

NATIONAL BUREAU OF STANDARDS REPORT

4185

Engineering Manual for Protective Construction

Part V

Heating and Air Conditioning
of Underground Installations

to

Protective Structures Section
Protective Construction Branch
Office of the Chief of Engineers
Department of the Army



**U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS**

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NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT

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Engineering Manual for Protective Construction
Part V
Heating and Air Conditioning
of Underground Installations

by

Heating and Air Conditioning Section
Building Technology Division

to

Protective Structures Section
Protective Construction Branch
Office of the Chief of Engineers
Department of the Army

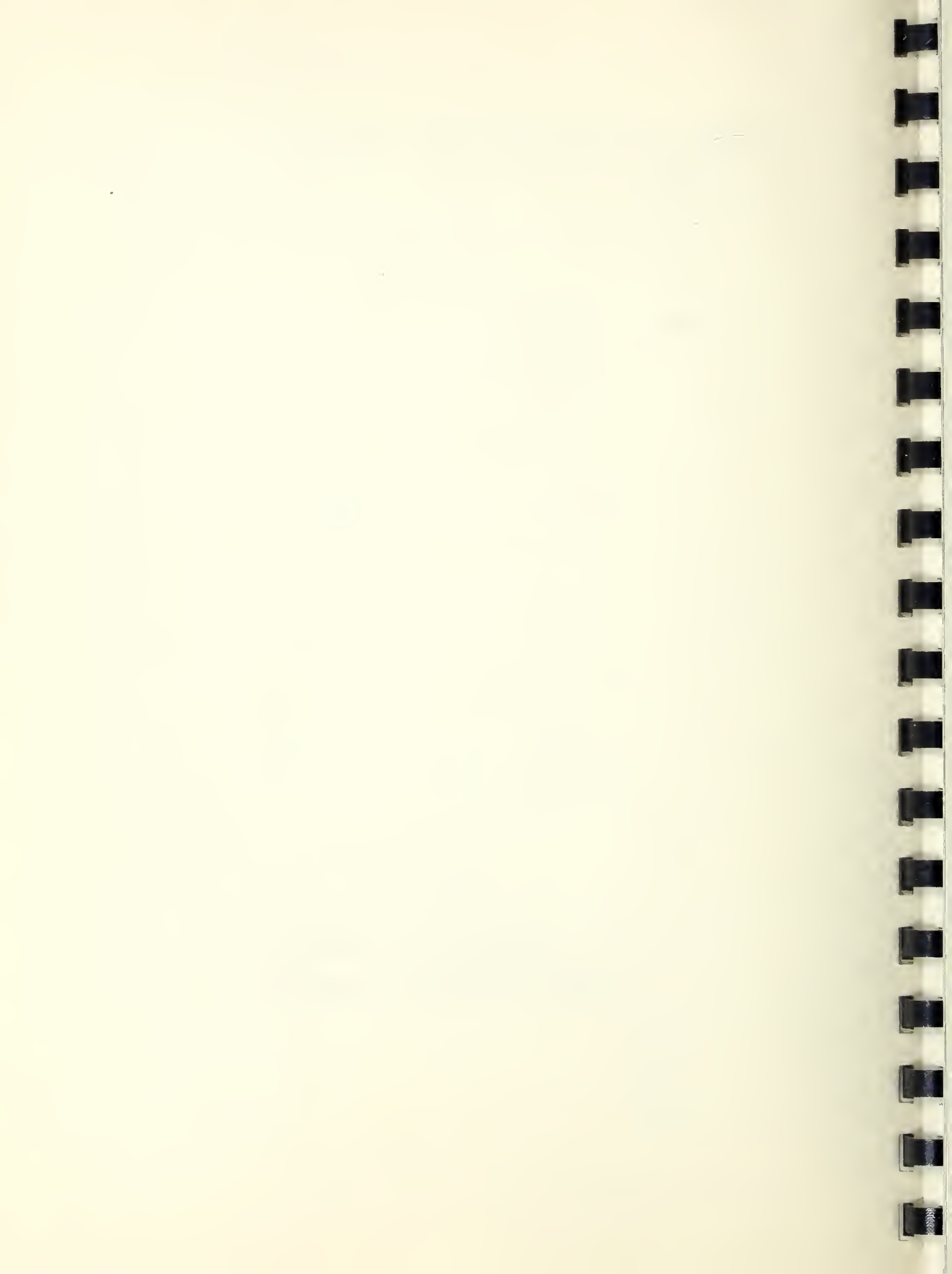


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PROTECTIVE CONSTRUCTION MANUAL
ENGINEERING MANUAL FOR PROTECTIVE CONSTRUCTION

PART V

HEATING AND AIR CONDITIONING OF UNDERGROUND INSTALLATIONS

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Underground Installations: Heating and Air Conditioning

CHAPTER I

Introduction

1-1 Purpose

The purpose of this Manual is to present in a practical and convenient form all useful engineering data and information available on heating and air conditioning of underground installations. This program was initiated by the Corps of Engineers in cooperation with the National Bureau of Standards and included a literature survey, a mathematical analysis of heat transfer to rock, and field investigations conducted in several existing underground installations. The conclusions and recommendations herein are based upon the results of these approaches.

Having responsibility for establishing procedures and criteria for designing underground constructions, the Office of the Chief of Engineers undertook this program of investigation to develop some necessary data that were lacking and to investigate the applicability of commonly accepted materials, equipment and design to underground installations.

The data gathered so far have been correlated into what is considered an acceptable design procedure although the work is expected to be refined and extended by future experience and experiment. As the advantages of underground installations

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become more apparent this Manual may attain a broad application and it is hoped that information gained in their use will be brought to the attention of this Office in order to supplement any major contribution this Manual may make to heating, ventilating and air conditioning.

Military structures, because of the destructiveness of modern means of attack and the possible increased potency of future weapons may be placed in mines or other excavations below ground. Circumstances in these type of installations are usually such that air temperature and humidity must be controlled to maintain conditions within satisfactory limits for occupancy and preservation of equipment, supplies and materials. Structures subject to dampness may have to be air conditioned for storage of perishable goods, hygroscopic materials or critical war material susceptible to deterioration in moist surroundings.

The omission of air conditioning systems in the initial design of military structures built during the war can be attributed in some instances to wartime restrictions imposed on the use of this equipment. However, it has since been realized that controlled air conditions are necessary for efficient work with papers, delicate tools or instruments as well as for material preservation and therefore a variety of heating, ventilating, and air conditioning equipment has been installed in seacoast fortifications and in military structures within the

United States. While for the most part the results have been satisfactory there are cases in which the measures taken either do not meet or greatly exceed the minimum requirements. The principles and phenomena involved are fairly well understood but there has been a lack of data on which to base ~~design~~ design and selection of equipment sizes.

1-12 Scope

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The scope/Manual includes system design, capacity selection and application of heating and air conditioning equipment to underground spaces intended for human occupancy, storage space or other use. Underground spaces may be utilized for protective structures, office or tactical administrative use, signal centers, machine or electrical equipment parts production or repair, storage of equipment, munitions, or documents, etc., or storage of food. The heating and air conditioning equipment for underground structures may include steam, hot water or warm air heating systems, mechanical or absorptive-type air conditioning systems, dehumidifiers, heat pumps and cooling towers or other means for disposing of waste heat, etc. There may be need for segregation of the air conditioning system into zones. Auxiliary equipment will include fans, duct work, pass^s, piping systems and controls. An underground chamber may or may not have a liner or inner structure, insulated or

The first part of the document is a letter from the Secretary of the State to the Governor, dated January 1, 1865. The letter discusses the state of the Union and the progress of the war. It mentions the recent victories of the Union forces and the hope that the war will soon be over. The letter also discusses the state of the economy and the need for government intervention. The letter is signed by the Secretary of the State, and is dated January 1, 1865.

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uninsulated. Ground water may add to the latent load or condensation on rock may reduce the latent load in air conditioning processes.

Temperature, humidity and other air conditions required in underground installations may not be different from those maintained in surface structures when the purposes are similar but air conditioning processes used and design procedures may be considerably different. The conditions peculiar to underground use are emphasized in this Manual and some data and information applicable to any heating and air conditioning problem are included for convenience and completeness.

Underground protective structures can be divided into three broad functional classes based on the use of the space; namely, storage, industrial, and military. The treatment of the space, the air conditions required, and the type of air conditioning equipment installed would be different for the three types of usage.

Underground storage spaces might be used for preserving food above or below freezing temperatures, for general storage of miscellaneous supplies and equipment, or for storage of military material such as explosives, precision machinery, or organic and fibrous materials that are hygroscopic. In such structures accurate control of temperature and humidity to the conditions best suited to the

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stored goods would be of primary importance, whereas human comfort and ventilation would be relatively unimportant and there would seldom be any large amounts of heat generated in the structure.

An underground industrial site might be a machine shop, a factory for precision instruments, explosives, or electronic equipment, a foundry or metallurgical plant, a fabrication plant or any one of many other important industrial activities. In such an installation the particular industrial process in use would often determine the capacity of the heating and air conditioning system required and would frequently have an important bearing on the temperature and humidity to be maintained. In some cases there would be a high heat release in the space requiring a high rate of ventilation or continuous air conditioning. Some processes might release toxic gases that would require high ventilation rates. Human occupancy would always be involved but might not be of high density. In installations having processes liberating large quantities of heat, gases, or vapors, conditions under the attack phase might rapidly become critical unless the processes could be stopped quickly.

A military installation might be a communications center, a fortification, an air raid shelter, a staff headquarters, or a research activity. In such structures the human heat load might frequently predominate although the heat release of equipment might also be high in some instances.

Such military sites would often need to remain in operation during attack conditions. Ventilation of the air might become critical during attack under high density occupancy. Greater attention would have to be given to providing adequate facilities for maintaining full working capabilities during abnormal conditions in this type of installation.

Each of the broad classes of usage described and some of the special uses in each class would require a different kind and number of commercial services or utilities, different types of air conditioning and ventilating systems, varying provisions for self-sufficiency under abnormal conditions, and oftentimes different optimum conditions of temperature and humidity under normal conditions.

1-03 Historical Background

Underground installations can be utilized more advantageously now than heretofore chiefly because a variety of heating and air conditioning equipment is readily available and knowledge of its use has increased rapidly in recent years. In the past, underground spaces appear to have been avoided for practical purposes, chiefly on account of darkness or heat and dampness
/in combination. For, if any, underground spaces were air conditioned for personnel comfort or efficiency or for the preservation of equipment or material prior to World War II. Some deep mines were cooled by refrigeration but the objective was

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to permit survival under conditions of heavy labor at low levels where valuable minerals would be otherwise unattainable.

Early measures taken to prevent dampness within heavy masonry structures included provision of small air passages in the walls through which air circulated as a result of natural draft or convection. They were intended to keep the wall temperatures near to the room air temperatures and thus preclude condensation. However, in many cases the effect was not adequate and the resulting conditions were often unsatisfactory.

It is reported to be the practice in some salt mines to pass the outside air introduced for ventilation through a worked-out portion of the mine. The air, if received hot and humid, is cooled to a degree and dried by the residual salt. In the working portion of the mine the air is warmed by the machinery and lights with a resultant lowering of the relative humidity.

Applications of a similar scheme to underground spaces other than salt mines are also recorded. Air is drawn through unused underground spaces where it is cooled and dried by contact with the rock. Then it is warmed to an acceptable temperature and introduced into the occupied spaces. The relative humidity falls when the air is warmed and thus an unused tunnel or other underground space is a means of air conditioning. When this process has been employed in the

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past, the underground space used for conditioning the air has usually been large compared to the occupied or conditioned space and the limits of the capacity of an unused tunnel or other space as an air conditioner were not known. It is contemplated that a more exhaustive study of this subject shall be made a part of the present program on underground air conditioning.

Underground spaces were utilized in Norway, Sweden, Germany and Japan during World War II chiefly as manufacturing or processing plants. Much useful information on this subject is contained in a report "Underground Installations, Foreign" (Ref. 8), but the report yields little design data on heating and air conditioning. It appears that air conditioning was not considered justifiable for most underground installation in a majority of these countries under the then prevailing war time conditions. Of the plants surveyed only seven percent had air conditioning and only forty-seven percent had other than natural ventilation. Heating was reported as provided in twenty-seven percent of the plants surveyed.

The paper "The National Gallery in war Time" (Ref. 9) is an account of the Underground storage of paintings from the British National Gallery. An existing site was selected that provided space for the whole collection and afforded 200 to 300 feet of rock cover. The initial air conditions were 47°F and 95 to 100 percent relative humidity. The underground space,

apparently an old mine, was large so six buildings were erected within it to contain the pictures. Each small building was warmed by means of a forced-circulation system apparently utilizing electric heat. For ventilation, small amounts of air from the space, at 47F and near saturation, were introduced into each building as required. It was found that when the buildings were warmed to 64F the interior relative humidity was near 97 percent which was considered satisfactory for long term storage of the pictures. No cooling means or dehumidifying means was required and no dehumidifications other than that provided by the heating system in conjunction with the enclosing, relatively cool chamber.

With this background of information this program was undertaken by the Office of the Chief of Engineers in cooperation with the National Bureau of Standards.

1-04 Structural Arrangements, Definitions

Some features of the structural arrangement of an underground installation affect the size and design of the air conditioning equipment and system. Relevant definitions are as follows:

Bare Chamber: An underground chamber with no covering on the rock walls or ceiling that will appreciably affect heat transfer; walls painted to improve illumination of the chamber are considered bare from the heat transfer standpoint. A chamber with a concrete floor poured on the underlying rock is considered a bare chamber.

Lined Chamber: An underground chamber with a wall covering of concrete or another material in contact with the rock walls and ceiling. The wall covering, or liner, may have sufficient thermal resistance to affect heat transfer from the chamber to the rock. Some liners may consist of insulating or acoustical material and may contain a vapor barrier.

Internal Structure: A building or enclosure erected within an underground chamber to house equipment or facilities. The internal structure reduces the heat transfer from the occupied space to the rock (Section 4-05) and influences the dehumidification load (Section 3-09).

Annular Space: The space around an internal structure, between it and the rock walls, floor and ceiling of an underground chamber.

1-05 Operating Conditions

An underground installation must be heated or air conditioned to accommodate the activity under various operating conditions. Some of the probable operating conditions of an underground space are as follows:

Stand-By: Facility ready for normal operation at short notice; may be occupied by a skeleton force for maintenance; air conditioned for maintenance of equipment and furniture.

Normal Operation, Maximum Capacity: Facility operating at full or design capacity; occupied by full complement of personnel; air conditioned for personnel efficiency (Section 2-04) and as required for operation of equipment.

Normal Operation, Partial Capacity: Facility operation at less than full capacity as when full output is not required; air conditioned for personnel efficiency and equipment operation in occupied parts; air conditioned for equipment maintenance in other parts.

Alert Conditions: Occupancy and activity the same as Normal Operation except for adjustments made in anticipation of attack.

Attack Condition: Occupancy and activity the same as Normal Operation except for alterations necessitated by attack.

Post Attack: Normal Operation to the extent permitted by damage due to attack.

Disaster Condition: Outside services including power, water supply, and possibly sewage disposal system cut off and outside air supply greatly reduced or cut off; personnel and facilities dependent on stored water, food and emergency power source; air revivification essential for survival of personnel.

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1-06 Symbols

Symbols utilized in this work are as follows:

- A = Area, ft^2 ; A_1 , A_2 and A_3 for floor, walls and ceiling respectively; A' for internal structure; A for exposed rock, A_w for wetted surface
- a = Radius, ft; a_1 for equivalent cylinder, a_2 for equivalent sphere
- B = Mathematical quantity for use in section 4-05
- C = Mathematical quantity for use in section 4-05
- C = Conductance, $\text{Btu hr}^{-1}\text{ft}^{-2}\text{F}^{-1}$
- c = Specific heat, $\text{Btu lb}^{-1}\text{F}^{-1}$; c' for water
- F = Mathematical quantity for use in sections of chapter 4.
- F = Degrees Fahrenheit or temperature difference, F.
- f = Function of; depends upon
- G = Mathematical quantity for use in equation 4-08
- h = Surface heat transfer coefficient, $\text{Btu hr}^{-1}\text{ft}^{-2}\text{F}^{-1}$
- K = Thermal conductivity, $\text{Btu hr}^{-1}\text{ft}^{-2}(\text{F}/\text{ft})^{-1}$
- k = Thermal conductivity, $\text{Btu hr}^{-1}\text{ft}^{-2}(\text{F}/\text{in.})^{-1}$
- L = Length, ft; distance from entrance of tunnel section 4-05
- L = Length, ft, of wetted area, figure 4-12
- M = Mass, lbs; M' = mass (lbs) of water per foot of tunnel or reservoir
- m = Length, ft. of underground space
- N = Mathematical quantity for use with equation 4-06
- n = Width, ft. of underground space.

Symbols utilized in this work are as follows:

A = Area, ft^2 ; A_1 , A_2 and A_3 for floor, walls and ceiling respectively; A_4 for internal structure; A for external

used rock, A_w for wetted surface

e = voids, ft ; e_1 for equivalent cylinder, ft

equivalent sphere

B = Mathematical quantity for use in section 1-05

C = Mathematical quantity for use in section 1-05

d = Diameter, ft or in

e = Eccentricity, ft or in ; e_1 for water

F = Mathematical quantity for use in sections of chapter 1.

G = Degree Fahrenheit or temperature difference, F .

H = Height of; depth of

I = Mathematical quantity for use in equation 1-05

J = Surface heat transfer coefficient, $ft^2-hr^{-1}-F^{-1}$

K = Thermal conductivity, $ft-hr^{-1}-F^{-1}$

k = Thermal conductivity, $ft-hr^{-1}-F^{-1}$

L = Length, ft ; distance from entrance of tunnel section

1-05

L = Length, ft , of water mass, figure 1-12

M = Mass, lb ; M = mass (lb) of water per foot of length

of rock vein

n = Length, ft , of unobstructed space

P = Mathematical quantity for use with equation 1-05

r = Width, ft , of underground space.

P_w = Water pressure, lb in.⁻²

p = Pressure, lb in.⁻²; p_s = vapor pressure, water on a surface; p_a , vapor pressure, water vapor mixed with air

Q = Heat transferred or absorbed, Btu

R = Ratio, for use with equation 4-05

q = Heat transfer rate, Btu hr⁻¹ft⁻², from air to rock;

q' for constant rate

q_1 = Heat absorption per foot of length of reservoir, Btu hr⁻¹ft⁻¹

q_2 = Heat absorption of reservoir, Btu hr⁻¹

s = Height, ft, of underground chamber

T = Temperature, F; T_o for outside air; T_p for initial rock; T_s for rock surface; T_1 for inside air design temperature, T_2 for annular space

t = Time, hours

θ = Temperature increase, degrees F; θ_s for rock surface

θ_1 for inside air; θ_L for air at distance L from tunnel entrance; θ_w for water in a reservoir

U = Heat transmittance, Btu hr⁻¹ft⁻²F⁻¹, for a wall or other heat barrier

U' = Heat transfer coefficient, Btu hr⁻¹ft²F⁻¹, from air in occupied space to surrounding rock; for no internal structure, $U' = h$

V = Velocity, ft hr⁻¹

p_w = water pressure, lb in.⁻²

p_a = pressure, lb in.⁻²; $p_a = p_w + p_g$, where p_g is gas pressure, lb in.⁻²

p_g = gas pressure, lb in.⁻²

p_g = gas pressure, lb in.⁻²

Q = heat transferred or absorbed, Btu

Q = heat, for the whole system, Btu

Q = heat transfer rate, Btu hr.⁻¹, from air to rock

q = heat transfer rate

q = heat absorption per foot of length of reservoir

q = heat transfer rate

Q = heat absorption of reservoir, Btu

Q = heat, Btu, of underground storage

T = temperature, °F, for outside air; T_i for inside air

T_i = temperature, °F, for inside air

T_i = temperature, °F, for inside air

T_i = temperature, °F, for inside air

T_i = temperature increase, degree F, for rock surface

T_i = temperature, °F, for air at distance L from

ground surface; T_i for water in a reservoir

U = heat transmission, Btu hr.⁻¹ ft.⁻², for a wall

U = heat transfer coefficient

U = heat transfer coefficient, Btu hr.⁻¹ ft.⁻², from

air in enclosed space to surrounding rock; for

no internal resistance, $U = h$

U = velocity, ft. sec.⁻¹, for air

V = Mathematical quantity for use with figures 4-1 and 4-2

W = Water flow rate, lb hr⁻¹; W' for evaporation of water

w = Angular velocity

Z = Mathematical quantity for use in section 4-05

p = Density, lb ft⁻³; p' for water

FT²; INTERNAL AREA, A_I FT²; VOLUME =

1-07 Data Forms

Some forms for recording data and to serve as work sheets are suggested as follows:

Form A - Design Information

B - Heating and Cooling Loads

C - Rock Heat Absorption, Warm-up

D - Rock Heat Absorption, Normal Operation

E - Heat Absorption Capacity of a Reservoir

F - Cooling or Heating of air in Tunnels or Shafts

These forms are expected to be improved as indicated

by future use and experience. Extra copies should be obtained or provided as required for different problems.

RAIL FALL

SIDE

ROCK TEMPERATURE INTERNAL (INDICATED) F

REQUIRED AIRS AND CONDITION F; MPH

PERSONS

Y = mathematical quantity for use with Equation 1-1

and μ

W = Water flow rate, lb/hr; W' = evaporation rate

water

v = angular velocity

Z = mathematical quantity for use in Equation 1-2

ρ = density, lb/hr; ρ' = evaporation rate

1-07 Data Format

Some forms for recording data are given in Table 1-1.

Tables are prepared as follows:

Table 1 - Data Information

2 - Number and Coding Labels

3 - Data Description, Summary

4 - Data Description, Detail Description

5 - Data Description, Summary of a Variable

6 - Coding or Labeling of Data in Tables or Charts

These forms are expected to be prepared as indicated

by future use and experience. Some copies should be

obtained or provided as required for different values.

FORM A

UNDERGROUND INSTALLATION AIR CONDITIONING DESIGN
DATA AND COMPUTATIONS

DESIGN INFORMATION

DATE:

LOCATION: _____

PURPOSE: _____

DIMENSIONS, ROCK CHAMBERS

LENGTH, M = FT; WIDTH, N = FT; HEIGHT, S = FT

FLOOR AREA, A' = FT²; INTERNAL AREA, A = FT²; VOLUME = FT³

REMARKS: _____

DIMENSIONS, INTERNAL STRUCTURE (IF USED)

LENGTH = FT; WIDTH = FT; HEIGHT =

FLOOR AREA = FT²; INTERNAL AREA = FT²; VOLUME = FT³

DEPTH OF OVER BURDEN FT

GEOLOGICAL FORMATION _____

GROUND WATER CONDITION _____

CLIMATE

WINTER

SUMMER

MIN.

DES.

MAX.

DES.

DB, F _____

WB, F _____

RH, % _____

RAIN FALL, INS.

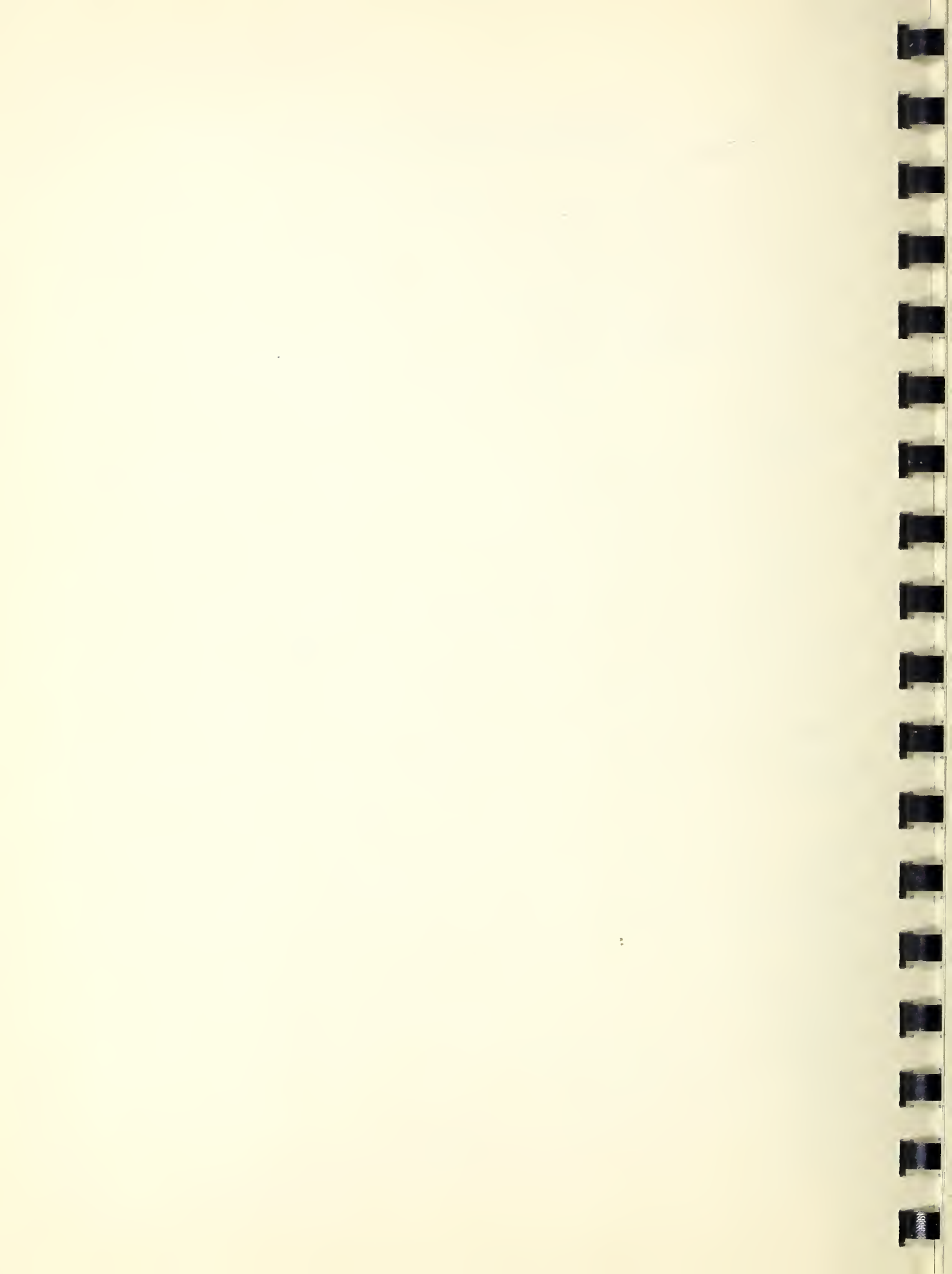
SNOW, INS.

ROCK TEMPERATURE, INITIAL UNDISTURBED, F

REQUIRED INSIDE AIR CONDITION F; %RH

PERSONNEL PERSONS

PREPARED BY:



FORM B

UNDERGROUND INSTALLATION AIR CONDITIONING DESIGN

HEATING & COOLING LOADS

HEAT GAIN BTU HR ⁻¹		SENSIBLE	LATENT
PERSONNEL,	PERSONS x 270 (SENS.); x 230 (LAT)		
LIGHTS;	KW x 3415		
ELECTRIC MOTORS	KW x 3415		
COOKING EQUIPMENT			
OTHER EQUIPMENT			
TOTAL INTERNAL LOAD			
FRESH AIR SUPPLY, SUMMER			
TOTAL COOLING LOAD			
FRESH AIR SUPPLY, WINTER			
	CFM x 1.08 (θ ₁ - θ _L) =		

TIME FROM START, HOURS	2000	5000	10,000	20,000
ROCK HT. ABS. BTU HR ⁻¹				
TOTAL COOLING LOAD				
NET COOLING LOAD				
TOTAL HEATING LOAD				



FORM C

UNDERGROUND INSTALLATION AIR CONDITIONING DESIGN
DATA AND COMPUTATIONS

HEAT ABSORPTION BY ROCK SURROUNDING AN UNDERGROUND
INSTALLATION; WARM-UP PERIOD

CHAMBER DIMENSION, FT.: LENGTH, M= ; WIDTH, N= ; HEIGHT, S=

INTERNAL AREA, EQ. 4-01, $A = 2(MN + MS + NS)$ = FT²

EQUIV. CYL, RADIUS, EQ. 4-02, $a_1 = A/2\pi M$ = FT

EQUIV SPHERE, RADIUS, EQ. 4-03, $a_2 = \sqrt{A/4\pi}$ = FT

V_1/V (CYLINDER)* FIG. 4-1 =

V_2/V (SPHERE)* FIG. 4-2 =

ROCK: DENSITY, ρ = ; CONDUCTIVITY, K^{**} = ; SP. HEAT, C = ; TEMP., T_R = F

$\theta_1 = T_i - T_R$ = ; U' (SEE 4-08) =

FIND RELATION BETWEEN WARM-UP TIME (t , HOURS) AND HEAT INPUT, q' (BTU. HR⁻¹ FT⁻²)
BY MEANS OF EQUATION 4-04.

$F = Kt/\rho ca^2$ (USE a_1 FOR CYLINDRICAL CASE, a_2 FOR SPHERE) =

FIND $F(F)$ = , FROM FIG. 4-3 (CYL), IN 4-4 (SPHERE).

SOLVE FOR HEAT REQD FOR WARM-UP PERIOD WITH THE EQUATION

$$q' = \frac{K\theta_1}{aF(F) + K/U'}, \text{ BTU HR}^{-1}\text{ FT}^{-2} =$$

ROCK HEAT ABSORPTION, TOTAL PER HOUR, Aq' = BTU HR⁻¹

*IF V_1/V EXCEEDS V_2/V , UTILIZE CYLINDRICAL CASE

*IF V_2/V EXCEEDS V_1/V , UTILIZE SPHERICAL CASE

**BTU PER HOUR FOR ONE SQUARE FOOT AND FOR A TEMPERATURE GRADIENT OF ONE DEG F
PER FOOT OF THICKNESS.





FORM E

HEAT ABSORPTION OF AN UNDERGROUND RESERVOIR (PIPE OR TUNNEL)
 FILLED WITH WATER

PERMISSIBLE TEMP. RISE OF WATER, $\theta_w =$ DEG F IN TIME, $t =$ HOURS FOR

A HEAT ABSORPTION OF $q_2 =$ BTU HR⁻¹

PROPERTIES OF ROCK:

THERMAL CONDUCTIVITY, $K =$; DENSITY, $\rho =$; SP. HEAT, $C =$

PROPERTIES OF WATER:

DENSITY, $\rho' = 62.4$; SP. HEAT, $C' = 1.0$

DIMENSIONS OF RESERVOIR (FOR RECTANGULAR CROSS-SECTIONS)

WIDTH, $N =$ FT.; HEIGHT, $S =$ FT.; LENGTH, $L =$ FT.

RADIUS OF EQUIVALENT CYLINDER, $a = (S + N)/\pi =$ FT.

IN EQUATION 4-08, $\theta K/q_1 = F(F, G)$

$$F = kt/\rho ca^2 =$$

$$G = 2\rho C/\rho' C' =$$

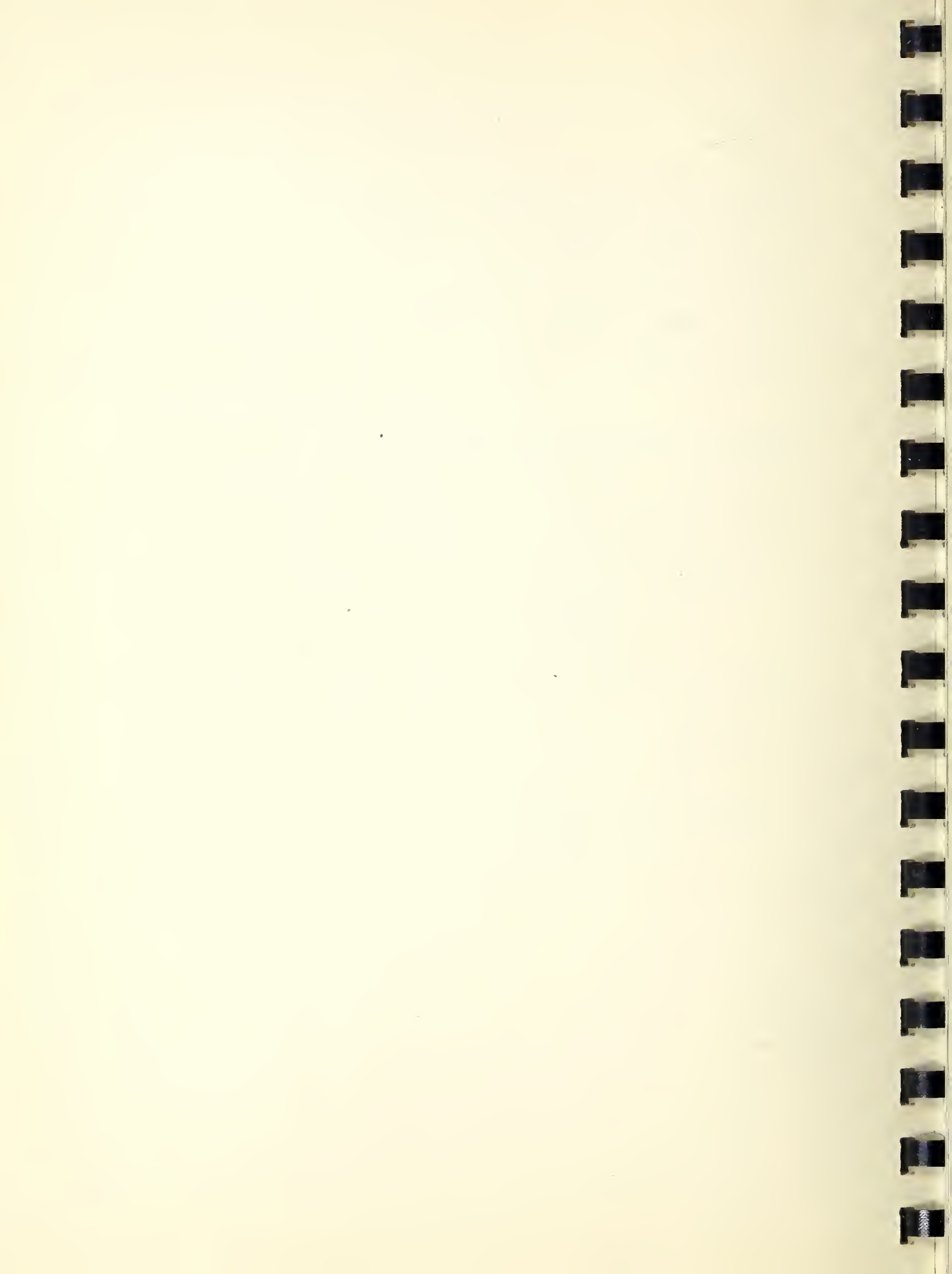
VALUES OF $F(F, G)$ ARE GIVEN BY THE CURVES ON FIGURE 4-7

THEN $\theta K/q_1 = F(F, G) =$

$$q_1 = \text{BTU HR}^{-1}\text{FT}^{-1}$$

REQUIRED LENGTH, $L = q_2/q_1 =$ FT.

VOLUME, $= SNL =$ FT.³



COOLING OR HEATING OF AIR IN TUNNELS (OR SHAFTS)
CONTINUOUS AIR FLOW, ANNUAL WEATHER CYCLE

DIMENSIONS OF TUNNEL

LENGTH L = FT; WIDTH N = FT; HEIGHT, S = FT

PERIMETER, P, $2(N + S)$ = FT; C.S. AREA, NS = FT²

HYDRAULIC RADIUS, $2NS/P = Q$ = FT

PROPERTIES OF AIR ENTERING TUNNEL FROM OUTSIDE

MEAN ANNUAL TEMP. = INITIAL ROCK TEMP., TR = F

TEMP. DIFF., OUTSIDE AIR AND MEAN ANNUAL TEMP., θ_0 = F

MAX. VALUE OF θ_0 , θ'_0 = F

AIR VELOCITY IN TUNNEL $V =$ FT HR⁻¹

PROPERTIES OF ROCK

CONDUCTIVITY, K = ; DENSITY, ρ = ; SP. HEAT, C =

COEF. OF HEAT TRANS. AIR TO ROCK, h = ; DIFFUSIVITY, α =

CONSTANTS COMPUTED FROM ABOVE DATA FOR USE IN EQUATIONS ON PAGE 2

$w = 0.000717$ RADIANS PER HOUR

$b = h/k \sqrt{\alpha/w}$ =

$z = a \sqrt{w/\alpha}$ =

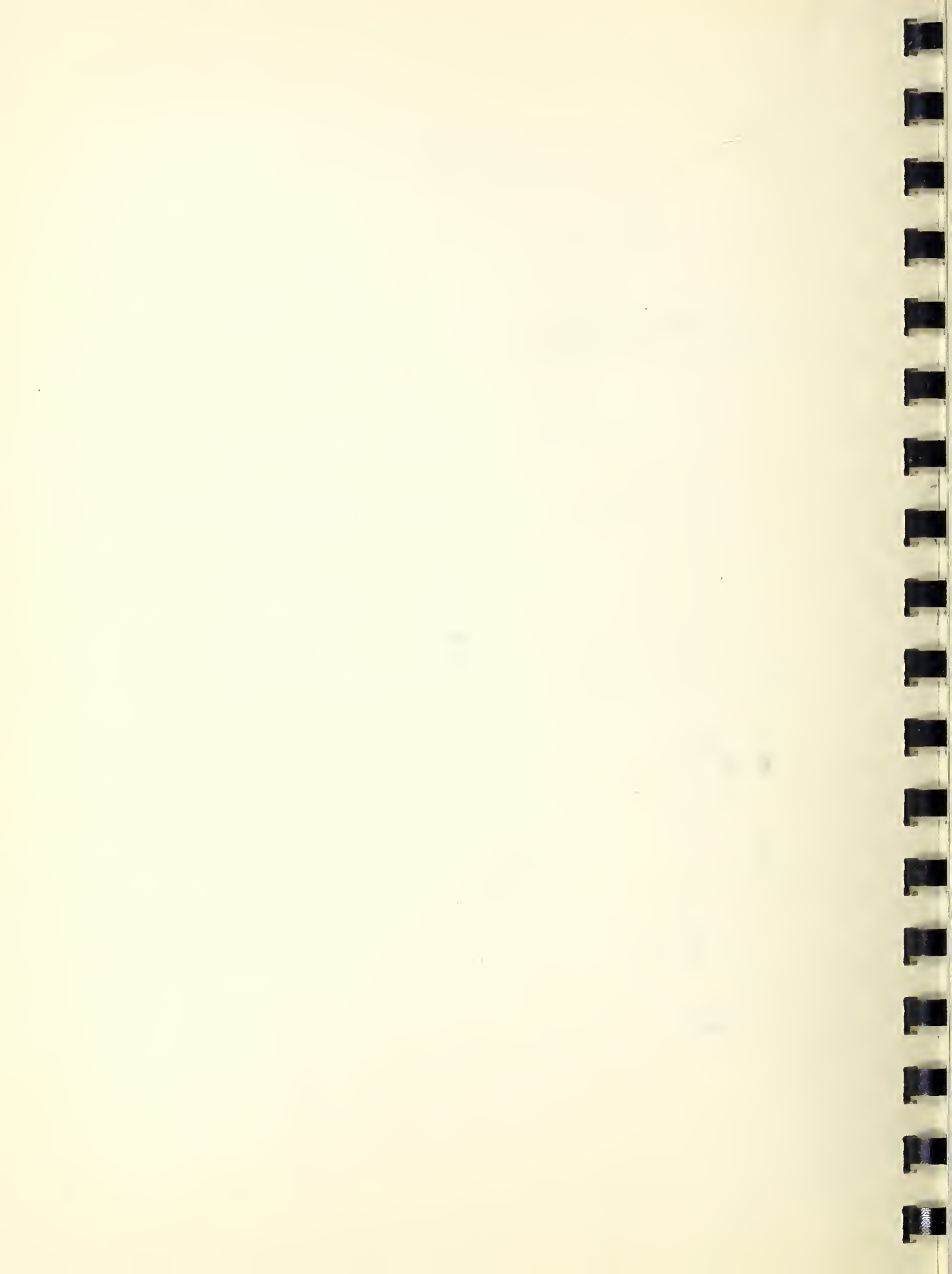
$C' = hL/Va$ =

$C = F_1(b, z)$ FIG. 4-8 =

$B = F_2(b, z)$ FIG. 4-9 =

$C''C$ =

$C''B + wL/v$ =



SOLUTION OF EQUATION FOR TUNNEL HEAT TRANSFER

MAXIMUM AND MINIMUM TEMP. AT POINT L IN A TUNNEL, (EQ. 4-11)

$$\theta'_L = \pm \theta'_0 e^{-CC'} =$$

$$T'_L = T_R + \theta'_L = \quad , \text{ ALSO } T_R - \theta'_L =$$

TEMP. θ'_L , IN TUNNEL AT POINT L AT TIME t, (EQ. 4-10)

$$\theta'_L = \theta'_0 \frac{e^{-CC'} \cos (wt - WL/V - C'B)}{\cos (wt - \quad)}$$

OUTSIDE AIR TEMP. θ_0 (EQ. 4-09)

$$\theta_0 = \theta'_0 \cos wt$$

RATE OF HEAT LOSS OR GAIN BY AIR IN TUNNEL AT POINT L AND TIME t, (EQ. 4-12)

$$q = 0.0566 V a^2 (\theta_0 - \theta'_L)$$

TEMPERATURES AND HEAT FLOW RATES DURING ANNUAL WEATHER CYCLE

		JUL 15	SEP 15	NOV 15	JAN 15	MAR 15	MAY 15
TIME	HRS	0	1460	2920	4380	5840	7300
wt	RADIANS	0	1.047	2.094	3.142	4.189	5.236
OUTSIDE TEMP, * θ_0	, F	$\theta'_0 =$			$-\theta'_0 =$		
TEMP. AT L, *							
TEMP DIFF ($\theta_0 - \theta'_L$), F							
HEAT LOSS OR GAIN, BTU/HR ⁻¹							

*FOR ACTUAL TEMPERATURES, ALGEBRAICALLY ADD THE MEAN ANNUAL TEMP. T_R TO θ_0 OR θ'_L .



CHAPTER 2

Principles: Design Objectives

2-01 Function of Underground Installations

The design of the heating and air conditioning system for an underground installation depends on the location, function, size and shape. These factors are likely to be established by the agency requiring the space or by some higher authority, on a basis of anticipated needs. Form A is suggested for recording the necessary data.

Underground installations may serve as protective structures for tactical administrative offices or communication centers; as shops or factories producing machine parts, electronic equipment, chemical products or instruments, or as storage space for machine parts, instruments, electronic equipment, food, clothing, munitions or other equipment. Hospital wards as well as domestic facilities including kitchens, lavatories and berthing accommodations, may be required in conjunction with any of these other functions.

The heating and air conditioning system must maintain conditions suitable for personnel efficiency (2-04) in working spaces and for material preservation (2-05) in storage spaces as well as shops, offices and other spaces where equipment is utilized. These conditions must be maintained during the standby, normal operating and, so far as possible, during the attack and post attack conditions (1-05). Air conditioning

THE HISTORY OF THE UNITED STATES

CHAPTER I. THE DISCOVERY OF AMERICA.

THE DISCOVERY OF AMERICA BY CHRISTOPHER COLUMBUS.

THE HISTORY OF THE UNITED STATES.

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or revivification of the air must also be considered for a condition of extreme emergency or disaster (2-07).

2-02 Design Criteria and Limitations

The size, shape and depth of cover chosen for an underground installation may be influenced by function. A storage space for clothing, food, etc., may be irregular in shape and have a relatively shallow cover of earth and rock. More important equipment or facilities essential to defence may be installed in deeper workings. The chambers in deeper workings are likely to be long and tunnel-like. The installation may occupy one or several stories and there may or may not be an inner structure (1-04).

Location determines the climate and the geological formation (4-06) that will surround a proposed underground structure. Climate (1-10) in turn, governs the conditions of outside air (2-06) available for ventilation, the prevalence of underground water (4-10), availability of water for equipment cooling (5-12), and the initial earth or rock temperature (4-07).

Floor area and volume of an occupied space depends upon population, function and internal load (2-10)(3-01).

Environmental conditions, in particular temperature, humidity, purity and, to a lesser extent, motion must be selected with reference to personnel efficiency (2-04) or endurance (2-07) and material preservation (2-05).

1. The first part of the document is a list of names and addresses of the members of the committee. The names are listed in alphabetical order and the addresses are given in full.

2. The second part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of chairman and vice-chairman.

3. The third part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of secretary and treasurer.

4. The fourth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of member-at-large.

5. The fifth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of member-at-large.

6. The sixth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of member-at-large.

7. The seventh part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of member-at-large.

8. The eighth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of member-at-large.

9. The ninth part of the document is a list of the names and addresses of the members of the committee who have been elected to the office of member-at-large.

Outside or fresh air must be supplied except under emergency conditions for personnel (2-06), for engines or boilers (2-08) for kitchen and lavatories (2-09) and for any special processes involved.

Air filters are usually recommended for all air to be passed through conditioning coils, used in engines or to ventilate shops where delicate equipment is stored, made or repaired. Air purifiers are essential for all fresh or outdoor air if maximum security is required (5-15).

The initial temperature (4-07), thermal conductivity and heat capacity of the surrounding rock (4-06) affect the heating and cooling loads in an underground chamber (5-01).

2-03 Air Conditioning Requirements

For design purposes an interior air condition of 75°F and 50 percent relative humidity can be assumed in many cases. This condition is within the practicable range attainable with conventional equipment (5-09) and available data show it to be suitable for personnel efficiency (2-04) and for material preservation (2-05) under usual circumstances. In general air conditions for underground installations should be similar to those selected for surface structures utilized for the same or similar purposes. Fresh or outside air supply (2-06) may be reduced since comfort is not always a prime objective. Since infiltration is unlikely in an underground installation, the air supply and exhaust systems must be adequate to handle the

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air required at all times.

Air conditions maintained in a space may differ from those assumed for design purposes, as indicated by practical consideration after operations have commenced. Special air conditioners may be required for special purposes, such as storage or work with unusual materials.

2-04 Air Conditions for Personnel Efficiency

Experience has shown that personnel can sustain a considerable range of temperature from about 65 to 85 F without serious loss of efficiency, particularly if the humidity is controlled and is adjusted downward when the temperature increases or vice versa. The condition 75F and 50 percent relative humidity may be assumed for design purposes (2-03) but other conditions in the comfort zone (Ref.1) are also satisfactory for many purposes. The comfort zone is defined as that area on a psychrometric chart for which 50 percent or more of the subjects were found to be comfortable during cool tests conducted by the American Society of Heating and Air Conditioning Engineers. The comfort conditions are still under examination and new findings are in prospect, particularly relating to effects of radiation. Changes in design criteria are not likely to be extensive, however, so far as air conditioning underground installations are concerned where convection heating and cooling will predominate. The findings are more likely to result in adjustments to existing data.

The condition 75F and 50 percent relative humidity is warmer than the 65 or 70F often recommended for indoor winter temperature. However, in many occupied spaces, cooling rather than heating will be required due to internal loads and use of the higher temperature reduces the size and load of the cooling equipment. It is common experience that many people are more comfortable at a DB temperature of 75F winter and summer than at a DB temperature of 70F. The condition 75F and 50 percent is safely below the conditions of excessive sweating which can interfere with the performance of instrument makers, draftsmen, typists and others working with papers and office equipment.

Fresh or outside air must be supplied to occupied spaces in proportion to the population (B-05).

B-05 Air Conditions for the Preservation of Materials

Available data indicate that a humidity in the range from 40 to 65 percent is satisfactory for the preservation of most technically useful materials at substantially steady temperature conditions, either in storage or in use as in shops, offices or communication centers.

An important exception is unprotected mild or carbon steel which requires a humidity of 15 percent or below for no damage or 30 percent or below for tolerable damage in 30 months. This means that special low humidity may be required in instrument shops where such steel is worked or stored without oil or rust preventive treatment.

Probably the most comprehensive information now available on the relation between humidity and deterioration of materials are those gathered under the auspices of the U.S. Navy and reported in reference 1. The data in Table 2-1 were extracted from that source.

Table 2-1: A table with multiple columns and rows, containing data extracted from reference 1. The text is extremely faint and illegible, but the structure suggests a data table with several columns and approximately 20 rows of entries.

TABLE 2-1

Humidity Tolerance of Some Materials
for 30 Month Period

Item <u>Damage, Severity</u>	<u>Humidity</u>			<u>Nature of Damage</u>
	A*	B*	C*	
Mild Steel, polished, unprotected	15	30	65	Rust
Steel (Ball Bearings Rust Preventive applied by Manufacturer)		65	90	"
Steel (Ball Bearings heavy Polar Comp.)		65		
Alloy Steel		90		
Galv. Steel		65	90	Tarnish and rust
Brass and Bronze	15*	90*		Tarnish
Aluminum and its alloys		90*		"
Rubber, Plastic, Rayon		90*		Mildew
Flax, wool, Cotton, Hair				
Leather, Sponge, Hemp.		65	90	"
Sisal, Paper, Wood				
Soap, Bars			90	Disintegration
Tinned Cans (canned food)		45		
Cloth (Life Preserver)		65	90	Rotting of Cover
Paint Brushes		65		
Small Arms, Lubricated		65	90	Mildew and rust
Instruments (clocks, Gages Volt Meters, Telescopes, etc.)		45		

*A - No visible deterioration

*B - Very slight deterioration

*C - Intolerable deterioration

The data in Table 2-1 indicates the necessity for a low humidity for the preservation of unprotected carbon steel but such steel as in the form of small arms, lubricated, can tolerate 65 percent like most of the other items listed. An upper humidity limit for tinnead cans was not found but such cans probably can withstand at least 50 percent relative humidity.

During the tests on which the data in Table 2-1 are based only the humidity and not the temperature, was controlled. The tests were conducted in enclosures exposed to the weather and the inside temperatures closely followed the weather. This probably approximates the condition within a ship in storage which was the point of interest in this investigation. As a result of the tests and other considerations, a humidity of 35 percent was chosen for the interior of many ships placed in storage following World War II. This 35 percent is considerably below the demonstrated tolerance of many materials but it affords a factor of safety against equipment failure and against sharp temperature changes that might cause condensation on some objects due to temperature lag resulting from heat capacity.

An advantage of underground storage is steadiness of temperature. For this reason a smaller factor of safety is deemed adequate in an underground chamber and it appears that a condition of 75° and 50 percent humidity, recommended for personnel efficiency and feasibility with conventional compressor

The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the success of any business and for the protection of the interests of all parties involved. The text also mentions the need for regular audits and the importance of having a clear system of accounting.

The second part of the document deals with the various methods of financing a business. It compares different sources of capital, such as bank loans, venture capital, and public offerings. It also discusses the advantages and disadvantages of each method and provides some guidelines for choosing the most appropriate financing option for a particular business.

The third part of the document focuses on the management of a business. It covers topics such as hiring and firing, setting performance goals, and creating a positive work environment. It also discusses the importance of effective communication and the role of the manager in ensuring the success of the organization.

The final part of the document provides a summary of the key points discussed in the previous sections. It reiterates the importance of accurate record-keeping, proper financing, and effective management. It also offers some final thoughts on the challenges of running a business and the rewards of success.

equipment is satisfactory for storage and use of most materials and equipment. Special low humidity may be required for instrument shops or other spaces where steel or other sensitive materials are worked without lubrication or rust preventives.

Water is essential to most kinds of material deterioration. Some metals are attacked by oxygen, atmospheric contaminants or electrolytic action in the presence of water. Organic materials support mold or mildew, when damp or moist. Obviously, therefore, condensation must be prevented on or within materials in storage. Some materials, however, are sufficiently hygroscopic to absorb ~~considerable~~ amounts of water at humidities less than 100 percent. Therefore some humidity safely below the saturation point must be maintained.

Pure, distilled, water is an active solvent for some materials and may be responsible for some deterioration. Atmospheric contaminants including sulfur dioxide and hydrogen sulfide, present in some industrial region atmospheres, are injurious to some materials. The amounts present during the tests on which Table 2-1 is based are not known. The tests were conducted at the Philadelphia Navy Yard.

Excessive dryness is harmful to some materials. Commutator brushes in electric motors suffer by "dusting" at low humidities. Paper, excelsior, straw, leather, hemp rope and feathers, as in bedding, become brittle and disintegrate upon handling under these conditions. Typical glue does not seriously lose strength in dry atmospheres but woods in general

shrink and the forces generated are often sufficient to break joints in furniture or other wooden equipment. Dry batteries also deteriorate more rapidly at low humidities.

The metal parts of munitions can be stored under the same condition as machine tools. For propellants, air conditions with relative humidity not exceeding 60 percent and temperature between 50 and 60°F have been recommended. In surveillance tests it has been found that powder that had lost potency had been exposed to either dampness or relatively high temperature for considerable periods. It is also regarded as good practice to avoid sub-freezing temperatures and extreme dryness. Exact data on the conditions causing deterioration are lacking -- and the best means of preventing or retarding deterioration is to maintain optimum conditions at all times.

Explosives may often be stored in relatively small chambers remote from each other to minimize the effects of accidents. The air conditioning equipment for such chambers should be selected with reference to minimizing pipe and duct runs. Since occupancy may be infrequent, little or no ventilation may be required. This indicates that equipment capable of dehumidifying and moderately heating such chambers is applicable in many typical cases.

2-05 Fresh Air for Personnel

The amount of fresh or outside air required actually depends on activity or rate of doing work. Present practice, however, is to supply sufficient air to avoid unpleasant odors from persons, from tobacco smoke, from cooking or other products due to occupancy. No reason appears for departing from this practice in underground installation for any normal period of operation. Selection of a fresh air requirement is complicated by the factor of intermittent occupancy which relates room volume to air change rate for equal air freshness. This situation is reflected in the data in Table 2-2, taken from reference 1.

TABLE 2-2

Minimum Outdoor Air Requirements to Remove
Objectionable Body Odors Under Laboratory Conditions

<u>Type of Occupancy</u>	<u>Air Space, ft³</u> <u>Per Person, Ft. Air Supply cfm</u>	
Heating Season, Air not conditioned		
Sedentary Adults of Average Socio- Economic Status	100	25
	200	15
	300	12
	500	7
Laborer	200	25
Sedentary Adults, Heating Season	200	12
" Cooling Season	200	4

The first part of the report is devoted to a general survey of the situation in the country. It is found that the economy is in a state of depression, and that the government is unable to meet its obligations. The report then proceeds to a detailed analysis of the various causes of the economic crisis, and suggests measures for its relief. It is concluded that the only way to bring about a recovery is by a radical reorganization of the government and the economy.

CONCLUSION

The report concludes that the economic situation is grave, and that immediate action is required to prevent a further decline. It is recommended that the government should take the following steps:

- 1. To reduce the public expenditure.
- 2. To increase the public revenue.
- 3. To improve the efficiency of the government.
- 4. To encourage private enterprise.

Year	Revenue	Expenditure	Surplus/Deficit
1920	100	120	20 Deficit
1921	110	130	20 Deficit
1922	120	140	20 Deficit
1923	130	150	20 Deficit
1924	140	160	20 Deficit
1925	150	170	20 Deficit
1926	160	180	20 Deficit
1927	170	190	20 Deficit
1928	180	200	20 Deficit
1929	190	210	20 Deficit
1930	200	220	20 Deficit

The available data are not conclusive. Those contained in reference 1 and 2 indicate that 10 cfm per person is satisfactory for space occupied by non-smokers while 15 cfm or more is necessary to prevent objectionable odors when heavy smoking prevails. Lower rates of air supply might serve satisfactorily for underground installations during normal operation but technical data on which to base such recommendations are not available.

Fresh air must be conditioned, sometimes including cleaning, before introduction to occupied spaces. If complete protection is required against radioactive particulates, gases and biological agents it must also be purified (3-13).

2-27 Disaster Condition Air Supply

During an extreme emergency or disaster condition all outside services may be cut off and the supply of fresh air may be stopped either because of power failure or deliberately because the locality has been contaminated with radioactive material, biological agents or gases. Under this condition the occupants of an underground installation may be forced to rely on resources available in the installation for their respiration air supply. The situation will be similar in many respects to that in a submerged submarine.

People thus isolated from a fresh air supply can subsist for some hours or days on the air in the space and the length of time depends on the volume of the air available and the number of persons present. Each elementary person can be

The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the success of any business and for the protection of the interests of all parties involved. The text also mentions the need for regular audits and the importance of having a clear system in place for handling financial data.

The second part of the document focuses on the role of the management team in ensuring the smooth operation of the business. It highlights the need for effective communication and collaboration between all departments. The text also discusses the importance of setting clear goals and objectives for the organization and the need for a strong leadership structure.

The third part of the document addresses the issue of financial management. It discusses the importance of budgeting and the need for a clear understanding of the organization's financial position. The text also mentions the need for regular financial reporting and the importance of having a strong financial foundation.

The fourth part of the document discusses the importance of human resources. It emphasizes the need for a strong and motivated workforce and the importance of providing training and development opportunities for all employees. The text also mentions the need for a clear system of compensation and benefits.

The fifth part of the document discusses the importance of marketing and sales. It emphasizes the need for a clear marketing strategy and the importance of having a strong sales team. The text also mentions the need for regular market research and the importance of having a clear understanding of the needs and preferences of the target market.

The final part of the document discusses the importance of legal and regulatory compliance. It emphasizes the need for a clear understanding of all applicable laws and regulations and the importance of having a strong legal and regulatory framework in place. The text also mentions the need for regular legal and regulatory updates.

expected to consume on the order of 2.65 cubic feet of oxygen and exhales about 0.7 cubic feet of carbon dioxide and liberate 0.17 pounds of water vapor per hour. When the atmospheric oxygen content is reduced from the normal 21 percent to about 14 percent or when the CO₂ content is increased from the normal fraction of 0.03 percent to more than 3 percent serious loss of vitality and ability occurs. Some fatal cases result in death by suffocation. The data given on figures 2-1 and 2-2 based on sedentary occupancy show that considerably time must elapse before these danger points are approached if the volume of the space is large compared to the number of occupants but in a crowded space the limits may be reached in a comparatively short time.

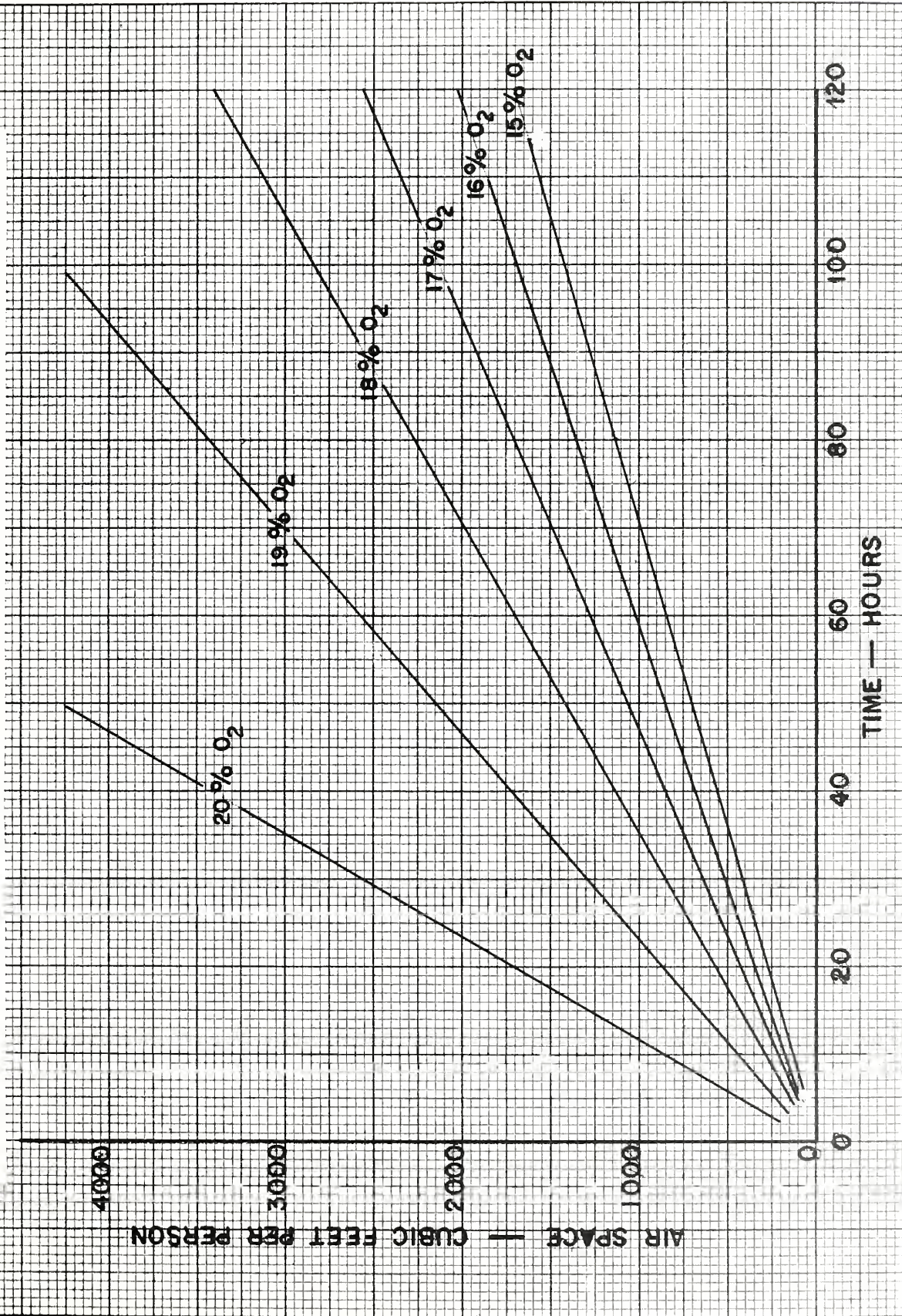
Some preventive means can be provided, for use before dangerous limits are approached, based on submarine practice. Carbon dioxide can be removed from the air by means of various absorbents. In use for submarines the absorbents are spread on rubber blankets or other suitable surface and exposed to the air. Increasing the air flow in contact with the material, as by means of fans, if available, accelerates the reaction. Oxygen can be provided under pressure in bottles or it can be generated by burning special chlorate candles. Table 2-3 shows the amount of chemicals required for air revivification under dynamic conditions.

These processes also liberate heat so the relative importance of temperature rise and humidity rise should be taken into account in the design for the disaster condition. On any

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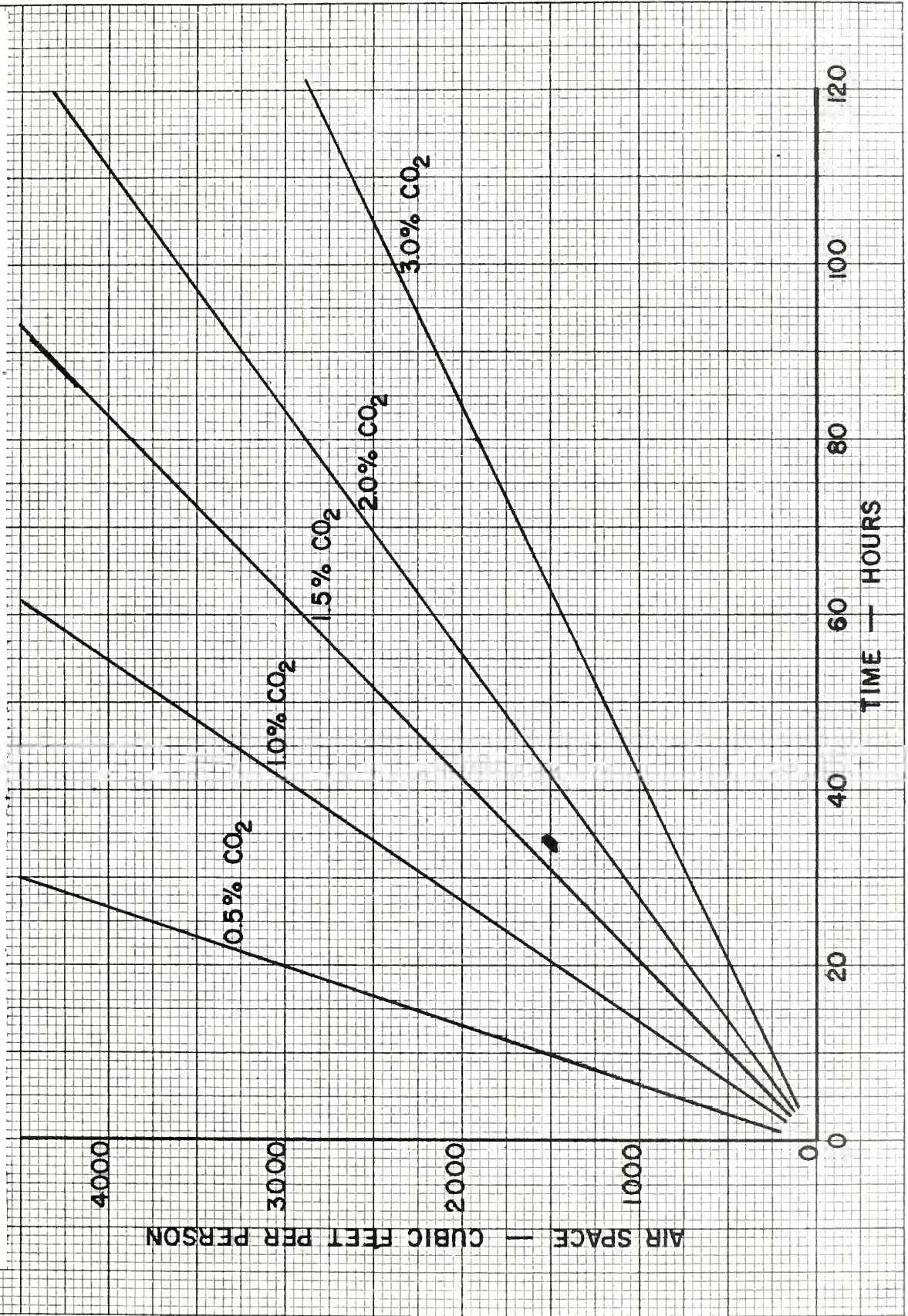
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FIG. 2-1 OXYGEN DEPLETION IN UNVENTILATED OCCUPIED SPACES.



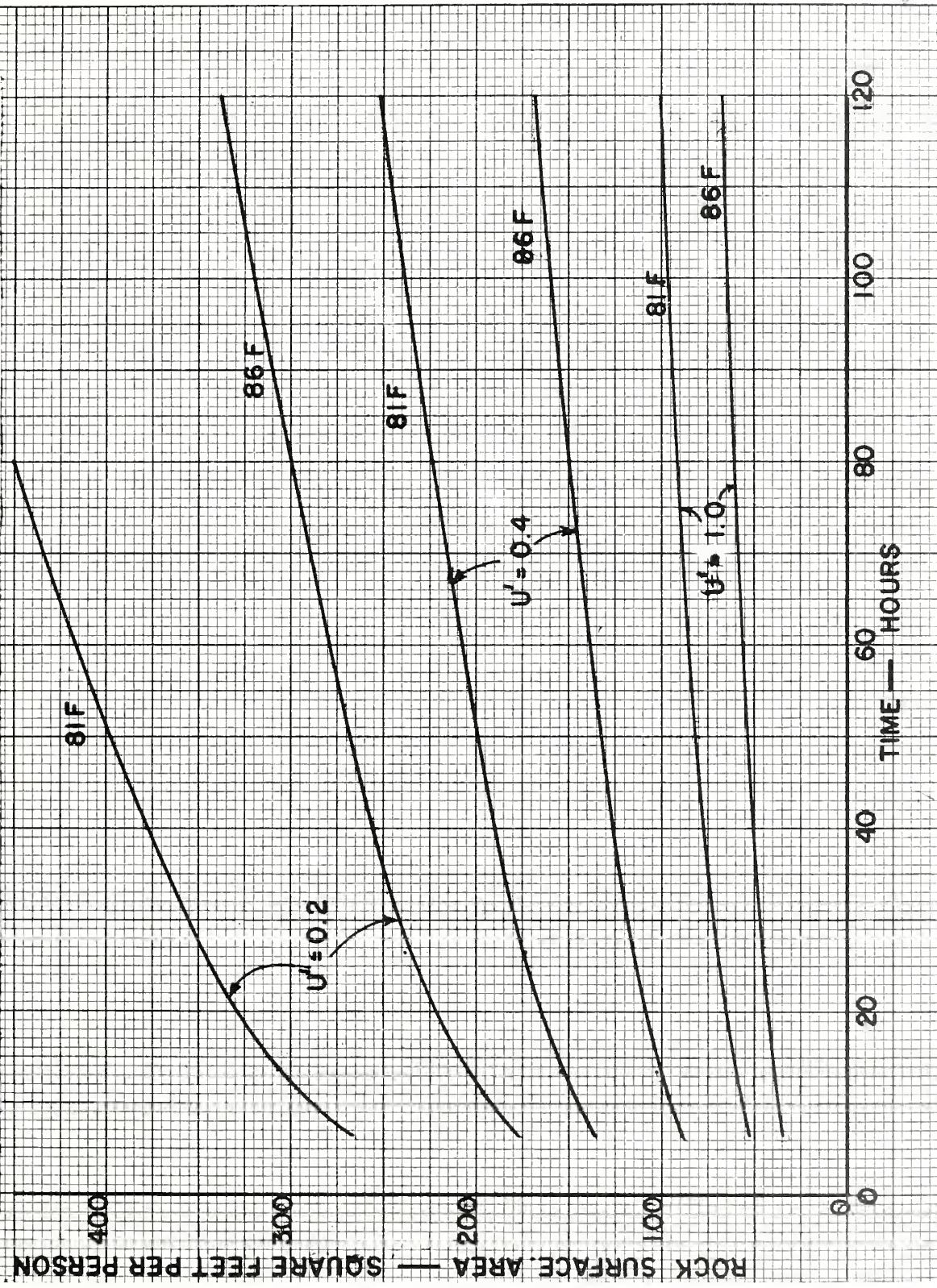
1-6-1578

FIG. 2-2 CARBON DIOXIDE CONCENTRATION IN UNVENTILATED OCCUPIED SPACES.



2-1-16-12

FIG. 2-3 TEMPERATURE RISE IN UNVENTILATED OCCUPIED SPACES.



1-6-11-10

rise in air above normal heat will flow into the rock temporarily and the dewpoint would be determined largely by rock surface temperature. Therefore, relative humidity would not approach 100 percent for some time.

Personnel in a crowded space, subsisting as above, can be expected to suffer from excessive heat and humidity. The probable period of isolation has been estimated for some purposes as one week while relief or rescue is pending. During that time the temperature is not expected to become unbearable in the absence of normal supplies of heat and power. It is estimated that personnel under disaster conditions might be exposed to temperatures of 85 or 90 F at humidities approaching 100 percent. This is not beyond human endurance but it is beyond the range at which work with paper, instruments or electronic equipment can be reliably accomplished. An enforced limitation of activity during disaster conditions would prolong the period of comfort. In extreme situations lying down on the bare rock surface would promote heat transfer from the body.

If personnel are expected to perform under a disaster condition, some means of reducing the humidity is essential.

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Table A-3. Properties of Chemicals for Air Revivification

Chemical	CO ₂ Absorbed	O ₂ Liberated	Weight Required lbs/man-hour	Water Vapor Formation	Sensible Heat Liberation, BTU
Lithium Hydroxide	x		0.124	yes	150 per cu. ft. CO ₂
Soda-Lime	x		0.34	yes	135 per cu. ft. CO ₂
Baralyme	x		0.474	yes	
Sodium Superoxide	x	x	0.283	no	174 per cu. ft. CO ₂ and O ₂
Potassium Tetroxide	x	x	0.364	no	147 per cu. ft. CO ₂ and O ₂
Chlorate Candle		x	0.24	no	54 per cu. ft. O ₂

Note: These chemicals, if used, must be handled and stored with due caution. In particular sodium superoxide and potassium tetroxide are strong oxidizing agents and can be a fire hazard. This fact may preclude their use in some cases. Chlorate candles should come packaged specifically to avoid fire hazard.

Table A-3 is based on forced air flow through the chemicals (except chlorate candle) and an oxygen consumption of 1 cubic foot per man-hour and carbon dioxide liberation of 0.53 cubic foot per man-hour.

STATE OF TEXAS,
COUNTY OF _____

Case No.	Plaintiff	Defendant	Amount	Filed	Term
100-12345	J. Smith	M. Jones	\$100.00	1/15/24	12 Months
100-23456	A. Brown	C. White	\$250.00	2/10/24	18 Months
100-34567	D. Green	E. Black	\$500.00	3/5/24	24 Months
100-45678	F. Gray	G. Blue	\$750.00	4/1/24	36 Months
100-56789	H. Red	I. Purple	\$1000.00	5/1/24	48 Months

I, _____, County Clerk of the County of _____, Texas, do hereby certify that the foregoing is a true and correct copy of the records of the County Clerk's Office as of this date.

Witness my hand and the seal of the County Clerk's Office at _____, Texas, this _____ day of _____, 2024.

County Clerk

CHAPTER 3

Design Information and Data

3-01 Heating and Cooling Load Estimates (3-02 through 3-06)

Steps recommended for determining the net loads for heating and air conditioning equipment are set forth below. The purpose is to determine first, the required rate of steady heating to bring the chamber from its initial temperature to a desired air temperature (warmup period), and second, the net rate of heating or cooling required to maintain the chamber at the desired constant air temperature subsequently.

A. For the warmup period (use Form C(1-07))

(1) For each chamber, compute the constant rock heat absorption rate, q' , for the desired warmup period, t_0 , and final chamber temperature, T_1 . Determine Aq' for each chamber.

(2) For the whole installation, add the values of Aq' for the several chambers.

B. For the constant air temperature or thermostated periods (use Forms B and D (1-07) dealing with each room or chamber separately).

(1) Determine the maximum internal sensible and latent heat loads. This represents the condition of normal operation at maximum capacity.

(2) Determine the internal sensible and latent loads under the stand-by condition.

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(3) Determine the rate of rock heat absorption for a bare chamber, or the wall, floor and ceiling heat loss for an internal structure, at selected times.

(4) Subtract item 3 from the sensible heat load in item 1 to yield the cooling load for the rock during normal operation. If item 3 exceeds the sensible heat load in item 1, heating rather than cooling is required for the room.

(5) Subtract the sensible heat load in item 1 from item 3 to obtain the heating load during the stand-by condition. If this sensible heat load exceeds item 3, cooling is indicated during the stand-by condition.

(6) Add the separate net sensible and latent loads for the several rooms for use in determining size and type of heating, cooling and dehumidifying equipment.

3-02 Heating Loads

The heating load of an underground chamber is the sum of the heat absorption of the surrounding rock (3-02), the heat used to evaporate water from damp exposed surfaces (3-10), and the heat necessary to warm ventilating air (2-06). Any heat liberated by machines, personnel or processes (3-06) in the space can be deducted from the heating load in any room or chamber provided such heat is well distributed.

The warming of an underground space typically falls into two periods, the warmup and the thermostated period (1.04). The heat required for warming the rock surrounding a chamber can be computed (4-02) by means of equation 4-04. The heat absorbed

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by the surrounding rock when a constant temperature is maintained in the chamber can be computed (4-02) by means of equation 4-05.

3-03 Warmup; Bare Chamber

Installation of permanent heating equipment with sufficient capacity to supply all the heat necessary to achieve a very short warmup period is not recommended. The initial heat absorption rate of rock surrounding a warmed chamber (4-02) is comparatively very high. If a quick warmup is necessary, temporary oil burning heaters should be considered because permanent equipment large enough for the purpose will be much over size after a few months of operation. Electric heating (5-05) is practicable for a warmup period. However, the cost is comparatively high and the necessary wiring, transformer and heaters add to the cost unless they are provided for and chargeable to some other purpose. If a few months can be allowed for the warmup, it should be possible to warm the space with the permanent heating equipment, avoiding the necessity for temporary heaters. Fuel-burning heaters, if used, may often be supplied with combustion air and vented, as a temporary measure, through shafts or tunnels provided for other purposes.

Power equipment such as electric motors or internal combustion engines, used during excavation, contribute heat to a space and may alleviate the warmup problem.

THE UNIVERSITY OF CHICAGO
DIVISION OF THE PHYSICAL SCIENCES
DEPARTMENT OF CHEMISTRY
5712 SOUTH UNIVERSITY AVENUE
CHICAGO, ILLINOIS 60637

RECEIVED

TO THE DIRECTOR OF THE DIVISION OF THE PHYSICAL SCIENCES
FROM THE DEPARTMENT OF CHEMISTRY
RE: [Illegible text]

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The rock heat absorption is likely to be the greatest heat loss from the bare chamber during the warmup period. This is governed at any instant by the equation

$$q' = U' (T_1 - T_2) \quad 3-01$$

q' = heat flow, Btu per hour per square foot of rock surface exposed to the chamber

U' = heat transfer coefficient, Btu per hour, for one square foot of rock surface and for each degree difference in temperature between the air in the chamber and the rock surface

T_1 = temperature of the air in the chamber, F, average

T_2 = temperature of the rock surface, F, average

Equation (3-01) is often inadequate because the rock surface temperature, T_2 , is unknown. The rock around a curved space receives heat and T_2 changes accordingly. This more complicated case is covered by Equation 4-04. (4-03)

3-04 Heating Load-Bare Chamber - Normal Operation

The necessary heat supply or net load at any instant is equal to the rock heat absorption minus the total internal load. The rock heat absorption decreases with time when the chamber air is held at a steady temperature. It is governed at any instant by Equation 3-01 but since, this equation does not take account of changes in T_2 , Equation 4-05 is recommended for computing rock heat absorption.

When the internal load (3-05) exceeds the rock heat absorption the difference must be removed by some air conditioning means.

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So far as heating load is concerned, a chamber lined with concrete can often be treated the same as an unlined chamber of the same size. The thermal properties of concrete are similar to those of rock and the thickness is relatively small. Acoustical or other insulating materials applied to walls or ceiling affect the heat transfer. Equation 3-01 is applicable to lined chambers, but the value of U' must be appropriately chosen for any wall surfacing material used (4-08).

3-05 Heating Load, Inner Structure

It should be possible in many instances to warm up an inner structure in a satisfactorily short time by means of the permanently installed heating equipment. The inner structure insulates the occupied space from the surrounding rock thereby reducing the heat required to attain and maintain the desired temperature. Heating equipment is usually installed with some excess capacity as a factor of safety and this can be utilized during the warmup period. The relation between heat input and warmup time can be computed by means of equation 4-04 (4-03).

Under the normal or steady temperature condition, the rock surrounding an inner structure warms more slowly than the rock around a bare chamber. The heat loss from the structure to the rock at any instant can be computed by means of equation 4-05, (4-03). Equation 3-01 is valid for an inner structure at any instant with a proper value of U' (4.10).

At the beginning of the year, the following figures were reported:

The following table shows the results of the operations of the company during the year ended December 31, 1925. The figures are in thousands of dollars.

Item	1925	1924
Net sales	1,200	1,100
Cost of goods sold	800	750
Gross profit	400	350
Operating expenses	300	280
Operating income	100	70
Interest expense	20	15
Income before taxes	80	55
Taxes	10	8
Net income	70	47

Notes to Financial Statements

1. The company's operations are seasonal, with the highest volume occurring during the fourth quarter of each year. The following table shows the results of the operations of the company during the four quarters of the year ended December 31, 1925.

Quarter	1925	1924
First	250	200
Second	280	220
Third	350	280
Fourth	320	200
Total	1,200	1,100

(Continued)

2. The company's operations are seasonal, with the highest volume occurring during the fourth quarter of each year. The following table shows the results of the operations of the company during the four quarters of the year ended December 31, 1925.

Quarter	1925	1924
First	250	200
Second	280	220
Third	350	280
Fourth	320	200
Total	1,200	1,100

The heat loss from an inner structure at any instant can also be computed by the equation

$$q = U (T_1 - T_2) \quad (3-02)$$

q = heat flow, Btu per hour for one square foot

U = heat transmittance, Btu per hour for one square foot of wall, ceiling or floor and for each degree F in air temperature difference inner and outside the structure

T_1 = air temperature, inside the structure, F

T_2 = air temperature outside the structure in the annular space between the structure and the rock

Values of U (4-05) are not the same for underground structures as they are for exposed walls of surface buildings. For surface buildings, the value of U is ordinarily based on an assumption of a wind with a velocity of 15 miles per hour on the outside. Underground, the outside surface film coefficient and the transmittance, U , must be selected with proper reference to air velocity. In many cases the same inside and outside film coefficient, 1.65, probably is adequate.

Equation 3-02, like equation 3-01, is often insufficient because one temperature, T_2 , is variable with time. The heat loss of the structure at any instant can be computed by means of equation 4-05, (4-03).

3-06 Cooling Loads

The net cooling load of an underground space is the sum of all internal loads minus the heat absorption of the surrounding rock (4-03). The internal loads include heat and moisture from personnel, waste heat from boilers, engines, electric motors, lights, cooking equipment or other apparatus

(1941) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100

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utilizing electric energy. Most of the power utilized in underground installations is likely to be supplied electrically and the heat liberated from electric equipment can be computed by the relation:

$$1 \text{ KW} = 3412 \text{ Btu per hour}$$

Also

$$1 \text{ Horsepower} = 2545 \text{ Btu per hour} = .746 \text{ KW}$$

However, because the efficiency is less than 100 percent, it is often assumed for estimating purposes that a consumption of one kilowatt of electric energy is necessary to produce one horsepower, at least for small motors.

For a motor driving a machine that converts the power to heat, such as a lathe, a grinding machine etc., all the energy utilized appears as heat in the surrounding space. If a motor drives a pump or blower, a fraction of the input energy is imparted to the fluid being pumped; the rate of energy or heat liberation in the space around the motor and driving gear is equal to the input power times the decimal equal to one minus the overall efficiency of the motor and driving mechanisms.

All the energy from electric lights, either incandescent or fluorescent, is converted into heat. Part of this heat may be removed by special water or air cooling means in some cases; otherwise it forms part of the cooling load.

THE UNIVERSITY OF CHICAGO
DEPARTMENT OF CHEMISTRY
57 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607

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RESEARCH ASSISTANT
DEPARTMENT OF CHEMISTRY
57 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607

RESEARCH ASSISTANT
DEPARTMENT OF CHEMISTRY
57 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607

RESEARCH ASSISTANT
DEPARTMENT OF CHEMISTRY
57 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607

RESEARCH ASSISTANT
DEPARTMENT OF CHEMISTRY
57 SOUTH EAST ASIAN AVENUE
CHICAGO, ILLINOIS 60607

Personnel liberate heat and water vapor and the rate depends on state of activity. Some typical data for design purposes are given in Table 3 - 1.

Table 3 - 1. Sensible, Latent and Total Metabolic Heat Loss Per Person, BTU hr⁻¹

Room Temp.	Sitting or Moving Slowly			Light Working		
	Sensible	Latent	Total	Sensible	Latent	Total
84	180	220	400	150	510	660
82	200	200	400	180	480	660
80	220	180	400	210	450	660
78	240	160	400	240	420	660
76	256	144	400	270	390	660
74	272	128	400	300	360	660
70	300	100	400	350	310	660
60	360	70	430	460	200	660
50	440	40	480	550	110	660
40				610	110	720

Cooking is responsible for both sensible and latent loads. For electric cooking, the total load is equivalent to the energy utilized, but part is latent while the remainder is sensible load. In most instances it may be possible to vent vapor from kitchens and avoid imposing the latent and some of the sensible load on the air conditioning coils.

If an apparatus is cooled by the evaporation of water into the surrounding air, the total load is not affected; part of the load becomes latent and the rest remains sensible load.

Personal literature used and water vapor and the rate
 of evaporation of water. Some typical data for these
 purposes are given in Table 3 - 1.

Table 3 - 1. Sensible, latent and total metabolic
 heat loss for various room temperatures

Room Temp.	Sensible Heat Loss		Latent Heat Loss		Total
	Btu/hr	Watts	Btu/hr	Watts	
64	150	43	250	72	400
68	200	55	200	55	400
72	250	70	150	41	400
76	300	83	100	28	400
80	350	96	50	14	400
84	400	110	0	0	400
88	450	123	0	0	450
92	500	137	0	0	500
96	550	150	0	0	550
100	600	164	0	0	600

Calculating the sensible heat loss and latent heat
 loss for electric heating, the latent heat is equivalent to the energy
 utilized, but lost to latent heat the remainder is sensible heat.
 In most instances it may be possible to vent water from kitchen
 and avoid heating the latent and some of the sensible heat in
 the air conditioning coils.
 The air required is cooled by the evaporation of water into
 the surrounding air, the latent heat is not released; part of
 the load becomes latent and the rest remains sensible load.

Fresh or outdoor air introduced for ventilation (2-06) must at times be cooled and dehumidified. The resultant load may be reduced by passage of the air through supply shafts or tunnels (4-05).

3-07 Dehumidification; Bare Chamber

The dehumidification load of a bare chamber includes water vapor from equipment and processes, if any, and personnel (3-06), dehumidification of fresh air (2-06), and evaporation from surrounding damp rock. Bare rock condenses water from the surrounding air whenever its surface is below the dew point, and, conversely, water evaporation from damp rock, or from pools, whenever the surface temperature exceeds the dew point (4-10). The rock therefore tends to govern the humidity in the chamber by holding the dew point at its own surface temperature. The rock cannot be relied upon indefinitely as a dehumidifying means because its surface warms with time when receiving heat from the air in the chamber (4-03).

Water in the liquid state either from leaks due to fissures in the rock or from condensation must be drained away by trenches, gutters, pipes, etc. Water in the vapor state, from personnel or processes as well as that due to evaporation from damp surfaces, must be removed by ventilation or by dehumidification effected by the air conditioning means provided.

3-08 Dehumidification; Lined Chamber

Use of vapor barriers (4-09) or of thermal insulating materials (4-08) in direct contact with rock surrounding under-

fresh or outdoor air introduced for ventilation (2-05)

must be lined or cooled and dehumidified. The resultant load may be reduced by means of the air handling supply units or fans (4-02).

3-07 Dehumidification; Basic Chapter

The dehumidification load of a space consists of the

water vapor from people and processes, air and

permeation (3-05), dehumidification of fresh air (2-06), and

evaporation from surrounding wet rock. Some rock condenses

water from the surrounding air whenever its surface is below

the dew point, and, conversely, water evaporation from damp

rock, or from pools, whenever the surface temperature exceeds

the dew point (4-10). The rock therefore tends to cover the

humidity in the chamber by holding the dew point at its own

surface temperature. The rock cannot be relied upon indefinitely,

as a dehumidifying means because its surface warms with time

when receiving heat from the air in the chamber (4-03).

Water in the liquid state either from leaks into the chamber

in the rock or from condensation will be drained away by

trenches, gutters, pans, etc. Water in the vapor state from

personnel or processes as well as that due to evaporation from

sharp surfaces, must be removed by ventilation or by dehumidifi-

cation effected by the air conditioning means provided.

3-08 Dehumidification; Lined Chapter

Use of vapor barriers (4-07) or of thermal insulation

materials (4-06) to direct contact with rock surrounding masses-

ground spaces is not generally to be recommended. The hydrostatic pressures that can be generated due to the depth of an underground working are greater than can be restrained by ordinary vapor barrier materials or even by moderately heavy concrete liners. Assuming that water head is at times as deep as the overburden, the possible pressure is represented by the equation:

$$P_w = 0.43 d \quad (3-03)$$

P_w = hydrostatic pressure, p.s.i.

d = depth, ft

Insulating material applied directly to rock walls or to concrete in contact with such walls is likely to be wet either by condensation or by ground water or both, with resulting damage to the insulating material or to its fastenings. A vapor barrier inside the insulation does not protect it from ground water and such a barrier outside the material does not protect it from condensation.

From these considerations it appears that, if insulation is to be used, an air space is desirable between the insulation and the rock and, if the air space is provided, there are some advantages to making its width sufficient to permit access for purposes of inspection and repair, particularly for multi-story installation. This done, the liner becomes substantially an inner structure and can be treated as such.

Ground-water is not generally to be considered. The hydrostatic pressure that can be generated due to the depth of an unstratified water table is greater than can be resisted by ordinary water-bearing materials (even if moderately heavy concrete liners). However, that water head is at times as high as the overburden, the hydrostatic pressure is represented by the equation:

(12-13)

$$P_w = 0.434 h$$

where P_w = hydrostatic pressure, p.s.f.

h = depth, ft

Insulating material applied directly to rock walls or to concrete in contact with such walls is likely to be wet either by condensation or by ground water or both, with resulting damage to the insulating material as to its resistance. A vapor barrier inside the insulation does not protect it from ground water and such a barrier outside the material does not protect it from condensation.

From these considerations it appears that, if insulation is to be used, an air space is desirable between the insulation and the rock and, if the air space is provided, there are some advantages to making the walls and ceiling to permit access for purposes of inspection and repair, particularly for water-tight insulation. This does, of course, limit the amount of insulation, as lower resistance can be treated as usual.

A concrete liner may be installed in an underground space to improve its appearance or to reduce the changes of spalling but it should not be considered effective as either thermal insulation or a vapor barrier. The dehumidification load in such a space is subject to the same considerations as those for a bare chamber.

3-09 Dehumidification; Inner Structure

If the walls, ceiling, and floor of an inner structure are vapor proof, the water vapor to be removed by the air conditioning apparatus is equal to that liberated by the equipment and personnel (3-06) within the structure.

Conditions in the annular space do not directly affect those within the structure.

If the walls, ceiling, and floor of the inner structure are pervious, the water vapor to be removed by the air-conditioning apparatus is then the algebraic sum of the water vapor liberated by personnel and equipment and that entering the inner structure through the walls, ceiling, and floor by permeation, or by convection from the annular space.

Compared to convection, migration of water vapor by either capillarity or diffusion through a material may have feeble and often negligible effects in transferring water vapor. Leaks exist in most ordinary structures and therefore if a difference in air pressure is maintained between the inside and outside of an inner structure, the interior humidity is likely to be governed by the resultant air flow.

... concrete liner may be installed in an underground space to improve its appearance or to reduce the danger of spalling but it should not be considered effective as other special insulation or a vapor barrier. The design and construction of such a space is subject to the same considerations as those for a bare chamber.

3-09 Demineralization; Lower Structures

If the walls, ceiling, and floor of an inner structure are vapor proof, the water vapor to be removed by the conditioning apparatus is equal to that liberated by the equipment and process (3-05) within the structure. Conditions in the smaller space do not directly affect those within the structure.

If the walls, ceiling, and floor of the inner structure are pervious, the water vapor to be removed by the conditioning apparatus is that the electrical work of the water vapor liberated by processes and equipment and that entering the inner structure through the walls, ceiling, and floor of the structure, or by convection from the smaller space.

Compared to conduction, migration of water vapor by direct capillary or diffusion through a material may have little and even negligible effect in insulating walls and vapor. There is also in most ordinary structures and materials if a difference in air pressure is maintained between the inside and outside of an inner structure, the insulating ability is likely to be improved by the venting of air from

In the absence of an air pressure difference, migration of vapor through a barrier such as a wall or ceiling may be estimated on the assumption that the flow is proportional to the vapor pressure difference and to the permeance of the barrier (4-09).

The surrounding rock can be relied upon as a dehumidifying (and cooling) means so long as its surface remains cool. If the surface becomes warm, due to heat received from the inner structure or due to the passage of warmer air through the annular space, the rock will cease to be a means for maintaining a satisfactorily low humidity.

3-10 Waste Heat Disposal

During normal operation waste heat from such equipment as Diesel engines, refrigeration condensers, etc., can be dissipated in water as from a brook, river, or creek if available or into the air by means of air cooled or evaporative condensers or cooling towers. However, during attack or under some post attack conditions (1-05) it may sometimes be necessary to utilize heat disposal means built into or in conjunction with the underground installation.

An underground reservoir is an obvious and practical heat sink for use when outside water service is cut off. It must be adequate in size or capacity to absorb the waste heat from the equipment to be operated for the duration of the estimated period of isolation.

In the absence of an air pressure differential, migration of vapor through a barrier such as a wall or ceiling will be restricted on the assumption that the flow is proportional to the vapor pressure difference and to the permeance of the barrier (4-27).

The surrounding room can be taken down as a semi-infinite (and cooling) mass so long as the system remains cool. If the surface process were, one to heat resistance from the indoor structure on the to the outside of room air through the barrier space, the wall will cause to be a source for heat being a positive/negative for heat.

3-10 Waste Heat Removal

During normal operation waste heat from such equipment as diesel engines, refrigeration compressors, heat pumps, etc. is dissipated to water in a pond, river, or creek if available or into the air by means of air cooled or evaporative coolers or cooling towers. However, during a hot spell or when some heat source conditions (4-28) in any conditions of necessary facilities must be used some heat into or in conjunction with the underground installation. An underground reservoir is an obvious and practical heat sink for use when surface water sources are not available. It must be adequate in size or capacity to absorb the waste heat from the equipment to be operated for the duration of the extended period of installation.

There are two ways to utilize an underground reservoir (4-04). The water can be passed through the equipment to be cooled and wasted outside the installation, or the water can be used to absorb heat while remaining in the reservoir. Somewhat more heat can be absorbed by a reservoir of a given size when the heat is added to the water while it remains in the reservoir because the surrounding rock also absorbs heat. A possible disadvantage of the method for a reservoir of limited size, is that the surrounding rock will be left warm at the end of a period of isolation and may require too much time and water for cooling in preparation for the next attack. If a reservoir is large compared to the load imposed upon it, the arrangement can serve for a long period of time.

For estimating purposes it can be assumed that, for an internal combustion engine, about 30 percent of the heat value of the fuel burned appears in the jacket cooling water. For an air conditioning refrigerating machine, the condenser and jacket cooling water receive about five times the heat equivalent of the electric energy that drives the compressor.

The heat absorbing capacity of a reservoir with wastage of water outside after use is given by equation 4-07. The heat absorbing capacity of an underground reservoir as a function of time, if the water is recirculated and retained, is given by equation 4-08.

There are two ways to utilize an underground reservoir (p-01). The water can be passed through the aquifer to be cooled and water outside the installation, or the water can be passed to absorb heat while remaining in the reservoir. Somewhat more heat can be absorbed by a reservoir of water also when the heat is added to the water while it remains in the reservoir because the surrounding rock also absorbs heat. A possible disadvantage of the method for a reservoir of limited size, is that the surrounding rock will be left warm at the end of a period of installation and may require for some time and water for cooling in preparation for the next winter. If a reservoir is large compared to the load imposed upon it, the movement can save for a long period of time.

For estimation purposes it can be assumed that, for an internal combustion engine, about 30 percent of the heat value of the fuel burned appears in the jacket cooling water. For an air conditioning evaporating machine, the compressor and jacket cooling water receive about five times the heat equivalent of the electric energy that drives the compressor.

The heat absorbing capacity of a reservoir with respect to water outside the reservoir is given by equation p-01. The heat absorbing capacity of an underground reservoir as a function of time, if the water is not circulated and retained, is given by equation p-02.

3-11 Air Conditioning Effect of Tunnels or Shafts

The initial or undisturbed temperature in a tunnel or shaft with an overburden of 50 feet or more is likely to be at or near the mean annual temperature which is in the range 50 to 55 F in many regions. This is usually above the winter outside design temperature and below the summer outside design temperature and dew point for such regions. A tunnel or shaft is therefore a possible means for tempering the air in winter or of partially conditioning it in summer. For a long tunnel and a small flow, the air passed through a tunnel assumes nearly the earth temperature, say 55 F. Also, such a tunnel can dehumidify outdoor air in summer, and humidify it in winter if ground water is present. A large wet tunnel with a small air flow can therefore condition air to approximately 55 F saturated at all seasons. Air at this condition, warmed to 75 F, assumes a relative humidity of 50 percent.

A tunnel in continuous use for transporting outdoor air extracts heat from the air in summer and imparts an approximately equal amount of heat to the air in winter. The outdoor temperature, plotted against time throughout a year describes an approximate cosine curve and the air leaving the tunnel describes a similar curve but with a smaller amplitude. The amplitude of the air temperature variation at the exit end of the tunnel indicates the heating and cooling effects of the tunnel. For a long tunnel and small air flow this

The effect of insulation is considered in a tunnel or shaft with an elevation of 50 feet or more is likely to be at or near the mean annual temperature which is in the range 50 to 55 F in many regions. This is usually above the winter outdoor air temperature and below the summer outdoor design temperature and may give an annual average of shaft air temperature a possible range for design. The air in winter is usually conditioned in summer, for a long tunnel and a small shaft, the air passed from a tunnel summer design temperature, and also, since a small and somewhat moist air in summer, and usually is in winter it is not water is present. A large wet tunnel with a small air flow and constant conduction air is approximately 50 F returned at all seasons. Air at this condition, heated to 70 F, causes a relative humidity of 50 percent.

A tunnel in conditions for the circulating winter air experts need from the air in summer but require an equal metal) equal amount of heat to the air in winter. The outdoor temperature, which is about the equivalent of a year outdoor an appropriate design of air leaving the tunnel. The described a similar curve for air in winter. The application of the air temperature outside of the shaft of the tunnel indicates the heating and cooling system of the tunnel. For a long tunnel and small air flow rate

amplitude will be small, as discussed above. For any specific tunnel there is a limit to the cooling and heating capacity, depending on the dimensions, the nature of the surrounding rock, etc. The mathematical relations governing heating and cooling of outside air by tunnels are given by equation 4-10, (4-05). Remarks about tunnels in this section apply substantially also to shafts or other openings of equal dimensions.

3-12 Evaporation from Pools or Damp Surfaces

Ground water can have several effects that influence structure and equipment design, including the following. It can exert pressure on any vapor barrier or liner installed to prevent its ingress into underground spaces as shown by equation 3-03. It can affect the conductivity and heat capacity of porous or hygroscopic rock (4-08). To evaporate water from damp surfaces or open pools requires heat (4-10) and can add to the heating load. Water evaporating absorbs the same latent heat as it gives up when it condenses. Therefore in some cases the effect of evaporation as from damp surfaces in a space being cooled is not to change the total air conditioning load but is to convert part of the load from the sensible to the latent type. If a machine or apparatus is cooled by the evaporation of water and if the resulting vapor is vented outside without reaching the cooling coils, the heat conveyed is not added to the cooling load.

... will be small, as discussed above. The air
specific gravity there is a little less than the
density, depending on the dimensions, the nature of the
surrounding work, etc. The theoretical velocity of
falling and cooling of particles is given by
equation (10-11). It is seen that the rate of
fall is essentially also a function of the
dimensions.

3-12 Evaporation from Pools of Heavy Liquors
... can have several effects and influences
... and ...
It can exert pressure on the vapor surface or liquid surface
to prevent its escape into the atmosphere and thus
evaporation (3-12). It can also be ...
capacity of liquid or ...
water from deep ...
and can act to ...
the same liquid level as in ...
Therefore in some cases the ...
deep surface is a ...
total air ...
load from ...
or ...
the resulting ...
cooling ...

Chapter 4

HEAT ABSORPTION OF ROCK AROUND UNDERGROUND SPACES

4-01 Principles

The geological formation around an underground installation is termed rock in this chapter. Usually, at required depths, locations will be chosen where the space will be surrounded by rock, rather than clay, sand or another material, in consideration of strength and stability requirements.

The temperature in an occupied underground space is usually maintained above that of the surrounding rock and consequently heat flows from the space to the rock. In the absence of internal load, the heat supplied to the space must equal that absorbed by the rock. When the internal load, such as the heat from lights, motors or other equipment and personnel, exceeds the heat absorbed by the rock, the difference must be removed by some cooling means such as an air conditioning apparatus.

The rock surrounding a continuously warmed space itself becomes warm with time, its surface temperature increases and its heat absorption rate decreases. Consideration of these effects is obviously essential in the computation of heating or air conditioning loads but unfortunately heat flow of this transient type is not subject to simple analysis. The pertinent differential equations

Chapter 1

HEAT INSULATION OF AIR-CONDITIONED SPACES

1-1 Principles

The principal reason for insulating air-conditioned spaces is to reduce the heat loss or gain through the walls, ceiling, and floor. This is done by using materials that have a low thermal conductivity. The insulation will be placed on the exterior of the walls, ceiling, and floor, rather than on the interior. This is because the exterior is more exposed to the weather and the insulation will be more effective in reducing heat loss or gain. The insulation will also be placed on the exterior of the ducts and pipes that carry the conditioned air. This is because the ducts and pipes are exposed to the weather and the insulation will be more effective in reducing heat loss or gain. The insulation will also be placed on the exterior of the roof. This is because the roof is exposed to the weather and the insulation will be more effective in reducing heat loss or gain.

The temperature in an occupied space is usually maintained above that of the surrounding air. This is done by using a heating system. The heating system will be placed in the space to be heated. This is because the heating system will be more effective in heating the space. The heating system will also be placed in the ducts and pipes that carry the heated air. This is because the ducts and pipes are exposed to the weather and the heating system will be more effective in heating the air. The heating system will also be placed in the exterior of the walls, ceiling, and floor. This is because the exterior is more exposed to the weather and the heating system will be more effective in heating the space. The heating system will also be placed in the exterior of the ducts and pipes that carry the heated air. This is because the ducts and pipes are exposed to the weather and the heating system will be more effective in heating the air.

The room temperature is usually maintained above that of the surrounding air. This is done by using a heating system. The heating system will be placed in the space to be heated. This is because the heating system will be more effective in heating the space. The heating system will also be placed in the ducts and pipes that carry the heated air. This is because the ducts and pipes are exposed to the weather and the heating system will be more effective in heating the air. The heating system will also be placed in the exterior of the walls, ceiling, and floor. This is because the exterior is more exposed to the weather and the heating system will be more effective in heating the space. The heating system will also be placed in the exterior of the ducts and pipes that carry the heated air. This is because the ducts and pipes are exposed to the weather and the heating system will be more effective in heating the air.

are too complex for every-day use and for this reason an approximate method has been evolved and checked against experimental results obtained in several underground spaces.

The recommended method for estimating heat absorption by surrounding rock is based on consideration of an assumed underground space, either spherical or cylindrical in shape, with thermal characteristics similar to those of a chamber to be utilized. The heat flow equations pertaining to spheres or cylinders are simpler than those for other shapes. The data presented for use with the equations in this manual (4-03) are based on numerical solutions of the equations for cylinders and spheres obtained by means of a large electronic computer, available at the National Bureau of Standards.

Usually, a new underground space must be warmed to some acceptable temperature in preparation for occupancy. Heat may be supplied to the space for this purpose at a relatively large, constant rate. If the desired temperature and permissible warm-up time are specified, the required heat supply rate can be computed by means of Item 6 under procedure (4-02).

After the warm-up, presumably a constant temperature will be desired in the space, at or near 75°. The heating or air conditioning system is then expected to operate on thermostat. The surrounding rock absorbs heat at a rate

are too small for every-day use and for this reason an approximate method has been evolved and checked against experimental results obtained in several experiments.

The recommended method for estimating heat transfer by conduction took its basis on consideration of an assumed cylindrical space, either spherical or cylindrical in shape, with internal characteristics similar to those of a cylinder to be defined. The next flow equation pertinent to spaces of cylinders are simpler than those for other shapes. The data presented for use with the equations in this manual (p-40) are based on theoretical relations of the equations for cylinders and spheres obtained by means of a large electronic computer, available at the National Bureau of Standards.

Generally, a new underground space must be defined to some acceptable degree in its shape for calculation. Heat may be applied to the space for this purpose at a relatively large, constant rate. In the case of temperature and permissible volume of the space, the volume heat supply rate can be computed by means of the following relations (p-41).

Also, the following, previously mentioned equations will be useful in the space, at or near the surface on its bounding surface in this respect to compute the temperature. The surrounding rock usually has a rate

that decreases with time and the absorption rate at any instant can be computed by means of Items 7 and 8 under procedure (4-02).

4-02 Procedure for Estimating Heat Transfer, Air to Rock

The procedure recommended for estimating heat transfer from an underground space to surrounding rock is as follows:

1. Compute the internal surface area of the space. Projected areas can be used; irregularities left in walls, ceilings, and floors after blasting can be ignored. Equation 4-01 is applicable.
2. Obtain the value of V_1/V for the cylinder by means of Figure 4-1 and of V_2/V for the sphere by means of Figure 4-2.
3. If V_1/V exceeds V_2/V , utilize the cylinder as the best approximation to the space considered; if V_2/V exceeds V_1/V , utilize the sphere.
4. Compute the radius of a cylinder of the same internal area using Equation 4-02 and compute the radius of a sphere of the same internal area by means of Equation 4-03.
5. Determine the initial temperature of the rock, thermal conductivity, density, specific heat, and overall coefficient of heat transfer. These may be found from

that ϵ is small and the approximation is good. This can be seen by noting that ϵ is small and ϵ is small.

4-2 Procedure for Estimating Heat Transfer

The procedure recommended for estimating heat transfer for flow in a rectangular duct is as follows:

1. Compute the internal surface area of the duct. Projected areas can be used; hydraulic radius R_h in which $R_h = D_h/4$ and D_h is the hydraulic diameter.

2. Obtain the value of Nu for the geometry of means of Figure 4-1 and of Nu for the space of means of Figure 4-2.

3. If Nu exceeds Nu_{crit} , utilize for h the value of best approximation to the value obtained; if Nu exceeds Nu_{crit} , utilize for h .

4. Compute the value of a grid size of the same order as the value of Nu and compare the value of a value of the same internal area of means of Figure 4-3.

5. Determine the initial temperature of the fluid, thermal conductivity, density, specific heat, and viscosity coefficient of heat transfer. These may be found from

geologic data, testing of samples, or estimated from information given in section 4-06, 4-07, and 4-08.

6. For a given warm-up time (4-03), determine the required heat input by means of Equation 4-04. Utilize Figure 4-3 for the cylindrical case or 4-4 for the spherical case in conjunction with this equation. Data Form C is suggested as a work sheet (1-07).

7. Compute the rock heat absorption for the constant air temperature, or thermostated condition (4-03), by means of Equation 4-05. Equation 4-05 will yield the heat absorption for the cylinder or for the sphere, whichever was selected for an approximation to the space being considered.

8. Adjust the results obtained under Item 7; divide the heat absorption obtained for the cylinder by the ratio V_1/V or divide the results obtained for the sphere by the ratio V_2/V . This will yield an approximation to the heat absorption for the space under consideration that can be used in heating and air conditioning load estimates. Data Form D is suggested as a work sheet (1-07).

scientific data, testing of samples, or enclosed form follow-

section given in sections 1-02, 1-07, and 1-08.

6. For a given sample (see 1-01), determine the required test input by means of Equation 1-01. Utilize

Figure 1-3 for the calibration curve of 1-1 for the

applicable case in conjunction with this equation. Data

Form C is suggested as a work sheet (1-07).

7. Compare the test load absorption for the test load

air temperature, or temperature condition (1-05), by

means of Equation 1-02. Equation 1-02 will yield the test

absorption for the original air for the element, whichever

was selected for an approximation to the test load tem-

perature.

8. Adjust the results obtained under item 7, divide

the test absorption obtained for the cylinder by the ratio

V_1/V_2 or divide the results obtained for the sphere by the

ratio V_2/V_1 . This will yield an approximation to the test

absorption for the space under consideration that can be

used in heating and air conditioning load estimates. Data

Form D is suggested as a work sheet (1-08).

4-03 Equations for Heat Transfer, Air to Rock

Equations applicable to the procedure for computing heat absorption by rock are as follows:

Area of an Underground Chamber, either square or rectangular.

$$A = 2 (mn + ms + ns) \quad (4-01)$$

A = wall, ceiling and floor area, ft²

m = length, ft

n = width, ft

s = ceiling height, ft

If the space is not a parallelepiped, that is if the ceiling is arched or if either major irregularities in shape exist, the area, A, should be adjusted accordingly by some appropriate method.

Radius of a cylinder with thermal characteristics approximately similar to those of the space considered:

$$a_1 = \frac{A}{2\pi m} \quad (4-02)$$

Radius of a sphere with thermal characteristics approximately similar to those of the space considered:

$$a_2 = \sqrt{\frac{A}{4\pi}} \quad (4-03)$$

Rock heat absorption; steady heat input required to warm the rock surrounding a space in a specified time:

$$\frac{\theta_s K}{q'a} = t (F) \quad (4-04)$$

10-3. Equations for Heat Transfer and Loss

Equations relative to the procedure for computing heat absorption by rock are as follows:
Area of an irregular shape, $A = \frac{1}{2} \sum (x_i y_{i+1} - x_{i+1} y_i)$

(10-1) $A = \frac{1}{2} (x_1 y_2 + x_2 y_3 + \dots + x_n y_1 - x_2 y_1 - x_3 y_2 - \dots - x_n y_{n-1})$

$A = \text{wall, ceiling and floor area, ft}^2$

$n = \text{number of sides}$

$w = \text{width, ft}$

$h = \text{ceiling height, ft}$

If the space is not a parallelepiped, that is if the ceiling is curved or if other extra characteristics in shape exist, the area, A , should be adjusted accordingly by some appropriate method.

Radius of a cylinder with thermal characteristics similar to those of the space considered;

(10-2) $r = \sqrt{\frac{A}{2\pi}}$

Radius of a sphere with thermal characteristics similar to those of the space considered;

(10-3) $r = \sqrt[3]{\frac{3V}{4\pi}}$

Rock heat absorption: $Q_{\text{rock}} = U_{\text{rock}} A_{\text{rock}} (T_{\text{rock}} - T_{\text{air}})$

(10-4) $\frac{Q_{\text{rock}}}{T_{\text{rock}}} = \frac{U_{\text{rock}} A_{\text{rock}}}{T_{\text{rock}}} (T_{\text{rock}} - T_{\text{air}})$

- θ_s = Temperature rise of rock surface, above initial temperature, deg. F
- K = Thermal conductivity of rock, Btu hr⁻¹ft⁻¹
- q' = Rock heat absorption rate, Btu hr⁻¹ft⁻²
- a = Radius, ft; a_1 , for the cylinder; a_2 for the sphere; selected for the approximation from Equation 4-02 or 4-03
- F = Kt/pca^2 ; F_1 , cylinder; F_2 , sphere
- t = Time permitted for warm-up period, hrs
- p = Density of rock surrounding the space, lb ft⁻³
- c = Specific heat of the rock, Btu lb⁻¹F⁻¹

To utilize Equation 4-04 first compute the value of F , then determine the value of $\theta_s K/q'a$ from Figure 4-03 for the cylinder or Figure 4-4 for the sphere. From the value of $\theta_s K/q'a$ thus estimated, determine the heat absorption of the rock q' , in Btu per hour and per square foot. It will be noted that the heat absorption rate, determined with Equation 4-04 depends on rock surface temperature rise, θ_s .

Rock Heat Absorption; Constant Air Temperature (Thermostated Condition)

$$q = (1 - \theta_s/\theta_1) U' \theta_1 / R \quad (4-05)$$

θ_2 = Temperature rise of rock surface

above initial temperature, deg. F.

K = Thermal conductivity of rock

See Eq. (17-1)

q_1 = Rock heat absorption rate, see Eq. (17-2)

r = radius, ft; for the cylinder; $2r$ =

the diameter; selected for use in Eq. (17-3)

radius from location $h=0$ or $h=0.5$

$p = Kt/\rho c r^2$; T_1 , cylinder; T_2 , sphere

r = line corrected for semi-infinite, see

Eq. (17-3) of rock surrounding the sphere

See Eq. (17-3)

θ = Specific heat of the rock, see Eq. (17-1)

To utilize Equation (17-1) first compute the value of

p , then determine the value of θ_2 from Figure (17-3) for

the cylinder or sphere. From the value

of θ_2 , $K/\rho c r^2$ is thus estimated, assuming the heat absorption

of the rock q_1 in the rock and the sphere is

will be noted that the heat absorption rate, determined with

Equation (17-3) depends on rock surface temperature rise, θ_2 .

Rock Heat Absorption; Constant Air Temperature (Continued)

(Continued)

$$p = (1 - \frac{1}{2} \sqrt{\frac{K}{\rho c r^2}}) \frac{K}{\rho c r^2} \theta_2 \quad (17-5)$$

q = Rock heat absorption rate, Btu hr $^{-1}$ ft $^{-2}$.

The value of θ_s/θ_i in Equation 4-05 is given by Equation 4-06, and is a function of F which involves the time, t , for which the thermostated condition has been continued. It will be seen that the rock heat absorption rate q decreases as time t increases. See Form D (1-07).

U' = Overall average coefficient of heat transfer, Btu hr $^{-1}$ ft $^{-2}$, for each degree temperature difference between the rock surface temperature and the temperature of the air within the heated or air conditioned space. For an internal structure, the relevant air temperature is that inside the structure. (4-08)

θ_i = Temperature difference, air temperature to be maintained in the air conditioned space minus initial rock temperature, deg F.

θ_s = Temperature rise of rock surface, above initial rock temperature, deg. F.

R = V_1/V for the cylinder or V_2/V for the sphere. Values are taken from the charts, Figures 4-1 and 4-2. These values are

g = back heat absorption rate, W/m^2 (12-15)

The value of g is defined as a function
given by equation (12-15), and as a function
of T which involves the time, t , for which
the heat transfer coefficient has been
determined. It will be seen that the heat
loss approximates zero. (See also 12-15)

It is assumed that the coefficient of heat transfer
for the air is h_a , for each case. The
heat difference between the two surfaces
temperature and the temperature of the
air which has passed over the surface
is $T_s - T_a$. The heat transfer coefficient
is h_a . The heat transfer coefficient
is h_a .

Q_1 = Temperature difference, air temperature to
be maintained in the air duct, W/m^2
along initial flow direction, W/m^2
 Q_2 = Temperature difference of flow surface, W/m^2
initial flow direction, W/m^2
 $R = \sqrt{V}$ for the diameter of \sqrt{V} for the
surface. Values are given from the curve.
Along $R=1$ and $R=2$. These values are

used also for choosing between the cylindrical and spherical approximate solutions as stated in item 3 under procedure

$$\frac{\theta_s}{\theta_1} = f(F, N) \quad (4-06)$$

Values of θ_s/θ_1 are taken from the charts, Figure 4-5 for the cylinder or Figure 4-6 for the sphere. On this figure

$$N = aU'/K$$

The quantity N must be computed for use with the charts.

For an internal structure under the thermostated condition, the heat loss per square foot from any particular room at any time equals $U_o(T_i - T_a)$, which can be shown to equal

$$qU_o \left[\frac{R}{U'} + 0.7 \right]$$

where q is given by Equation 4-05, U_o is taken from Table 4.1 (4-08) for the internal structure, and R and U' are as defined for Equation 4-05. The total heat loss from the room is the sum of the losses from the walls, ceiling, and floor.

used also for plotting between the
 cylindrical and spherical coordinates
 calculation is made in case 3 under

procedure

(10-04)

$$\frac{\partial \theta}{\partial t} = f(r, \theta)$$

Values of $\frac{\partial \theta}{\partial t}$ are taken from the charts, Figure 1-2
 for the cylinder or Figure 1-3 for the sphere. On this

Figure

$$h = 0.17 \sqrt{k}$$

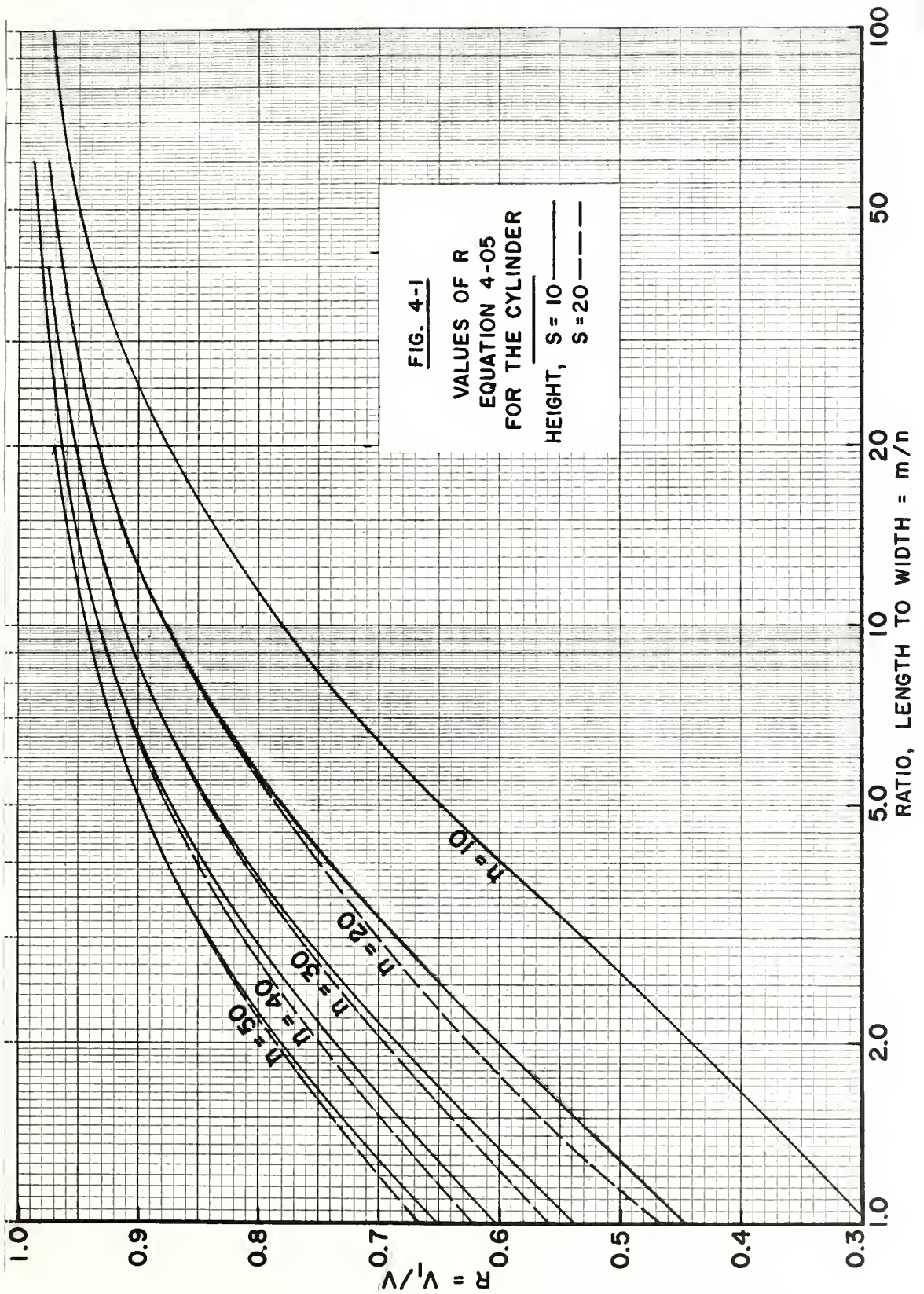
The quantity h must be corrected for air film resistance.
 For an internal resistance which has been neglected con-
 dition, the heat loss per square foot from any horizontal
 room at any time equals $U_c(T_1 - T_a)$, which can be shown to

equal

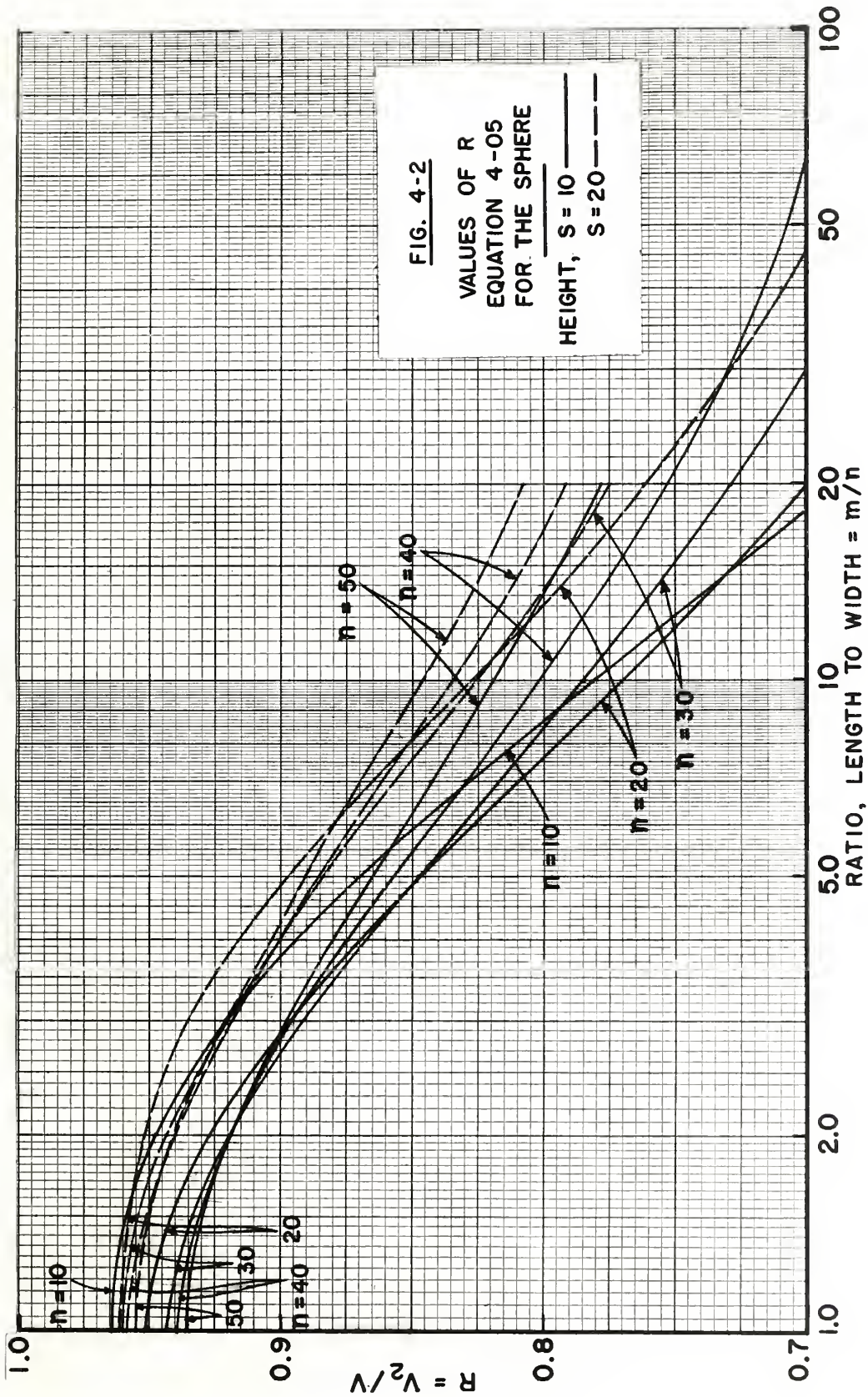
$$U_c \left[\frac{h}{h_c} - 0.17 \right]$$

where h is given by equation 1-10, U_c is given by Table
 1-1 (1-10) for the internal resistance, and h_c and U_c are
 as defined for Equation 1-10. The heat loss from the
 room is the sum of the losses from the walls, ceiling, and

floor.



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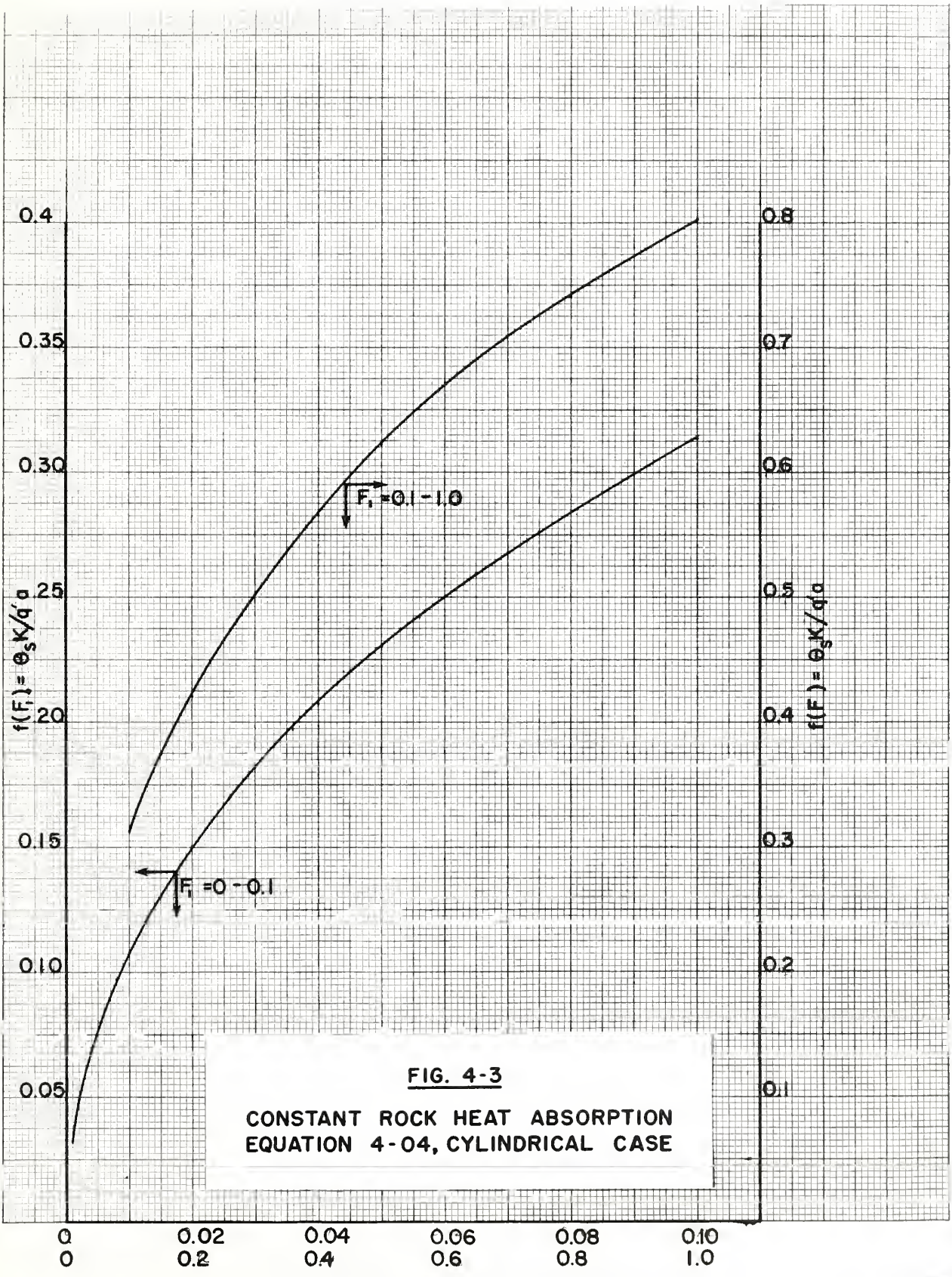
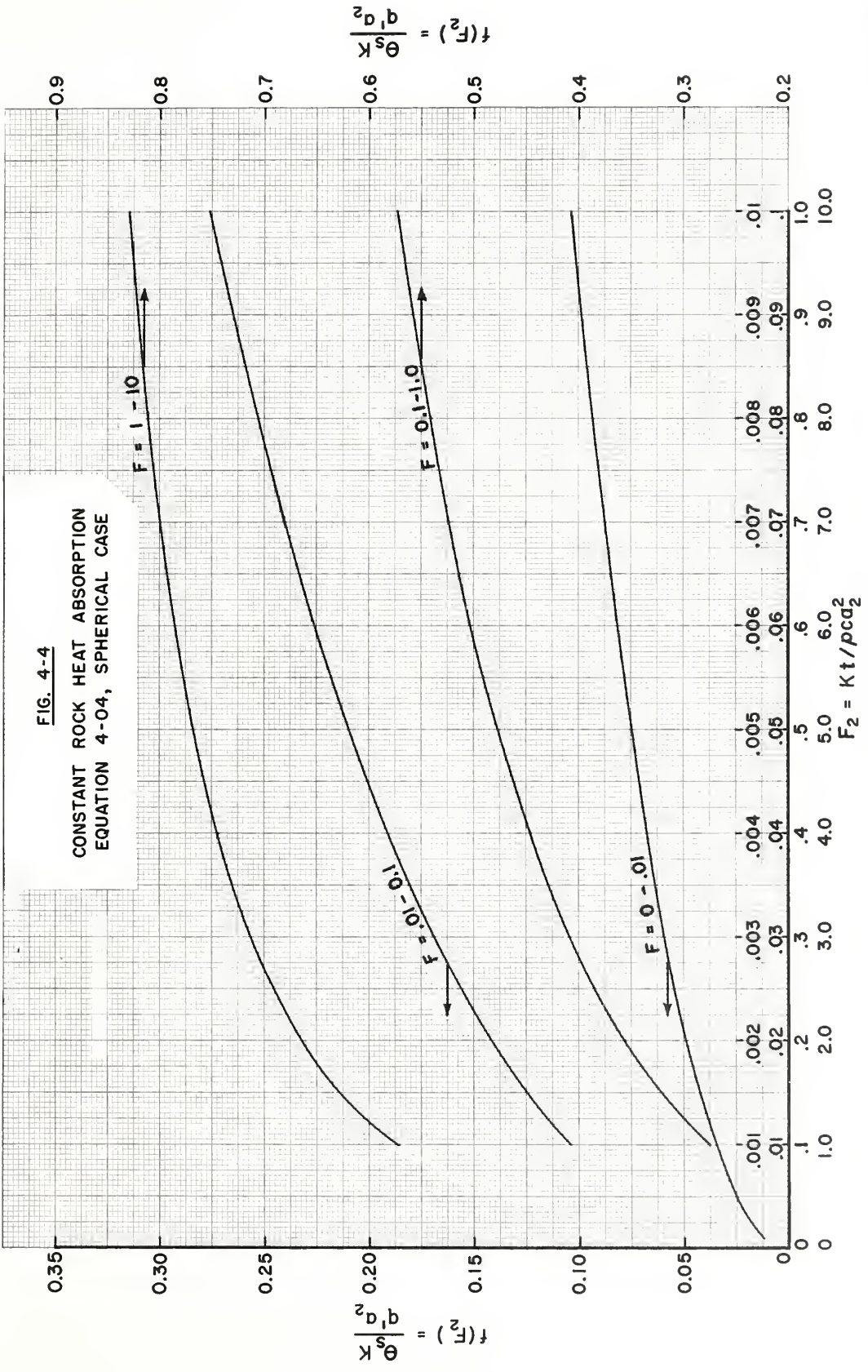


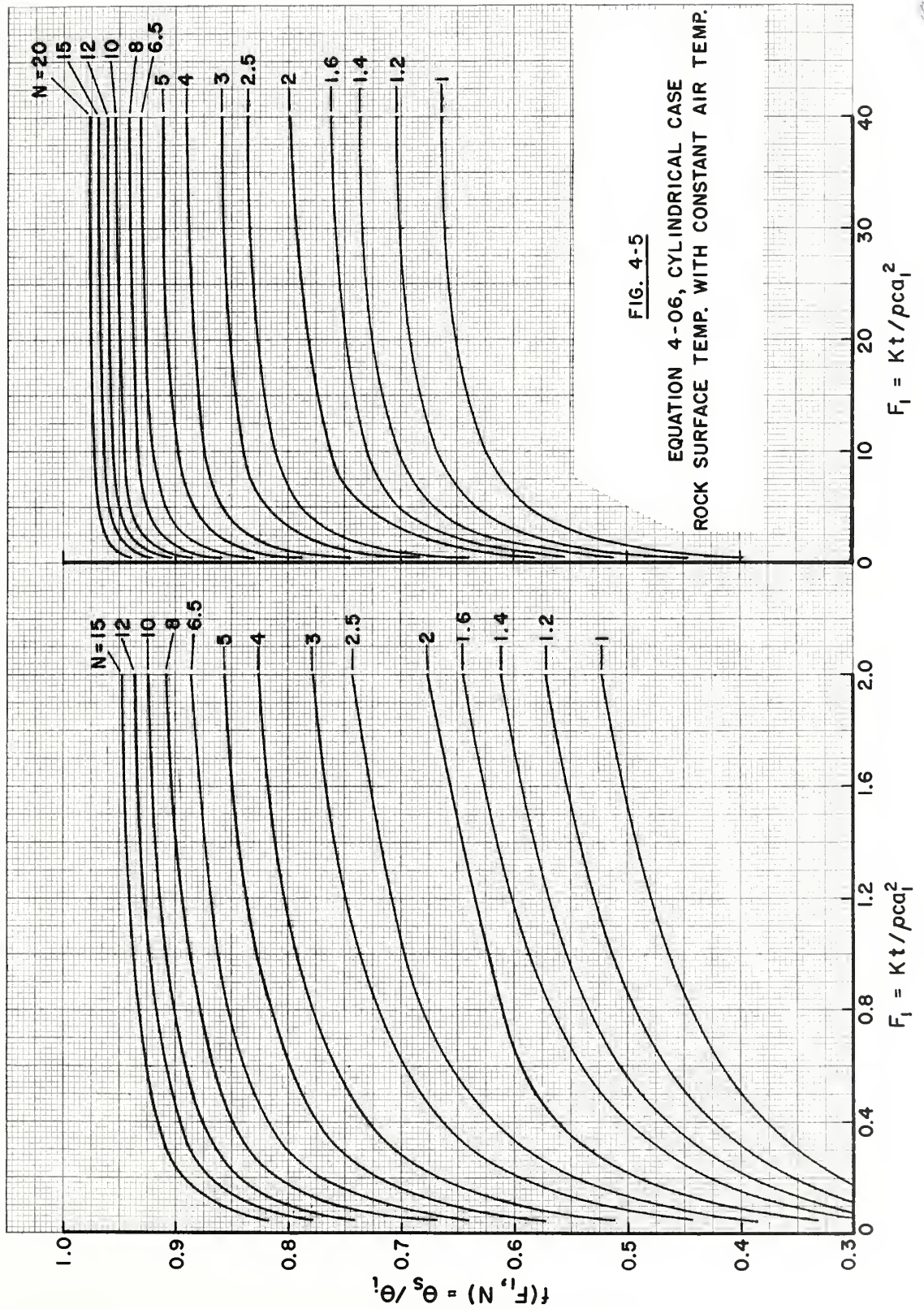
FIG. 4-3
CONSTANT ROCK HEAT ABSORPTION
EQUATION 4-04, CYLINDRICAL CASE



24962-3



24962-4



24962-1

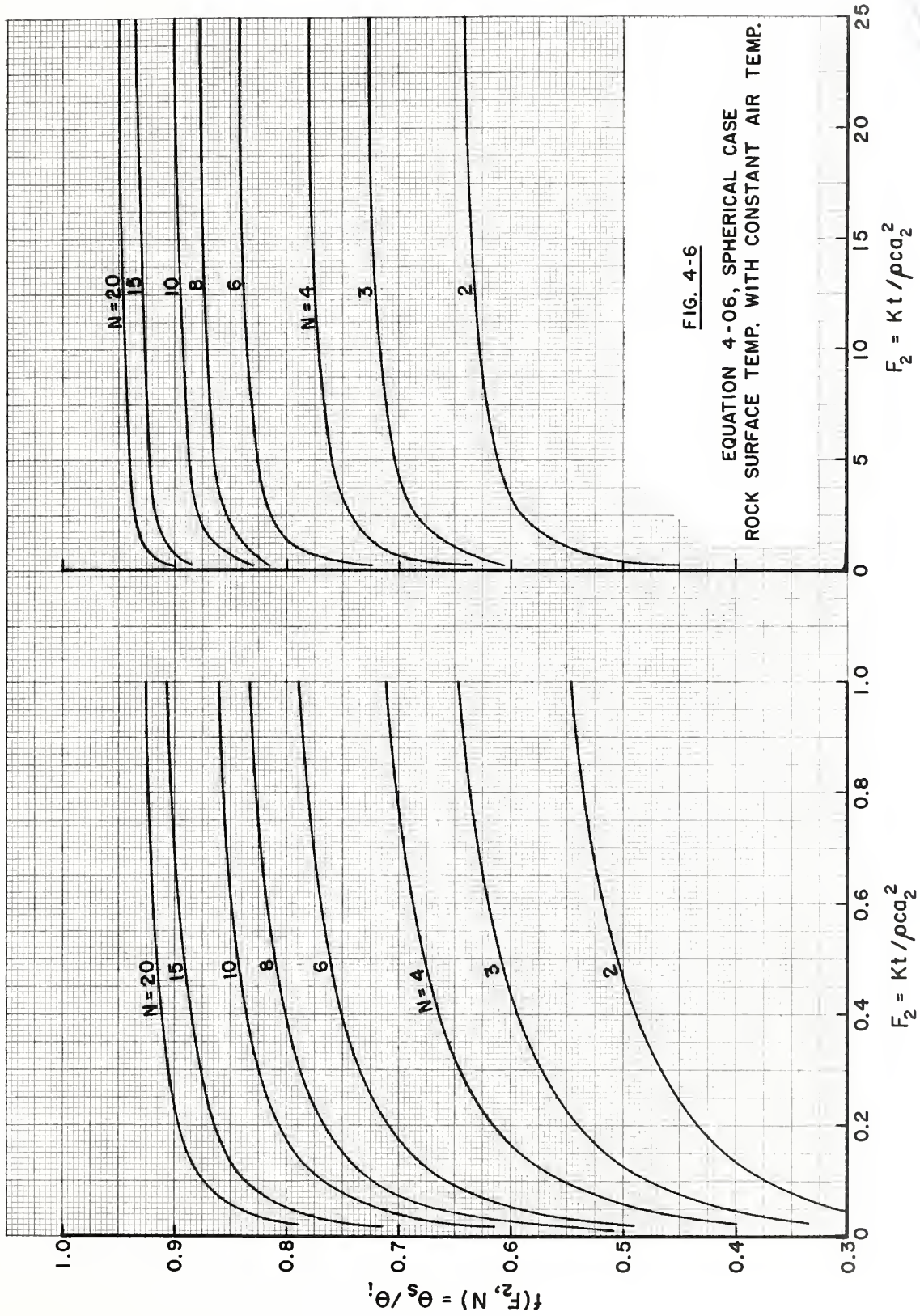


FIG. 4-6

EQUATION 4-06, SPHERICAL CASE
ROCK SURFACE TEMP. WITH CONSTANT AIR TEMP.

$$F_2 = Kt / \rho c a^2$$

$$F_2 = Kt / \rho c a^2$$

24762 K

4-04 Heat Absorption of Underground Reservoirs

An underground reservoir of water may be provided as a sink for the waste heat from engines, air conditioning equipment or other apparatus for use during emergencies (1-5) when outside services are cut off (3-10). Spaces prepared for this purpose are likely to be long and tunnel-like for reasons of economy in excavation and to provide necessary rock surface area. Therefore, in the capacity calculations the tunnel shape is assumed and the cylindrical approximation is employed.

If the water is used to absorb heat from engine jackets or refrigeration condensers, etc., and is then wasted outside the installation, its heat absorbing capacity can be computed by the equation:

$$Q_w = M (T_w - T_p) \quad (4-07)$$

Q_w = Heat absorbing capacity of the water, Btu

M = Mass of water in the reservoir, lbs

T_w = Temperature; water discharged from engine jacket or condenser, etc. F

T_p = Temperature; water available from reservoir;

F

If the water is recirculated from the reservoir to the engine jackets or condenser and back to the reservoir the heat-absorbing capacity is increased by the heat-absorbing capacity of the surrounding rock and the total capacity can be computed by means of the equation:

Heat Absorption of Underground Reservoirs

An underground reservoir of water may be provided as a sink for the waste heat from engines, air conditioning equipment or other apparatus for use during emergencies (1-2) when outside supplies are cut off (3-10). It is prepared for this purpose and likely to be long and narrow like for reasons of economy in excavation and to provide necessary rock surface area. Therefore, in the early calculations the tunnel shape is assumed and the overall approximation is employed.

If the water is used to absorb heat from engine jackets or refrigeration condensers, etc., and is then heated outside the installation, its heat absorbing capacity can be computed by the equation:

$$Q_w = M (T_w - T_p)$$

Q_w = Heat absorbing capacity of the water, Btu
 M = Mass of water in the reservoir, lbs
 T_w = Temperature; water abstracted from engine jacket or condenser, etc.
 T_p = Temperature; water available from reservoir

If the water is recirculated from the reservoir to the engine jackets or condensers and back to the reservoir the heat-absorbing capacity is increased by the recirculating capacity of the surrounding rock and the total capacity can be computed by means of the equation:

$$\frac{\theta_w K}{q_1} = f(F, G) \quad (4-08)$$

where

- θ_w = Temperature rise of water above the initial water temperature, deg F
- q_1 = Constant heat transfer rate to the water from an external source such as engine jackets or condenser, Btu hr⁻¹ per foot length of reservoir
- $F = Kt/pc a^2$
- t = Time from initial application of q_1 , hours
- $a = (s+n)/\pi$, radius of equivalent cylinder, ft
- s = Height of reservoir, ft
- n = Width of reservoir, ft
- $G = \frac{2 \pi a^2 pc}{M'c'}$
 = $2pc/\rho'c'$ (for a cylinder completely filled with water)
- M' = Mass of water in reservoir, lbs per foot length of reservoir
- ρ' = Density of water, lbs ft⁻³
- c = Specific heat of rock, Btu lb⁻¹f⁻¹
- c' = Specific heat of water, Btu lb⁻¹f⁻¹
- m = Length of reservoir, ft

Equation 4-08 is plotted in Figure 4-7 and Form E is suggested as a worksheet for its use. This equation yields the heat absorption per foot of length, q_1 , for a tunnel of radius, a , for a specified water temperature rise θ_w in a specified time, t .

$$\frac{\partial \psi}{\partial t} = \dots$$

where

$\psi =$ temperature rise of water above the

initial water temperature, $10^{\circ}F$

$\gamma =$ constant heat transfer rate to the water

from an external source such as engine

radiation or condensation, $10^{\circ}F$ per 10^3

length of reservoir

$$p = \rho \gamma$$

$t =$ time from initial application of γ above

of reservoir, π , radius of equivalent cylinder, 10^3

$a =$ height of reservoir, 10^3

$n =$ width of reservoir, 10^3

$$\frac{\partial \psi}{\partial t} = \dots$$

$\psi =$ temperature rise of water above the

initial water temperature

$M =$ mass of water in reservoir, 10^3 per foot

length of reservoir

$\rho =$ density of water, 10^3 per 10^3

$c =$ specific heat of water, 10^3 per 10^3

$\gamma =$ specific heat of water, 10^3 per 10^3

$n =$ length of reservoir, 10^3

equation (1) is derived in Figure 1-7 and (2) is derived

based on a water mass of 10^3 . This equation states the

heat absorption per foot of length, 10^3 per 10^3 of water,

for a specified water temperature rise ψ in a specified

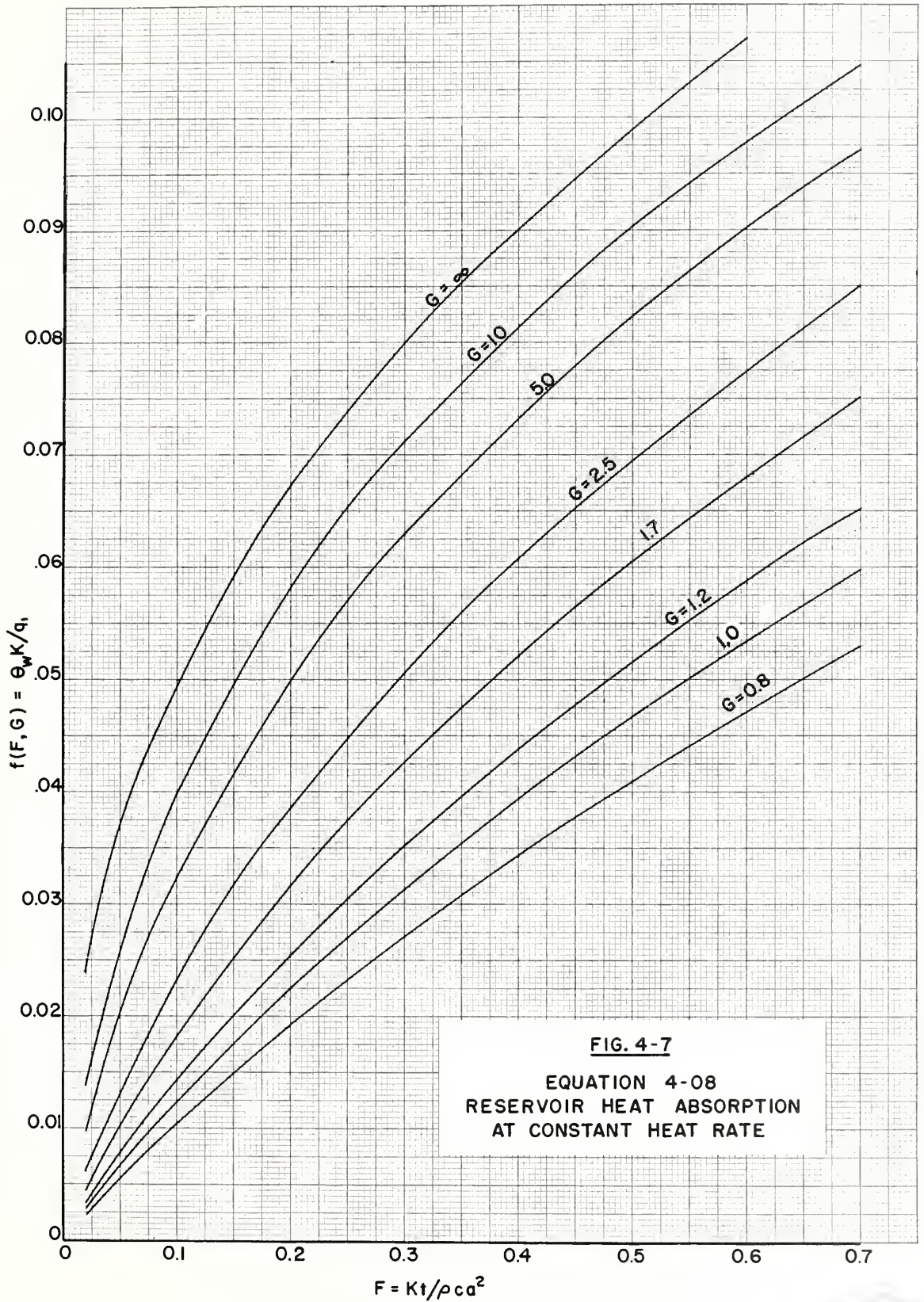


FIG. 4-7
EQUATION 4-08
RESERVOIR HEAT ABSORPTION
AT CONSTANT HEAT RATE



2-191-7-3

4-05 Heating or Cooling of Air by Tunnels or Shafts

Fresh or outside air needed for ventilation is often introduced to installations through shafts or tunnels with bare walls so that the air flows in contact with the surrounding rock. For a tunnel in continuous use, heat is alternately transferred from the air to the rock in summer and from the rock to the air in winter. Savings are possible under both conditions since the air is warmed in winter, thus reducing the heating load, and cooled in summer, thus reducing the cooling load (3-11). The temperature of the air at the exit, like that at the entrance, oscillates above and below the mean annual temperature but the amplitude of the temperature change is smaller at the exit.

This problem is subject to analytical treatment if it is assumed that the outside air temperature varies seasonally according to the equation.

$$\theta_o = \theta'_o \cos wt \quad (4-09)$$

θ_o = Outside air temperature, deg F, at time, t.

θ'_o = Outside air temperature minus mean annual temperature, deg F, maximum or minimum.

w = Angular velocity, 2π radians per year
= 0.000717 radian hr⁻¹

t = Time, hours (t = 0 when $\theta_o = \theta'_o$)

4-02 Heating or Cooling of Air by Tunnel or Shaft

Fresh or outside air needed for ventilation is often introduced to installations through shafts or tunnels with bare walls so that the air flows in contact with the surrounding rock. For a tunnel in continuous use, heat is alternately transferred from the air to the rock in summer and from the rock to the air in winter. Savings are possible under both conditions since the air is warmed in winter, thus reducing the heating load, and cooled in summer, thus reducing the cooling load (3-11). The temperature of the air at the exit, like that at the entrance, oscillates above and below the mean annual temperature but the amplitude of the temperature change is smaller at the exit.

This problem is subject to analytical treatment if it is assumed that the outside air temperature varies seasonally according to the equation.

$$\begin{aligned}
 \theta_o &= \theta_o' \cos \omega t \\
 \theta_o &= \text{Outside air temperature, deg F at time } t \\
 \theta_o' &= \text{Outside air temperature above mean annual temperature, deg F, maximum or minimum} \\
 \omega &= \text{Angular velocity, } 2\pi \text{ radians per year} \\
 &= 0.000717 \text{ radians } \text{min}^{-1} \\
 t &= \text{Time, hours } (t = 0 \text{ when } \theta_o = \theta_o')
 \end{aligned}$$

Based on this assumption, equations yielding results relevant to air conditioning are as follows:

For the temperature at distance L in the tunnel and at time, t,

$$\theta_L = \theta'_0 e^{-C't} \cos (wt - WL/V - C'B) \quad (4-10)$$

Maximum and minimum air temperature at point L:

summer and winter design temperatures

$$\theta'_L = \pm \theta'_0 e^{-C't} \quad (4-11)$$

Rate of heat loss or gain by the air in length L

at time, t:

$$q = 0.0566 Va^2 (\theta_0 - \theta_L) \quad (4-12)$$

Total heat gain of air in winter (equals total heat loss of air in summer)

$$Q = 157.7 Va^2 \theta'_0 \sqrt{1 + e^{-C't} - 2e^{-C't} \cos (WL/V + C'B)} \quad (4-13)$$

where A = Average cross section area of airway, ft²

a = 2A/P, hydraulic radius of airway, ft.

B = f₂ (z, b) (Figure 4-9)

b = h/K $\sqrt{a/w}$

C = f₁ (z, b) (Figure 4-8)

C' = $\frac{hL}{Va}$

e = Base of natural logarithms

Based on the assumption, equations relating variables relevant to air conditioning are as follows:

For the temperature at distance x in the tunnel and at time t ,

$$T_x = T_a + (T_b - T_a) e^{-C_1 x} \quad (1-10)$$

Maximum and minimum air temperature at point x :

summer and winter design temperatures

$$T_{x, \text{max}} = T_{a, \text{max}} + (T_{b, \text{max}} - T_{a, \text{max}}) e^{-C_1 x} \quad (1-11)$$

Rate of heat loss or gain by the air in length x at time t :

$$Q_x = 0.0256 V_a (T_a - T_x) \quad (1-12)$$

Total heat gain of air in winter (equal total heat loss of air in summer)

$$Q = 127.7 V_a \theta_1 \sqrt{1 + e^{-C_1 x}} \cos(\omega t + \phi) \quad (1-13)$$

where A = Average cross section area of airway, ft^2

$a = 2A/P$, hydraulic radius of airway, ft .

$B = \frac{1}{2} (z, \text{ ft})$ (Figure 1-9)

$$b = h \sqrt{a/w}$$

$C = f_1 (z, \text{ ft})$ (Figure 1-9)

$$C_1 = \frac{h_0}{V_a}$$

e = Base of natural logarithms

- h = Coefficient of heat transfer between the moving air and the surface of airway, $\text{Btu hr}^{-1}\text{ft}^{-2}\text{F}^{-1}$
 K = Thermal conductivity of rock, $\text{Btu hr}^{-1}\text{ft}^{-2}(\text{F}/\text{ft})^{-1}$
 L = Distance from outside entrance of airway, ft.
 P = Average perimeter of airway, ft.
 T = Period, 8760 hr (1 year)
 V = Velocity of air stream, ft hr^{-1}
 w = Angular velocity, $2\pi/T = 0.000717$ radians hr^{-1}
 $z = a\sqrt{w/a}$
 α = Thermal diffusivity $\text{ft}^2\text{hr}^{-1}$
 θ = Departure of temperature from the mean annual temperature, F; θ' , maximum departure or amplitude; θ_0 , outside air; θ_L , at distance L in airway

B, C, and Equations 4-11 and 4-12 are based on the assumption that the density and specific heat of air are 0.075 lb ft^{-3} and $0.018 \text{ Btu ft}^{-3}\text{F}^{-1}$, respectively.

Form F is suggested as a work sheet for problems of this type. If a tunnel or shaft is used intermittently as an airway, the equations in this section do not apply without modification and the effects of such an airway cannot be estimated unless the method of using it is stated.

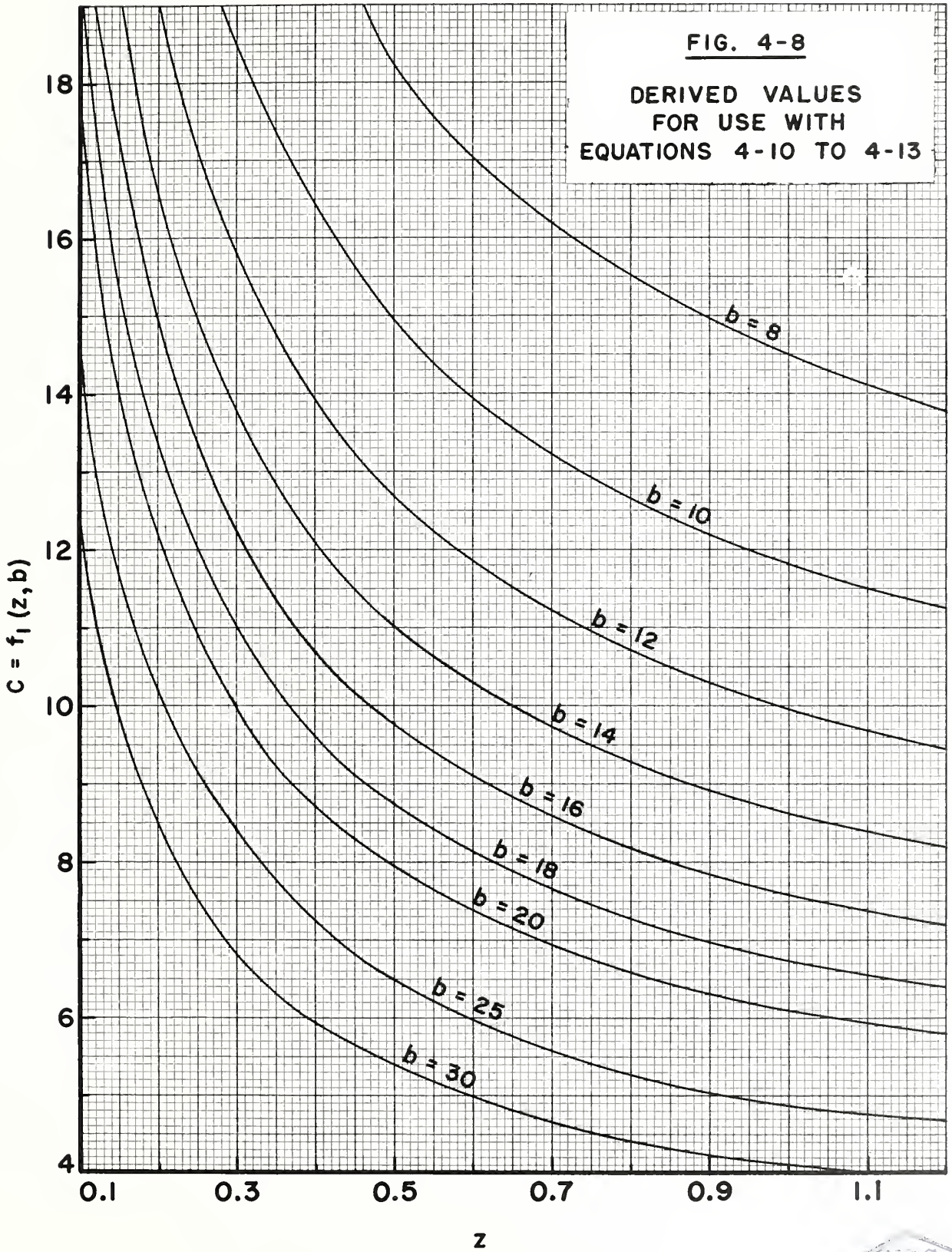
Values of h , the surface film coefficient of heat transfer for various values of V , the air velocity, in the tunnel or shaft are given on figure 4-10.

0.1 0.3 0.5 0.7 0.9

h = Coefficient of heat transfer between the moving
 air and the surface of airway, $h = \frac{K}{L} \frac{A_s}{A_c} \frac{V}{\mu}$
 K = Thermal conductivity of rock, $K = \frac{h L A_c}{A_s V \mu}$
 L = Distance from surface entrance of airway, ft.
 P = Average perimeter of airway, ft.
 T = Period, 0.750 hr (1 year)
 V = Velocity of air stream, ft hr⁻¹
 w = Air mass velocity, $w = \frac{V}{\mu} = 0.000177 \text{ lb ft}^{-2} \text{ hr}^{-1}$
 $\alpha = \sqrt{\frac{k}{\rho c}}$
 ρ = Thermal diffusivity $(\text{ft}^2 \text{hr}^{-1})$
 θ = Departure of temperature from the mean annual
 temperature, θ ; θ 's maximum departure or coefficient
 of outside air, θ' , at distance L in airway
 h, c , and equations 1-15 and 1-16 are based on the assumption
 that the density and specific heat of air are 0.075 lb/ft³
 and 0.018 Btu/lb-ft², respectively.
 Form 1 is suggested as a work sheet for problems of
 this type. If a tunnel or shaft is used, it is recommended
 on airway, the equation in this section do not apply without
 modification and the effects of such an airway cannot be
 estimated unless the nature of mining is stated.
 Values of h , the surface film coefficient of heat
 transfer for various values of V , the air velocity, in the
 tunnel or shaft are given on Figure 1-10.

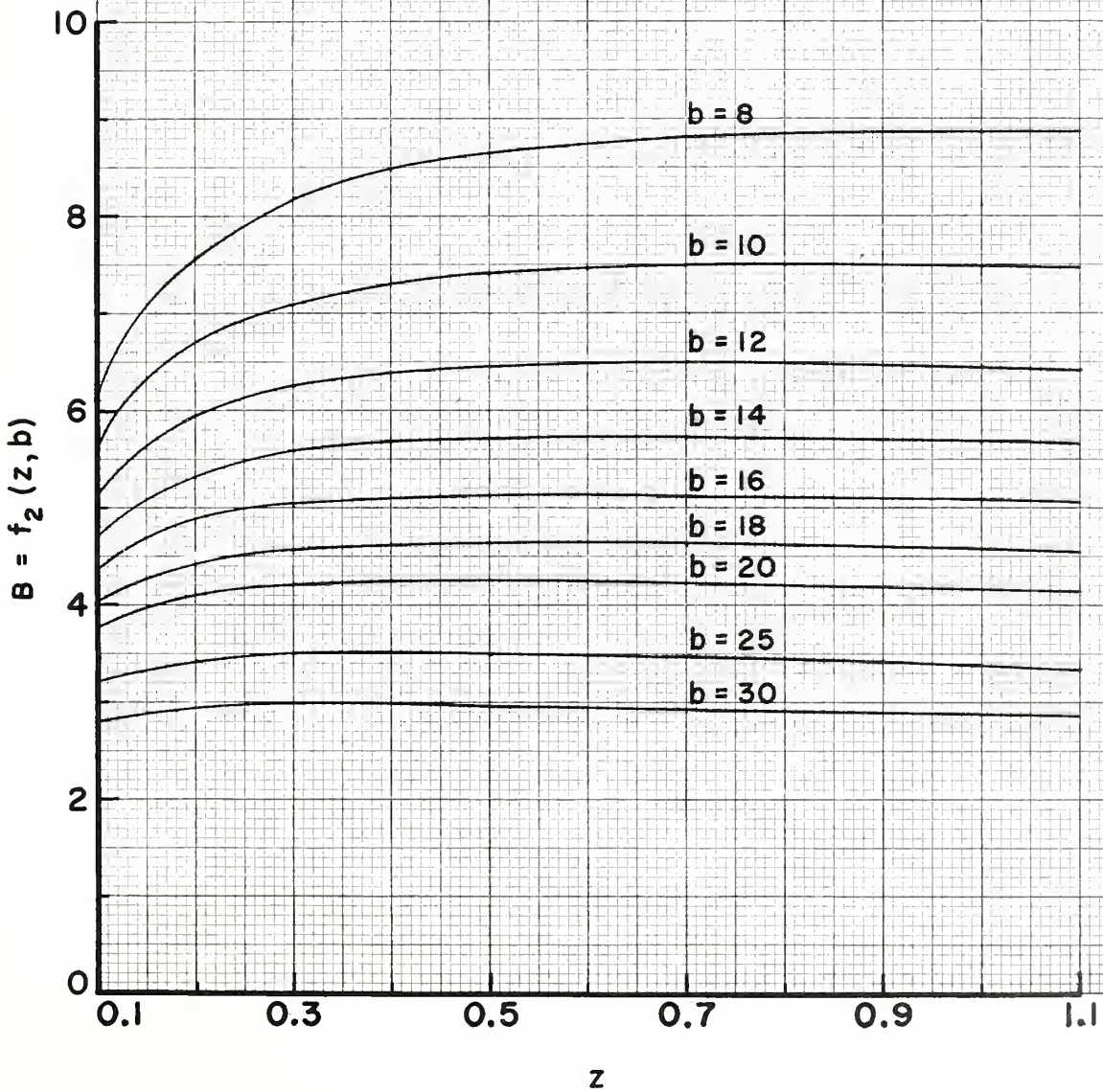
FIG. 4-8

DERIVED VALUES
FOR USE WITH
EQUATIONS 4-10 TO 4-13



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FIG. 4-9
DERIVED VALUES
FOR USE WITH
EQUATIONS 4-10 TO 4-13

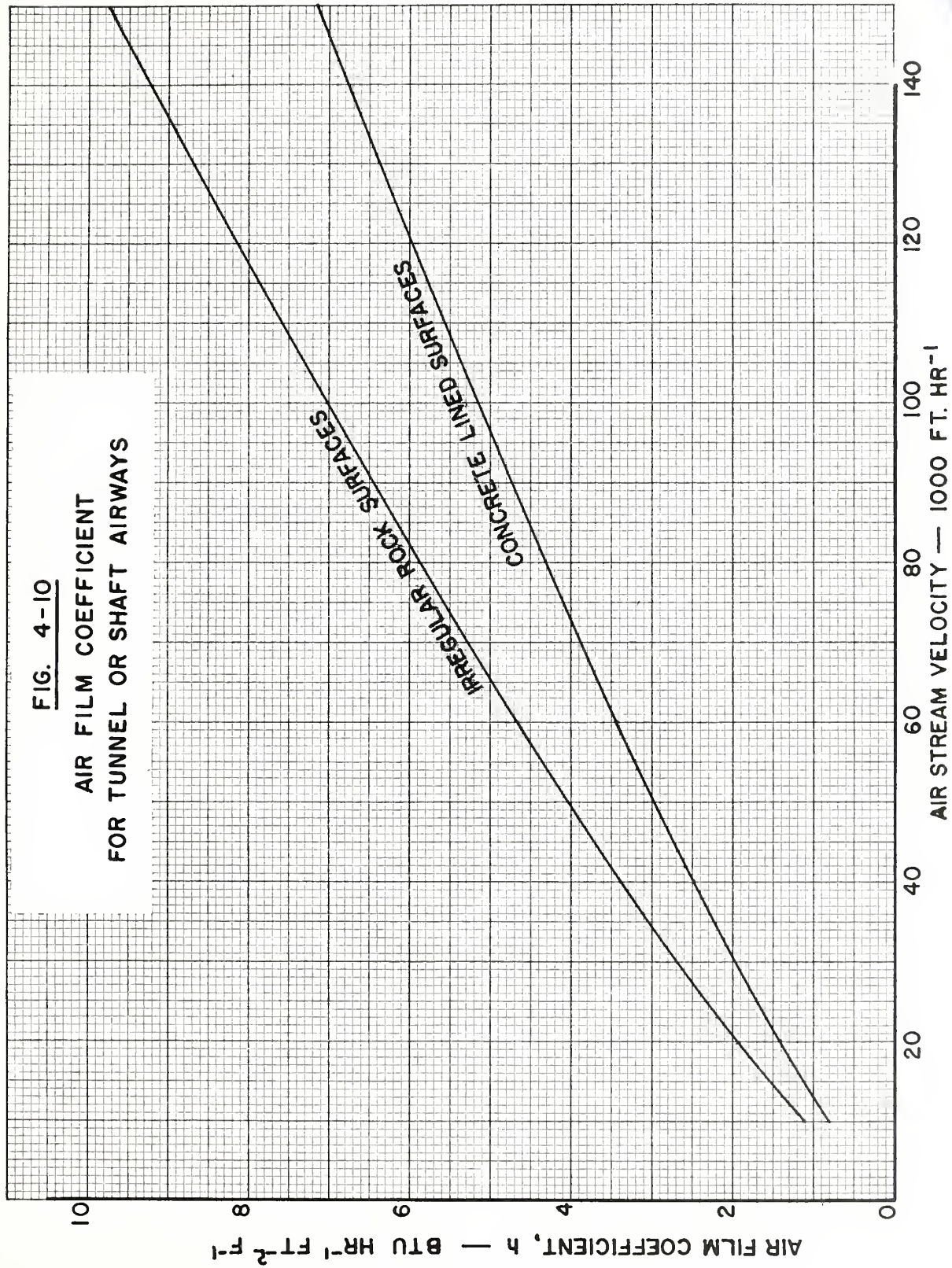


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FIG. 4-10

**AIR FILM COEFFICIENT
FOR TUNNEL OR SHAFT AIRWAYS**



27957-7

4-06 Thermal Properties of Rock

Rock heat absorption computations depend on the thermal properties of the rock and it is unfortunate that the available data are incomplete and, in some degree, discordant. For estimating purposes it is recommended that a specific heat of $0.2 \text{ Btu lb}^{-1}\text{F}^{-1}$ be assumed for any rock and for use in the equations in this chapter although rock specific heats as low as $0.16 \text{ Btu lb}^{-1}\text{F}^{-1}$ have been reported.

For greenstone, present in the mountains of Virginia, tests and experience show a thermal conductivity of about $1.5 \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{F}/\text{ft})^{-1}$, with a density of 186 lbs ft^{-3} . These figures have been used in demonstration problems in connection with this work and are regarded as good assumptions at least for preliminary estimates in many cases. When precision is required, however, more precise values can be obtained either by testing some specimens for conductivity or by the use of figure 4-11 in conjunction with a petrographic analysis of some specimens. Facilities for making these tests or analyses are maintained in several laboratories in this country.

For igneous and metamorphic rocks the density generally falls in the range from 150 to 190 lbs ft^{-3} , and that of the sedimentary rocks in the range from 100 to 175 lbs ft^{-3} .

For igneous and metamorphic rocks, the thermal conductivity falls in a range from 1.2 to $2.0 \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{F}/\text{ft})^{-1}$.

Rock heat absorption measurements depend on the thermal properties of the rock and it is unfortunate that the available data are incomplete and, in some degree, contradictory. For existing purposes it is recommended that a specific heat of 0.2 Btu lb-1-F-1 be assumed for use in the equations in this chapter although some specific heats as low as 0.15 Btu lb-1-F-1 have been reported.

For limestone, present in the mountains of Virginia, tests and experience show a thermal conductivity of about 1.5 Btu hr-1-ft-2-F-1 with a density of 165 lb ft-3. These figures have been used in demonstration problems in connection with this work and are regarded as good approximations at least for preliminary estimates in many cases. When precision is required, however, more precise values can be obtained either by testing some specimens for conductivity or by the use of Figure 4-11 in conjunction with a petrographic analysis of some specimens. Facilities for making these tests by analysis are maintained in several laboratories in this country.

For igneous and metamorphic rocks the density generally falls in the range from 150 to 190 lb ft-3, and that of the radiometric rocks in the range from 160 to 175 lb ft-3. For igneous and metamorphic rocks, the thermal conductivity falls in a range from 1.5 to 2.0 Btu hr-1-ft-2-F-1.

Granites are found to be in the range 20-40 percent quartz, 50-73 percent feldspar and 5-12 percent mafic. The factors which determine the thermal conductivity of sedimentary rocks are numerous; composition, porosity, temperature, grain size and shape, and fluid content all have to be considered.

4-07 Initial Underground Conditions

At depths of 50 to 70 feet, the temperature of earth or rock can be expected to approximate the mean annual temperature for a region in the absence of disturbing factors such as underground fires or large subterranean streams. At greater depths, the temperature is found to be higher, increasing at the rate of about 1F per hundred feet. Earth temperatures thus determined are regarded as adequate for air conditioning estimates for underground spaces although a check of the figures is desirable during the survey of any proposed site.

The earth's surface is warmed chiefly by solar radiation and it is cooled by wind, rain or snow and by radiation to the sky, particularly at night. There is therefore an approximately regular diurnal cycle in the surface temperature but its effect disappears, practically speaking, at a depth of a foot or so in the earth. The annual surface temperature variation is greater and its effects may be significant to depths of 15 or more feet for some purposes. Some measurements were made at various depths down to 13 feet near

Grates are placed to be in the range 20-30 percent open, 20-73 percent below and 2-15 percent above. The factors which determine the thermal conductivity of the rocks are numerous, including porosity, temperature, grain size and shape, and liquid content all have to be considered.

4-07 Initial Underground Conditions

At depths of 50 to 75 feet, the temperature of water or rock can be expected to approximate the mean annual temperature for a region in the absence of disturbing factors such as underground lines of large subterranean streams. As greater depths, the temperature is found to be higher, increasing at the rate of about 1° per hundred feet. Both temperatures thus determined are regarded as accurate for all conditioning essential for underground space although a check of the figures is desirable during the course of any proposed work.

The earth's surface is warmed directly by solar radiation and it is cooled by wind, rain or snow and by radiation to the sky, particularly at night. There is therefore an annual major regular annual cycle in the surface temperature and the effect is more marked, particularly in winter, at a depth of a foot or so in the earth. The annual surface temperature variation is greater and its effect less significant at depths of 10 or more feet for some latitudes. Some measurements were made at various depths from 10 to 100 feet.

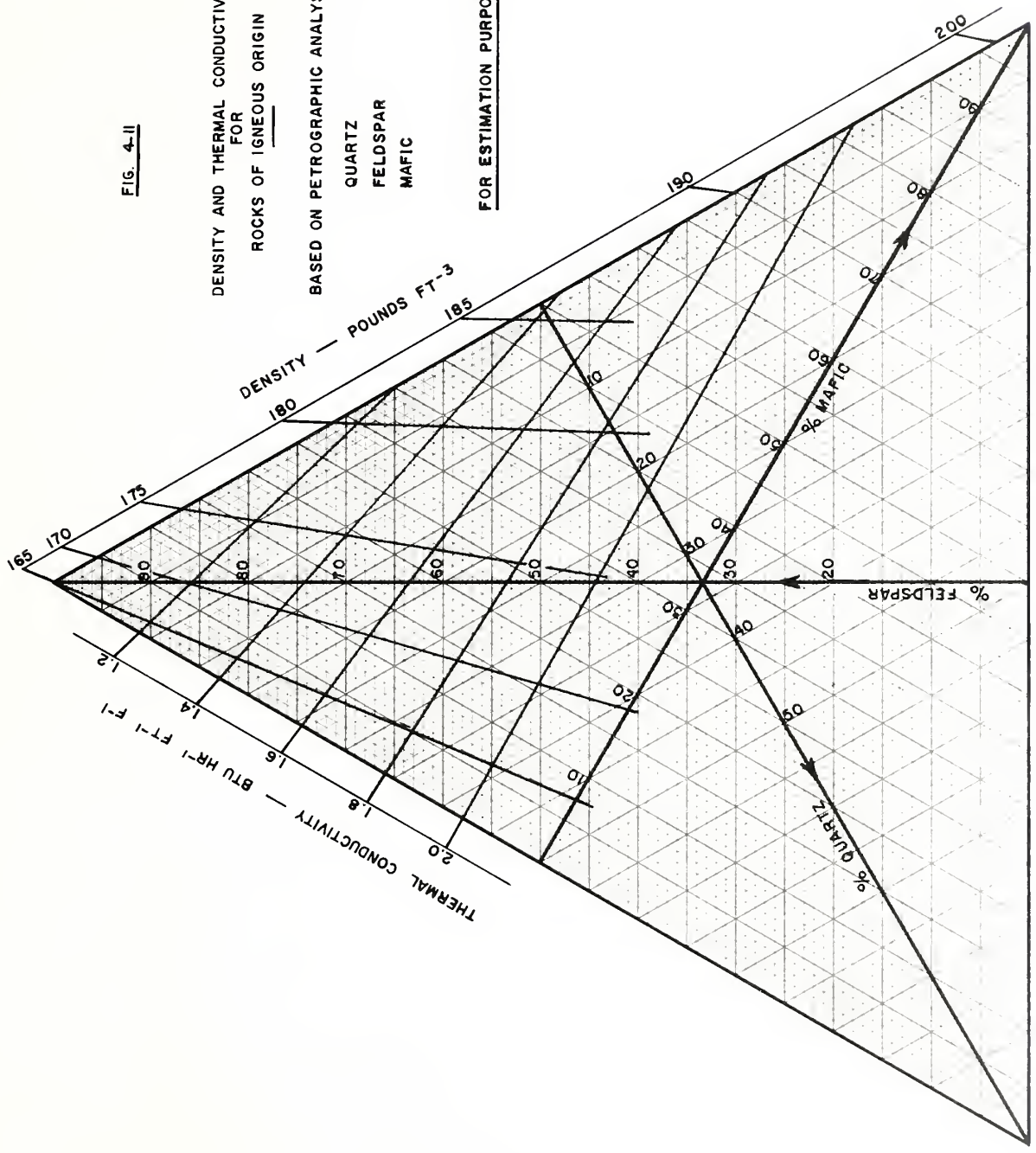
FIG. 4-II

DENSITY AND THERMAL CONDUCTIVITY
FOR
ROCKS OF IGNEOUS ORIGIN

BASED ON PETROGRAPHIC ANALYSIS:

- QUARTZ
- FELDSPAR
- MAFIC

FOR ESTIMATION PURPOSES ONLY



24962-7

Values of U and of U' for some materials and structures are given in table 4-1 for illustration and possible use in heat transfer estimates. The fact that particular materials and constructions are mentioned in the table is not a recommendation that these materials or constructions should be used. The designing engineer may select other materials in which case suitable values for the coefficients should be otherwise determined.

For a rock surface such as that left after blasting, the surface air film heat transfer coefficient averaged $h = 1.4 \text{ Btu hr}^{-1}\text{ft}^{-2}\text{F}^{-1}$ in some tests in an underground chamber with only natural air motion. This figure is based on projected wall area, ignoring irregularities left after blasting. For the surface conductances of interior structures, a value of $f_0 = f_1 = 1.65$ is recommended for present purposes. With these values, heat transfer coefficients of walls, ceilings and floors of interior structures can be computed by means of the following equations:

$$U_0 = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.65}} \quad (4-14)$$

$$U' = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.25}} \quad (4-15)$$

C = Conductance of wall, ceiling or floor of interior structure

Values of U and of R for some materials and structures are given in table 1-1 for illustration and possible use in heat transfer estimates. The fact that particular materials and constructions are mentioned in the table is not a recommendation that these materials or constructions should be used. The designing engineer may select other materials in which case suitable values for the coefficients should be otherwise determined.

For a rock surface such as that left after blasting the surface air film heat transfer coefficient is given by $h = 1.6 \text{ Btu hr}^{-1} \text{ ft}^{-2} \text{ } ^\circ\text{F}^{-1}$ in some tests in an open chamber with only natural air motion. This figure is based on projected wall area, ignoring irregularities that occur in blasting. For the surface conductance of interior structures, a value of $f_0 = f_1 = 1.65$ is recommended for ordinary exposures. With these values, heat transfer coefficients of walls, ceilings and floors of interior structures can be computed by means of the following equations:

$$U_o = \frac{1}{\frac{1}{1.65} + \frac{1}{c} + \frac{1}{1.65}} \quad (1-11)$$

$$U_i = \frac{1}{\frac{1}{1.65} + \frac{1}{c} + \frac{1}{1.65}} \quad (1-12)$$

c = Conductance of wall, ceiling or floor of interior structure

TABLE 4-1

Heat Transfer Coefficients for Underground Structures

Material or Structure	U_0	U'
Bare rock surface		1.40
Studs with 3/8" gypsum board on one side	0.67	0.59
Studs with 3/8" gypsum board on both sides	0.37	0.35
Studs with 1/2" insulating board on one side	0.36	0.34
Studs with 1/2" insulating board on both sides	0.19	0.18
Brick, one course - 4" thick no finish	0.60	0.54
Brick, one course - 4" thick 3/8" gypsum bd.	0.51	0.47
Brick, one course - 4" thick 1/2" insulating bd.	0.32	0.30
Brick, two course 8" thick, no finish	0.41	0.38
Concrete, 8" thick, no finish	0.54	0.49
Concrete construction floors, (3") no ceiling, no flooring	0.68	0.60
Concrete construction floors, (3") no ceiling, 1/8" asphalt tile	0.66	0.59
Metal roof deck, bare	0.90	0.77
Metal roof deck, roofing and 1/2" insulating board	0.33	0.31
Wood roof 1" roofing and 1/2" insulating bd.	0.25	0.24

U_0 = heat transfer coefficient, based on temperature difference between air in conditioned space and air outside, in the annular space, with zero wind.

U' = heat transfer coefficient, Btu per hour for each square foot of rock surface area and for each degree F difference in temperature between rock surface and air in conditioned spaces.

TABLE A-1

Heat Transfer Coefficients for Underlaid Structures

U _o	U _i	Material or Structure
0.10		Raw rock surface
0.25	0.17	Studs with 3/8" spaced board on one side
0.33	0.27	Studs with 3/8" spaced board on both sides
0.30	0.26	Studs with 1/2" insulating board on one side
0.18	0.19	Studs with 1/2" insulating board on both sides
0.23	0.23	Brick, one course - 4" thick, no finish
0.17	0.21	Brick, one course - 4" thick 3/8" spaced BA
0.30	0.22	Brick, one course - 4" thick 1/2" insulating BA
0.38	0.21	Brick, two courses 3" thick, no finish
0.15	0.24	Concrete, 8" thick, no finish
0.20	0.25	Concrete construction floors, (2") no ceiling, no flooring
0.22	0.26	Concrete construction floors, (3") no ceiling, 1/8" asphalt tile
0.77	0.30	Metal roof deck, bare
0.71	0.23	Metal roof deck, roofing and 1/2" insulating board
0.26	0.28	Wood roof 1" roofing and 1/2" insulating BA

U_o = heat transfer coefficient, based on temperature difference between air in conditioned space and air outside in the outdoor space, with area ratio.

U_i = heat transfer coefficient, based on temperature difference between air in conditioned space and air outside in the outdoor space, with area ratio.

4-09 Vapor Permeability of Materials

A vapor barrier material may sometimes be included in the walls, ceiling or floor of an internal structure to reduce the latent air conditioning load or to preclude harmful condensation inside the wall, ceiling or floor construction. The danger of condensation in parts of an underground structure is not considered great particularly if the space is continuously air conditioned because the temperature differences or gradients are not severe compared to these that occur in surface buildings. Data are lacking but it appears that condensation might occur in a construction such as a double-faced wall containing insulation. A vapor barrier might therefore be installed in or near the outer surface as precautionary measure.

A method for predicting vapor transfer and condensation in walls is presented in "Moisture Condensation in Building Walls" (ref. 17) with some data on the permeabilities of some materials used in buildings. The method is based on the theory that water vapor transfer through a material is proportional to vapor pressure difference between the two sides and that resistances are additive as they are for heat flow. It is known that this is only an approximation but it may be close enough for practical estimating purposes. Another uncertainty in this field concerns the vapor permeance of materials which differs considerably

A vapor barrier material may sometimes be located in the walls, ceiling or floor of an internal structure to reduce the latent air conditioning load or to reduce humidity condensation inside the wall, ceiling or floor construction. The danger of condensation in walls of an underground structure is not considered great particularly if the space is essentially air conditioned because the temperature differences or gradients are not severe compared to those that occur in surface buildings. Data are lacking but it appears that condensation might occur in a construction such as a double-faced wall containing insulation. A vapor barrier might therefore be installed in or near the outer surface as practically necessary.

A method for predicting vapor transfer and condensation in walls is presented in "Relative Humidity in Building Walls" (ref. 17) with some data on the permeabilities of some materials used in buildings. The method is based on the theory that water vapor transfer through a material is proportional to vapor pressure difference between the two sides and that resistances are additive in series and in parallel. It is known that this is only an approximation but it may be close enough for practical engineering purposes. Another uncertainty in this field concerns the vapor permeance of materials which differs considerably

between specimens of the same material. However, the data in Table 4-2 were selected to show the range of the permeances of some materials used in buildings as observed by Babbitt (a) and Teesdale (b), reported in Reference 17.

TABLE 2

Permeance of Some Materials to Water Vapor

Material	Thickness Inches	Permeance P	Resistance (1/P)
Wood - spruce	(a) 0.563	3.48	0.287
Wood - pine	(a) 0.645	2.52	.397
Paper, kraft, 1 sheet	(a) 0.004	168.00	.004
Asphalt felt, 15-lb., dull surface	(a) 0.032	13.50	.074
Asphalt-coated paper, 50 lb	(a) -	1.04	.962
Plasterboard, between heavy sheets of paper	(a) 0.37	70.20	.014

Unit of permeance, $P = 1 \text{ grain ft}^{-2}\text{hr}^{-1}(\text{lb}/\text{in}^2)^{-1}$ (Permeance in perms = 0.49 P)

4-10 Underground Water

In damp regions or seasons water may enter an underground chamber in either of two ways. It may soak through pervious rock and appear as dampness on the surface, perhaps with streams running or dripping downward, or it may leak in

between specimens of the same material. However, the data in Table 1-2 were selected to show the range of the permeances of some materials used in buildings as observed by Habibe (a) and Tashkale (b), reported in Reference 17.

TABLE 2

Permeance of some Materials to Water Vapor

Material	Thickness inches	Permeance 1	Permeance (1/1)
Wood - spruce	(a) 0.75	2.18	0.287
Wood - pine	(a) 0.62	2.22	.337
Paper, Kraft, 1 sheet	(a) 0.001	100.00	.001
Asphalt felt, 15-lb. roll surface	(a) 0.032	12.50	.075
Asphalt-cement paper, 20 lb	(a) -	.01	.002
Fiberboard, between heavy sheets of paper (a) 0.37	(a) 0.37	10.50	.031

Unit of permeance, $P = 1 \text{ grain ft}^{-2} \text{ hr}^{-1} \text{ (in}^2 \text{ Hg)}^{-1}$ (Reference 17) in paper = 0.102

1-10 Undermount Water

In these regions or sections water may enter in undermount chamber in either of two ways. It may come in through cracks and appear as leakage on the outside, or it may leak in streams running on driving downwind, or it may leak in

through faults or fissures. At the greater depths, entrance of water through fissures, rather than through pervious rock, is usual because a site in hard rock is likely to be chosen, if possible, for structural strength. Such rock is likely to be impervious or nearly so. Because the possible hydrostatic pressures are high (3-08) it is customary to drain off excess water rather than attempt to stop the leaks or to treat the rock surface and make it impervious.

Evaporation from rock surfaces may have significant effect on the humidity in bare chambers. When such a chamber is first warmed, the rock can act as a dehumidifier and tend to hold the dewpoint at the surface temperature. In the course of time, the rock surface temperature increases and water evaporating from the surface becomes part of the latent load. Figure 4-13 is a means of estimating the evaporation from wet or damp surfaces, based on data in reference 18. The curve gives the average rate of evaporation, M^1 , in $\text{lb hr}^{-1}\text{ft}^{-2}$ for a wet surface L ft long in the direction of air flow parallel to the surface for a velocity of V ft min^{-1} and for a vapor pressure difference $(P_s - P_a)$ psi, where P_s is the vapor pressure of water at the temperature of the wet surface, and P_a is the vapor pressure of the moving air.

Estimates of evaporation from rock are difficult because the area of the wet surface cannot be predicted with certainty for any proposed underground chamber. In the installation so far examined in the eastern United States the wet area did not

through joints or fissures. At the greater depths, evidence
of water through fissures, rather than through pervious rock,
is usual because a side in hard rock is likely to be closed,
if possible, for structural strength. Such rock is likely
to be impervious or nearly so, because the possible hydro-
static pressures are high (3-50) it is necessary to drain
off excess water rather than attempt to stop the leakage or
to treat the rock masses and make it impervious.

Evaporation from rock surfaces may have significant
effect on the humidity in bare exposures. When such an
exposure is first warmed, the rock can act as a dehumidifier
and tend to hold the dewpoint at the surface temperature.
In the course of time, the rock surface temperature in-
creases and water evaporating from the surface becomes part
of the latent load. Figure 1-1 is a means of estimating
the evaporation from wet or dry surfaces, based on data in
reference 10. The curve gives the average rate of evaporation,
 E , in lb/hr-ft² for a wet surface at a given air temperature
of air flow parallel to the surface for a velocity of 7 ft
min-1 and for a vapor pressure difference (p_v-p_a) of 1.0, where
p_v is the vapor pressure of water at the temperature of the
wet surface, and p_a is the vapor pressure of the ambient air.

Estimates of evaporation from rock are difficult because
the area of the wet surface cannot be predicted with certainty
for any proposed underground structure. It has been estimated
for examination in the eastern United States that only 10%

exceed 10 percent of the total. In the arid regions of the west, dampness on the walls would be rare.

For an internal structure, evaporation from the rock may not be important since the ingress of vapor to the conditioned space can be limited by vapor barriers if necessary; also, if the annular space is used as an exhaust plenum, most of the vapor due to evaporation is carried out by the leaving air. However, materials or equipment such as pipes, ducts, wiring, or timber enclosed in the annular space or in contact with the rock should be capable of withstanding humidities of 100 percent since parts of this space may contain saturated air at times.

If a structure is so arranged that the rock remains cool, at say 55F, while the interior structure is held at some higher temperature, say 75F and 50 percent humidity, the rock can serve as a condenser and assist in dehumidifying the structure. In this case the vapor barrier is not needed. This effect can be useful during emergency periods with arrangements suitably designed to employ it. In this case either dampness or free water in the annular space, being drained away, has no objectionable effects since evaporation does not occur from the surface.

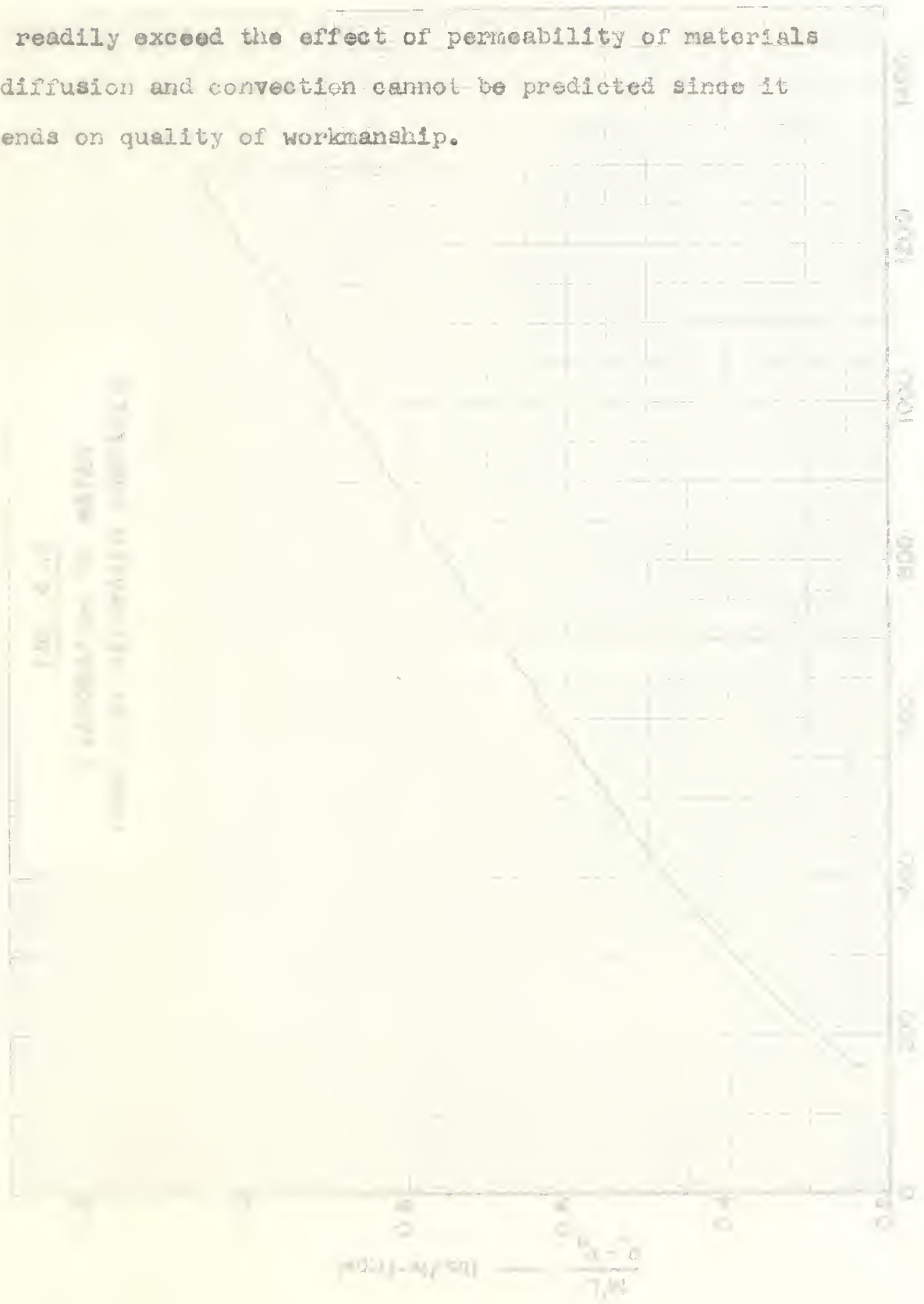
Metals and metal foils are practically perfect vapor barriers except for possible leaks at joints. If leaks exist in any vapor barriers the resulting vapor transfer by convection

exceed 10 percent of the total in the air regions of the
west, dimness on the walls would be noted.
For an internal atmosphere, evaporation from the
may not be important since the amount of vapor to be
conditioned space can be limited by vapor barrier if neces-
sary; also, if the smaller space is used as an exhaust space,
most of the vapor due to evaporation is carried out of the
leaving air. However, materials or equipment such as pipes,
doors, windows, or timber enclosed in the smaller space or in
contact with the rock should be capable of withstanding
humidity of 100 percent since parts of this space may
contain saturated air at times.
It is suggested that the rock contain
cool, at say 50°F, while the interior atmosphere is kept at
a wet bulb temperature, say 75°F and 70 percent humidity.
The rock can serve as a condenser and sealed in airtight
the structure. In this case the vapor barrier is not needed.
This effect can be useful during summer and winter with
arrangements suitably designed to explain it. In this case
either dampness or free water in the smaller space, being
designed well, had no objectionable effects since evaporation
does not occur from the surface.
Metals and metal foil are practically useless vapor
barriers except for possible leaks at joints. It is now stated
in any vapor barrier the remaining vapor resulting from evaporation

can readily exceed the effect of permeability of materials or diffusion and convection cannot be predicted since it depends on quality of workmanship.

FIG. 4. (a)

PERMEABILITY OF MATERIALS
 AND CONVECTION



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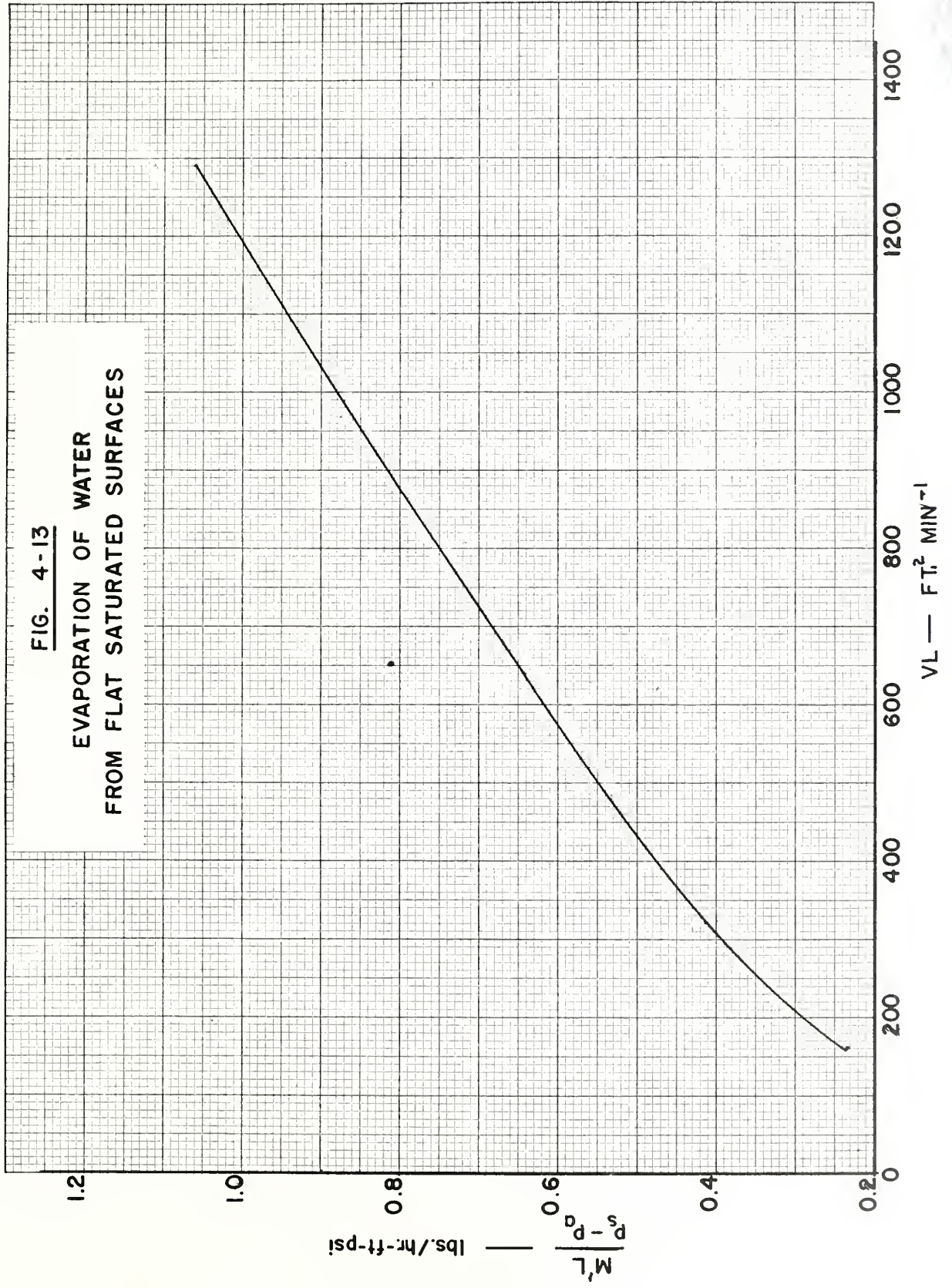
... and ...

... and ...

... and ...

FIG. 4-13

EVAPORATION OF WATER
FROM FLAT SATURATED SURFACES



2-1-18

THE NATIONAL BUREAU OF STANDARDS

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