvious that the shape of the graph will depend on the way in which $t_e$ varies throughout the day.

## Attic Space Temperature Variation

In order to develop a basis for predicting temperatures in attic spaces over temperature-controlled shelters, a heat balance analysis on the attic space was made. Let the following notations be used:

$t_o$ = Outdoor dry-bulb temperature.

$t_{en}$ = Sol-air temperature for north slope of roof.

$t_{es}$ = Sol-air temperature for south slope of roof.

$t_{ea}$ = Average of $t_{en}$ and $t_{es}$.

$t_a$ = Attic space dry bulb temperature.

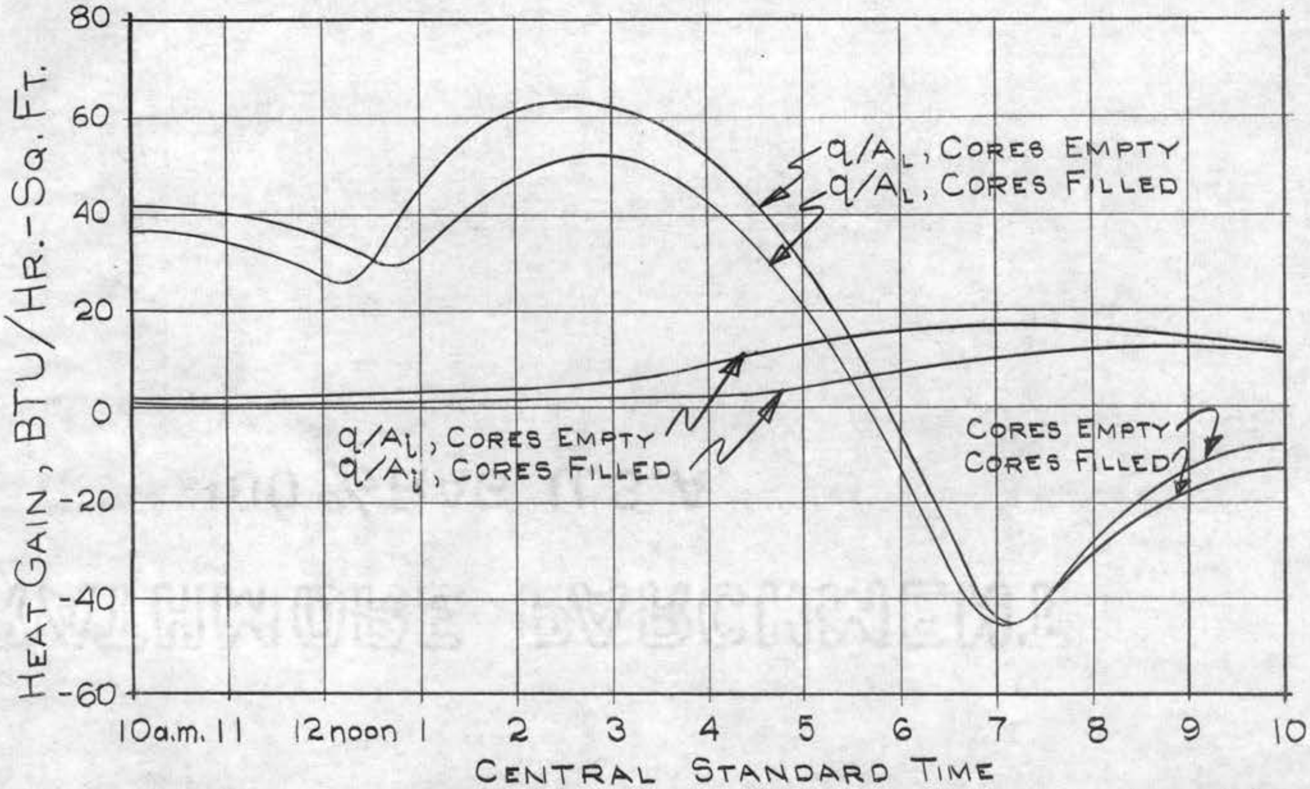

Fig. 16 – Summertime Heat Gain Characteristics For 8" Pumice Aggregate Concrete Block In West-Facing Wall.

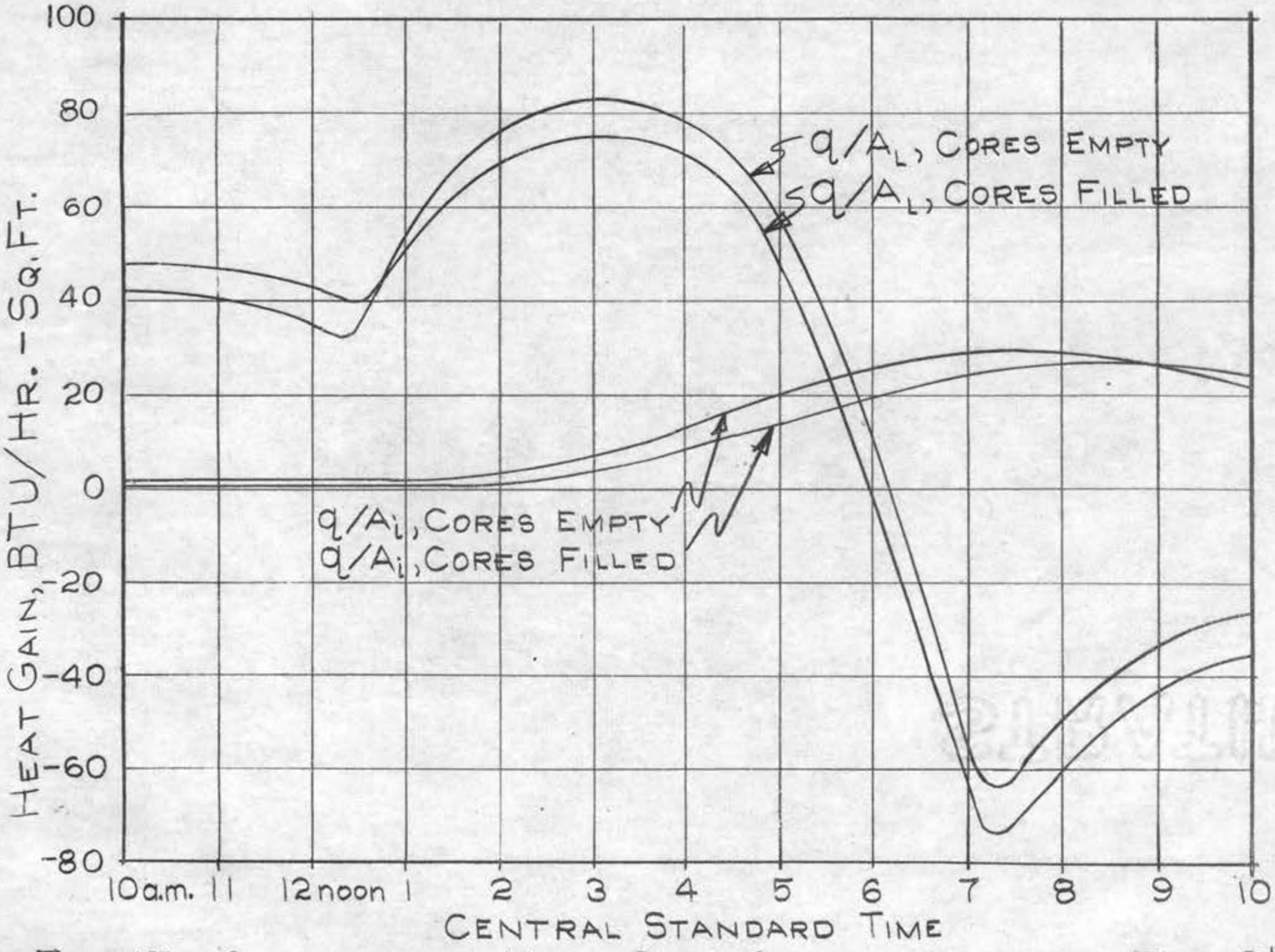

Fig. 17 – Summertime Heat Gain Characteristics For 8" Sand And Gravel Aggregate Concrete Block In West-Facing Wall.

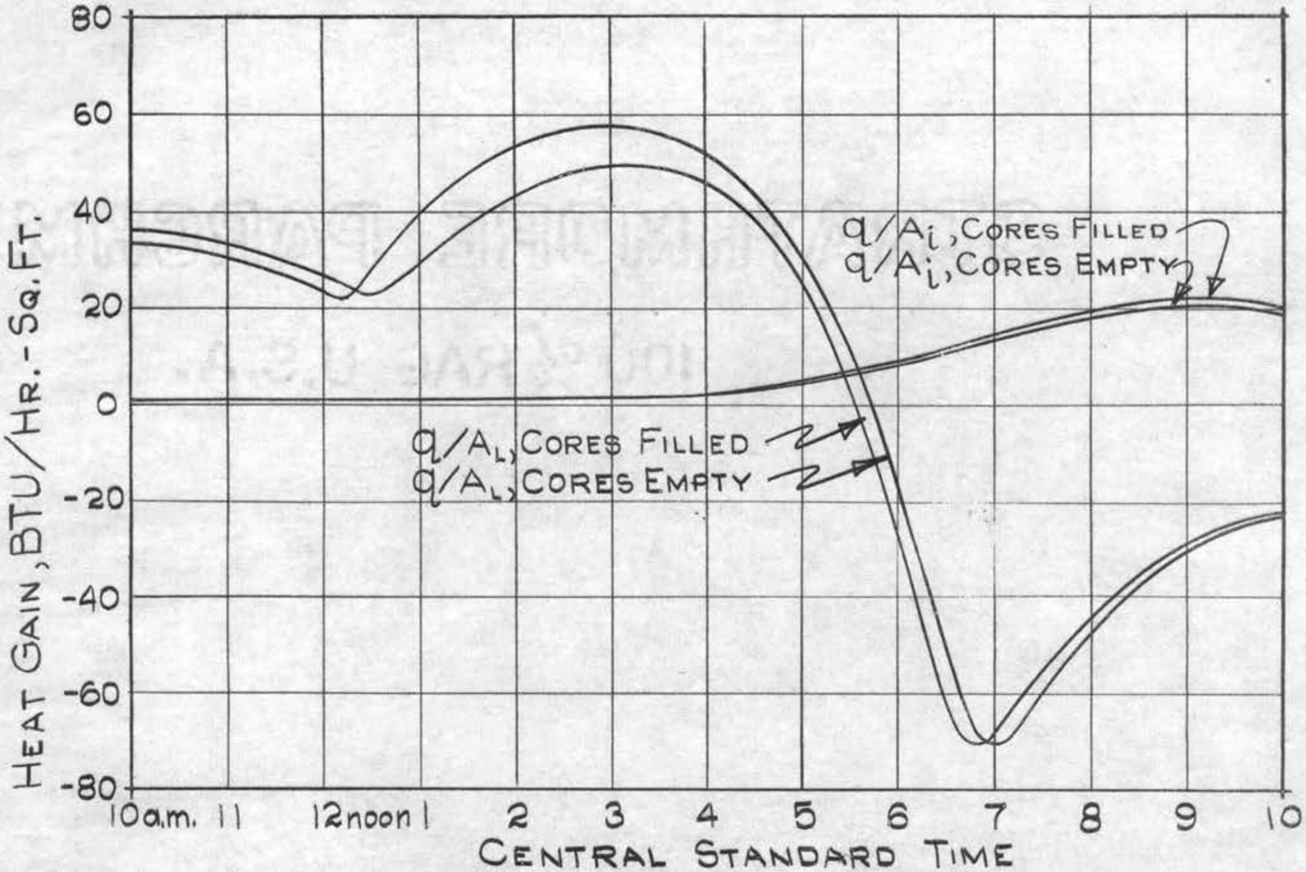

Fig. 18 - Summertime Heat Gain Characteristics for 8" Expanded Shale Aggregate Concrete Block in West-Facing Wall.

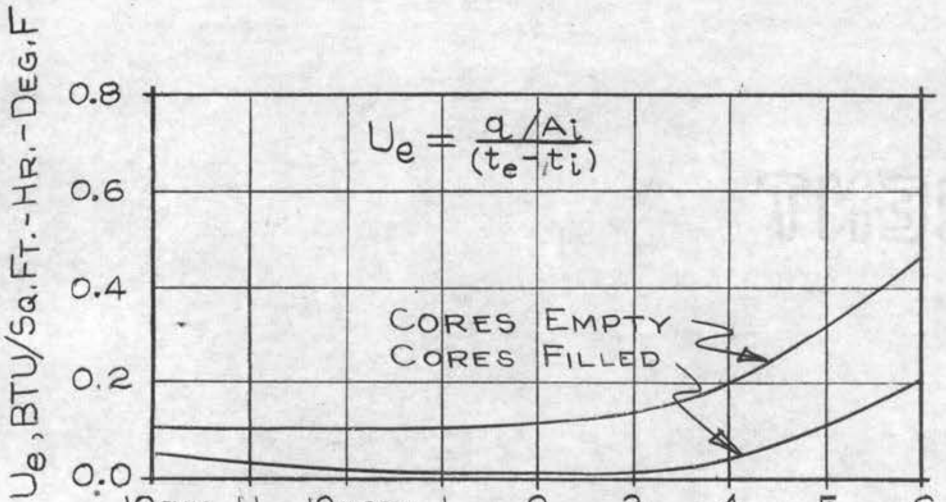

Fig. 19 - U$_e$ for Pumice Aggregate Concrete Block in West-Facing Wall.

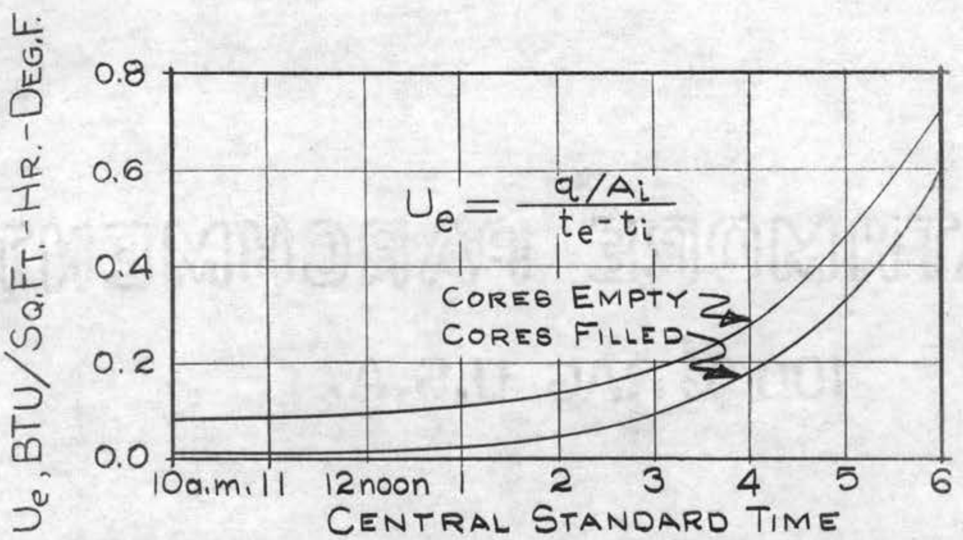

Fig. 20 - $U_e$ for Sand and Gravel Aggregate Concrte Block in West - Facing Walls.

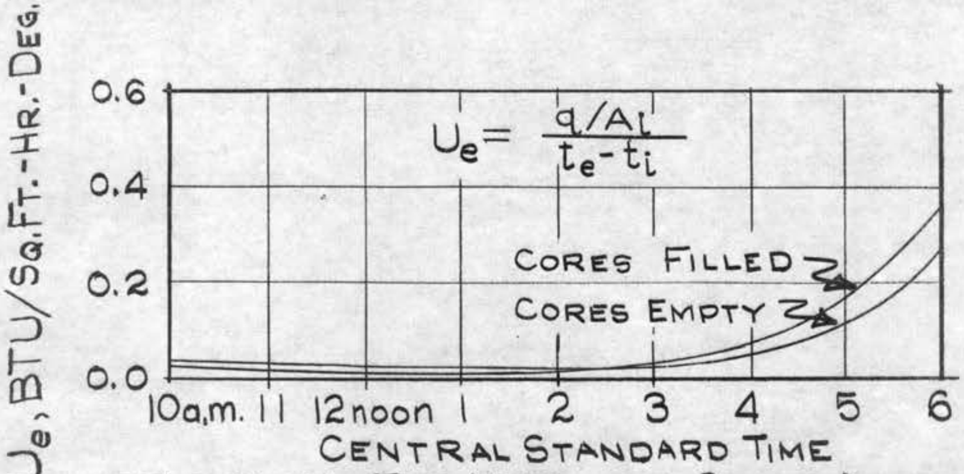

Fig. 21 - $U_e$ for Expanded Shale Aggregate Concrete Block in West - Facing Walls.

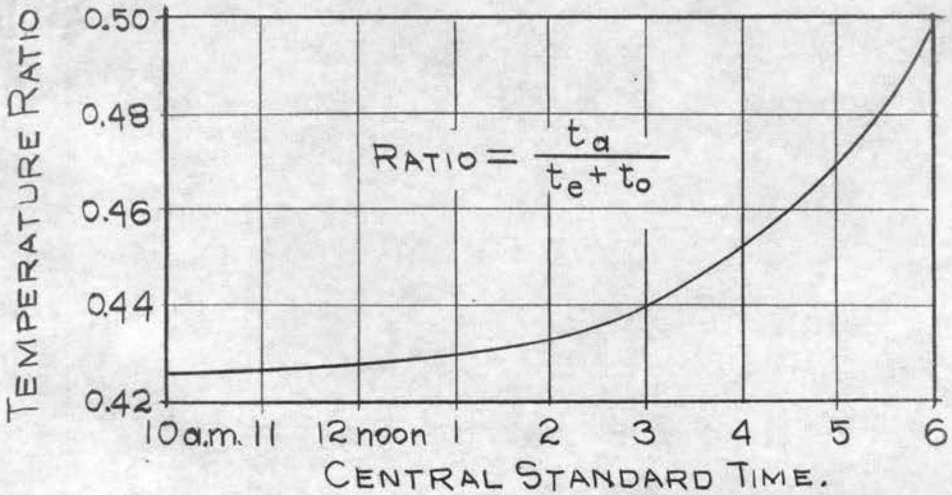

Fig. 22 - Attic Space Temperature Ratio for Temperature-Controlled Shelter

## TABLE VIII

### HEAT GAIN, TIME LAG AND DECREMENT FOR WALL PANELS IN TEMPERATURE CONTROLLED SHELTER

| KIND OF WALL CONSTRUCTION | | MAXIMUM HEAT GAIN TO OUTDOOR SURFACE | | MAXIMUM HEAT GAIN TO INDOOR AIR | | TIME LAG HRS. | DECREMENT FACTOR |
|---|---|---|---|---|---|---|---|
| Type Concrete In Masonry Units | Core Filling | $q/A_L$ btu/hr.-sq.ft. | CST P.M. | $q/A_1$ btu/hr.-sq.ft. | CST P.M. | | |
| Pumice | None | 63 | 2:30 | 17 | 7:30 | 5 | 0.270 |
| Pumice | Pumice Agg. | 52 | 3:00 | 12 | 9:30 | 6½ | 0.231 |
| Sand and Gravel | None | 83 | 3:00 | 30 | 7:30 | 4½ | 0.363 |
| Sand and Gravel | Pumice Agg. | 75 | 3:00 | 27 | 8:30 | 5½ | 0.360 |
| Expanded Shale | None | 58 | 3:00 | 20 | 9:00 | 6 | 0.345 |
| Expanded Shale | Expanded Shale Agg. | 49 | 3:00 | 22 | 9:00 | 6 | 0.449 |

$t_i$ = Shelter space dry bulb temperature.

$U_{ce}$ = Overall (air-to-air) coefficient of heat transfer for ceiling, btu per hr.-sq.ft.-deg.

$U_r$ = Overall (air-to-air) coefficient of heat transfer for roof, btu per hr.-sq.ft.-deg.

M = Air circulation rate through attic space, lbs. outdoor air per hr. (Dry air assumed).

$A_{ce}$ = Total ceiling area, sq. ft.

$A_n$ = Total area of north slope of roof, sq. ft.

$A_s$ = Total area of south slope of roof, sq. ft.

$C_p$ = Constant pressure specific heat for dry air, btu per lb.-deg. F.

If heat transmission through the gable end walls is neglected, the following heat balance for the attic space can be written:

$$(A_rU_r/2)(t_{en} - t_a + t_{es} - t_a) - MC_p\,(t_a - t_o) - U_{ce}A_{ce}(t_a - t_i) = 0$$

After rearranging and substituting $(t_{en} - t_a)$ for $(t_{en} - t_a + t_{es} - t_a)/2$, we obtain:

$$t_{ea} + t_o\,(MC_p/A_rU_r) + t_i\,(U_{ce}A_{ce}/A_rU_r) =$$
$$t_a \left[1 + (MC_p/A_rU_r) + U_{ce}A_{ce}/A_rU_r\right]$$

It is apparent that, if $t_i$ is held constant, $t_{ea}$, $t_a$, and $t_o$ will be related by an expression of the general form:

$$t_{ea} + K_1\,t_o + K_2 = K_3\,t_a.$$

Also, for low rates of air movement through the attic space, in the order of 1 1/4 m.p.h., the value of $MC_p/A_r\,U_r$ will be close to unity, in which case:

$$t_a = f\,(t_{ea} + t_o)$$

It appeared possible that the ratio $t_a/(t_{ea} + t_o)$ might vary with time in a consistent manner. This ratio was plotted by half-hourly intervals to obtain the graph shown in Fig. 22. These data are the averages of temperatures for Aug. 19, Aug. 24, Aug. 25, Aug. 26, and Sept. 1, all 1950. Sol-air temperatures were computed separately for the north and south slopes of the roof by the expression:

$$t_e = \frac{b}{f_o} I_t + t_o$$

where the terms have the same definitions as previously given. The results of these computations are given in Table IX. A constant value of $b/f_o = 0.10$ was selected for computation of sol-air temperatures for the aluminum roof covering. This would correspond to a value of $b = 0.40$ and $f_o = 4.0$, or any other set of numbers in the ratio 1 to 10. The 1948 Heating Ventilating Air Conditioning Guide lists a value of $f_o = 4.0$ for a wind velocity of 10 m.p.h. and a surface corresponding to glass or white paint on pine lumber. Allen, Walker, and James in Heating and Air Conditioning recommend a value of $b = 0.40$ for very light-colored surfaces including white-painted and similar surfaces. The Permanente Products Company, manufacturers of aluminum roof coverings suggests that $b = 0.10$ be used for bright aluminum roofing sheets and $b = 0.40$ for aged aluminum roofing sheets.

Instantaneous intensities of solar and sky radiation, $I_t$, were computed by the expression,

$$I_t = I_n \left(-\sin\theta\cos\beta\cos\alpha + \cos\theta\sin\beta\right) + 0.85\, I_{sh},$$

for the south slope of the roof, and,

$$I_t = I_n \left(\cos\beta\cos\alpha\ \sin\theta + \cos\theta\sin\beta\right) + 0.85\, I_{sh}$$

for the north slope of the roof.

In these expressions:

$I_t$ = Total solar and sky radiation intensity on the roof surface, btu per sq.ft.-hr.

$I_n$ = Solar radiation intensity at normal incidence, btu per sq.ft.-hr.

$\beta$ = Altitude angle of the sun.

$\alpha$ = Azimuth angle of the sun.

$\Theta$ = Slope angle of the roof, measured from horizontal.
( $\Theta = 26°34'$ for the temperature-controlled shelter).

$I_{sh}$ = Sky radiation intensity on a horizontal surface,
btu per hr.-sq.ft.

It is shown by the graph of $t_a/(t_{ea} + t_o)$ that all of the values of this ratio during the hot part of the day fall within the range 0.42 to 0.50. For estimating purposes, an intermediate value, say 0.45, could be used to compute the attic temperature at any hour. Then, heat gain from the attic space to the shelter space could be computed by:

$$q/A = U_{ce}\ (t_a - t_i).$$

The graph of $t_a/(t_{ea} + t_o)$ obtained for the temperature-controlled shelter would not necessarily apply to attics in other structures with different ceiling and roof construction, different amounts of attic ventilation, or different orientations.

# TABLE IX

## SOL-AIR TEMPERATURES FOR SOUTH-FACING ROOF SLOPE, $t_{es}$, AND NORTH-FACING ROOF SLOPE, $t_{en}$, FULL PITCH ROOF, $b/f_o = 0.10$.

DEGREES FAHRENHEIT. 1950

| CST | Aug. 19 | | Aug. 24 | | Aug. 25 | | Aug. 26 | | Sept. 1 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $t_{es}$ | $t_{en}$ | $t_{es}$ | $t_{en}$ | $t_{es}$ | $t_{en}$ | $t_{es}$ | $t_{en}$ | $t_{es}$ | $t_{en}$ |
| 10:00 a.m. | ----- | ----- | 112.8 | 99.6 | 112.8 | 106.0 | 114.6 | 107.5 | 105.4 | 97.4 |
| 10:30 | ----- | ----- | 115.0 | 102.9 | 115.0 | 107.1 | 117.8 | 109.6 | 108.9 | 99.8 |
| 11:00 | ----- | ----- | 117.1 | 104.8 | 117.1 | 108.4 | 120.7 | 111.7 | 111.1 | 101.1 |
| 11:30 | ----- | ----- | 119.6 | 106.0 | 119.6 | 110.4 | 122.7 | 113.0 | 113.9 | 103.1 |
| 12:00 | ----- | ----- | 120.9 | 108.4 | 120.9 | 111.3 | 124.8 | 114.8 | 115.6 | 104.4 |
| 1:00 p.m. | 117.6 | 107.8 | 122.7 | 111.7 | 122.7 | 113.1 | 125.7 | 115.8 | 116.9 | 105.7 |
| 1:30 | 117.7 | 108.4 | 122.2 | 112.0 | 122.2 | 112.8 | 125.0 | 115.3 | 117.1 | 105.9 |
| 2:00 | 117.4 | 108.5 | 121.2 | 112.6 | 121.2 | 112.1 | 124.7 | 115.2 | 115.3 | 105.2 |
| 2:30 | 115.8 | 108.0 | 119.0 | 111.4 | 119.0 | 111.5 | 122.5 | 114.6 | 113.6 | 104.5 |
| 3:00 | 115.0 | 108.0 | 118.0 | 113.4 | 118.0 | 111.7 | 120.4 | 113.5 | 111.6 | 103.3 |
| 3:30 | 108.4 | 103.0 | 116.2 | 108.8 | 116.2 | 111.0 | 116.4 | 110.9 | 108.3 | 102.2 |
| 4:00 | 107.5 | 103.4 | 113.1 | 106.4 | 113.1 | 109.1 | 113.6 | 109.3 | 103.8 | 98.7 |
| 4:30 | 103.8 | 101.3 | 111.5 | 105.4 | 111.5 | 108.6 | 109.8 | 107.2 | 101.6 | 97.7 |
| 5:00 | 100.1 | 99.1 | 104.1 | 101.9 | 104.1 | 102.7 | 105.7 | 104.4 | 96.6 | 94.4 |
| 5:30 | 95.0 | 95.9 | 98.8 | 98.9 | 98.8 | 98.8 | 101.2 | 101.2 | 89.5 | 88.8 |
| 6:00 | 87.9 | 89.7 | 93.3 | 94.0 | 93.3 | 94.0 | 94.2 | 94.7 | 82.8 | 83.9 |

## VI. CONCLUSIONS

1. An average outdoor - indoor temperature difference of at least 10 Fahrenheit degrees was maintained in the temperature-controlled shelter with an evaporative cooler capacity of approximately 0.7 changes per minute of the air in the shelter space. Similar results could probably be obtained under Oklahoma summertime conditions with other shelters of comparable construction.
2. Indoor temperatures usually remained below the control temperature of 80 F until noon or later without cooler operation. If cattle had occupied the shelter for prolonged periods during forenoons, this condition would probably not have occurred.
3. A time lag of from 4 1/2 to 6 1/2 hours between times of maximum heat gain to the outdoor surfaces and maximum heat gain from indoor surfaces to indoor air, respectively, occurred in 8 inch concrete block, west-facing walls. The most time lag occurred with lightweight concrete block whose core spaces were filled with a granular insulating material. Such core filling increased the time lag as much as 1 to 1 1/2 hours compared to the same kind of block with empty cores.
4. Computed heat gain rates based on measured temperatures and radiation intensities in combination with certain selected film conductance and surface absorptivity coefficients showed that maximum instantaneous heat gain rate to indoor air was from 23 to 45 percent of the maximum instantaneous heat gain rate to the outdoor surfaces of the west-facing concrete block wall panels. The lowest percentage corresponded to pumice aggregate concrete block with the core spaces filled with pumice aggregate. The highest percentage corresponded to sand

and gravel aggregate concrete block with no filling in the cores.

5. It appears possible that the concept of an "effective" overall heat transmission coefficient for summertime periodic heat flow through walls exposed to solar radiation might be used as a simple method for estimating summertime heat gain through building walls. Computations made for this "effective" overall heat transmission coefficient, $U_e = (q/A_i)/(t_e - t_i)$, showed that it varied with time in a consistent manner for six kinds of concrete masonry panels in the west wall of the temperature-controlled shelter.
6. Attic space temperatures, $t_a$, over the temperature-controlled shelter appeared to be influenced by $t_{ea}$, the average sol-air temperature for the roof covering, and $t_o$, the outdoor dry bulb temperature. The graph of the ratio $t_a/(t_{ea} + t_o)$ vs. time could be used to predict attic space temperatures. The ratio $t_a/(t_{ea} + t_o) = 0.45$ appeared to be a suitable intermediate value for estimating attic space temperatures required in computations of heat gain from the attic space to the shelter space at all hours during hot parts of a summer day.

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