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ENVIRONMENTAL STUDIES OF A 100-MAN UNDERGROUND SHELTER

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ADMINISTRATIVE INFORMATION

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OCD REVIEW NOTICE

This report has been reviewed in the Office of Civil Defense and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

ACKNOWLEDGMENTS

The efforts of a number of individuals were required to carry out these tests. The assistance rendered by R.J. Crew and N.J. Vella in designing the experiment and setting up the test apparatus was invaluable. They also contributed greatly to the success of the tests due to their assistance in actually carrying out the first three test runs. Mr. A.J. Guay assisted in carrying out test runs 4 and 5 and contributed immeasurably to the task of data reduction. The Mechanical Engineering Department of Oklahoma State University applied a newly installed thermal analyzer to these shelter test data at no cost to the Government. We are indebted to Dr. J.A. Wiebelt, Associate Professor of Mechanical Engineering at OSU, for cooperation in setting up their study and to Lt. W.L. Othling, who prepared the report of this work, reproduced in the Appendix.

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ABSTRACT

Temperature studies were conducted during both simulated and human occupancy tests on the NRDL 100 man shelter. The temperature of the shelter remained comfortable during 14 days of human occupancy. The ventilating air movement through the shelter designed for 16 cfm per occupant was adequate to reduce the carbon monoxide concentration from heavy smoking to below safe tolerance limits and it removed 69 % of the heat generated by the occupants with only 31 % of the heat being dissipated through the walls. The shelter temperature varied between 74 and 90°F with an outside air temperature of 50 to 94°F during the simulated occupancy test and between 70 and 82°F during the human occupancy tests with an outside air temperature of 36 to 67°F. Poor distribution of the inlet air resulted in uncomfortably cool areas in the front of the shelter during the human occupancy test.

A preliminary analysis was conducted on a thermal analyzer to determine its potential as a tool for predicting shelter temperatures under various climatic conditions. This analysis showed only about 10 % deviation from the measured temperature reported here.

SUMMARY

The Problem

To determine the adequacy of the NRDL 100 man shelter design to maintain comfortable living conditions for at least 14 days of human occupancy.

Findings

Under the conditions of the test the temperature and humidity of the shelter remained within comfortable limits for 14 days of human occupancy test except for cool drafts at the front of the shelter due to poor distribution of the inlet air. The average heat output by the occupants was 485 Btu/hr per man. The ventilating air movement through the shelter of 16 cfm per occupant was adequate to reduce the carbon monoxide concentration due to heavy smoking to below safe tolerance limits. It removed 69 % of the heat generated by the occupants with only 31 % of the heat being dissipated through the walls. The effective temperature in the shelter varied between 74 and 80° during the simulated occupancy run when the ambient air temperature varied between 50 and 94°F. During the human occupancy test the effective temperature was 70 to 82° with the outside air temperature varying between 36 and 67°F.

A preliminary study on a thermal-electrical analyzer at Oklahoma State University showed approximately 10 % variation from the measured conditions. This indicated that reliable studies can be made in the laboratory for predicting the environmental conditions in this shelter located in various climates.

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CHAPTER 1

INTRODUCTION

The protection of the nation from the hazardous radioactive fallout of a nuclear war has been given much consideration in recent years. The most common considerations are the protection of individuals in family shelters and the protection of large groups in community-built shelters.

A prototype 100-man shelter was constructed by NRDL in 1959 at Camp Parks approximately 40 miles east of San Francisco. A variety of experiments have been performed in this shelter to establish adequacy of the ventilation in maintaining comfortable temperature and humidity, to study the psychological effects of confinement in a group shelter, to study the need for closure during mass fires, and fallout ingress experiments to determine the need for filters in the ventilation system. The results of these studies are abstracted in reference (1).

In the design of a community shelter it is essential that the cost be kept to a minimum, whether these shelters are to be financed by the government or by private enterprise. The problem of building a shelter at lowest possible cost automatically requires that both the floor area and the gross volume per man be reduced to a minimum. To maintain physical comfort in a shelter under these conditions, sufficient ventilating air must be provided to carry off the heat and moisture generated by the occupants. These factors were weighed against cost in the design of the U. S. Naval Radiological Defense Laboratory 100 man shelter and a blower was selected which was expected to maintain a comfortable environment at minimum cost.[2]

The methods available for theoretical analysis of the heat-transfer conditions in the shelter were limited so it became necessary to conduct temperature studies during actual human occupancy tests. As a precautionary measure prior to conducting these tests a study was made with 100 devices which simulated human occupants.

CHAPTER 2

EXPERIMENTAL CONDITIONS

2.1 SHELTER CONSTRUCTION

Figure 1 is an artist's sketch showing the basic design features. It is a galvanized multi-plate steel arch type structure (Standard Navy Ammunition Hut) with a floor area of 25 ft x 48 ft. It is buried with the top flush with the ground level and then covered with a 3 ft mound of soil. It has a capacity of 100 people with a floor space of 12 sq ft per man and a gross volume of 117 cu ft per man. It has 4 tiers of bunks on each side with a sleeping capacity of 96. These bunks can be rolled up to provide more space in the daytime. Air intake openings are located in the entry-way at the top of the stairs as shown in Fig. 2. Fresh air is drawn in with a blower located outside the inner door. The air comes into the shelter space through a duct over the inner door and is exhausted out a vent located at the rear. The air intake can be closed and the exhaust vent dropped down to give an air tight closure. Tanks are provided for water and gasoline storage, the gasoline being used to operate an emergency power unit.

The soil surrounding the shelter was of two types as shown in Fig. 3. Construction specifications called for backfilling up to a level 8 ft from the floor with select fill compacted to a specific density. The contractor chose to use pea gravel for this select fill. The original soil removed during excavation was then put on top of this select fill.

2.2 INSTRUMENTATION

2.2.1 Temperature Measuring Stations

Upon completion of the shelter construction, holes were drilled through the walls and thermocouple probes were inserted at the locations shown in Fig. 4.

A series of probes were located on the center line at 4 ft, 8 ft, and 11 ft from the floor, at the top of the arch and one in the floor at the center. An additional set was located midway between the front and the

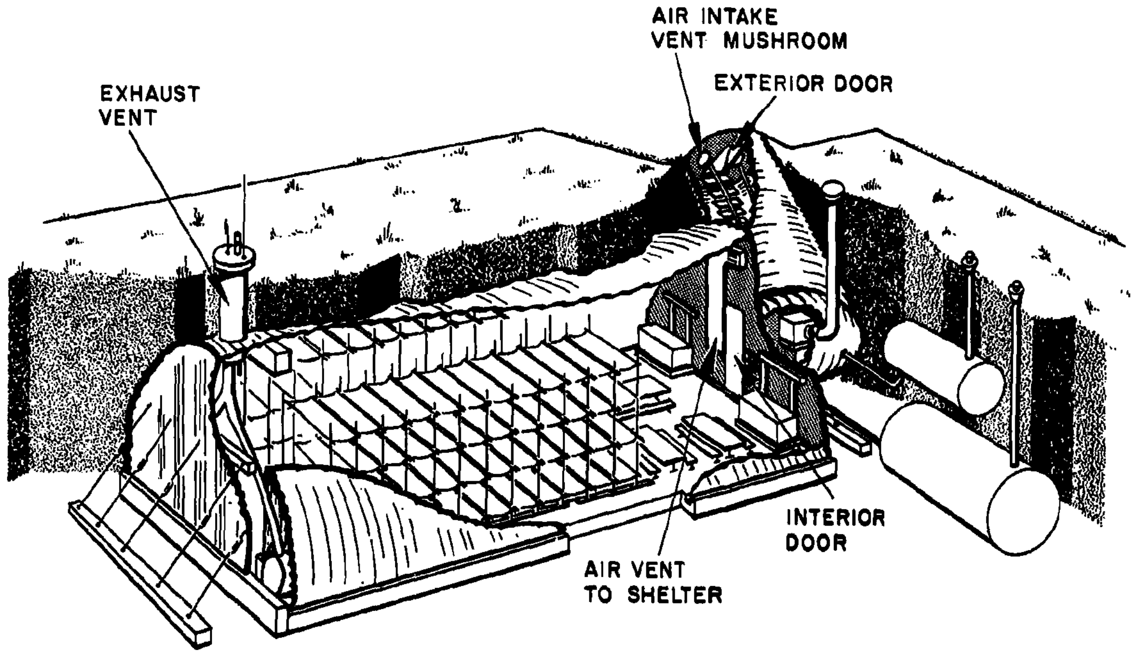


Fig. 1 Cut-away Diagram of Shelter

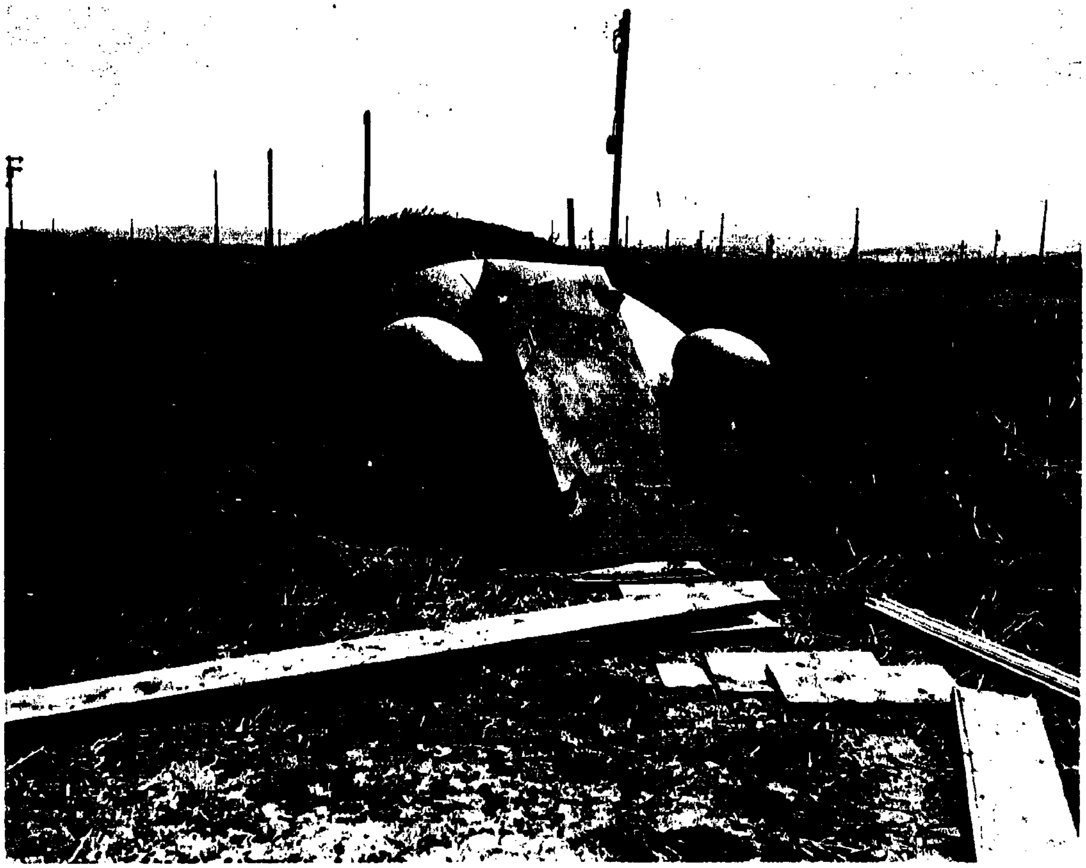
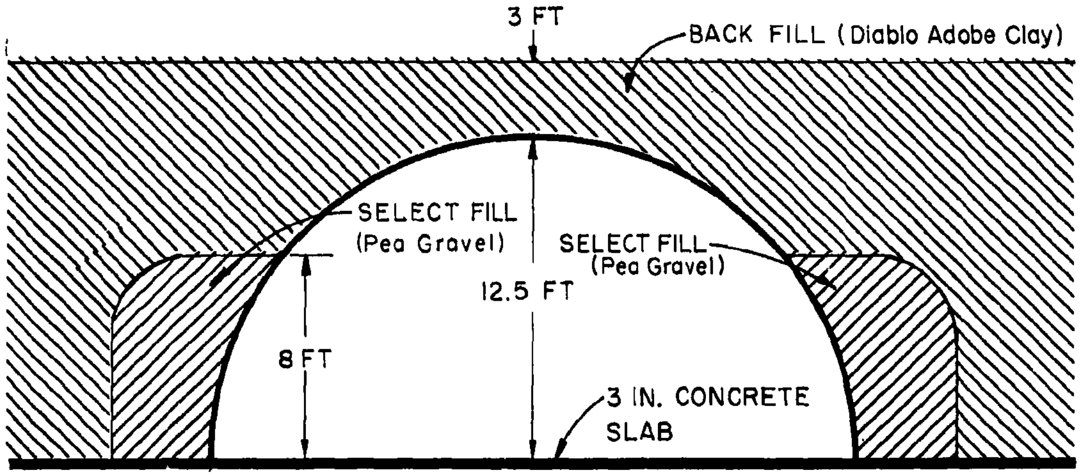


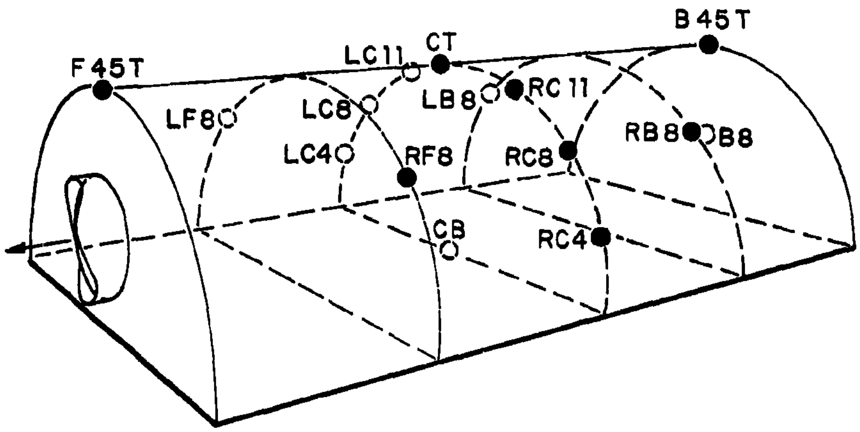
Fig. 2 Shelter Entrance Showing Blast Bulkhead, Exterior Door, Mushroom Shaped and Intake Vent Covers



SURFACE AREA OF SHELTER IN CONTACT WITH THE VARIOUS SOILS

SOIL	CONTACT AREA
SELECT FILL (SF)	1160 SQ FT
BACK FILL (BF)	1175 " "
FLOOR (F)	1200 " "

Fig. 3 Soil Conditions Surrounding the NRDL Shelter



F-FRONT SECTION L-LEFT SIDE
C-CENTER LINE T-TOP
B-REAR SECTION R-RIGHT SIDE

NUMBERS DESIGNATE THE HEIGHT ABOVE THE FLOOR. FOR EXAMPLE- LF-8-LEFT FRONT 8FT FROM FLOOR. RC-11-RIGHT CENTER 11 FT FROM FLOOR.

F45T & B45T } THERMOCOUPLE LOCATED IN CORNER AT 45° ANGLE.

Fig. 4 Temperature Measuring Stations

center line and another one midway between the rear and the centerline at the 8 ft level. A single probe was located in the back wall at the 8 ft level. The thermocouples at each station consisted of five couples, one on the inside of the metal surface, one at the outside surface and one each at 1 ft, 2 ft and 3 ft into the surrounding fill.

The external surface and the thermocouples at 1 ft, 2 ft and 3 ft from the shell of the shelter were positioned on thin-wall, half-inch diameter phenolic resin tubes that were pushed through holes in the shelter wall (Fig. 5). The thermocouple leads were secured to the outside of the plastic tubes at proper locations. After positioning the four couples on each tube, one end was sealed and the tube then filled with sand. A half inch pipe with a loosely fitting steel point in the end was driven into the soil at the desired locations and the probe slipped into place. The pipe was then pulled out over the lead wires, leaving the steel point and the probe in the soil.

The internal surface temperature thermocouples were attached to the wall with masking tape. Wet and dry bulb temperatures were taken at the entrance, center of shelter and at the exhaust. The thermocouple leads were all taken out through an opening in the top of the shelter near the exhaust vent and connected to continuous strip chart recorders. Continuous temperature recordings were made with an automatic printout of each temperature every 8 minutes.

During the simulated occupancy tests, wet bulb thermocouples were located at the entrance to the shelter, inlet over the inner door, center of the room and at the exhaust. The evaporation at these thermocouples was accomplished by a small electric fan.

2.2.2 <u>Human Simulators</u>

The simulators were designed to simulate the latent and sensible* heat output of a human. These human simulators consisted of a nichrome wire heating coil mounted in the bottom of a five gallon paint pail. The pails were covered with cotton flannel to serve as a wick. The moisture output of the simulators was provided by dripping water onto the top of the pail. The water output was regulated by a valve at each simulator and the total flow of water into the shelter was controlled in the instrument shack. The amount of water to be added was varied with the temperature at the center of the room.

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*Sensible heat added to the shelter is a direct addition of heat to the enclosure by any one or all of the mechanisms of conduction, convection, and radiation. A gain of latent heat is considered to occur when there is an addition of water vapor to the air of the enclosure.

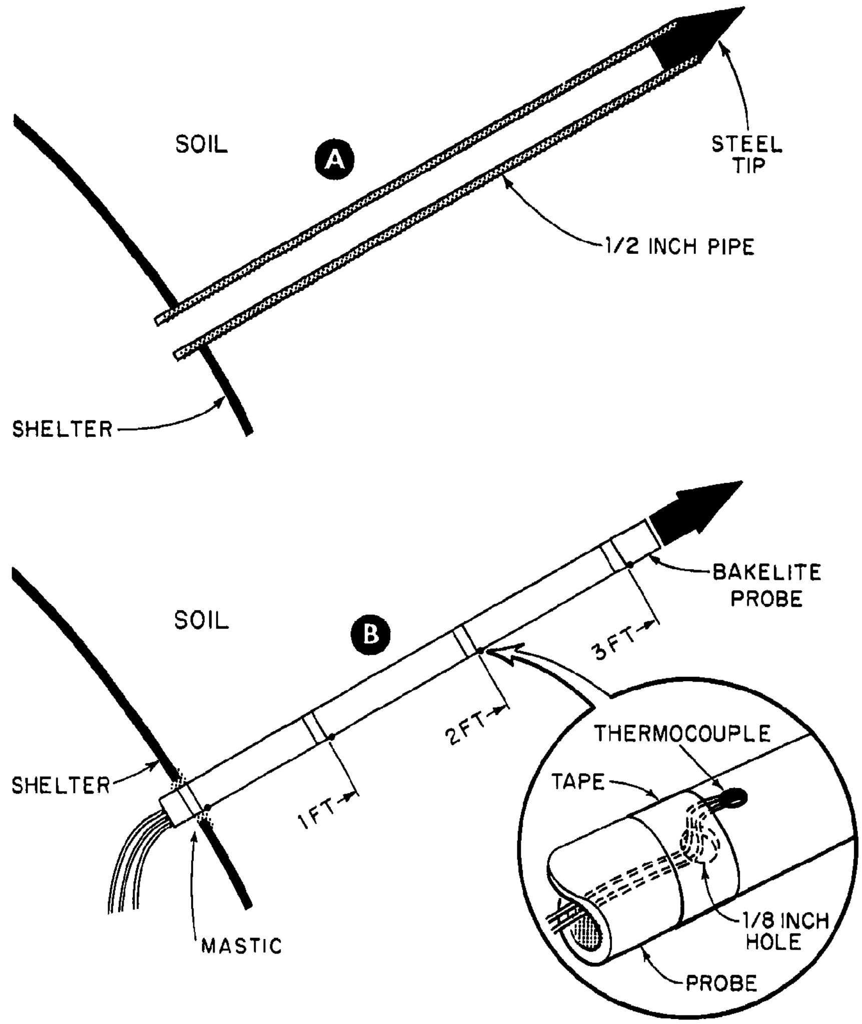


Fig. 5 A. Pipe Driven Into Soil Prior to Inserting Thermocouple Probe
B. Thermocouple Probe in Location in Soil After Removing Pipe

Thirty-six simulators were located on each side in the approximate position of the center bunk as shown in Fig. 6.

The remaining 28 simulators were located in the front section at the tables as shown in Fig. 7.

2.2.3 Carbon Monoxide Measuring Equipment

The carbon monoxide measuring instrument was provided by the U. S. Forest Service. This equipment, developed by the Forest Service Pacific Southwest Forest and Range Experiment Station, consisted of surplus detectors which had previously been used as warning device in aircraft. These detectors split the flow of a gas sample through two cells connected by a thermopile. One cell contains activated hopcalite* which catalyzes the oxidation of carbon monoxide. The resulting temperature difference between the two cells is a function of the carbon monoxide concentration in the air being sampled. This temperature difference results in an emf being generated in a thermopile which is recorded on a strip chart recorder. The unit is calibrated to give approximately 100 millivolts for a concentration of one percent (by volume).

*Hopcalite - a mixture of oxides of copper, cobalt, manganese and silver, used in gas masks as a catalyzer converting carbon monoxide to carbon dioxide.

Fig. 6 Human Simulators, Each at the Approximate Center of the Bunks

Fig. 7 Human Simulators in the Forward Section of the Shelter

CHAPTER 3

TEST PROCEDURES

3.1 TEMPERATURE TESTS

A total of five tests were conducted as shown in Table 1. During the simulated runs No. 1 and 2, the water output of the simulators was regulated by a valve at each station and the total flow of water into the shelter was measured by a flowrator in the supply line. The amount of water added was varied with the center room temperature in accordance with the values given in Fig. 8. The total heat into the shelter by the simulators was maintained at 470 Btu/hr per man, which is an estimate of the heat that would be generated by a shelter occupant. This value is based on data from the Heating and Ventilating Guide of the American Society of Heating, Refrigeration and Air-Conditioning Engineers which give 380 Btu/hr as the heat generated by a human seated-at rest, 430 standing at ease, and 760, walking at 2 mph.

Preliminary heat balance calculations on runs No. 1 and No. 3 indicated inaccuracies in the heat transfer coefficient for soil, because of the diurnal temperature variations in the inlet air. Therefore runs 4 and 5 were conducted with air vents closed. These tests were continued for a sufficient length of time to establish a constant rate of heat loss to the soil.

3.2 METHOD OF PREDICTING SHELTER THERMAL CONDITIONS

Heat transfer in this shelter is a complex process and predicting the shelter environment under various climatic conditions is difficult. Therefore arrangements were made with the Mechanical Engineering Department of Oklahoma State University to determine the feasibility of using a system which they have developed and called a thermal analyzer to determine shelter thermal behavior under various specified conditions.

TABLE 1

Test Conducted

Run No.	Occupancy	Inlet Air	Exhaust	Heat Input	Moisture Added	Test Duration	Date of Test
1	100 Simulators	1600 cfm	Open	47,000 Btu/hr	Varied with center room temp.	10 days	10/20/59 to 11/3/59
2.	100 Simulators	None	Closed	47,000 Btu/hr	Varied with center room temp.	24 hrs	11/3/59 to 11/4/59
3	100 Humans	1600 cfm*	Open	100 men	Natural body loss	14 days	12/3/59 to 12/17/59
4	100 Simulators	None	Closed	30,490 Btu/hr	None	11 days	5/17/60 to 5/28/60
5	100 Simulators	None	Closed	47,024 Btu/hr	None	7 days	6/6/60 to 6/13/60

*The blower was turned off occasionally in the early morning hours to reduce chilling in the front section of the shelter. The shut down time varied from 30 min to 2 hrs and 45 min.

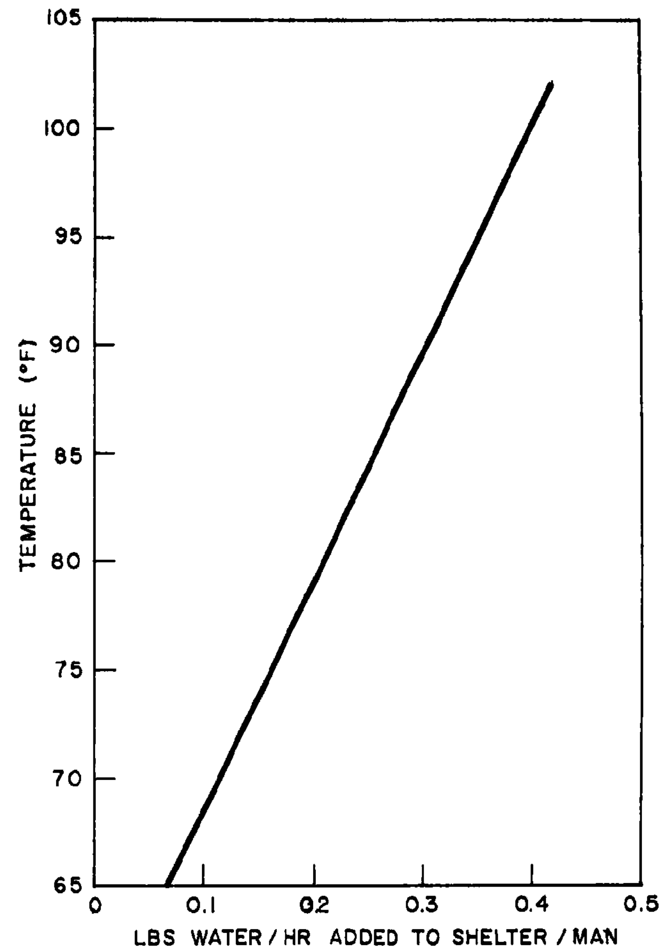


Fig. 8 Relationship of Water Emitted by 100 Persons to Temperature of Their Environment (based on data from the ASHVE Guide)

The thermal analyzer applies the principles of thermal-electrical analogy which is based on the similarity of the equations describing heat and electrical conduction. The partial differential equation for temperature distribution in a solid conducting heat can be compared to the partial differential equation for the distribution of electrical potential produced by a current flowing through an electrical network with lumped parameters. The rate at which thermal energy is stored can be compared to the rate of flow of charge into a capacitor. Therefore a resistance-capacitance electrical circuit serves as an analogue for heat flow in a slab. In this analogy, electrical current corresponds to heat flow, electrical voltage differences to temperature differences, electrical resistance corresponds to thermal resistance, and electrical capacity corresponds to thermal capacity. The physical system is lumped or sub-divided into geometrical sections of simple shape and form. The thermal properties of each section are considered to be concentrated at the central nodal point of each section or volume, and heat is imagined to be conducted between nodal points through a network of fictitious heat-conducting rods of appropriate thermal conductance. Details of procedures used in the development of this analysis are given in the Appendix.

3.3 CARBON MONOXIDE MEASUREMENTS

Air samples were drawn continuously by a vacuum pump from the front, center, and rear of the shelter during the human occupancy tests (Run #3) and put through the carbon monoxide measuring equipment. Carbon monoxide samples were also drawn from these locations with the shelter empty while operating the gasoline driven motor generator to study its effect on the shelter environment.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 TEMPERATURE STUDIES

Figure 9 shows the shelter temperature during Run No. 1 (simulated occupancy). The relationship of center shelter temperature to the air temperature at the entrance to the shelter and the air temperature where it enters the shelter proper, i.e. over the inner door, are shown. The effective temperature in the center of the shelter is also shown. Effective Temperature as described by ASHRAE is an empirically determined index of the degree of warmth perceived on exposure to different combinations of temperature, humidity, and air movement. The effective temperature index cannot be measured directly, but is determined from dry and wet-bulb temperatures and air motion observations by reference to an Effective Temperature Chart prepared by the ASHRAE. This was prepared from studies in which trained subjects compared the relative effects of various air atmospheres by occupying, alternately, two adjoining air conditioned rooms. The acceptable effective temperature range for normally clothed men and women, at rest, during winter and summer months is 63 to 75. In an emergency situation this upper limit would undoubtedly be raised. At present an effective temperature of 85°F is considered acceptable for survival shelters.

At the beginning of the simulated shelter occupancy test (Run No. 1) the air entering the shelter was at 75 degrees and the center room temperature was 5 degrees lower. Within 4 hours the shelter air temperature was at 80° and never dropped below 75° for the duration of the run. The shelter temperature reflected the diurnal variations but was considerably damped. After the first day of occupancy the entrance air varied from 94 to 50 degrees and the shelter temperature varied from 90 to 75 degrees. The effective temperature varied from 72 to 82 degrees in the center of the shelter which is somewhat higher than the optimum effective temperature.

The shelter temperature during Run No. 3 (Human Occupancy) is shown in Fig. 10. The relationship of the center shelter temperature to the entrance and inlet air temperature are shown. The effective temperature in the center of the shelter is also shown. It will be observed that the ambient air temperature at the start of this test was approximately 10 degrees lower than in the simulated occupancy run. The entrance air reached a low of 36 and a maximum of only 67. The minimum shelter

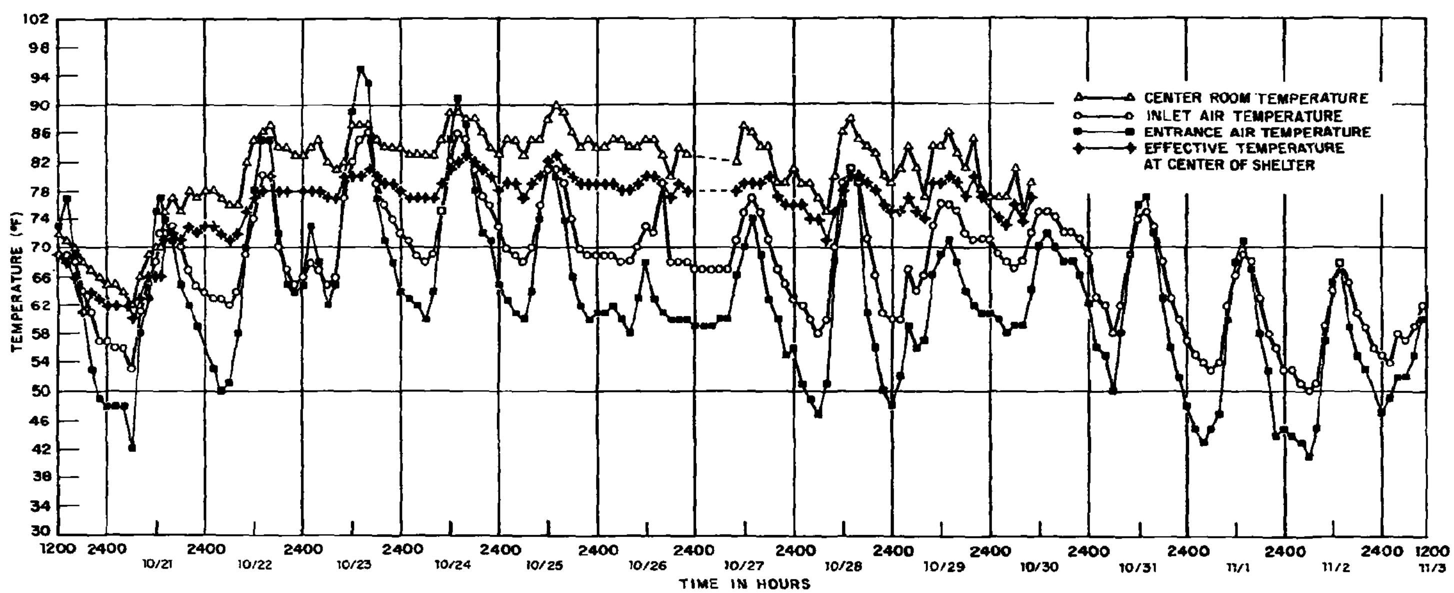


Fig. 9 Simulated Human Occupancy of Shelter (Run No. 1).

temperature was 70 and a maximum of 82. Although the temperature recordings showed a low of 70 in the center of the room the air entering the space dropped to as low as 45 degrees. Due to poor inlet air distribution there were cool drafts in the front portion of the shelter. To minimize the air intake problem the blower was turned off for short periods during the coolest part of the night. This procedure was followed for the first 6 days. During the sixth day the occupants felt that they had corrected the difficulties by bending the baffles in the inlet duct; however, it will be observed on Fig. 10 that after the sixth day there was a coincidental rise in the inlet air temperature. The low entrance air temperature for the first 6 days was 36 degrees and on the 7th and 8th day it was 48 and 42 respectively. After the first day of occupancy the center room temperature fluctuated from 70° to 82° and the effective temperature varied from 64° to 74°.

Although Run No. 2 was too short to give any significant temperature gradients through the soil the importance of the ventilating air in removing moisture from the shelter was demonstrated immediately after the shelter was closed down. Within 1-1/2 hrs after shutting off the air supply, moisture was condensing on the ceiling and within 2 hrs the entire metal surface was covered with moisture which started running down and collecting at the bottom. Within 10 to 15 min after turning on the blower at the conclusion of the run, it was comfortable near the front of the shelter and within 30 to 40 min it was comfortable throughout the shelter.

Analysis of Heat Losses in Shelter

The heat put into the shelter by either the simulators or human occupants must be expelled through the shelter walls or lost to the ventilating air. Therefore the total heat input to the shelter equals the heat lost to the air plus the heat lost to the soil, or

$$Q\ \text{total} = Q_{air} + Q_{soil} \tag{1}$$

In the simulated occupancy test the heat picked up by the air consisted of three components: q_1 - the heat expended in vaporizing the added water and heating this vapor to the exhaust temperature; q_2 - the heat expended in raising the water vapor in the inlet air to the exhaust temperature; and q_3 - the heat used in raising the inlet air to the exhaust temperature.

$$Q_{air} = q_1 + q_2 + q_3 \tag{2}$$

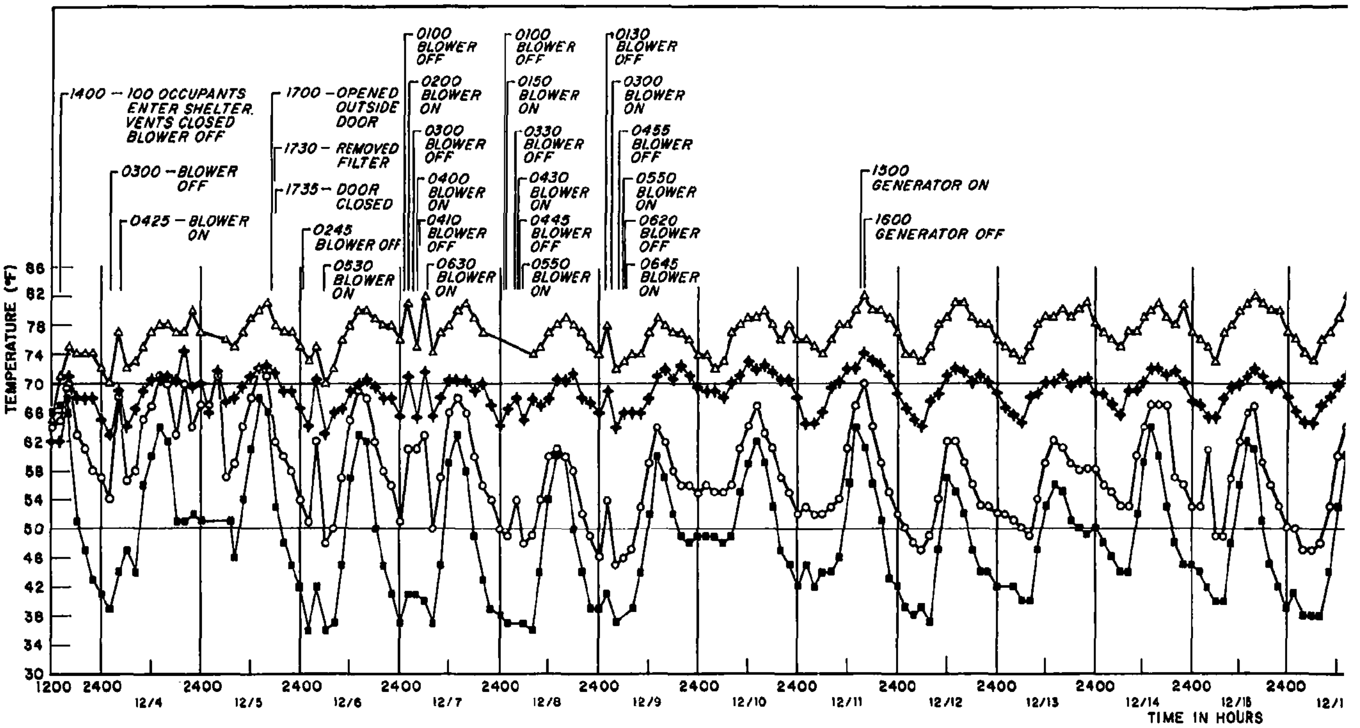
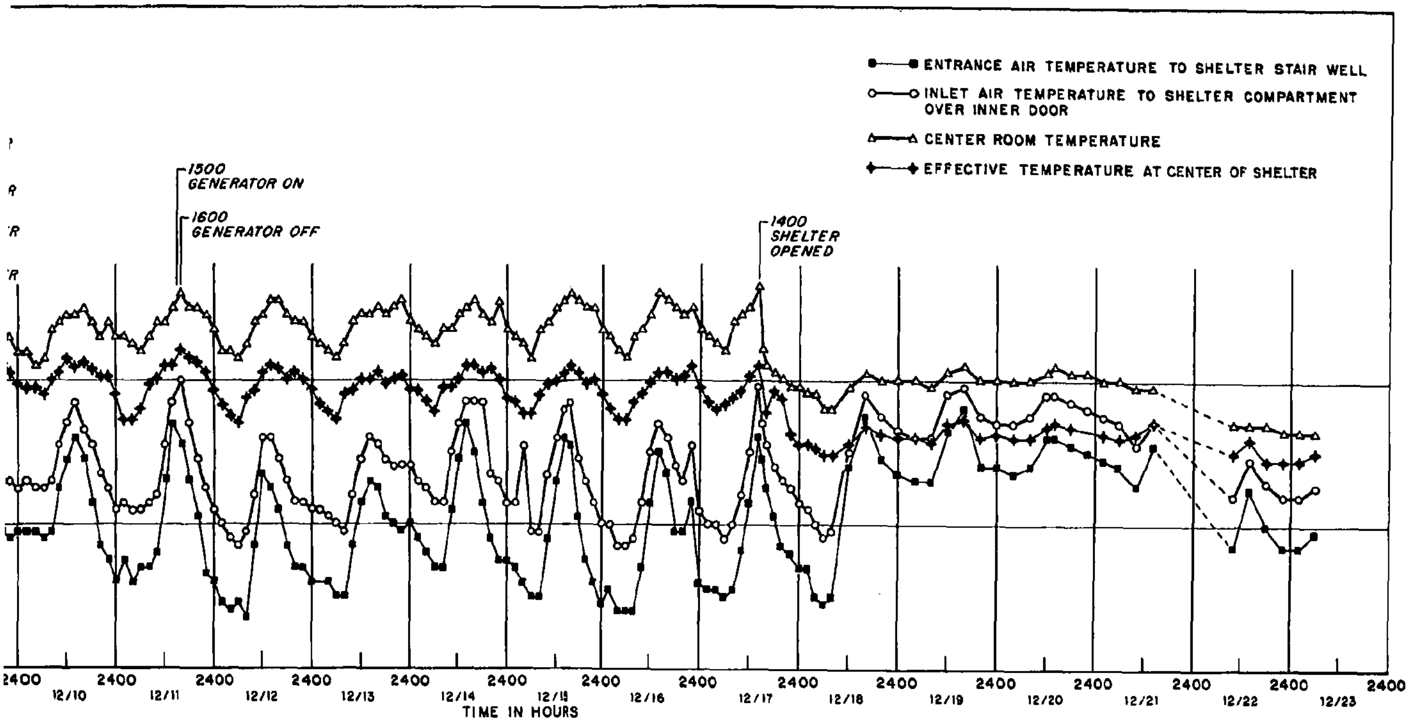


Fig. 10 Temperature Records of 14-Day Human Occupancy of Shelter. Run No

1



: 14-Day Human Occupancy of Shelter. Run No. 3 - Shelter human occupancy studies.

2

$$q_1 = h_g \text{ at } td_2 - h_f \text{ at } 66^{\circ}F \times \text{lbs of } H_2O \text{ added}$$
$$q_2 = h_g \text{ at } td_2 - h_g \text{ at } td_1 \times S_1 \times \text{lbs air/hr}$$
$$q_3 = 0.24\ td_2 - 0.24\ td_1 \times \text{lbs dry air/hr}$$

where h_g is Enthalpy of Saturated Vapor
td_2 is Exhaust Air Temperature
h_f is Enthalpy of Saturated Liquid Supplied to Simulators
td_1 is Inlet Air Temperature
S_1 is Specific Humidity of Exhaust Air (lbs of moisture/lb of dry air)
$0.24\ td_2$ is the Specific Heat of the Exhaust Air lbs (dry air/hr = 7730 lbs/hr at 1600 cfm)

In the human occupancy test $q_1 = 0$, since there is no water added to the shelter by artificial means.

The heat lost to the soil is expressed as follows:

$$Q_{soil} = k\ A\ \frac{dt}{dx} \tag{3}$$

where K is the Thermal Conductivity of the soil
A is the Area of the Shelter exterior surface
$\frac{dt}{dx}$ is the temperature gradient with distance from the shelter.

With the intake air to the shelter shut off during the calibration runs Numbers 4 and 5, the total heat input is equal to the heat lost to the soil or

$$Q_{total} = Q_{soil} = k\ A\ \frac{dt}{dx} \tag{4}$$

With a known quantity of heat being put into the shelter and the temperature gradient in the soil determined by measurement, the value of k can be calculated. These calibration runs (Nos. 4 and 5) were continued until the heat was being lost to the soil at a constant rate as determined by plotting dt vs dx. The values for dt/dx at each station after equilibrium was established are given in Tables 2 and 3 for Runs 4 and 5 respectively. Substitution of values of dt/dx into equation 4 gave a value of 1.00 for k on Run No. 4 and 1.08 on Run No. 5 or an average value of 1.04.

TABLE 2

Determination of Heat Transfer Coefficient for Shelter (k)
Test Run 4 Heat Input - 30,490 BTU/hr

Location of Measurement		dt/dx at Equilibrium									
		Select Fill			Back Fill			Floor			Select Fill
		RB-4	RC-4	RF-4	RF-11	RC-11	LC-11	FF	FC	FR	B-8
Date	Time										
6/4/60	0800	9.50	-	8.25	9.00	-	11.75	7.00	7.25	7.25	8.75
	1000	9.50	-	8.75	10.75	12.00	12.00	7.50	7.50	7.25	8.75
	1200	9.50	-	8.25	10.75	12.25	11.50	7.25	7.50	7.75	8.50
	1400	9.50	-	8.50	11.75	11.75	11.25	7.25	8.00	8.50	-
	1600	9.75	-	8.00	10.50	12.25	11.50	7.50	8.25	-	8.75
	1800	9.50	-	8.00	11.00	12.00	11.75	7.25	8.00	-	9.75
	2000	9.75	-	8.50	11.50	11.50	11.75	7.00	8.25	-	9.75
	2200	8.75	-	8.25	10.50	12.00	11.50	7.50	7.75	8.00	9.75
	2400	9.50	-	8.50	11.00	12.50	11.50	7.25	7.50	7.25	9.00
6/5/60	0200	9.75	-	8.75	13.00	12.00	12.25	7.50	8.00	7.25	8.50
	0400	9.25	-	8.50	12.00	11.75	11.25	7.25	7.50	8.00	9.00
	0600	9.25	-	8.25	11.75	11.50	11.50	7.75	8.25	7.75	8.00
	0800	9.25	-	8.25	10.50	11.75	11.25	8.00	7.25	-	8.00
	1000	9.50	-	8.30	10.75	12.75	10.75	7.50	7.50	7.75	8.66
	1200	9.75	-	8.50	12.00	11.75	12.25	7.75	8.00	8.00	8.75
	1400	10.00	-	8.50	12.25	11.25	11.25	7.00	8.00	7.50	9.25
	1600	9.20	-	8.60	11.60	11.80	11.00	7.40	8.20	7.10	9.00
	1800	10.00	8.00	8.20	11.90	10.80	11.30	7.50	7.60	-	8.70
	2000	9.33	-	8.33	11.80	12.50	11.25	7.50	7.80	6.50	9.00
	2200	9.00	-	8.30	11.60	12.10	11.60	7.20	7.80	6.80	8.90
	2400	9.83	-	8.00	11.50	12.00	11.50	7.50	7.33	8.75	8.67
6/6/60	0200	9.50	-	8.50	12.80	12.20	12.00	7.33	8.00	7.13	9.13
	0400	9.80	-	8.33	11.80	11.70	12.20	8.00	8.33	8.20	8.50
	0600	9.00	-	8.33	12.00	11.50	12.00	8.00	8.17	8.50	8.50
	0800	9.50	8.50	8.00	12.75	11.00	12.50	7.25	7.70	7.80	9.20
	1000	9.00	-	8.25	10.70	10.90	11.20	7.50	7.80	8.30	-
		Ave. or $\left(\frac{dt}{dx}\right)_{SF} = 8.89$			Ave. or $\left(\frac{dt}{dx}\right)_{BF} = 11.60$			Ave. or $\left(\frac{dt}{dx}\right)_{F} = 7.64$			Ave. or $\left(\frac{dt}{dx}\right)_{SF} = 8.87$

$Q = k \left(\frac{dt}{dx}\right) A$ $\qquad Q = 30{,}490$

$Q = k\ (33{,}110)$ $\qquad k = \frac{30{,}490}{33{,}110} = 1.00$

TABLE 3

Determination of Heat Transfer Coefficient for Shelter (k)
Test Run 5 Heat Input = 47,024 BTU/hr

Location of Measurement		dt/dx at Equilibrium									
		Select Fill			Back Fill			Floor			Select Fill
		RB-4	RC-4	RF-4	RF-11	RC-11	LC-11	FF	FC	FR	B-8
Date	Time										
6/9/60	2100	12.00	9.75	10.00	15.00	16.25	-	10.25	10.75	-	-
	2140	12.50	9.50	9.75	15.00	16.25	-	10.50	11.00	-	-
	2220	11.75	9.50	9.75	15.00	16.00	-	10.25	11.00	-	-
	2300	11.75	9.50	9.75	15.00	16.25	-	10.25	11.00	-	-
	2340	-	10.00	10.00	15.00	16.00	-	10.50	10.75	11.25	12.25
6/10/60	0020	11.00	11.50	10.00	14.75	16.25	-	10.50	10.75	-	12.25
	0100	11.50	-	9.25	14.75	16.25	-	10.50	10.75	11.25	12.00
	0140	11.50	9.50	10.00	14.50	16.25	-	10.50	10.75	-	13.00
	0220	11.25	9.50	10.50	15.00	16.25	-	10.50	11.00	-	13.00
	0300	11.75	11.00	10.50	15.00	16.25	-	10.50	10.50	-	13.00
	0340	11.50	11.00	10.25	15.00	16.50	-	10.50	11.00	-	12.50
	0420	11.25	9.75	10.25	15.00	16.00	-	10.50	11.00	-	12.50
	0500	11.25	10.00	10.25	15.00	16.25	-	10.50	11.00	-	12.25
	0540	11.25	10.00	10.25	15.00	16.25	-	10.50	11.25	-	12.25
	0620	11.25	9.50	10.00	15.00	16.00	-	10.75	11.00	-	12.50
	0700	11.25	10.00	10.25	15.00	16.00	-	10.25	11.00	-	12.00
	0740	11.25	9.75	10.25	15.00	16.00	-	10.75	11.00	-	12.00
	0820	11.25	9.75	10.50	15.00	16.00	-	10.50	11.00	-	12.75
	0900	11.00	9.75	10.75	15.50	16.00	-	10.50	11.00	-	12.25
	0940	11.00	10.25	10.50	15.25	16.00	-	10.75	11.00	-	12.50
	1020	11.50	9.50	10.75	15.00	16.00	-	10.75	11.00	-	12.50
	1100	11.75	10.00	10.50	17.50	16.00	-	10.50	11.25	-	12.00
	1140	11.00	9.75	10.00	15.00	16.00	-	10.50	11.25	-	-
	1220	11.25	-	10.25	15.00	-	-	11.00	11.50	-	-
	1300	10.75	10.00	10.00	15.00	17.00	-	10.50	11.50	-	-
	1340	11.25	10.00	10.50	15.25	16.00	-	10.50	11.25	-	12.00
	1420	11.25	11.00	10.00	15.00	14.50	-	10.50	11.25	-	11.50

Ave. or $\left(\frac{dt}{dx}\right)_{SF} = 10.51$ Ave. or $\left(\frac{dt}{dx}\right)_{BF} = 15.58$ Ave. or $\left(\frac{dt}{dx}\right)_{F} = 10.78$ Ave. or $\left(\frac{dt}{dx}\right)_{SF} = 12.35$

$Q = k \left(\frac{dt}{dx}\right) A$ $Q = 47{,}024$

$Q = k\,(43{,}436)$ $k = \frac{47{,}024}{43{,}436}$

The heat lost to the air and to the soil was calculated for each 2-hr interval from the above equations for both the simulated and human occupancy tests. The results are given in Tables 4 and 5. The averaged results for both runs are shown in Table 6.

It will be noted that the heat lost to the air on the simulated run is 68.7 % of the total as compared to 69.2 % on the human occupancy run. The calculated total heat input to the shelter on the simulated run is only 2.7 % lower than the measured input.

The total average heat loss during the human occupancy run was 48,198 Btu per hour or 482 Btu per person. This result is compared with typical published values in Table 7.

It is difficult to extend the data to other localities under various climatic conditions because of the large number of variables involved such as, soil conditions which affects the heat loss through the walls, diurnal temperature and humidity variations which affect the maximum, minimum, and effective temperature (E.T.), and air flow rate which affects the rate of heat loss from the shelter and influences the E.T. The data shows that the shelter was comfortable for the entire 14 days of human occupancy (Run. No. 3) during which the ambient temperature varied between 36 and 67°F.

The maximum E.T., however during the simulated occupancy test (Run No. 1) was 83 with an ambient temperature variation between 42° and 95° F. This E.T.is a few degrees higher than the optimum maximum of 75. The simulated occupancy test therefore, indicates that trouble may be encountered during the summer, in areas where the ambient temperature at night does not drop as low as it did during this test.

4.2 PREDICTING THERMAL BEHAVIOR OF SHELTER ENVIRONMENT

The thermal-electrical analogy is a useful tool in the prediction of the thermal behavior of complex heat transfer systems, but according to Oklahoma State University, little information was available in the literature on its use in predicting the thermal behavior of buildings.

The thermal electrical analogy is based upon the identity of the fundamental equations of heat flow within a rigid body and that of an electrical charge in a non-inductive circuit. In the analysis made at Oklahoma State University on their thermal analyzer the NRDL shelter interior was divided into six air nodes or cross-sections measuring 8 ft in depth. Node or section No. 1 was at the front of the

TABLE 4

Heat Losses during Simulated Occupancy Test (Run No. 1)

Date	Time	td_1	td_2	S_1	q_1	q_2	q_3	Q_{air}	dt/dx	Q_{soil}	Q_{total}
10/27/59	1600	75	87	.0123	277	456	22,417	23,150	3.78	13,897	37,047
	1800	71	86	.0126	181	584	27,828	28,593	3.66	13,456	42,049
	2000	67	85	.0114	170	643	33,239	34,052	3.70	13,603	47,655
	2200	65	85	.0106	181	671	37,777	38,629	3.73	13,713	52,342
	2400	63	83	.0097	159	614	37,204	37,204	3.81	14,007	51,211
10/28/59	0200	62	83	.0088	149	585	38,650	39,384	3.66	13,456	52,840
	0400	60	82	.0081	143	569	40,969	41,681	3.71	13,639	55,320
	0600	58	82	.0086	133	665	44,834	45,632	3.65	13,419	59,051
	0800	60	87	.0104	159	731	50,245	51,135	3.80	13,970	65,105
	1000	70	86	.0150	239	742	29,374	30,355	3.77	13,860	44,215
	1200	79	89	.0206	290	605	18,552	19,447	3.87	14,228	33,675
10/29/59	1000	73	87	.0114	192	537	26,282	27,011	3.96	14,559	41,570
	1200	76	87	.0136	277	504	20,871	21,652	3.96	14,559	36,211
	1400	76	88	.0121	256	486	22,417	23,159	4.38	16,103	39,262
	1600	75	87	.0117	239	470	20,871	21,580	4.14	15,220	36,800
	1800	72	86	.0109	250	505	20,098	20,853	4.09	15,036	35,889
	2000	71	87	.0112	229	597	27,828	28,654	3.97	14,595	43,249
	2200	71	87	.0112	202	597	30,147	30,946	3.97	14,595	45,541
	2400	71	87	.0112	186	597	30,147	30,930	3.80	13,970	44,900
10/30/59	0200	69	88	.0103	165	621	34,785	35,571	3.88	14,264	49,835
	0400	68	87	.0099	144	596	35,558	36,298	4.22	15,514	51,812
	0600	67	85	.0095	122	565	33,239	33,926	3.95	14,522	48,448
	0800	68	87	.0099	106	627	35,558	36,291	3.96	14,559	50,850
	1000	72	87	.0132	218	612	23,963	24,793	3.98	14,632	39,425
	1200	75	88	.0123	192	446	23,963	24,601	3.91	14,375	38,976

TABLE 5

Heat Losses during Human Occupancy Test (Run No. 3)

Date	Time	td_1	td_2	s_1	q_2	q_3	q_{air}	dt/dx	Q_{soil}	Q_{total}
12/10/59	1400	67	77	.0077	261	18,552	18,813	4.05	14,888	33,701
	1600	63	77	.0080	377	25,973	26,350	3.69	13,564	39,914
	1800	61	76	.0078	391	27,828	28,219	3.89	14,300	42,519
	2000	57	75	.0065	391	33,394	33,785	3.59	13,197	46,982
	2200	55	75	.0063	423	37,104	37,527	3.87	14,226	51,753
	2400	52	72	.0052	349	37,104	37,453	3.98	14,630	52,083
12/11/59	0200	53	72	.0064	405	35,249	35,654	3.95	14,520	50,174
	0400	52	71	.0057	365	35,249	35,614	3.94	14,483	50,097
	0600	52	70	.0057	343	33,394	33,737	3.86	14,189	47,926
	0800	53	74	.0064	450	38,958	39,408	3.98	14,630	54,038
	1000	54	75	.0067	471	38,958	39,429	3.98	14,630	54,059
	1200	61	77	.0052	281	29,684	29,965	4.00	14,704	44,669
	1400	67	77	.0082	278	18,552	18,830	3.85	14,153	32,983
	1600	70	79	.0082	247	16,697	16,944	3.85	14,153	31,097
	1800	64	78	.0077	363	25,973	26,336	4.04	14,851	41,187
	2000	59	78	.0066	418	35,249	35,667	4.04	14,851	50,518
	2200	55	59	.0066				4.11		
	2400	52	73	.0052	365	38,958	39,323	4.27	15,697	55,020
12/12/59	0200	50	71	.0046	323	38,958	39,281	4.03	14,814	54,095
	0400	48	69	.0043	303	38,958	39,261	4.24	15,586	54,847
	0600	47	68	.0040	250	38,958	39,208	4.24	15,586	54,794
	0800	49	73	.0044	353	44,525	44,878	4.04	14,851	59,729
	1000	54	73	.0057	361	35,249	35,610	4.08	14,998	50,608
	1200	62	76	.0064	296	25,973	26,269	4.11	15,108	41,377
	1400	62	77	.0088	442	27,828	28,270	3.93	14,447	42,747
	1600	59	76	.0066	372	31,538	31,910	3.95	14,520	46,430
	1800	56	75	.0063	399	35,249	35,648	3.94	14,483	50,131
	2000	53	77	.0054	434	44,525	44,959	3.94	14,483	59,442
	2200	53	75	.0054	396	40,814	41,210	3.91	14,373	55,583
	2400	52	72	.0052	349	37,104	37,453	3.82	14,042	51,495
12/13/59	0200	52	71	.0048	307	35,249	35,556	3.85	14,153	49,709
	0400	51	70	.0049	310	35,249	35,559	3.90	14,336	49,895
	0600	50	69	.0043	272	35,249	35,521	3.81	14,006	49,527

Continued

TABLE 5 (Cont'd)

Heat Losses during Human Occupancy Test (Run No. 3)

Date	Time	td_1	td_2	S_1	q_2	q_3	q_{air}	dt/dx	Q_{soil}	Q_{total}
12/13/59	0800	49	73	.0049	394	44,525	44,919	3.93	14,447	59,366
	1000	54	24	.0057	384	37,104	37,488	3.89	14,299	51,787
	1200	59	75	.0052	277	29,684	29,961	3.85	14,153	44,114
	1400	62	76	.0049	227	25,973	26,200	4.19	15,402	41,602
	1600	61	77			29,684		4.02	14,778	
	1800	59	75	.0046	245	29,684	29,929	4.02	14,778	44,707
	2000	58	76	.0042	253	33,394	33,647	4.02	14,778	48,425
	2200	58	76	.0042	253	33,394	33,647	4.03	14,814	48,461
	2400	58	75	.0038	217	31,538	31,800	4.29	15,770	47,570
12/14/59	0200	56	73	.0032	180	31,538	31,763	4.24	15,586	47,349
	0400	55	72	.0032	183	31,538	31,766	4.13	15,181	46,947
	0600	53	71	.0036	217	33,394	33,611	4.06	14,925	48,536
	0800	53	74	.0034	239	38,958	39,197	3.93	14,447	53,644
	1000	60	75	.0034	170	27,828	27,998	4.03	14,814	42,812
	1200	-	76	.0044				3.82		
	1400	67	78	.0048	178	20,407	20,585	4.12	15,145	35,730
	1600	67	78	.0048	178	20,407	20,585	4.08	14,998	35,583
	1800	67	77			18,552		4.26	15,660	
	2000	57	76			35,249		4.30	15,807	
	2200	56	75			35,249		4.43	16,285	
	2400	53	72			35,249		4.20	15,439	
12/15/59	0200	53	72			35,452		4.37	16,064	
	0400	61	70			16,766		4.76	15,292	
	0600	49	73			44,663		4.11	15,108	
	0800	49	73			44,756		4.27	15,697	
	1000	57	75			33,623		3.98	14,630	
	1200	62	76			26,186		4.02	14,778	
	1400	66	77			20,585		4.07	14,961	
	1600	67	78			20,563		4.06	14,925	
	1800	59	77			33,720		4.15	15,255	
	2000	56	75			35,426		4.22	15,513	
	2200	53	76			42,869		4.30	15,807	
	2400	[illegible]	73			42,869		4.23	15,549	

Continued

TABLE 5 (Cont'd)

Heat Losses during Human Occupancy Test (Run No. 3)

Date	Time	td_1	td_2	S_1	q_2	q_3	q_{air}	dt/dx	Q_{soil}	Q_{total}
12/16/59	0200	50	71	.0026	183	39,141	39,141	4.31	15,844	54,985
	0400	47	69	.0023	169	40,983	40,983	4.12	15,145	56,128
	0600	47	69	.0023	169	40,983	40,983	4.21	15,476	56,459
	0800	48	72	.0023	185	44,710	44,710	3.97	14,594	59,304
	1000	53	73	.0048	319	37,356	37,675	3.84	14,116	51,791
	1200	60	75	.0048	241	28,069	28,310	4.00	14,704	43,014
	1400	64	70	.0052	104	11,227	11,331	4.31	15,844	37,175
	1600	62	77	.0048	241	28,100	28,341	4.31	15,844	44,185
	1800	58	75	.0044	251	31,732	31,983	4.27	15,697	47,680
	2000	56	76	.0043	286	37,104	37,390	4.27	15,697	53,087
	2200	51	78	.0066	597	31,538	32,135	4.19	15,402	47,537
	2400	52	74	.0037	275	40,814	41,089	4.25	15,623	56,712
12/17/59	0200	50	72	.0034	272	40,814	41,086	4.03	14,814	55,900
	0400	50	71	.0034	251	38,958	39,209	4.13	15,182	54,391
	0600	48	71	.0034	263	42,670	42,933	4.13	15,182	58,115
	0800	50	73	.0038	297	42,670	42,967	4.03	14,814	57,781
	1000	54	74	.0043	289	37,140	37,429	4.19	15,402	52,831
	1200	60	75	.0054	271	27,828	28,099	4.24	15,586	43,685
	1400	69	77	.0090	243	33,394	33,637	4.17	15,329	48,966

TABLE 6

Total Heat Balance of Simulated Run Compared to Human Occupancy Run

Run No.	Occupancy	Inlet Air (cfm)	Q_{Total} Heat Input by Measurement	q_1	q_2	q_3	Q_{air}	Q_{soil}	Q_{Total} Calculated	% of Total Heat Lost to Air
1	100 Simulators	1600	47,000 BTU/hr	194	585	30,677	31,452	14,310	45,762	68.7
3	100 Humans	1600	Unknown	0	303	33,306	33,248	14,950	48,198	68.9

Simulated Run: $Q_{Total\ Calculated} = 97.3\ \%$ of $Q_{Total\ Measured}$

TABLE 7

Metabolic Rates* of Men at Different Activities

Activity	Average Metabolic Rate BTU per Hour
Sleeping	255
Awake, quiet	300
Seated, at rest	380
Standing, at ease	430
Normal Shelter Living (Determined in these studies)	482
Walking, 2 mph	760
Walking, 4 mph	1400

*All rates except Normal Shelter Living are from ASHRAE Guide and Data Book.

shelter and No. 6 at the rear. A complete report of this analyses is presented in the Appendix. Temperature variations of Air Node No. 3 as determined by the thermal analyzer is shown in Fig. 11 compared to the measured temperature in the center of the shelter during the human occupancy run. It will be noted that the temperature variations as determined by the thermal analyzer are 10 to 15 % lower than the measured temperatures. This was a preliminary study and it is believed that additional work would produce better results. The analysis procedure offers the possibility of an inexpensive and rapid method of determining underground shelter environment for a wide variety of climatic conditions.

4.3 CARBON MONOXIDE MEASUREMENTS

During the human occupancy tests the carbon monoxide concentration was less than 10 ppm from 0100 to 1000 each day. After 1000 each day, the concentration increased over a period of 1 to 2 hours to 60 to 80 ppm where it remained until 1600 to 1800. Thereafter, the concentration decreased gradually to the daily low at about 0100. The increase in carbon monoxide concentration can be explained by the increased amount of smoking during the daytime hours. The Navy tolerance for continued breathing of carbon monoxide is 150 ppm. At no time during the occupancy test was this level closely approached.

Separate tests were conducted with the motor generator running to determine if it increased the carbon monoxide concentration in the shelter. This motor generator, which is located in the entrance-way opposite the ventilation fan intake is intended to provide emergency electrical power for ventilation and lights. The concentration of carbon monoxide in the shelter was considerably below the 150 ppm tolerance, while running the motor generator with the blower on and both intake and exhaust vents open. Operating the motor generator however with the ventilating air intakes closed, the carbon monoxide concentration rose considerably above this tolerance. After approximately 1-1/2 hrs it appeared to be leveling off at 380 to 400 ppm as shown in Fig. 12. The carbon monoxide concentration dropped to a safe value within a few minutes after opening both the intake and exhaust air vents and turning on the blower. Although the motor generator is not intended to be operated under these conditions this test indicates the hazard that could be encountered if the shelter occupants had not received proper instructions.

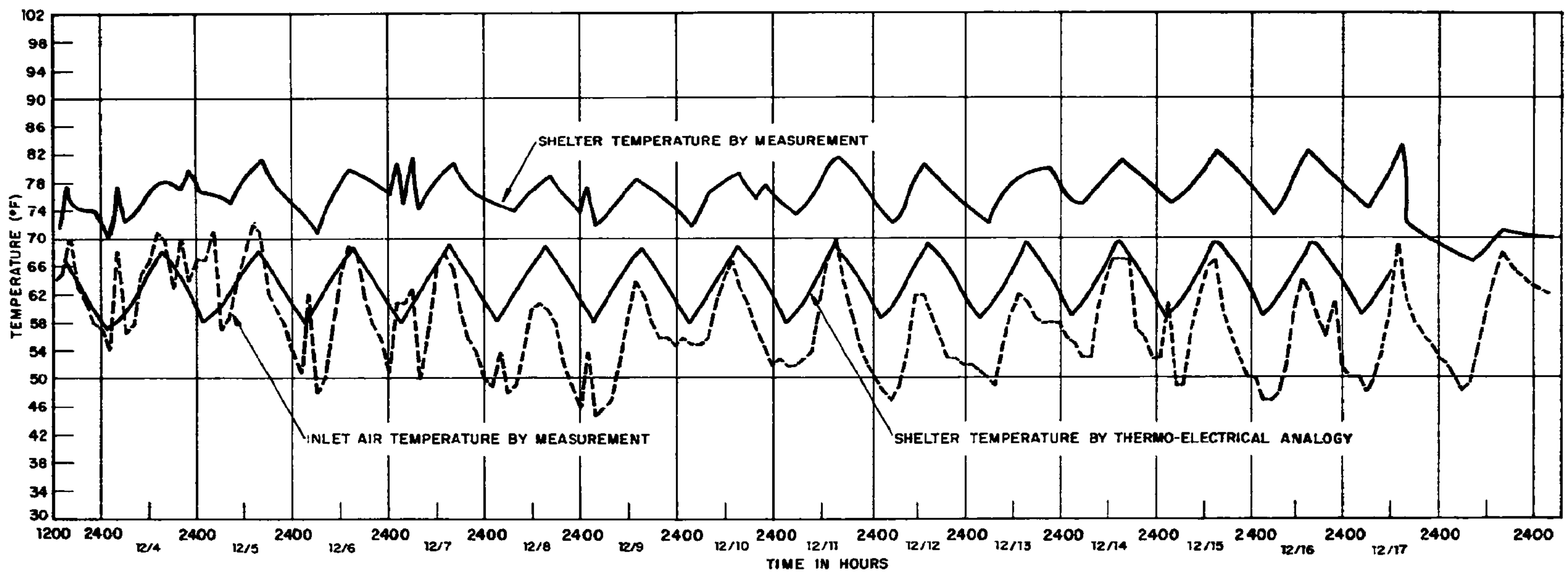


Fig. 11 Measured Temperature of Shelter Compared to Temperature by Thermo-Electrical Analogy for Run No. 3

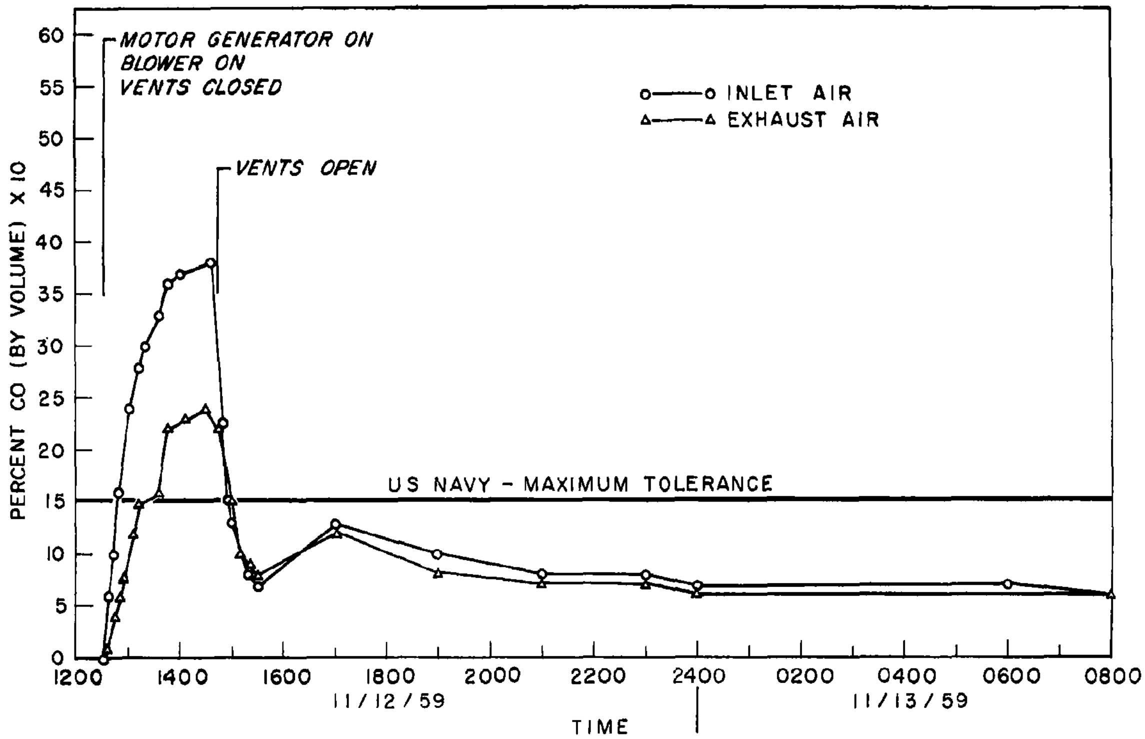


Fig. 12 Effect of Motor Generator on Shelter Carbon Monoxide Concentration

CHAPTER 5

CONCLUSIONS

The NRDL shelter design was proven satisfactory under the conditions of these tests. The temperature of the shelter remained comfortable during the entire 14 days of occupancy, however it is difficult to predict the shelter environment for other climatic conditions.

The shelter air temperature reflects the diurnal temperature variations of the entrance air but is considerably damped. After the first day of simulated occupancy the entrance air varied from 50 to 94 degrees and the shelter temperature varied from 74 to 90 degrees with an effective temperature variation of 74 to 80 degrees. During the human occupancy test, due to poor inlet air distribution, there were cold drafts in the front of the shelter when the ambient temperature dropped to the minimum temperature of 36° to 42°F. The maximum entrance air temperature during this test was 67°F. The air in the center of the shelter varied from 70° to 82° and the effective temperature varied from 64 to 74 degrees.

The major portion of the heat generated in the shelter was removed by the ventilating air. In both the human occupancy test and the test run using human simulators, 69 % of the heat was carried off by the ventilating air and only 31 % was lost to the soil surrounding the shelter.

The 1600 cfm of air flow through this shelter reduces the carbon monoxide from smoking to a concentration far below the Navy tolerance for submarines of 150 ppm, and it exceeded the maximum allowable concentration (MAC) established for industry of 100 ppm for only approximately 1 hour. The industry MAC of 100 ppm was established as maximum for 8 hours exposure. From 0100 to 1000 each day the concentration averaged 10 ppm. The peak of 60 to 80 ppm was reached each day by 1200 where it remained until it began to drop off between 1600 to 1800.

The location of the motor generator will result in dangerous quantities of carbon monoxide being created if this generator is operated by mistake with the ventilating fan on and the intake air vents closed.

Thermal-Electrical analyzer appears to offer practical method of predicting shelter environment.

CHAPTER 6

RECOMMENDATIONS

It is recommended that:

(1) The position of the motor generator be changed or a safety measure be devised to prevent it from being operated at conditions other than those for which it is intended.

(2) Changes be made in the inlet ducting to eliminate cold drafts at the center of the shelter during cold weather.

(3) Consideration be given to the further development of Thermal-Electrical Analogy as a tool to predict shelter environment over a wider range of climatic conditions.

REFERENCES

1. W. E. Strope. The USNRDL Shelter Research Program. U. S. Naval Radiological Defense Laboratory Report, USNRDL Reviews and Lectures No. 119, 21 August 1961.

2. W. E. Strope, L. G. Porteous, A. L. Greig. Specifications and Costs of a Standardized Series of Fallout Shelters. U. S. Naval Radiological Defense Laboratory Technical Report, USNRDL-TR-366, 16 October 1959.

APPENDIX

ANALYSIS OF AN UNDERGROUND SHELTER BY THERMAL-ELECTRICAL ANALOGY

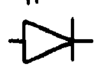
by

William L. Othling, Jr.

*Submitted to the faculty of the Graduate School of
Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
January, 1962

*Reproduced with the permission of Dr. J. A. Wiebelt, of the Mechanical Engineering Department of Oklahoma State University.

SYMBOLS

C	- Capacity (Thermal and Electrical)
C_p	- Specific Heat @ Constant Pressure. Btu/#$^\circ$F
E	- Voltage. Volts
i	- Current - Amperes
k	- Thermal Conductivity. Btu/hr.ft.$^\circ$F
m	- Mass Flow Rate. #m/hr
q	- Quantity of Heat Energy per Unit Time. Btu/hr
R	- Resistance (Thermal and Electrical)
ρ	- Density. #m/ft^3
T	- Temperature. $^\circ$F
τ	- Time
V	- Volume. ft^3
	- Capacitance (Electrical & Thermal)
	- Diode
	- Ground Connection
	- Resistance (Electrical & Thermal)

Subscripts

e	- Electrical Circuit
t	- Thermal Circuit

CHAPTER I

INTRODUCTION

The passive R-C electrical analogy for thermal systems is a powerful tool in the prediction of the thermal behavior of complex heat transfer systems, and many investigations using this method can be found in the literature. However, very few applications to the study of the thermal behavior of buildings can be found.

This paper presents a thermal analysis using the electrical analogy to determine the temperature variation within a one hundred man underground shelter. The system studied is a Navy Ammunition hut of steel-arch type structure, 48 feet long, with an arch radius of 12.5 feet, which is covered by a minimum of three feet of earth.

This structure was built by the United States Naval Radiological Defense Laboratories, (USNRDL), approximately forty miles from San Francisco, California, where physical and analytical studies of this system are in progress. These studies are directed toward determination of environmental conditions within an underground shelter, occupied by one hundred men for extended periods of time. Rough drafts of these studies were presented to the Mechanical Engineering Department of the Oklahoma State University by a representative of USNRDL. In the analysis presented, the system and boundary conditions are the same, to the extent that it is possible, as in the USNRDL tests. This permits the results of this analysis to be compared with those of the USNRDL tests.

In an analysis such as this, the main problems are not associated with the thermal-electrical analogy nor with the thermal analyzer. It is one of representation. The actual physical conditions and boundary conditions must be represented by an equivalent thermal network or circuit. In accomplishing this, the physical system is lumped or subdivided into a number of geometrical subvolumes. The thermal properties of each subvolume is considered to be concentrated at the central nodal point of each subvolume, and heat is imagined to be conducted between nodal points through a network of fictitious heat-conducting rods of appropriate thermal conductance. It should be apparent that the lumping of the physical system and the choice of values of properties assigned to nodal points will greatly influence the accuracy of such an analysis. Methods must also be devised for the representation of boundary conditions and any other parameters which might affect the thermal behavior of the system. Chapter II presents the equivalent thermal network that represents the system and this is related to an electrical network in Chapter III by means of the thermal-electrical analogy. The electrical circuit is then programmed on the thermal analyzer which leads to an analysis which is interpreted in terms of thermal properties.

CHAPTER II

THERMAL CIRCUIT

In an analysis such as this, it is necessary to idealize or simplify the problem so that it may be represented by a manageable thermal circuit. In doing this the following assumptions were made.

(1) The shelter is considered to be made up of two ends, floor, and siding, all of which represent paths of heat transfer from the enclosure.

(2) All thermal energy transferred through the structure is unidirectional. This is to say that there is no heat transferred between the paths mentioned in (1).

(3) Physical conduction paths are replaced by sections or lumps which represent the thermal properties of the path.

(4) The thermal properties of the lumps are constant and are mean values over the temperature range encountered.

(5) Net radiation exchange within the enclosure is negligible, except that which is included in the conductance from the men to the walls.

(6) Solar radiation input into the system is considered negligible.

(7) Phase changes, such as condensation on the walls are not considered.

(8) Contact resistances through the conduction paths are negligible.

The interior of the enclosure is divided into six nodes as pictured in Figure 1. The paths of heat transfer from these nodes are shown in Figures 14, 15 and 16, in the Appendix.

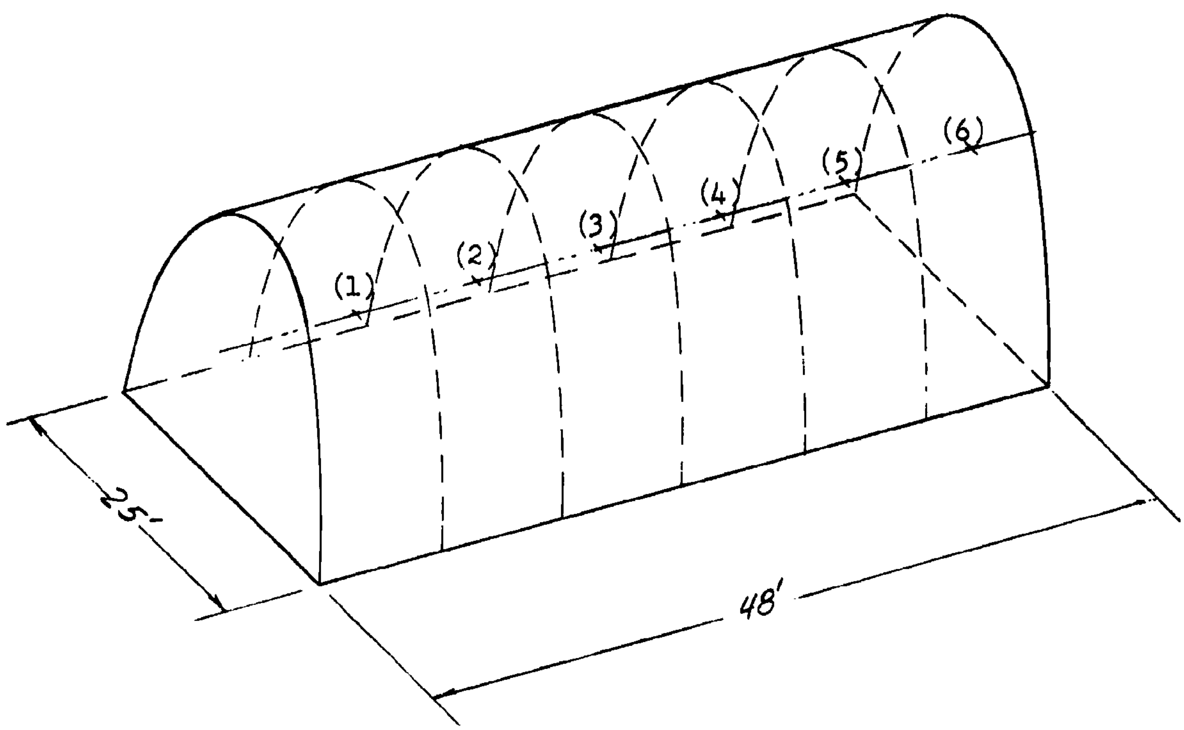


Figure 1. Overall Schematic of the Enclosure

The walls, adjacent rock, and earth are assumed to form a series resistance to the radial exchange of energy between the interior nodes of the shelter and its surroundings. The floor and adjacent earth also represent series resistances to the energy exchanges. In addition, the end walls of the enclosure represent additional conduction paths to be added to each end node.

An interior node can be represented by the network as shown in Figure 2. The resistances represent thermal resistance, and the capacitors represent thermal capacity of each lump in the conduction path., Figures 14, 15 and 16, will aid in the understanding of the physical picture.

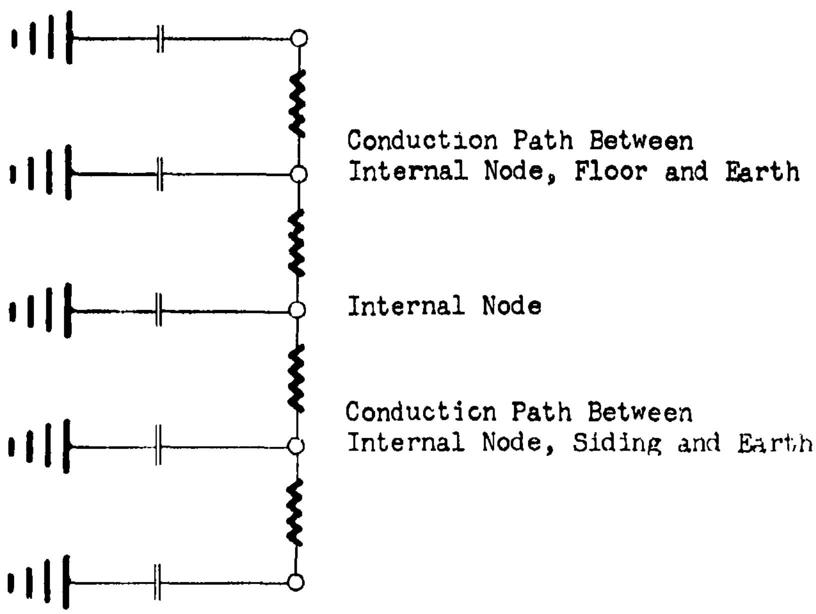


Figure 2. Thermal Circuit Representation of an Interior Node

The boundary conditions imposed on the thermal system consist of a heat input into the shelter to be maintained at 470 B/hr-man for one hundred men, and 1600 CFM of ventilating air forced in at one end of the shelter.

The one hundred men can be represented in the thermal circuit by a heat generation or energy input, "q" into each internal node of the enclosure.

The ventilating air presents a problem in that there is no analogy such as exists for the conduction of heat.

Physically the problem is as follows:

The ventilating air is assumed to vary between $40^{\circ}F$ and $60^{\circ}F$, while the enclosure temperature is expected to be ten to fifteen degrees above the mean temperature of the ventilating air. The flow of cooler air through the enclosure establishes a temperature gradient with the temperature increasing in the direction of the air flow. This gradient affects a flow of energy in a direction opposite to that of the air flow. This is shown schematically in Figure 3. Another important consideration is that the temperature of a particular node is affected by conditions upstream of the node only.

Air Flow →

o (0) o (1) o (2) o (3) o (4) o (5) o (6)

← Heat Flow

Figure 3. Schematic Showing Direction of Heat and Air Flow in the Enclosure

The incoming air impresses its temperature or potential on its entrance point which will be designated node (0). The increase of energy of the air moving from (0) to (1) can be described by $q_1 = mc_p(t_1 - t_0)$. If a resistance is defined as $R = 1/mc_p$, then Figure 4 would be an analogous thermal circuit. The symbol represents the potential of the incoming air.

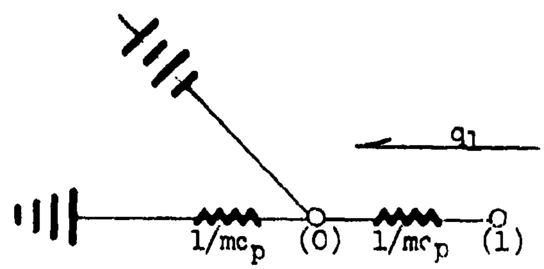


Figure 4. Ventilating Air Analogy Applied to the First Air Node

In considering node (2) which is only dependent on node (1), while node (1) is not dependent on node (2), we have:

$$q_2 = mc_p\,(T_2 - T_1)$$

or

$$q_2 = mc_p\,(T_2 - t_0) - mc_p\,(T_1 - t_0)$$

and

$$q_2 = mc_p\,(t_2 - t_0) - q_1$$

This is represented schematically in Figure 5.

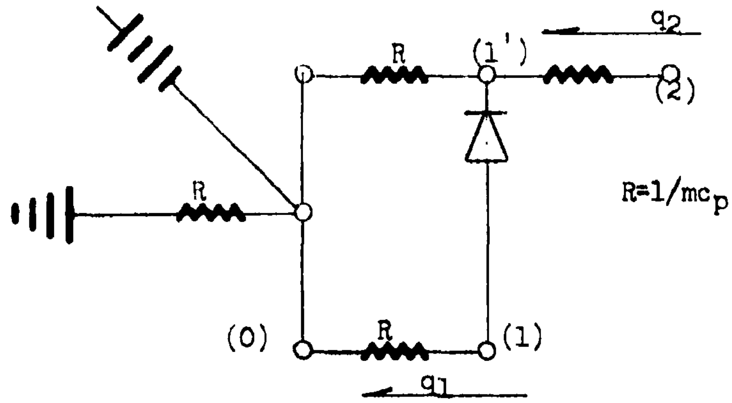


Figure 5. Ventilating Air Analogy Applied to First and Second Air Nodes

The symbol —▷|— in Figure 5 is an electrical symbol representing a diode. The diode used as shown, prevents the flow of energy from (1') to (1). This is a necessary condition in that node (1) is independent of any point down stream of it. Because the resistances in Figure 5 are equal, the potential of node (1') will equal that of node (1). It follows that q_2 is dependent only upon R, t_2 and t_1.

The circuit is now evaluated to determine if it is analogous to the physical conditions it represents. Physically the exchange of energy at node (2) is:

$$q_2 \text{ out} = mc_p t_2$$

$$q_2 \text{ in} = mc_p t_1$$

and

$$q_2 \text{ net} = mc_p(t_2 - t_1)$$

It is concluded that the physical conditions at node (2) are satisfied by the thermal circuit of Figure 5. It is pointed out again that the use of the diode prevents the flow of energy from (1') to (1). An energy balance on node (1) in Figure 5 would be identical to an energy balance made on node (1) in Figure 4.

The circuit for all six nodes is shown in Figure 6.

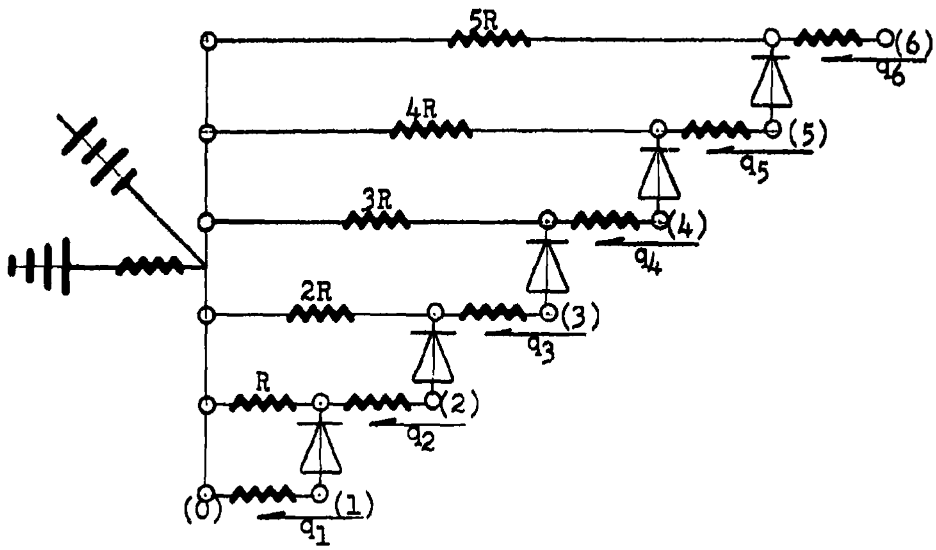


Figure 6. Ventilating Air Analogy Applied to all Six Air Nodes

Now evaluating the enclosure physically:

Energy into enclosure from air flow $q_{in} = mc_p t_0$

Energy out of enclosure from air flow $q_{out} = mc_p t_6$

The net flow out is $q_{net} = mc_p(t_6 - t_0)$

Summing the flow of energy from the enclosure using the thermal circuit:

$$q_6 = mc_p\ (t_6 - t_5)$$

$$q_5 = mc_p\,(t_5 - t_4)$$

$$q_4 = mc_p\,(t_4 - t_3)$$

$$q_3 = mc_p\,(t_3 - t_2)$$

$$q_2 = mc_p\,(t_2 - t_1)$$

$$q_1 = mc_p\,(t_1 - t_0)$$

$$q = mc_p\,(t_6 - t_0)$$

Therefore this circuitry is truly analogous to the physical conditions as established.

Figure 7 shows the thermal circuit for an interior node with boundary conditions included.

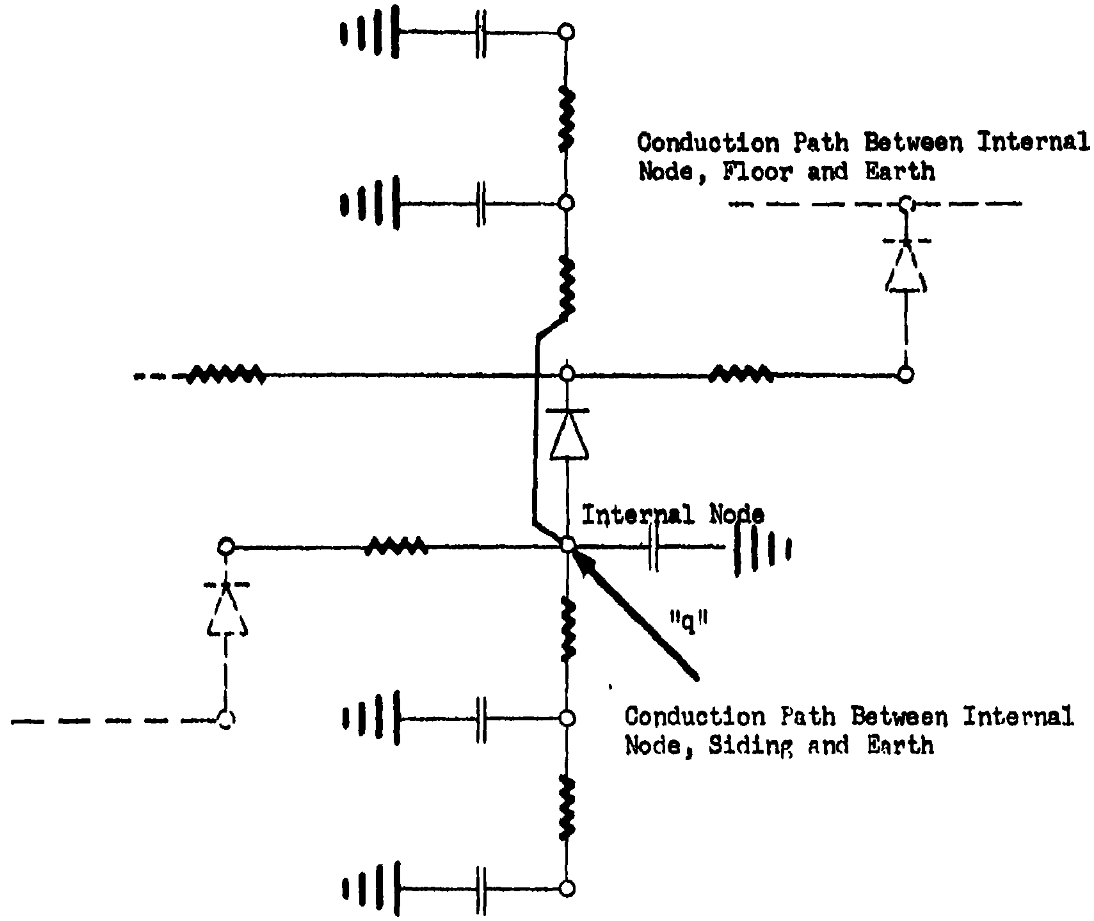


Figure 7. Thermal Circuit Representation of an Interior Node with Boundary Conditions Included

ANALAGOUS THERMAL CIRCUIT

The thermal electric analogy, which is based upon the identity of the fundamental equations of the flow of heat within a rigid body and that of a charge in a non inductive circuit, is well known.[1] Figure 8 is therefore a circuit diagram, representing the electrical as well as the thermal circuit. The scale factors or ratios derived to complete the analogy are shown in Table I.

TABLE I

SCALE FACTORS USED IN THE ANALOGY

Quantity	Units: Thermal:	Units: Electrical:	Scale Factors: Ratio:	Scale Factors: Value
Time	Hrs.	Sec.	τ_T/τ_e	1 hr/sec
Capacity	Btu/°F	Farads	C_T/C_e	10^8 $\frac{B/°F}{farad}$
Resistance	°F/Btu/hr	Ohms	R_T/R_e	10^{-8} hr°F/B
Potential	°F	Volts	T/E	1 °F/volt
Rate of Energy Transfer	Btu/hr	Coulombs/sec or Amperes	q/i	10^8 $\frac{Btu/hr}{amp}$

[1]The writer has written a paper on this subject. Bibliography Reference No. 8.

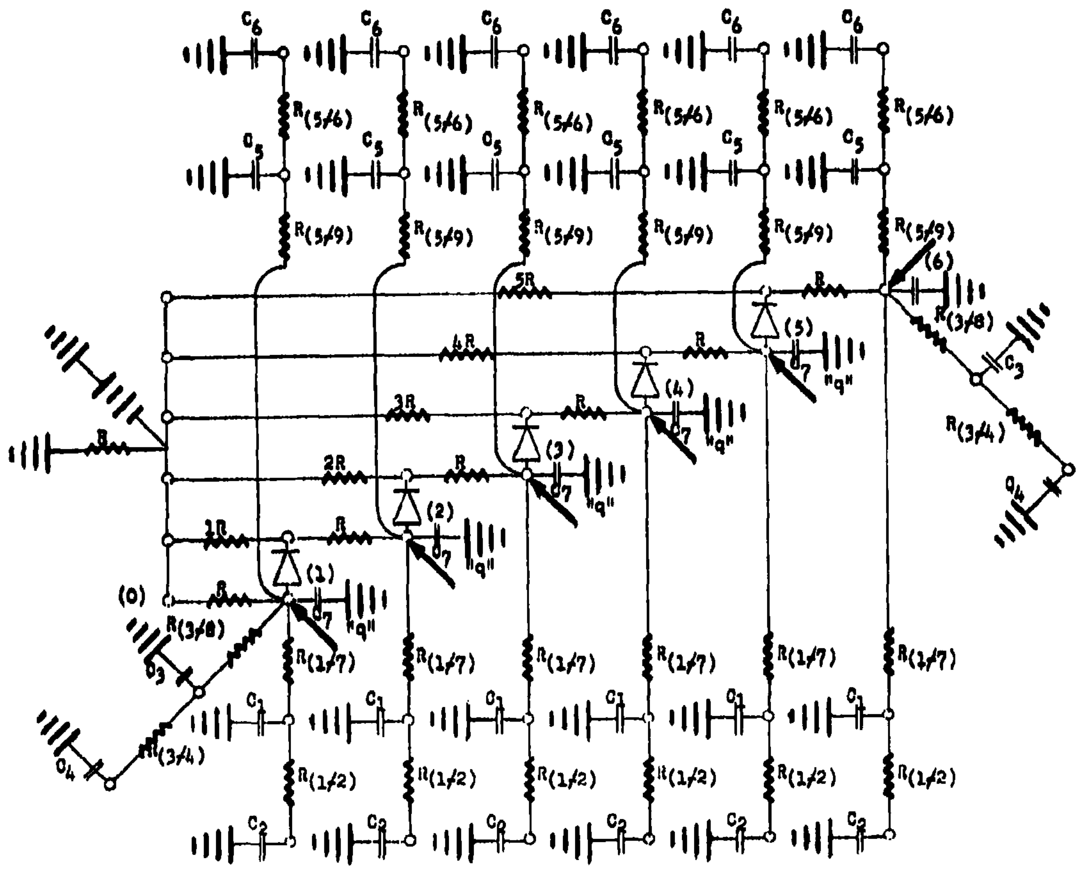


Figure 8. Circuit Diagram Representing the Electrical and Thermal Circuit

Of the first three ratios in Table I, thermal-electrical analogy permits the selection of two. The third one being fixed by the selection of the other two. The relating equation is $T_T/T_e = C_T/C_e \times R_T/R_e$

It was desirable in this analysis to choose a time ratio wherein days would be scaled down to a matter of minutes. For convenience, one hour of thermal time was set equal to one second of electrical time. In choosing the capacity and resistance scale factors, the limitations were the magnitude of the electrical resistors and capacitances available. It was also desirable to keep capacitor leakage at a minimum. The choice of these scale factors was therefore a compromise.

Of the last two ratios in Table I, the selection of one would determine the other. The relating equation for this is:

$$T/E = q/i \times R_T/R_e$$

Since R_t/R_e had been set, the choice of T/E and q/i was again a compromise between selecting values of current of an order of magnitude greater than that of the anticipated leakage current and voltages that were readily available.

The boundary conditions imposed upon the thermal circuit must be duplicated with regard to the electrical circuit. As mentioned previously, the diurnal temperature variation of the ventilating air was assumed to be between 40°F and 60°F. Having selected T/E equal to 1°F/volt, this was represented by a Donner Analog Computer, programmed to produce an output voltage which varied sinusoidally between 40 and 60 volts, with a 24 second period. According to the time ratio, 24 hours is represented by 24 seconds.

The input from the one hundred men is 47,000 B/hr. For each air node this amounts to 7,833 B/hr, or in the electrical circuit 78.3 μ amps. This was accomplished with a 400 Volt D.C. power supply connected by a large resistance (approx. 4 meg.Ω) to each air node. These resistances were adjusted while the problem was being run, so that proper current flow was achieved. The resistances labeled 2R, 3R, 4R and 5R, were also adjusted during running to insure that the desired voltage duplication was achieved.

Figure 9 and 10 are photographs of the test setup. The problem board upon which the electrical circuit is arranged, is the panel on the right side in Figure 10. The capacitor leads are seen on the left in the same photograph.

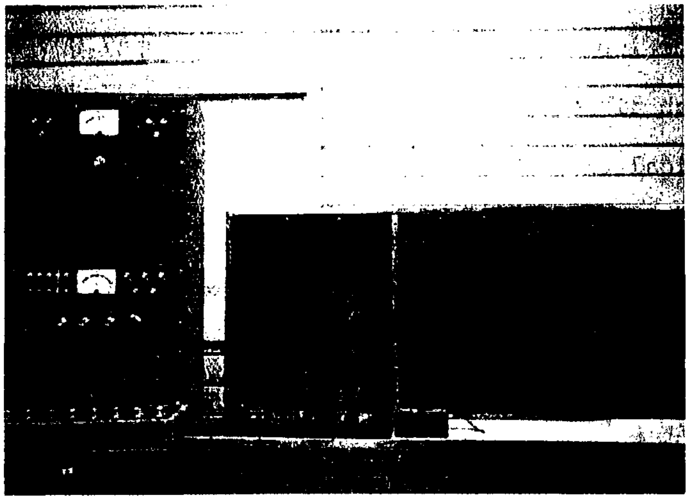


Fig. 9 Test Set Up

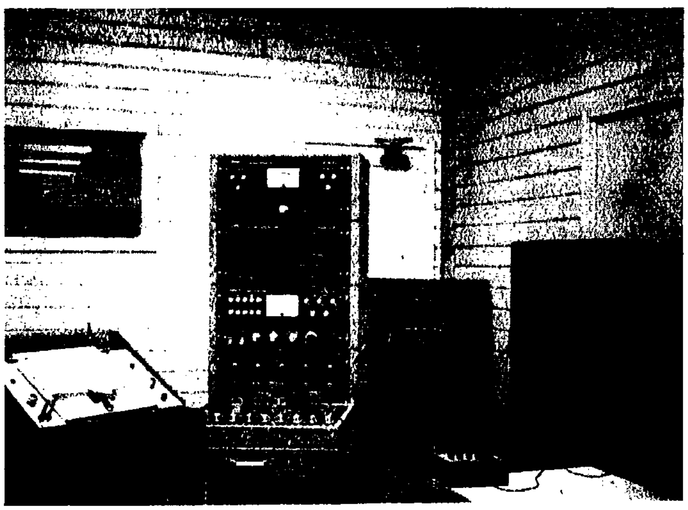


Fig. 10 Test Set Up

CHAPTER IV

MEASUREMENTS

During the course of this study, voltage measurements were taken at every node in the circuit. These measurements were recorded on a Sargent Recorder which received its input from the output of a very high impedence voltage measuring instrument or electrometer. The electrometers are an integral component of the Mechanical Engineering Department thermal analyzer. This data was not presented in this report because it was taken only as a means to determine if the circuit was performing properly.

Data presented in this report is in the form of graphs and is the temperature time variation of the two middle air nodes. The lower left hand portion of the curves, (Figures 11 and 12), are the readings at the middle nodes prior to the entrance of the hundred men into the shelter. What appears to be a discontinuity in the curve is the application of the input representing the one hundred men. This was included so that the temperature buildup with the entrance of the men could be shown. Values for the lower left hand portion of the curve should not be considered valid, since the ventilating air analogy was based upon the assumption that the ventilating air was of lower temperature than the air inside the shelter.

Measurements of the leakage resistance of each node in the circuit was recorded. Current leakage in the thermal analyzer represents an effective loss of energy from the thermal system and is therefore a source of error. Although this is undesirable, it must be realized that it exists. Measurement of the leakage resistance was accomplished by charging the capacitance on each node to 80 volts and observing the time for the node to drop to a given potential.

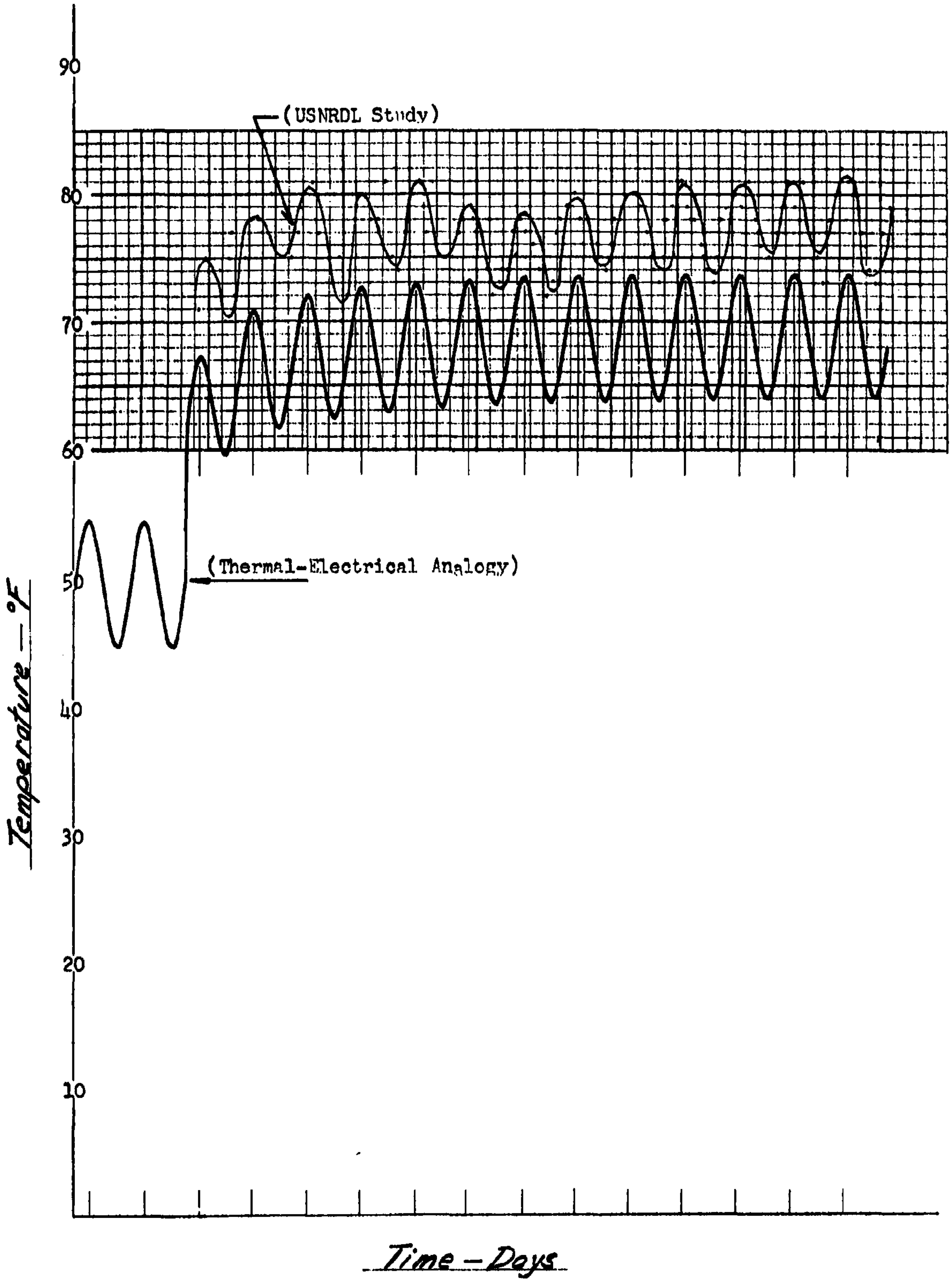


Figure 11. Temperature Variation of Air Node No. 4 Compared with USNRDL Data

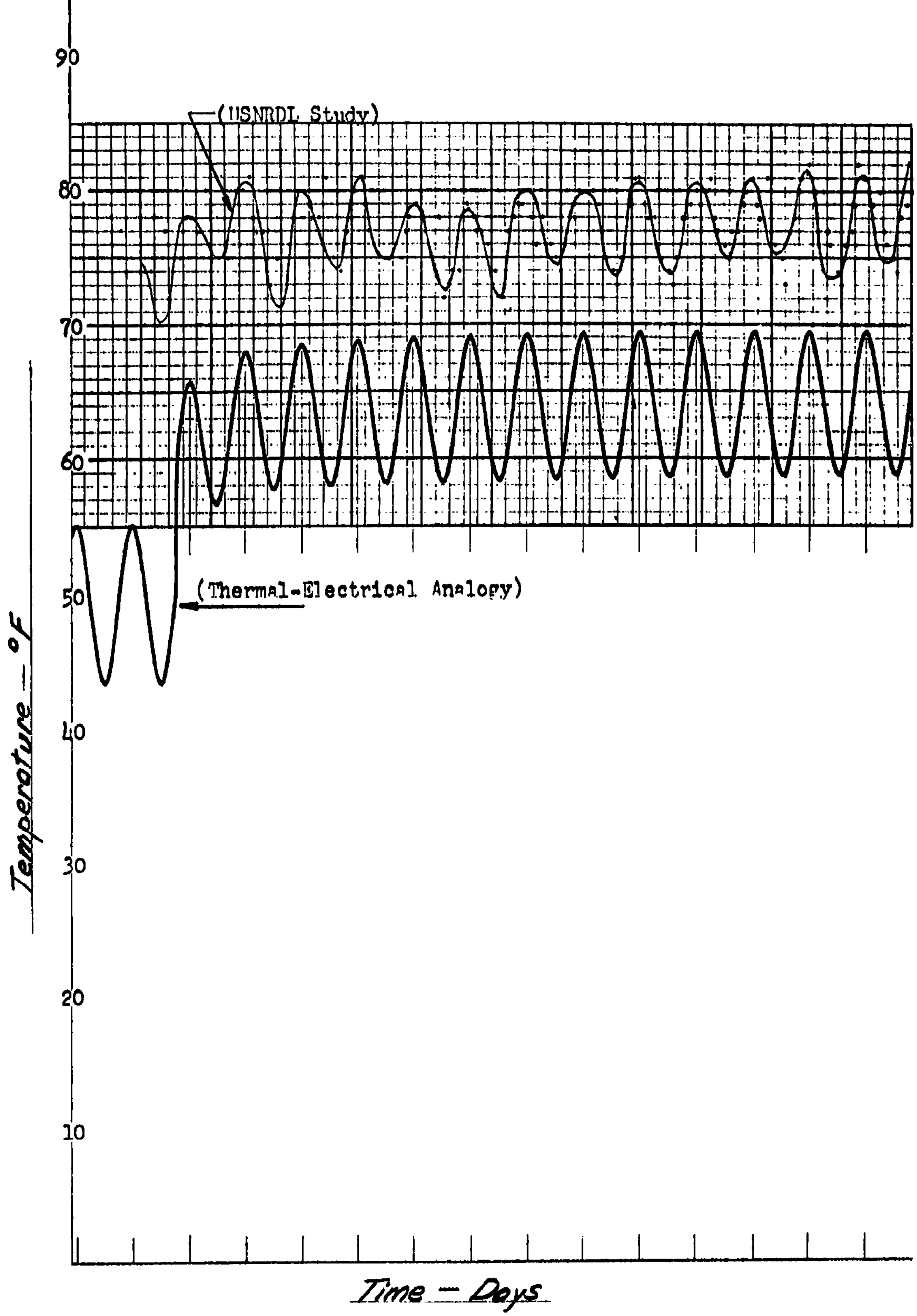


Figure 12. Temperature Variation of Air Node No. 3 Compared with USNRDL Data

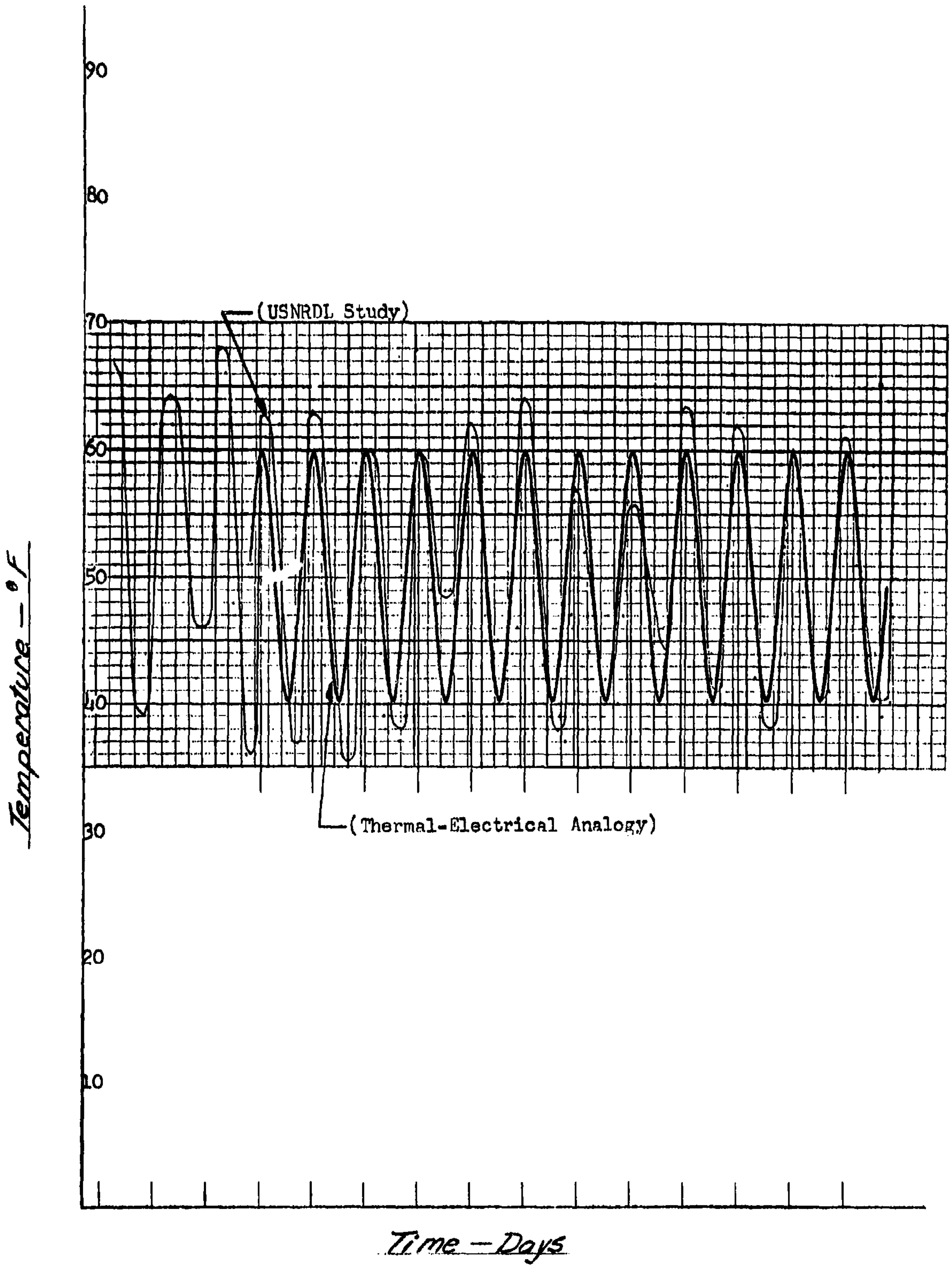


Figure 13. Comparison of Incoming Air Temperature

RESULTS AND CONCLUSIONS

The results of this study are the curves shown in Figure 11 and Figure 12. Also shown on these figures is a plot of the data representing the center room temperature during the USNRDL tests. Comparison of the center room data can best be made when our boundary conditions make the best possible fit with actual conditions as experienced by USNRDL. Figure 13 is a plot of the actual temperature variation of the ventilating air during the USNRDL test compared with our assumed temperature variation.

The difference in the results of this study and the USNRDL test is of the order of 8° to 10° and is very good when one is considering a complicated heat transfer system. When a differential equation is replaced by a finite difference equation, errors result. These errors are difficult to determine, but for the data taken in this study they are estimated to be negligible, especially with respect to leakage errors.

For the two nodes of interest, namely the two middle air nodes, the average leakage resistance in the conduction paths from these nodes is approximately 230 meg ohms. This corresponds to a leakage current of approximately 1.5 μ amps. This is very small compared to the 78 μ amps into each of these nodes. It is also small compared to the current which is flowing out of the nodes representing the ventilating air, which is of the order of magnitude of 100 μ amps.

A more accurate comparison with the USNRDL tests is not possible because the writer does not have detailed information as to the instrumentation and techniques used in temperature measurements during the USNRDL tests. The location of thermometers and thermocouples with relation to heat sources and proper shielding is very important. Any deviation from the proper technique could easily account for the difference shown.*

In a last analysis, it may be stated that a thermal circuit solution can only be as good as the representation of the actual physical system and the ability to evaluate the circuit parameters and boundary conditions. This study has demonstrated the value of the thermal analyzer in an economical and rapid solution of a complex heat transfer system.

*Author's note: Mr. Othling did not have complete experimental details at the time this report was prepared.

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APPENDIX *

COMPUTATION OF THE PARAMETERS

<u>Thermal Resistances and Capacities in the Conduction Path Through the Siding (Figure 14)</u>

Material	8 gage sheet steel
Thickness	.1644 inches
ρ	488 $\#/ft^3$
k	27 Btu/hr.ft.$^{\circ}$F
C_p	.112 Btu/$\#^{\circ}$F

Properties of the earth adjacent to the shelter:

ρ	108 $\#/ft^3$
k	.705 Btu/hr.ft.$^{\circ}$F
C_p	.26 Btu/$\#^{\circ}$F

The earth properties are those used in the USNRDL analytical study and are weighted values determined according to procedures used by the Army Corps of Engineers.

Properties of the Air Space:

γ	13.7 $ft^3/\#$
C_p	.24 Btu/$\#^{\circ}$F

*Appendix to Othling's original document.

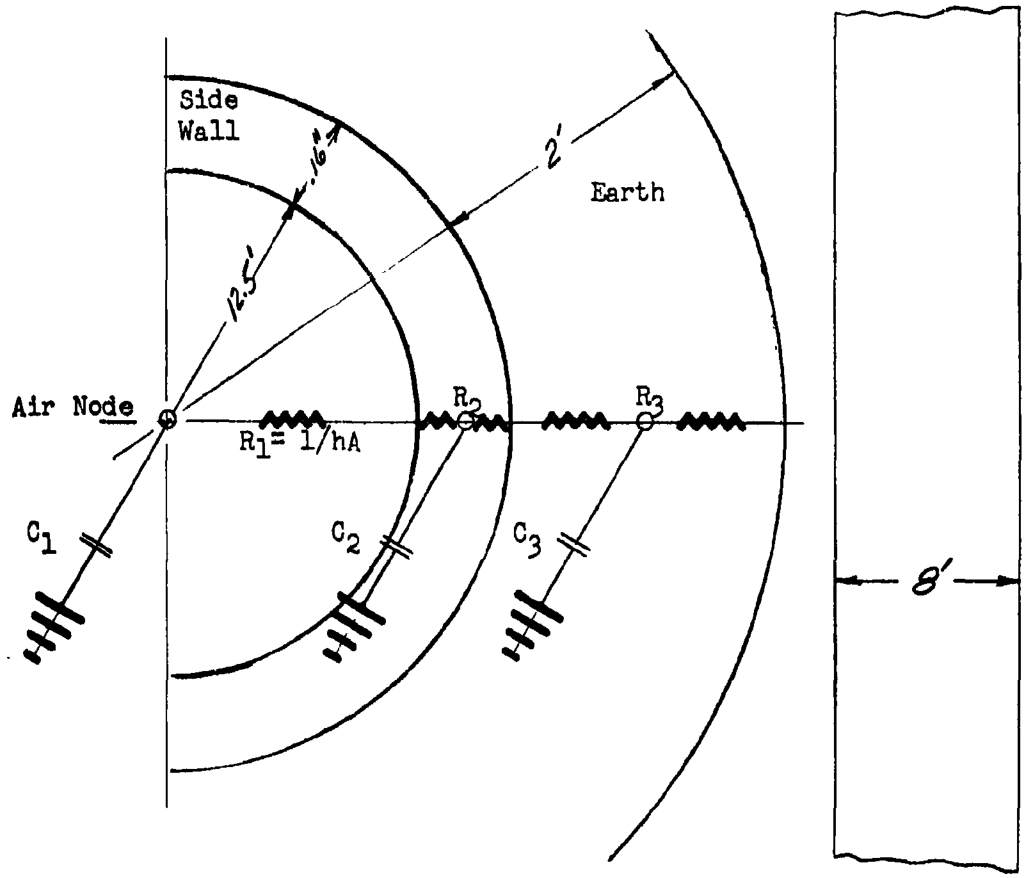

Figure 14. Conduction Path through Side Walls

For reflective surfaces with an effective emissivity of 0.05, the "Heating, Ventilating and Air Conditioning Guide" recommends an inside surface film coefficient of 0.8. This includes convection and radiation effects and is independent of the position of the surface and the temperature difference. Even though this particular choice of "h" is subject to discussion, it is of minor importance, in that it represents a small percentage of the total resistance to heat flow through the walls of the shelter.

h = .8 Btu/hr.ft.°F is the value used in the USNRDL tests and likewise will be used in this study.

$$R_1 = \frac{1}{hA} = \frac{1}{.8 \times \pi \times 12.5 \times 8}$$

$$= 3.98 \times 10^{-4} \text{ hr°F/Btu}$$

$$C_1 = \rho C_p V = \frac{.24 \times \pi \times 12.5^2 \times 8}{13.7 \times 2}$$

$$= 34.4 \text{ Btu/°F}$$

$$R_2 = \frac{\ln(r_2/r_1)}{2\pi k L} \text{ for small } r_2/r_1 \approx \frac{\Delta x}{kA}$$

$$= \frac{.1644 \times 2}{12 \times 27 \times \pi \times 12.5 \times 8} = .807 \times 10^{-6} \text{hr°F/Btu}$$

$$C_2 = \rho C_p V = \frac{488 \times .112 \times .1644 \times \pi \times 12.5 \times 8}{12}$$

$$= 236 \text{ Btu/°F}$$

$$R_3 = \frac{2\ln(r_2/r_1)}{2\pi K L} = \frac{\ln(13.5/12.5)}{.705 \times \pi \times 8}$$

$$= .00434 \text{ hr°F/Btu}$$

$$C_3 = \rho C_p V = \frac{108 \times .26 \times \pi(r_2^2 - r_1^2)8}{2}$$

$$= 1896 \text{ Btu/°F}$$

<u>Thermal Resistances and Capacities in the Conduction Path Through the Ends of the Shelter (Figure 15)</u>

Material	7 gage sheet steel
Thickness	.1793 inches

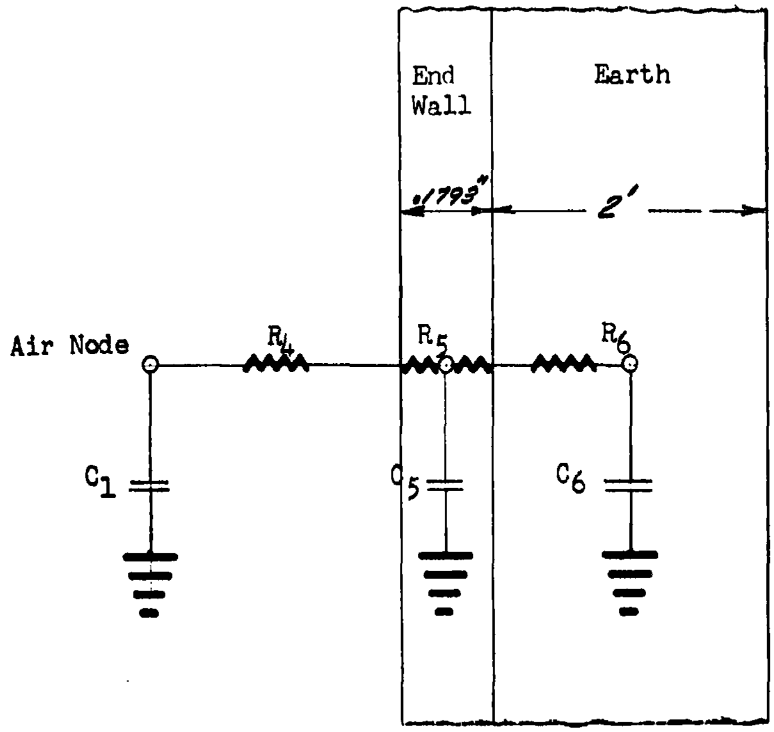

Figure 15. Conduction Path through End Walls

$$R_4 = \frac{1}{hA} = \frac{2}{.8 \times \pi \times (12.5)^2} = .0509 \text{hr}^\circ\text{F/Btu}$$

$$R_5 = \frac{\Delta x}{kA} = \frac{.1793}{2 \times 12 \times 27 \times 245.5} = 1.126 \times 10^{-6} \text{hr}^\circ\text{F/Btu}$$

$$C_5 = \rho C_p V = 488 \times .112 \times 245.5 \times \frac{.1793}{12} = 200 \text{ Btu/}^\circ\text{F}$$

$$R_6 = \frac{\Delta x}{kA} = \frac{1}{.705 \times 245.5} = .00578 \text{hr}^\circ\text{F/Btu}$$

$$C_6 = \rho C_p V = 108 \times .26 \times 245.5 \times 2 = 1.38 \times 10^4 \text{Btu/}^\circ\text{F}$$

<u>Thermal Resistances and Capacities in the Conduction Path Through the Floor (Figure 16)</u>

Material	Concrete
ρ	400 #/ft^3

k .75 Btu/hr.ft.°F

C_p .2 Btu/#°F

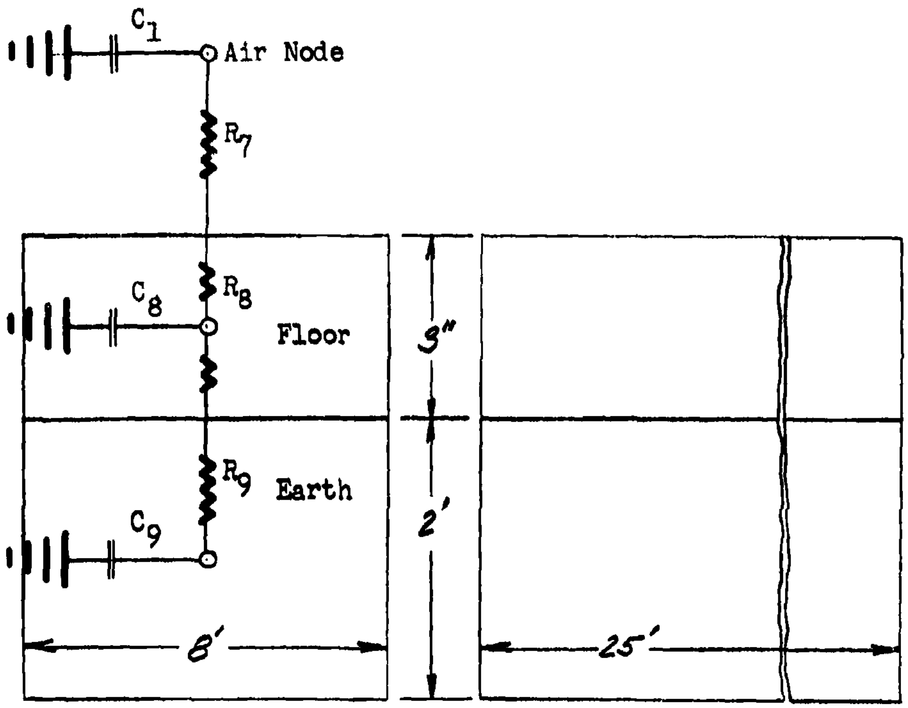

Figure 16. Conduction Path through Floor

$$R_7 = \frac{1}{hA} = \frac{1}{.8x25x8} = .00625 \text{ hr}^\circ\text{F/Btu}$$

$$R_8 = \frac{\Delta x}{kA} = \frac{1.5}{12x.75x25x8} = .833x10^{-3}\text{hr}^\circ\text{F/Btu}$$

$$C_8 = \rho C_p V = \frac{400x.2x25x8x3}{12} = 4,000 \text{ Btu/}^\circ\text{F}$$

$$R_9 = \frac{\Delta x}{kA} = \frac{1}{.705x25x8} = .00708 \text{ hr}^\circ\text{F/Btu}$$

$$C_9 = \rho C_p V = 108x.26x2x25x8 = 11,200 \text{ Btu/}^\circ\text{F}$$

Resistance R = $1/mc_p$ defined by ventilating air analogy:

Flow rate = 1600 C.F.M.

$$R = 1/mc_p = \frac{13.7}{1600x.24x60} = .594x10^{-3}\text{hr}^\circ\text{F/Btu}$$

TABLE II

SUMMARY OF RESISTANCES

Symbol	R_t	R_e	
$R_1 \neq R_2$	399×10^{-6}	$39.9\,k\Omega$	Convective & Side Walls
$R_2 \neq R_3$	.00434	.434 megΩ	Side Walls & Earth
$R_4 \neq R_5$	.0509	5.09 megΩ	Convective & End Walls
$R_5 \neq R_6$	.00578	.578 megΩ	End Walls & Earth
$R_7 \neq R_8$	.00708	.708 megΩ	Convective & Floor
$R_8 \neq R_9$	.00791	.791 megΩ	Floor & Earth
$R = 1/mc_p$	594×10^{-3}	$59.4\,k\Omega$	Ventilating Air

$$X_R = \frac{R_t}{R_e} = 10^{-8}\ \frac{hr\,^{\circ}F/B}{ohm}$$

TABLE III

SUMMARY OF CAPACITANCES

Symbol	C_t	C_e	
C_1	34.4	.344 μf	Internal Air
C_2	236	2.36 μf	Side Wall
C_3	1896	18.96 μf	Earth Adj. to Side Wall
C_5	200	2 μf	End Walls
C_6	1.38×10^4	138 μf	Earth Adj. to End Wall
C_8	4,000	40 μf	Floor
C_9	11,200	112 μf	Earth Adj. to Floor
	$X_C = \frac{C_t}{C_e} = 10^8 \frac{B/°F}{Farad}$		

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Naval Radiological Defense Laboratory
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1 August 1963 77 p. tables illus. 2 refs.
UNCLASSIFIED

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A preliminary analysis was conducted on a thermal analyzer to determine its potential as a tool for predicting shelter temperatures under various climatic conditions. This analysis showed only about 10% deviation from the measured temperature reported here.

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