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The Design, Construction, and Operation of a Guarded Hot Box

Don Williams Jr.

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WILLIAMS — A GUARDED HOT BOX

THE DESIGN, CONSTRUCTION, AND OPERATION OF A GUARDED HOT BOX

By

Don Williams, Jr.

A Thesis
In partial fulfillment of the
Requirements for the Degree of
Master of Science in Mechanical Engineering

The University of New Mexico
1950

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E F Castetter
DEAN

May 26, 1950
DATE

THE DESIGN, CONSTRUCTION, AND OPERATION OF A GUARDED HOT BOX

By

Don Williams, Jr.

Thesis committee

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CHAPTER I

HISTORY

For a number of years the Mechanical Engineering Laboratory of the University of New Mexico has been interested in thermal conductivity tests of the materials commonly used in southwestern building construction.

This type of construction and many of the materials used are unique to this area and as such present a relatively undeveloped sector in the field of heat transfer.

When work was begun on this project, it was not deemed feasible to use standard equipment such as guarded hot plate and hot box apparatus because of its initial cost. As a result, a test was developed by which the overall coefficient could be determined with a fair degree of accuracy.[1] This test, besides having the disadvantage of not being a standard test, is applicable only to rigid walls tested in a vertical position. Corrections for losses other than those through the test walls must be made, and the surface coefficients of the walls are measured at some undeterminable wind velocity. Tests by this method were conducted on most common types of wall sections used in this area, and the results of these tests are soon to be

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CHAPTER I

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published in a University Bulletin by Professor A. D. Ford.

In the spring of 1949, under the sponsorship of a research project on pumice concrete, a guarded hot plate apparatus was constructed in this laboratory.[2] This apparatus was designed to test the thermal conductivity of homogeneous building materials, using relatively small samples for such tests. Inasmuch as this is one of the standard thermal conductivity test setups, it improved the possibilities for research in this laboratory tremendously. However, the laboratory was still unable to make certain tests since this apparatus could test only small samples of homogeneous materials. Also, this apparatus could not differentiate between directions of heat flow.

To complete the thermal conductivity section of the laboratory, the guarded hot box was designed to test overall coefficients of built-up sections, to differentiate between directions of heat flow, and to eliminate many of the corrections necessary in the original method of testing mentioned. This equipment was built under the sponsorship of the Reflectal Corporation in order that a series of tests upon their product might be conducted here. This is also standard testing equipment, and using it, together with the guarded hot plate, makes

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[2] J. M. Ralls, A Study of the Thermal Conductivity of Pumice, 1949.

practically any thermal conductivity test possible in this laboratory.

CHAPTER II

THEORY

The guarded hot box is a device for measuring the coefficient of heat transfer through typical wall sections, and, with some modifications, through insulations. In order to determine this coefficient, it is necessary to know the temperature difference across the wall and the quantity of heat flowing through a given area of the test sample when thermal equilibrium has been reached.

The design of the guarded hot box is such that these values listed may be easily determined. The guarded hot box consists of a small box surrounded on five sides by a large box. The open side of the large box and of the small box are on the same vertical plane, and the wall section to be tested is placed against the open side, completing both boxes. Both boxes have their own heat source controlled from outside the refrigerated room in which the complete apparatus is contained. If these heat sources are adjusted until the inside temperature of both boxes is the same, the only loss of heat from the inner box will occur through the sample to be tested. By measuring the electrical power supplied to the inner box and the area of this box in contact with the test sample, the quantity of heat flowing per unit of area may be determined.

The temperature of the warm and cold surfaces of the test wall are determined by thermocouples mounted in the hot box, as are temperatures on both sides of the wall. With all this data, the overall coefficient

of the walls is easily calculated.

CHAPTER III

DESIGN

Most guarded hot boxes are made to test walls in a vertical position only. In the original design discussed a few years ago for this laboratory, this idea was carried out. This design had the hot box apparatus outside of the refrigerated room with the test wall mounted in the wall of this room. In this manner, one side of the test section was in contact with the guarded hot box and was heated to a known temperature by a known power input, while the other side was cooled to a known temperature. The inflexibility of this design, since it would test only sections mounted in the vertical position, led to its discard when the series of tests for the Reflectal Corporation were contemplated. The tests specified that their insulation be tested with heat flow up and down as well as horizontal.

In order that the direction of heat flow could be controlled, it was decided to mount the guarded hot box entirely within the refrigerated room, and, in addition, to mount it on trunions so that the box could be rotated in order to provide heat flow in any direction. At about this same time, a paper describing a similar device was discovered.[3] This paper was

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[3] Rowley and Lund, "Factors Affecting Heat Transmission Through Insulated Walls," Bulletin No. 2, Experiment Station, University of Minnesota.

followed as to general dimensions and design, but the physical differences in the laboratory setups required many modifications in order that this apparatus could be used most easily and effectively. The more notable of these modifications are that (1) the hot box apparatus was mounted on casters so that it could be moved in and out of the refrigerated room; (2) the overall dimensions of the apparatus were closely controlled to assure clearance when passing through the doorway of the refrigerated room; (3) all electrical and thermocouple connections were made to the box by multiprong, self-aligning connectors to facilitate movement and rearrangement of test setups; (4) the power system was completely redesigned to give greater control over heat distribution from the outside so that it would fit better into the laboratory arrangement. The thermostatic control system was eliminated and replaced by a continuous heat source system.

Other minor changes were made after the initial tests had been conducted to give better control and heat distribution throughout the apparatus.

CHAPTER IV

CONSTRUCTION

The size of the test wall section was first decided upon as 65-5/8 inches square. This dimension was arrived at to allow for standard framing of wall members and is the space required for five 2 x 4 studs (four stud spaces) on 16 inch centers. The test section of this wall is two stud spaces or approximately 32 inches square. The overall dimensions of the box are limited by the height and width of the doorway into the refrigerated room. These clearance dimensions are 79 inches high and 48 inches in width. This meant that the hot box would have to enter with the test wall in a vertical position, and that the depth of the box with the wall in place must be less than 48 inches. The top of the box in the vertical position would have to be less than 79 inches from the floor, and, at the same time, the trunion must be high enough to allow the box to be swung to a horizontal position within the refrigerated room without scraping the floor. All of the important clearance dimensions of the completed box are shown in Figure I.

The framework of the large box was made of 2 x 6 lumber except where trunions are attached. These trunions were attached to a beam made of a 4 x 4 backed with a 2 x 6. The sides were bolted together and the back bolted to the sides forming a five-sided box. A strip of two inch square lumber was placed around

CHAPTER IV

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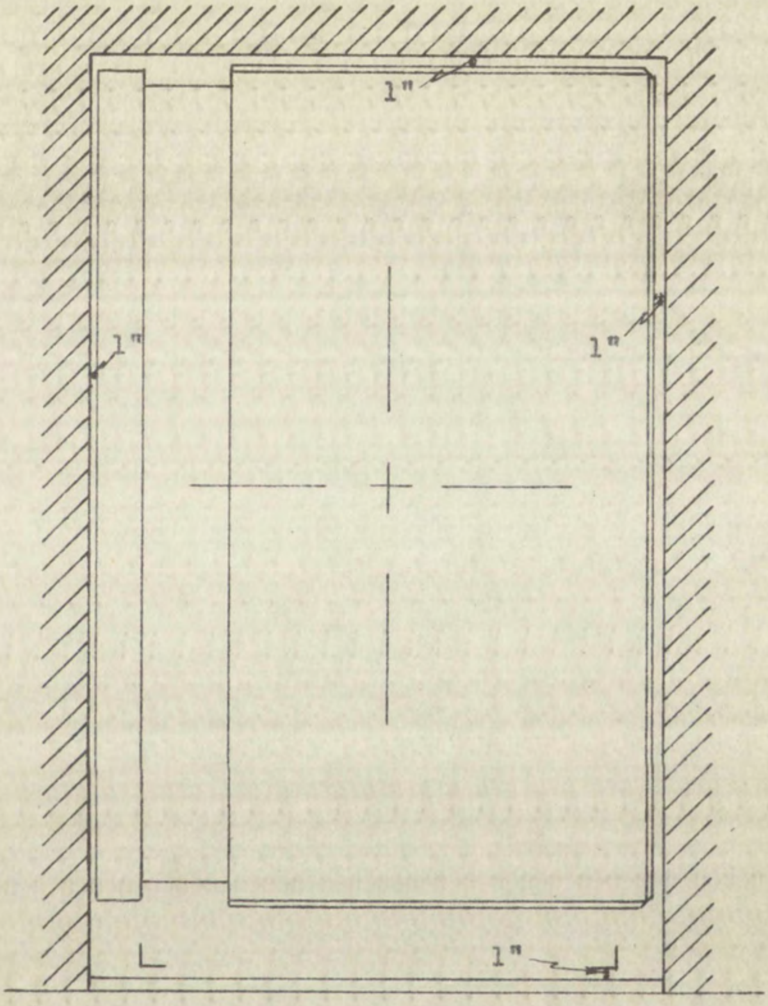

Figure I Clearance Dimensions

Guarded Hot Box entering refrigerated room with 10" wall installed.

the open side of the box to form a guide and support for the test wall section. The inside dimensions of the opening thus formed were 66 inches square. Type IV Alfol Insulation was applied to all walls of this box. This insulation consisted of two sheets of aluminum foil spaced in the air space between studs to form three air spaces. The rear side of the supporting paper was also covered with aluminum foil. The walls were then covered inside and out with one-half inch celotex. This framing is shown in Figures II and III together with the details of construction.

The inner box was made of 2 x 2 lumber nailed together to form a five-sided box. Alfol Insulation Type I was applied to these walls, and they were covered inside and out with one-half inch celotex. Alfol Type I Insulation consisted of one sheet of aluminum foil suspended between studs, forming two air spaces. This box was supported by four strips of lumber in the center of the large box.

Wiring entered the box from a board near the left trunion, which contained one end of the multiprong plugs used to connect the box to the control panel. Sponge rubber stripping on the hot box surfaces in contact with the test wall seal the hot box section and the guard box section from air leakage. Thermocouples were held against the wall section by piano wire springs, and other thermocouples were held in the air spaces by similar springs. These, too, were connected to multiprong connectors

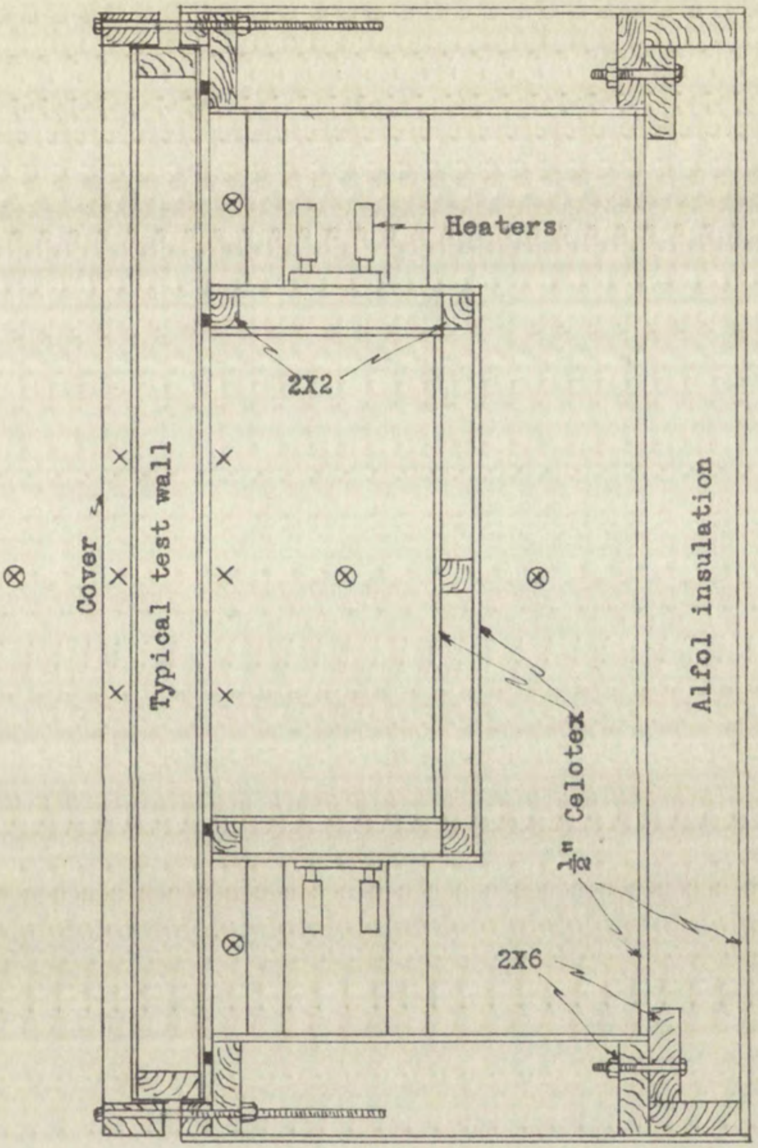

Figure II Profile Section Guarded Hot Box

⊗ Air temperature thermocouples

× Surface temperature thermocouples

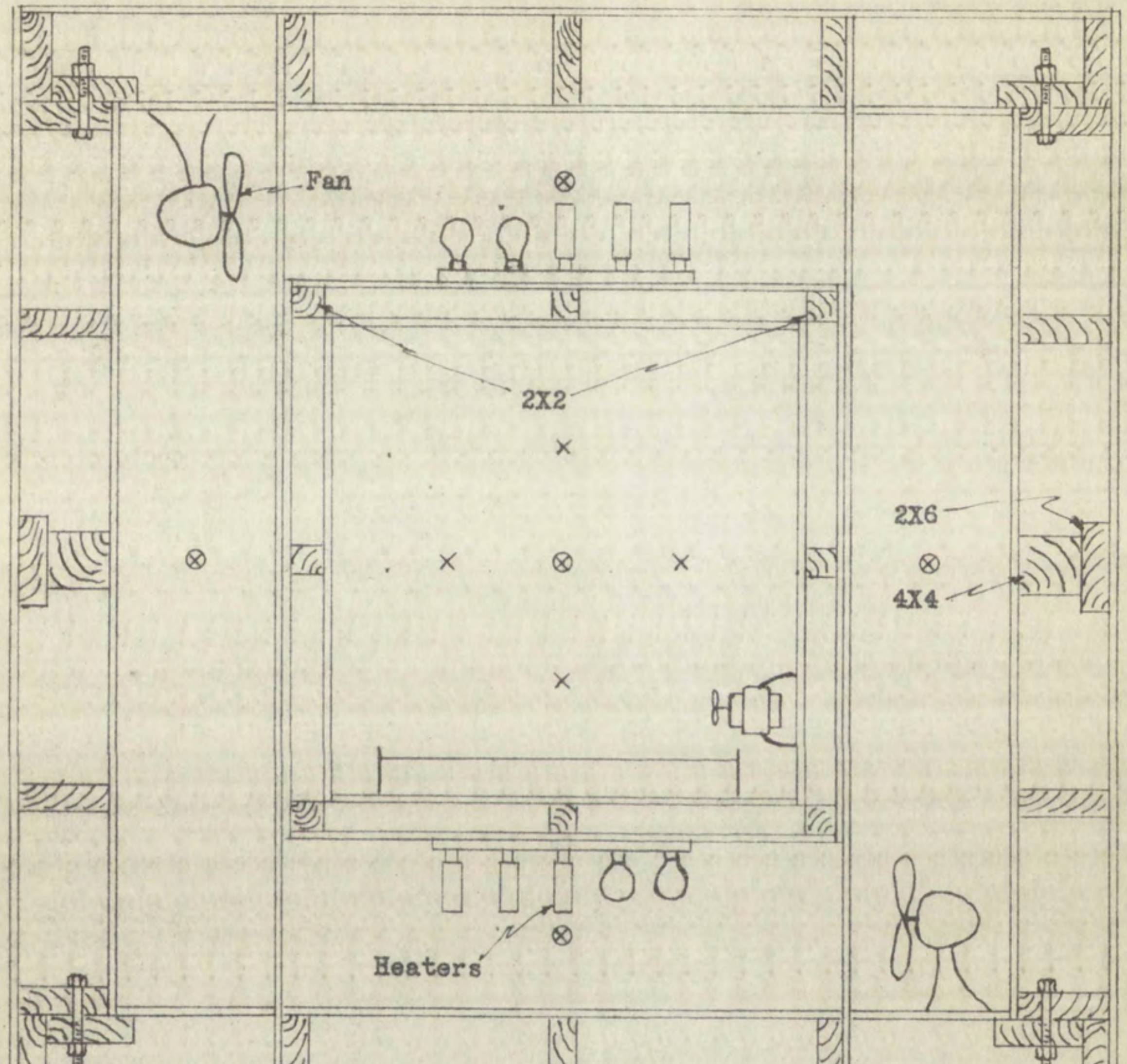

Figure III Frontal Section Guarded Hot Box

⊗ Air temperature thermocouples

× Surface temperature thermocouples

mounted on the board near the left trunion.

A cover with a ledge similar to the one mounted on the large box holds the wall section. This cover was made of 2 x 4 lumber with the corners braced with 2 x 4 and 2 x 6 diagonal braces. These braces also act as the bearing surface for the wall section upon the cover. Thermocouples were mounted on piano wire springs in such a position that they would be held opposite those on the inner surface. Other springs hold thermocouples for measuring the air temperature, and a terminal block mounted on the side of the cover makes it possible for additional thermocouples to be mounted within the wall section itself if such is desired. All thermocouples were connected to a multiprong connector mounted on the left side of the cover. The cover was fastened into place by twelve 5/8 inch bolts which screw into nuts permanently fastened into the wall of the large box.

The support for the trunions was made of 2 x 6 lumber fastened into 4 x 6 beams. The trunions rest in bronze bearings which were bolted through a quarter-inch steel bearing plate to the beams of the support. These beams formed an inverted "V" with the lower ends being held together by horizontal beams of 2 x 6 inch lumber. These lower supports were mounted on casters. The two trunion supports were held together by 2 x 2 inch angles forming the completed hot box support. The completed guarded hot box apparatus is shown in Figure IV.

The heating system may be divided into two parts — the

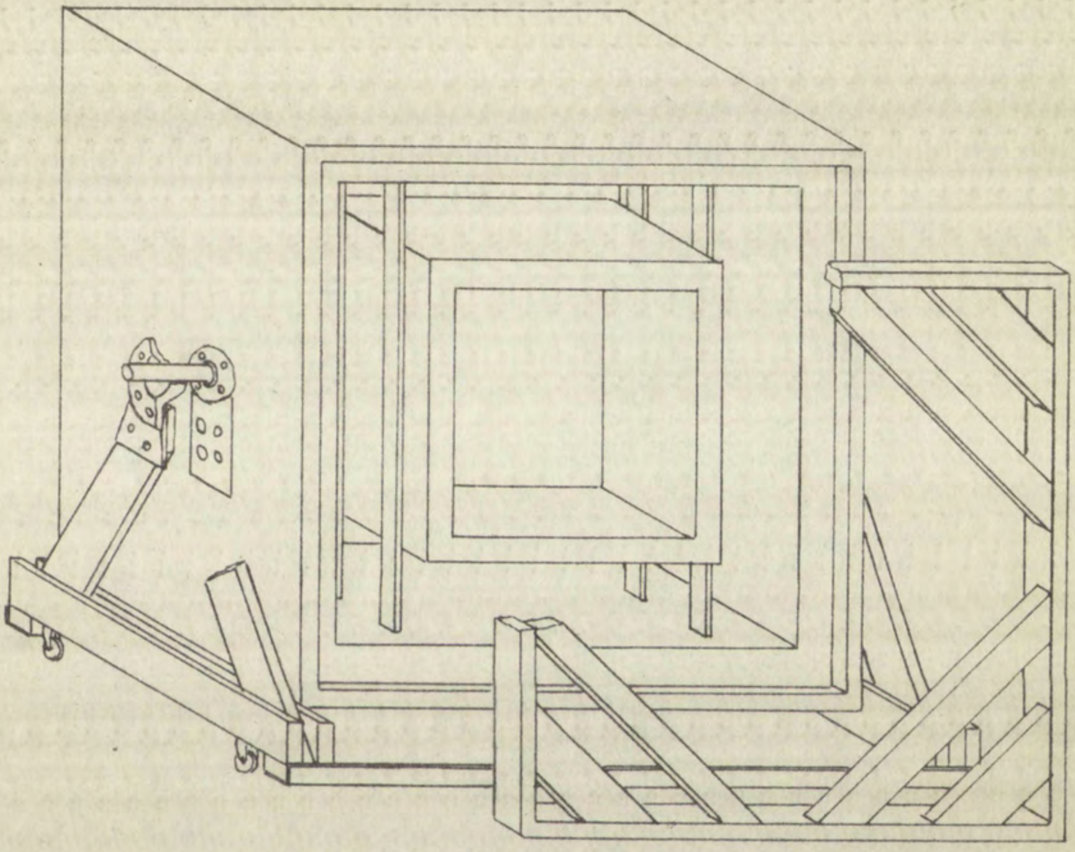

Figure IV Complete Guarded Hot Box Showing Cover in Section

inner box and the outer box. These systems are entirely independent, the power coming from different sources. Both systems have undergone considerable revision since the first test was conducted to give better control and heat distribution within the hot box.

In the outer system, the heating elements are divided into two identical groups, one placed below and one placed above the inner box. Fans are placed in the lower right hand and upper left hand corners of the large box to circulate air over the heating elements, providing an even temperature distribution throughout the guard section. The heating sections are composed of one 250 watt strip heater, three 75 watt heaters, and two 25 watt bulbs. The 75 watt heaters and 25 watt bulbs are mounted in screw type sockets while the strip heater is bolted into place. The bulbs are painted with aluminum paint to reduce heat loss by radiation. This insures that the main method of heat transfer between the heaters and walls is convection, and so the air temperature as measured by the thermocouples gives a true picture. The heating elements are controlled by seven switches on the control panel. One DPST power switch connects 115v to the control switches and turns on the fans in the outer box. Each of the SPST control switches connects one element of each section across the line. All switches are labeled as to their function on the control panel.

The difference in heat output of the top and bottom

sections may be controlled by a rheostat mounted under the control table. This rheostat acts as a voltage divider on the common or ground wire of the system. By adjustment of this rheostat, the voltage across one section may be increased while that across the other is decreased. This adjustment makes possible an even temperature distribution throughout the guard section. The wiring diagram for this section is shown in Figure V, and the control panel is shown in Figure VI.

The heating system for the inner box has undergone considerable revision since the first trial run was made. It was originally contemplated that this section would consist of four heating elements and a circulating fan operating on a variable AC voltage between 90 and 140 volts. It was soon discovered that this fan alone supplied too much heat for walls with low thermal coefficients. As a result, a number of attempts were made to eliminate the need for a circulating fan with no success.

At this point, a more detailed examination of the type of heating used in this apparatus might be helpful. The system used is a continuous flow as opposed to the intermittent or thermostatically controlled system which is usually employed for this purpose. The system used requires very careful adjustment to give the correct temperatures within the hot box, but despite this and the greater length of time required for such a test, it was decided that the advantages of this system outweighed the disadvantages. One of these advantages was that indicating

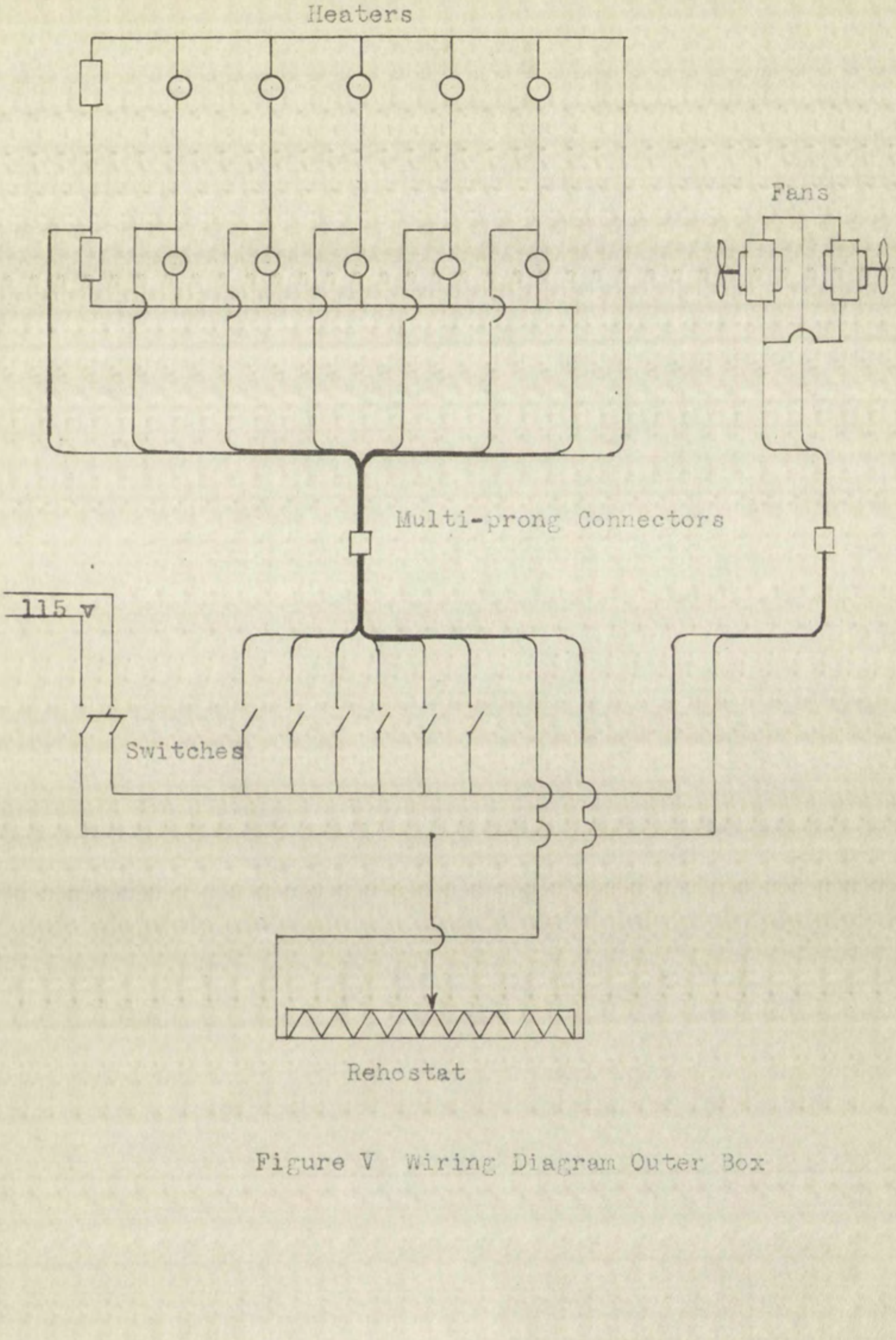

Figure V Wiring Diagram Outer Box

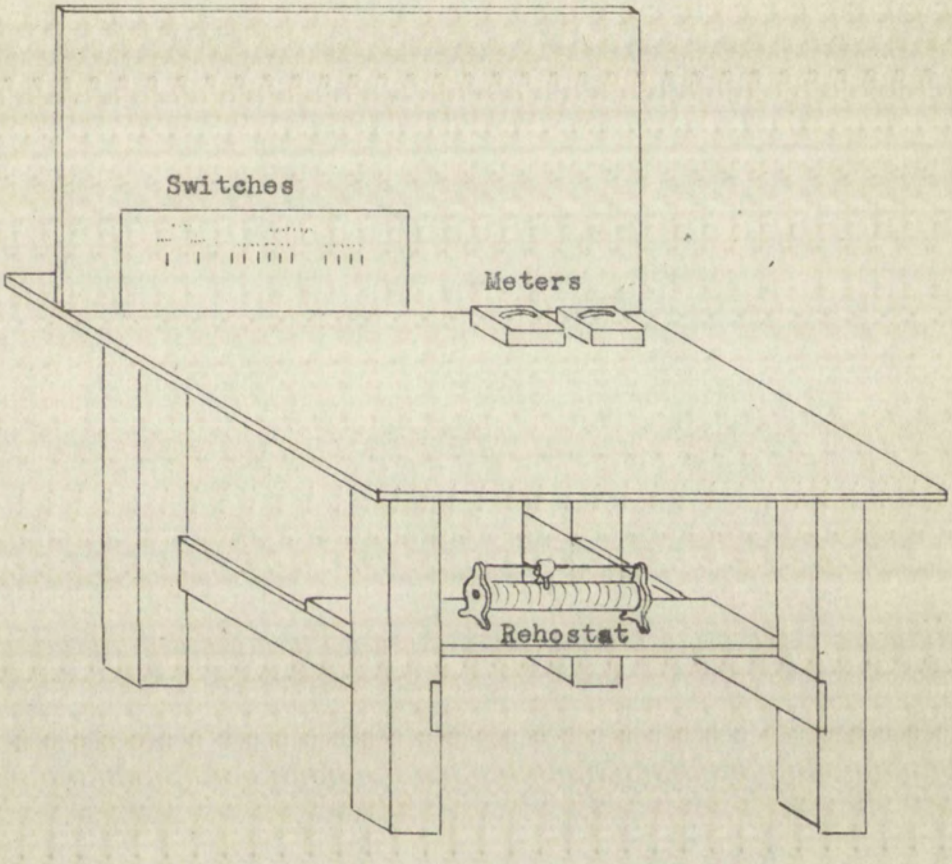

Figure VI Control Panel

meters could be employed instead of more expensive recording meters. This decision did not sacrifice any accuracy. In fact, indicating meters are generally more accurate than recording meters. Another advantage is that with a constant heat source, the heat flow through the test wall will be more nearly constant than with other systems. In addition, the intricate wiring required for thermostatic control is eliminated as well as the thermostat itself. This system also allows the use of DC current with the resultant ease of measuring the actual heat input. This means that since quadrature current is eliminated, so are its questionable heating effects.

In the final design, a universal motor, capable of being operated on as low as 10 volts DC, was used for a circulating fan. The only heating element was a length of small resistance wire. A variable DC voltage supply was all that was required for a continuously variable power supply which will supply the expected maximum and minimum power requirements of the hot box.

The variable DC voltage was supplied from a modified Phanotron full wave rectifier mounted near the hot box control table. This rectifier is a standard unit coupled by means of double throw switches to the secondary of either of two standard transformers. The filaments of the tubes in the rectifier are connected through a switch directly to the 115v AC line. The primary side of the transformers is connected through a double throw switch to the secondary of a 10KVA powerstat. The primary

side of the powerstat is connected through a switch to a 220v AC line. By varying the plate potential on the rectifier tubes by means of the powerstat, a variable DC voltage between 0 and 300 volts may be obtained. A wiring diagram of the complete inner box power system is shown in Figure VII.

Copper Constantan thermocouples were used throughout the hot box to measure temperatures. There were twenty thermocouples used in this apparatus, ten fixed within the hot box, five fixed to the cover, and five which could be placed within the test wall or mounted elsewhere and fastened to a terminal block on the cover. These thermocouples were made of Number 24 calibrated copper constantan lead wire with the junctions welded together. The junctions in the leads are kept to a minimum, and both sides of the junctions are kept as closely as possible at the same temperature. The thermocouples are led to 20 prong connectors on the hot box from which leads of the same wire continue to the terminal blocks at the selector switches. From the selector switches, one lead goes through the reference junction thermocouple held at 32° Fahrenheit and from there to the Leeds and Northrup Type K2 potentiometer. The other lead goes directly to the potentiometer. The complete wiring diagram of this system is shown in Figure VIII.

After the thermocouples were connected to the terminal blocks at the selector switches they were calibrated. This was done by immersing the junctions in a bath of water with an

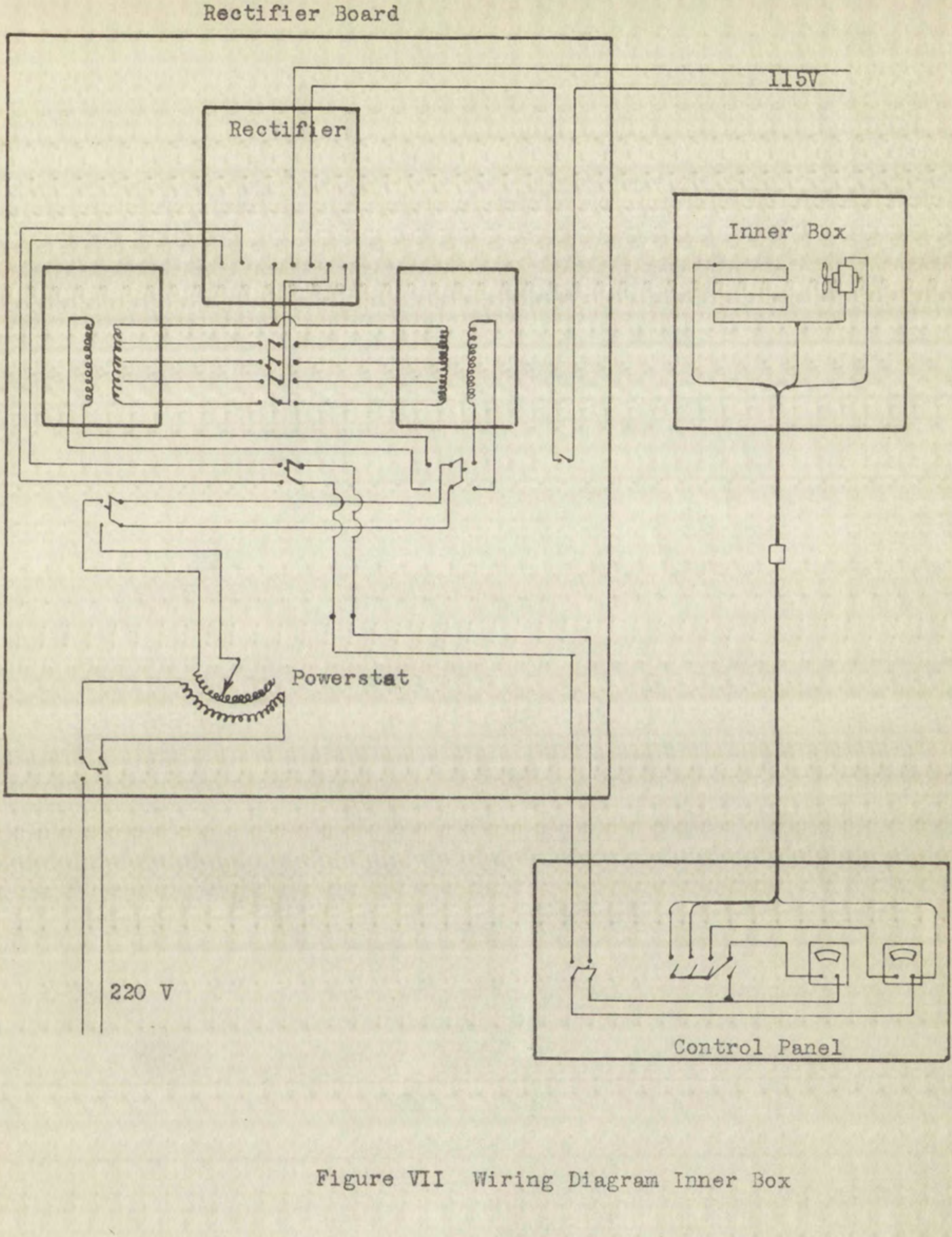

Figure VII Wiring Diagram Inner Box

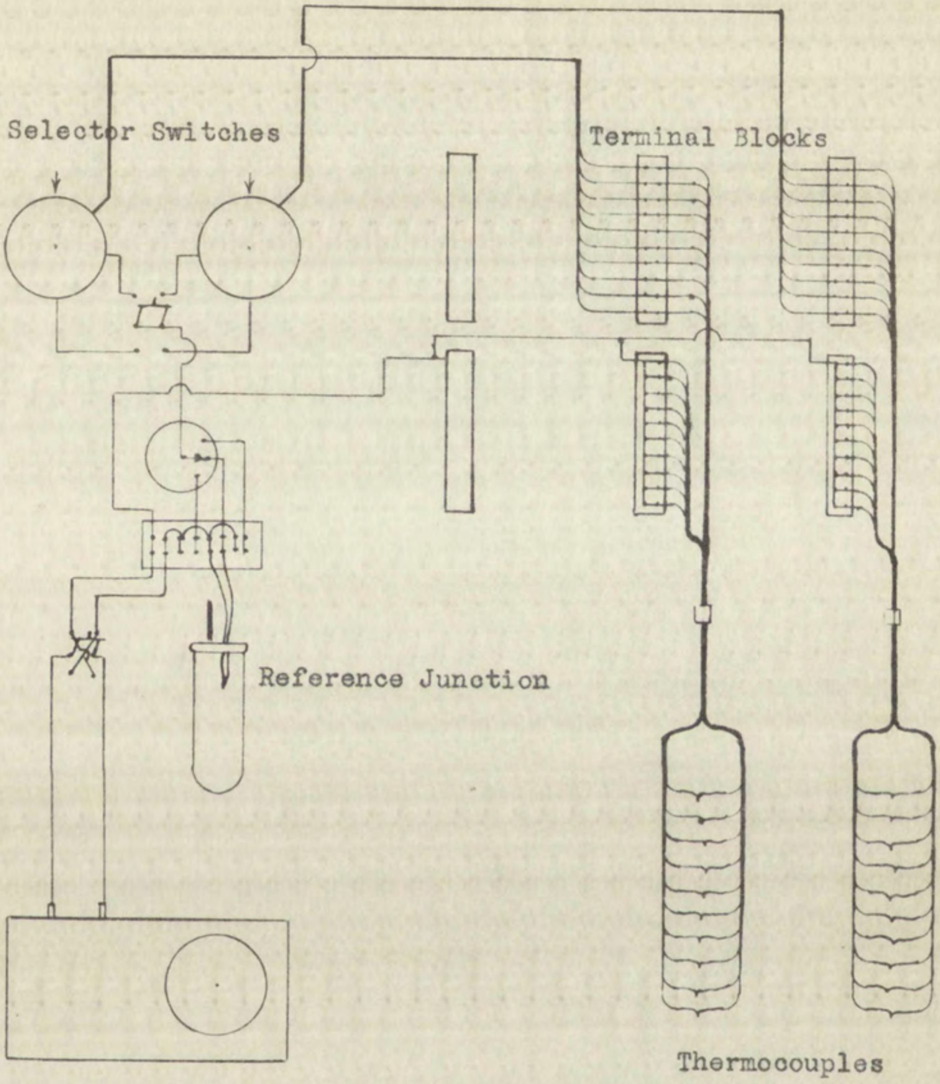

Figure VIII Wiring Diagram Thermocouples

accurate thermometer to read the temperature of the bath. By this calibration it was found that all twenty of the thermocouples read very close to the same temperature, and one correction curve could be plotted for the whole group. This curve is shown in Figure IX.

While the data for the correction curve was being taken, the effect of changing the temperature of the multiprong connectors was investigated with the result that no change in millivolt readings could be expected if such changes took place slowly.

These thermocouples were then fastened to piano wire springs which held them in the desired position against the test wall or in the air spaces. This system greatly simplifies setting up a new test and insures that results from one test will be comparable to another.

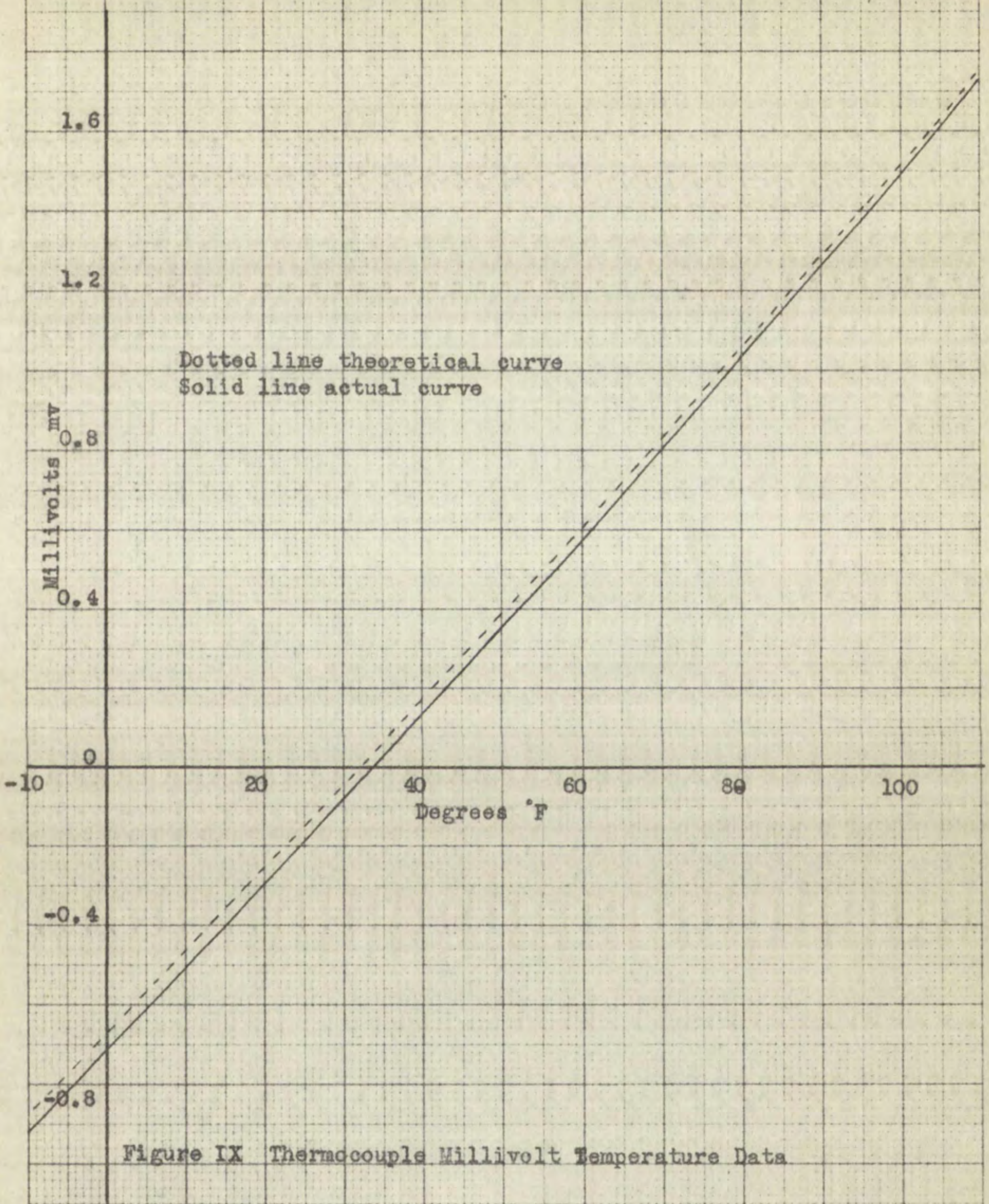

Figure IX Thermocouple Millivolt Temperature Data

CHAPTER V

OPERATION

The operation of the guarded hot box may be divided into two sections—the test and the calculations.

The actual conduct of the test involves the proper preparation of the test wall so that the required data will be obtained and careful adjustment of the heat inputs in the inner and guard sections to insure a reliable measure of the heat flowing through the test wall. When testing a wall section for the overall thermal coefficient, the standard thermocouples mounted in the hot box and its cover may be used. If some coefficient other than the overall wall coefficient is desired, the extra thermocouples may be placed where desired and used. In the tests conducted on reflective type of insulation, both of these systems were used. The placing of these extra thermocouples depends entirely upon the problem involved, and no generalization may be made.

The calculation of the thermal coefficient to the test section may be made by using the nomograph designed for this purpose (Figure X). This nomograph solves the equation

$$U = \frac{3.413\,(\text{volts})\,(\text{amps})}{6.8\,(\Delta T)}\ .$$

Use of this graph is recommended since it eliminates much possibility of error, and the results obtained are as accurate as

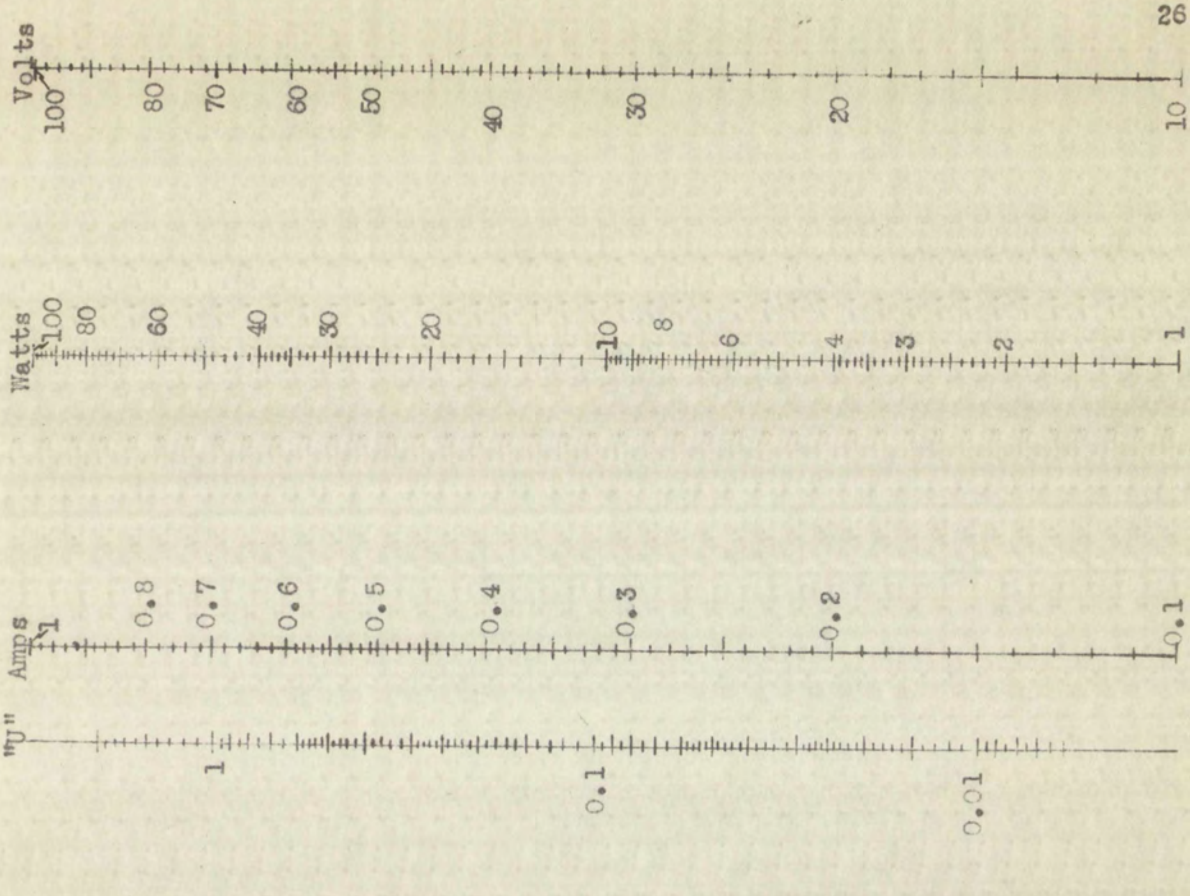

Figure X Nomograph $"U" = \frac{3.413\ (\text{volts})(\text{amps})}{6.8 \qquad \Delta T}$

is consistent with the data obtained. If exceptionally accurate data should be obtained, the nomograph will serve as a check on the calculations.

In tests conducted upon a standard wall in this laboratory, the wall was tested without insulation, and then the test was repeated with insulation installed. From these tests the thermal coefficient was calculated for the insulation.

A second nomograph was designed to help in this calculation (Figure XI) which solves the equation

$$\frac{1}{U} = \frac{1}{U^1} + \frac{1}{C}$$

where

U is the thermal coefficient of the wall with insulation,

U^1 is the thermal coefficient of the wall without insulation, and

C is the thermal coefficient of the insulation.

This method of calculating the coefficient of the insulation is not recommended except as a check for other methods of calculation. The reason for this statement is obvious when the nomograph is studied. A very small error in either of the coefficients U or U^1 will be magnified in the value of C. As a check, this method can confirm other methods for determining the value of the insulation directly.

As an example of the tests obtainable with this apparatus, the following tests are reported.

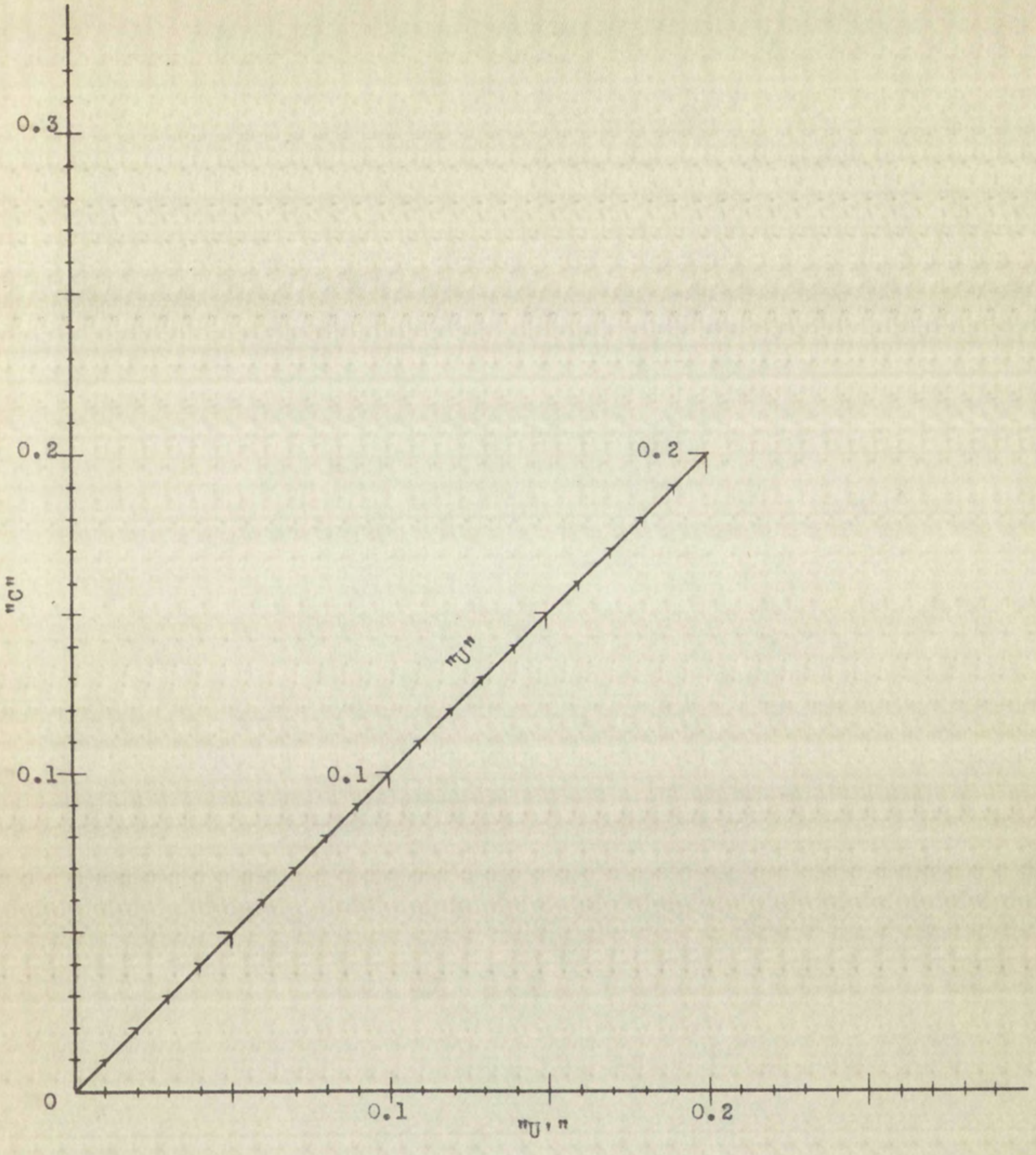

Figure XI Nomograph $\frac{1}{"U"} = \frac{1}{U'} + \frac{1}{C}$

A "standard" wall was built of two one-half inch sheets of celotex fastened to opposite sides of standard 2 x 4 studding. The sheet on the inner side was fastened into place with screws so that it could later be removed and insulation be installed within the air space. The wall was first tested without insulation with thermocouples mounted so that they touched the surfaces of the wall. Theoretically, these thermocouples should read the surface temperature of the wall, but actually they probably read some temperature between the surface and the air temperatures. When the wall was tested in this manner with the wall in a vertical position, the thermal coefficient was found to be 0.21.

The theoretical value for this wall was calculated using values and methods as given in the Heating, Ventilating, and Air Conditioning Guide. These calculations are shown in Appendix A. Calculation of the wall without exterior surface coefficients gives 0.232 for the thermal coefficient. Assuming still air on both sides and including these surface coefficients, the thermal coefficient becomes 0.186. Since the experimental coefficient is approximately halfway between these calculated values, the coefficient determined may be considered correct. In an actual test of a wall for its thermal coefficient, air temperatures would be used, and the velocity of air over the surfaces determined. In such a case, even closer correlation could be expected.

The experimental coefficient as determined in the previous

case was used to calculate the coefficient for Alfol Type I Insulation. The same wall was filled with this insulation and a second test conducted in the same manner as the first. In this case, the coefficient for the wall was 0.1135. By use of the nomograph in Figure XI, the coefficient for the insulation itself was determined as 0.246. As it has already been stated, this method is not recommended except as a check on other methods of determining this factor. In one such method, the temperature difference was measured from the surface of the paper backing of the insulation to the temperature of the air space between the foil and the outer wall surface. The coefficient was determined in this case as 0.265. The results of these tests are believed to be in close enough agreement, and the thermal coefficient for the insulation was determined as 0.265.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The results of the tests conducted on Alfol (reflective type) Insulation show the guarded hot box apparatus to be an accurate, versatile, and convenient device for the determination of thermal coefficients. The results obtained compare favorably with the coefficients given in the Heating, Ventilating, and Air Conditioning Guide, and are, in general, more accurate than the results of calculations based upon the Guide. In future studies of southwestern building constructions, this apparatus should prove most helpful.

The apparatus as constructed and operated at the present time is complete and needs no major changes. However, certain modifications in associated equipment are indicated.

At present, it is impossible to obtain as low a temperature in the refrigerated room as is desired. Probably the easiest and cheapest way of correcting this situation would be to install a false floor in this room, insulating it from the present floor. This is deemed advisable since only the floor is uninsulated at present. It is believed that reflective type insulation would be satisfactory in this installation.

The actual physical setup of the refrigerating equipment leaves some things to be desired, but, on the whole, it is considered satisfactory. The defrosting system, however, is not

satisfactory. With continuous use of the refrigerated room, frequent defrosting becomes necessary, and it was often found that the present defrost water line was frozen solid. Such a condition required that the complete room be allowed to warm up until this line thawed.

It is strongly recommended that the board upon which the thermocouple terminal blocks are mounted be shielded from the radiation of the sun in a better manner. It has been found that the results obtained during the day are erratic, and, as a result, most of the results reported were obtained after dark. This could be accomplished in a number of ways, but probably the easiest would be to cover the top of the panel board on which the thermocouple terminal blocks are mounted and to paint the windows behind this board. This would also make reading the galvanometer easier.

Further study should include the measurement of the wind velocities across the surface of the test wall. With the present setup, winds could be manufactured by a large fan blowing across the surface of the wall and the wind velocity measured with a velometer. It also would be interesting to measure the thermal coefficient under conditions such as rain or snow might produce. A spray of water on the exposed surface of the test wall should satisfy these conditions, and there are no published results of similar tests insofar as the author has been able to determine. Such tests as these would undoubtedly lead to further fields of

study which would expand the usefulness and versatility of the guarded hot box apparatus even further.

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APPENDIX A

Calculations for Celotex Wall

Data:

K for Celotex $= 0.33$

$$\frac{x}{K} = \frac{0.5}{0.33} = 1.515$$

C for Air Space $= 1.10$

$$\frac{1}{C} = 0.91$$

K for Studding $= 0.80$

$$\frac{x}{K} = \frac{3.625}{0.80} = 4.62$$

Surface Coefficient f for still air $= 1.65$

$$\frac{1}{f} = 0.61$$

Calculations - Surface Coefficients Neglected:

$$U_a = \frac{1}{1.515 + 0.91 + 1.515} = \frac{1}{3.940} = 0.254$$

$$U_f = \frac{1}{1.515 + 4.62 + 1.515} = \frac{1}{7.650} = 0.131$$

$$U_t = \frac{14.375(0.254) + 1.625(0.131)}{16} = 0.242$$

Calculations - Surface Coefficients Included:

$$U_a = \frac{1}{0.61 + 1.515 + 0.91 + 1.515 + 0.61} = 0.194$$

$$U_f = \frac{1}{0.61 + 1.515 + 4.62 + 1.515 + 0.61} = 0.103$$

$$U_t = \frac{14.375(0.194) + 1.625(0.103)}{16} = 0.186$$

D.T.

Date Due

FEB 22	1952		
MAR	7 1952		
MAR 26	1952		