NATIONAL BUREAU OF STANDARDS REPORT

4545

Engineering Manual for Protective Construction

Part V

Heating and Air Conditioning of Underground Installations

by

R. S. Dill
B. A. Peavy

Report to
Office of the Chief of Engineers
Department of the Army

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Radio Standards. High Frequency Standards. Microwave Standards.

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Heating and Air Conditioning of Underground Installations

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R. S. Dill
B. A. Peavy
Heating and Air Conditioning Section
Building Technology Division

To

Protective Structures Section
Protective Construction Branch
Office of the Chief of Engineers
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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

PROTECTIVE CONSTRUCTION BRANCH

ENGINEERING MANUAL FOR PROTECTIVE CONSTRUCTION

PART V

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Underground Installations: Heating and Air Conditioning

CHAPTER 1

Introduction

1-01 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 Office of The Chief 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 become more apparent, this Manual may attain a broad application, and it is hoped that information gained in the use of underground installations 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 types 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 data are lacking on which to base design and selection of equipment sizes.

1-02 Scope

The scope of this 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, pumps, piping systems and controls. An underground chamber may or may not have a liner or inner structure, insulated or 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 are different for the three types of usage.

Underground storage space 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 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. Vitiation 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 dampness, or heat and dampness, in combination. Few, 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 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 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. 7), but the report yields little design data on heating and air conditioning. It appears that air conditioning was not considered justifiable for most underground installations 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 47F 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 57 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:

Standby: 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 operating 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 Condition: 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.

Emergency Condition: Outside services including power, water supply, and possibly sewage disposal system cut off; installation expected to continue performing its mission, utilizing self-contained power source, water supply, etc.; outside air supply greatly reduced or cut off.

Disaster Condition: Installation inoperative due to damage or exhaustion of supplies; occupants dependent on stored food and water and possibly on revivification of the air for survival.

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, Btu $hr^{-1}ft^{-2}F^{-1}$

c = Specific heat, Btu $lb^{-1}F^{-1}$; 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, Btu $hr^{-1}ft^{-2}F^{-1}$

K = Thermal conductivity, Btu $hr^{-1}ft^{-2}(f/ft)^{-1}$

k = Thermal conductivity, Btu $hr^{-1}ft^{-2}(f/in.)^{-1}$

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

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

Qa= Air flow rate, cfm

R = Ratio, for use with equation 4-05

q = Heat transfer rate, Btu $hr^{-1}ft^{-2}$, from air to rock; q' for constant rate

q_1= Heat absorption per foot of length of reservoir, Btu $hr^{-1}ft^{-1}$

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 work surface; T_i for inside air design temperature, T_a for annular space

t = Time, hours

θ = Temperature increase, degrees F; θ_s for rock surface; θ_i for inside air; θ_L for air at distance L from tunnel entrance; θ_w for water in a reservoir

U_o= Heat transmittance, Btu $hr^{-1}ft^{-2}F^{-1}$, for a wall or other heat barrier

U'= Heat transfer coefficient, Btu $hr^{-1}ft^{-2}F^{-1}$, from air in occupied space to surrounding rocks; for no internal structure, $U' = h$

V = Velocity, ft hr^{-1}

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

ρ = Density, lb ft^{-3}; ρ' for water

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, Warmup

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.

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'= FT^2; INTERNAL AREA, A= FT^2; VOLUME = FT^3

REMARKS: ____________________

DIMENSIONS, INTERNAL STRUCTURE (IF USED)

LENGTH = FT; WIDTH = FT; HEIGHT =

FLOOR AREA = FT^2; INTERNAL AREA = FT^2; VOLUME = FT^3

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

	SENSIBLE	LATENT
HEAT GAIN BTU HR^{-1}		
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 ($\theta_1 - \theta_L$) =		

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, $A = 2\ (MN + MS + NS)$ = FT^2

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, $\rho =$; CONDUCTIVITY $K^{**}=$; SP.HEAT, $C=$; TEMP., $T_R=$ F

$\theta_1 = T_1 - T_R =$ F; 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.

$F = Kt/\rho c a^2$ (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

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

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 D

HEAT ABSORPTION BY ROCK SURROUNDING AN UNDERGROUND INSTALLATION; NORMAL OPERATION

PROPERTIES OF ROCK:

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

PROPERTIES OF STRUCTURE:

HEAT TRANS. COEF. AIR TO ROCK, U'= ; RADIUS OF EQUIV.CYL. OR SPHERE, a = FT

MAINTAIN AIR TEMP. , T_1, ABOVE INITIAL TEMP. T_R; $T_1 - T_R = \theta_1$

ROCK SURFACE TEMP., T_S, USE ABOVE INITIAL TEMP., T ; $T_S - T_R = \theta_S$ AT ANY INSTANT.

WITH EQUATION 4–05, SOLVE FOR ROCK HEAT ABSORPTION,

q = BTU $HR^{-1} FT^{-2}$

$N = aU'/K$ = ; R (FIG 4–1 OR 4–2) =

TIME FROM START, HOURS, t	2000	5000	10,000	20,000
$F = Kt/\rho c a^2$				
$\theta_S/\theta_1 = f(F,N)$; EQ. 4–06				
$q = U'\theta_1 (1 - \theta_S/\theta_1)/R$				
HOTAL HEAT ABSORBED = Aq PER HOUR				

FORM E

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

PERMISSIBLE TEMP. RISE OF WATER, θ_W= DEG F IN TIME, t= HOURS FOR

A HEAT ABSORPTION OF q_2= BTU HR^{-1}

PROPERTIES OF ROCK:

THERMAL CONDUCTIVITY, K= ; DENSITY, ρ = ; SP. HEAT, c=

PROPERTIES OF WATER:

DENSITY, ρ' = 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, $\theta K/q_1 = f\,(F,\ G)$

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

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

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

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

q_1 = BTU HR^{-1}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 = FT^2

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

PROPERTIES OF AIR ENTERING TUNNEL FROM OUTSIDE

MEAN ANNUAL TEMP. = INITIAL ROCK TEMP, [illegible] [illegible] TR [illegible] F

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

MAX. VALUE OF θ_0, θ_0' = F

AIR VELOCITY IN TUNNEL [illegible] [illegible] 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 DATE FOR USE IN EQUATIONS ON PAGE 2

w = 0.000717 RADIANS PER HOUR

[illegible] $= h/K\sqrt{\alpha/w}$ =

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

[illegible]$'$ $= hL/Va$ =

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

$B = F_2($[illegible]$, z)$ FIG. 4-9 =

$C'C$ =

$C'B + w$[illegible]$/V$ =

SOLUTION OF EQUATION FOR TUNNEL HEAT TRANSFER

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

$$\theta_L' = \pm\, \theta_O'\, e^{-CC'} =$$

$T_L' = T_R + \theta_L'$ = , ALSO $T_R - \theta_L'$ =

TEMP. θ_L, IN TUNNEL AT POINT L AT TIME t, (EQ. 4-10)

$$\theta_L = \theta_O'\, e^{-CC'} \cos\,(wt - wL/V - C'B)$$

$$= \underline{\qquad\qquad} \cos\,(wt - \qquad\qquad)$$

OUTSIDE AIR TEMP. θ_O (EQ. 4-09)

$$\theta_O = \theta_O' \cos wt$$

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

$$q = 0.0566\, V a^2 (\theta_O - \theta_L)$$

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_O	, F	$\theta_O' =$			$-\theta_O' =$		
TEMP. AT L,*							
TEMP DIFF $(\theta_O - \theta_L)$, F							
HEAT LOSS OR GAIN, BTU/HR^{-1}							

*FOR ACTUAL TEMPERATURES, ALGEBRAICALLY ADD THE MEAN ANNUAL TEMP. T_R TO θ_O OR θ_L.

1-08 Equations

Rock heat absorption - instantaneous

$$q = U' (T_i - T_s) \tag{3-01}$$

Heat transmittances through walls of an inner structure

$$q = U (T_i - T_a) \tag{3-02}$$

Hydrostatic pressure-relation to depth or heat of water

$$P_w = 0.43d \tag{3-03}$$

Area of a rectangular chamber (parallel walls, ends, floor, and ceiling)

$$A = 2 (mn + ms + ns) \tag{4-01}$$

Radius of a cylinder with thermal characteristics similar to those of a rectangular chamber

$$a_1 = A/2 \quad m \tag{4-02}$$

Radius of a sphere with thermal characteristics similar to those of a rectangular chamber

$$a_2 = \quad A/4 \tag{4-03}$$

Heat loss to rock during warmup period (constant heat absorption rate)

$$\theta_s K/q'a = f\ (F) \tag{4-04}$$

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

Utilize fig. 4 - 3 or 4 - 4 to find values of f (F)

Heat loss to rock with constant temperatures maintained in an installation

$$q = U'\ \theta_i (1 - \theta_s/\theta_i)/R \tag{4-05}$$

Determine R from fig. 2-1 (cylinder) or 2-2 (sphere)

For values of θ_s/θ_i in equation 4-05

$$\theta_s/\theta_i = f(F,\ N) \tag{4-06}$$

$$F = Kt/\rho c a^2; \quad N = aU'/K$$

Values of f (F, N) are given on figure 2-5 (cylinder) or 2-6 (sphere)

Heat extracted by water from engine jackets, condensers, etc.

$$Q_W = M (T_W - T_p) \qquad 4\text{-}07$$

Heat absorbing capacity of water-filled reservoir or pipe

$$Q_W K/q_1 = f (F, G) \qquad 4\text{-}08$$

$F = Kt/\rho c a^2$; $G = 2\rho c/\rho' c'$

Values of f (F, G) are given on figure 2-8

Temperature of outside air at time t for assumed steady periodic annual change

$$\theta_o = \theta'_o \cos w\, t \qquad 4\text{-}09$$

Temperature in a tunnel at point L and time t when outside air follows steady periodic change

$$\theta'_L = \pm O'_o\, e^{-C'C} \qquad 4\text{-}11$$

Rate of heat loss or gain by air in a tunnel at time t and up to point L

$$Q = 0.0566\, Va^2 (\theta_o - \theta_L) \qquad 4\text{-}12$$

For heat transfer coefficient (transmittance) from an interior structure, air to air

$$U = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.65}} \qquad 4\text{-}13$$

For heat transfer coefficient from an interior structure to surrounding rock

$$U' = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.25}} \qquad 4\text{-}14$$

1-09 Figures

1-10 Tables

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 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 defense 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 (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).

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 (5-18).

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 75F and 50 percent relative humidity can be assumed in many cases. This condition is within the practicable range attainable with conventional equipment (6-1) 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 system must be adequate to handle the 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 85F 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 some 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 is 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 68 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 on the cooling equipment. It is common experience that many peoples 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 (2-06).

2-05 Air Conditions for Material Preservation

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, office 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 is that gathered under the auspices of the U. S. Navy and reported in Reference 3. The data in Table 2-1 were extracted from that source.

TABLE 2-1

Humidity Tolerance of Some Materials for 30 Month Period

Item	Humidity			Nature of
Damage, Severity	A*	B*	C*	Damage
Mild Steel, polished, unprotected	15	30	65	Rust
Steel (Ball Bearings Rust Preventive applied by Manufacturer)		65	90	Rust
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+		Tarnish
Rubber, Plastic, Rayon		90+		Mildew
Flax, Wool, Cotton, Hair Leather, Sponge, Hemp. Sisal, Paper, Wood		65	90	Mildew
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 indicate 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 tinned 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 75F and 50 percent humidity, recommended for personnel efficiency and feasibility with conventional compressor equipment is satisfactory for storage and use of most materials and equipment. Special low humidity may be required for instrument shops or other space 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 damaging 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.(Ref. 4).

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 60F 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 temperature 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.

2-06 Outside Air Requirements

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

Type of Occupancy	Air Space Per Person, Ft^3	Air Supply CFM
Heating Season, Air not conditioned		
Sedentary Adults of Average Socio-Economic Status	100	25
	200	16
	300	12
	500	7
Laborer	200	23
Sedentary Adults, Heating Season	200	12
Sedentary Adults, Cooling Season	200	4

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 (5-18).

2-07 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 deliberately or because of power failure 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 sedentary person can be expected to consume on the order of 0.85 cubic foot of oxygen and exhale about 0.7 cubic foot 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 CO_2 content is increased from the normal fraction of a percent to more than three percent, serious loss of vitality and ability occurs. Somewhat worse conditions result in death by suffocation. The data given on figures 2-1 and 2-2 based on sedentary occupancy show that considerable 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 emergencies the sorbents 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 revificication 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 rise in DB above normal heat will flow into the rock temporarily and the dew point 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.

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

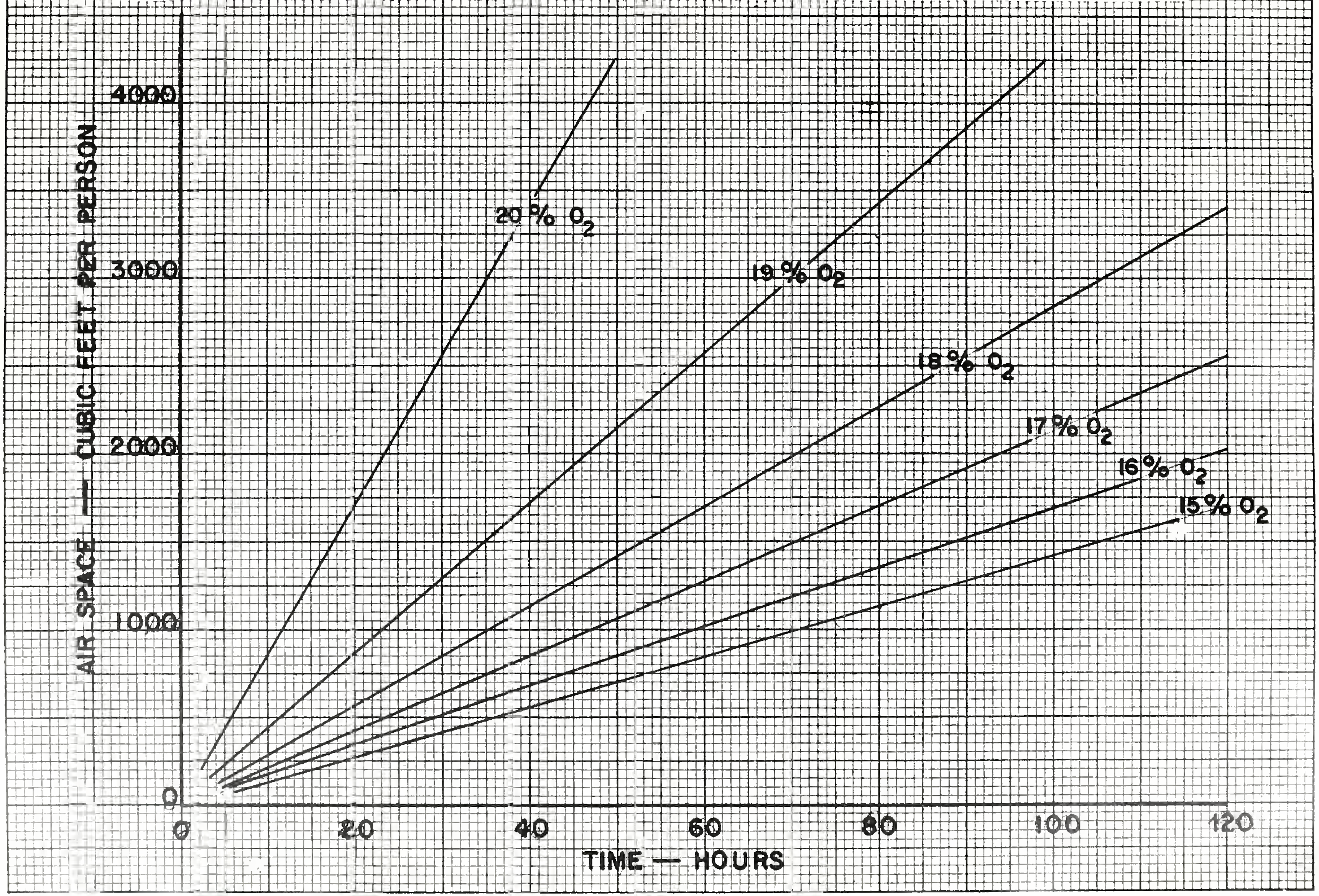
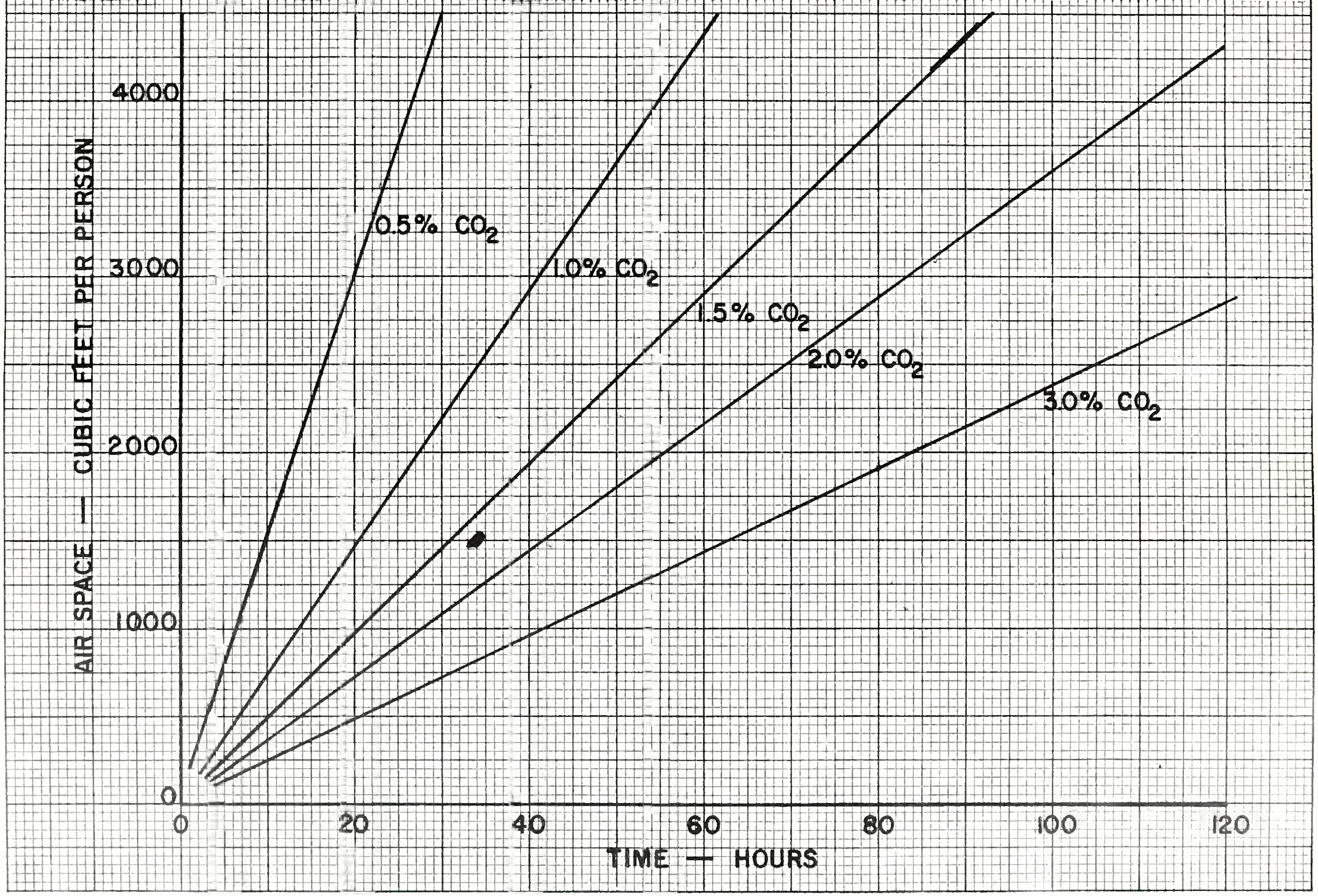
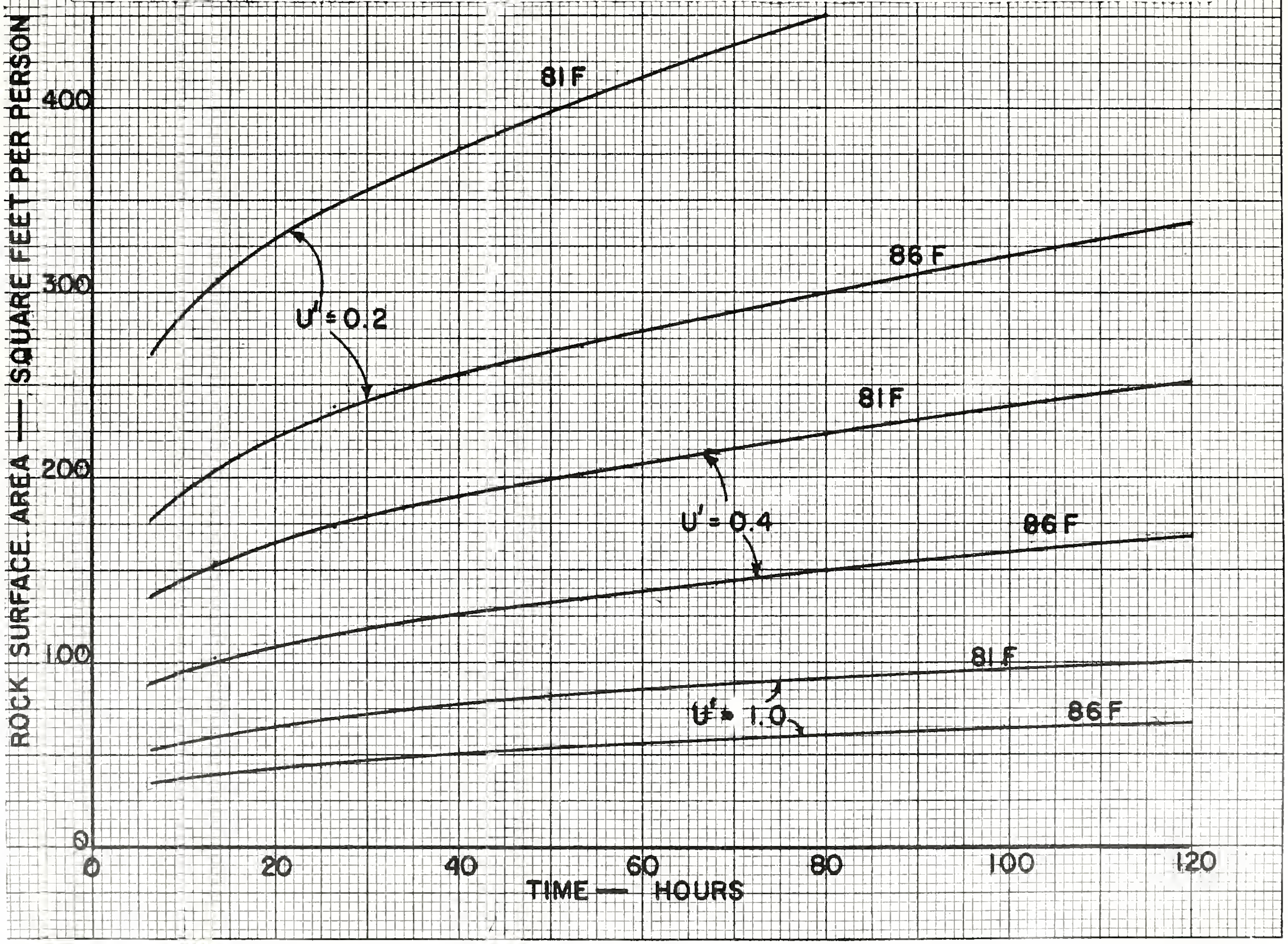


FIG. 2-2 CARBON DIOXIDE CONCENTRATION IN UNVENTILATED OCCUPIED SPACES.



24N 7-2

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



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 90F 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. If personnel are expected to undertake some necessary tasks under a disaster condition, some means of reducing the humidity is essential. 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.

Table 2-3. Properties of Chemicals for Air Revivification

Chemical	CO_2 Absorbed	O_2 Liberated	Chemical Required, lbs. per man-hr.	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	0.288	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	94 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 2-3 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 0.83 cubic foot per man-hour.

2-08 Combustion Air and Cooling Water Requirements, Engines and Boilers

Power generating and heating equipment may be installed underground for the purpose: (1) to obtain more economical services, (2) to generate electricity in case of commercial power outage, and (3) to make the underground installation self-sustaining under the operating conditions of (1-05). Fuel-burning equipment most readily meets these purposes. Because of the limited space usually available for power plants steam boiler plants for power generation are not considered because of the high combustion air requirements. This leaves the gasoline and diesel power generating equipment. Gasoline equipment is a producer of carbon monoxide gas and should be used with due precaution to leaks in the exhaust systems. Steam and hot water boilers may be used to satisfy heating loads and domestic hot water supply.

Table 2-4 gives the specific fuel consumption, combustion air and cooling water requirements. While it is realized this equipment may operate under all types of load, the values given in Table 2-4 are deemed suitable for design purposes.

TABLE 2-4

Power Generating Equipment

	Diesel	Gasoline
Specific fuel consumption, lb/KW-hr	0.6	0.81
Combustion air, cfm/KW	2.4	2.3
Cooling water, gpm/KW	0.54	0.54

For heating apparatus, the fuel consumption is approximately 10 gallons and the air supply is 15,000 cubic feet for every million Btu's of heat load.

The air for combustion does not have to be directly supplied from the outside, but may be taken from air exhausted from other facilities, such as toilet and kitchen exhaust or that exhausted due to replenishment by outside air for personnel.

2-09 Kitchens and Lavatories

Because natural ventilation is not practical for enclosed structures or facilities of the underground installation such as kitchens, dining areas, and lavatories, mechanical ventilation is a necessity. Air quantities necessary for proper ventilation of these facilities have been cited in different ways by those interested in this subject. Agreement by all parties is that there should be no recirculation of air supplied to kitchens, lavatories, toilet rooms, bathrooms and rest rooms (Ref. 20).

For kitchens handling foods at least eight outside air changes per hour should be provided. From another source the quantity of air exhausted from a kitchen shall be not less than four cfm for each square foot of floor area. The quantities exhausted through hoods over ranges, etc. shall be sufficient to maintain a velocity of 60 to 75 fpm through the projected area (Ref. 21).

For lavatories, toilet rooms, bathrooms and rest rooms at least four air changes per hour shall be provided. From another source, exhaust air quantities for mechanically ventilated toilets shall be 50 cfm for each water closet or urinal or 2 cfm for each square foot of floor area, whichever is greater. The air for this purpose may consist wholly or in part of air supplied to offices and work rooms and exhausted via corridors.

2-10 Climate

The underground installation is not exposed to the severity of sun, wind and extremes of weather like a building on the surface. The pertinent climatic characteristics for the underground installation are the initial temperature of the surrounding rock mass (4-07) and the temperature variations in the outdoor supply air (4-05). Although the precipitation for a given locale may have some effect on the amount of seepage water to be encountered underground, the porosity of rock and occurrence and amount of fissures in the rock would make the amount of seepage quite unpredictable.

The initial temperature of the surrounding rock mass is discussed in Section 4-07. Figure 2-4 (Ref. 22) shows the approximate temperature of water from wells in the United States at depths from 30 to 60 feet below the surface. At greater depths the temperature increases approximately 1F per hundred feet. Figure 2-4 is also useful for the determination of the mean annual temperature of the outside air supply to an installation. The mean annual temperature is closely approximated by subtracting 2F from the values given in Figure 2-4.

Figure 2-5 (Ref. 23) gives the mean annual range of temperature which is defined as the difference between the mean temperature of the warmest and coldest month. The mean temperature variation for a given locale may be determined from Figures 2-4 and 2-5. For example, a given locality has a mean annual temperature of 52F and a mean annual range of temperature of 46F, the extreme mean temperatures are then $52 + 46/2 = 75F$, and $52 - 46/2 = 29F$. For section 4-05, the temperature amplitude θ_o, is determined by dividing the mean annual range of temperature by two. For the above example $\theta_o = 23F$.

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, to, and final chamber temperature, T_i. 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 standby condition.

(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 room 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 2 from item 3 to obtain the heating load during the standby condition. If this sensible heat load exceeds item 3, cooling is indicated during the standby 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 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 spaces 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 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

$$q' = U' (T_i - T_s) \qquad 3\text{-}01$$

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

T_s = temperature of the rock surface, F, average

Equation (3-01) is often inadequate because the rock surface temperature, T_s, is unknown. The rock around a warmed spaced receives heat and T_s 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_s, Equation 4-05 is recommended for computing rock heat absorption.

When the internal load (3-06) exceeds the rock heat absorption the difference must be removed by some air conditioning means.

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' (4-08).

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

$$q = U\ (T_i - T_a) \qquad (3\text{-}02)$$

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 inside and outside the structure

T_i = air temperature, inside the structure, F

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

Values of U (4-08) 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_a, 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 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

$$1 \text{ Horsepower} = 2546 \text{ Btu per hour} = .746 \text{ KW}$$

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.

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	Sitting or Moving Slowly			Light Working		
Temp.	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				510	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.

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 evaporates 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, except for small structures in large chambers (5-10). 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 underground 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 the water head is at times as deep as the overburden, the possible pressure is represented by the equation

$$P_W = 0.43\ d \qquad (3\text{-}03)$$

P_W = hydrostatic pressure, psi

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 materials 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.

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 consideration as those for a bare chamber.

3-09 Dehumidification, Inner Structure

If the walls, ceiling, and floor of an inner structure are vaporproof, 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. 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.

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.

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 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.

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 are too complex for everyday 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 warmup time are specified, the required heat supply rate can be computed by means of Item 6 under Procedure (4-02).

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

6. For a given warmup 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).

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.

$$A = 2\,(mn + ms + ns) \qquad (4\text{-}01)$$

A = wall, ceiling and floor area, ft^2

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:

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

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

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

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

$$\frac{\theta_s K}{q'a} = f\ (F) \qquad (4\text{-}04)$$

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

K = Thermal conductivity of rock, Btu $hr^{-1}ft^{-1}$

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

a = Radius, ft; s_1, for the cylinder; a_2 for the sphere; selected for the approximation from Equation 4-02 or 4-03

F = $Kt/\rho ca^2$; F_1, cylinder; F_2, sphere

t = Time permitted for warmup period, hrs

p = Density of rock surrounding the space, lb ft^{-3}

c = Specific heat of the rock, Btu $lb^{-1}F^{-1}$

To utilize Equation 4-04 first compute the value of F, then determine the value of $\theta_a K/q'a$ from Figure 4-03 for the cylinder or Figure 4-4 for the sphere. From the value of $\theta_a K/q'a$ thus established, 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)

$$q = (1-\theta_s/\theta_i)\ U'\theta_i/R \qquad (4\text{-}05)$$

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

$$\frac{\theta_s}{\theta_i} = f\ (F,\ N) \qquad (4\text{-}06)$$

Values of θ_s/θ_i 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.

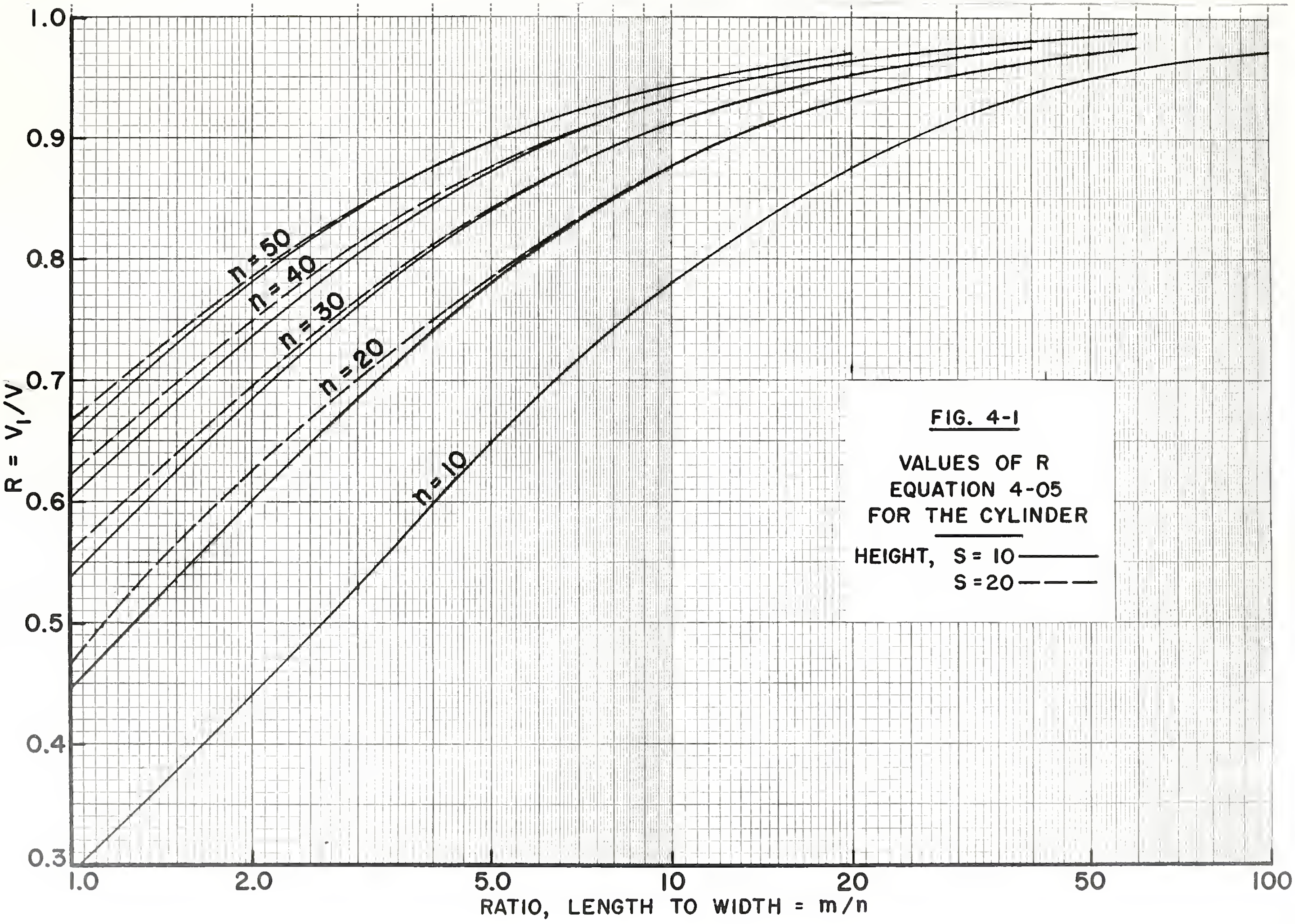


FIG. 4-1

VALUES OF R
EQUATION 4-05
FOR THE CYLINDER

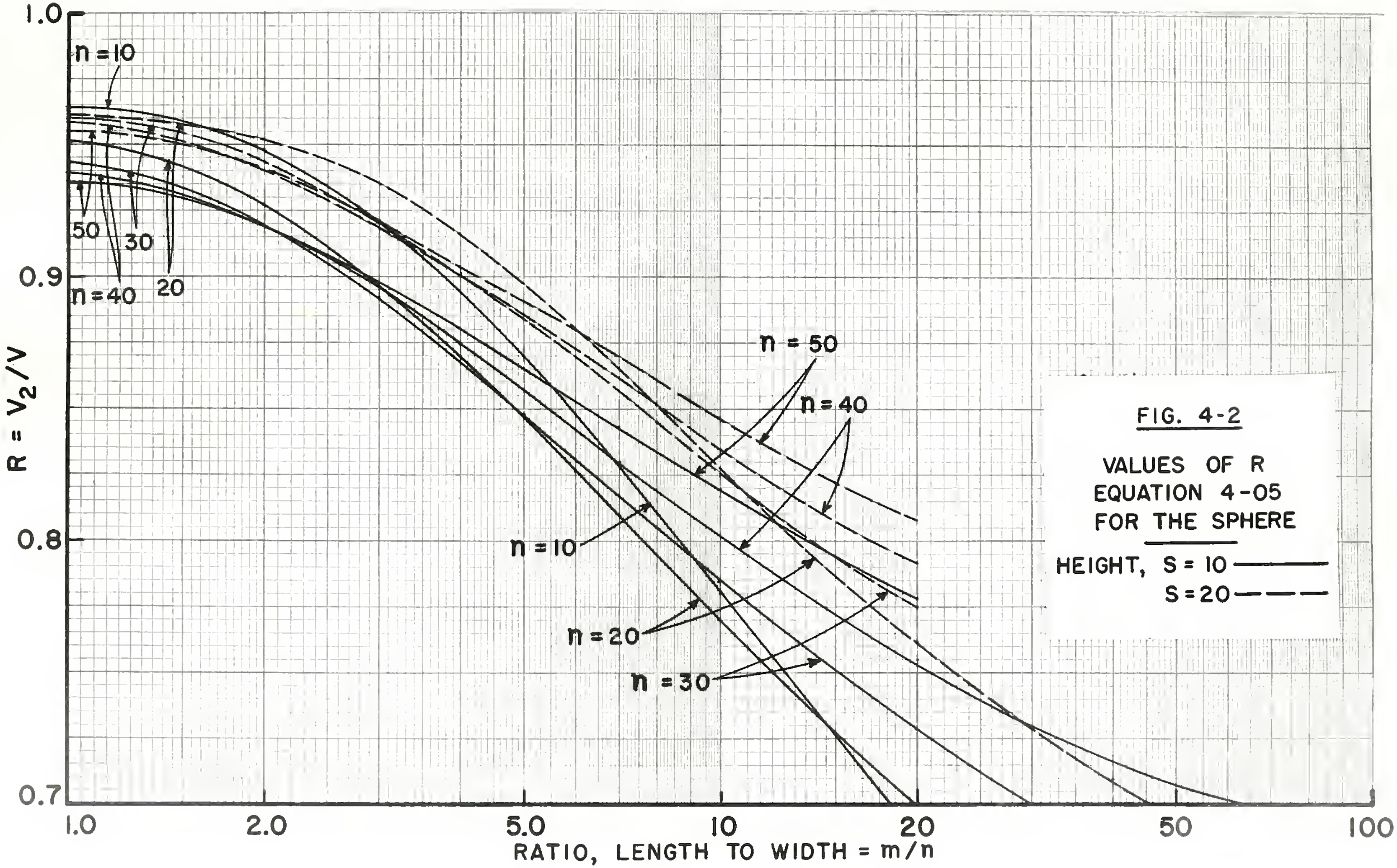


FIG. 4-2

VALUES OF R
EQUATION 4-05
FOR THE SPHERE

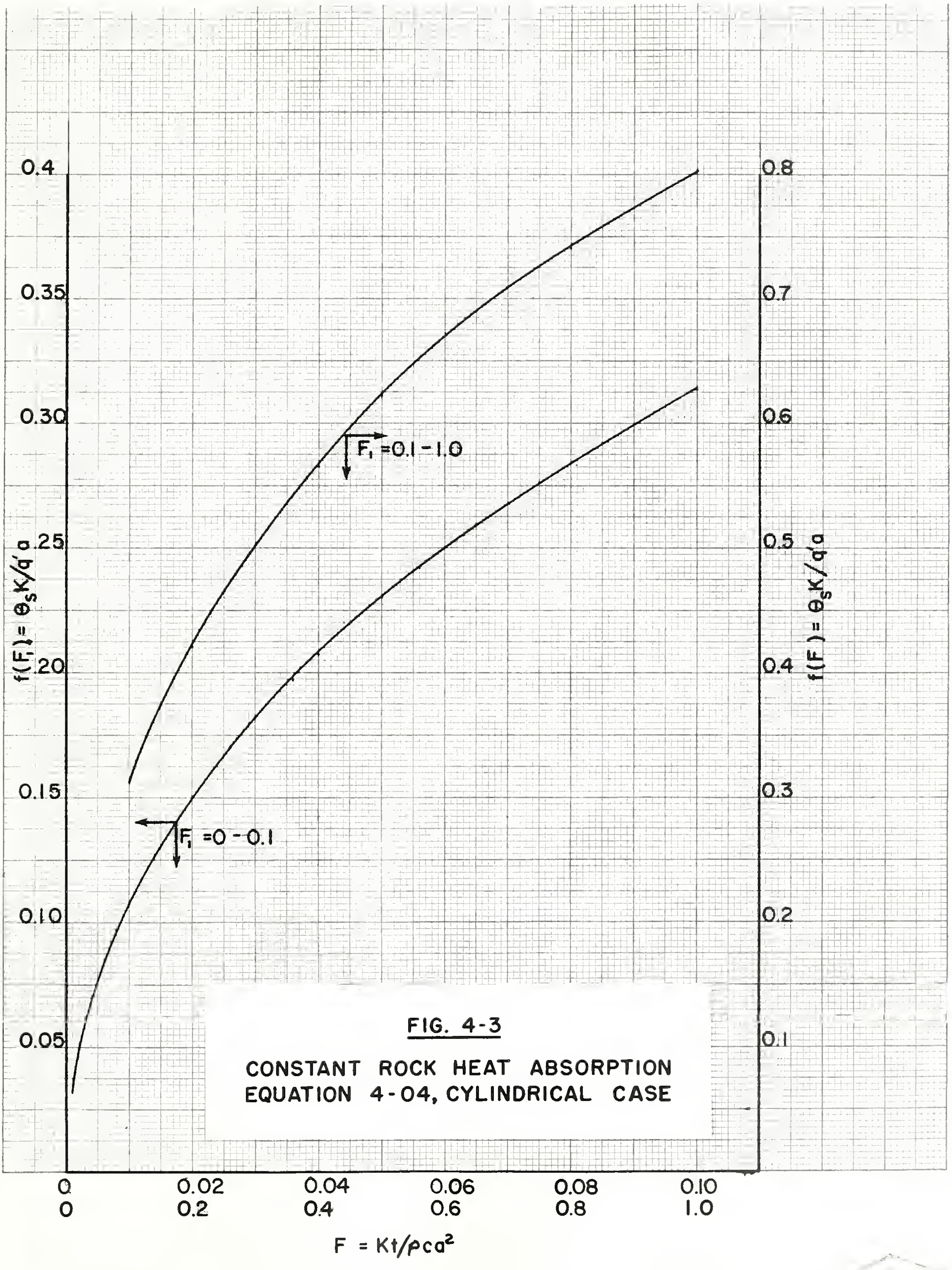


FIG. 4-3

CONSTANT ROCK HEAT ABSORPTION
EQUATION 4-04, CYLINDRICAL CASE

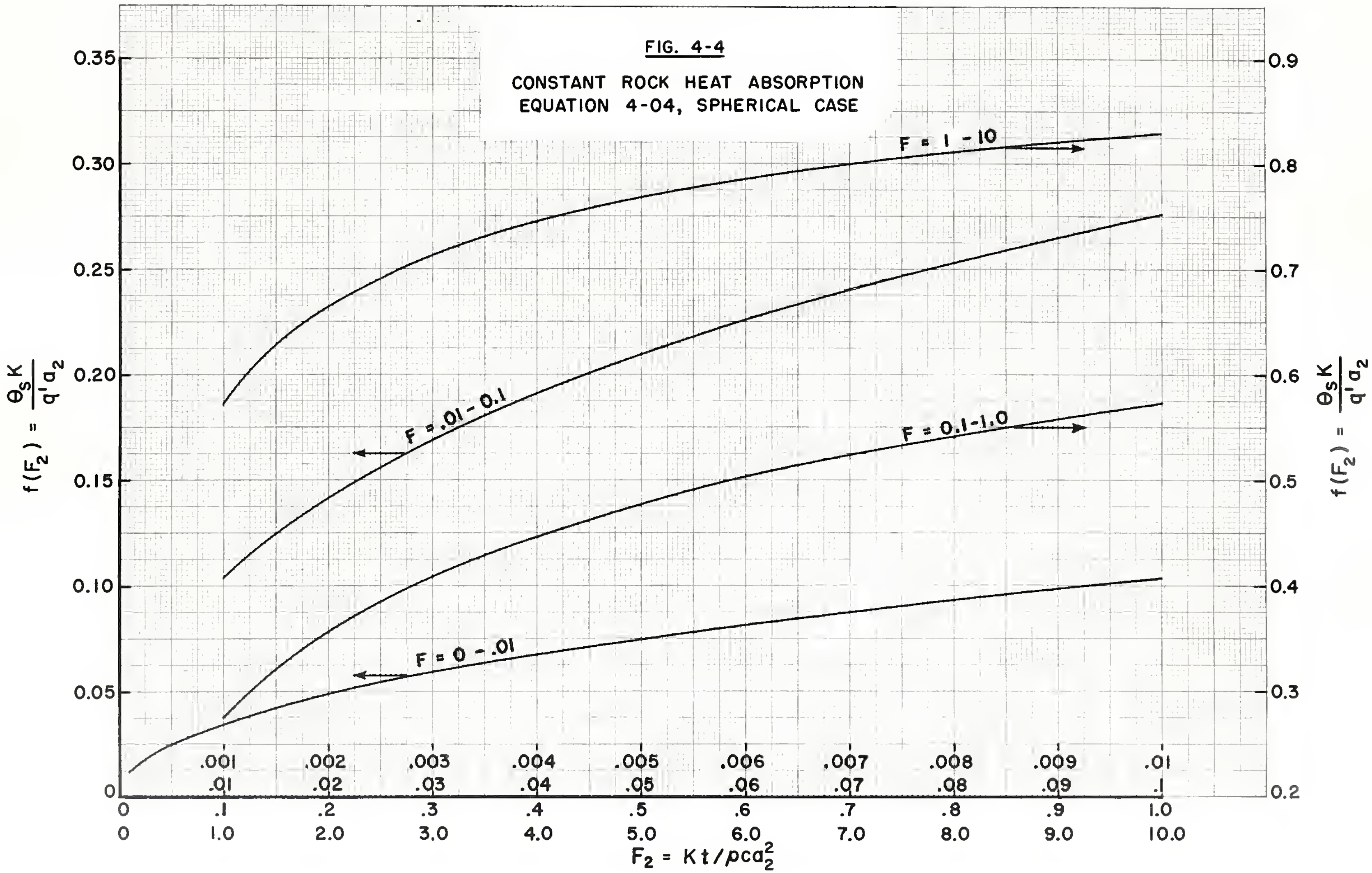


FIG. 4-4

CONSTANT ROCK HEAT ABSORPTION
EQUATION 4-04, SPHERICAL CASE

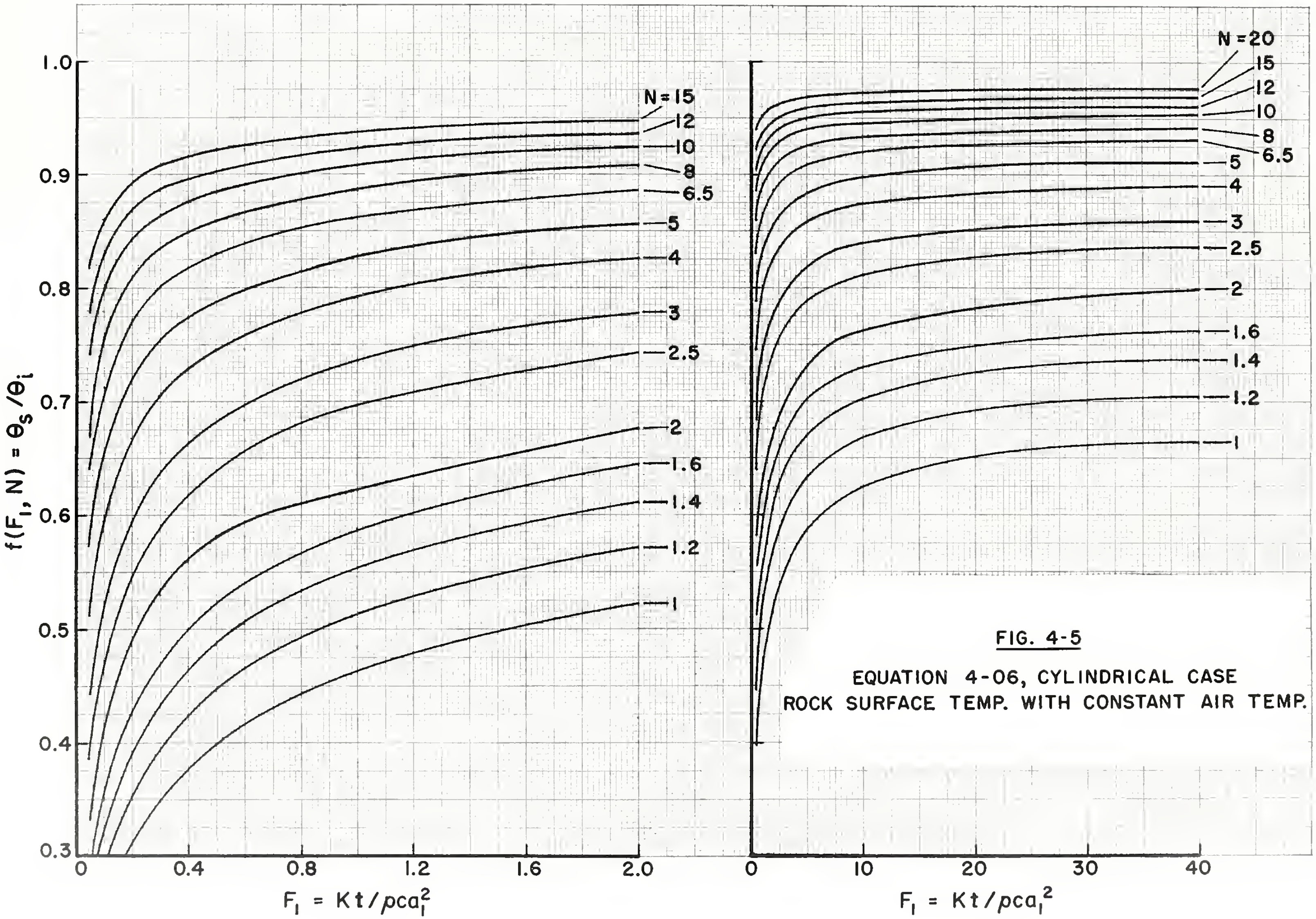


FIG. 4-5

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

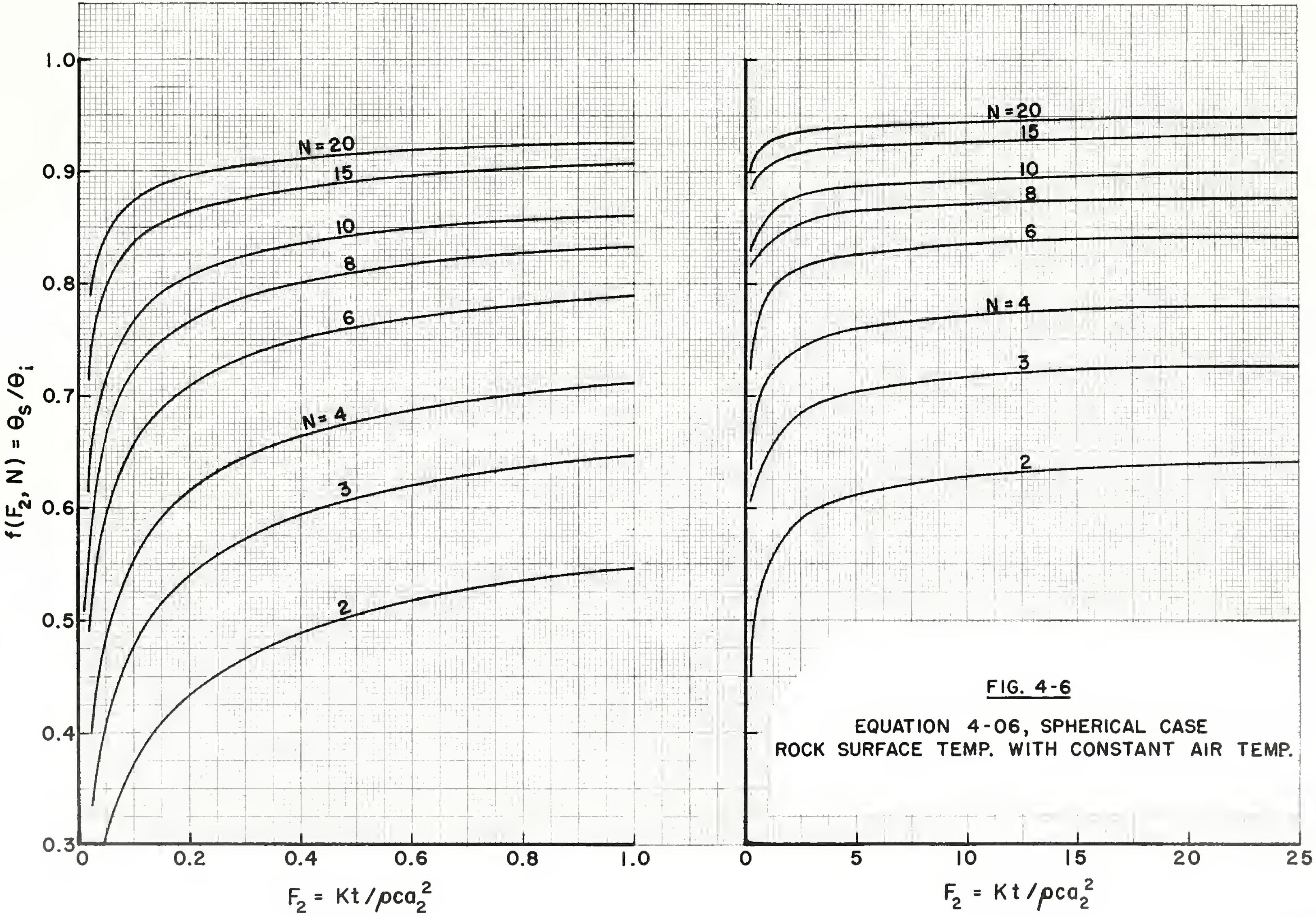


FIG. 4-6

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

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:

$$Q_W = M\ (T_W - T_P) \qquad (4\text{-}07)$$

Q_W = Heat absorbing capacity of the water, Btu

M = Mass of water in the reservoir, lbs

T_W = Temperature; water discharged for 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:

$$\frac{\theta_W K}{q_1} = f\ (F,\ G) \qquad (4\text{-}08)$$

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 condensers, Btu hr^{-1} per foot length of reservoir

F = $Kt/\rho ca^2$

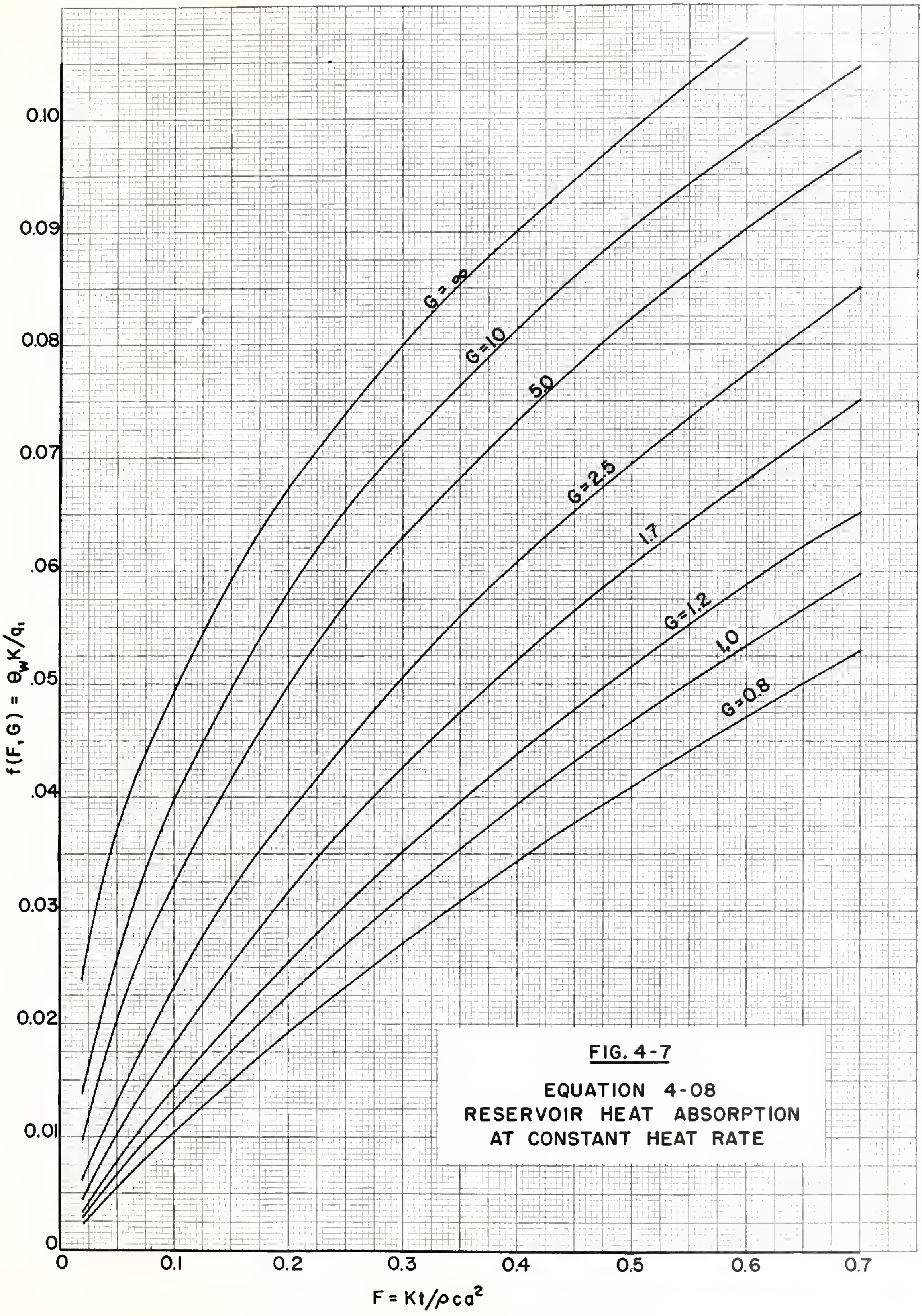


FIG. 4-7

EQUATION 4-08
RESERVOIR HEAT ABSORPTION
AT CONSTANT HEAT RATE

24 IV 73

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

$$G = \frac{2\pi a^2 \rho c}{M'c'}$$

$= 2\rho c/\rho' c'$ (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 $lb^{-1}F^{-1}$

c' = Specific heat of water, Btu $lb^{-1}F^{-1}$

m = Length of reservoir, ft

Equation 4-08 is plotted in Figure 4-7 and Form E is suggested as a work sheet 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.

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

$$\theta_o = \theta_o' \cos wt \qquad (4\text{-}09)$$

θ_o = Outside air temperature minus mean annual 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 ($t = o$ when $\theta_o = \theta_o'$)

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,

$$\theta_L = \theta_o' e^{-C'C} \cos (wt - WL/V - C'B) \qquad (4\text{-}10)$$

Maximum and minimum air temperatures at point L: summer and winter design temperatures

$$\theta_L' = \pm \theta_o' e^{-C'C} \qquad (4\text{-}11)$$

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

$$q = 0.0566\ Va^2 (\theta_o - \theta_L) \qquad (4\text{-}12)$$

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

$$Q = 157.7\ Va^2\theta_o' \sqrt{1+e^{-C'C}-2e^{-C'C}\cos (wL/V + C'B)} \qquad (4\text{-}13)$$

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

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

$$B = f_2 (z, b) \qquad (4\text{-}9)$$

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

$C = f_1 (z, b)$ (Figure 4-8)

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

e = Base of natural logarithms

h = Coefficient of heat transfer between the moving air and the surface of airway, Btu $hr^{-1}ft^{-2}F^{-1}$

K = Thermal conductivity of rock, Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$

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}

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

α = Thermal diffusivity ft^2hr^{-1}

θ = Departure of temperature from the mean annual temperature, F; θ', maximum departure or amplitude; θ_o, outside air; θ_L, at distance L in airway

B, C, and Equations 4-12 and 4-13 are based on the assumption that the density and specific heat of air are 0.075 lb ft^{-3} and 0.018 Btu $ft^{-3}F^{-1}$, 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.

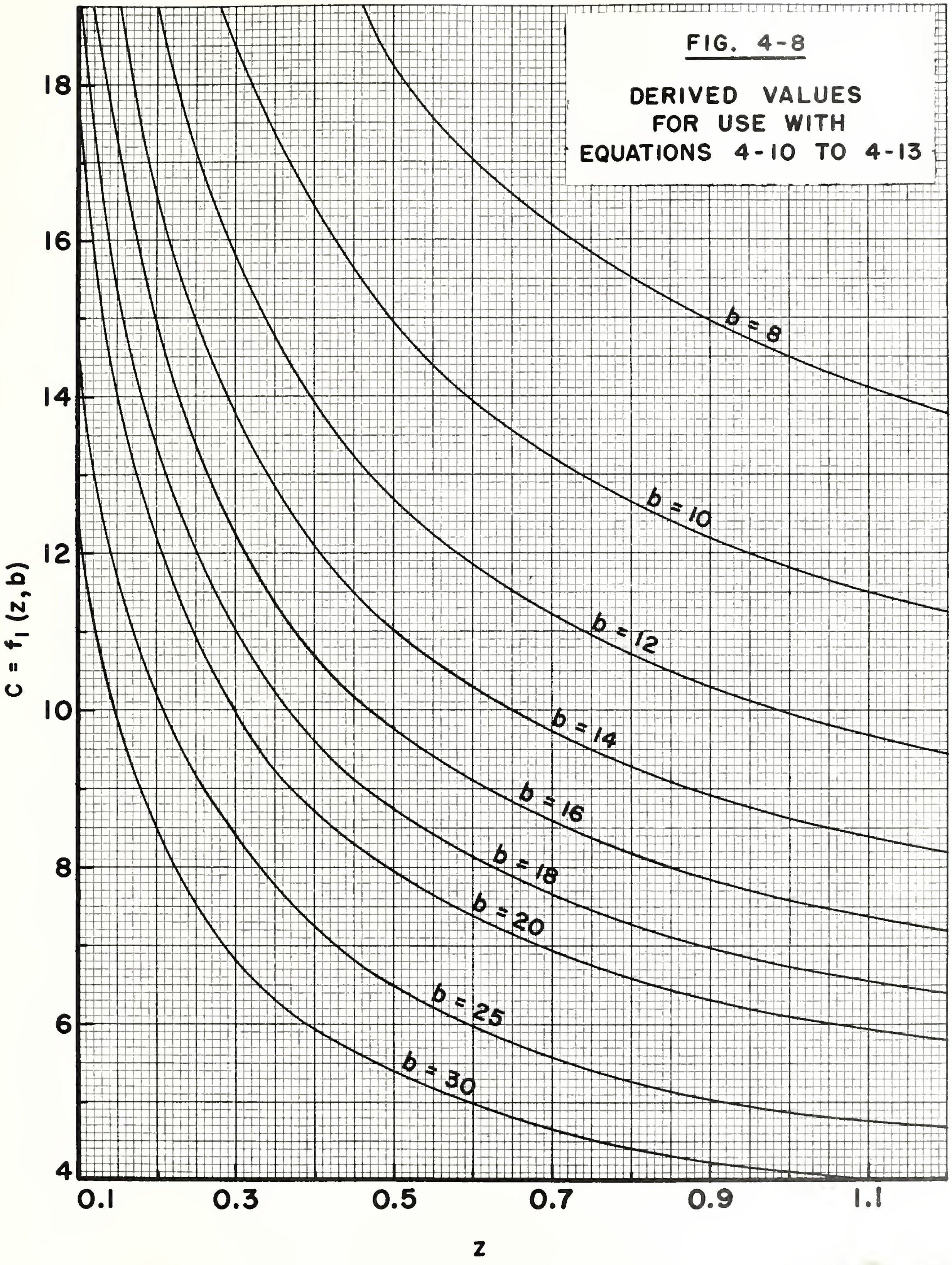


FIG. 4-8

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

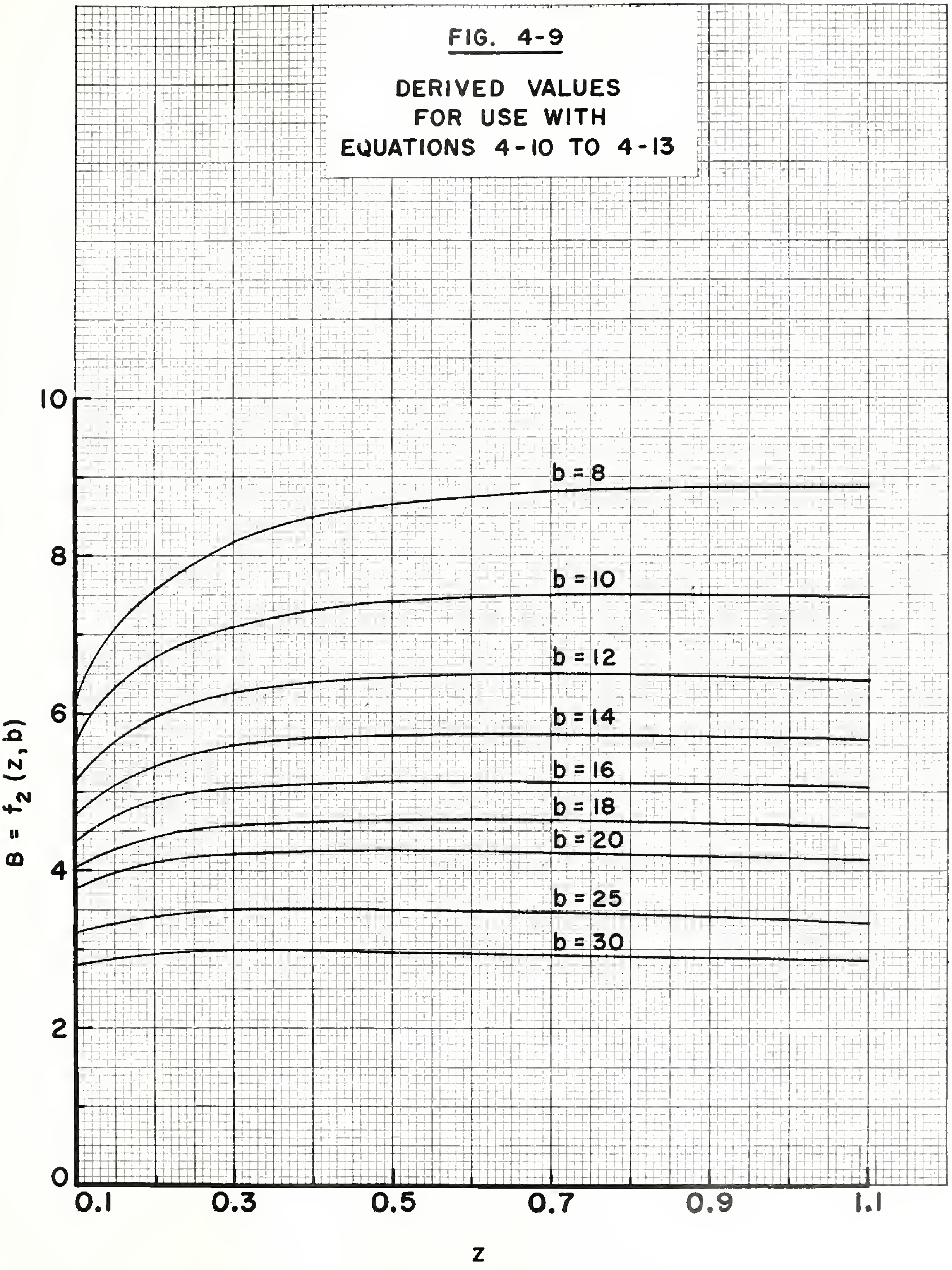
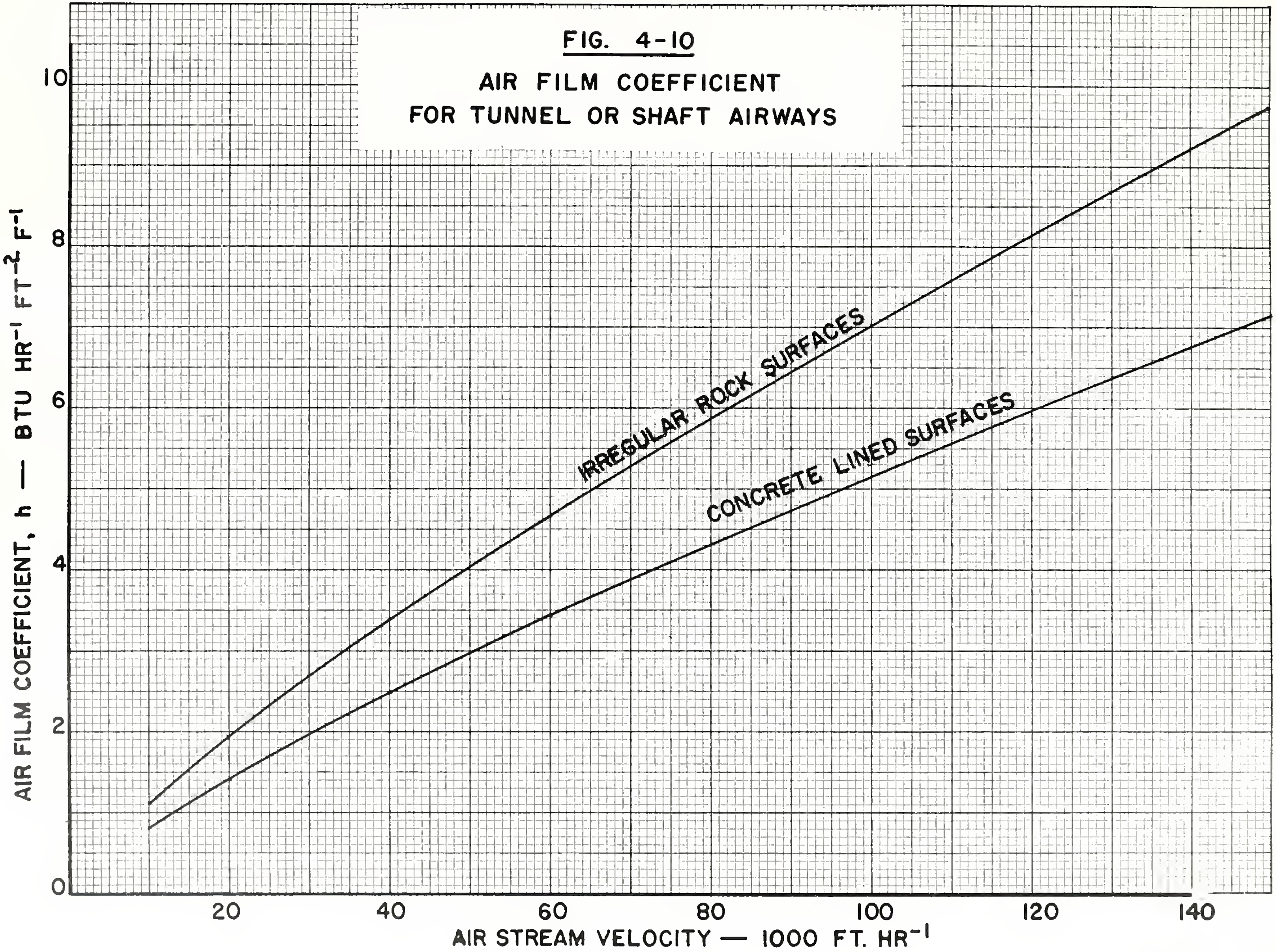


FIG. 4-9

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

FIG. 4-10

AIR FILM COEFFICIENT
FOR TUNNEL OR SHAFT AIRWAYS



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 Btu $lb^{-1}F^{-1}$ be assumed for any rock and for use in the equations in this chapter although rock specific heats as low as 0.16 Btu $lb^{-1}F^{-1}$ have been reported.

For greenstone, present in the mountains of Virginia, tests and experience show a thermal conductivity of about 1.5 Btu $hr^{-1}ft^{-2}(F/ft)^{-1}$, 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 Btu $hr^{-1}ft^{-2}$ $(F/ft)^{-1}$. 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.

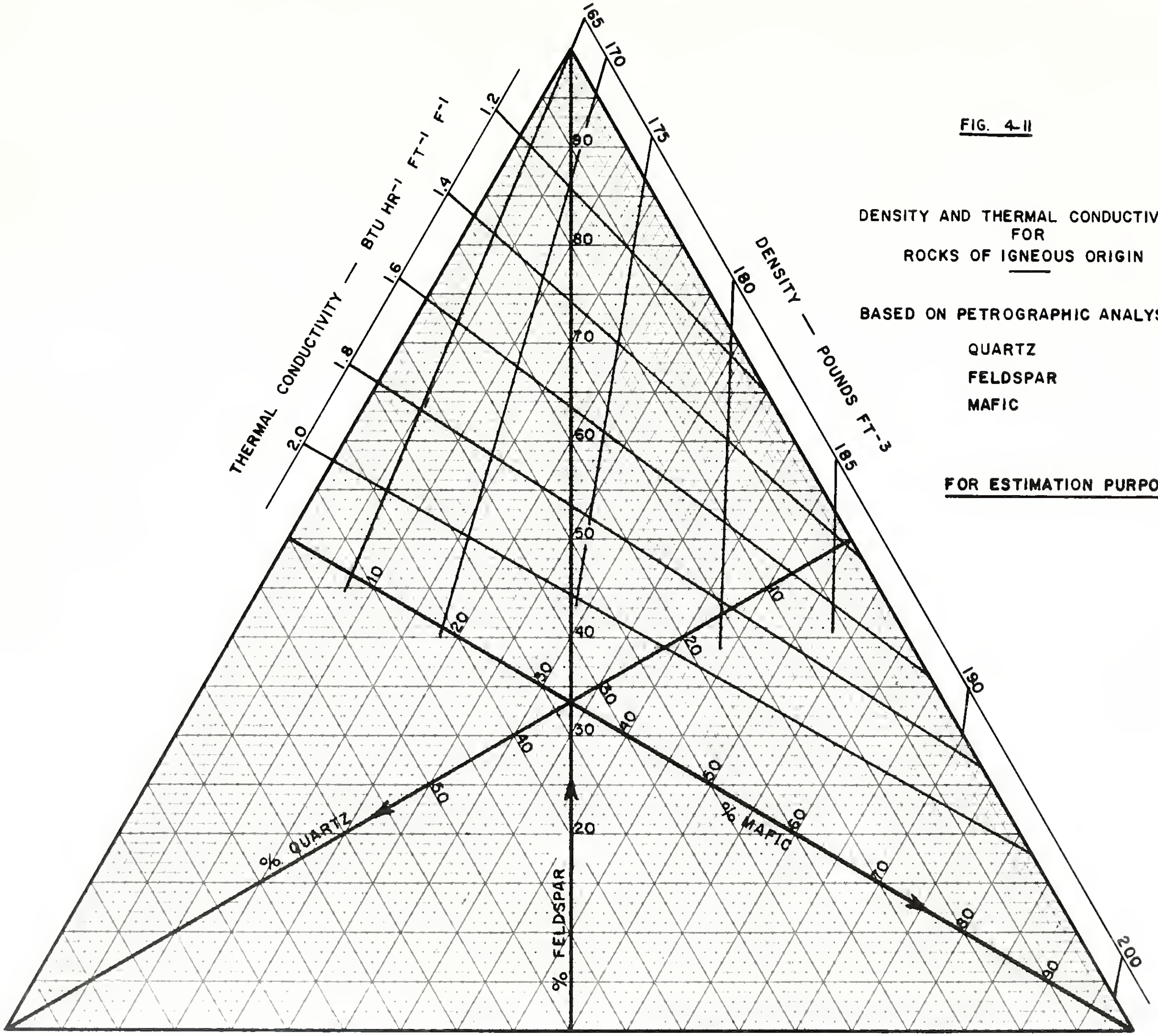


FIG. 4-11

DENSITY AND THERMAL CONDUCTIVITY
FOR
ROCKS OF IGNEOUS ORIGIN

BASED ON PETROGRAPHIC ANALYSIS:

QUARTZ
FELDSPAR
MAFIC

FOR ESTIMATION PURPOSES ONLY

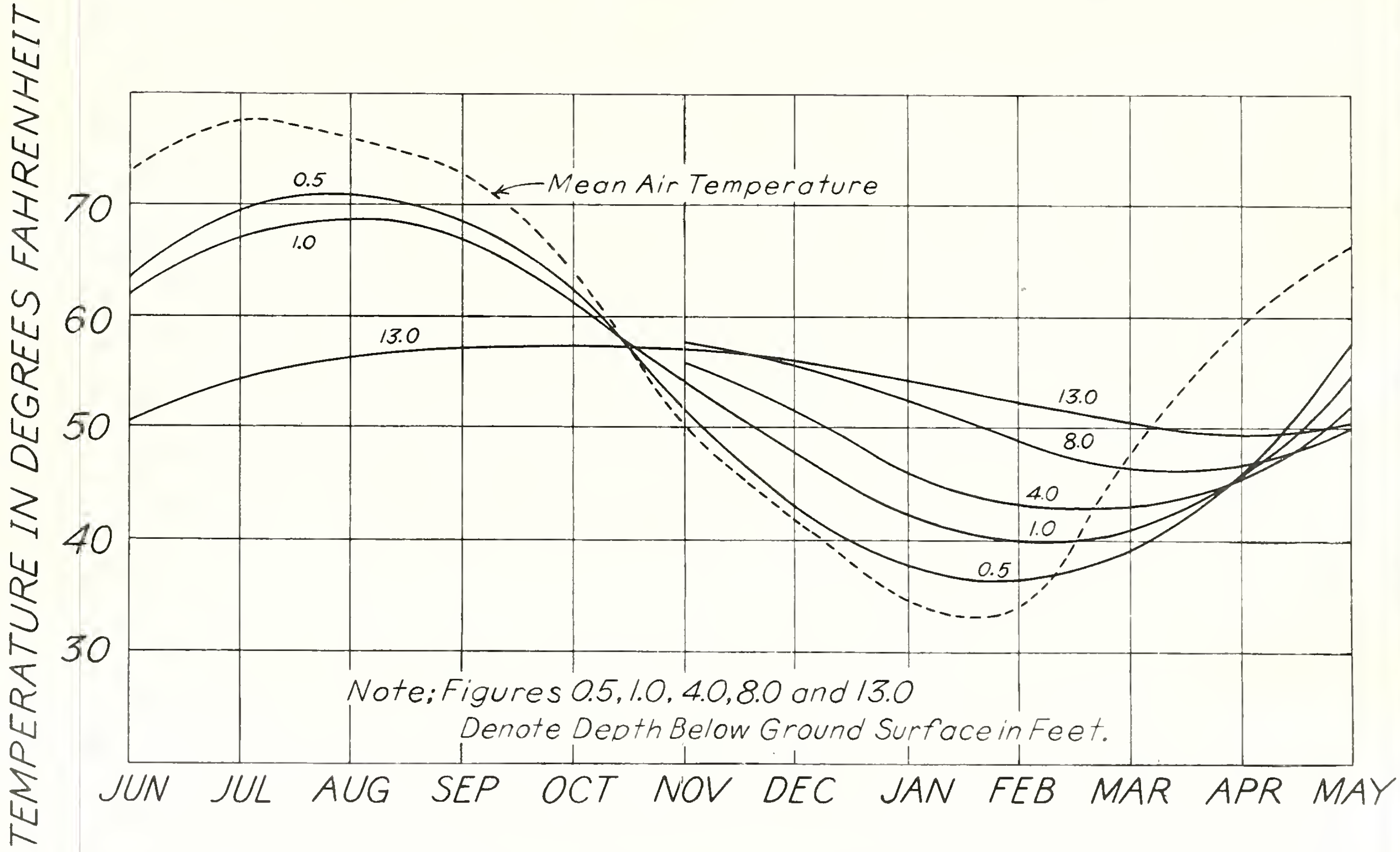

TEMPERATURE IN DEGREES FAHRENHEIT
70
60
50
40
30
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
Mean Air Temperature
0.5
1.0
13.0
13.0
8.0
4.0
1.0
0.5
Note; Figures 0.5, 1.0, 4.0, 8.0 and 13.0
Denote Depth Below Ground Surface in Feet.

FIG. 4-12

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 Washington, D. C. and the results are shown on Figure 4-12 (Ref. 16). The curves indicate an annual amplitude of about 4F and a mean temperature of about 53F at a depth of 13 feet.

4-08 Thermal Properties of Materials and Structures

Thermal conductances and other properties of materials or structures listed in texts or handbooks including the "Guide" (Ref. 1) are applicable in connection with underground structures, with one notable exception. Values of U as commonly listed for walls or other exposed members are based on an assumed wind of 15 mph velocity on the outside. An interior structure in an underground chamber is not exposed to such a wind although there may be motion or turbulence due to fans, etc. For estimating, it is recommended that the outside surface coefficients of exposed ceilings, walls, and floors in interior structures be considered to have the same values as those ordinarily used for inside surface coefficients.

The coefficient U', appearing in equations 3-01, 4-05 etc., represents the heat flow in Btu per hour for each square foot of rock surface for each degree of difference between the temperature of the surrounding rock and the temperature in the conditioned space. For an interior structure, one significant temperature is that within the space and the other, that of the surrounding rock surface.

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 Btu $hr^{-1}ft^{-2}F^{-1}$ 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 $f_o = f_i = 1.65$ is recommendeded 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:

$$U_o = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.65}} \tag{4-14}$$

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

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

TABLE 4-1

Heat Transfer Coefficients for Underground Structures

Material or Structure	U_o	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 board	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 board	0.25	0.24

U_o = 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.

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 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 a 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 meterial 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 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	(b) -	1.04	.962
Plasterboard, between heavy sheets of paper	(a) 0.37	70.20	.014

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

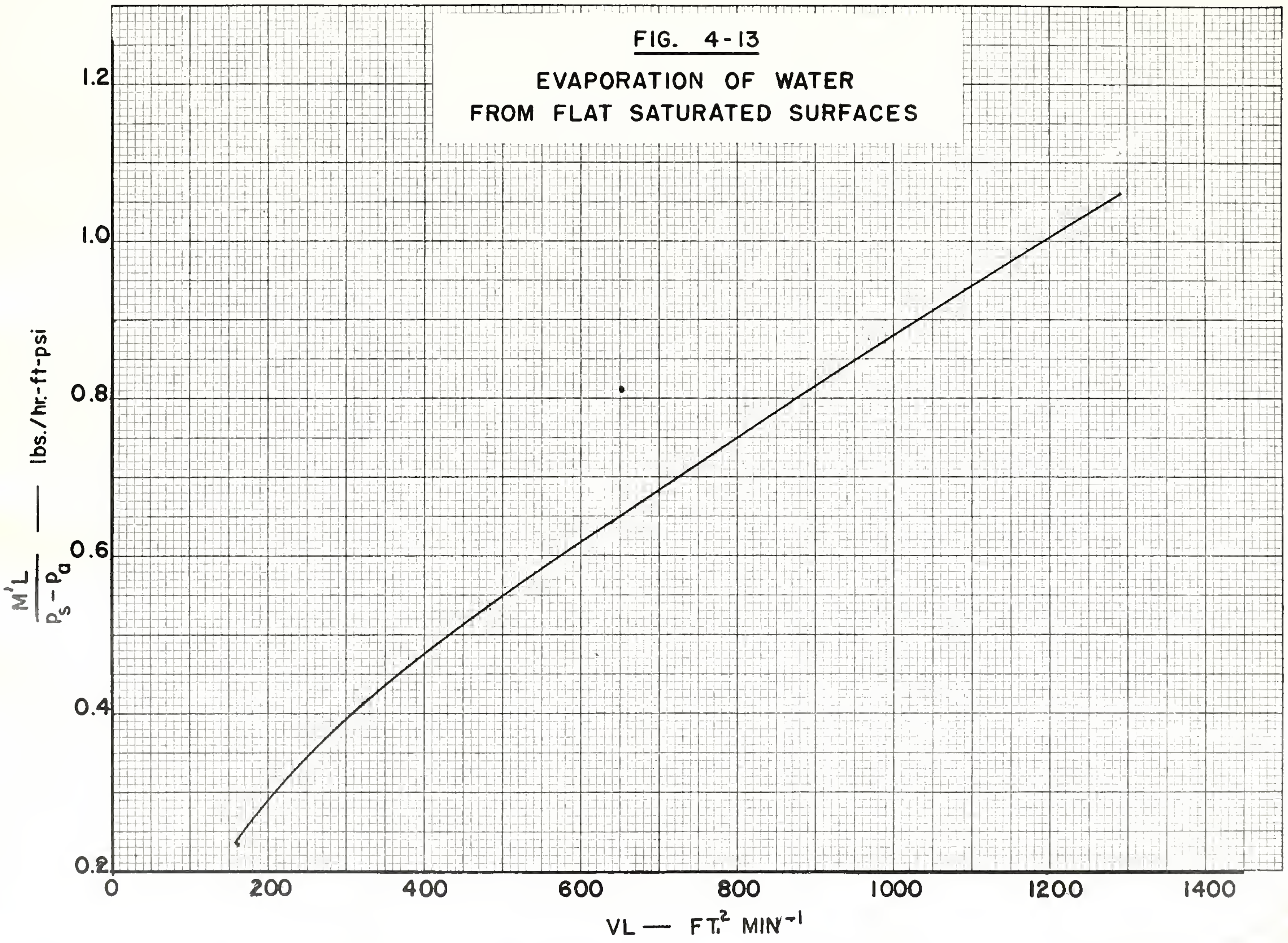


FIG. 4-13

EVAPORATION OF WATER FROM FLAT SATURATED SURFACES

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 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 effects 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 dew point 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 lb $hr^{-1}ft^{-2}$ 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 (Ps-Pa) psi, where Ps is the vapor pressure of water at the temperature of the wet surface, and Pa 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 installations so far examined in the eastern United States the wet area did not 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 can readily exceed the effect of permeability of materials or diffusion, and convection cannot be predicted since it depends on quality of workmanship.

CHAPTER 5

Air Conditioning Processes and Systems

5-01 Sizes and Shapes of Underground Chambers

Underground chambers intended for protective purposes may be from one hundred to several hundred feet below the surface. Sizes vary in accord with requirements but, in usual cases, such chambers are typically in the form of long, narrow tunnels. The width is not likely to be less than 8 to 10 feet nor the ceiling height less than 10 or 12 feet because smaller openings do not permit use of conventional excavating machinery. Cost of excavation in dollars per cubic yard is less when the opening permits use of power shovels and trucks for handling the spoil. Widths are not likely to exceed 30 or 40 feet, depending on the strength of the rock. In height, the space may be single or multistory. Lengths are limited only by such factors as pipe or duct runs, accessibility, etc. Lengths of 200 feet or more, are sometimes used.

Chambers at lesser depths, not designed to resist atomic bomb attack, may be round or irregular in shape with pillars left during excavation to support the roof.

Large chambers may be subdivided into rooms to improve acoustical conditions, for privacy as in offices, or to isolate areas for other purposes.

5-02 Access Tunnels and Shafts

The simplest kind of underground installation may consist of a single chamber and have a single shaft or tunnel for both access and ventilation. A tunnel is usually preferred because, with a slight slope, it can serve also for natural drainage and because it is more convenient for access, particularly for equipment or material. Larger installations or those designed for human occupancy usually have at least a tunnel plus a shaft and may have a multiplicity of either to provide adequate services, access and ventilation. Forced ventilation is essential for most occupied installations.

Either a tunnel or shaft used as an air intake has an appreciable air conditioning effect, serving to warm and sometimes to humidify air in winter and to cool and dehumidify it in summer (4-05). This effect can be

deducted from the total required heating or cooling capacity from the occupied spaces.

5-03 Simple Installation, Single Shaft

An installation consisting of a chamber below ground with a single shaft to the surface, may seldom be recommended on account of the inconvenience of access and the difficulty of ventilation and drainage. This action of natural ventilation in such installations is considered here for completeness. Under this condition, natural ventilation will be slight, as it is in a deep well. In the absence of gas from the earth, it may be possible for a few men to work in such a chamber for short periods, but precautions are essential and forced ventilation should be provided for any lengthy occupancy. If undisturbed, the chamber will remain near the rock temperature and the humidity near saturation. In winter, the enclosed air may be warmer than that above ground and thus have a tendency to rise. Ventilation by chimney action, however, is practically inhibited by the interference of the air rising through the shaft with that which must enter through the same opening to replace it. In summer, the enclosed air will usually be cooler than that above ground. There will therefore be no ventilation by chimney action and the air in the chamber will stagnate.

5-04 Simple Installation; Two or More Shafts

An installation of this kind is self-ventilating in winter but is not ventilated by chimney effect in summer. In winter or when the air in the chamber is warmer than the atmosphere outside, chimney action, once started by wind or a difference in height of two shafts, will cause a continuous air change with air flowing down one shaft and up another. Under this condition the chamber is self-drying. Outside air, if warmed by passing through a shaft and chamber, can absorb water as vapor and conduct it to the outside.

In summer, or when the chamber is cooler than the atmosphere outside, the air stratifies or stagnates in the chamber and the humidity approaches saturation if water is present. Ventilation is limited to that due to wind effects or to the minor amount caused by changes in barometric pressure.

5-05 Simple Installation, Single Tunnel

An installation consisting of a chamber with a single tunnel for access and drainage may be useful in some cases for the storage of munitions or other material requiring infrequent attention. In a bare chamber, the air approaches the temperature of the surrounding rock and the humidity approaches 100 percent if water is present. However, if an enclosure or inner structure is provided and is warmed either electrically or otherwise, its interior assumes a relative humidity less than 100 percent. (5-10)

Temperature differences between the chamber and the outside will exist during summer and winter but no considerable natural ventilation can be relied upon through a single tunnel. For any occupancy other than occasional entrance such as to place or remove stored goods, forced ventilation should be provided. This can be accomplished by means of a fan and duct, arranged in the tunnel, to blow outside air into the chamber.

5-06 Simple Installation, Tunnel and Shaft

A simple installation consisting of an underground chamber with a tunnel and shaft tends to be self-ventilating during all seasons. In winter, or when the interior is warmer than the atmosphere outside, air flows by chimney action in through the tunnel and out through the shaft and in summer, or when the temperature relation is reversed, the air flow reverses, and the air passes down through the shaft and out through the tunnel. In winter, the chamber tends to be self-drying because water evaporates from the rock, which is warmer than the dew point of the air, and is conveyed to the outside by the air current. In summer, in humid regions, the rock may condense water from the air and become wet. Drainage of the condensate may be necessary by means of trenches or/also pipes in the tunnel. To a lesser degree, daily weather changes cause ventilation of such installation for the same reasons.

Small insulated structures in such a chamber can be air conditioned by warming (5-10) in that the relative humidity can be thus reduced. In other weather, outside air can be used to cool the chamber and surrounding rock, removing the heat and moisture escaping from the inner structure, thus facilitating this air conditioning process.

For heavy or continuous occupancy or if noxious gases are involved, forced ventilation may be essential.

5-07 Installations with Multiple Access Openings

A large installation intended for the protection of personnel or processes is likely to have two or more access tunnels, first, so that an alternate is available if one tunnel is blocked by battle damage or otherwise and, second, for convenience in handling traffic. Access tunnels can be used for the discharge of vitiated air from an installation but their use as air intakes is not generally recommended. If used as intakes, access tunnels are found to be too wet in summer and too cold in winter with walls, floor and ceiling often coated with ice. Either condition is bad for personnel, vehicles and cargo. Usually, the exhaust from Diesel engines, flue gases from boilers, and other fumes, are vented through special shafts while exhaust from kitchens and toilet facilities is vented with the air from the other occupied spaces. Separate air intakes are desirable, and shafts are often preferred to tunnels for this purpose because the distance downward to the installation is less than the horizontal distance from outside. The shaft is often less expensive because it is shorter, although the cost of excavation in dollars per cubic yard may be less for a horizontal than for a vertical opening. In some cases a sheet-metal fresh air duct, run through an access tunnel, may be preferable to a separate ventilation tunnel or shaft.

5-08 Types of Inner Structures

It is possible to install practically any kind of structure in an underground chamber that is used on the surface, but an inner structure in an underground chamber is not exposed to the sun and wind like a building on the surface. The humidity in many underground spaces is initially high, but the temperature is usually mild so that the use of heavy insulation is not justified except in special cases. The vapor transfer problem may require different treatment. The roof of an internal structure may be designed to catch both dripping water from the ceiling of the chamber, and spalling rock fragments.

Internal structures differ in size and in the ratio of their size to that of the enclosing chambers. For some purposes, small structures may be erected in large chambers (5-10). Often, internal structures are designed to fit enclosing chambers with relatively small clearances to

utilize all available space. Simple partitions, even if they do not reach to the ceiling, afford some privacy in offices and may be used to improve acoustical conditions (5-09).

Addition of thermal insulation to the walls, ceiling and floor of an internal structure is not essential unless the interior of the structure is heated to some temperature above that of the surrounding annular space for considerable periods of time. If the two spaces are kept at the same temperature, insulation between them cannot have any effect. If the annular space and surrounding rock are cooler than the structure when it is being cooled by air conditioning, the rock will reduce the cooling load by absorbing heat. In this case the use of insulation may be detrimental.

Application of vapor barrier materials in the walls, ceilings or floors of internal structures is not beneficial under most ordinary circumstances. In fact, layers of material that are impervious or nearly so may increase the chances of difficulty due to condensation under some conditions. If the surrounding rock is at a temperature below the dew point in the conditioned space, the rock assists in the dehumidifying process and the vapor barrier retards it. If the annular space is used as a return plenum, the vapor pressure difference through the walls tends toward zero.

These considerations indicate that, from the air conditioning standpoint, the walls and ceiling of an internal structure can consist of any material presenting an acceptable finish to the interior, suitably supported on a frame. As previously mentioned, a roof is often desirable to exclude drip.

If either an interior structure or its contents are subject to deterioration from dampness, the structure should be continuously air conditioned, not only during normal operation, but during standby or unoccupied periods, however long. If the internal load is small and the surrounding rock remains cool, the air conditioning process may consist in simply warming the structure to reduce the relative humidity (5-10). Use of thermal insulation facilitates control of relative humidity by this means.

5-09 Acoustical Treatments

Sound waves reverberate in a bare rock chamber and render some treatment necessary in occupied spaces where a

low sound level is essential. It is usually impractical to apply acoustical material directly to the surfaces of the rock on account of water pressure (3-08) or wetting by condensation. Interior structures are a solution to the problem, and the treatments of walls and ceilings for sound absorption can be the same as those for surface buildings. In chambers where a ceiling is not needed for protection against dripping water or spalling rock, partitions not reaching to the top of the chamber (5-08) are a possible solution to the problem and should be comparatively economical.

Air conditioning devices, including fans, blowers, pumps, and compressors, are often sources of noise. Treatment of such equipment, and of ducts or pipes, to minimize propagation of noise is covered in texts on air conditioning.

5-10 Small Structures in Large Underground Chambers

Under favorable circumstances the relative humidity inside an interior structure can be satisfactorily controlled for material preservation by simply warming the air within the structure. The surrounding rock is relied upon to control the humidity since condensation occurs on its surface when the dew point exceeds the rock surface temperature. Insulation of the walls of the internal structure is desirable to retard the warming of the rock by heat from the structure but these walls must be pervious to permit migration of water vapor from the structure to the rock.

This arrangement may be useful when a large cool underground space is available and the required air conditioned space and the internal load are small. Excavation of a suitable chamber probably would be uneconomical but sometimes an abandoned mine or other underground opening may be so utilized.

A leakproof roof is essential to protect the interior or contents of the structure from drip, should any occur. The walls must be pervious and vapor barriers are not desirable because the surrounding rock is relied upon to control the humidity (3-07). Heavier insulation reduces the heat requirement of the structure and slows the heating of the surrounding rock by heat from the structure. This either lengthens the period of possible use of such an installation before the relative humidity becomes excessive or permits the use of a larger internal structure

in a chamber of limited size. This type of air conditioning can be facilitated if the chamber is selectively ventilated with cold air, as in winter and at night, since heat escaping from the inner structure can thus be removed. The surrounding rock serves as a large heat sink and makes this process possible.

5-11 Air Conditioning Processes for Larger Installations

Several air conditioning processes or arrangements merit consideration for the larger underground installations. Recirculation of part of the air for economy in operation is essential, while fresh or outdoor air in proportion to population (2-04) must be supplied with any system and may be either added to the recirculating air at some convenient point or ducted to the individual zones or rooms as required by the design. Halls can be used for return air but the annular space around the internal structure has been favored by designers for this purpose.

Either central air conditioning equipment (5-12) or zone or room air conditioners (5-15) are feasible. The problem of locating large ducts is avoided if zone or room conditioners are used and the control problem is in some degree simplified. Either self-contained air conditioners with built-in condensing units or remote-type air conditioners with chilled water coils (5-15) can be used. Heating may be accomplished by a separate system or by heating coils included in the air conditioners.

A special arrangement consists in cooling the annular space around an internal structure with conditioned air and ducting the return air instead of the supply air (5-13).

5-12 Central Air Conditioning Systems

The use of large central air conditioning systems in buildings has declined in recent years and the apparent reasons are the necessity for large, long ducts, inflexibility under moderate loads as in mild weather, and the relative low cost of unit equipment due to quantity production. The same reasons favor individual room or zone conditioners in underground installations.

In typical systems so far utilized underground, conditioned air is ducted to the working spaces while the annular space around the inner structure may be used as an

exhaust plenum. Fresh or outside air is introduced into the supply system at one or more convenient points with care to assure good distribution.

The air flow must be sufficient to remove heat and water vapor originating in the various rooms or spaces and fresh air must be supplied in proportion to population (2-06).

Control of air flow is usually accomplished by automatic dampers, actuated either by a pneumatic or an electric system, governed by thermostats.

5-13 Cooling Effect Applied to Annular Space

It is possible to cool an internal structure in an underground installation by utilizing the annular space between the structure and surrounding rock as a cold air plenum. The advantage is that the surrounding rock, remaining cold, can serve as a heat sink in time of emergency when the outside power supply is cut off and the air conditioning system is out of operation.

In a suggested arrangement, air is drawn by a fan from the structure and forced through a cooling coil from which it is discharged into the annular space. Adjustable louvers or other openings are provided in the walls or ceiling of the structure through which air from the annular space enters due to the differential pressure created by the fan. These louvers or other adjustable openings are installed in the various rooms in accord with their individual requirements for air conditioning. The annular space and hence the surrounding rock are kept at or near the initial rock temperature by the cooling coil which absorbs the heat liberated in the structure. Thermal insulation of the structure is not beneficial when the structure must be cooled, but insulation can save heat if the structure must be warmed during any considerable length of time such as an unoccupied period.

Such an installation can be ventilated with fresh or outdoor air drawn through a shaft or tunnel by a fan and forced through air cleaners or purifiers, if required, into the annular space. Vitiated air can be exhausted from a structure through louvers and a duct system, if required, and out through an entrance tunnel or other opening. Kitchens, baths or sources of objectionable or noxious gases, dusts or vapors should be vented with the exhausted air.

without recirculation. Heating, if required, must be accomplished with a separate system.

Heat losses or gains through the walls, ceiling and floor of the inner structure can be computed by the steady-state equation (3-02) and heating and cooling loads can be computed in the ordinary manner. The rate of warming of the surrounding rock during an emergency period when power is not available for air conditioning can be computed by means of equation (4-05).

If the cooling load is small, installations of this type approach the conditions of a small structure in a large chamber (5-10). The cooling equipment obviously becomes smaller with the load.

Chilled water lines in cool annular spaces do not require insulation since the cooling and dehumidification accomplished by such piping is effective in air conditioning the space. Drip from pipes, if any, can usually be conveniently drained away.

The annular space, to be used as a cold air plenum, must obviously not be connected to an access tunnel.

5-14 Self-Contained Air Conditioners

Use of a multiplicity of self-contained air conditioners, one for each room or zone, simplifies the zoning and control problems, possibly improves overall reliability in some degree and is a means of avoiding the use of large, long ducts with the attendant necessity for insulating them. Noise (5-09) may be important if such equipment is used since occupants may be situated close to the source. Self-contained air conditioners include condensing units in preassembled cases or packages and, for use underground, these condensers presumably will be water cooled and water from outside must be piped to and away from each machine. Fresh air must be ducted to the spaces served in proportion to population and, preferably, this air should be either tempered in the supply system or pass through a conditioning coil before entering the occupied space. Self-contained air conditioners may contain hot water or steam coils for use when heating is required. Condensate due to the dehumidifying process must be drained away, and this probably can be accomplished conveniently in most cases by piping to conduct the condensate to a drain in the annular space or under the floor.

Self-contained air conditioners can be arranged to serve as heat pumps and thus warm spaces when required as well as to cool and dehumidify them. Most of the heat for warming a space with this arrangement is taken from the water used at other times to cool the condenser. Precautions against freezing the heat exchanger may be essential.

5-15 Chilled Water Systems

Use of chilled water in unit air conditioners for individual rooms or zones has the advantage of simplicity and flexibility of control. Chilled water lines should be insulated if they pass through spaces with high dew points to prevent condensation on their surfaces with resultant corrosion and to conserve the cooling effect of the water (5-13). In air conditioned spaces, such pipes may require insulation to prevent excessive cooling of some rooms or spaces and deficient cooling of others more remote from the water chiller.

Control may be effected by starting and stopping the fans in the units, by means of dampers to control the air flow through the cooling coils, by regulating the flow of chilled water to the coils or by a combination of these methods.

Cold water from wells, streams, ponds or cooling towers can be used in cold weather instead of the water chiller, thus reducing the refrigeration load and expense of operation.

Heating coils can be installed in the air conditioning units along with the cooling coils if desired. Fresh or outside air for ventilation must be separately ducted into each occupied space or zone.

5-16 The Ice Reservoir as a Heat Sink

An important design feature of some protective installations is the ability to function for a period of time while isolated from outside sources of power, water, etc. This usually means that the use of outside cooling towers, ponds, and wells is also precluded so that some self-contained heat sink is required, and the properties of ice strongly recommend it for the purpose.

A suggested heating and air conditioning system for an underground installation includes the following equipment:

An ice reservoir with sufficient capacity to absorb heat from the installation through a chilled water air conditioning system during an emergency period.

A water reservoir to receive all waste heat from engine water jackets, refrigeration condensers, etc. Such waste heat is used in a hot water system for space heating when and where required. Excess waste heat is ordinarily dissipated by means of cooling towers, ponds or other means external to the installation.

(Both reservoirs can consist of unlined excavations near the installation but separated from each other by a sufficient thickness of rock to prevent excessive heat exchange between them.)

A chilled water air cooling system with a unit air conditioner in each room or zone in the installation, receiving cold water as required from the cold reservoir.

A hot water heating system includes either separate heating devices, like radiators or convectors, or heating coils in the air conditioning units for warming the various spaces.

One or more refrigerating machines to extract heat from the ice reservoir; rejected heat is supplied to the heating system and excess waste heat is dissipated outside under normal operation or delivered to the water reservoir during emergency.

A boiler or boilers to supply heat if waste heat from the equipment is insufficient at any time, to supply steam for cooling if required, and to temper the fresh air if required.

Controls, except safety devices, tempering valves, and room or zone thermostats, are manual. The large heat capacity of the ice reservoir results in slow temperature changes under any condition of operation so that refrigerating machines or boilers need be started or stopped only at comparatively long intervals.

Under normal operation, the refrigerating machines operate sufficiently to keep a substantial part of the

water frozen in the ice reservoir. Water from this reservoir is mixed in tempering valves with water recirculated through the cooling coils in the air conditioners to cool and dehumidify zones or rooms where required. A water temperature at or near 50F is suggested for the water supply to the cooling coils. Warm water from engines or refrigerating equipment is circulated to supply heat to rooms or zones when required.

During an emergency or "buttoned up" condition, the refrigerating machines are stopped to relieve the Diesel or other power source of the refrigeration load. The ice reservoir continues to act as a heat sink for the air conditioning load and can continue to serve this function, until it approaches some temperature near 50F. The water reservoir acts as a heat sink for the Diesel engines until its temperature approaches the boiling point.

When either the ice reservoir approaches 50F or the warm reservoir approaches the boiling point, the refrigerating machines must be started and the ice reservoirs must serve as a heat sink for both the power plant and the refrigerating machines as long as possible. The limit probably is an ice reservoir temperature near 110F since higher condenser water temperatures may result in intolerable pressures in the compressors.

The limit of endurance of the installation is reached when the temperature in the warm reservoir approaches the boiling point and that in the ice reservoir reaches the highest permissible without destructive head pressures in the compressors.

Designs of reservoirs for emergency periods of specified length can be based on equations included in Chapter 4.

The water would, of course, be much more effective as a coolant, in Btu per pound, if its latent heat of vaporization could be utilized, but Diesel engines probably are not constructed to withstand boiling water in their jackets.

CHAPTER 6

Equipment and Operation

6-01 Equipment Selection

Use of equipment requiring a minimum of floor area and volume is essential for saving on first cost because every cubic foot of necessary space must be excavated in rock. This recommends against the use of large ducts and inordinately large apparatus. A general advantage lies with small ducts and high velocities, and small, high capacity equipment including fans, coils, boilers, if used, etc. The limiting factor on machine speed and air velocity is often noise which must be kept within tolerable limits for each space, depending on its intended use.

Tolerances should be stated for specified design conditions (2-03). A requirement of 75F and 50 percent relative humidity, without a stated tolerance, can result in the installation of unnecessarily large equipment. An economical and usually practical requirement is a temperature of 75 ± 2F and a relative humidity not exceeding 50 percent. Humidities significantly below 50 percent, if they occasionally occur, are not likely to cause serious discomfort or to affect furniture or equipment.

6-02 Economy of Operation

Use of natural means as far as possible for effecting air conditioning processes is an obvious way to promote economy of operation. An underground installation may be cooled with outside air in winter if such air in sufficient quantity can be delivered to the space at some temperature below about 65F. Water, if available from outside, may be used for cooling in a chilled water system if its temperature is about 50F or below. A shaft or tunnel large enough to cool a space at considerable depth below the ground surface during normal operation may be inordinately expensive, but cooling with winter air may be feasible for shallow installations or for deeper installations during a standby condition when the load is small. For the deeper installation the shaft or tunnel provided to furnish fresh air during full occupancy may be ample to cool the space with winter air during standby or partial occupancy. These generalizations must be used as guides in the design or selection of equipment for particular installations. They cannot be made more specific because circumstances are different for each case.

When, as in summer, cold outside air or water is not available for cooling, mechanical refrigeration must be relied upon. Examination of some typical cases indicates that the important loads under the most severe condition, such as fully occupied installation under full operation in summer, are as follows:

1. Equipment, including electronic gear
2. Personnel
3. Lights
4. Conditioning of fresh air

For this condition, the refrigerating machines must carry the full load except for the heat absorbed by surrounding rock which may not be important if item 1 is high. Significant economies cannot then be achieved by special manipulations. However, experience shows that protective structures may be on standby with partial or zero occupancy for long periods, and it is during such times that economies are possible as follows:

Minimize the fresh air supply to cool rooms or spaces. It is unnecessarily expensive to supply mechanically conditioned air in sufficient quantity for full occupancy when a space either is not occupied or contains only a skeleton force. Controls, either manual or automatic, are desirable that will regulate the fresh air supply in accord with occupancy, as closely as possible.

Utilize waste heat in spaces requiring heat. Unoccupied spaces are cooled by the surrounding rock and under this circumstance may require heat to maintain a suitable relative humidity for material preservation. Heat rejected by refrigerating machines may be used for this purpose, in an adaptation of the heat pump principle. Heat from engine jacket water can be utilized if a storage means such as a reservoir is provided.

6-03 Air Conditioning System Components

Conventional, commercially available, heating and air conditioning equipment is in general adaptable to underground use. In a typical system, the fresh air coming from a tunnel or shaft may first pass through a tempering coil (6-04) to warm the air in winter, and assist in preventing condensation and drip from ducts. If close control of humidity is required, the air may next pass through an air

washer (6-05) or spray coil (6-06). Such devices are not considered necessary in most cases because a cooling coil (6-07) can be relied upon to cool and dehumidify the air with sufficient precision in summer and the precision expected of an air washer is not required in winter. An air cleaner (6-08) ahead of the coils is a precaution against a deposit of dust or lint on the tubes or fins that might impede the air flow or heat transfer. An air filter also tends to eliminate variations in velocity and make the flow uniform across the face of a coil or air washer, and this is beneficial to the performance of coils or air washers. An air purifier (6-08) is required in many protective structures to exclude biological agents and radioactive particles. Such a device is frequently installed so that outside air passes through it before entering other components of the system, at least during emergency periods. The conditioned fresh air is taken by a fan or blower (6-09) and distributed to the various rooms or zones through a duct system (6-10).

For conditioning each room or zone, air may be recirculated through an air conditioner which may include both heating and cooling coils as well as an air filter (6-08) and a fan or blowers (6-09). Unit air conditioners may not require ducts if set in the rooms they serve. Conditioners serving zones may supply air through ducts (6-10) connected to grilles or louvers (6-11) in the various rooms. Return air may pass directly to a unit air conditioner or, for a zone, a passageway or hall may serve as a return. Grilles in doors are often used to permit egress of air from rooms to halls.

If low humidities are required for special purposes, and if moderate warming and no cooling are required in some space, either a chemical dehumidifier (6-12) or a mechanical dehumidifier (6-13) may be used advantageously, and if extraordinarily low humidities are required, a chemical dehumidifier may be preferable.

6-04 Tempering Coils

Tempering coils in surface buildings are usually heated with steam instead of water to reduce the probability of damage due to freezing in winter. Steam can also be used in a coil serving an underground installation, and without seriously affecting cost, if steam must also be supplied for other purposes, such as cooking. However, if steam is not otherwise required and if the

installation is heated with hot water, it is in many cases possible to use hot water in the tempering coil without danger of freezing for the following reasons.

If the fresh air supply is cut off, the coil will not freeze because its temperature will be governed by the surrounding rock, which remains above the freezing point. If the water supply to the coil is shut off due to equipment failure or other causes while the air flow continues, the air may have been warmed considerably by its passage through the supply shaft or tunnel so that the temperature may not go below freezing. The air temperature at the coil at any instant can be computed by means of equations given in section 4-05.

The purpose of tempering coils is to so warm the fresh air in winter that condensation on ducts is avoided. Heating to some temperature near that of the occupied rooms is sufficient since the heating system should be designed to carry the loads in the various rooms or zones. One set of coils is therefore sufficient for the incoming air. Modulation of water or steam flow or use of a bypass with automatic dampers is a means of avoiding overheating of the air in mild weather. The coil is shut off in summer.

If the fresh air ducts are insulated both to minimize heat exchange and to prevent condensation on their external surfaces, cooling loads can be reduced by permitting air at winter temperature to pass directly to conditioned spaces without preheating. Tempering coils, therefore, may not be required in some installations. However, this depends also on the ability of some air purifiers (6-8) to function when receiving cold air.

6-05 Air Washers

Air washers (Ref. 1) are a means for comparatively precise control of humidity because air, passing through a copious water spray, emerges in a condition approaching saturation. The temperature of the spray water and of the entering air can be manipulated to attain a required dew point such that a specified relative humidity results when the effluent air is heated to a required temperature. Air washers, however, are bulky devices; they require attendant equipment, including pumps and piping; and their operation can be regarded as uneconomical if the air must be reheated by burning fuel after dehumidification. To avoid these complications, coils appear to be preferred for most air

conditioning purposes and their smaller size recommends them for underground installations except where extraordinarily close humidity control is required for special purposes. Coils are a practical means for maintaining the air conditions ordinarily essential for occupied spaces or material storage (2-04),(2-05).

Air washers are not covered by any generally accepted standard testing or rating procedure. Selection is usually based on knowledge of the performance of conventional designs. Cabinets or cases of air washers are usually sheet metal, rectangular in shape and long enough to accommodate from one to several banks of spray heads between diffuser plates near the entrance, to promote uniform air flow, and eliminator plates near the exit, to capture airborne water droplets and provide additional wetted surface. Glass wool mats are sometimes used as eliminators; the material presents large areas of wetted surface per unit volume to the air flow.

In air washers, air velocities in the range from 250 to 600 fpm have been used; 450 fpm is typical. Spray banks are about 2 1/2 feet apart. With this arrangement humidifying effectiveness in the range from 60 to 75 percent can be attained with a single bank of spray heads and from 85 to 95 percent with two banks of spray heads (Ref. 1). Higher effectiveness is obtained when the spray heads face upstream.

Humidifying effectiveness is defined by the formula

$$e_h = \frac{T_1 - T_2}{T_1 - T'} \times 100$$

in which

e_h = humidifying effectiveness, percent

T_1 = dry-bulb temperature, entering air, F

T_2 = dry-bulb temperature, leaving air, F

T' = Thermodynamic wet bulb temperature, entering air, F.

6-06 Air Heating and Cooling Coils

In the heating and, to a wider extent, in the refrigerating and air conditioning field, the word "coil" denotes a heat exchanger made of pipe or tubing, either with or without fins. Pipe in true coil form was once much used for heat exchangers and the same "coil", by custom, has come to signify a broad class of heat exchange, in which single or multiple parallel tubes permit heat transfer from one body of fluid to another. For a heating coil, steam or hot water may be passed through the tubes and in a refrigerating coil, either a refrigerant or chilled water may be used in the tubes. The internal film resistance is usually less than the external so the use of "extended surface" coils, with fins affixed to the outside of the tubes is common. Such extended surface reduces the total heat flow resistance so that smaller, lighter apparatus is required for a given duty. Plain coils without fins are recommended for heat exchange between liquids but extended surfaces are beneficial for exchange between liquid or boiling refrigerants and air or other gas. Also, plain coils may be indicated for heating or cooling air where dirt or frost are likely to be serious problems.

To select a heating coil to serve a given space the following factors must be known or estimated.

Heating load, Btu per hr. (3-02)

Temperature, air entering coil, F.

Temperature air leaving coil, F.

Face velocity, fpm

Air flow, cfm

Allowable pressure drop, ins., W.G.

Dimensions of coil

Dimension of the allowable space

With these data it is usually possible to select a coil for a given heating load from tables in manufacturers' catalogues for the use of either hot water or steam as a heating medium.

To select a cooling and dehumidifying coil, the following data are necessary.

Sensible cooling load, Btu per hr. (3-06)

Latent cooling load, Btu per hr (3-06)

Wet and dry bulb temperatures of the air entering and leaving the coil, F.

Face velocity, fpm

Air flow, cfm

Allowable pressure drop

Dimensions of the coil

Dimensions of the allowable space

The most convenient and practical precedure for coil selection is to utilize the above data in conjunction with data on coil characteristics found in manufacturers' catalogues.

Heat transfer in coils is complex, and practical solutions of problems concerning it are based on test data extrapolated by means of empirical methods. This subject is treated in the "Guide" (Ref. 1) and other handbooks and texts.

A Test Code for coils entitled "Standard Method of Testing and Rating Forced - Circulation Air-Cooling and Air-Heating Coils" has been accepted by the Air Conditioning and Refrigeration Institute and the Heating and Cooling Coil Manufacturers Association. Many manufacturers make the necessary tests or gather the pertinent data by methods of their own. Sometimes tests of coils are desirable after installation to determine compliance with guarantees.

The total output of a steam coil can be determined by measuring the steam condensation rate, in pounds per hour. This multiplied by the change in enthalpy or total heat of the steam in condensing yields the output in Btu per hour. Coils heated or cooled by water or cooled by a refrigerant are more difficult to check because fluid flow rates and temperature or enthaply changes are difficult to measure in normal operation. The necessary

measurements are possible in most cases with sufficient care and skill. A result within ten percent of the true output would be regarded as a good determination.

6-07 Air Conditioning Units

An air conditioning unit consists of a cooling coil, sometimes accompanied by a heating coil, with a fan and usually one or more air cleaners, enclosed in a case or cabinet, conventionally made of sheet metal. A self-contained unit includes a refrigerating machine, which may be either air or water cooled. In a remote unit, chilled water, liquid refrigerant, or a solution, is utilized in the cooling coil. Openings or duct connections are provided in the case for the supply and return air.

Selection of air conditioning units can usually be based on catalogue data, as in the case of coils (6-06). Requirements for self-contained units are set forth in ARI Standards 1-10-55, "Room Air-Conditioners" and 2-10 "Self-Contained Air Conditioners (other than Room Air-Conditioners)", published by the Air Conditioning and Refrigeration Institute. Tests for capacity are required by these standards under ASRE Standard 16-52, "Standard Methods of Rating and Testing Air Conditioners", published by the American Society of Refrigerating Engineers.

6-08 Air Cleaners and Purifiers

Air cleaners are desirable to protect coils, motors and fans from dust and lint. Since lint probably is the material most responsible for coil stoppages and since it is easily captured, relatively simple filters with low resistances to air flow are usually satisfactory for this purpose.

The fresh or outdoor air for an underground installation may be drawn from a location that is clean most of the time and it will be cleaned to a degree by passing through the supply shaft or tunnel. However, extraordinary winds may stir up dust, or dust may be created by blasting or mining operation after an installation is occupied. For these reasons an air cleaning means for the fresh air ahead of any other conditioning equipment is recommended.

Recirculated air often contains considerable lint due to the wear of clothing, draperies, paper, etc., so that air cleaners are essential in recirculated air ducts ahead of fans or coils.

Automatic self-cleaning oil-bath air filters are found in some Government agencies where the air flow is large because they require attention only at long intervals. Efficiencies expected are not higher than those for less expensive apparatus. Of the panel-types, the throwaway filter is preferred by some operators because it is cheap enough to discard and hence does not require cleaning. On the other hand, cleanable or automatic self-cleaning filters may be chosen if storage space is scarce because it is not necessary to stock replacements.

Electrostatic filters are recommended if very fine dust is a problem. Such equipment is effective in arresting particles in the submicron range such as carbon, tobacco smoke, and tarry matter resulting from the combustion of oil or coal.

Air filters are at present tested in different ways by different manufacturers. A dust-spot test has been developed at the National Bureau of Standards and serves as a basis for purchase specifications for electrostatic air cleaners as well as panel type air filters. Electrostatic devices are tested with airborne dust without any artificial contaminant. Field tests of such equipment are feasible. Throwaway and cleanable filters are tested with Cottrell precipitate, which is fly-ash from boilers burning pulverized coal captured in a Cottrell precipitator at a local power plant.

An efficiency of 90 percent or more is usually specified for electrostatic air cleaners when tested after installation with dust naturally prevalent at the site. No dust is added to the air for the test. Panel type filters typically exhibit efficiencies in the range from 65 to 90 percent when tested with Cottrell precipitate by the dust-spot method.

Air purifiers are designed and constructed by the Chemical Corps. Information on this type of purifier may be found in "Collective Protection against Chemical, Biological and Radiological Warfare Agents", Part VI of the Engineering Manual for Protective Construction.

6-09 Fans

For the selection of a fan, data are required as follows:

Capacity, cfm

System resistance external to fan, inches, W.G.

Air temperature, F., or density, lbs. ft.$^{-3}$

Space or weight limitation

Duct sizes and connections

Noise limitations

Voltage and currents

The dimensions and performance data on commercially available fans are generally contained in manufacturers' catalogues. The performance data are usually based on tests conducted according to one of the existing codes such as "Standard Test Code for Testing Centrifugal and Axial Fans", (1950 Bulletin No. 110 of the National Association of Fan Manufacturers); "Standards for Fans", (1947, Publication 47-128 of the National Electrical Manufacturers Association); "Test Code for Fans", (1946 publication PTC 11-1946, of the American Society of Mechanical Engineers); and "Testing and Rating Ventilating Fans (Axial and Propeller Types)", (1951, Commercial Standard CS 178-51, published by the Government Printing Office).

Fan performance is usually expressed in terms of static pressure instead of velocity pressure or total pressure because the static is the pressure available for forcing air through a duct system regardless of its shape. Utilization of velocity pressure depends on the shape of the duct system which is often unknown to the fan designer or manufacturer.

Fans have been defined (Ref. 1) as low-pressure air or gas moving devices that do not cause density changes greater than seven percent in the fluid passing through them. A change of seven percent in density corresponds to about one pound per square inch for air at one atmosphere pressure. One psi is much greater than the pressure generally required for air conditioning systems so fans, rather than blowers, compressors or pumps, are used for moving air through them.

Fans are of two general types: the axial flow and the centrifugal. Axial flow fans may be propeller, tubeaxial or vaneaxial types and centrifugal fans may have forward, or backward curved or straight blades on their rotors. Selection must be based on air flow and pressure requirements and on space, weight, and noise limitations, if any.

6-10 Duct Systems

The term duct system usually signifies an arrangement of sheet metal conduits designed to contain and direct the flow of air from a source such as an air conditioner to a space being served and either back again to the source or to the outside. Air returned to the source is usually called recirculated air. That rejected outside is classed exhaust air or vitiated air; it must be replaced in the system by fresh air from out of doors. Especially in underground installations, tunnels or shafts may be used as air conduits and can properly be regarded as part of the duct system.

For the design of a duct system, the air supply required for each space served and for the whole system must be determined. This is usually based on the heating and cooling load estimates (3-01) and the outside air requirements (2-06). For heating any space by means of air, the heat delivered by the air must equal or exceed the heat loss; while for cooling, including dehumidifying a space, the air flow must be sufficient to carry away both the heat and the water vapor liberated in the space.

The design of conventional warm air heating systems has been standardized and simplified (Ref. 1) but, especially for large underground installations, greater air flows are likely to be required for cooling and dehumidifying than for heating. Hence, the duct design procedure usually employed for cooling air conditioning systems (Ref. 1) is likely to be more properly applicable in most cases. This procedure is based on the properties of standard air but the data given in tables and charts in the handbooks are considered sufficiently exact for practical use with air near normal atmospheric pressure, between 50F and 90F and at any relative humidity.

In a large installation the use of small, short ducts is made possible by the employment of a zoned system with a multiplicity of air conditioners, but the fresh air supply and return ducts must extend from the outdoors to the farthest occupied space. The fresh air duct, therefore, may require extraordinary care in its design.

Sheet iron for ducts in underground spaces should be galvanized or otherwise treated for corrosion resistance. Aluminum is considered satisfactory for most purposes as ordinarily furnished, but this metal is subject to attack by caustic substances. It should not be used in contact with masonry or concrete nor exposed to drip or seepage of

water containing lime or other caustics. Its resistance to acid is satisfactory. Tables of recommended thicknesses and structural details for iron and for aluminum ducts are contained in handbooks (Ref. 1).

High velocities are to be favored in underground installations since their use permits the ducts to be smaller. Space underground must be excavated from rock so use of smaller ducts, requiring less space, often results in lower first cost.

6-11 Steam and Hot Water Heating Systems

In an underground installation the heating load is likely to be small compared to that for a surface building of equal dimensions because an underground structure is not exposed to the weather. Also, the heating load is likely to be smaller compared to the cooling load than in typical surface structures. These factors often make it desirable that the heating system shall be an adjunct to the cooling system and not a separate system.

Either hot water or steam can be used to warm air by means of coils included in unit air conditioners. Use of water facilitates utilization of waste heat since hot water systems operate at much lower temperatures than conventional steam systems.

6-12 Chemical or Sorbent-Type Dehumidifiers

Sorbent-type or chemical dehumidifiers can be advantageously utilized for spaces in which extraordinarily low humidity is required or in which temperature control is less important than humidity control (Ref. 1). Substances on the market for use in such equipment include both "adsorbents" and "absorbents". By definition, an adsorbent does not change either chemically or physically when it becomes wet. Commonly used adsorbents include silica gel and activated alumina. Typical absorbents are calcium chloride and lithium chloride.

As an expedient, either an adsorbent or an absorbent material may be utilized to dry a space by simple contact with the air. For instance, calcium chloride exposed in trays will absorb water from the air and the resulting solutions can be thrown away. For any but temporary installations, however, equipment is to be recommended capable of alternately utilizing the sorbent for dehumidifying air and then reactivating it by means of heat and ventilation. Such an apparatus may consist of a cabinet or case

containing fans and a filter, with duct connections for "wet" air and dehumidified air, as well as ventilating air. Heat for reactivating the sorbent may be supplied electrically, by steam and sometimes by the combustion of a fuel. Adsorbents are utilized in sizes ranging from 300 mesh to 8-14 mesh screen. Absorbents are usually employed as aqueous solutions which may be sprayed into the air being dehumidified as in an air washer or exposed to it on the surfaces of metal plates or of mats of fibrous material like glass wool. Reactivation may be accomplished in a second air washer through which heated (up to 300F) outdoor air is passed. The heat evaporates some of the water from the solution and this water is carried outside as vapor.

The necessity for ducts from outside may cause inconvenience in some installations. The required length may be considerable for a deep installation and, if part of the system is below the dew point temperature, condensation with possible drip through joints, occurs.

Selection of a dehumidifier is based on the following data:

The moisture load, in grains or pounds per hour, from all sources

Temperature of the air entering the dehumidifier, F

Required relative humidity, percent

Space or weight limitation

Energy available for reactivation

With this information suitable apparatus probably can be found listed in manufacturers' catalogues.

Since dehumidifiers may be rated in pounds of water per hour or per 24 hours while psychrometric charts show humidities in grains of water per pound of air, the following relation is useful:

7000 grains = 1 pound, avoirdupois

For estimating purposes it is often assumed that the temperature of air being dehumidified increases about 10 degrees F for each grain of water per cubic foot removed from it. For reactivation, the energy required is somewhat

greater than the latent heat of the water removed. The difference is the "heat of wetting" which is different for the different sorbent materials.

6-13 Mechanical Dehumidifiers

A mechanical dehumidifier consists of a refrigerating machine so arranged that air passes through a cooling coil and then through the condenser. The air is cooled and dehumidified by the cooling coil and is then used to cool the condenser . Such a machine can carry a relatively large latent load but does not cool the space it serves; in fact heat is delivered to the space served, if the machine is within it, equivalent to the power it utilizes.

Machines of this type are very useful in spaces with considerable latent loads and in which moderate heating is either desirable or of no consequence. They have been utilized in large numbers as basement dehumidifiers in residences and either the same kind or larger models are applicable to some underground installations. They have the advantage, over chemical dehumidifiers, that the condensate is removed as liquid which can be drained away through pipes rather than as vapor in air that must be expelled through ducts. They may be incapable of attaining humidities as low as are sometimes required because the cooling coil may frost before the required dew point is reached.

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