TM 5-858-7

TECHNICAL MANUAL

DESIGNING FACILITIES
TO RESIST
NUCLEAR WEAPON EFFECTS
FACILITY SUPPORT SYSTEMS

This reprint includes all changes in effect at the time of publication; change 1.

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TM 5--858-7, 15 October 1983, is changed as follows:

Page i. change the title of Appendix C from "REFERENCES" to "BIBLIOGRAPHY."
Page i. After Appendix C. add Appendix "D. REFERENCES. . . . . . D–l. "
Page 1–1.. Change title of TM 5-858-4 to "Shock Isolation Systems."
Page B-2, paragraph B-7. Delete OPNAVINST-9330-7A.
Page C-1. Delete lines 1, 2, 3, 17, 18, 19, and 20.
Page D-I. Appendix D is added as follows:

By Order of the Secretary of the Army:

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WASHINGTON, DC, *15 October 1983*

DESIGNING FACILITIES TO RESIST NUCLEAR WEAPON EFFECTS
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***This manual together with TM 5–858–1; TM 5–858–2; TM 5–858–3; TM 5–858–4; TM 5–858–5; TM 5–858–6; TM 5–858–8 supersedes TM 5–856–1, 1 July 1959; TM 5–856–2, 15 March 1957; TM 5–856–3, 15 March 1957; TM 5–856–4, 15 March 1957; TM 5–856–5, TM 5–856–8, 15 January 1960; and TM 5–856–9, 15 January 1960.**

CHAPTER 1

INTRODUCTION

1 –1. General.

a. This series of manuals, entitled Designing Facilities to Resist Nuclear Weapon Effects, is organized as follows:

TM 5-858–1	Facilities System Engineering
TM 5-858-2	Weapon Effects
TM 5-858–3	Structures
TM 5-8584	Stock Isolation Systems
TM 5-858–5	Air Entrainment, Fasteners, Penetration Protection, Hydraulic-Surge Protective Devices, EMP Protective Devices
TM 5-858-6	Hardness Verification
TM 5-858-7	Facility Support Systems
TM 5-858–8	Illustrative Examples

A list of references pertinent to each manual is placed in an appendix. Additional appendixes and bibliographies are used, as required, for documentation of supporting information. Pertinent bibliographic material is identified in the text with the author's name placed in parentheses. Such bibliographic material is not necessary for the use of this manual; the name and source of publications related to the subject of this manual is provided for information purposes.

b. The purpose of this series of manuals' is to provide guidance to engineers engaged in designing facilities that are required to resist nuclear weapon effects. It has been written for systems, structural, mechanical, electrical, and test engineers possessing state-of-the-art expertise in their respective disciplines, but having little knowledge of nuclear weapon effects on facilities. While it is applicable as general design guidelines to all Corps of Engineers specialists who participate in designing permanent military facilities, it has been written and organized on the assumption a systems-engineering group will coordinate design of the facilities.

c. Technical Manual 5-858 addresses only the designing of hardened facilities; other techniques to achieve survival capacity against nuclear weapon attacks are deception, duplication, dispersion, nomadization, reconstitution, and active defense. A facility is said to be hardened if it has been designed to directly resist and mitigate the weapon effects. Most of the hardening requirements are allocated to the subsidiary facilities, which house, support, and protect the prime mission materiel/personnel (PMMP). This manual is applicable to permanent facilities, such as those associated with weapon systems, materiel stockpiles, command centers, manufacturing centers, and communications centers.

d. The nuclear weapon threats considered are listed below. Biological, chemical, and conventional. weapon attacks are not considered.

—Weapons aimed at the facility itself or at nearby targets

—A range from many, relatively small-yield weapons to a single super-yield weapon

—Weapon yields from tens of kilotons to hundreds of megatons

—Weapon delivery by aerial bombing, air-to-surface missile, surface-to-surface missile, or satellite-launched vehicle

—Detonation (burst) of a weapon in the air, at the ground surface, or beneath the ground surface

—Direct-overhead bursts for a deep-buried facility

—Near-miss bursts for a near-surface facility, producing peak over-pressures from tens to thousands of psi at the facility

e. The designing of facilities resistant to nuclear weapon effects is an evolving specialty using a relatively narrow data base that incorporates both random and systematic uncertainties. The range of these uncertainties may vary from significant (order of 1 to 2 magnitudes) to normal (10 to 100 percent variation from average values). The applicable uncertainty value depends on the specific weapon effect or hardening objective under consideration. Loading uncertainty is generally more significant than resistance uncertainty. Awareness of the appropriate uncertainty (extent of ignorance) factor is essential not only for system engineering tradeoffs, but in the utilization of available analysis or test procedures. Studies and experiments are being conducted to improve methodology, to better define random uncertainties, and to reduce systematic uncertainties. This manual will be revised as significant improvements occur in either methodology or data base.

1-2. TM 5–858-7: Facility support systems.

This volume presents design guidelines for the facility support systems: Power supply, waste-heat rejection, air quality control, and utilities and services. The designing of these facility support systems is essentially independent of the nuclear weapon effects, but is heavily influenced by the fact that there is a survival requirement for the system.

CHAPTER 2

POWER SUPPLY

2–1. Three operating modes.

a. Overview. View the power supply system within the context of three operating modes: preattack, transfer, and transattack/postattack. Usually, it will be most effective to use a different system to satisfy each of these three modes.

b. Preattack power. Use either commercial power or a dedicated power-supply to satisfy the preattack power requirements. Use commercial power if it is compatible with the system power requirements. Conventional civil-power technology is quite adequate to adapting commercial power to a hardened system. The basic weakness is that loss of commercial power forces the system to operate on the transattack/postattack power supply, which has, of course, a finite endurance.

(1) This is a fundamental issue: When does a mysterious, or even a not-so-mysterious, loss of commercial power constitute an "attack" on the system? An onsite, dedicated preattack power supply reduces the potential for a mysterious loss of power but does not eliminate it.

(2) If commercial power is not satisfactory, use an onsite, surface power plant. State-of-the-art, open-cycle systems are satisfactory candidates, whether the surface plant is unhardened or is nominally hardened. Diesel-powered generators are the most promising candidates for small and moderate power levels. Fossil-fueled or nuclear-powered steam-turbine generator systems offer comparable thermal efficiency only in large (>10 MW) installations.

c. Transfer power. Design of transfer power systems are controlled by functional requirements of the total facility. Delay tolerance and facility reliability must be considered in selecting subsystems to transfer power mode from preattack condition to transattack/postattack. The transfer-power system can be as simple as a compressed-air supply controlled by battery and sequencing valve that can start the engine of the postattack power system. More typically, it will be a combination of such a system with an uninterruptible power system (UPS) in the form of a battery-inverter supply for critical loads.

d. Transattack/postattack power. This is the critical operating mode and requires selection of subsystem compatible with requirements for the hardness level of the entire facility. With prime-mission materiel/personnel (PMMP) needs defined, design the transattack/postattack power-supply system to include no fewer than the following capabilities:

—Satisfy peak-power and peak-energy demands.
—Satisfy normal power demands at acceptable efficiency.
—Provide acceptable power quality.
—Provide acceptable preattack availability.
—Provide acceptable endurance availability/reliability.
—Accommodate preattack exercising.

(1) Choose the effective degree of atmospheric isolation of the power supply system and the attendant waste-heat rejection system. Bear these three facts in mind:

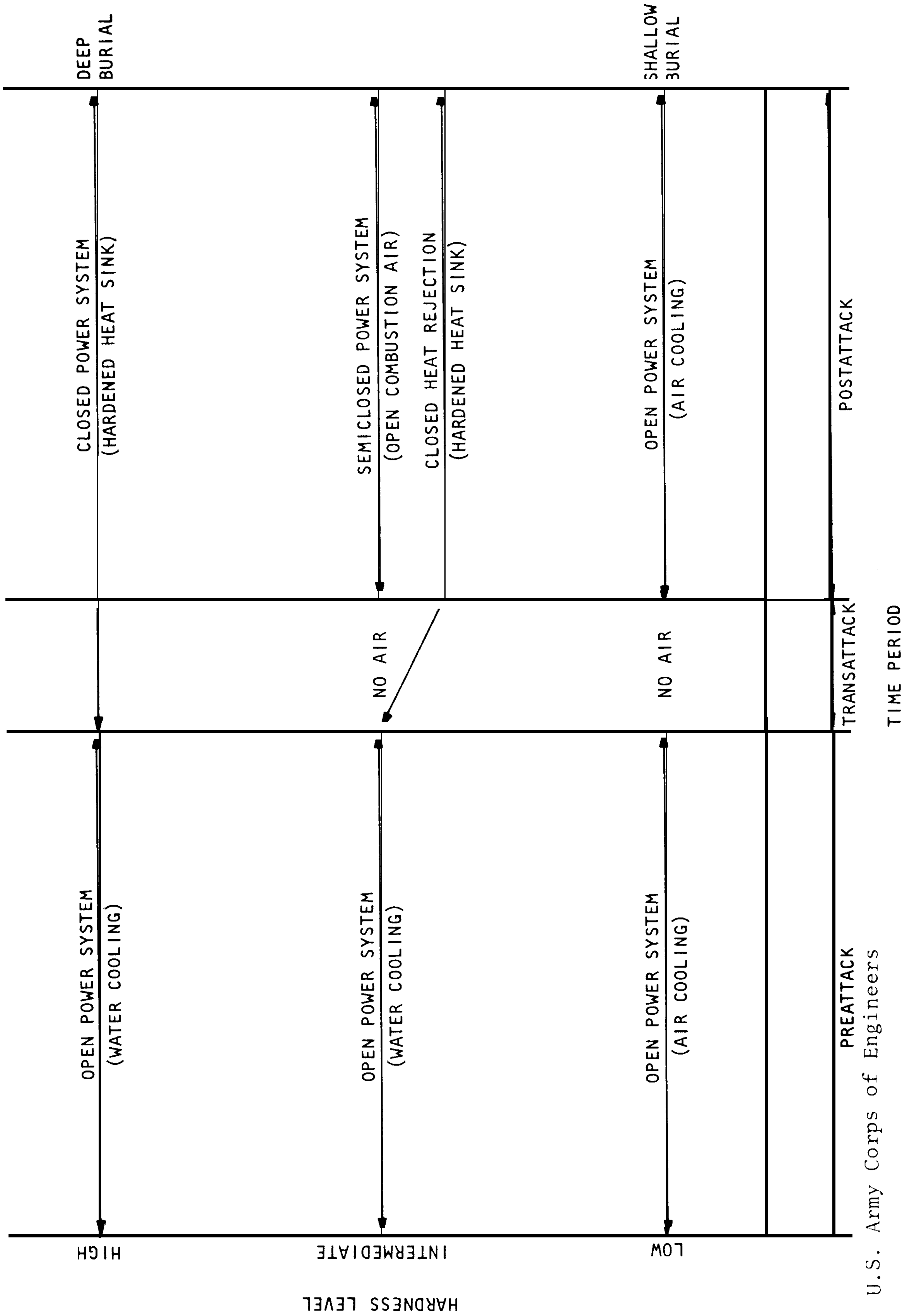
—Except for exported communication signals, the total electrical energy produced reappears in the facility as waste heat to be added to the waste-heat rejection load.
—For open-power systems that use air cooling, the parasitic electrical power demands of the waste-heat rejection system greatly increases the power level requirements of the power-supply system.
—The costs of a closed-cycle power supply system and a closed-cycle waste-heat rejection system can dictate the cost of the entire facility.

In general, the more severe the survivability requirement, the more effective must be the closed-cycle operation of both the power supply system and the attendant waste-heat rejection system (fig. 2-l).

(2) During the preattack (peacetime) period, the transattack/postattack system would be periodically operated to demonstrate readiness; otherwise, it would idle in a standby mode or stand dormant. In other than the dormant mode, consumables must be replenished to maintain acceptable "button-up."

2–2. Open cycle.

a. Candidate systems. The diesel engine is the best candidate for prime mover in open power systems. Compared to diesels, steam-turbine-powered systems are relatively inefficient except in the multimegawatt range. They have the additional handicap of requiring heat removal at relatively low temperatures. The same objections apply to nuclear steam-powered systems, as well as the further handicap of exorbitant capital cost at the low power levels generally required for hardened facilities. Gas-turbine systems may present an alterna-



U.S. Army Corps of Engineers

Figure 2-1. Power-supply system types vs. system hardness level tive at some power levels, but are inefficient at lower power ranges. Missions requiring very low total power may be served by battery-powered systems, which are discussed in paragraph 2-3b.

b. Parasitic power demand. Open waste-heat rejection systems using air cooling add substantial parasitic power loads. The total parasitic load includes coolant circulation pump power; refrigeration (largely compressor) power for facility air cooling; normal radiator or cooling tower fan power; and booster fan power to overcome the air entrainment system (AES) air-flow head loss. (AES is discussed in TM 5–858–5.) Fan power rapidly becomes the dominant parasitic electrical load at values of head loss greater than about 5 in. of water. The total power demand of the power system can be determined only after the air-flow head loss due to AES blast protection has been established. This requires at least a conceptual design for the AES, and that design, in turn, must be based on the airblast management concepts, primarily for the waste-heat rejection system (chap. 3). An engine combustion air supply and exhaust system should be closely integrated with the waste-heat rejection system, air supply and exhaust.

c. Weapon-effect protection. It is important to distinguish between cooling system air demand and combustion air demand. Cooling-system air requirements for evaporation-cooled systems are on the order of 50 times greater than the average requirements for combustion air supply and exhaust; radiator-cooled systems are about 100 times greater. Consequently, both the physical size of the components and the kinds of components involved make airblast protection for open-cycle, air-cooling systems an order of magnitude more difficult than that for combustion air supply and exhaust systems. Most air-cooling system components will necessarily be larger and more difficult to harden than corresponding combustion air system components.

(1) For air-cooling systems, the cooling towers, radiators, and fans are airblast-sensitive components. In combustion air systems, superchargers, scavenging blowers, and intake and exhaust ducting will have limited air shock and pressure-transient tolerance. For either system, dust separation and filtration equipment, air ducts, and particularly flexible duct connections between hard-mounted and shock-isolated equipment will require special consideration.

(2) Experiments have shown diesel engines themselves to be relatively unaffected by pressure transients to several hundreds of psi applied simultaneously to intake and exhaust. Eliminate potential problems with superchargers by using naturally aspirated engines. Use blast valves and relief valves to protect, and momentarily bypass, the air-cleaning equipment. Special high-strength intake and exhaust ducting will be needed. Air-shock resistant, hard-mounted supply, and exhaust ducts are straightforward design problems. Adapt standard commercial high-pressure expansion joint designs to meet the requirements of supply and exhaust connections between hard-mounted and shock-isolated duct segments.

(3) Choices between hardening techniques and ruggedization of subsystems and components associated with both air supply and power supply are delineated in volume five of this technical manual. Shock isolation of equipment mentioned herein is described in volume four. Remember, this is a total system-engineering approach, all facets integrated.

d. Endurance. Endurance requirements will be a direct function of power profile and subsystem efficiency at all profile power levels, which will determine the volume of stored fuel and, for cooling tower systems, the volume of stored cooling tower make-up water. These storage volumes strongly affect the endurance-dependent design of a facility. Usually, off-peak power operation of a single engine will substantially reduce prime mover efficiency and increase relative fuel and cooling demand per unit electrical power produced. Substantial total power demand reductions are possible if booster fan power in the air-entrainment system can be reduced at low heat loads by variable speed fan drives and variable pitch fans, or by cutting out part of a multifan system. Base preliminary estimates of fuel storage requirements on the weighted average power demand over the total power profile.

2-3. Closed cycle.

a. Candidates. Candidates for closed-cycle power-supply systems include:

—Battery
—Fuel Cell
—Combined Fuel Cell and Battery Systems
—Nuclear Reactor
—Diesel
—Stirling

Except for the battery, none of the closed-cycle power-supply systems listed have been developed to the point where they can be considered as practical, reliable candidates. Continued research, development, and testing are still required in order to transfer the developing systems to practical applications.

b. Battery. Except for a paucity of data on mechanical shock resistance, battery-powered electrical systems offer a nearly ready-made design approach to closed-cycle power systems. The required rectifier charger-inverter equipment is available off-the-shelf from a number of manufacturers. Lead-acid cell batteries are commonly used in battery systems. More than 100 years of extensive development, and use of lead-acid cells has resulted in extremely high reliability of such batteries when properly maintained. Except at very high rates of discharge, batteries generate virtually no waste heat.

(1) Since lead-acid batteries are capable of very high power output for short periods, the peak power output capability of battery systems is usually limited only by the inverter units. The rectifier units are normally designed to carry the rated inverter load with sufficient excess capacity to permit simultaneous battery charging at about 1/8 of the 8-hour battery rating, or 1/8 of the maximum discharge rate as limited by the inverter capacity, whichever is smaller. With better inverter systems operated. in a standby mode, the changeover to battery power on failure of the external power source is virtually undetectable on an oscillogram of the inverter a.c. output. The high reliability of the inverter section is obtained by the use of high quality parts, oversizing, and redundancy, but at relatively high cost in size, weight, and dollars. Installed cost, weight, and volume (exclusive of batteries) for the larger capacity systems (250 kW or more) are comparable to those for complete, high quality, diesel-generator installations. Simpler, more compact, and less costly inverter systems can be built, and could be adequate for some prime-mission requirements; however, lack of reliability data could be a serious problem.

(2) Rectifier-inverter systems are available as integrated units up to about 250 KW (300 kVA) capacity. These units can be paralleled to obtain outputs to 3 MW or more. In high-quality systems the overall rectifier-inverter system efficiency will range from about 50 percent to 88 percent, at 25 and 100 percent, respectively, of rated load. Waste heat should probably be based on an average rectifier-inverter system efficiency of no higher than 80 percent. Most of the losses will be in the inverter section.

(3) The calcium-hardened lead-acid cell is strongly recommended to eliminate potential poisoning by gaseous antimony hydride. These are lead-acid cells in which the alloying material used to harden the lead plates is calcium rather than antimony. Calcium-hardened cells are somewhat higher in first cost than regular lead-acid cells, but are longer lived, require less maintenance, and have much lower internal losses. On open circuit these cells undergo a loss of energy capacity on the order of 0.0042 percent/hour (about 3 percent in 30 days), based on the 8-hour rating, as indicated by the float charge current necessary to maintain a fully charged condition. The rates of loss and compensating float charge are nearly constant over this useful life (20 to 25 years). In comparison, the open circuit energy loss rate for new antimony-hardened, lead-acid cells is about eight times greater (about 0.032 percent/hr) and increases with age. Whenever the specified pastattack endurance period exceeds a few days, the 0.028 percent/hour differential becomes an important consideration.

(4) For large installations, the largest standard cell, rated at 8000 amp-hr (or 15 kWh) under standard conditions, will maximize storage density. A 46-MWh installation of this type, including maintenance access space, support structure, shock isolation, and rattlespace, and fitted to a cylindrical capsule configuration, has been estimated to have a packing factor of about 0.17 and to require about 4350 ft^3 of installation volume per MWh of battery capacity. Based on 82 percent overall postattack system efficiency, the space requirement wou1d be about 5305 ft^3/MWh of net useful energy. At current (1976) design weights, the battery cell net weight would be about 143,000 lb/MWh. These weights and volumes do not include the capsule shell itself. See TM 5—858-4 for area and volume needs of shock isolation platforms needed under various specified threats.

(5) The large unit weight anti space indicated for large battery installations make it important to recognize that the numbers quoted are intended only for preliminary estimates and apply to typical (lead-acid cell) batteries. Variations in discharge time, system efficiency, and cell operating conditions can increase initial cell requirements.

c. Fuel cell. Fuel cells convert chemical energy directly to direct current electrical energy. Individual fuel cells usually operate at less than one volt, and become useful power sources only as batteries or stacks of individual cells connected in series to produce higher voltages. In addition to the fuel cells themselves, all fuel-cell systems include a relatively complex array of auxiliaries to provide and control fuel, oxidizer, and electrolyte flow, and waste-heat rejection. Since fuel-cell output is direct current, it is necessary to consider fuel-cell systems in conjunction with inverters to make useful comparisons with other potential power sources considered herein. This necessarily reduces overall thermal efficiency and increases total power-system weight and space requirements.

(1) In higher power ranges no fuel-cell system has been perfected that is cost-effective (1973)

compared to the more widely used electrical power generation systems. With few exceptions, very limited data are to be found on reliability of fuel cells in service. Fuel cells offer some advantages to the designer of hardened facilities and their development should be watched.

(2) Of the fuel-cell types that have been most extensively tested, the hydrogen-oxygen fuel cell used in the Apollo space program is of the type best suited to closed-cycle operation and possibly the only specific system design for which reliability data are available. The Apollo fuel-cell system was designed for maximum power-to-weight ratio and maximum efficiency and is, consequently, relatively costly (on the order of $100,000 to $400,000/kW at 1976 costs). The system is packaged in units rated at about 1.4 kW d.c. output at 27 to 31 V. The claimed efficiency, based on the low heat value of the hydrogen fuel, is nearly 90 percent. Based on the high heat value, which is of prime interest from the standpoint of waste-heat generation, the efficiency would be about 75 percent.

(3) Limited data from larger hydrogen-oxygen fuel-cell systems indicate that increased power demand of auxiliary systems will reduce the overall system efficiency. Based on an average inverter efficiency of 85 percent, the probable overall, average thermal efficiency is on the order of 50 percent. Hydrogen-oxygen fuel cell systems have an advantage over all power sources except batteries in that their part-load efficiency does not decline below rated-load efficiency until the load falls to about 20 percent of rated load. If hydrogen and oxygen are stored as liquids, problems associated with excess boil-off and long-term storage of cryogenics should not be overlooked.

(4) Cost considerations make it unlikely that hydrogen-oxygen fuel-cell inverter systems will be used to meet very high peak power demands, but such systems may be applicable to long term, low-level power profiles. They are readily adaptable to closed-cycle operation since the only waste effluents are heat and water and the cell operating temperatures are high enough (about 500°F) to permit coolant temperatures on the order of 250°F and a final water temperature of nearly 212°F for an unpressurized heat sink.

(5) Phosphoric acid fuel cell power plants have been developed and are currently being tested. A 40 kW phosphoric-acid-type fuel cell has been developed under joint sponsorship of the U.S. Department of Energy (DOE) and the utility industry represented by the Gas Research Institute (GRI). This fuel cell is costly (approximately $500,000 for a 40 kW unit based on a test project). Phosphoric acid fuel cells should be commercially available in the latter—1980's. A natural gas supply is the recommended fuel; however, bottled gas can be provided. Most units are provided electric-powered reformer units; however, if necessary the hydrogen gas can be obtained by use of the destructive distillation of coal and wood, which is an expensive process. These units are being tested in a cogeneration mode, with the thermal energy being used for space heating and domestic hot water heating.

(6) For a relatively low-powered system and a moderately long endurance period, say 10 kW and 60 days, the fuel-cell system space requirement based on the Apollo system and a packing factor of 0.2 would be only about 300 ft^3; the storage space at 50 percent overall system efficiency for liquid hydrogen and oxygen will be substantially greater. For liquid gas storage in shock-isolated dewars, with reasonable allowances for ullage, replacement of "boil off" at 30-day intervals, and a packing factor that allows for pumps, plumbing, and rattle-space, the estimated fuel-cell system gas storage space requirements would be on the order of 1500 ft^3, or about 104 ft^3/MWh. The ratios of shock-isolated weight and shock-isolated space appear to be 100:1 and 50:1, respectively, in favor of the fuel-cell system over the battery power system.

(7) The direct capital costs of the fuel-cell system plus fuel and oxygen supply for the system identified (14.4 MWh at 10 kW) would be competitive with a battery-powered system. Further major reductions in fuel-cell costs are entirely probable, but substantial reductions in battery costs are less likely.

d. Combined fuel-cell and battery systems. Where power profiles call for standby periods at low-power level interspersed with shorter periods of substantially higher power demand, there may be considerable advantage in combined fuel-cell/battery systems. Together fuel cells and batteries would support the peak loads and the fuel-cell system would support the standby load and recharge the batteries during low power demand.

(1) In a single example, doubling the peak output of the fuel-cell system discussed above, with the same total energy output (14.4 MWh), would nearly double the first cost of the system. However, if the peak output were to be doubled to 20 kW for 8-hour in 24-hour by use of a battery in parallel with the fuel-cell system, the battery recharge requirement (at 80 percent discharge/ charge efficiency) would absorb about 62.5 percent of the fuel-cell system capacity during the remaining time, leaving 37.5 percent or 3.75 kW of the net fuel-cell system output for the facility's load during a 16-hour day. With the same liquid hydrogen and

oxygen storage space the total energy output of the system would be reduced by about 8 percent (lost in battery charging), but the system cost would increase only about 1 1/2 percent (for batteries and additional inverter capacity) and the system space occupancy would increase only about 0.5 percent.

(2) There are numerous variations of combined fuel-cell and battery systems. In all such systems, maximizing use of direct current power will minimize inverter costs and losses. In general, the greater the peak power demand relative to facility standby power demand and the smaller the energy demand at peak power relative to the total energy requirement, the greater will be the advantage of using batteries to support peak loads on fuel-cell power systems.

e. Nuclear reactor. Nuclear-reactor power systems always appear attractive, since they are inherently closed systems with respect to the energy source. Cost data on reactor power systems within the power range up to 3MW are very scant. Costs of record of the smaller power systems developed for the Army Nuclear Power Program (ANPP) strongly indicate costs could be competitive with those for battery or Apollo type of fuel-cell powered systems at net useful power and energy levels on the order of 20 KW and 35 MWh, respectively.

(1) Any estimate of the space requirements for the shock-isolated, power-dependent elements of small reactor-powered systems is subject to very large uncertainties. However, for the same net electrical power output, it is probable that the volume requirement of reactor systems will be 5 to 10 times greater than those for the power-dependent elements of battery or fuel-cell systems. Based on the average efficiency and waste-heat rejection temperature of the ANPP power systems, heat-sink volume requirements will be on the order of four times that for fuel-cell systems.

(2) All reactor power systems in the power range of interest are one-of-a-kind experimental systems with limited operating history, hence without reliability data. No reactor power system designed as a shock-isolated installation for a high ground-shock environment is known to have been assembled or operated. For the first such system, the system operating characteristics, overall thermal efficiency, reliability, and costs must be verified by actual system construction and operation. The complete power system, including reactor, shielding, steam generators, turbogenerator, feed water heaters, and feed water pumps, must be mounted on a common, shock-isolated support structure. Any redundancy requirement would have a major effect on power-system cost effectiveness.

f. Diesel. In principle, closed-cycle diesel systems are relatively simple. Standard diesel fuels may be used. Part of the exhaust gas is cooled and enriched with oxygen from storage, and recirculated to replace the normal air supply. Excess water is condensed from the exhaust and excess carbon dioxide is removed by a caustic scrubber. Trace quantities of other gases and impurities from the exhaust stream are dissolved in the scrubber solution; all exhausted scrubber solutions are rejected to storage. The only change in actual engine-operating conditions is the substitution of an artificial working fluid for air. The Navy and Aerojet-General Corp. (Hoffman et al., 1970) have experimented with a working fluid of water vapor, carbon dioxide, and oxygen. Design of the scrubber system would depend on power generation requirements.

(1) In general, closed-cycle diesel systems are feasible. However, to maximize thermal efficiency and minimize space needs (chiefly heat sinks), a substantial development effort would be required to identify the optimum water vapor, oxygen, and carbon dioxide mix; engine input temperatures; caustic scrubber conditions; waste-heat rejection temperatures; and equipment configuration. A further substantial test effort would be required to establish reliability and availability data. For the most part, all major items ‘of equipment would be off-the-shelf and the entire development and test program would be an order of magnitude less costly and of substantially shorter duration than that required for a nuclear-reactor powered system.

(2) While available data are inadequate for firm design analyses, it is possible to estimate probable costs and space requirements. Assume the closed-cycle system efficiency to be at least 65 percent of that of a normal, open-cycle diesel-electric system, and the cost no more than 50 percent higher than the open-cycle diesel. Using these conservative assumptions, small, closed-cycle power system (say, 10 to 100 kW) average costs would be on the order of $600/kW, and the cost per unit net power should decline to about $400/kW in the 1 to 3 MW range (1976 prices). Even if subjected to wide variations, these costs are down more than two orders of magnitude from those probable for battery, fuel cell, or small nuclear-reactor-based power systems.

(3) Space requirement for shock-isolation equipment and power-dependent elements augmenting the closed-cycle diesel system may not differ greatly from those of battery or fuel cell systems, but will be substantially less than the space

requirements for nuclear-reactor power systems. Based on the overall system efficiency and flow rates reported for the Aerojet experimental system (overall thermal efficiency about 20 percent), the fuel and oxygen demand would be about 900 lb/MWh and 3200 lb/MWh, respectively. Assuming hard-mounted fuel storage with a small allowance for ullage and tank, the fuel volume occupancy would still be only about 17 ft^3/MWh. Oxygen, if stored as a liquid in dewars on shock-isolated structures, would require a total storage space of about 120 ft^3/MWh. Caustic scrubber solution must be stored separately but would not add appreciably to total space requirements.

(4) The heat of formation of either potassium carbonate or sodium carbonate is on the order of 1100 Btu/lb of carbon dioxide absorbed. This heat adds to the total waste-heat load.

(5) A recent survey (1977) of 15 projects to test hydrogen-fueled internal-combustion engines indicated that 26 conventional automotive engines were modified for hydrogen fuel and 14 were being road tested. With hydrogen in place of hydrocarbon fuel, a caustic scrubber and solution storage would be eliminated and the system simplified. However, the fuel storage space would be increased because of cryogenic storage of hydrogen.

g. *Stirling.* The Stirling engine is an external-combustion engine that can use any fuel. The Stirling engine has not been widely used because the diesel engine costs less. The current high and rising cost of petroleum-based fuels has caused renewed interest in the Stirling engine because of its potentially high thermal efficiency. However, in a closed-cycle system the efficiency of the Stirling engine may be similar to that of a diesel engine.

(1) If it is assumed (conservatively) that lower parasitic loads would permit the Stirling engine system to operate at a thermal efficiency of 25 percent the required heat-sink capacity should be based on a waste-heat load of 4 MWh_t/MWh_e. Hydrogen and oxygen consumption would be about 56 and 444 lb/MWh_t, values are 12.5 and 6.2 ft^3/MWh_t, respectively. The cryogenic hydrogen and oxygen storage space requirement would be about 300 ft^3/MWh_e.

(2) The weight and space occupancy of power-dependent system equipment should be less for the Stirling than for the diesel system. Hydrogen fuel would eliminate need for a caustic scrubber system.

CHAPTER 3

WASTE-HEAT REJECTION

3–1. Design requirements.

a. Preattack. Reject all waste heat to the atmosphere during the preattack time frame. The design of these open rejection systems is similar to those found in conventional facilities.

b. Transattack/postattack. Design the transattack/postattack waste-heat-rejection system to include no fewer than the following capabilities:

—Accommodate the peak waste-heat generation.
—Accommodate the cumulative wast-heat generation.
—Provide acceptable preattack availability.
—Provide acceptable endurance availability/reliability.
—Accommodate preattack exercising.

(1) Choose the effective degree of atmospheric isolation of the transattack/postattack waste-heat rejection system. In an open system, the heat sink is the atmosphere; in a closed system the heat sink is generally a closed (underground) coolant-filled cavity. In general, the more severe the survivability requirement, the more effective the closed system (fig. 2–l).

(2) After identifying the primary sources of wast eheat, design the transattack/postattack rejection system to fit the level of hardness specified for the facility:

Open

Nominally Hardened Facilities	(tens of psi overpressure)
Moderately Hardened Facilities	(hundreds of psi)
Sup-hard Facilities	(thousands [and greater] of psi)

closed

3–2. Waste-heat sources.

a. General. Estimating heat loads for the design of cooling systems in hardened facilities differs only in minor details from heat-load estimation for more conventional facilities. For hardened facilities, eliminate atmospheric air heat and humidity for design consideration. Consider three heat sources: heat from geological media, heat from personnel, and heat from power generation and consumption. Include a reasonably accurate evaluation of the influence of metabolic heat and the heat of carbon dioxide absorption reactions.

b. Geological heat. When an underground opening is maintained at a temperature different from that of the medium, such as a chilled-water heat sink in warm rock, there will be appreciable but declining heat transfer at the interface as a temperature gradient is established in the rock. The heat-transfer rate is influenced by the temperature differential and the medium properties. Many variables influence the relative importance of this heat source; methods for obtaining quantitative estimates of the source are given in TM 5–855-4.

c. *Personnel related.* Personnel-dependent heat sources become increasingly important as population increases and will be the principal heat load for those facilities that are primarily personnel shelters. Table 3–1 gives metabolic values corresponding to various activity levels for personnel, including a breakdown of sensible and latent (dehumidification) heat rates, which can be used for estimating total heat loads for design of facility cooling and dehumidification systems. In applying these heat rates, use the personnel activity profiles to determine the total heat load. The allowances for heat from personnel-dependent electrical power loads may be subject to substantial revision on the basis of specific facility design criteria, but are included in the interest of completeness.

(1) The sensible heat shown for lighting, air conditioning, and miscellaneous is intended to cover only that fraction of electrical power required for personnel needs in occupied facilities. It does not include the associated waste heat or additional power to operate the heat-rejection systems. All other values are based on average, adult-male metabolism.

(2) The heats of carbonate formation with possible reactants for carbon dioxide absorption can vary between limits of about 850 and 1800 Btu per pound of carbon dioxide gas converted to the carbonate form; but the more probable reactants and processes have reaction heats in the range of 1000 to 1100 Btu per pound of carbon dioxide. Carbon dioxide absorption will produce about 15 percent of total personnel-dependent heat.

d. Power generation and consumption. Power supply systems are the primary waste-heat source for facilities other than personnel shelters. Except for electrical power removed from a facility via communications or power cables, the total electrical power consumed by the facility will reappear as waste heat. Consequently, estimate the power-system-dependent waste heat as the total energy input to the power-generation system, minus any

Table 3-1. Personnel Heat Production

Heat Source	Heat Production, Btu/mh		
	Light Work	Seated at Rest	Sleep
Latent, Metabolic	420	220	120
Sensible:			
Metabolic	180	180	180
CO_2 Reaction[†]	160	110	80
Lightg., A/C, Misc.[‡]	300	200	150
Total Sensible	640	490	410
Total Heat	1060	710	530

(C.M. Humphreys, et al., "Sensible and Latent Heat Losses from Occupants of Survival Shelters," ©1966, ASHRAE Journal 8:5, May, pp. 82-84, released by permission of ASHRAE Journal)

[†] Based on carbonate formation heat of 1100 Btu/lb CO_2.

[‡] Arbitrary allowance for personnel-dependent electrical power degraded to heat.

exported power. Estimate air heating by radiation and convection from equipment, including power-generation equipment, by conventional methods. As indicated in chapter 2, the parasitic power demand is very strongly influenced by the heat-rejection system used.

3-3. Nominally hardened facilities.

a. The waste-heat rejection system for nominally hardened facilities is an open system for both the preattack and postattack periods. Design the system for waste-heat rejection to the air through one of two types of subsystems located in hardened facility cavities: air-cooled heat exchanger, or evaporation-cooled water tower. Use a hardened AES to conduct inlet and outlet air from the facility cavities to the ground surface. Air from the atmosphere will be the transport medium. The AES will handle air for both the personnel and the air-breathing power generation systems.

b. Air-cooled heat exchangers have the single advantage of not requiring a consumable water supply. Consequently, their endurance (aside from weapon effects) is limited only by the fuel supply of the power system. In nearly all other aspects, the direct air-cooled system compares poorly with the evaporation-cooled system, especially in that the air-cooled system has a higher parasitic power demand and is more vulnerable to damage through the AES. Design an air-cooled system for the worst-case ambient air temperature.

c. Evaporation cooling with hardened cooling towers or hardened refrigeration condensers requires about half of the air flow necessary for direct air cooling. Because the air flow is smaller, both the parasitic power demand and its resulting waste heat are reduced. In addition, cooling water is provided at lower maximum temperatures (typically less than 85°F) than are possible with direct air cooling, therefore increasing the percentage of waste heat handled with water-cooled heat exchangers and decreasing the mechanical refrigeration load. The major disadvantage of an evaporative cooling system is the requirement for a make-up water supply of approximately 55 ft^3/MWh of waste heat rejected. Therefore, the make-up water storage capacity imposes an additional limitation on the facility's endurance. Also, evaporative condensers are undesirable from a maintenance standpoint. Design evaporatively cooled systems for the worst-case air conditions.

3-4. Moderately hardened facilities.

a. As the hardness level requirement and corresponding burial depth increase, the open waste-heat rejection system becomes less feasible for postattack because of the increasing vulnerability of the AES and the rapid increase in the requirement for parasitic power to transport the air via the AES.

b. Reduce the necessary AES air-handling capacity by restricting use of atmospheric air to that required for personnel and air-breathing power generators. About 20 percent of the facility waste heat can be rejected via engine exhaust through the AES outlet duct for a diesel-generator power system. For preattack, reject the rest of the facility waste heat by water transport system to a surface-located, unhardened water-cooling tower. For postattack, reject the balance of waste heat to a closed heat sink. (The cooling tower will be used preattack to maintain the heat sink unreadiness at the required temperature, and must be sized accordingly.)

c. The AES for a moderately hardened facility could also be used to reject high-temperature waste heat via ebullient cooling. Use of this method of waste-heat rejection would decrease the heat-sink storage volume by factors from 10 to 25 for that fraction of the heat rejected as steam from ebullient cooling.

3-5. Superhard facilities.

a. During the preattack period, the waste heat of a superhard facility would be rejected to the atmosphere via, for example, a water transport system to a surface-located, unhardened water-cooling tower, sized to maintain the closed heat sink at the required temperature condition. However, superhard facilities are deeply buried, and during postattack will require completely closed waste-heat rejection and air-reconstitution systems. Design considerations for the closed-air reconstitution system are discussed in chapter 4. Factors to be considered in the design of closed heat sinks are discussed below.

b. In closed-system waste-heat rejection, the total waste heat is rejected to a closed heat sink, which is generally a water-filled cavity. Heat sink volume depends on the initial water temperature and the maximum allowable final water temperature. The maximum final water temperature will depend on the type of electric power supply system used and the design of the waste-heat transport system. Without allowance for heat-sink inefficiencies and heat load from geologic media, the heat-sink volume in cubic feet per magawatt-hour of thermal energy is approximately equal to 57,000/ΔT, where ΔT is the water temperature rise in “F. When ebullient cooling is used, the water storage volume is less than 55 ft^3/MWh. The heat-sink volume can also be reduced by use of ice-water mixtures.

c. Heat-sink volume requirements are greatly influenced by the power system’s efficiency and maximum heat-rejection temperatures. Some approximations useful for preliminary design estimates of water-filled heat sinks are given in table 3–2. The heat-sink volumes given in the table are based on the assumptions indicated for waste-heat distribution and heat-rejection temperatures. All waste heat is treated as power-system dependent, with the total electrical power converted to low-temperature waste heat.

d. To attain the greatest possible heat-sink usage with the least possible heat-sink volume, strive for the smallest feasible differential between the maximum heat-rejection temperature and the maximum heat-sink temperature. The minimum differential assumed to be practical is 5°F, achievable with direct water-cooing or substantially larger-than-normal counterflow heat exchangers. However, the minimum practical differential achievable with air cooling will not be less than 10°F. For example, if air cooling of personnel shelters is the controlling requirement, the maximum heat-sink temperature will be limited to about 72°F, unless mechanical refrigeration is used.

e. The waste-heat distribution for the closed-cycle diesel system, as shown in table 3–2, allows for a 25 percent increase in total waste heat in the low temperature range for carbon dioxide absorption. The assumed overall thermal efficiencies for the diesel and Stirling engine systems are intentionally conservative because the closed-system efficiency and heat balance are the least clearly defined for these systems. For 7 of the 10 cases listed, the low-temperature cooling requirement limits the maximum heat-sink temperature, i.e., the final water temperature cannot approach the maximum reject temperature. The assumption of 90 percent heat-sink efficiency may or may not be conservative. Unquestionably, there will be some mixing of cold heat-sink water with warm return water and some conductive heat transfer within the heat sink. Such mixing and conductive transfer will reduce the effective heat-sink capacity to some degree.

f. The last column in table 3-2 compares heat-sink volume required per unit of electrical power produced by different power systems, based on the assumed system efficiencies and heat-sink conditions. Substantial reductions in heat-sink volume are possible by reducing the initial heat-sink temperature from 60°F to 40°F. Use of mechanical refrigeration to raise the rejection temperature of

Table 3-2. Approximate Heat-Sink Requirements for Closed-Cycle Waste-Heat Rejection

	Waste-Heat Temperature Distribution				Heat-Sink Design				
	Low Range		High Range		Average Water Temp.		Volume (90% Efficient)		
Power System	Total Heat, %	Maximum Rejection Temp., °F	Total Heat, %	Maximum Rejection Temp., °F	Initial °F	Maximum Final °F	$\frac{yd^3}{MWh_t}$	Power Conversion Efficiency, %	$\frac{yd^3}{MWh_e}$
Battery Inverter	82	80	18	90	40 60	83 78	52 125	82	64 152
Fuel-Cell Inverter	50	90	50	212	40 60	130 110	25 45	50	50 90
Nuclear Reactor	14*	90	86	128	40 60	123 123	27 36	14	194 255
Closed-Cycle Diesel	36†	90	64	212	40 60	165 129	18 33	20	90 165
Closed-Cycle Stirling	25	90	75	212	40 60	207 160	13 23	25	54 90

U.S. Army Corps of Engineers

*Average of 7, low-power ANPP systems.

†Increased to reflect added heat of carbon dioxide absorption.

low-temperature waste heat could reduce heat-sink volume for the battery inverter and fuel cell-inverter systems, but would have limited value for the other three systems under the conditions assumed.

g. Since low-temperature waste heat usually controls heat-sink requirements, raise the cooling-system efficiency wherever possible by maximum use of direct liquid cooling of equipment. In the case of large-size equipment, it is generally a matter of selecting liquid-cooled rather then air-cooled equipment. In the case of smaller equipment it may mean specifying liquid cooling for small units where air cooling has been customarily considered more cost effective. Consider liquid cooling for air compressors, and receivers, vacuum pumps, refrigeration compressors, and power transmission elements such as bearings, clutches, brakes, and transmissions. Wherever possible, specify direct heat removal from refrigeration compressors by cooling-water or oil-to-water cooling systems, rather than using the refrigerant to cool the compressor. It may be possible to use liquid cooling, rather than traditional air cooling, for electrical generators, motors, and transformers; radio transmitter tubes, tank coils, and tuning capacitors; power factor correction capacitors; and high-power solid-state device heat sinks.

h. Mechanical refrigeration offers a potentially more effective approach to efficient heat-sink utilization. Mechanically refrigerated dehumidifiers and water chillers for part of the low-temperature cooling allow higher heat-sink temperatures, compared to the temperatures required with direct cooling systems. Potential gains may be limited by the refrigeration system's power demand and the additional waste heat produced. For a spread of 40°F between the temperatures of the chilled water and the condenser cooling water, the power demand for refrigeration is about 20 percent of the heat rejected, which increases the heat-sink requirements by the same percentage. Larger temperature spreads due to either low chilled-water temperature or higher condenser-water temperature will reduce the refrigeration efficiency and increase the added power and waste-heat loads.

i. The use of refrigeration brines offers a technically feasible and well-developed (although not necessarily cost effective) method of developing lower initial heat-sink temperatures without using ice. Disadvantages are the requirements for increased use of inhibitors to minimize the corrosive effect of brines, and for increased refrigeration costs to maintain the heat sink at the lower temperatures feasible with brine. However, compared to fresh water used between 40°F and 90°F, a sodium chloride brine would extend the feasible initial heat-sink temperature down to about 15°F and reduce the volume requirement by about 33 percent. Similarly, use of calcium chloride brine over the range of −55°F to 90°F could reduce heat-sink volume by about 66 percent.

CHAPTER 4

AIR-QUALITY CONTROL

4–1. Introduction.

a. This chapter deals primarily with quality control of the air required to support personnel. Reference is made to operating equipment when necessary, but does not address the quantity (or quality) of air needed for combustion systems. View the air-quality control system within the context of two operation modes: preattack, and transattack/postattack. In general, it will be most effective to use an open ventilization system during the preattack time frame. The design of this sytem is similar to the ventilation systems found in conventional facilities, except that a hardened air entrainment system (A ES) will be used to exchange air between the facility and the atmosphere. The AES is discussed in TM 5-858-5.

b. Design the transattack/postattack air-quality control system to include no fewer than the following capabilities:

—Provide acceptable preattack availability.

—Provide acceptable quality control of air-flow velocity, temperature, humidity, oxygen, carbon dioxide, contaminants—as delineated below.

—Accommodate exercising preattack.

c. Transattack/postattack ventilation systems that communcate with the atmosphere must provide for removal of large dust loads and insidious chemical, biological, and radiological warfare contaminants. This is an extremely difficult task that should be avoided by using a closed ventilation system whenever possible.

4–2. Air-flow velocity. Design the system for minimum circulation velocity of 50 ft/min in any part of the facility that is contaminated by carbon dioxide, water vapor, or toxic and combustible gases and of 100 ft/min in areas normally occupied by personnel. Substantially higher air velocities may be justified in some occupied locations to maintain required effective temperatures at higher dry-bulb temperatures, without excessive demands for power to dehumidify the air.

4–3. Air temperature.

a. Temperature control in hardened facilities will typically require heat removal. Two prime considerations govern the establishment of design air temperatures: personnel comfort and efficiency, and cooling requirements for air-cooled equipment.

b. Where personnel efficiency is the prime consideration, the average effective air temperature should be about 73°F ±1°F, and the dry-bulb temperature should be limited to about 80°F ±2°F in order to permit combined cooling and dehumidification at moderate coolant temperatures. (The indicated dry-bulb and effective temperatures together with an air velocity of 100 ft/min are consistent with a relative humidity of 50 percent, which is also considered the optimum for control of air-borne bacteria.)

c. For facilities that are primarily personnel shelters (as opposed to operational facilities), personnel efficiency and comfort could be compromised to the extent of permitting somewhat higher effective and dry-bulb temperatures. With higher ambient temperatures the maximum useful heat-sink temperature range and capacity could be increased by raising the cooling water temperature, for example, from 68°F to 78°F. However, the apparent advantage is illusory where the major heat load is the metabolic heat of personnel, since at higher temperatures the percentage of total metabolic heat rejected as water vapor (latent heat) increases rapidly and dehumidification requires lower coolant temperatures (50°F or less).

d. Where operating equipment is the important consideration, air temperatures will be limited by equipment cooling requirements. In general, the reliability of electronic and electrical power equipment is inversely proportional to the air temperature. Battery-inverter systems, for example, are prime candidates for closed-cycle power systems, and the recommended operating temperature for inverter systems and storage temperature for batteries is usually no higher than 75°F. Inverter system availability and battery cell life improve at lower ambient air temperatures.

e. For cooling facility air, use air-to-chilled water or air-to-refrigerant fan-coil units. To minimize power demand and heat-sink requirements for air cooling, specify liquid-to-liquid heat exchangers to remove waste heat from equipment at the source wherever possible.

f. For any heating required, use the waste heat of the power systems as much as possible to minimize heat generation. Where this is not feasible, specify electrical heating rather than gas, to preclude gaseous combustion products that would need venting at further expense.

4-4. Humidity.

a. The humidity gains in the closed-ventilation system of well-constructed facilities will originate largely from the respiration and perspiration of personnel, and are treated as a waste-heat load. Where there are no other overriding considerations, 50 percent relative humidity should be maintained for human comfort and control of air-borne bacteria.

b. Chemical dehumidification will usually be undesirable because nearly all commercial absorbent and adsorbent systems must be thermally regenerated, which adds additional heat load to the waste-heat rejection system. Where there is already a substantial load of sensible heat to be removed, consider dehumidifying by direct extraction of latent heat via condensation.

c. Although the use of water spray towers may be the most efficient means of dehumidification at low water temperatures, a possible rise in heat-sink water temperature during the facility mission period would require the use of mechanical refrigeration for dehumidification. Dehumidification system design should be based on the maximum heat-sink temperature allowable at the end of the mission. At cooling coil temperatures approaching the freezing point, provide the automatic defrosting of dehumidifier coils.

d. To minimize space requirements, specify integrated cooling and dehumidification units.

4-5. Oxygen. If the principal oxygen demand is by personnel, us the values given in table 4–1 to estimate the rate of consumption. In view of the probable low cost of oxygen for this purpose, an arbitrary allowance of 3 lb per man-day is reasonable. The most practical storage will usually be in standard, 250-ft^3, high-pressure cylinders up to a total of about 12,000 ft^3. For larger storage requirements, specify larger capacity cylinders to improve the packing factor and to simplify ducting. Use standard two-stage pressure regulators to set the flow rate. Since variation of oxygen content between the normal 21 percent and about 17 percent is acceptable, highly accurate or automatic control of oxygen flow is not essential. Periodic checking of oxygen concentration and manual adjustment of flow rate is adequate.

4-6. Carbon dioxide.

a. Carbon dioxide buildup in hardened-facility ventilation air will originate largely, if not exclusively, from personnel. Formation rates can be estimated from the data in table 4–1. Carbon dioxide is present in atmospheric air at about 0.03 percent by volume, and acts on the human nervous system to maintain involuntary respiration. At levels in excess of 1 percent it begins to cause hyperventilation, increased oxygen consumption, and increased respiratory carbon dioxide production; concentrations higher than about 4 percent are toxic. The natural air content of 0.03 percent carbon dioxide should not be reduced by the carbon dioxide-control system, but this is not likely to be a problem. The maximum carbon dioxide conent of the room exhaust air should not exceed 1 percent and the corresponding concentration in return air should be less than 0.08 percent.

b. Carbon dioxide can be removed readily from air by causing the gas to react with strong bases (caustics) to produce carbonates. The reactions are exothermic and will add significantly to any personnel-dependent heat sources. From several feasible combinations of reactant and process, the optimum method will be chosen by considering cost, convenience, and minimum release of waste heat, in approximately that order. In a gas absorption system widely used by industry, a sodium hydroxide solution is recirculated counter-current to the carbon dioxide-contaminated air stream, through a spray or packed scrubber tower. This system is recommended for large-capacity carbon dioxide removal systems for hardened facilities on the basis of reactant, and low heat of reaction (about 1020 Btu per pound of carbon dioxide absorbed).

c. If the scrubber solution temperature exceeds the desired dew point temperature of the air, an additional load will be placed on the humidity control system. In addition to the heat of carbonate formation, latent heat and sensible heat transferred to or from the air stream must also be considered in the heat-load calculations for the scrubber. In any case, the scrubber design should be coordinated with the design of the air temperature and humidity control systems.

d. The wet scrubber system is highly amenable to continuous process application with automatic control. In such a system, carbon dioxide removal efficiency and outlet concentration are controllable and adjustable while the system is in operation by varying solution concentration, temperature, flow rates, and air-stream velocity through the scrubber.

e. Dry process absorption in attractive for relatively small-capacity carbon dioxide rem-oval requirements (less than about 5 lb per hour). These systems consist of trays or canisters of dry granular absorbents through which air is circulated at low velocity. Since absorbers must be replaced pe-

Table 4-1. Personnel-Dependent Oxygen Requirement and Carbon Dioxide Production

Activity	Rating	Light Work	Seated at Rest	Sleep
Metabolic Rate (80°F & mrt)*	Btu/mh	600	400	300
Oxygen Consumption†	Lb/mh	0.125	0.083	0.062
CO_2 Production†	Lb/mh	0.147	0.098	0.074

U.S. Army Corps of Engineers

*After Humphreys et al. (1966); mrt: mean radiant heat.

†After Williams (1968)

riodically, dry process absorption is a batch process and therefore has had limited industrial use. However, dry lithium hydroxide, LiOH, has been used as a carbon dioxide absorber in both submarines and space capsules. Dry LiOH absorbers remove moisture as well as carbon dioxide from the air; this may necessitate the air be dehumidified to maintain a 50 percent humidity level. The heat generated by water absorption could be several times greater than the heat of carbonate formation.

f. An absorption system based on Baralyme (a trade name for a mixture of 20 percent barium hydroxide hydrate and 80 percent calcium hydroxide) was designed and tested by NCEL (Williams, 1968) as a carbon dioxide control system for survival shelters. The LiOH-based system is the more extensively tested and the more efficient in terms of carbon dioxide absorbed per unit weight and per unit volume. The cost (1978) is about the same (on the order of $4.10 for LiOH compared with about $3.50 for Baralyme per man-day).

4–7. Contaminants.

a. Particulates. Control of particles such as dust and lint is of great importance for good control of airborne bacteria in closed ventilation systems. Extensive tests in hospitals and barracks have demonstrated that a high percentage of infectious bacteria are transported by dust or lint and can be eliminated by effective dust control. Particles will be eliminated by regularly serviced, high-efficiency filter sytems in supply ducts to all manned areas. Prefilters can be treated with a bactericidal emulsion spray. Electrostatic precipitators cannot be used because of the problem caused by ozone buildup.

b. Flammable and toxic gases. Internally generated gases can build up to significant concentration levels in closed systems. Potentially combustible or toxic vapors and gases can be released by numerous very ordinary products including cleaners, solvents, inks, anesthetics, antiseptics, disinfectants, refrigerants, and photocopy chemicals. In open ventilation systems, most of these contaminants are minor problems that require, at most, increased air flow for dilution and direct discharge to outside air. In closed systems, however, control measures should include prevention, monitoring, and treatment, with the emphasis on prevention. All liquid and gaseous products used in facilities having closed-ventilation systems should be investigated as potential sources of the more than 200 toxic and flammable gases for which concentration limits in ventilation air have been established by OSHA (1972) and others. Where potential sources cannot be eliminated, strict regulations controlling their storage and use should be mandatory provisions of the facility operating procedures. Specify the installation of monitoring sensors near potential sources and at possible concentration points and provide suitable air-treatment equipment either as part of the full-time air processing system or for use as required.

(1) Most gases and vapors are somewhat soluble in water and tend to dissolve in the condensate in dehumidification equipment or in wet-scrubber solutions. Additionally, acid gases such as the oxides of nitrogen will be removed by chemical reaction in carbon dioxide scrubbers. Many gases and vapors, particularly organics, are effectively removed by activated charcoal filters. Restrict maximum permissible concentrations of gases and vapors to 25 percent of their lower flammability limit, unless the maximum allowable concentration must be further reduced because of their toxic properties.

(2) Catalytic oxidation is effective for eliminating combustible gases. However, use caution in specifying oxidation devices where the air may contain contaminants that could break down to release still more hazardous compounds (e. g., chloroform releases phosgene gas). Specify the use of catalytic oxidation devices on an “as required” basis, since they operate at elevated temperatures (usually with electrical heating) and add to both electrical-power and waste-heat loads. Provide battery installations in closed ventilation systems with one or more standard US Navy catalytic hydrogen eliminators. The poison gas antimony hydride can be completely eliminated by restricting batteries to those using calcium rather than antimony as a hardening agent in the lead alloy.

c. Ozone control. The low allowable concentration of ozone in ventilation air (0.1 ppm) can make this gas a problem in closed ventilation systems. The principal sources are high-voltage corona discharge and electrical arcs. Smooth, non-weathered, insulation of high-voltage lines will minimize corona discharge. Arcing in motor and generator brushes and control switches, relays and circuit breakers can be minimized by use of solid-state brushless motors; solid-state zero-current switching; solid-state transient suppressors; and various surge voltage protectors, gas discharge devices, and vacuum spark gaps available in the electrical power and communications fields.

d. Odors. Control of odors will require use of activated charcoal filters.

CHAPTER 5

UTILITIES AND SERVICES

5–1. Introduction. The numbers, kinds, and relative importance of the utilities and services required for hardened facilities vary with the prime mission assignment, manning requirements, and length of specified endurance period. However, the only design considerations appreciably different from normal standards stem from the problems of maintaining postattack personnel isolated from ambient atmosphere and external support. Control of groundwater, prevention of fire, and details of personnel services are delineated in this chapter.

5-2. Groundwater control.

a. Gravity drainage. For hardened underground facilities under postattack conditions, gravity drainage of seepage water into a reservoir is the only viable concept. The problem will be compounded by weapon-induced ground shock increasing water permeability in the surrounding media. Successful gravity drainage depends on overburden dewatering, wet-rock drainage, and underground reservoir capacity, all of which are site dependent.

b. Site selection. Review of long-term climatological data and detailed investigation of groundwater sources, flow paths, and flow volumes should be part of all hardened facility site-selection studies. Assessment of the severity of groundwater problems will strongly influence site selection.

c. Overburden dewatering. As early as possible during construction of any buried facility, the surface drainage should be reworked to minimize local surface-water infiltration. Overburden that contains aquifers above a buried facility should be surrounded by grout curtains and dewatered. Where heavily flowing aquifers are cut off, reroute the interrupted flow at the upstream face of the grout to prevent elevation of the water table. Specify permanent installation of water-table logging wells, dewatering wells, and a pumping system adequate to eliminate free groundwater down to the level of impervious rock within the site area.

d. Wet-rock drainage. During construction, all rock in the vicinity of permanent underground cavities must be investigated for water sources by drilling from the cavities before permanent liners are installed. Wet-rock areas will be mapped and permanent drain piping installed. Within five cavity diameters of cavity surfaces increase the number of drain holes until the total drainage rate becomes constant or declines. Permanent flow-monitoring sensors will be installed in the trunk drains so that flow rates can be read at any time and continuously recorded. Wet rock at cavity surfaces should be grouted to a depth of at least one cavity radius from the opening, or to the depth required to eliminate seepage at the rock surface, whichever is greater.

e. Reservoir capacity. For conservative design, assume the total discharge drains into the underground reservoir during the postattack endurance period. The combined discharge of the underground drainage and overburden dewatering systems will be monitored during construction on a year-round basis, with particular attention paid to seasonal variations. The final estimate of total volume required for the postattack drainage reservoir will be based on three values:

—Maximum flow rates during the season producing greatest water volume

—Total volume of discharge from surface, facility, and buried drainage

—Maximum volume of hygienic water required for personnel use during postattack

5–3. Fire protection.

a. Fire prevention in hardened facilities has more than normal importance because of closed ventilation systems or very limited provision for obtaining outside air to dilute smoke or fumes. Construction materials and furnishings should exclude pyrotechnic metals and other combustibles. Operating procedures and regulations should minimize storage and handling of paper and other combustibles. Waste paper should be collected frequently, compacted, and baled. Smoking should be prohibited or confined to specific safe areas.

b. The outer shells of hardened facilities usually will be reinforced concrete, but the operating areas usually will be housed in shock-isolated inner structures of steel, often more than one story high. Conformance to National Fire Code NFPA 220, 4-hour classification shall be adhered to except as modified herein. Floor areas should be subdivided in units preferably not larger than 2500 ft^2, with floor-to-ceiling walls having not less than two-hour fire-resistive rating. All openings, included ventilation ducts, through fire-rated floors and walls are to be provided with self-closing fire-door or fire-damper assemblies. Stair and elevator shafts will be enclosed with three-hour walls and fire-door assemblies. Except for blast-resistant doors, fire-door assemblies must bear the Underwriter's Laboratory Class "B" label.

c. Elimination of combustible materials should remove the potential for a class "A" fire. However, if there is a Class "A" hazard and if exposed equipment can tolerate water, use high-pressure water fog or water-based foam extinguishing systems. Where water or water-based foam are used, the dehumidification system will be sized to reestablish within 24 hours the relative humidity selected for operating conditions.

d. Wherever possible, specify airtight enclosures for any equipment subject to Class "B" or "C" fires, and specify an internal atmosphere of nitrogen or carbon dioxide to be maintained in the enclosures. For facilities having closed ventilation systems, a carbon dioxide cover should be used, leakage should be monitored, and the absorption system sized so that CO_2 concentration never exceeds 5 percent at any time, 4 percent for more than 8 hours, nor 1 percent for more than 24 hours. Normal waste heat generated within artificial atmospheres of carbon dioxide or nitrogen will be removed by fan-coil units mounted inside the enclosures.

e. Facility operational procedures will stress quick fire control by personnel using fire hoses with fog nozzles or portable Class B–C foam, or powdered dry chemical or carbon dioxide extinguishers. Carbon dioxide extinguishers should not be supplied where foam or powdered chemical extinguishers are acceptable. Foams and dry chemicals must be limited to those that do not release toxic vapors or gases when heated. Never use carbon tetrachloride extinguishers.

f. Personnel gas masks should be provided in redundant and readily accessible locations. Masks meeting U.S. Bureau of Mines Standards will be used whenever it is necessary for personnel to enter an area where there is a fire or where a fire has occurred.

5-4. Personnel support services.

a. Quantitative. Personnel support services will vary with the facility prime mission and with the maximum possible number of personnel within the facility at the time of attack. The possibility of attack during change of shift must be included. The specified personnel survival period is likely to be based on the predicted radiation hazard, independent of the prime mission endurance, and will probably be 30 days or more. Consequently, differences in the required personnel support services will be quantitative rather than qualitative.

b. Quarters. In the absence of other specifications, quarters planning and space allowances will be based on the specifications provided in appendix B.

c. Furnishings. All furnishings will be built in or securely anchored to the structure to resist accelerations of not less than 1 g in any direction. All movable supply items will be stored in racks, drawers or cabinets where they can be secured against damage by an acceleration of not less than 1 g, accompanied by displacements on the order of inches, in any direction. Walkways, walls, fixed equipment, and furnishings in occupied areas will be provided with continuous handrails or grab bars for personnel safety under ground-shock effects.

d. Lighting systems. Lighting is exclusively a personnel-dependent system and fixed lighting should be limited to normally occupied areas. To minimize lighting requirements, interior finishes will be light colored. Lighting levels in occupied areas will be the minimum consistent with safety and efficient operations. Lighting calculations and layout should be based on: use of high-efficiency fluorescent lamps producing not less than 70 lumens per watt for lamps rated at 25 watts or more; and use of high-efficiency fixtures without baffles or covers. All lighting fixtures and conduits will be secured to resist at least 1 g acceleration in any direction. Emergency lighting will be supplied by incandescent, battery-charged units using sealed-cell batteries; the complete assemblies will be mounted to resist 1 g acceleration.

e. Supplies. Storage of consumable supplies within hardened facilities is based on continuous personnel occupancy for drills, alert periods, and the postattack survival periods. Supplies consumed during drills and alert periods will be replaced weekly so that the maximum supply inventory need not exceed that required for the specified survival period plus one week.

f. Food. The food supply will maximize use of prepared dehydrated foods and minimize requirements for refrigeration and cooking. Food will be heated in well-insulated ovens vented directly to air revitalization equipment to avoid odors in ventilation air.

g. Potable water supply. Potable water will be stored in sterile, sealed containers suitable for use in pipeless unit dispensers and will be taken from the stored supply in order of time of storage (first in/first out). Water will be checked regularly for bacterial or other contamination.

h. Hygienic water. Water for washing and showers can be piped for the return side of the waste-heat rejection system cooling water if a fresh-water heat sink system is used. Provide for a consumption rate of 4 gallons (O. 54 cubic feet) per man-day. Waste water will be disposed to the facility drainage reservoir. The hygienic water supply should be chlorinated to inhibit bacterial growth.

i. Waste disposal. Solid wastes will be compacted to minimize storage space and fire hazard. Garbage and sanitary waste will be disposed of by the same type of waterless recirculating oil flushed disposal systems being used increasingly by the U.S. Park and Forest Services at locations where conventional sewage systems are impractical. These systems use a mineral oil flushing and cover fluid, which is filtered, chlorinated, and recirculated. This system has virtually no aerobic bacterial action, only limited anaerobic action and methane generation; however, as a precaution, the entire system would be vented to a catalytic oxidizer, a carbon dioxide absorber, a dehumidifier, and an activated charcoal filter, in that order. The residual gases will be negligible, and processing through the ventilation air-revitalization system should be practicable. Sludge storage tank capacity may be conservatively sized at 0.5 gallons per man-day of personnel occupancy. The typical minimum tank capacity is 200 gallons and actual capacity is usually based on sludge pump-out at 30-day intervals. To this must be added capacity to accommodate the survival period.

APPENDIX A

GLOSSARY

Air Entrainment System:	Accomplishes continuous or a periodic transfer of air (gas) between the atmosphere and the facility; abbreviated AES.
Blast Valve:	Prevents entry of airblast overpressure into hardened facilities.
Endurance:	Combined transattack and postattack time frames in which the facility must fulfill its functions.
Hard Mounted:	Equipment attached directly to its supports without the use of shock isolation.
Heat Sink:	A medium used to absorb the waste heat rejected by power generation or air-conditioning systems. Ice or water in cavities is generally used for hardened systems.
Moderately Hardened Facility:	Facility hardened to hundreds of psi overpressure.
Nominally Hardened Facility:	Facility hardened to tens of psi overpressure.
Postattack:	The timeframe beginning after the last burst.
Preattack:	The time frame prior to first burst or to button-up.
Preattack Availability:	Percent of time during a given preattack period (or, alternatively, the probability) that the component is in a fully operable or committable state at the start of the attack or button-up, when the attack occurs at an unknown (random) point in time.
Prime Mission:	Primary mission of the system to which the facility is a subsidiary element.
Rattlespace:	Displacement envelope of a shock-isolated equipment or structure.
Superhard Facility:	Facility hardened to thousands (and greater) of psi overpressure.
Survivability:	The probability that a facility/subsystem/component failure-mode will physically survive a nuclear-weapon attack and retain its physical integrity during the specified endurance period.
Transattack:	The time frame between the first burst (or button-up) and the last burst.
UPS:	Uninterruptible power supply.

APPENDIX B

PERSONNEL SUPPORT SERVICES

B–1. Introduction. The following criteria are presented as guidance for the providing of personnel support services. The references provide philosophy and details that can be used to meet these criteria.

B–2. Quarters.

a. Provide 4-man rooms for 90 percent of personnel.

b. Provide 2-man rooms for 10 percent of personnel.

c. Provide l-man rooms for Commanding Officer and deputy (room to include bathroom facilities). Figure B–1 shows examples of the above.

B–3. Sanitary spaces.

a. Location to be as near as feasible to living quarters.

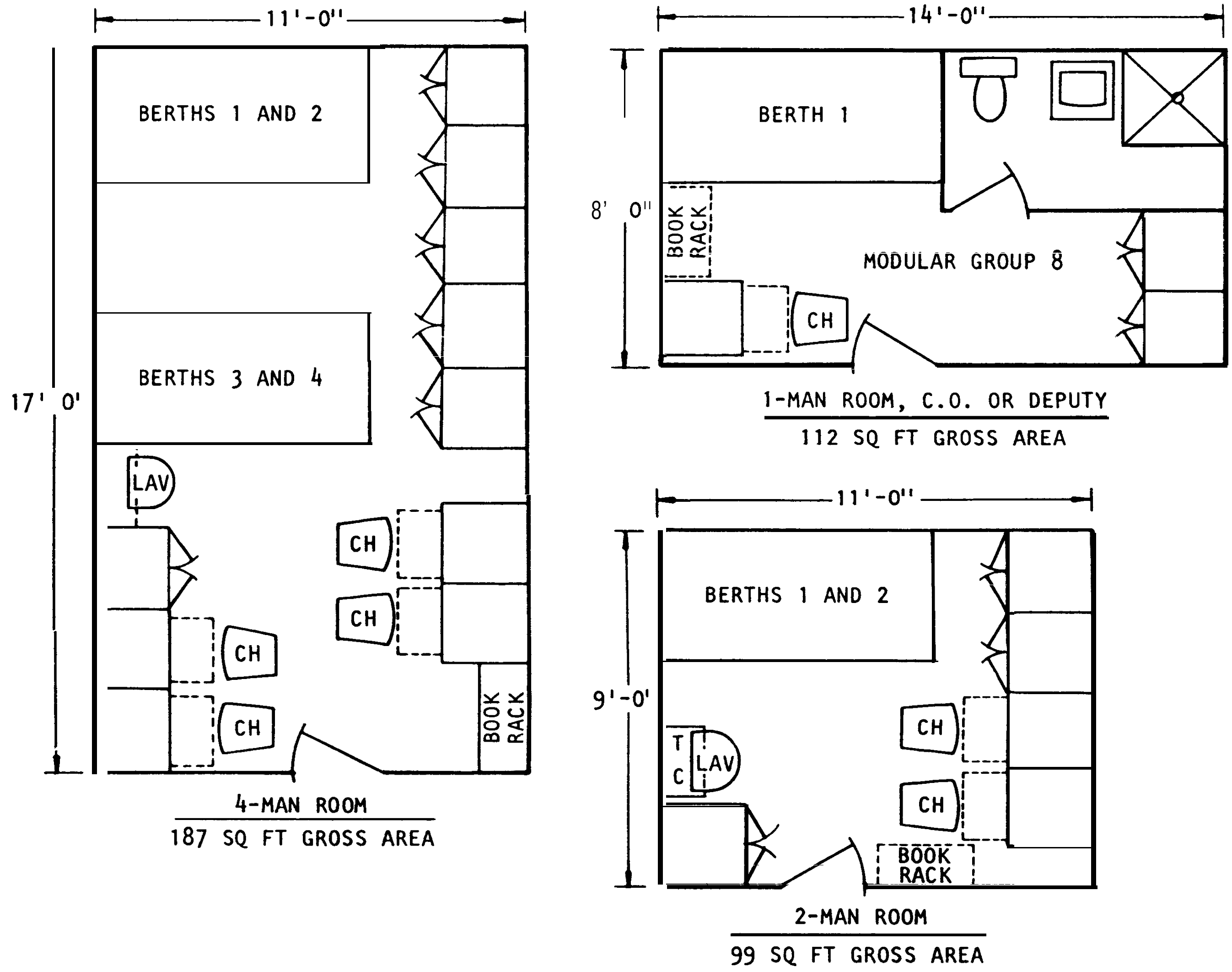
b. Washrooms designated as decontamination spaces to have a minimum of two doorways.

c. Sanitary fixture requirements.

—Lavatory— 1 for every 8 persons.
—Shower—1 for every 10 persons.
—Urinal—1 for every 20 males.
—Watercloset—l for every 8 males.
—Watercloset—l for every 4 females.

B-4. Food preparation and dining.

a. Cafeteria style dining.



4-MAN ROOM
187 SQ FT GROSS AREA

1-MAN ROOM, C.O. OR DEPUTY
112 SQ FT GROSS AREA

2-MAN ROOM
99 SQ FT GROSS AREA

U. S. Army Corps of Engineers

Figure B–1. Typical living quarters

b. Seating to be planned for 40 percent of the complement. Eating area to be planned at 10 ft^2 per seat. Four-person tables to be used

c. Each serving line to serve 600 persons an hour and 150 seats to meet this rate. Adjustments to this criterion will be based on total complement and eating schedule.

d. Scraping stations to be provided.

e. Criteria for United States Navy ships 300 ft to 600 ft to be utilized for detail requirements.

f. Food preparation areas to be consistent with the food supply.

B-5. Recreation areas.

a. Motion Pictures—Utilize eating area.

b. Library—Provide 1 1/2 books per person and 1 linear ft of shelving per five persons. Shelves to be installed in recreation room.

c. Recreation Rooms—Provide seats for one-fourth the complement. Provide 15 ft^2 (gross area) for each seat.

B-6. Services.

a. Laundry—Provide for 18 pounds per week per person in complement, using a central service.

b. Barber Shop - 1 chair for every 200 persons.

c. Retail Store (ships store) —Provide facility.

d. Brig—Provide a room with a three-tier berth, a lavatory, and a watercloset. A shower stall to be provided outside this room.

B–7. References:

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APPENDIX D

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TM5-858-3	Structures
TM 5-858-4	Shock Isolation Systems
TM 5-858-5	Air Entrainment, Fasteners, Penetration Protection, Hydraulic-Surge Protective Devices, EMP Protective Devices
TM 5-858-6	Hardness Verification
TM5-858-7	Facility Support Systems
TM 5-858-8	Illustrative Examples

Department of the Navy

NAVSHIP-0933-LP-005-0810	Naval Ship Systems Habitability Manual
NAVSEA-0933-LP-005-5050	U.S. Navy Shipboard Furniture Catalog

Department of Transportation

CSGN, 1 Oct 1976	Habitability Study

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Journal 8:5-66	Sensible and Latent Heat Losses from Occupants of Survival Shelters

National Fire Protection Association (NFPA)Publications Dept., Batterymarch Park, Quincy, MA 02269

No. 220-1979	Types of Building Construction

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