NATIONAL BUREAU OF STANDARDS REPORT

6246

Engineering Manual for Protective Construction

Part V

Heating and Air Conditioning
of Underground Installations

Revision by

B. A. Peavy
H. E. Robinson
R. S. Dill (Deceased)

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

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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Revision by

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Heat Transfer Section
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To

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

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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

PROTECTIVE CONSTRUCTION BRANCH
ENGINEERING MANUAL FOR PROTECTIVE CONSTRUCTION

PART V

HEATING AND AIR CONDITIONING OF UNDERGROUND INSTALLATIONS

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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 criri-cal 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 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.

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 7 percent had air conditioning, and only 47 percent had other than natural ventilation. Heating was reported as provided in 27 percent of the plants surveyed.

The paper, "The National Gallery in War Time" (Ref. 9), is an account of the underground storage of paintings from the British National Gallery. An existing site was selected that provided space for the whole collection and afforded 200 to 300 feet of rock cover. The initial air conditions were 47 F and 95 to 100 percent relative humidity. The underground space, apparently an old mine, was large, so six buildings were erected within it to contain the pictures. Each small building was warmed by means of a forced-circulation system, apparently utilizing electric heat. For ventilation, small amounts of air from the space, at 47 F and near saturation, were introduced into each building as required. It was found that when the buildings were warmed to 64 F, 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 dehumidification was provided, 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

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, having thermal resistance materially affecting 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 (4-05) and influences the dehumidification load (3-05).

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 (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, revivification of the air for survival.

CHAPTER 2
PRINCIPLES AND 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.

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 were 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 internal structure (1-04).

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

Floor area and volume of an occupied space depends upon population, function, and internal load.

Environmental conditions, in particular air 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 (6-08).

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 (3-01).

2-03 Air Conditioning Requirements

For design purposes, an interior air condition of 75 F and 50 percent relative humidity can be assumed in many cases. This condition is within the practicable range attainable with conventional equipment (6-01), and available data show it to be suitable for personnel efficiency (2-04) and 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.

Flexibility of equipment is necessary to allow adjustments to cope with the range of operating conditions imposed by circumstances (1-05) or to accommodate changes from design conditions that may be shown desirable by experience.

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 (65 to 85 F) without serious loss of efficiency, particularly if the humidity is controlled and is adjusted downward when the temperature increases, or vice versa. The condition 75 F and 50 percent relative humidity may be assumed for design purposes, 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 are concerned.

The condition 75 F and 50 percent relative humidity is warmer than the 68 or 70 F 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 of the cooling equipment. It is common experience that many people are more comfortable at a DB temperature of 75 F winter and summer than at a DB temperature of 70 F. The condition 75 F and 50 percent relative humidity is safely below that causing 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, offices, or communication centers.

An important exception is unprotected low 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. 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 75 F 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.

TABLE 2-1

Humidity Tolerance of Some Materials
for 30-Month Period

Item Damage, Severity	Humidity A*	B*	C*	Nature of 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, Voltmeters, Telescopes, etc.)		45		

*A - No visible deterioration
*B - Very slight deterioration
*C - Intolerable deterioration

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-cell batteries also deteriorate more rapidly at low humidities.

The metal parts of munitions can be stored under the same condition as machine tools. For propellants, air conditions with relative humidity not exceeding 60 percent and temperature between 50 and 60 F have been recommended. In surveillance tests, it has been found that powder that had lost potency had been exposed to either dampness or relatively high temperature for considerable periods. It is also regarded as good practice to avoid sub-freezing 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. Equipment capable only of dehumidifying and moderately heating such chambers may be adequate in many such applications.

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 involves the factor of intermittent occupancy, which, for equal air freshness, allows different air supply rates for different room volumes, as shown by 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

	Air Space Per Person, Ft^3	Outdoor Air Per Person, cfm
Heating Season, With or without air recirculation		
Sedentary Adults of Average Socio-Economic Status	100	25
	200	16
	300	12
	500	7
Laborer	200	23
Heating Season, Total Circulation 30 cfm		
Sedentary Adults	200	12
Cooling Season, Total Circulation 30 cfm		
Sedentary Adults	200	4

The available data are not conclusive. Those contained in References 1 and 2 indicate that 10 cfm of fresh air 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 tolerably for underground installations, 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 (6-08).

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 because of power failure, or deliberately because the locality has been contaminated with radioactive material, biological agents, or gases. Under this condition, the occupants of an underground installation may be forced to rely on resources available in the installation for their respiration air supply. The situation will be similar in many respects to that in a submerged submarine.

People thus isolated from a fresh air supply can subsist for some hours or days on the air in the space, and the length of time depends on the volume of the air available and on the number of persons present, as well as their activity. 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 fractional percentage 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. An outside air supply of two cubic feet per minute per person assures a carbon dioxide content less than two percent for an indefinite period of 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 surfaces and exposed to the air. Increasing the air flow in contact with the material, as by means of fans, if available, accelerates the reaction. Oxygen can be provided under pressure in bottles, or it can be generated by burning special chlorate candles. Table 2-3 shows the amount of chemicals required for air revivification under dynamic conditions.

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		.34	yes	135 per cu ft CO_2
Baralyme	x		.474	yes	
Sodium Superoxide	x	x	.288	no	174 per cu ft CO_2 & O_2
Potassium Tetroxide	x	x	.364	no	147 per cu ft CO_2 & O_2
Chlorate Candle		x	.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 one cubic foot per man-hour and carbon dioxide liberation of 0.83 cubic foot per man-hour.

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 dewpoint would be determined largely by rock surface temperature. Therefore relative humidity would not approach 100 percent for some time.

AIR TEMP. RISE -

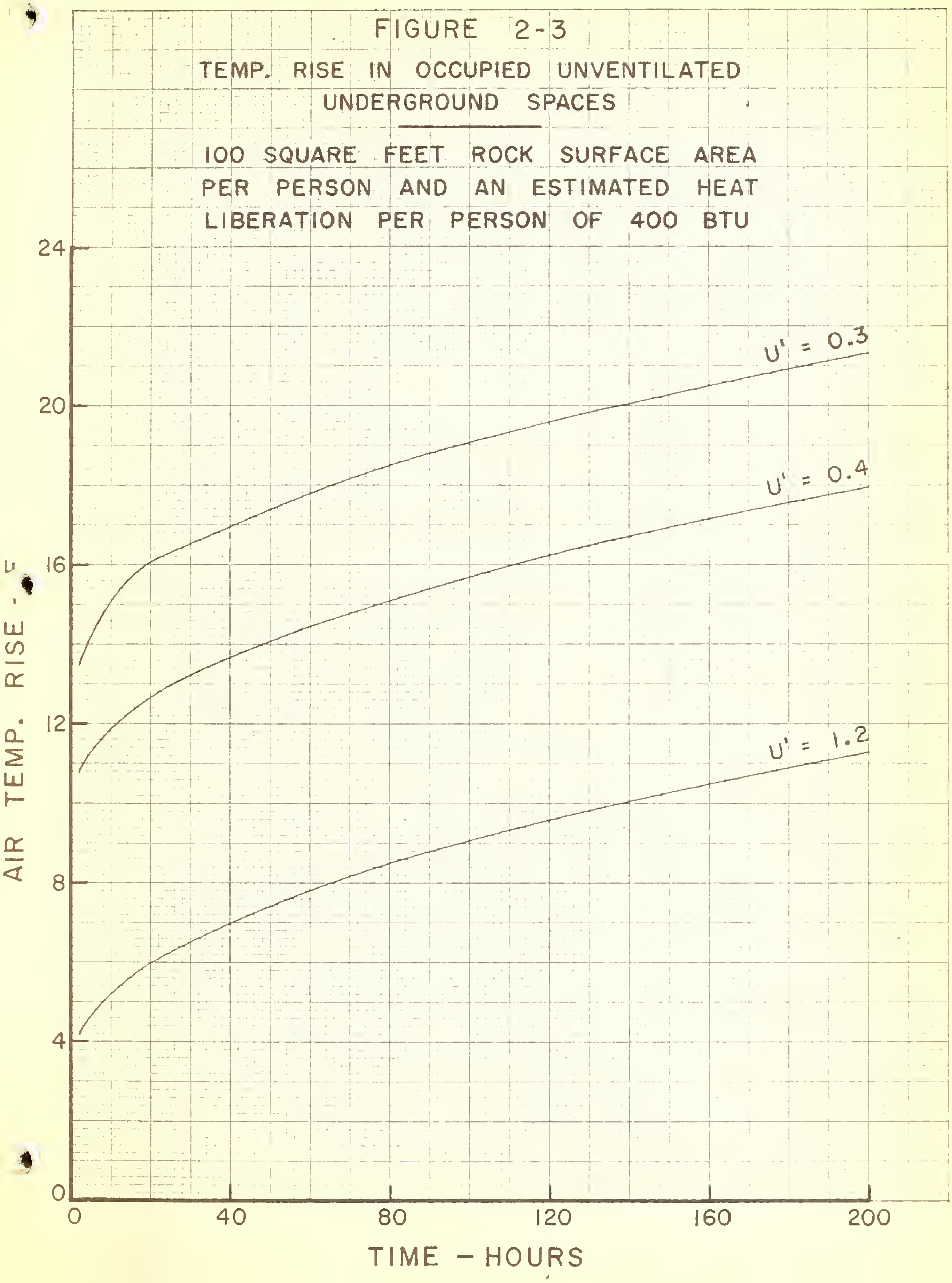


FIGURE 2-3
TEMP. RISE IN OCCUPIED UNVENTILATED UNDERGROUND SPACES
100 SQUARE FEET ROCK SURFACE AREA PER PERSON AND AN ESTIMATED HEAT LIBERATION PER PERSON OF 400 BTU
U' = 0.3
U' = 0.4
U' = 1.2
AIR TEMP. RISE - F
0
4
8
12
16
20
24
0
40
80
120
160
200
TIME - HOURS

Personnel in a crowded space, subsisting as above, can be expected to suffer ultimately from excessive heat and humidity. The probable period of isolation has been estimated for some purposes as one week while relief or rescue is pending. During that time, the temperature is not expected to become unbearable in the absence of normal supplies of heat and power. It is estimated that personnel under disaster conditions might be exposed to temperatures of 85 to 90 F at humidities approaching 100 percent. This is not beyond human endurance, but it is beyond the range at which work with paper, instruments, or electronic equipment can be reliably accomplished. 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.

The temperature rise in occupied, unventilated underground spaces is estimated from Figure 2-3, which is based on Equation 4-04 and the following assumptions:

1. The equivalent cylindrical radius (4-03) for the chamber is 15 feet

2. The thermal properties of the surrounding rock are:

$$K = 1.45 \text{ Btu/hr-ft-F}$$
$$K/\rho c = 0.038 \text{ ft}^2\text{/hr}$$

3. The heat input rate is on a per person basis, i.e., 400 Btu/hr per person for Figure 2-3, and

4. Rock surface area is on a per person basis, i.e., 100 square feet of rock surface area per person.

For other values of the heat input rate and rock surface area per person, temperature rises can be computed by the following relationships:

Temperature rise =

$$\frac{\text{(Actual heat input rate per person)(temp. rise from Fig. 2-3)}}{\text{4(Actual rock surface area per person)}}$$

The coefficient of heat transfer U' is discussed in Section 4-08. A U'-value of 1.2 is comparable to a bare chamber, while the U'-values of 0.3 and 0.4 approximate an uninsulated internal structure.

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 emergency conditions (1-05). Fuel-burning equipment most readily meets these purposes. Because of the limited space usually available for power plants and the high combustion air requirements, steam boiler plants for power generation are not considered. This leaves gasoline and Diesel engine and gas-turbine 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 of engines. 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

Typical Fuel, Air, and Cooling Water Requirements for 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, oil fuel consumption is approximately 10 gallons, and air for combustion is 15,000 cubic feet, for every million Btu 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 underground installations, 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 should be not less than four cfm for each square foot of floor area. The quantities exhausted through hoods over ranges, etc., should 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 tmperature 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 the rock and occurrence and amount of fissures in the rock make the amount of seepage 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 1 F 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 air temperature is closely approximated by subtracting 2 F 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 temperatures of the warmest and coldest months. The mean temperature variation for a given locale may be determined from Figures 2-4 and 2-5. For example, if a given locality has a mean annual temperature of 52 F and a mean annual range of temperature of 46 F, the extreme monthly mean temperatures are then 52 + 46/2 = 75 F, and 52 - 46/2 = 29 F. 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, θ'_o = 23 F.

2-11 For references and index to other Chapters of Part XXV see Chapter 1.

CHAPTER 3
DESIGN INFORMATION AND DATA

3-01 Heating and Cooling Load Principles

When an underground chamber is being prepared for use, its temperature is usually initially at or near the natural underground condition (4-07). The rock surfaces may or may not be wet over large areas. For most occupancies, the desired air conditions are a DB temperature of about 75 F and relative humidity of about 50 percent (55 F dewpoint), and an initial period of heating is required. For a short warmup period, it is usually necessary to supply heat in addition to that generated by the occupancy. A steady heat input to the chamber will cause the air temperature to rise a few degrees above the existing temperature of the rock face of the chamber, and the air temperature will then rise further only as the rock is warmed by the heat absorbed (4-03, Equation 4-04). When the desired air temperature is ultimately reached, regulation of the heat input, preferably by a thermostat, is required to maintain a constant air temperature. Under this condition, the absorption of heat by the rock (4-03, Equation 4-05) will slowly diminish with time (over several years), and the rock face temperature will gradually approach that of the air.

At some stage in this process, it is probable that the heat generated by the occupancy will become greater than the rate of absorption by the rock. At this point, cooling will be necessary to maintain a constant air temperature, in an amount governed by the excess of the generated heat over the heat absorption rate of the rock.

If large areas of the rock are moist, or much water vapor is generated by the occupancy, limitation of the relative humidity to 50 percent may require removal of vapor, either by ventilation with outdoor air or by dehumidification equipment, even during the warm-up period (3-05). The latent heat of the vapor, depending on its source and disposal, may materially affect the sensible heat balance of the chamber.

3-02 Warm-up Period

a. Bare Chamber - Installation of permanent heating equipment with sufficient capacity to supply all the heat necessary to achieve a very short warm-up period is not recommended. The initial heat absorption rate of rock surrounding a warmed chamber (4-03) is comparatively very

high. If a quick warm-up is necessary, temporary 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 is practicable for a warm-up period. However, the cost is comparatively high and the necessary wiring, transformer, and heaters add to the cost unless the are provided for and chargeable to some other purpose. If a few months can be allowed for the warm-up, 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, contributes heat to a space and may alleviate the warm-up problem.

The rock heat absorption is likely to be the greatest heat loss from the bare chamber during the warm-up period. Determination of rock heat absorption is covered by Equation 4-04.

b. Internal Structure - It should be possible in many instances to warm up an internal structure in a satisfactorily short time by means of the permanently installed heating equipment. The internal 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 warm-up period. The relation between heat input and warm-up time can be computed by means of Equation 4-04.

3-03 Operation at Steady Air Temperature

a. Bare Chamber - 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. Equation 4-05 is recommended for computing rock heat absorption.

When the internal load 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. In general, insulating materials applied to the rock will tend to reduce the warm-up period, and lengthen the time for the rock to approach the chamber air temperature during the constant air temperature period.

b. Internal Structure - Under the normal or steady temperature condition, the rock surrounding an internal 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.

3-04 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 computed by the relations

1 KW = 3412 Btu per hour
1 Horsepower = 2545 Btu per hour = 0.746 KW

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 equivalent of the over-all 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

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).

3-05 Dehumidification

a. Bare Chamber - The dehumidification load of a bare chamber includes water vapor from equipment and processes, if any, and personnel (3-04), 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 air dewpoint, and, conversely, water evaporates from damp rock, or from pools, whenever the surface temperature exceeds the dewpoint (4-10). The rock therefore tends to govern the humidity in the chamber by

holding the dewpoint at its own surface temperature. The rock cannot be relied upon indefinitely as a dehumidifying means, because its surface warms with time when receiving heat from the air in the chamber (4-03) (See 5-10).

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.

b. 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

$$P_W = 0.43\ d$$

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 material or to its fastenings. A vapor barrier on the chamber side of the insulation does not protect it from ground water, and such a barrier on the rock side of 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 chances of spalling, but it should not be considered effective as

either thermal insulation or a vapor barrier. The dehumidification load in such a space is subject to the same considerations as that for a bare chamber.

c. Internal Structure - If the walls, ceiling, and floor of an internal structure are vapor-proof, the water vapor to be removed by the air conditioning apparatus is equal to that liberated by the equipment and personnel (3-04) within the structure. Conditions in the annular space do not directly affect those within the structure.

If the walls, ceiling, and floor of the internal 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 internal structure through the walls, ceiling, and floor by permeation, or by convection from the annular space.

Compared to convection, migration or 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 internal structure, the interior humidity is likely to be affected 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 adequately cool. If the surface becomes warm, due to heat received from the internal structure or due to the passage of warmer air through the annular space, the rock will cease to be a means for maintaining an acceptable humidity.

3-06 Waste Heat Disposal

During normal operation, waste heat from such equipment as Diesel engines, refrigeration condensers, etc., can be dissipated in water as from an available stream or pond, 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 special heat disposal means (4-04) incorporated within 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 need.

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 by recirculating it from and to the reservoir until it reaches its maximum utilizable temperature, and then be passed finally through the equipment and wasted outside. Somewhat more heat can be absorbed by a reservoir of a given size when the water is recirculated to the reservoir, because the surrounding rock also absorbs heat. A possible disadvantage of recirculating to a reservoir is that the surrounding rock will be left warm at the end of a period of emergency and may require much time and water for cooling in preparation for a next attack.

For estimating purposes, it can be assumed that for an internal combustion engine about 30 percent of the heating 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 4-06. The heat absorbing capacity of an underground reservoir as a function of time, if the water is recirculated and retained, is given by Equation 4-07.

3-07 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 of 50 to 55 F in many regions. This is ~~usually~~ above the winter outside design temperature and below the summer outside design dry-bulb and dewpoint temperatures. A tunnel or shaft is therefore a possible means for tempering the air in winter and partially conditioning it in summer (4-05). For a long tunnel and small flow, the air passed through a tunnel assumes nearly the earth temperature, say 55 F, and therefore the tunnel can dehumidify outdoor air in summer, and if ground water is present can humidify it in winter. Such 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.

For a 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 Equations 4-11 and 4-12. Remarks about tunnels in this section apply substantially also to shafts or other openings of equal dimensions.

3-08 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 (3-05). It can affect the conductivity and heat capacity of pervious 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 air temperature in an occupied underground space is usually maintained above the initial temperature of the surrounding rock. Accordingly, heat flows from the air to the rock, at a rate dependent on their temperature difference. With time, the nearby rock is warmed, and the heat input required to maintain a given air temperature decreases. When or if the internal heat load, such as the heat liberated from lights, motors or other equipment, and personnel, exceeds the rate of heat absorption by the rock, the space air temperature will rise, unless the excess heat is removed by some cooling means such as ventilating air or air conditioning.

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 mathematical solutions are too complex for everyday use, and for this reason a simpler approximate method of calculation 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 analytical numerical solutions of the equations for cylinders and spheres in terms of functions numercially evaluated by means of the digital computer facilities of the National Bureau of Standards.

Usually, a new underground space must be warmed to some acceptable air temperature in preparation for occupancy. Heat may be supplied to the space for this purpose at a

relatively large, constant rate, until the desired air temperature is attained. If the permissible warm-up time is specified, the required heat supply rate can be computed as indicated in Item 5 of Section 4-02.

After the warm-up, presumably a constant air temperature will be desired in the space, at or near 75 F. 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 as indicated in Item 6 of Section 4-02.

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

Data forms found in Appendix A to this Chapter are recommended for use in the following steps for estimating the heat transfer from an underground space to surrounding rock.

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. (Form A.)

2. Obtain values for R, for the cylinder from Figure 4-1, and for the sphere from Figure 4-2. If R_1 for the cylinder exceeds R_2 for the sphere, the cylinder is the best approximation to the space considered. Utilize the sphere if its R-value exceeds that for the cylinder. (Form B.)

3. Compute the radius of a cylinder of the same internal area as that of the space, using Equation 4-02, or compute the radius of a sphere of the same internal area by means of Equation 4-03, whichever is applicable. (Form B.)

4. Ascertain the initial temperature of the rock, thermal conductivity, density, specific heat, and coefficients of heat transfer. These may be found from geological data, testing of samples, or estimated from information given in Sections 4-06, 4-07, 4-08, and 2-10. (Form B.)

5. For a given warm-up time (4-03), determine the required heat input by means of Equation 4-04. In conjunction with this equation, utilize Figure 4-3 for the cylindrical case, or Figure 4-4 for the spherical case. (Form B.)

6. Compute the rock heat absorption rate for the constant air temperature, or thermostatted condition (4-03) by means of Equation 4-05. Equation 4-05 will yield the

heat absorption rate for the cylinder (Figure 4-5) or for the sphere (Figure 4-6), whichever was selected for an approximation to the space being considered. (Form C.)

4-03 Equations for Heat Transfer, Air to Rock

Equations applicable to the procedure for computing heat transfer into or from 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 parallelpiped, that is, if the ceiling is arched or if other major irregularities in shape exist, or if there are doors or partitions of significant size, the area, A, should be adjusted accordingly by some appropriate method.

<u>Equivalent Cylinder or Sphere</u>

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:

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

<u>Warm-up Period</u>

Steady heat input required to raise the air temperature in a space in a specified time from the initial rock temperature to a desired air temperature.

$$q' = \frac{K\theta_i}{af(F) + K/U'} \qquad (4\text{-}04)$$

q' = Steady heat input to air in the space, Btu/hr-ft^2

K = Thermal conductivity of surrounding rock, Btu/hr-ft-F

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

a = Equivalent radius of space, ft: a_1 for the cylinder, a_2 for the sphere; selected from Equation 4-02 or 4-03, whichever corresponds to the highest R-value (Figures 4-1 and 4-2)

F = $Kt/\rho ca^2$; F_1, cylinder, F_2, sphere; $f(F_1)$ is found in Figure 4-3 and $f(F_2)$ in Figure 4-4

t = Time for warm-up period, hr

ρ = Density of rock surrounding the space, lb/ft^3

c = Specific heat of rock, Btu/lb-F

U' = Coefficient of heat transfer between conditioned space and rock face, Btu/hr-ft^2-F; see Section 4-08

<u>Thermostatted Period - Constant Air Temperature</u>

Heat input (decreasing with time) necessary to maintain a desired steady air temperature in a space:

$$q = f(F,N)\ \theta_i U'/R \qquad (4\text{-}05)$$

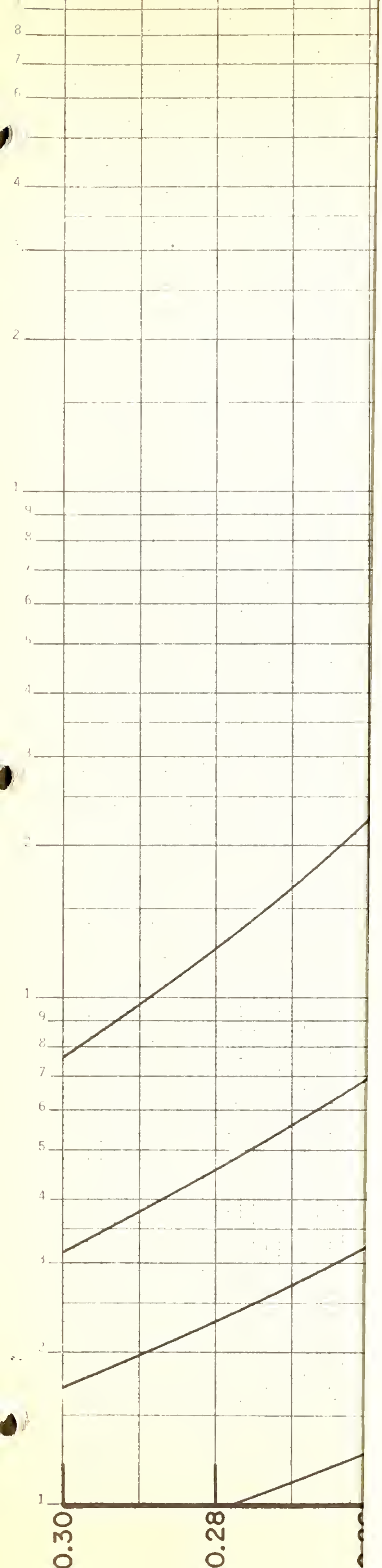
All symbols for Equation (4-04) are applicable.

q = Rock heat absorption rate (decreasing with time), Btu/hr-ft^2

N = aU'/K; values for $f(F,N)$ are found in Figures 4-5 and 4-6

t = Time measured from the start of the warm-up period of the space, hr

R = Factor involving the ratio of the volume of heated rock around the cylinder or sphere to that around the actual configuration. Values of R as a function of the dimensions of a space are taken from Figures 4-1 and 4-2.


0.30
0.28

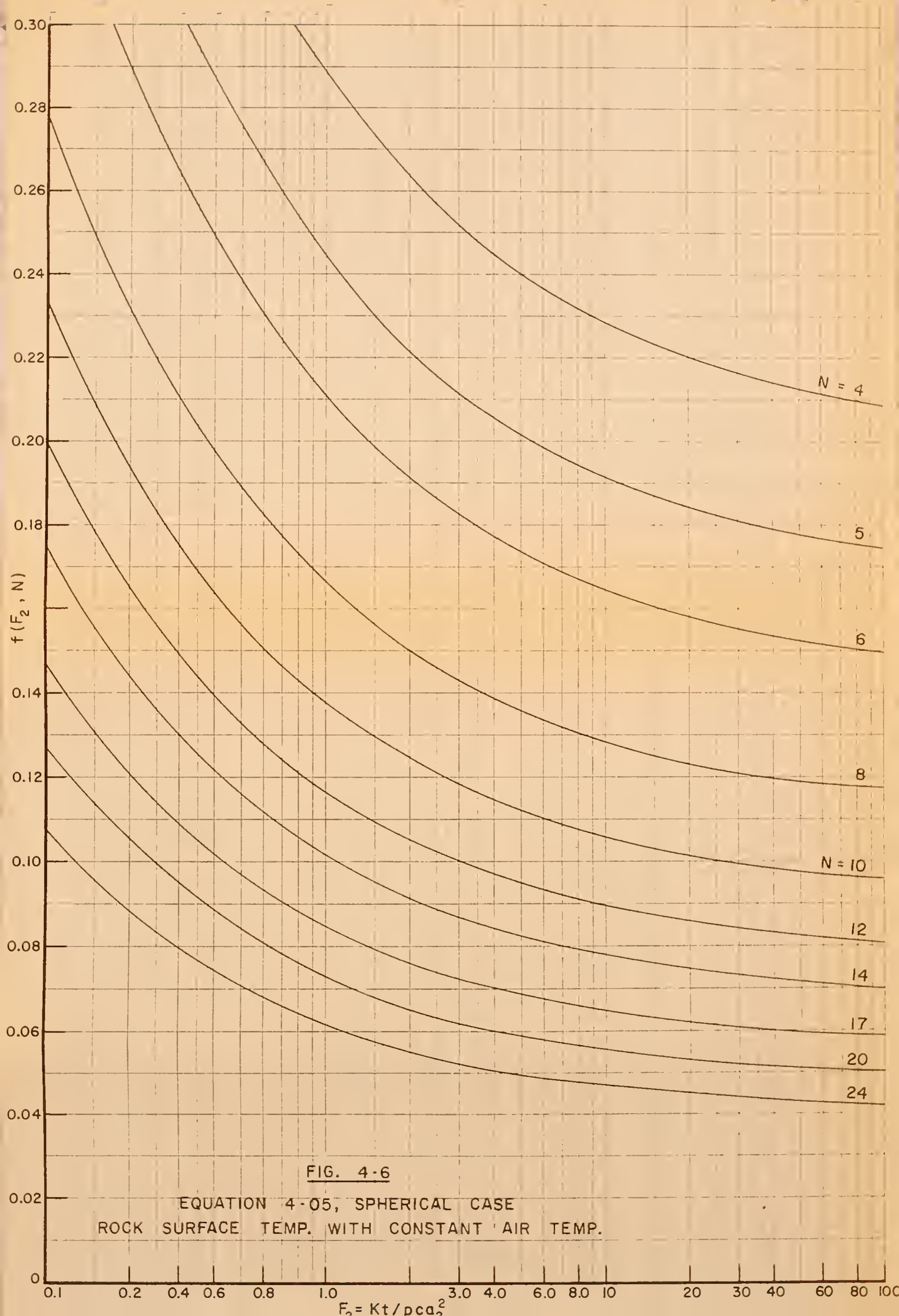
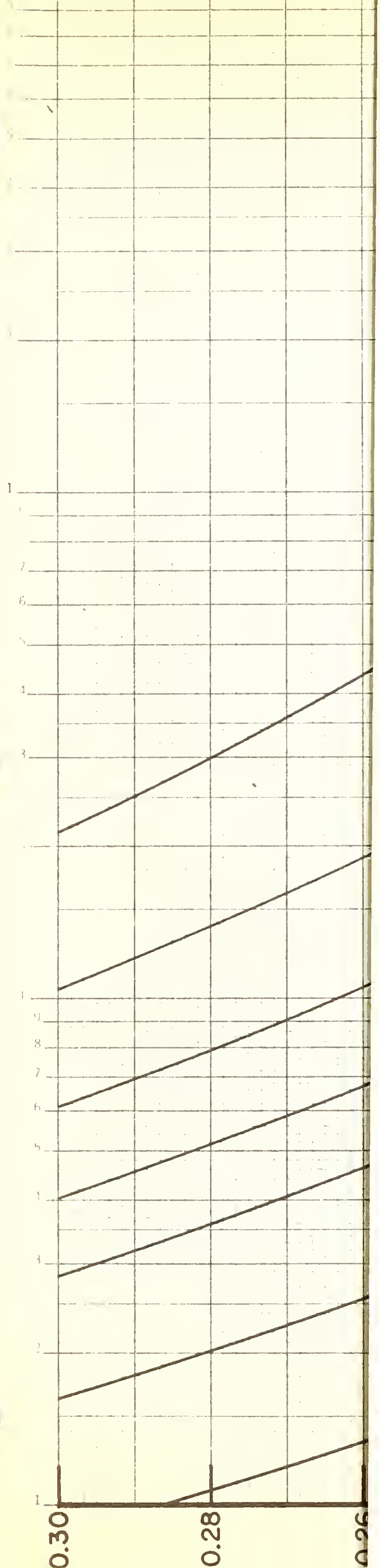


FIG. 4-6

EQUATION 4-05, SPHERICAL CASE

ROCK SURFACE TEMP. WITH CONSTANT AIR TEMP.


0.30
0.28

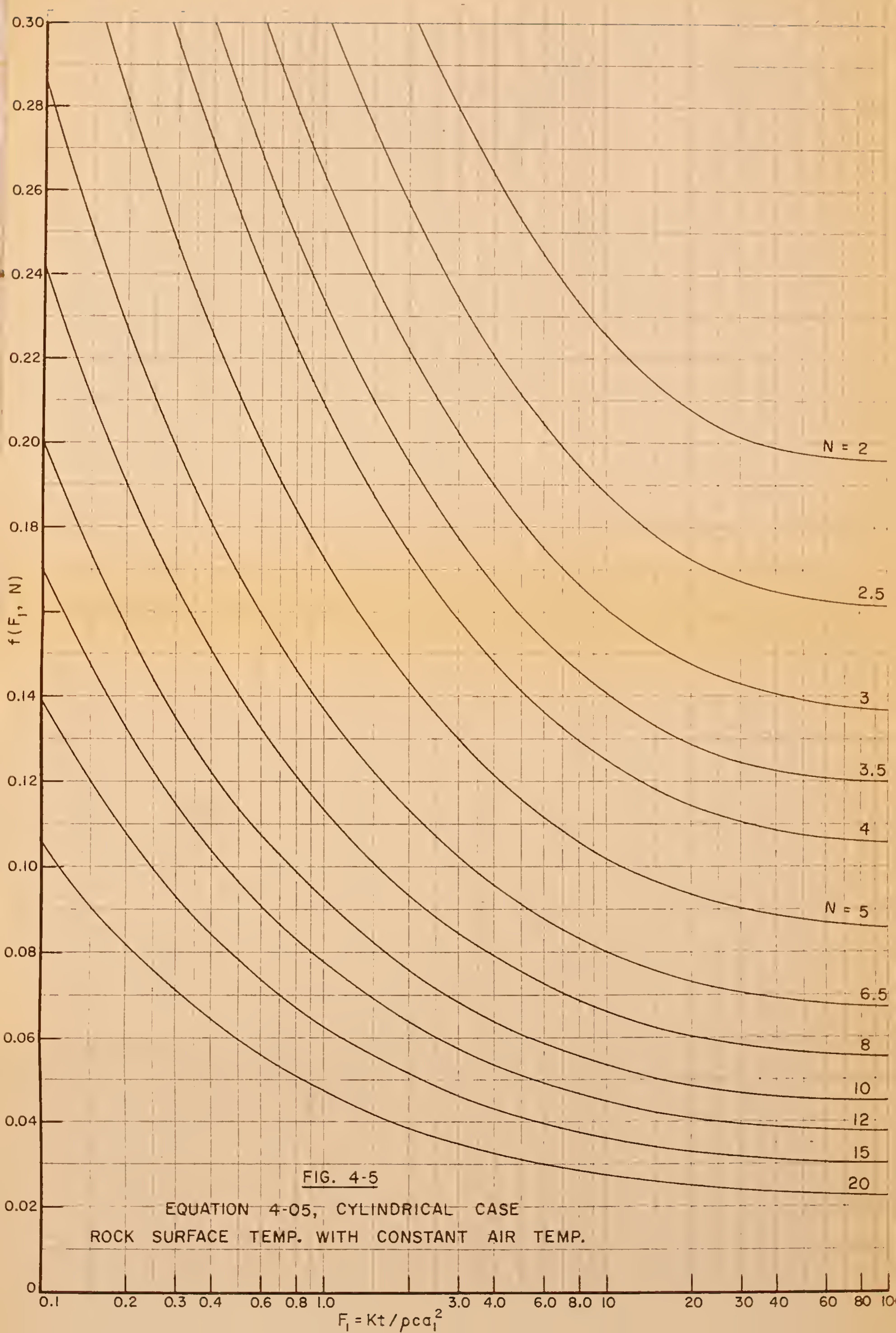


FIG. 4-5

EQUATION 4-05, CYLINDRICAL CASE

ROCK SURFACE TEMP. WITH CONSTANT AIR TEMP.

For sample problems involving the use of the equations found in Section 4-03 and for further discussion refer to Appendix B.

4-04 Heat Absorption of Underground Reservoirs

An underground reservoir of water, or water and ice, may be provided as a sink for the waste heat from engines, air conditioning equipment, or other apparatus, for use during emergencies (1-05) when outside services are cut off (3-06). 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.

Reservoir Use with Water Wastage

If the water in the reservoir is pumped through engine jackets or refrigeration condensers, etc., to absorb heat and is then wasted outside the installation, the time t in which the reservoir will be emptied can be computed by the equation:

$$t = M(T_W - T_p)/Q_W, \text{ hr} \tag{4-06}$$

M = Mass of water in reservoir, lb

T_W = Temperature of water discharged from engine jacket or condenser, etc., F

T_p = Temperature of water available from reservoir; F

Q_W = Heat to be absorbed by the water, Btu/hr

Reservoir Use with Water Recirculated and Not Wasted

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

$$\frac{\theta_W K}{q_1} = f(F,G) \tag{4-07}$$

where θ_W = Temperature rise of water above the initial water temperature, F

q_1 = Constant rate of heat input to the water from external sources such as engine jackets or condensers, Btu/hr per foot length of reservoir

$F = Kt/\rho ca^2$

t = Time from initial application of q_1, hr

a = $(s+n)/\pi$, radius of equivalent cylinder, ft

s = Height of reservoir, ft

n = Width of reservoir, ft

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

M' = Mass of water in reservoir, lb/ft^3 length of reservoir

ρ = Density of rock, lb/ft^3

c = Specific heat of rock, Btu/lb-F

c' = Specific heat of water, Btu/lb-F = 1.0

m = Length of reservoir, ft

The function f(F,G) of Equation 4-07 is plotted in Figures 4-7 and 4-7A, and Form D (Appendix A) is suggested as a work sheet for its use. This equation yields the heat absorption rate per foot of length, q_1, for a reservoir of equivalent radius, a, for a specified water temperature rise θ_W in a specified time, t.

In order to obtain the best effect from a reservoir used as a short-time heat sink, water should be taken from the lowest point in the reservoir and heated water discharged to the highest point, because the warmest water will stratify in the upper levels, while the water taken from the bottom will be the coldest available for cooling purposes.

When the water temperature reaches its maximum allowable temperature, the water of the reservoir is wasted outside the installation, and the time to waste the water can be determined using Equation 4-06.

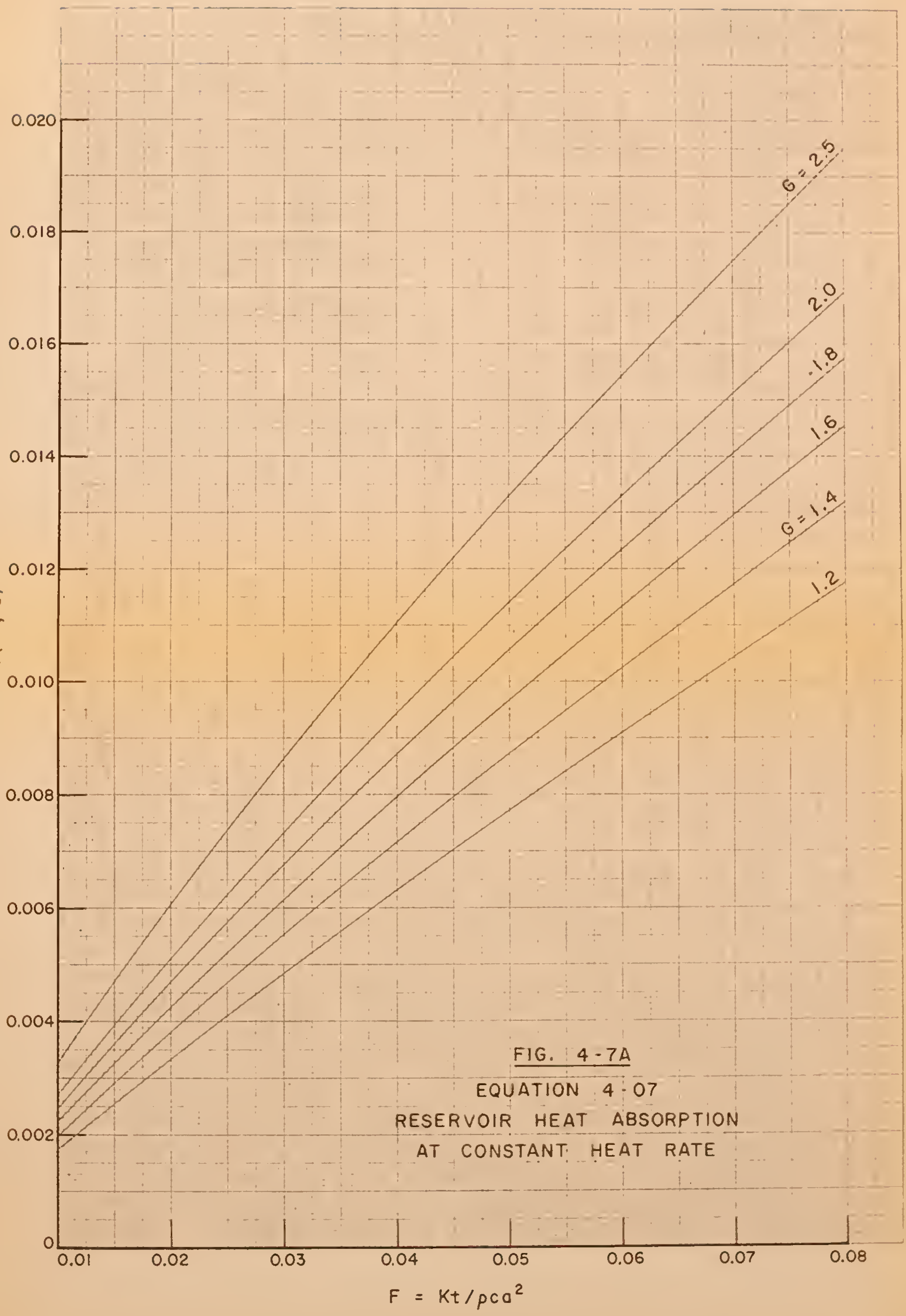


FIG. 4-7A

EQUATION 4-07

RESERVOIR HEAT ABSORPTION AT CONSTANT HEAT RATE

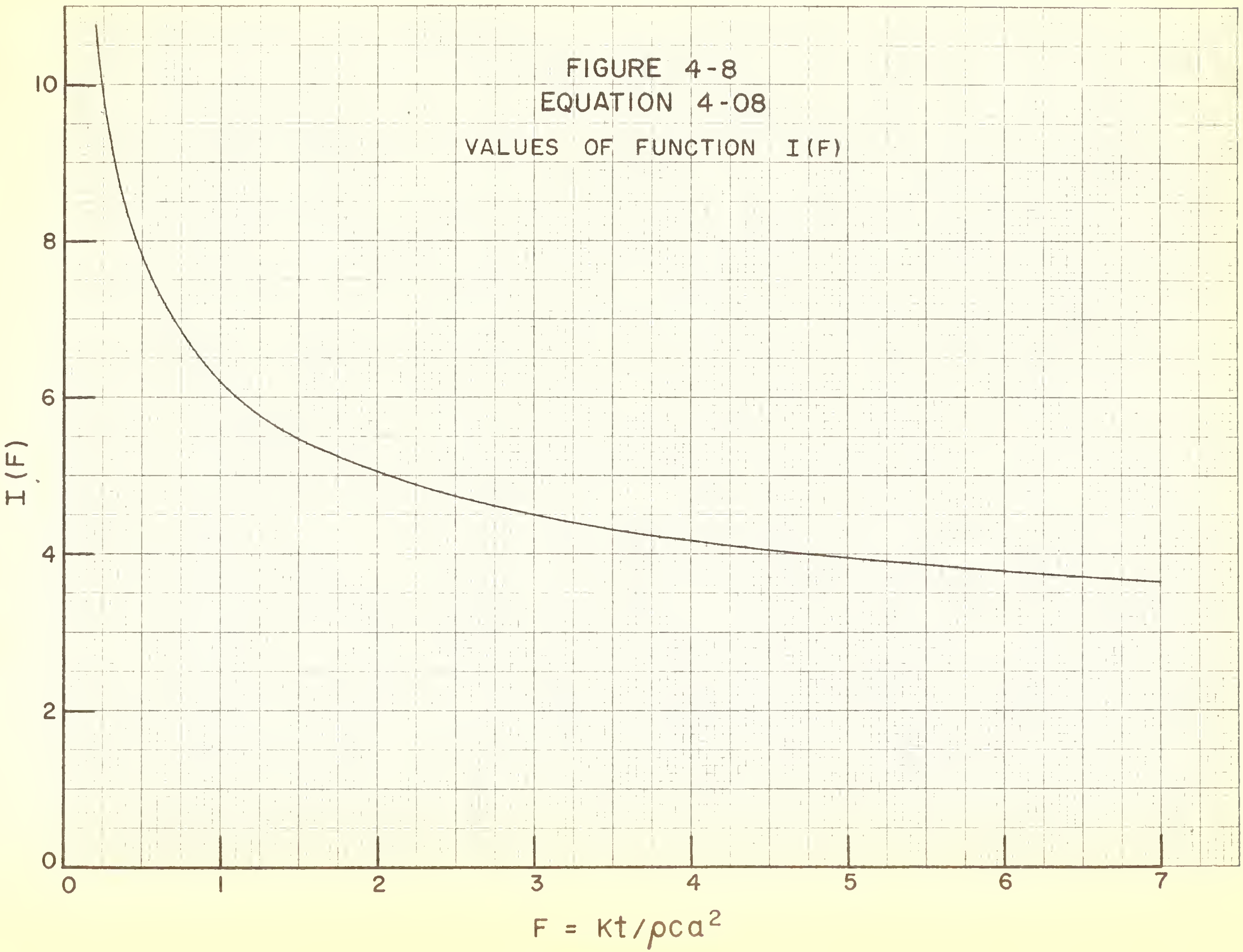


FIGURE 4-8
EQUATION 4-08
VALUES OF FUNCTION I(F)
I (F)
0
2
4
6
8
10
0
1
2
3
4
5
6
7
F = Kt/ρca²

Condensers of refrigeration equipment allow an entering water temperature as high as 100°F. Temperatures above this reduce efficiency and may be damaging to the refrigeration equipment due to high pressures. Heat exchangers of prime movers such as diesel engines may allow entering water temperatures up to 160 F or higher. Because of the differences in the allowable water temperature rises, separate reservoir systems should be designed to accept heat from the two separate heat sources.

Cooled Reservoirs

In some cases, it may be felt necessary to maintain a given reservoir at a temperature below the initial rock temperature, in order to provide additional heat absorbing capacity for an emergency period.

Cooling the Reservoir: The rate of heat removal from the water necessary to lower its temperature by Θ_i degrees F in a given period of time may be computed from Equation 4-07. When the desired water temperature has been reached, further heat must be continually abstracted from the water to remove the heat being transferred from the surrounding rock. The required rate of heat abstraction by refrigeraion equipment under this condition is given by the following equation:

$$q_i = K\Theta_i I(F) \tag{4-08}$$

where q_i = Rate of heat abstraction from water at time t, Btu/hr per foot length of reservoir

Θ_i = Temperature difference between initial rock temperature and the constant water temperature to be maintained in the reservoir, F

$F = Kt/\rho ca^2$

t = Time from start of cooling of reservoir, hr

and I(F) is found on Figure 4-8. Other symbols are found following Equation 4-07.

Heat Sink Capacity of Cooled Reservoir: The capacity of the cooled reservoir to absorb heat at a constant rate q_1 for a time t, until the water temperature rises Θ_W degrees F above its temperature at the start, can be determined using Equation 4-07.

Iced Reservoirs

If the reservoir is filled or partially filled with a mixture of water and ice, the water temperature will remain at or near 32 F during the addition of heat until all the ice is melted. During this period of time, no heat will be transferred to the surrounding rock, and the time in hours required to melt the ice can be computed by the equation:

$$t = \frac{144W}{Q} \qquad (4\text{-}09)$$

where Q = Constant rate of input of heat to the reservoir, Btu/hr

W = Weight of ice in the reservoir, lb

144 = The latent heat of fusion of ice, Btu/lb. After the ice has melted, heat will be transferred to the rock, due to the temperature rise of the water. The further heat sink capacity of the reservoir after the ice has melted can be determined as for the cooled reservoir, using Equation 4-07.

The design of an underground reservoir using an ice and water mixture demands careful consideration of the method of distributing ice along the length of the reservoir. Further discussion of this subject is given in Section 5-16. A reservoir filled with ice only at the front end maintains an average water temperature of about 34 F in the remaining length of reservoir and serves to provide an additional heat sink capacity due to sensible cooling of the water and surrounding rock below the initial temperature of the rock.

For sample problems involving the use of equations found in Section 4-04, refer to Appendix C.

4-05 Heating and 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 transferred alternately from the air to the rock in summer and from the rock to air in winter. Savings are possible under both conditions, since the delivered air is warmed in winter and cooled and possibly somewhat dehumidified in summer, thus reducing the heating and cooling loads, respectively (3-07). The temperature of the air at exit, like

that at entrance, oscillates above and below the mean annual temperature, but the amplitude of the temperature change is smaller at exit.

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

$$\theta_o = \theta_o' \cos wt \qquad (4\text{-}10)$$

where the time, t, is equal to zero on July 15, giving a maximum temperature on July 15 and a minimum temperature on January 15. θ_o' is the amplitude or maximum temperature departure of outside air from the mean annual air temperature. Because the variation of outdoor temperature is based on seasonal changes and not on diurnal changes, θ_o' may be calculated as shown in Section 2-10.

Based on the above assumptions, equations are given for calculating the following temperatures:

1. The temperature departure, θ_L, at a distance L from the outside entrance to the tunnel and at time, t:

$$\theta_L = \theta_o' \, e^{-AA'} \cos(wt - A'B) \qquad (4\text{-}11)$$

2. The amplitude, or maximum air temperature departure at point L:

$$\theta_L' = \theta_o' \, e^{-AA'} \qquad (4\text{-}12)$$

where A = g(z,N), Figure 4-9

A' = KL/c'W'

a = 2 S/P, equivalent radius, ft

B = f(z,N) Figure 4-9

c' = Specific heat of air = 0.24 Btu/lb-F

e = Base of natural logarithms = 2.718..

h = Coefficient of heat transfer between air and surface of rock, Btu/hr-ft^2-F (Suggested values are given in Figure 4-10)

K = Thermal conductivity of rock, Btu/hr-ft-F

L = Distance from outside entrance of airway, ft

N = ah/K

P = Average transverse perimeter of airway, ft

S = Average transverse area of airway, ft^2

t = Time, hr

W' = Weight rate of air flow, lb/hr

w = Angular velocity = $2\pi/8760$ = 0.000717 radian/hr

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

α = Thermal diffusivity of rock = $K/\rho c$, ft^2/hr

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. Refer to Section 2-10.

Form E is suggested as a work sheet for problems of this type. If a tunnel or shaft is used only intermittently as an airway, the equations in this section do not apply. However, it is believed that these equations will give conservative values for heat exchange in that full utilization of the heat capacity of the surrounding rock is not realized for the intermittent operation.

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.

Appendix D contains an illustration of the use of Equations 4-11 and 4-12.

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-F 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-F have been reported.

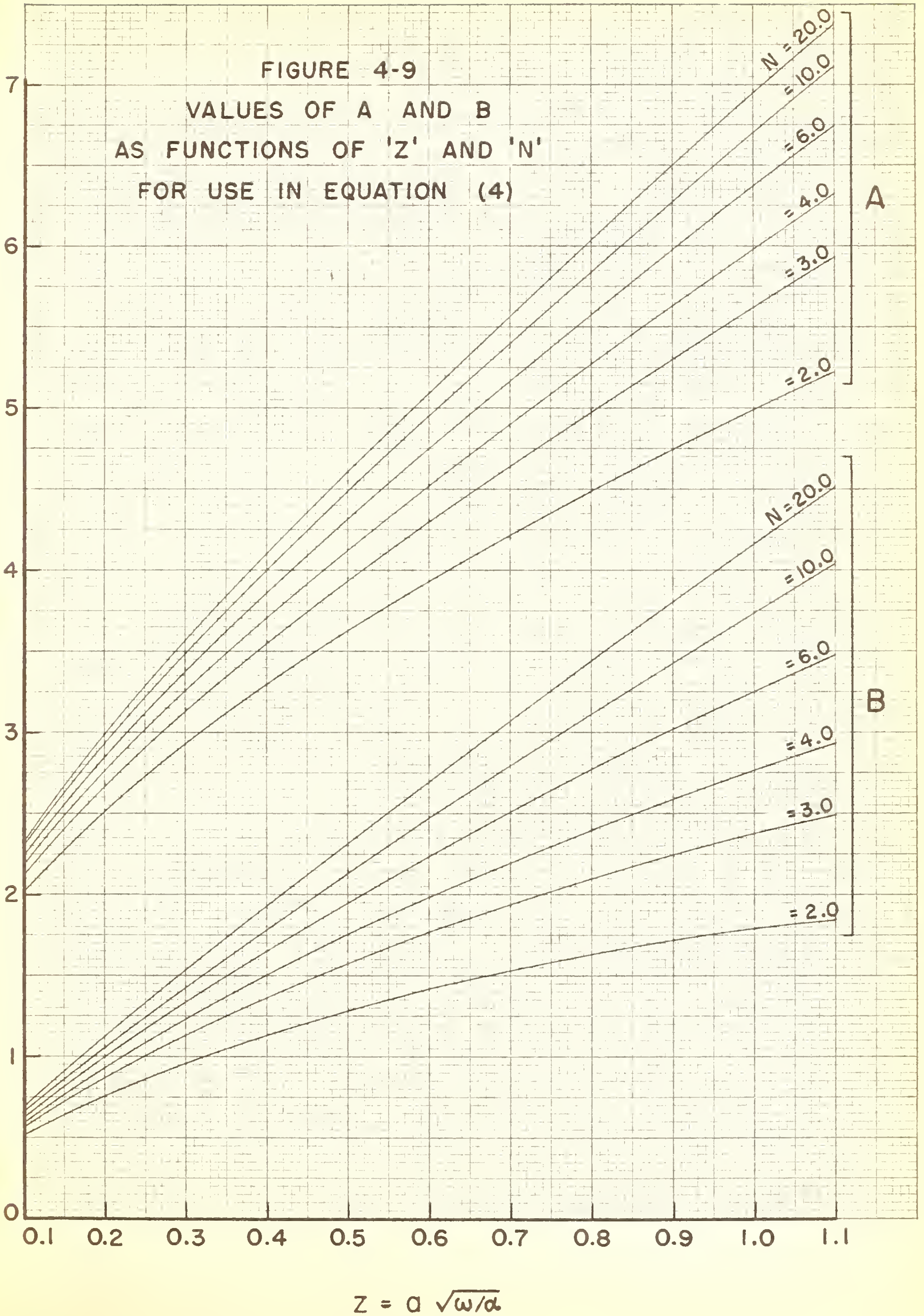


FIGURE 4-9
VALUES OF A AND B
AS FUNCTIONS OF 'Z' AND 'N'
FOR USE IN EQUATION (4)
N = 20.0
= 10.0
= 6.0
= 4.0
= 3.0
= 2.0
A
N = 20.0
= 10.0
= 6.0
= 4.0
= 3.0
= 2.0
B
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
Z = a √ω/α

For greenstone, present in the mountains of Virginia, experimental measurements show a thermal conductivity of about 1.5 Btu/hr-ft-F, with a density of 186 lb/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 tests on selected specimens, or by the use of Figure 4-11 in conjunction with petrographic analyses of specimens. Facilities for making these tests or analyses are maintained in several laboratories in this country.

The density of igneous and metamorphic rocks generally falls in the range from 150 to 190 lb/ft^3, and that of the sedimentary rocks in the range from 100 to 175 lb/ft^3. For igneous and metamorphic rocks, the thermal conductivity falls in a range from 1.2 to 2.0 Btu/hr-ft-F. 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, and which have to be considered, are numerous: composition, porosity, temperature, grain size and shape, and fluid content.

4-07 Initial Underground Conditions

At depths of 50 to 70 feet, the undisturbed temperature of earth or rock can be expected to be within a few degrees of the mean annual air temperature for the region (2-10), 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 1 F 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 a proposed site.

The earth's surface is warmed chiefly by solar radiation and it is cooled by wind, rain, or snow, and by radiation to the sky, particularly at night. There is therefore an approximately regular diurnal cycle in the surface temperature, but its effect disappears, practically speaking, at a depth of a foot or so in the earth. The annual surface temperature variation is greater and its effects may be significant to depths of 15 or more feet for some purposes. Some measurements were made at various depths down to 13 feet near Washington, D. C., and the results are shown on Figure 4-12 (Ref. 16). The curves indicate an annual amplitude of about 4 F, and a mean temperature of about 53 F, 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. 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 internal 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 of internal structures be considered to have the same values as those ordinarily used for inside surface coefficients.

The coefficient U', appearing in Equations 4-04 and 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 air temperature in the conditioned space and the temperature of the surrounding rock. For an internal structure, one significant temperature is that within the space, and the other is that of the surrounding rock surface.

Values 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.

During experiments in an empty underground chamber with rock surfaces such as those left after blasting, the air-to-rock heat transmer coefficient, U', with only slight air motion, ranged from 1.4 to 1.0 Btu/hr-ft^2-F, depending on the temperature difference between the air and the rock, with an average value of 1.2, based on projected wall area, ignoring irregularities left after blasting. For a bare chamber typically filled with air-warmed objects such as furniture and equipment, radiation between the objects and the rock would tend to yield values of U' approaching 1.65 Btu/hr-ft^2-F. For the surface conductances of internal structures, a value of $f_o = f_i = 1.65$ is recommended for present purposes. With these values, heat transfer coefficients of walls, ceilings, and floors of internal structures can be computed by means of the following equations:

$$U' = \frac{1}{\frac{1}{1.65} + \frac{1}{C} + \frac{1}{1.25}} \qquad (4\text{-}13)$$

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

TABLE 4-1

Heat Transfer Coefficients for Underground Structures
$Btu/hr\text{-}ft^2\text{-}F$

Material or Structure	
Bare rock surface	1.2 to 1.65
Studs with 3/8" gypsum board on one side	0.59
Studs with 3/8" gypsum board on both sides	0.35
Studs with 1/2" insulating board on one side	0.34
Studs with 1/2" insulating board on both sides	0.18
Brick, one course - 4" thick 3/8" gypsum board	0.47
Brick, one course - 4" thick no finish	0.54
Brick, one course - 4" thick 1/2" insulating board	0.30
Brick, two course - 8" thick no finish	0.38
Concrete, 8" thick no finish	0.49
Concrete construction floors, (3") no ceiling, no flooring	0.60
Concrete construction floors, (3") no ceiling, 1/8" asphalt tile	0.59
Metal roof deck, bare	0.77
Metal roof deck, roofing and 1/2" insulating board	0.31
Wood roof 1" roofing and 1/2" insulating board	0.24

U' = heat transfer coefficient, based on temperature difference between chamber air and rock surface.

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. There is no danger of condensation in parts of an underground structure, except on chilled pipes or surfaces, provided the temperature of the surrounding rock is between the dewpoint and dry-bulb temperatures maintained in the conditioned space. In such an application, a vapor barrier may nevertheless be warranted to reduce vapor ingress and the latent air conditioning load, if the dewpoint in the surrounding space is higher than that in the internal structure. If the surrounding rock should be at a temperature lower than the dewpoint maintained in the internal structure, which is unlikely for more than a relatively short time, vapor permeation through the walls, which would reduce the air conditioning latent load, would be impeded by a vapor barrier. Methods for predicting vapor transfer and condensation in walls are available (Ref. 17 Ref. 1 (Chapter 10)).

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 or a film on the surface, or it may leak in through faults or fissures. Because the possible hydrostatic pressures are high (3-05), it is probably more practical to drain off excess water rather than to attempt to stop leaks or to treat the rock surfaces and make them impervious.

Evaporation from wet or damp 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 dewpoint at the rock surface temperature. In the course of time, the rock surface temperature increases and water may evaporate from the surface and become 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', in $lb/hr\text{-}ft^2$ for a wet surface L ft long in the direction of air flow parallel to the surface for a velocity of V ft/min and for a vapor pressure difference of (P_s-P_a) psi, where P_s is the vapor pressure of water at the temperature of the wet surface, and P_a is the vapor pressure of the moving air.

Estimates of evaporation from rock are difficult because the area of the wet surface cannot be predicted with certainty for a 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 approaching 100 percent, since parts of this space may contain saturated air at times.

For the particular case of a small internal structure in a large chamber, see 5-10.

Appendix 4A

DATA FORMS

The data forms in this appendix are suggested to provide a systematic procedure for computing temperatures and heat flow rates from the equations in Chapter 4. The forms may be altered or broadened in order to suit individual preferences.

Appendix 4A - Data Form A

Underground Installation Air Conditioning Design Data and Computations

Design Information   Date:

Location and purpose: ____________________

Dimensions, rock chamber

Length, m, ft^2 = ; Floor area, A', ft^2 =

Width, n, ft = ; Internal area, A, ft^2 =

Height, s, ft = ; Volume, ft^3 =

Remarks: ____________________

Dimensions, internal structure (if used)

Length, ft = ; Floor area, ft^2 =

Width, ft = ; Internal area, ft^2 =

Height, ft = ; Volume, ft^3 =

Depth of overburden, geological formation, and moisture conditions: ____________________

Climate, outside air	Winter		Summer	
	Minimum	Design	Maximum	Design
DB, F				
RH, %				

Rock temperature, initial undisturbed, F =

Required inside air condition, F = ; %RH =

Appendix 4A - Data Form B

Heat Absorption by Rock Surrounding an Underground Installation; Warm-Up Period
(Refer to Section 4-03 and Appendix 4B)

Chamber dimensions: Length, m, ft =

Width, n, ft =

Height, s, ft =

Internal area, Eq 4-01, A, ft^2 = 2(mn + ms + ns) =

Equiv. cyl, radius, Eq 4-02, a_1, ft = $A/2\pi m$ =

Equiv. spher. radius, Eq 4-03, a_2, ft = $\sqrt{A/4\pi}$ =

R_1* (cylinder) Figure 4-1 =

R_2** (sphere) Figure 4-2 =

Rock properties: Density, ρ, lb/ft^3 =

Thermal conductivity, K, Btu/hr-ft-F =

Specific heat, c, Btu/lb-F =

Initial undisturbed temp. (4-07), T_r, F =

Design air temperature, T_1, F =

$\theta_1 = (T_1 - T_r)$, F =

U', (4-08), Btu/hr-ft^2-F =

Desired warm-up time, t, hours =

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

$q' = \dfrac{K\theta_1}{af(F) + K/U'}$, Btu/hr-$ft^2$ =

Total rock heat absorption rate, Aq', Btu/hr =

*If R_1 exceeds R_2, utilize cylindrical case ($a = a_1$ and Fig. 4-3)

**If R_2 exceeds R_1, utilize spherical case ($a = a_2$ and Fig. 4-4)

Appendix 4A - Data Form C

Heat Absorption by Rock Surrounding an Underground Installation
Steady Temperature or Thermostatted Case

(Refer to Section 4-03 and Appendix 4B)

Equivalent radius, rock properties and necessary temperatures are found on Data Form B. Using Equation 4-05, solve for the rock heat absorption rate as a function of time.

Equation 4-05: $q = U'\Theta_1 f(F,N)/R$

$N = aU'/K =$

Time from start of warm-up period, t, hr	2000	5000	10,000	
$F = Kt/\rho ca^2$				
f(F,N)*				
q (Eq 4-05), $Btu/hr\text{-}ft^2$				
Rock heat absorption rate, Aq, Btu/hr				

*f(F,N) is found from Fig. 4-5 for the cylindrical case and from Fig. 4-6 for the spherical case.

Heat Absorption of an Underground Reservoir Filled with Water (Refer to Section 4-04 and Appendix 4C)

Determination of necessary reservoir length, given other variables:

Permissible temp. rise of water, θ_W, F =

Necessary time duration, t, hours =

Heat absorption rate by the reservoir, Q, Btu/hr =

Rock properties: Density, ρ, lb/ft^3 =

Thermal conductivity, K, Btu/hr-ft-F =

Specific heat, c, Btu/lb-F =

Properties of water: Density (average, ρ', lb/ft^3 = 62.4

Specific heat, c', Btu/lb-F = 1.0

Dimensions of reservoir for rectangular cross-section:

Width, n, ft =

Height, s, ft =

Radius of equiv. cylinder, $a = (s+n)/\pi$, ft =

From Equation 4-07, $\theta_W K/q_1 = f(F,G)$

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

$M' = 2x62.4\ (s+n)$, lb/ft length =

$G = 2\pi a^2 \rho c/M'c'$ =

f(F,G), from Fig. 4-7 or 4-7A =

$q_1 = \theta_W K/f(F,G)$, Btu/hr-ft =

Required length of reservoir, $L = Q/q_1$, ft =

Total volume of reservoir, Volume = snL, ft^3 =

Appendix 4A - Data Form E

Cooling or Heating of Air in Tunnels or Shafts
Continuous Air Flow, Annual Weather Cycle
(Refer to Section 4-05)

Dimensions of tunnel:

Length, L, ft =	;	Perimeter, P = 2(n+s), ft	=
Width, n, ft =	;	Area, S = ns, ft^2	=
Height, s, ft =	;	Equiv. radius, a = 2S/P, ft	=

Outside air conditions (2-10):

Mean annual temp, T_a, F =
Mean annual range of temp, T_m, F =
Maximum departure, $\theta_o' = T_m/2$, F =

Air capacity:

Air flow rate, V, ft^3/min =
Air density, ρ', lb/ft^3 =
Air flow rate, $W' = 60\rho' V$, lb/hr =
Velocity, v = V/S, ft/min =

Properties of rock

Density, ρ, lb/ft^3 =
Thermal conductivity, K, Btu/hr-ft-F =
Specific heat, c, Btu/lb F =
Thermal diffusivity, $\alpha = K/\rho c$, ft^2/hr =

Coefficient of heat transfer, h (Fig. 4-9), Btu/hr-ft^2-F =

w = 0.000717 radian/hr

$z = a\sqrt{w/\alpha}$ =	;	A (Fig. 4-9) =
N = ah/K =	;	B (Fig. 4-9) =
A' = KL/0.24 W' =	;	

Extreme temperature at distance L from air entrance, Eq. 4-12:

Maximum temp; $T_a + \theta_o' e^{-AA'}$ =
Minimum temp; $T_a - \theta_o' e^{-AA'}$ =

APPENDIX 4B

Heat Absorption by Rock Surrounding Underground Spaces: Some Practical Aspects

4B-1 Introduction

Rock heat absorption is an important factor in the heating and air conditioning of underground spaces, and the purpose of this appendix is to indicate the range of rock heat absorption rates that may occur in practice and to show the effects of differences in such factors as size of space, thermal properties of rock, and heat transfer coefficient, U'. The equations of Section 4-03 are utilized and rock heat absorption is discussed in terms of q', the steady heat flux from air to rock assumed for a warm-up period, and q, the decreasing heat flux from air to rock that occurs when the air in an underground chamber is maintained at an approximately constant temperature.

4B-2 Applicable Problems and Equations

In order to show the differences that occur due to variation in size of space, thermal properties of rock, and coefficient of heat transfer U', computed solutions of the rock heat absorption equations are shown graphically in Figures 4B-1 to 4B-4 for certain values of these variables as given in the table below.

Chamber Sizes	1	2	3
Length, m, ft	200	200	200
Height, s, ft	10	10	30
Width, n, ft	17.4	35.3	39.4
Surface area, A, ft^2 (Eq 4-01)	11310	18830	30120
Equiv. radius, a_1, ft (Eq 4-02)	9	15	24
R (from Figure 4-1)	0.875	0.875	0.875

Thermal Properties of Rock	1	2
Thermal conductivity, K, Btu/hr-ft-F	1.2	1.7
Density, ρ, lb/ft^3	179	165
Specific heat, c, Btu/lb-F	0.21	0.18
Thermal diffusivity, $K/\rho c$, ft^2/hr	0.032	0.057

Heat Transfer Coefficients	1	2
Transmittance from air in conditioned space to rock face, U', Btu/hr-ft^2-F	1.2	0.4

Figures 4B-1 and 4B-2 show solutions of Equation 4-04 for the warm-up period with steady heat input, and Figures 4B-3 and 4B-4 give solutions of Equation 4-05 for the constant air temperature period with decreasing heat absorption by the rock.

All computations for heat flow q or q' are based on a temperature difference, θ_i, of 25 F. This temperature difference represents an air temperature of 75 F and an initial rock temperature of 50 F. If a value of heat flow for a different θ_i is desired, it may be found from the following relationships

$$q = q_o \theta_i/25$$

$$q' = q'_o \theta_i/25$$

where the subscript o denotes the values of heat flow shown in the figures computed for the temperature difference of 25 F.

The numerical computation of the results presented graphically is illustrated below, for the case defined by the variables listed under 1 in the table.

Surface area:

Equation 4-01: $A = 2(mn + ms + sn)$
$= 2(200 \times 17.4 + 200 \times 10 + 10 \times 17.4)$
$= 11{,}310 \text{ ft}^2$

Equivalent radius:

Equation 4-02: $a = \frac{A}{2\pi m} = \frac{11{,}310}{2\pi \times 200}$
$= 9 \text{ ft}$

From Figure 4-1: $R = 0.875$, for $m/n = 11.5$
$F = \frac{Kt}{\rho c a^2} \quad \frac{0.032\ t}{(9)^2}$
$= 0.000395\ t$

Constant heat input necessary to raise air temperature 25 F in 20 days:

Since $F = 0.000395 \times 20 \times 24 = 0.19$

From Figure 4-3: $f(F) = f(0.19) = 0.414$

Equation 4-04: $q' = \frac{K\Theta_i}{af(F) + K/U'} = \frac{1.2x25}{9x0.414 + 1.2/1.2}$
$= 6.34$ Btu/hr-ft^2 or
$= 6.34x11,310 = 71,700$ Btu/hr for 20 days.

The average heat input needed for operation with constant air temperature, one year (8760 hours) after the start of the initial warm-up:

$$F = 0.000395x8670 = 3.46$$

$$N = a\ U'/K = 9x1.2/1.2 = 9$$

From Figure 4-5: $f(F,N) = 0.073$

Equation 4-05: $q = f(F,N)\ U'\Theta_i/R = 0.073x1.2x25/0.875$
$= 2.5$ Btu/hr-ft^2 or
$= 38,280$ Btu/hr

4B-3 General Discussion

The problems of Section 4B-2 deal with the cylinder as an approximation for the computation for heat flow because a cylindrical configuration is likely to be the best approximation for most underground installations. The spherical configuration is also possible; it exhibits much the same properties as the cylindrical.

To obtain a warm-up, heat may be supplied to a chamber at a fast rate during phase 1. Permanent heating installed to maintain temperature during phase 2 may be inadequate to provide an adequately fast warm-up. In such a case, utilization of temporary heating equipment to supplement the heating capacity may be desirable.

a. Effect of size of chamber - The equivalent radius defined in Equation 4-02 is a measure of all three of the dimensions of length, width, and height. Figures 4B-1 through 4B-4 show that the rate of heat absorption per square foot of rock surface at any given time decreases as the equivalent radius increases. For example, from Figure 4B-1, for U' = 1.2 and time = 80 days, the steady heat input for the three equivalent radii is as follows:

a = 9 ft, q' = 4.0 Btu/hr-ft^2, or 45,240 Btu/hr for the chamber

a = 15 ft, q' = 3.62 Btu/hr-ft^2, or 68,160 Btu/hr for the chamber

a = 24 ft, q' = 3.42 Btu/hr-ft^2, or 103,010 Btu/hr for the chamber

The total heat input rate necessary, of course, increases with increase in radius as expected.

b. Effect of thermal properties of rock - An increase in the thermal diffusivity ($K/\rho c$) of the rock increases the amount of heat necessary to warm a space in a given time. This can be shown from Figures 4B-1 and 4B-2 for a case where a = 9 ft, U' = 1.2, and time = 80 hours.

from Figure 4B-1, $K/\rho c$ = 0.032, q' = 4.0 Btu/hr-ft^2
from Figure 4B-2, $K/\rho c$ = 0.057, q' = 4.71 Btu/hr-ft^2

The thermal properties used in the problems of Section 4B-2 represent approximate extremes for common rocks, so that heat flow for most installations probably lie between the values shown in Figures 4B-1 to 4B-4.

c. Effect of the coefficient of heat transfer, U' - The factor U' represents the heat transfer coefficient from the air in a conditioned space to the surrounding rock in Btu/hr-ft^2-F. The temperature difference, in deg F, is measured between the air in the conditioned space and the rock surface. Observations in a bare chamber indicated that the value U' = 1.2 adopted for the present computations is approximately appropriate. For an internal structure, the relevant temperature difference is that between the air within the structure and the rock surface, and the average U' value depends on the construction of the walls, floors, and ceilings (Equation 4-13).

The rate of heat transfer to the rock is at all times given by $U'\Delta T$, where ΔT is the existing temperature difference between the air and the rock surface. However, U' for a bare chamber decreases approximately as the one-third power of ΔT, and in addition, its effect on the rate of rock heat absorption also decreases with time, as is shown by the tendency of the curves for U' = 1.2 and U' = 0.4 in Figures 4B-1 to 4B-4 to converge with time.

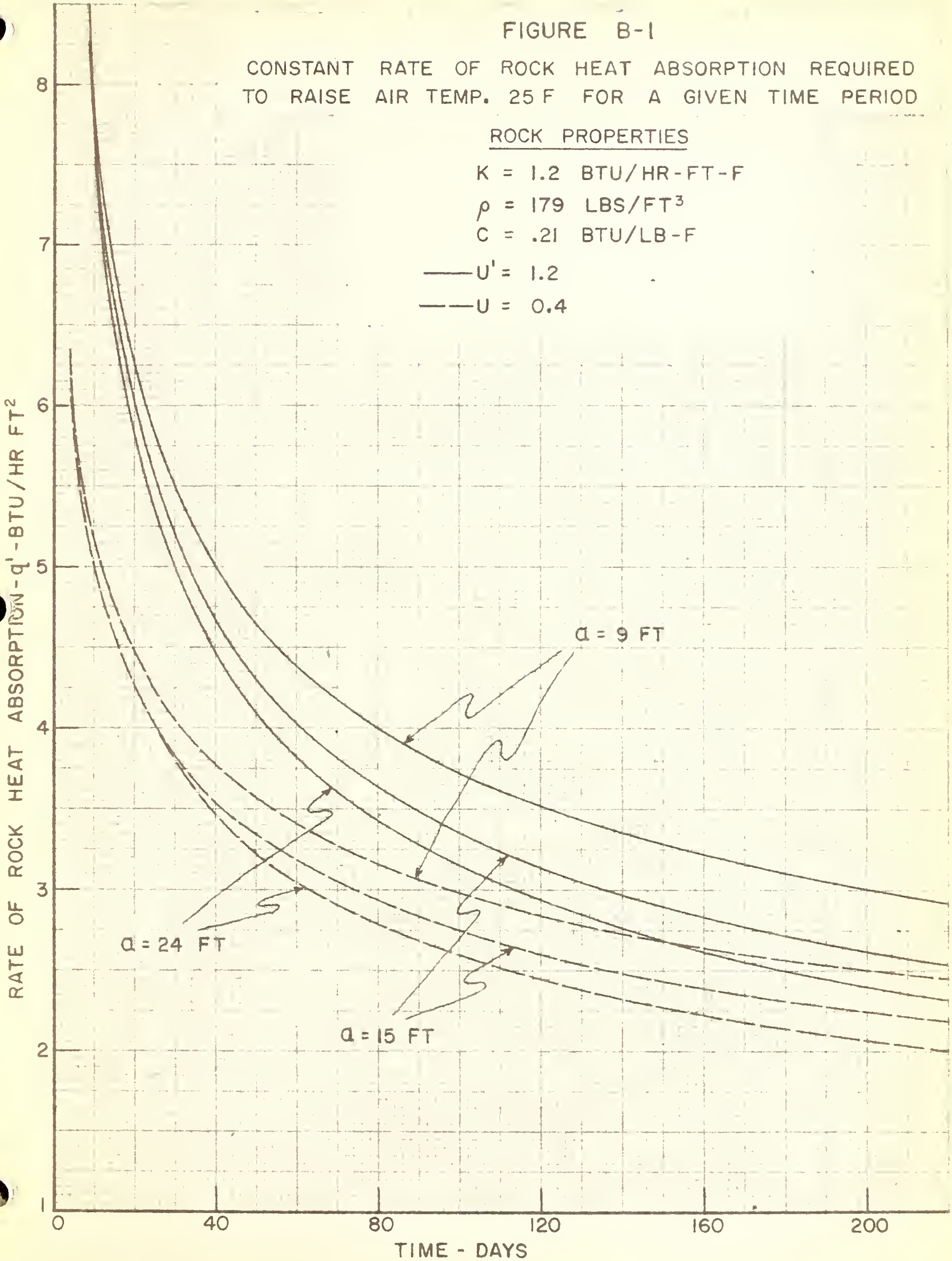


FIGURE B-1
CONSTANT RATE OF ROCK HEAT ABSORPTION REQUIRED TO RAISE AIR TEMP. 25 F FOR A GIVEN TIME PERIOD
ROCK PROPERTIES
K = 1.2 BTU/HR-FT-F
ρ = 179 LBS/FT³
C = .21 BTU/LB-F
U' = 1.2
U = 0.4
a = 9 FT
a = 24 FT
a = 15 FT
RATE OF ROCK HEAT ABSORPTION-q'-BTU/HR FT²
TIME - DAYS
1
2
3
4
5
6
7
8
0
40
80
120
160
200

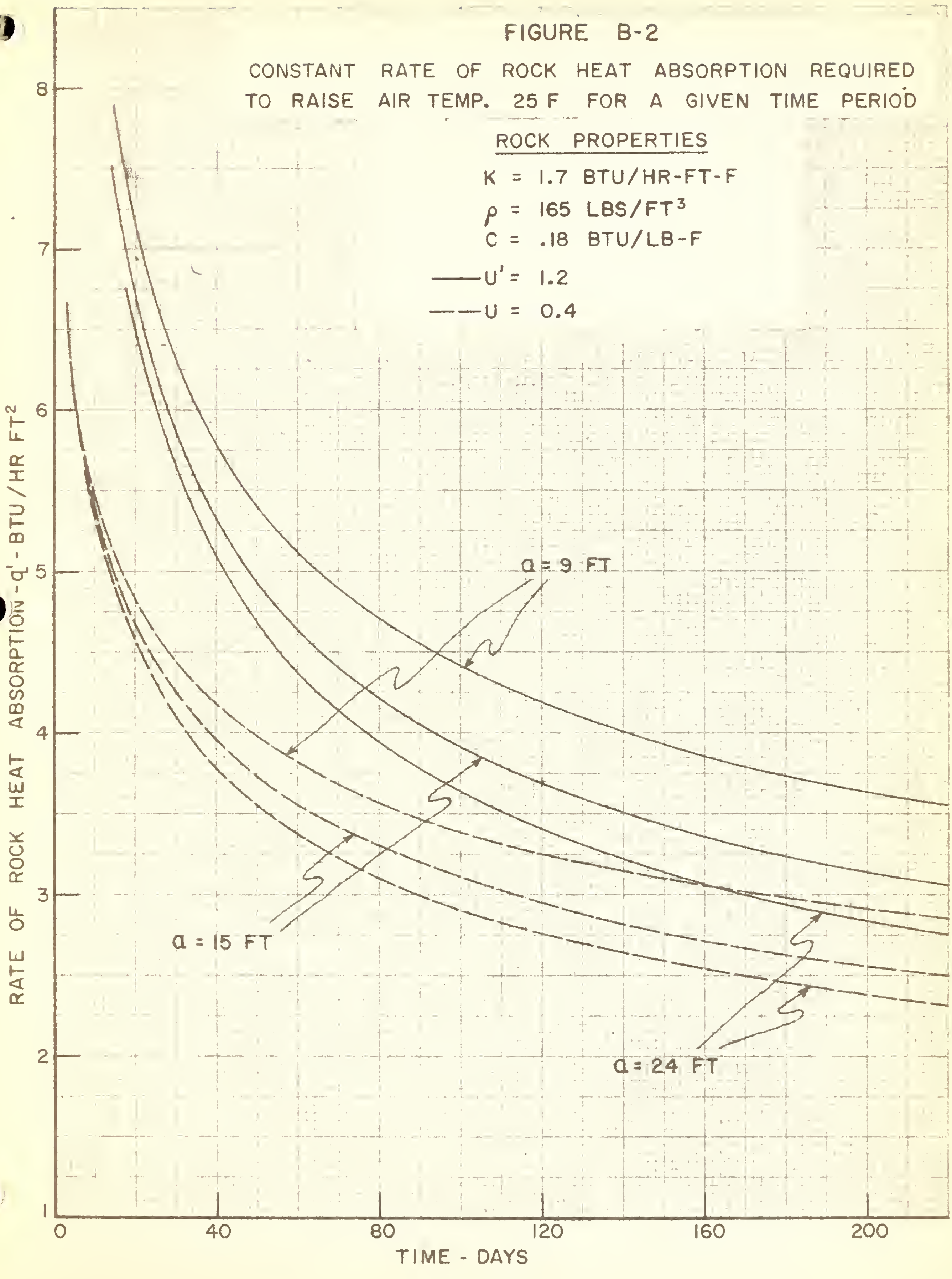


FIGURE B-2
CONSTANT RATE OF ROCK HEAT ABSORPTION REQUIRED TO RAISE AIR TEMP. 25 F FOR A GIVEN TIME PERIOD
ROCK PROPERTIES
K = 1.7 BTU/HR-FT-F
ρ = 165 LBS/FT³
C = .18 BTU/LB-F
U' = 1.2
U = 0.4
a = 9 FT
a = 15 FT
a = 24 FT
RATE OF ROCK HEAT ABSORPTION - q' - BTU/HR FT²
TIME - DAYS
1
2
3
4
5
6
7
8
0
40
80
120
160
200

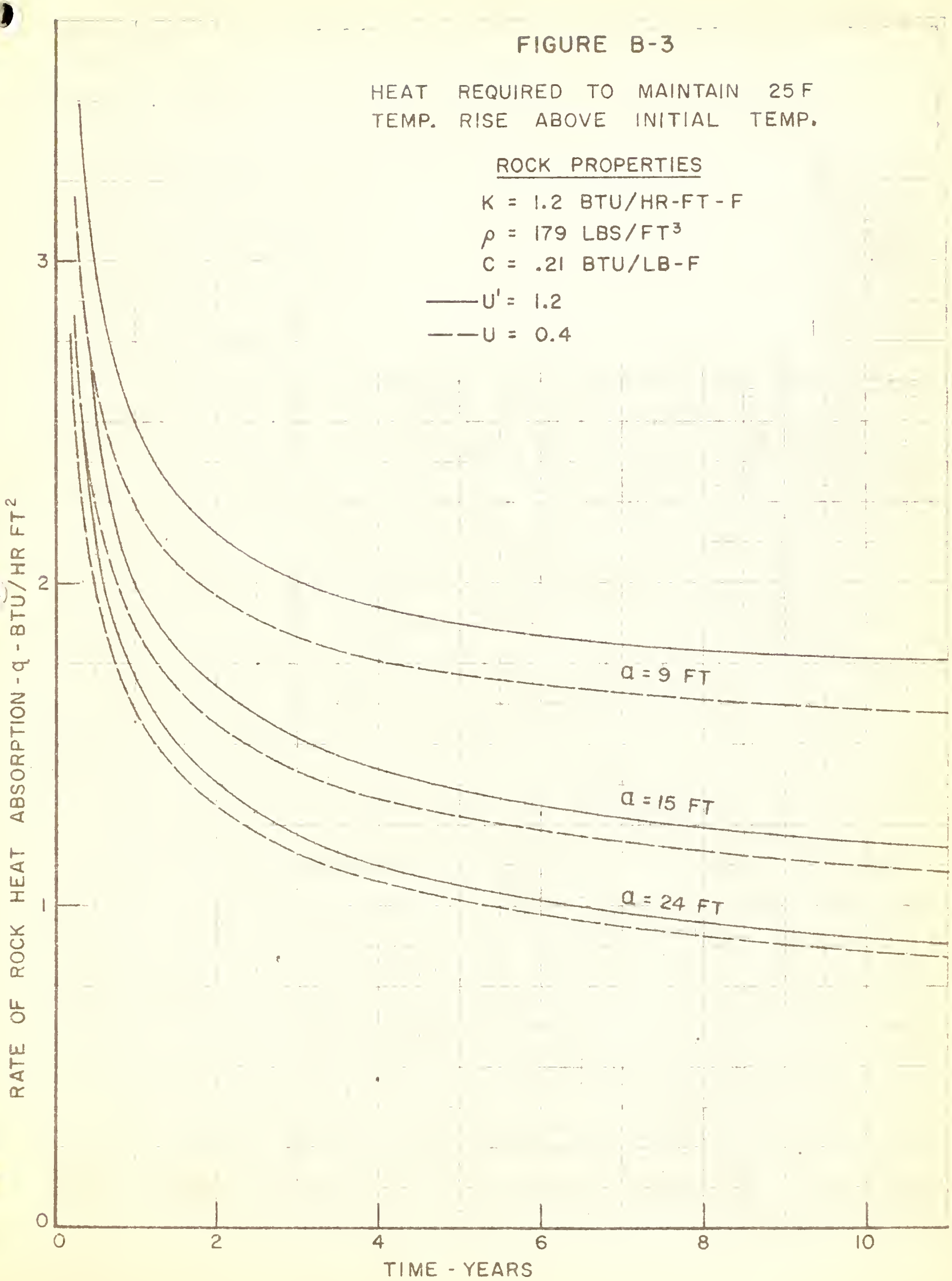


FIGURE B-3
HEAT REQUIRED TO MAINTAIN 25 F
TEMP. RISE ABOVE INITIAL TEMP.
ROCK PROPERTIES
K = 1.2 BTU/HR-FT-F
ρ = 179 LBS/FT³
C = .21 BTU/LB-F
U' = 1.2
U = 0.4
a = 9 FT
a = 15 FT
a = 24 FT
RATE OF ROCK HEAT ABSORPTION - q - BTU/HR FT²
TIME - YEARS
0
1
2
3
0
2
4
6
8
10

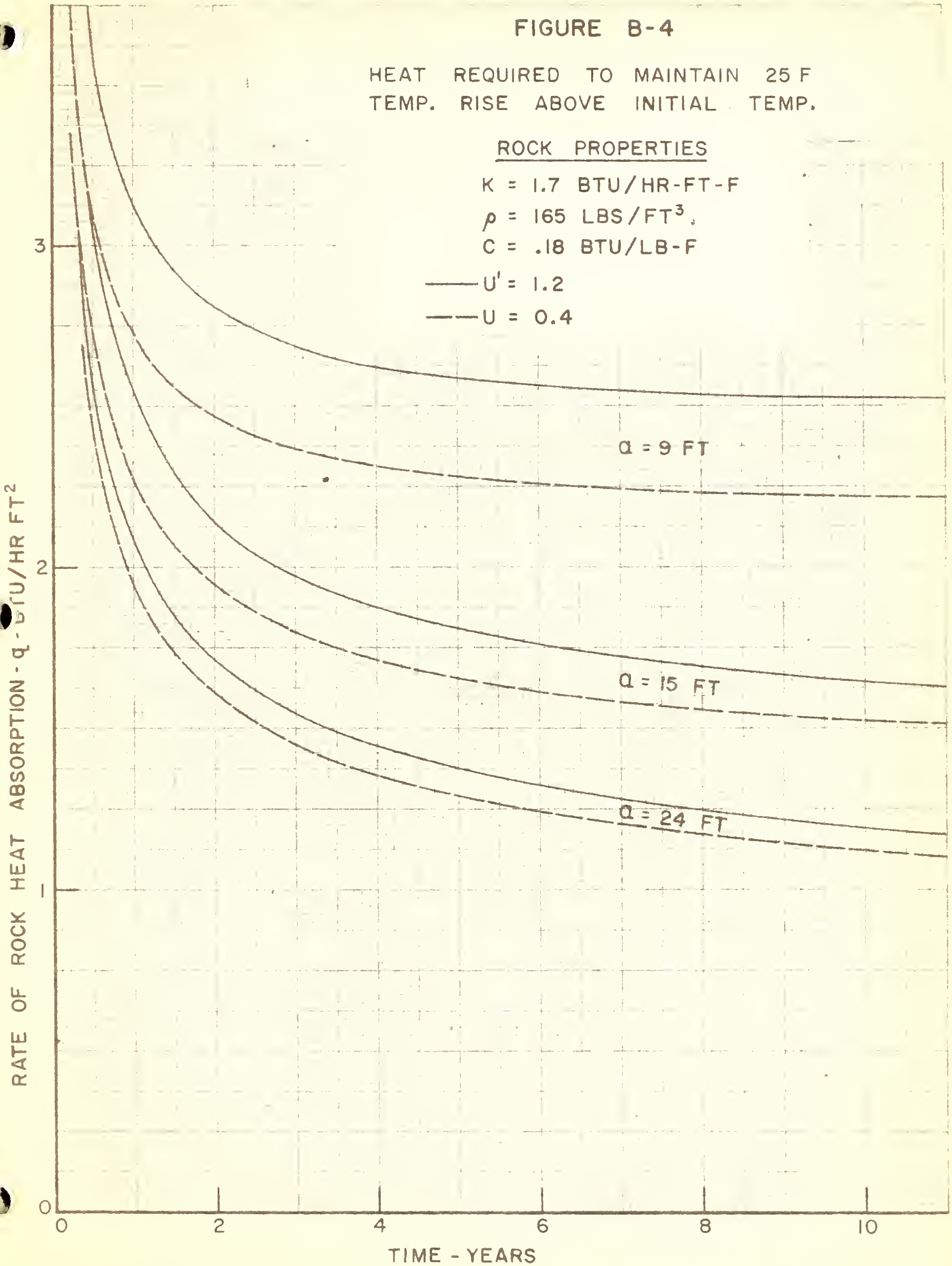


FIGURE B-4
HEAT REQUIRED TO MAINTAIN 25 F TEMP. RISE ABOVE INITIAL TEMP.
ROCK PROPERTIES
K = 1.7 BTU/HR-FT-F
ρ = 165 LBS/FT³
C = .18 BTU/LB-F
U' = 1.2
U = 0.4
a = 9 FT
a = 15 FT
a = 24 FT
RATE OF ROCK HEAT ABSORPTION - q - BTU/HR FT²
TIME - YEARS
0
1
2
3
0
2
4
6
8
10

APPENDIX 4C

Problems Illustrating Use of Equations for Underground Reservoirs

INTRODUCTION

The underground reservoir as a sink for waste heat disposal during an emergency condition has been discussed in Sections 3-06, 4-04, and 5-16. The purpose of this appendix is to illustrate by problems the use of the equations of Section 4-04, and to discuss the relative merits of the heat absorbing capacity of the surrounding rock as a function of time and the equivalent radius.

4C-1 Sample Problems - Variation of Equivalent Radius.

Assume the heat generation rate for an underground installation during an emergency period is two million Btu/hr, and that the installation must be self-sustaining for a period of ten days. The reservoir temperature is initially 52 F and the highest water temperature permissible is 100 F. Determine the necessary lengths of reservoirs for the cross-sections given in Table 4C-1. Thermal properties of the surrounding rock are:

$$K = 1.45 \text{ Btu/hr-ft-F}$$

$$\rho = 185 \text{ lb/ft}^3$$

$$c = 0.2 \text{ Btu/lb-F}$$

and for equation 4-07

$$F = Kt/\rho ca^2 = \frac{1.45 \times 10 \times 24}{185 \times 0.2 \times a^2} = 9.4/a^2$$

$$G = \frac{2\pi a^2 \rho c}{M'c'} = \frac{2\pi \times 185 \times 0.2a^2}{1.0 \times M'} = 232.5\ \frac{a^2}{M'}$$

$$\frac{\theta_w K}{q_1} = \frac{(100-52)1.45}{q_1} = \frac{69.6}{q_1} = f(F,G)$$

TABLE 4C-1

Computation of reservoir lengths for 10-day operation

	No. 1	No. 2	No. 3
Width of reservoir, n, ft	15	20	20
Height of reservoir, s, ft	15	20	30
Equivalent radius, $a = (s+n)/\pi$	9.54	12.73	15.91
M', 62.4sn, lb/ft length	14,040	24,960	37,440
$F = 9.4/a^2$	0.1033	0.0580	0.0371
$G = 232.5\ a^2/M'$	1.51	1.51	1.57
f(F,G), from Fig. 4-7A	0.0171	0.0105	0.0073
$q_1 = 69.6/f(F,G)$, Btu/hr ft	4,070	6,629	9,534
Length, $m = 2\text{x}10^6/q_1$, ft	491	302	210
Volume of water, mns, ft^3	110,475	120,800	126,000
Total heat added, $240\text{x}2\text{x}10^6$, (10^6 Btu)	480	480	480
Heat in water, 48x62.4xVol., (10^6 Btu)	330.9	361.8	377.4
Heat in rock, (10^6 Btu)	149.1	118.2	102.6
Percentage of heat in rock, %	31.1	24.6	21.4
Water contact surface, ft^2	29,460	24,160	21,000

Table 4C-1 shows that for a reservoir of smaller cross-section and longer length, a greater proportion of the heat is absorbed in the surrounding rock, and that this proportion is approximately proportional to the surface area in contact with the water. Also, the volume of water or amount of excavation is less for the reservoir with the smallest cross-section.

If a reservoir is to be used ultimately as a heat sink for the waste heat from a prime mover such as a Diesel engine, the maximum water temperature can probably be higher

than 100 F. For case Number 2 with other conditions the same but with the maximum allowable water temperature equal to 160 F instead of 100 F, the length of the reservoir is

$$m = \frac{2 \times 10^6 \times 0.0105}{(160-52)1.45} = 134 \text{ ft;}$$

the volume of reservoir required is 53,600 ft^3; and the percentage of the total heat input absorbed by the rock is 24.6 percent.

It will be noted that the percentage of the heat absorbed by the rock did not change. The reason is that this percentage is governed by the time available for heat absorption by the rock, for a reservoir of a given equivalent radius.

4C-2 Sample Problems - Variation of Time

Case Number 2 of Section 4C-1 will be used as an example, in which lengths of reservoir will be determined for a heat input rate of 2 x 10^6 Btu/hr for time durations 6, 8, 10, 12, and 14 days, and for a water temperature rise from 52 F to 100 F.

$$G = 1.51$$

$$F = Kt/\rho ca^2 = 1.45t/185 \times 0.2 \times (12.73)^2 = 0.000242t$$

It will be noted that the percentages of total heat absorbed by rock in Table 4C-2 increase as the duration of heat input increases. This shows the influence of time when the reservoir size is adjusted to yield the same temperature rise Θ_w, for different durations of heat input.

To illustrate further, consider the reservoir 192 ft long in Table 4C-2, which was raised in temperature from 52 to 100 F in six days with a heat input rate of 2 x 10^6 Btu/hr. If the heat input rate had been 1 x 10^6 Btu/hr, the same temperature rise would have occurred in 13.8 days, and 30.5 percent (versus 20.1 percent) of the input heat would have been absorbed by the rock. The total heat added to the reservoir would have been 331 x 10^6 Btu (versus 288 x 10^6 Btu). This shows the increases of heat sink duration and capacity that result when the rate of waste heat input to a given reservoir is restricted as much as possible.

TABLE 4C-2

Step-by-Step Computation of Reservoir Lengths
(Width = Height = 20 ft)

	Time, Days				
	6	8	10	12	14
$F = 0.000242t$	0.0348	0.0465	0.0580	0.0697	0.0813
$f(F,G)$	0.0067	0.0086	0.0105	0.0123	0.0141
$q_1 = 69.6/f(F,G)$	10,388	8,093	6,629	5,659	4,936
Length, $m = 2x10^6/q_1$	192	247	302	353	405
Vol. of water, mns, ft^3	76,800	98,800	120,800	141,200	162,000
Total heat added, (10^6 Btu)	288	384	480	576	672
Heat in water, (10^6 Btu)	230	296	361.8	422.9	485.2
Heat in rock, (10^6 Btu)	58	88	118.2	153.1	186.8
Percent of heat in rock, %	20.1	22.9	24.1	26.6	27.8

4C-3 Sample Problems - Cooling of Reservoir

In some cases it may be necessary to maintain the temperature of the water in the reservoir at a temperature lower than the initial earth temperature. As a sample problem, take the reservoir of case Number 2 of Section 4C-1, for which the dimensions are 20 by 20 by 302 ft. Determine the refrigeration necessary to cool it from an initial temperature of 52 F to 40 F in 25 days, and determine the refrigeration necessary to maintain the water at 40 F subsequently.

For equation 4-07

$$G = 1.51$$

$$F = \frac{1.45 \times 25 \times 24}{185 \times 0.2 \times (12.73)^2} = 0.145$$

From Fig. 4-7, $f(F,G) = 0.0233$

$$q_1 = \frac{(52-40)1.45}{.0233} = 747 \text{ Btu/hr ft}$$

$$Q = \frac{747 \times 302}{12,000} = 18.8 \text{ tons of refrigeration}$$

With 18.8 tons of refrigeration, the water is cooled from 52 F to 40 F in 25 days.

The refrigeration necessary to maintain the reservoir at 40 F (Table 4C-3 can be computed from Equation 4-08 and Fig. 4-9.

From Equation 4-08

$$Q = \frac{K\theta_i mI(F)}{12,000} = \frac{1.45(52-40)302}{12,000}I(F)$$

$$= 0.438I(F), \text{ tons of refrigeration.}$$

TABLE 4C-3

Refrigeration necessary to maintain 40 F water in a 20x20x302 ft reservoir

Time after start of cooling	$F = Kt/\rho ca^2$	I(F), Fig. 4-9	Q, tons
60 days (1440 hr)	0.35	8.7	3.81
4 months (2880 hr)	0.70	7.0	3.06
1 year (8760 hr)	2.12	5.0	2.18
3 years (26,280 hr)	6.36	3.7	1.62

4C-3 Sample Problem - Reservoir Filled with an Ice and Water Mixture

The reservoir (20 ft by 20 ft by 302 ft length) of case Number 2 of Section 4C-1 is employed to illustrate the case of a reservoir containing 40 percent ice by volume. The time duration of the usefulness of the reservoir is determined by using the reservoir water as chilled water until the water has been heated to a temperature of 50 F,

and thereafter using the reservoir water as condenser water for refrigeration compressors for water temperature in the range from 50 to 100 F. Because refrigeration equipment is not operating during the time when the temperature is below 50 F, the heat input rate to this reservoir is reduced by the rate of energy input required to drive this equipment (3-06). If the heat input rate to the reservoir is two million Btu/hr with operation of this equipment, and its coefficient of performance is assumed to be 4, then the heat input rate without its operation is approximately 1.6 million Btu/hr.

From Table 4C-1, the total reservoir volume is 120,800 cubic feet and the ice volume is 48,320 cubic feet and, for an ice density of 57.5 lb/ft^3, the weight of ice, W is 2.778 x 10^6 lb. From Equation 4-09, the time t_1 to melt the ice is:

$$t_1 = \frac{144W}{Q} = \frac{144x2.778x10^6}{1.6x10^6} = 250 \text{ hours.}$$

The weight of water in the reservoir after ice meltage is 62.4 x 72,480 + 2.778 x 10^6 pounds, or M' = 24,170 pounds per foot length of reservoir. To determine the time t_2 for a temperature rise from 32 to 50 F at a heat input rate of 1.6 x 10^6 Btu/hr, Equation 4-07 yields

$$f(F,G) = \frac{\theta_w K}{q_1} = \frac{(50-32)x1.45x302}{1.6x10^6} = 0.0049$$

and $$G = \frac{2\pi(12.73)^2x185x0.2}{24,170x1.0} = 1.56$$

From Figure 4-7A $F = Kt/\rho ca^2 = 0.024$

and $$t_2 = \frac{0.024x185x0.2x(12.73)^2}{1.45} = 99 \text{ hours.}$$

To determine the time t_3 for a temperature rise from 50 to 100 F at a heat input rate of 2 x 10^6 Btu/hr, and with the assumption that the rock temperature is substantially uniform at 50 F at the end of time t_2, Equation 4-07 yields

$$f(F,1.56) = \frac{(100-50)x1.45x302}{2x10^6} = 0.0109$$

From Figure 4-7A $F = 0.059$

and $t_3 = 244$ hours.

The time duration of the reservoir without wastage of the water is the sum of the times $t_1 + t_2 + t_3 = 593$ hours. In comparison to the same reservoir with an initial water temperature of 52 F, the time duration for the reservoir is extended 343 hours by the use of a 40 percent ice and water mixture in the reservoir. Similarly, the time duration is increased only 103 hours with the initial temperature of the water at 32 F. With wastage of the water through the condenser, the extension t_4 of the time duration can be calculated by Equation 4-06, if it is assumed that the maximum discharge temperature of the refrigeration condensers is 110 F.

$$t_4 = \frac{M(T_p - T_w)}{Q_w} = \frac{7.301 \times 10^6 (110-100)}{2 \times 10^6} = 36 \text{ hours.}$$

This yields a total time duration of 629 hours or 26.2 days.

Design considerations and further discussion regarding the ice reservoir is found in Section 5-16.

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 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 to 40 feet, depending on the strength of the rock. In height, the space may be single or multi-story.

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 for 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. The behavior 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 in the tunnel, arranged either to conduct outside air into the chamber, or to exhaust air from 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 dewpoint 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 and winds cause ventilation of such installations 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 thus be 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 should become blocked 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. Vehicular exhaust gases may contaminate the intake air. Also, 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. 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 Internal 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.

The air in the annular space around an internal structure is likely to be at relative humidities in excess of 70 percent if even moderate areas of the rock are damp or wet. The outer parts of internal structures, their supports, and service pipes and lines in the annular space, must be of materials resistant to, or protected from, corrosion due to high humidities.

Internal structures differ in size and in the ratio of their size to that of the enclosing chambers. Often, internal structures are designed to fit enclosing chambers, with relatively small clearances. 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 may be useful if the interior of the structure is to be heated to some temperature above that of the surrounding annular space for relatively short periods of time. If the two spaces are kept at the same temperature, or when, after long periods of time, the rock surrounding the chamber approaches the chamber or internal structure air 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. In some circumstances, a small internal structure in a large chamber may advantageously be thermally insulated (5-10).

Application of vapor barrier materials in the walls, ceilings, or floors of internal structures is not beneficial under all circumstances (4-09).

Thus, from an air conditioning standpoint, the walls and ceilings 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 so that the surrounding rock remains cool and at a temperature lower than the desired interior dewpoint, the air conditioning process may consist in simply warming the structure to reduce the relative humidity (5-10).

5-09 Acoustical Treatments

Sound waves reverberate in a bare rock chamber and some treatment may be 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 (3-05) or wetting by condensation. Internal structures are a solution to the problem, and the treatments of walls or 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.

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 internal 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 dewpoint 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 permeable 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 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 (3-05, 4-09). 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 or permits the use of a larger internal structure in a given chamber. 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 absorbed from the inner structure can thus be removed. The surrounding rock serves as a large heat sink and makes this process possible.

5-11 Annular Space Used as Cold Air Plenum

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 held at or near the initial rock temperature. An outstanding advantage of such an arrangement is that the surrounding rock, remaining cool, would in a time of emergency offer a large contiguous heat absorptive capacity.

This would be available to reduce considerably the cooling load required of the air conditioning system, and without any supplied air conditioning, would greatly extend the period of tolerable temperatures and humidities in the installation.

In such an arrangement, air is discharged into the annular space at a temperature approximately equal to the natural initial temperature of the rock (4-07). The cool air in the annular space plenum is drawn into and distributed in the internal structure as required to maintain the desired interior conditions. The air discharged from the internal structure, except for that exhausted as vitiated air, may be discharged directly into the annular space through a cooling coil which lowers its temperature to that of the surrounding rock. Alternatively, it could be returned to a central cooling system and, after being cooled, ducted back to the annular space.

In this arrangement, the cooling load is equal to the internal heat generation, since the rock is not being changed in temperature. The dewpoint in the interior structure would be approximately the same as that in the annular space, which in turn would be limited to not more than the temperature of the rock surface. For this reason, very steady control of the internal structure dewpoint is possible, at a value governed by the rock temperature. In many areas in this country, natural rock temperatures are in the range 50 to 55 F, which would conduce to internal structure conditions of 75 F dry-bulb and 42 to 50 percent relative humidity (2-04, 2-05). In areas where the natural rock temperature is colder or warmer, heating or cooling of the rock to maintain a desired dewpoint is possible.

Thermal insulation of the structure is not useful when the structure must be cooled, but insulation would be beneficial if the internal structure must be warmed during a prolonged unoccupied period, to maintain a desired relative humidity.

The heat-absorbing capacity of the rock surrounding the annular space in such an arrangement, which would be available for use during a period of emergency operation, can be calculated by means of Equation 4-04 (4-03), using for the steady heat input to the rock the generated structure heat load minus the cooling being supplied by the air conditioning system as regulated during the emergency period. In Equation 4-04, for this case, the U'-value should be that for a bare chamber (4-08).

To obtain optimal limitation of the temperature and relative humidity in the internal structure during such operation in an emergency period, with restricted cooling by the air conditioning system, the annular space air should be drawn into the structure through the cooling coil, and the structure air discharged to the upper levels of the annular space, which are reversals of the air flow directions during normal operation.

If the annular space is to be used as a cold air plenum, leakage of air between the plenum and access passageways should be prevented to avoid discharge of cold air into warm passageways.

5-12 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 (2-06) must be supplied with any system in an appropriate manner. Hallways in internal structures or the surrounding annular spaces can be used for return air passages.

Either central air conditioning systems (5-13) or zone or room air conditioners (5-14) 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 (5-11).

5-13 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 a return plenum. Fresh or outside air is introduced into the supply system at one or more convenient points, with care to assure good distribution. The total 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).

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 over-all 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 pre-assembled 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 dewpoints to prevent condensation on their surfaces, with resultant

corrosion and to conserve the cooling effect of the water. In air conditioned spaces, such pipes may require insulation to prevent troublesome condensation and dripping.

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 or temperature 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. The use of reservoirs as heat sinks during emergency periods is discussed in Section 4-04, which also presents the equations necessary for computations. As mentioned in 4-04, the difference in acceptable cooling water temperatures for refrigeration compressors and Diesel engines practically demands two reservoir systems, either or both of which may be iced.

At the start of emergency use as heat sinks, either or both of the iced reservoirs can be used to furnish chilled water directly to unit air conditioner cooling coils until the reservoir temperature rises to about 50 F. At this time, operation of the refrigeration compressors will become necessary, and the heat rejected to their condensers must be absorbed by the reservoir reserved for air conditioning equipment use. The computation of the time for the reservoir to rise in temperature is accomplished by means of Equation 4-07 (See Appendix 4-C).

The maximum temperature limit for the water in the air conditioning reservoir is probably in the range of 100 to 110 F, since higher water temperatures may result in

excessive head pressures in the refrigerating compressors. When this temperature is reached, the discharged condenser water is furnished to the Diesel engine cooling system and wasted outside.

The Diesel engine reservoir can be raised to higher temperatures before its water reaches maximum recommended entering temperature, after which its water must be wasted outside. The two reservoirs should be proportioned, with respect to their respective loads, so that when the Diesel reservoir is emptied, the engine can be cooled by water wasted from the air conditioning condensers, until this supply also has been exhausted.

A reservoir filled with an ice and water mixture requires a method of distributing ice along the length of the reservoir. Ice introduced at the open end of a reservoir does not distribute itself along the length of the reservoir to a sufficient depth and some mechanical means must be made available for this purpose. The most satisfactory ice distribution method appears to be to use ice in small cubes, cylinders, or chunks and a helical-screw conveyor. The screw conveyor should reach from the open to the far end of the reservoir and be mounted a distance above the water level somewhat more than one-tenth of the depth of the water, so that ice would not reach the screw conveyor for movement until the underlying ice rested upon the floor of the reservoir. Ice would be dumped into the reservoir at the open end from ice making machines. When the ice at the dumping point piled up to the level of the screw conveyor, it would be moved in the direction of the far end, filling the reservoir to the bottom as the ice front progressed. A simple pendant-lever control at the far end of the reservoir moved by the ice front, would automatically stop operation of the conveyor and ice-making equipment when the reservoir became completely filled. Meltage of the ice front by heat transfer from the surrounding rock would allow the pendant-lever control to fall to an operating position, causing more ice to be added to the reservoir. For inspection and maintenance of the screw conveyor, a walk-way should be placed near the conveyor.

Laboratory experiments have indicated that the best shape of ice for movement in a reservoir is cubical, spherical, or cylindrical, in pieces on the order of one inch in size. Ice in the crushed or flake form tends to agglomerate in compacted slushy masses which resist movement. Experiments have shown that the average ice volume

in a water and ice mixture is from 40 to 50 percent for hollow cylinder ice, and it is probable that for non-hollow small shapes, the ice volume percentage would be materially greater.

The ice reservoir may be used as a source of chilled water for the air conditioning system during normal operating (non-emergency) conditions. But this is not recommended, because the ice-making equipment producing ice for a reservoir operates at lower efficiencies than conventional equipment for air conditioning.

5-17 For references and index to other Chapters of Part XXV see Chapter 1.

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 75 F 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 ±2 F 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 65 F. Water, if available from outside, may be used for cooling in a chilled water system, if its temperature is about 50 F 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 warm water 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 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 time 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 a temperature above the design dewpoint 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 are means of avoiding overheating of the air in mild weather. The coil is shut off in summer.

If the fresh air ducts are insulated 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 (6-08) 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).

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 exchangers, 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.

The most convenient and practical procedure for coil selection is to utilize 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.

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 or brine, or a liquid refrigerant 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, relative 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 operations 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 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 types air filters.

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

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 a 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. 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 (Ref. 1).

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 50 F and 90 F 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 may therefore 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, such as glass wool. Reactivation may be accomplished in a second air washer through which heated (up to 300 F) 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 dewpoint temperature, condensation with possible drip through joints occurs.

Selection of a dehumidifier may be based on information given in Ref. 1 and in manufacturers' catalogs.

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 dehumidiers 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 dewpoint is reached.

6-14 For references and index to other Chapters of Part XXV, see Chapter 1.

U. S. DEPARTMENT OF COMMERCE
Lewis L. Strauss, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its headquarters in Washington, D. C., and its major laboratories in Boulder, Colo., is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside front cover.

WASHINGTON, D. C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Anolog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Ionospheric Communication Systems.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio-Meteorology.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

NBS