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DESIGN AND INSTALLATION MANUAL FOR THERMAL ENERGY STORAGE

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Kenneth J. Nield
Raymond R. Rohde
Ronald M. Wolosewicz

Solar Applications Group

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PREFACE TO THE SECOND EDITION

The first edition of the manual was printed in February, 1979 as an Argonne National Laboratory report. Copies were made available through the National Technical Information Service, and approximately 400 copies were distributed at the Department of Energy's Solar Energy Storage Options Workshop in San Antonio, Texas, March 19 and 20, 1979. In Summer 1979 we sponsored a series of four seminars on thermal energy storage to disseminate information on storage and solicit constructive criticisms which could be used in preparation of the second edition. The more than 100 seminar participants provided many helpful suggestions, and we are grateful for their assistance.

The second edition is a substantial revision of the original work. A new chapter on latent heat storage, an appendix on units and conversions, and an index have been added. In the first chapter, more details are provided on the method of sizing storage by calculation, discussion of characteristics of various types of insulation has been added, and the method of calculating insulation requirements for storage has been improved. Discussion of several rock bed configurations has been added to the chapter on air-based systems, and the rock bed performance map has been made easier to use. Information on corrosion and corrosion protection and plastic tank liners has been added to the chapter on liquid-based systems, and the cost information has been made more definitive. The chapter on domestic hot water storage contains the most recent information on plumbing codes and the types of heat exchangers that can satisfy code requirements. Appendix C has been extensively revised and now includes a derivation of economic insulation thickness. Appendix D has been extensively revised to clarify methods of heat exchanger sizing. Throughout the manual there are numerous minor additions and clarifications that improve its readability and usefulness.

We thank two people who have continued their excellent work from the first edition. Bonnie Nolan typed the second edition manuscript using a Vydec™ word processor, and Beverly Peavler of Idaho Falls, Idaho edited the second edition.

The project was sponsored by the Department of Energy, Office of Solar Applications. Fred Morse, Director, and J. Michael Davis, Assistant Director, and Dr. A. I. Michaels, Manager of the Solar Thermal Storage Program, provided support, encouragement, and guidance.

ACKNOWLEDGMENTS

We acknowledge and thank the numerous persons and organizations that have made this manual possible. The project was sponsored by the Department of Energy, Division of Conservation and Solar Applications. Fred Morse, DOE Branch Chief, and J. Michael Davis, P.E., DOE Program Manager, gave us support and guidance during the preparation of the manual.

Four consultants provided information and expertise that could not have been supplied by our own efforts. Dubin-Bloome Associates, P.C., of New York City provided sample specifications that are the basis for several appendices, plus a wealth of background information. Altas Corporation of Santa Cruz, California provided an excellent analysis of heat exchanger sizing (Appendix D) and information on the physical properties of heat transfer fluids (Appendix B). Globe Engineering Company of Chicago provided general information on water tanks used in several chapters and appendices. Beverly Peavler of Bolingbrook, Illinois edited the main text using Wylbur, formatted and composed it with SCRIPT programs, and copy-edited and proofread the appendices.

We are deeply indebted to a great number of persons and organizations in all phases of the solar industry who freely gave us their time and the benefit of their experience. Without their generous contributions this manual would not be as complete or as useful as we hope it is. Room does not permit the listing of all who contributed to our background knowledge, but some who were especially helpful are listed below.

J. Meeker, formerly of New England Electric, and New England Electric, Westborough, Massachusetts; Neil Barker of PPG Industries, Pittsburgh, Pennsylvania; M. Berrett and D. Berrett of Engineering Services, Inc., Portsmouth, Rhode Island; S. Keller of Kalwall Corporation, Manchester, New Hampshire; J. Cummings of Daystar Corporation, Burlington, Massachusetts; D. Myers of V. R. Myers Pump and Supply Company, Fort Wayne, Indiana; R. Gorman of Energy Systems Planning Division, TRW, Inc., McLean, Virginia; R. Guenzel of Korman Corporation, Jenkintown, Pennsylvania; and the personnel of the Franklin Institute National Solar Heating and Cooling Information Center, Philadelphia, Pennsylvania.

The manual was reviewed twice by a committee of experts whose diverse backgrounds in the solar energy field enabled them to bring to our attention weaknesses in the manual. In addition, the committee offered many positive suggestions that have been incorporated into the handbook. The committee members are:

Paul F. Kando, PRC Energy Analysis Company, McLean, Virginia
Harold Lorsch, Franklin Institute Research Laboratories, Philadelphia, Pennsylvania
Frank Smith, Solar Logic, Inc., Elkins Park, Pennsylvania
Robert Kedl, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Dennis Jones, National Bureau of Standards, Washington, D.C.
Ellis Pickering, SRI International, Menlo Park, California
Guy Gupton, Gupton Engineering Associates, Atlanta, Georgia
Allan I. Michaels, Argonne National Laboratory, Argonne, Illinois
C. J. Swet, Department of Energy, Washington, D.C.

Jackie Bertoletti, Mary Lou Bluth, and Bonnie Nolan did an excellent job of typing the appendices and tables, as well as many early drafts of the main text. The Graphic Arts Department of Argonne National Laboratory deserves credit for the drawings and artwork.

We also thank the manufacturers who have allowed us to use drawings of their products or to refer to their trademarks and products in the sample specifications. These manufacturers are named on the pages where their drawings, trademarks, or product names appear.

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DESIGN AND INSTALLATION MANUAL
FOR THERMAL ENERGY STORAGE

ABSTRACT

The purpose of this manual is to provide information on the design and installation of thermal energy storage in active solar systems. It is intended for contractors, installers, solar system designers, engineers, architects, and manufacturers who intend to enter the solar energy business. The reader should have general knowledge of how solar heating and cooling systems operate and knowledge of construction methods and building codes. Knowledge of solar analysis methods such as f-Chart, SOLCOST, DOE-1, or TRNSYS would be helpful.

The information contained in the manual includes sizing storage, choosing a location for the storage device, and insulation requirements. Both air-based and liquid-based systems are covered with topics on designing rock beds, tank types, pump and fan selection, installation, costs, and operation and maintenance. Topics relevant to latent heat storage include properties of phase-change materials, sizing the storage unit, insulating the storage unit, available systems, and cost. Topics relevant to heating domestic water include safety, single- and dual-tank systems, domestic water heating with air- and liquid-based space heating systems, and stand alone domestics hot water systems. Several appendices present common problems with storage systems and their solutions, heat transfer fluid properties, economic insulation thickness, heat exchanger sizing, and sample specifications for heat exchangers, wooden rock bins, steel tanks, concrete tanks, and fiberglass-reinforced plastic tanks.

INTRODUCTION

PURPOSE

The purpose of this manual is to provide the practical information you will need to select, design, and install the type of thermal energy storage system that best fits your needs. We hope this manual will help you ensure that your thermal energy storage system operates as intended throughout its lifetime and will enable you to avoid the pitfalls that have plagued some earlier systems.

Although do-it-yourselfers will find this manual useful, it is written primarily for professional design and installation personnel in the solar energy industry. These include contractors, installers, solar system designers, engineers, architects, and manufacturers.

We have assumed that the reader has a general knowledge of how solar systems work, as well as knowledge of construction techniques and local building codes. If you lack this background, the books about solar systems listed in the bibliography near the end of this manual should be helpful to you.

SCOPE AND ORGANIZATION

The manual provides a comprehensive treatment of thermal storage for the active solar heating and cooling systems in common use today. It includes both sensible and latent heat storage for air- and liquid-based solar systems. In addition, much of the information can be applied to off-peak storage for load management.

The five main chapters contain general information on storage systems while the appendices contain details on specific subjects. Mathematical equations in the five main chapters are simple and few in number. The installation methods and sample specifications presented will be especially useful to contractors and installers of solar systems. Designers, engineers, and architects are expected to have more detailed knowledge of solar system design methods such as f-Chart, SOLCOST, DOE-1, and TRNSYS. Some of the appendices require more mathematical expertise than the five main chapters and are aimed primarily at these readers. The appendices on heat transfer fluids, economic insulation thickness, and heat exchanger sizing fall into this category.

Chapter 1 discusses general characteristics of thermal energy storage systems, including characteristics of sensible heat storage media; size, location, insulation of storage devices, and heat exchangers. You should understand the material in Chapter 1 before continuing, because it provides a background for the rest of the manual.

Rock beds for thermal energy storage are discussed in Chapter 2. Special characteristics of rock beds, rock bed performance, and construction are a few of the topics covered, along with a design example. Chapter 3 discusses liquid-based storage systems. Some topics covered in this chapter are tank type and costs, corrosion, plastic liners, pumps and other system components, and tank installation. Chapter 4 contains information on latent heat storage including material properties, sizing latent heat storage, insulation, available systems, and costs. Domestic hot water thermal energy storage systems, either stand-alone or as part of space heating systems, are discussed in Chapter 5, along with methods of safeguarding the drinkable water in the systems.

Data and information are presented in both English (pounds, feet, Btus, and so forth) and metric (kilograms, meters, watts, and so forth) units to appeal to the widest audience. In the text and tables metric equivalents enclosed in parentheses follow quantities given in English units. Most graphs have scales for both English and metric units. An appendix on units and conversion factors is included.

You can find sources of additional information about many aspects of solar energy systems in the bibliography. Specific questions about almost any topic relating to solar energy may be addressed to the National Solar Heating and Cooling Information Center, P.O. Box 1607, Rockville, Maryland 20850. You can call them by dialing toll-free 800-523-2929 or, if you are in Pennsylvania, 800-462-4983.

CHAPTER 1
GENERAL INFORMATION ABOUT SENSIBLE HEAT STORAGE SYSTEMS

In a sensible heat storage system, the heat flowing into storage raises the temperature of the storage material. When space heating is needed, heat is removed from storage and the temperature of the storage material drops. The most common sensible heat storage systems are built around rock beds or water tanks; rock beds will be discussed in detail in Chapter 2, water tanks in Chapter 3.

Figure 1-1 represents a typical air-based system, which uses a rock bed for storage; Figure 1-2 represents a typical liquid-based system, which uses water for storage. Many variations of these space heating systems are possible, but the storage systems will always need (1) a heat storage material, (2) a well-insulated container, and (3) provisions for efficiently adding and removing heat.

We will first describe some general characteristics of sensible heat storage materials--heat capacity and daily operating range, which affect the size of the storage device, and temperature stratification, which affects its performance. We will then discuss finding a location for and insulating the storage device and moving heat into and out of storage.

HEAT CAPACITY

Heat, or thermal, capacity is a material's ability to store sensible heat. In the English system of units it is measured in terms of the number of British thermal units (Btu) required to raise the temperature of 1 pound of the material by 1 degree Fahrenheit. Water has a heat capacity of 1 Btu per pound per degree Fahrenheit (Btu/lb·°F). Most other materials have a lower heat capacity than water; rock, for example, has a heat capacity of 0.21 Btu/lb·°F. In metric (SI) units, the heat capacity of water is 4184 joules per kilogram per degree Celsius (J/kg·°C), and the heat capacity of rock is 879 J/kg·°C.

The amount of sensible heat materials can store per unit mass is not the only basis by which storage materials' thermal capacities are compared. Engineers frequently work with a derived quantity known as the volumetric heat capacity, which is found by multiplying the material's heat capacity by its density. The volumetric heat capacity describes the quantity of sensible heat the material can store per unit volume for every degree of temperature change.

Table 1-1 gives the heat capacities and volumetric heat capacities of some common storage materials. The voids referred to in the table are the spaces that exist between individual pieces of piled up rock or other loose material. The proportion of these spaces to the total volume of the rock bed is called the void fraction. Numerous experiments have shown that loose

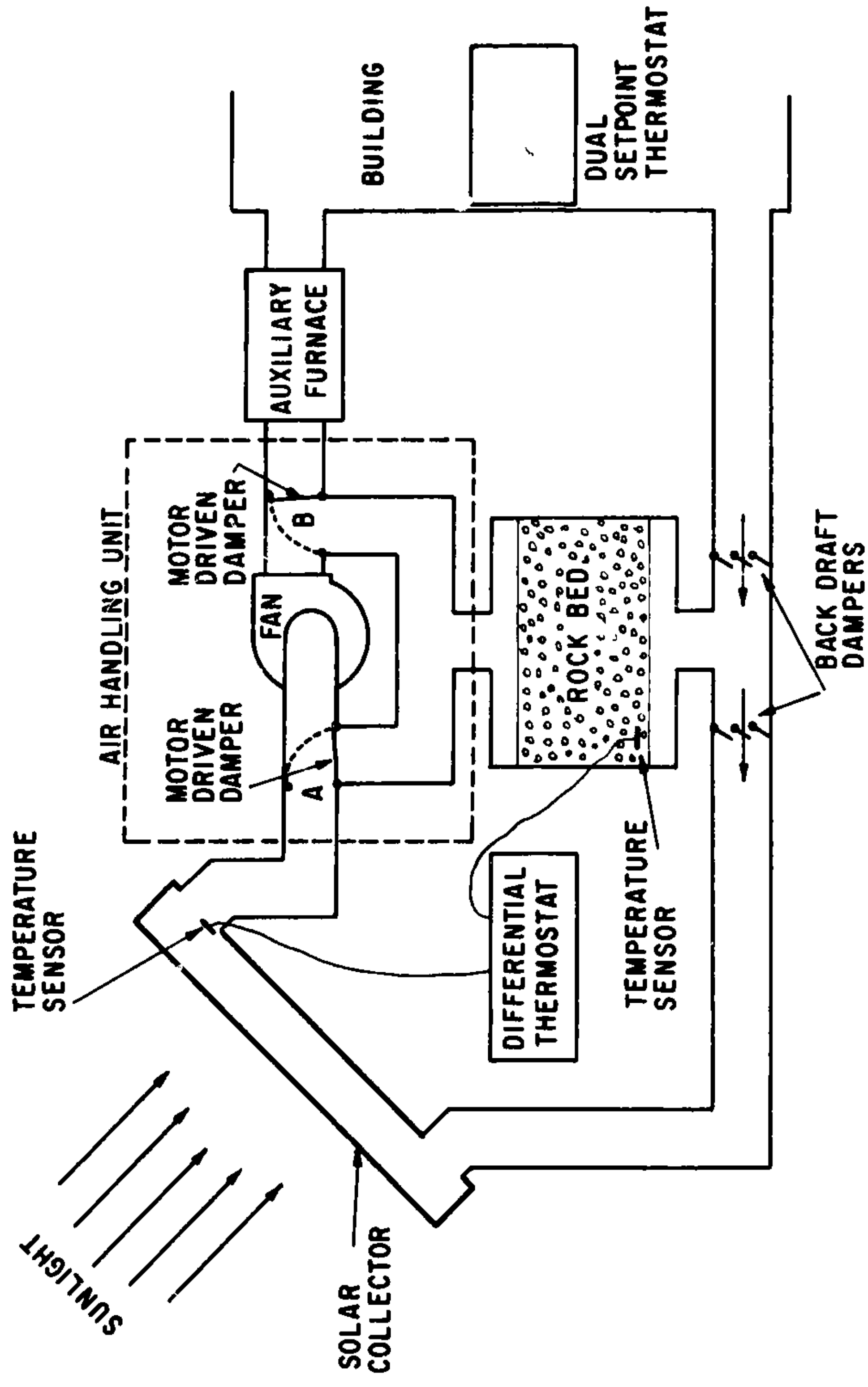

Figure 1-1. Typical Air-based System

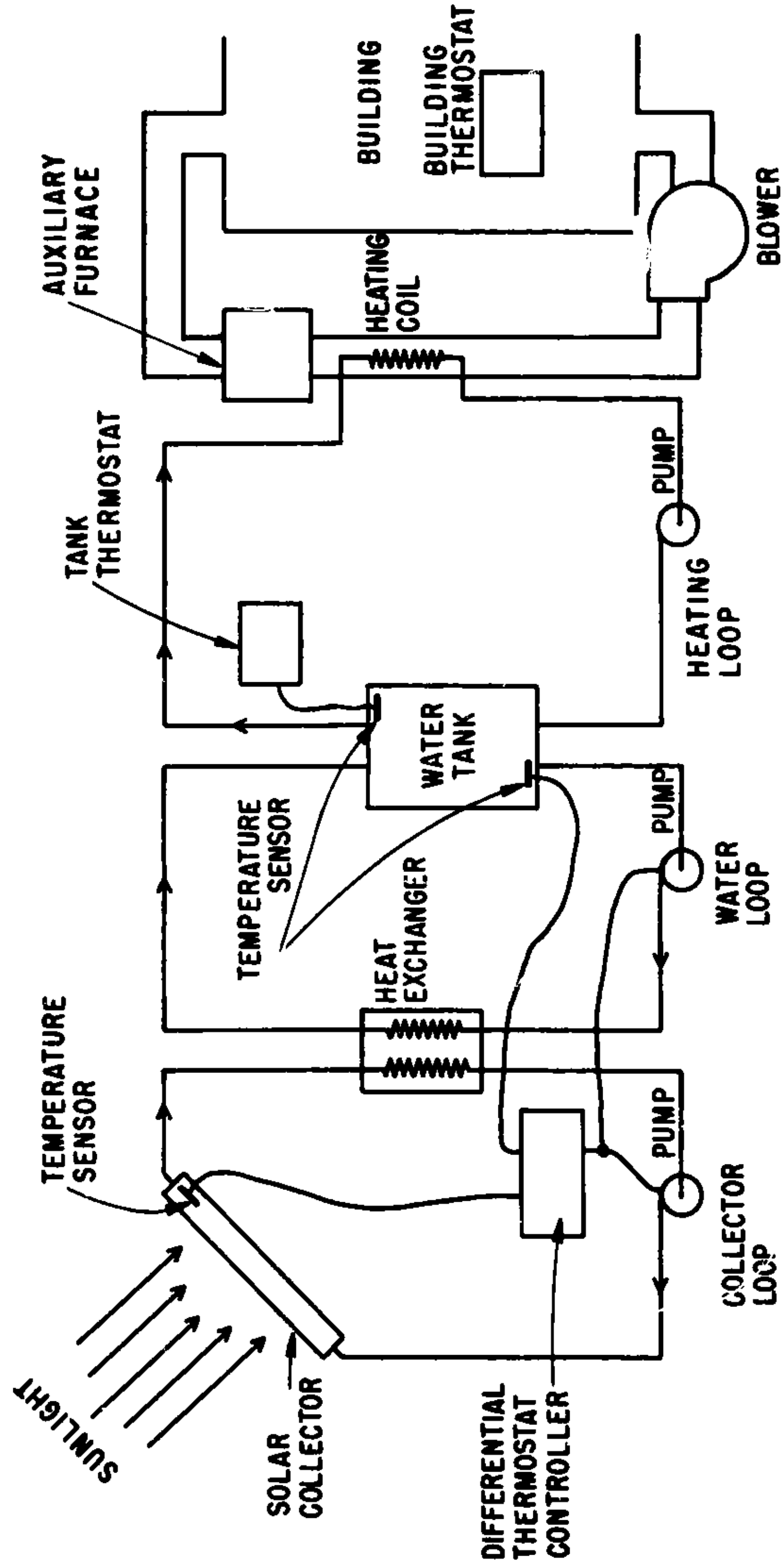

Figure 1-2. Typical Liquid-based System

materials pack with a void fraction of from 20 to 30 percent. These loose materials behave as if their thermal capacities were reduced by this same percentage.

As you can see in Table 1-1, 1 cubic foot of water can store 62.4 Btu for every degree Fahrenheit of temperature rise. A cubic foot of rock packed to a 30-percent void fraction can store only 24.3 Btu per degree of temperature rise. Therefore, to store the same quantity of heat over the same temperature range the rock bed's volume would have to be 2.6 times greater than that of the water tank.

DAILY TEMPERATURE RANGE

A sensible heat storage system's daily temperature range is also closely related to the size of the storage device. Both air- and liquid-based systems typically operate over a daily temperature range of under 60°F (33°C) on a sunny winter day. The exact range is highly variable from system to system, season to season, and day to day. Factors that influence the daily temperature range include the amount of sunshine available, the size of the storage device, the heat capacity of the storage material, the demand for heat, the type of system, the way the system is connected to the load, and the temperature limitations of materials in the system.

Table 1-1. Sensible Heat Storage Materials

Material	Density, lbs/ft^3 (kg/m^3)	Heat Capacity, Btu/lb·°F (J/kg·°C)	Volumetric Heat Capacity, Btu/ft^3 °F (MJ/m^3·°C)	
			No Voids	30% Voids
Water	62.4 (1000)	1.00 (4180)	62.4 (4.18)	-
Scrap Iron	489 (7830)	0.11 (460)	53.8 (3.61)	37.7 (2.53)
Scrap Aluminum	168 (2690)	0.22 (920)	36.96 (2.48)	25.9 (1.74)
Scrap Concrete	140 (2240)	0.27 (1130)	27.8 (1.86)	26.5 (1.78)
Rock	167 (2680)	0.21 (879)	34.7 (2.33)	24.3 (1.63)
Brick	140 (2240)	0.21 (879)	29.4 (1.97)	20.6 (1.38)

Note: SI units in parentheses follow English units.

The daily temperature range, $T_{max} - T_{min}$, is related by the following equation to the amount of usable heat, Q, measured in Btu (joules), stored in the device:

$$Q = m\, C_p(T_{max} - T_{min}). \qquad (1\text{-}1)$$

Here m is the mass of the storage material in pounds (kilograms) and C_p is the heat capacity in Btu/lb·°F (J/kg·°C) of the storage medium.

Example 1-1: Suppose you must store 400,000 Btu from the solar collectors on a sunny winter day, and you want to limit the daily temperature range on that day to 40°F. How much water will be required?

Solving Equation 1-1 for m and substituting the values for stored heat, daily temperature range, and heat capacity yields the required mass of water.

$$m = \frac{Q}{C_p(T_{max} - T_{min})} \qquad (1\text{-}2)$$

$$= \frac{400{,}000 \text{ Btu}}{1 \frac{\text{Btu}}{\text{lb.}^\circ\text{F}} \times 40^\circ\text{F}}$$

$$= 10{,}000 \text{ lb } (4540 \text{ kg}) \text{ of water.}$$

Since one gallon of water weighs 8.34 pounds, this amounts to 1200 gallons of water.

SIZING

There are two principal methods of sizing storage units: sizing by rule of thumb and sizing by calculation. Of the two methods, sizing by rule of thumb is by far the simpler; but, used alone, it cannot guarantee a storage device size that results in the most economical system. However, sizing by rule of thumb is also used as a starting point for sizing by calculation.

Sizing by Rule of Thumb

For residential direct space heating or domestic hot water heating systems, storage capacity should be about 10 to 15 Btu per degree Fahrenheit per square foot of collector (Btu/°F·ft^2), or 200 to 300 kilojoules per square meter per degree Celsius (KJ/m^2·°C). Dividing this amount by the heat capacity from Table 1-1 yields the mass of storage material required.

For rock the required mass is about 50 to 75 pounds per square foot of collector (240 to 360 kilograms per square meter of collector); for water the required mass is 10 to 25 pounds per square foot of collector (50 to 75 kilograms per square meter of collector). Alternatively, dividing the 10 to 15 Btu/°F·ft^2 by the volumetric heat capacity yields the required volume of storage material. Since a rock bed usually has a void fraction of about 30 percent, the required storage volume is about 0.41 to 0.62 cubic feet of rock per square foot of collector. For convenience, these numbers are usually rounded upward to 0.50 to 0.75 cubic feet of rock per square foot of collector (0.15 to 0.23 cubic meters of rock per square meter of collector). About 0.16 to 0.24 cubic feet of water per square foot of collector is required. If these numbers are converted to gallons and rounded upward the result is 1.25 to 2.0 gallons of water per square foot of collector (50 to 75 liters per square meter of collector).

With a daily temperature range of 40°F (22°C) for a larger storage unit or 60°F (33°C) for a smaller one, the unit can store about 15 x 40 = 600 Btu per square foot of collector (6.8 megajoules per square meter of collector). This is very roughly comparable to the amount of heat a solar collector can provide for space heating or domestic hot water heating on a sunny winter day.

It may not always be possible to install the optimum-sized storage device because of limitations of space or, in liquid-based systems, tank availability. Figure 1-3 shows what happens when storage capacity is varied. (We assume here that other factors, such as heating load and collector area, remain the same.) As you can see, if the storage capacity is less than about 10 Btu/°F·ft^2, the fraction of the heating load supplied by solar energy is less than it should be--that is, some of the heat collected is wasted.

If the storage capacity is greater than about 15 Btu/°F·ft^2, the greater storage capacity will not significantly increase the percentage of the heating load supplied by solar energy. If the storage unit is grossly oversized, heat losses will be excessive. However, a slightly oversized storage unit will have only slightly higher heat losses than a properly sized one and will cost only slightly more. These penalties are minor compared with the penalty for making the storage unit too small. Therefore, if a standard-sized storage unit does not fall within the rule of thumb for your system, choose the next larger rather than the next smaller size.

The rules of thumb do not generally apply to storage for solar-assisted heat pump, industrial, load management, air conditioning, or seasonal storage systems. Storage capacity for solar-assisted heat pumps can be double the amount specified by the rule of thumb, because heat pumps operate best over a small temperature range. If the solar system is used to heat an industrial building where the use pattern is similar to that in a residential building, the rule of thumb can be used. But the more the use pattern of the industrial solar system differs from that of the residential system, the greater the error in sizing storage will be.

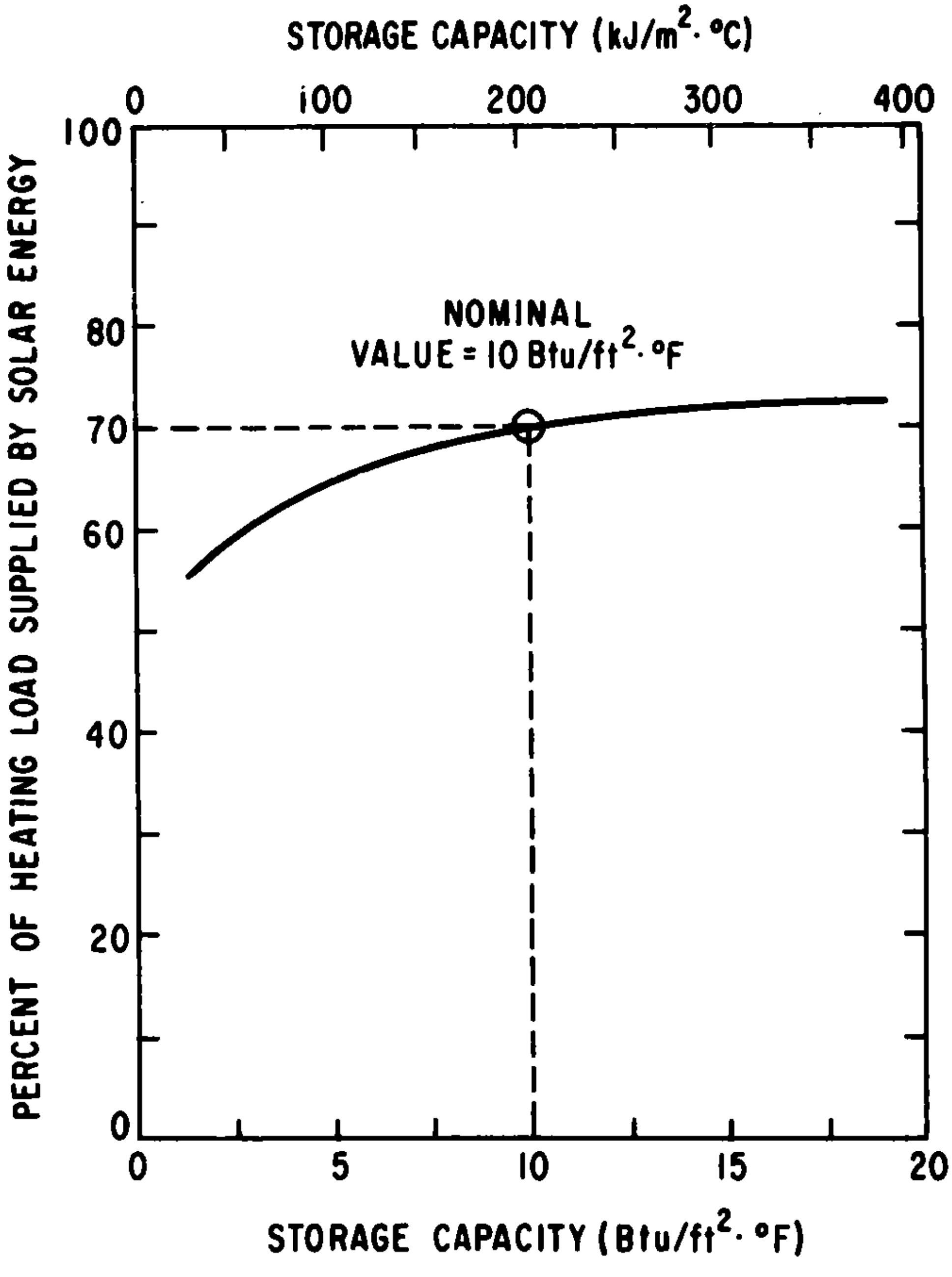

Figure 1-3. Effect of Varying Storage Capacity upon Percentage of Heating Load Supplied by Solar Energy

Heating load and collector area remain constant.

Source: D. Balcomb et al. *Solar Heating Handbook for Los Alamos.* Los Alamos Scientific Laboratory Report UC-5967/CONF-75027-1, May 1975.

Sizing by Calculation

Numerous methods of analyzing the performance of solar systems are available, as Table 1-2 shows. Some methods are limited in the types of systems they can model, and some do not provide the economic analyis necessary for sizing by calculation. Although detailed presentation of these methods is beyond the scope of this manual, we will include a general outline of the method for sizing storage.

Step 1: Before you can determine the most cost-effective size for the storage device, you must determine approximately the most cost-effective collector size. You will need the following data as inputs to your calculations:

- Collector performance.
- Collector cost.
- Rule of thumb storage size.
- Several (about five) collector areas covering the range of sizes you are interested in.

After applying an analysis method such as f-Chart you will have calculated a life-cycle savings in dollars corresponding to each collector area you have used as an input. These points can be plotted on a graph similar to that in Figure 1-4a. The point of maximum life-cycle savings corresponds to the optimum collector area. Although Figure 1-4a shows a smooth curve, the actual curve may be discontinuous, because it is impossible to purchase a fraction of a collector panel. You may also compare different collector designs in this step.

Step 2: Having determined the approximate optimum collector area, you are now ready to determine the optimum storage size. Step 2 is similar to Step 1, but the inputs to it are:

- Collector performance.
- Optimum collector area.
- Storage cost.
- Economic data and estimates.
- Several (about five) storage sizes covering a range on each side of the rule of thumb size.

After applying the analysis method, you will be able to plot a curve of life-cycle savings versus storage size similar to that in Figure 1-4b. The optimum storage size corresponds to the maximum life-cycle savings.

If necessary, Steps 1 and 2 can be repeated to obtain a more accurate estimate of the optimum collector and storage sizes. In most cases, doing each step once or twice is enough. There is no need to continue the calculations to the point where the cost of another calculation exceeds the improvement in life-cycle savings.

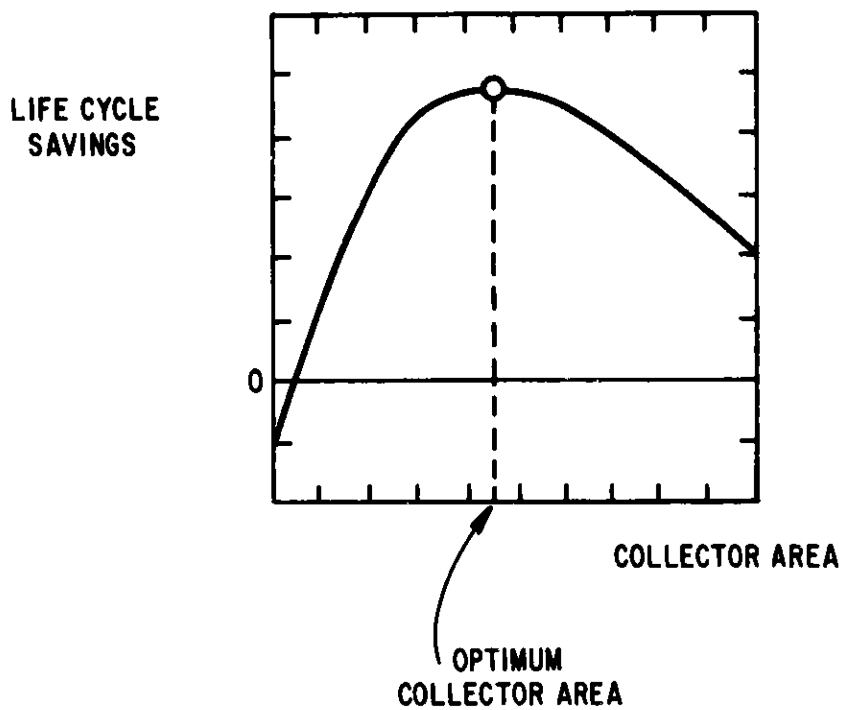

Figure 1-4a. Determination of Optimum Collector Area

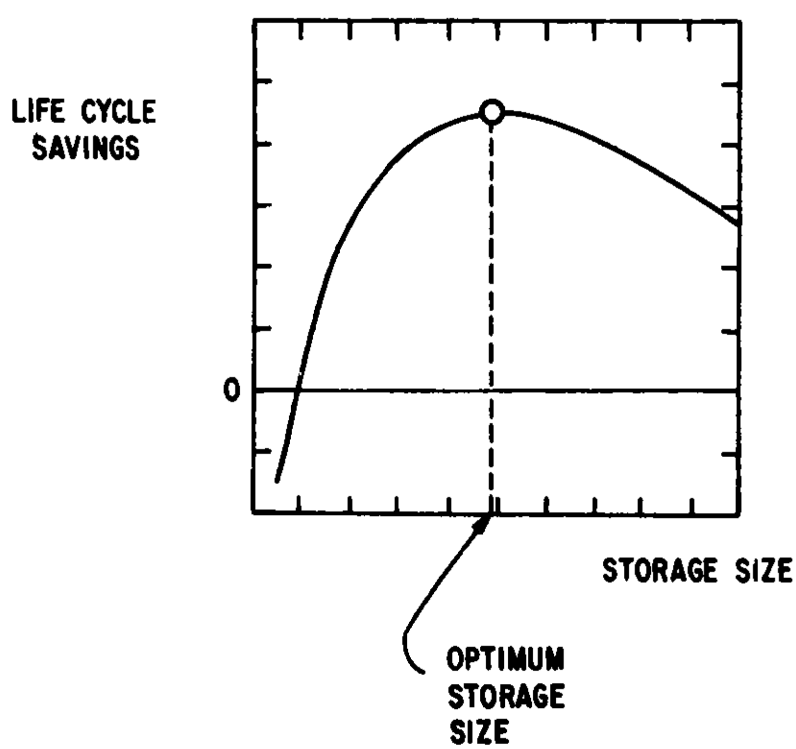

Figure 1-4b. Determination of Optimum Storage Size

Table 1-2. Calculation Methods for Active Solar Systems

1. BLAST (Building Load Analysis System Thermodynamics)

   Contact: Doug Hittle
   U.S. Army Construction Engineering Research Laboratory
   P.O. Box 4005
   Champaign, IL 61820
   (217)352-6511

2. DEROB (Dynamic Energy Response of Buildings)[a]

   Contact: Francisco Arumi or David Northrup
   University of Texas
   Department of Architecture
   Austin, TX 78712

3. DOE-1 (formerly CAL-ERDA)

   Contact: Fredrick Winkelmann
   Lawrence Berkeley Laboratory
   One Cyclotron Road
   Berkeley, CA 97420
   (415)843-2740 ext. 5711

4. f-CHART

   Contact: f-CHART, Market Development Branch
   Solar Energy Research Institute
   1536 Cole Boulevard
   Golden, CO 80401
   (303)234-7171

   Contact: Sandy Klein
   f-CHART
   P.O. Box 5562
   Madison, WI 35705

5. HISPER (High Speed Performance)[a]

   Contact: W. A. Brooksbank
   Building 4201
   Systems Development Office, FA31
   National Aeronautics and Space Administration
   George C. Marshall Space Flight Center
   AL 35811
   (205)453-1248

6. HUD-RSVP (HUD Residential Solar Viability Performance)

   Contact: Dr. Frank Weinstein
   National Solar Heating and Cooling Information Center
   P.O. Box 1607
   Rockville, MD 20850
   (202)223-8105

7. SCOTCH

   Contact: Bob McClintock
   SCOTCH PROGRAMS
   P.O. Box 430734
   Miami, FL 33143
   (305)665-1251

8. SEEC I-V (Solar Environmental Engineering Co. I-V)

   Contact: Solar Environmental Engineering Co.
   P.O. Box 1914
   Fort Collins, CO 80522
   (303)221-4370

Table 1-2 (continued)

9. **SESOP**

Contact: Henry T. Crenshaw
Lockheed Space and Electronics
1816 Space Park Drive
Houston, TX 77062
(713)333-6261

10. **SOLCOST**

Contact: SOLCOST
International Business Service, Inc.
Solar Group
1010 Vermont Ave. N.W.
Washington, DC 20005

11. **SOLOPT**

Contact: Dr. Larry O. Degelman
Department of Architecture
Texas A&M University
College Station, TX 77843
(713)845-1015

12. **SOLTES** (Simulation of Large Thermal Energy System)

Contact: SOLTES
M. E. Fewell
Division 1262
Sandia Laboratory
Albuquerque, NM 87115
(505)264-7315

13. SYRSOL[a]

Contact: Dr. Manas Ucor
Mechanical Engineering Department
College of Engineering
Syracuse University
Syracuse, NY 13210
(315)423-3038

14. TRNSYS[a]

Contact: Warren Bucks
University of Wisconsin
Solar Energy Laboratory
1500 Johnson Drive
Madison, WI 53706
(608)263-1589

Source: Solar Energy Research Institute, 1536 Cole Boulevard, Golden, Colorado. *Solar Heating and Cooling Analysis Methods*, August, 1978.

[a]Does not include economic analysis.

THERMAL STRATIFICATION

When heat is delivered into a sensible heat storage material, thermal stratification can occur. That is, some parts of the storage material can become hotter than other parts. In theory, a perfectly stratified system can perform 5 to 10 percent more efficiently than a thermally mixed system if the system is designed to take advantage of stratification. (Recent work by Lin, Sha, and Michaels indicates that stratification can improve performance by more than 10 percent.) Whether thermal stratification can be maintained in practice depends on the type of system used.

Stratification is relatively easy to achieve in rock beds with vertical air flow. The solar-heated air enters at the top of the rock bed and flows downward through many labyrinthine paths, losing most of its heat by the time it leaves the bottom of the rock bed. Thus, the rock bed is hot at the top but relatively cool at the bottom. Since rocks can't move, this temperature differential is easily maintained. The collector operates at a lower, more efficient average temperature than it would if there were no stratification, and more useful heat can be collected. Thermal stratification from top to bottom of a rock bed compensates for the lower efficiency of air-type collectors compared with liquid-type collectors.

Thermal stratification can also occur in water tanks, but pumping the water to the collector or the heat exchanger tends to cause the hotter and cooler water to mix, destroying stratification. Even natural convection from a coil-in-tank heat exchanger can upset the stratification process. Although several inexpensive methods improve stratification in water tanks, you should not count on receiving its full benefits if you plan to use this type of thermal energy storage. Research is presently being done to provide more definitive information on maintenance of stratification in water tanks.

LOCATION

In principle, the storage device should be as close as possible to the solar collectors to minimize the collector-to-storage losses. Since the solar collectors are usually mounted on the roof, the roof or attic might seem a logical site for the storage container, and it is a common practice to store solar-heated domestic hot water on rooftops in the tropics. If thermal storage is to be used for space heating, however, the storage unit's weight makes such a location impractical. Moreover, the climate in the United States frequently causes builders to seek more sheltered locations for thermal storage devices--usually basements, crawl spaces, garages, or underground. The following sections describe the advantages and disadvantages of these various locations; Tables 1-3 and 1-4 summarize this information.

Basement

Basements or other heated indoor areas are good locations for thermal storage devices. Tanks or rock beds in heated areas generally require less insulation than in outdoor installations, and the building protects the storage device from weathering. Any heat lost from storage escapes into heated areas, so these losses are not considered losses to the solar system during the heating season.

The main disadvantage of indoor storage devices is that they take up valuable space. In addition, heat lost from storage into the living area is uncontrollable. In summer, the losses from a hot storage device can increase the air conditioning load unless the storage area is well ventilated or the system is shut down for the summer.

Although a basement will generally provide enough room for a water tank to be installed, getting a large tank into the building is a major problem. Cast-in-place concrete tanks and plastic-lined wooden tanks can be assembled inside existing buildings. Although steel and fiberglass tanks can be installed in basements of new construction, repair or replacement of these tanks would be expensive. For this reason, we do not recommend installing a large one-piece tank in a basement.

If you plan to install a rock bed in a basement, you must consider the floor-to-ceiling space available. Most basements have 7 feet of clearance between the floor and the ceiling. By careful design, you can keep a rock bed within this size limit; but in some cases you will have to remove part of the basement floor slab to gain more clearance.

Appropriate foundations must be developed for all storage devices, since they are extremely heavy. A structural engineer should determine what type of footings are required to support the storage unit's weight.

Crawl Space

Heat losses from storage devices in unheated locations such as the crawl space are irrecoverable. This is a disadvantage during the heating season, but a potential advantage during the air conditioning season. If the crawl space is well ventilated and insulated from the air conditioned rooms, heat escaping from the storage device will not add to the air conditioning load.

Most crawl spaces do not have enough vertical clearance for a rock bed with vertical air flow to be installed. Although rock beds with horizontal air flow have been built, maintaining uniform air flow and thermal stratification in them is more difficult than in rock beds with vertical air flow. Therefore, we do not recommend installing a rock bed in a crawl space that does not have an unusually large amount of vertical clearance.

Table 1-3. Advantages and Disadvantages of Storage Locations

Advantages

Utility Room or Basement	Unheated Garage	Crawl Space
• Insulation requirement is minimal	• Insulation is protected from weather	• Insulation is protected from weather
• Insulation is protected from weather	• Leaks are easily detected	• Thermal losses may contribute to building heat in winter
• Thermal losses contribute to building heat in winter	• Access for repairs is easy	
• Leaks are easily detected	• Steel or FRP tanks can be installed in an existing garage	
• Access for repairs is relatively easy		

Disadvantages

Utility Room or Basement	Unheated Garage	Crawl Space
• Living space is reduced	• Garage space is reduced	• Thermal losses may add to air conditioning load in summer
• Thermal losses add to air conditioning load in summer	• Extra insulation is required	• Access is difficult for retrofit or repairs
• Leaks may damage building interior	• Freeze protection is required in most of U.S.	• Tank shape may require extra insulation
• Steel or FRP tanks are difficult to install in an existing building	• Leaks may damage the garage	
	• Thermal losses cannot be recovered	

Table 1-3 (continued)

Advantages	
Outdoors, Above Grade	**Outdoors, Below Grade**
• Access is easy	• Thermal losses do not add to air conditioning load
• Thermal losses do not add to air conditioning load	• Storage unit does not reduce living space

Disadvantages	
Outdoors, Above Grade	**Outdoors, Below Grade**
• Extra insulation is required	• Access for repairs is difficult
• Weather protection is required	• Groundwater may cause problems
• Thermal losses cannot be recovered	• Thermal losses cannot be recovered
• Freeze protection is required in most of U.S.	• Vermin may burrow into insulation
• Vermin may burrow into insulation	• Careful design is required to ensure sufficient net positive suction head for pump

Table 1-4. Storage Location, Applicability, and Special Requirements

Storage Location	Applicability: New Building	Applicability: Retrofit	Special Requirements: Weather-proof Insulation	Extra Insulation	Freeze Protection	Protection from Groundwater	Long-Lifetime Components
Utility Room or Basement	yes	X	no	no	no	no	yes
Unheated Garage	yes	yes	no	yes	yes	no	no
Crawl Space	yes	X	no	yes	no	no	yes
Outdoors, Above Grade	yes	yes	yes	yes	yes	no	yes
Outdoors, Below Grade	yes	yes	yes	yes	X	yes	yes

Note: Items marked "X" must be determined by the individual situation.

To install a storage device in a crawl space, follow the recommendations for below grade installations. Considering the difficulties of installing a storage device in an existing crawl space, this location should be considered primarily for new construction. Even in this case, the cramped working quarters could make repair costly.

Garage

The garage is an excellent location for steel or fiberglass water tanks, since they can be easily removed and replaced through the large door. Other types of water tanks, as well as rock beds, can also be used here. The garage protects the storage device from the weather.

Tanks in unheated garages must be protected from freezing. Heat losses from storage devices in this location are irrecoverable, and the storage device reduces the space available for cars.

Outdoors

The storage device can be located outside the building either above or below grade. In either case, the storage container must be well insulated and built on a good foundation. The ducts or pipes to and from the storage unit must be insulated, weatherproofed, and possibly waterproofed. Vermin are occasionally a problem in outdoor tanks. Use vermin-proof insulation or surround the insulation with half-inch mesh wire cloth. Heat losses from outdoor storage devices are irrecoverable.

Above Grade

In an aboveground installation, the storage device should be placed inside a shelter or covered with roofing and siding. This protection must be designed in compliance with local codes for wind resistance and for snow loads.

Water tanks in unheated locations must be protected from freezing. In moderate climates, an electric immersion heater will do this satisfactorily.

Below Grade

The main problem with buried storage devices is that groundwater can soak the insulation (even if it is closed-cell foam). In several instances, the resulting high losses have forced owners to abandon underground storage devices.

The following guidelines should be followed if you choose to install the storage device underground.

- If possible, avoid burying the storage device so deep that the highest level of groundwater (usually in Spring) rises above the bottom of the insulation.
- Use pea gravel beneath the foundation to allow water to drain.
- Use waterproof insulation, such as closed-cell foam, even in dry areas. We recommend that for an underground storage device you use twice the insulation thickness specified in the following section, because groundwater can degrade the performance of even a closed-cell foam. Urethane foams in contact with earth tend to degrade rapidly.
- Do not rely upon dry earth for insulation.
- If possible, direct rainwater away from the storage unit. Avoid situations where undisturbed soil (especially clay) surrounding the hole where the storage unit is installed forms a catch-basin for rainwater.
- Position tank vents so that neither rainwater nor groundwater can enter the tank. If the lid is separate from the body of the storage device, the joint <u>must</u> be above the highest groundwater or floodwater level. A waterproof barrier <u>must</u> be installed to direct rainwater away from the joint.

If a substantial portion of the tank is buried below the freeze line, no freeze protection will be required.

LIMITING HEAT LOSS

Characteristics of Thermal Insulation

The most important characteristic of thermal insulation is its resistance to the flow of heat. This resistance is given the symbol R and has units of degrees Fahrenheit-square feet-hours per Btu ($°F \cdot ft^2 \cdot hr/Btu$), or degrees Celsius-square meter per watt ($°C \cdot m^2/W$). The larger the value of R, the greater the insulation's resistance to heat flow. Since many types of insulation can be applied in various thicknesses, it is convenient to use the R-value per unit thickness, which is given the symbol r in this manual and has units of degrees Fahrenheit-square feet-hours per Btu per inch ($°F \cdot ft^2 \cdot hr/Btu \cdot in$), or degrees Celsius-square meters per watt per centimeter ($°C \cdot m^2/W \cdot cm$).

Table 1-5 gives values of r for various common insulating and building materials. Several types of insulation have characteristics that make them especially suitable for some applications but unsuitable for others.

Fiberglass and mineral wool are inexpensive general-purpose insulation materials. Because they insulate by trapping air between their fibers, they tend to lose their insulating value when compressed. That is, a 5-1/2-inch-thick batt of fiberglass compressed to fit into a 3-1/2-inch cavity will work no better than a 3-1/2-inch-thick batt. Because these materials are porous, they must be protected from wind, and they cannot be used in locations where they might become soaked with water.

Cellulose fill is a very inexpensive insulation, but it must be fireproofed to be used safely in buildings. It cannot be used where it might become wet.

Vermiculite and perlite are expanded mineral products that are used as loose fills. They are fireproof and can withstand high temperatures. As loose fills they should not be used where they might become wet, but they are sometimes used as a part of the aggregate in concrete to make a waterproof insulation.

Glass foam is a relatively expensive material that is waterproof and fireproof, resists crushing, and can withstand high temperatures.

Polystyrene foam is a versatile material that can be purchased as beads for loose fill or as boards. Its disadvantages are that it is weak, cannot withstand high temperatures, is flammable, and is easily destroyed by solvents. Despite these disadvantages, closed-cell polystyrene foam is excellent for underground applications. Like other plastics, polystyrene foam must be protected from weathering and sunlight. Urethane foam has properties similar to those of polystyrene foam, but it can support slightly heavier loads, can withstand higher temperatures, and is much more resistant to solvents.

Urea-formaldehyde foams are most frequently applied as a two-part, spray-on mixture. Because the composition and density of spray-on foams can be difficult to control, we recommend reducing the r-value given in Table 1-5 (which was obtained in a laboratory under ideal conditions) by half. Users of urea-formaldehyde insulation have experienced several types of problems, including shrinking and sagging, deterioration in underground applications, and offensive odors caused by the formaldehyde, but its convenience of application often justifies its use.

Because most of the insulation materials used in construction use trapped air to restrict the flow of heat, their r-values are likely to approach or exceed the r-value of still air of 5.56 $°F \cdot ft^2 \cdot hr/Btu \cdot in$ (0.386 $°C \cdot m^2/W \cdot cm$). A few closed-cell foams have been expanded with gasses such as refrigerants 11 or 12, which have a higher thermal resistance than air. When these foams are new, their resistance to the flow of heat can exceed that of air, but as they age the gasses diffuse out and are replaced by air, causing their r-values to diminish.

A similar reduction in resistance to flow of heat occurs when foams are used in a wet environment. Water diffuses into the foam and replaces part of the trapped air. Because of this problem, we recommend expecting only half the r-values listed in Table 1-5 for closed-cell insulation when it is used underground or in other wet locations.

Table 1-5. Densities and r-values of Common Building and Insulating Materials

Material	Density, lb/ft^3 (kg/m^3)	r-value, °F·ft^2·hr/Btu·in (°C·m^2/W·cm)
Acoustic Tile	18.0 (288.)	2.53 (0.175)
Aluminum (1100 Alloy)	171.0 (2740)	0.000651[b] (45x10^{-6})
Asbestos-Cement Board	120.0 (1920)	0.26[b] (0.018)
Brick: Common	120.0 (1920)	0.20[b] (0.014)
Face	130.0 (2080)	0.11[b] (0.0076)
Cellulose Fill	2.5-3.0 (40-48)	3.70[b] (0.257)
Cement (Mortar or Plaster with Sand)	16.0 (1860)	0.20[b] (0.014)
Concrete, Medium Weight		
Dried Aggregate	140.0 (2240)	0.11[b] (0.0076)
Undried Aggregate	140.0 (2240)	0.08[b] (0.0055)
Concrete, Heavy Weight	80.0 (1280)	0.40[b] (0.028)
Concrete, Light Weight	30.0 (481)	1.11[b] (0.077)
Concrete Block, Heavy Weight		
4-inch	101.0 (1620)	0.18[a] (0.012)
6-inch	85.0 (1360)	0.15[a] (0.010)
8-inch	69.0 (1110)	0.13[a] (0.009)
12-inch	76.0 (1220)	0.11[a] (0.0076)
Concrete Block, Medium Weight		
4-inch	76.0 (1220)	0.28[a] (0.019)
6-inch	65.0 (1040)	0.23[a] (0.016)
8-inch	53.0 (849)	0.18[a] (01012)
12-inch	58.0 (929)	0.18[a] (0.012)
Concete Block, Light Weight		
4-inch	65.0 (1040)	0.33[a] (0.023)
6-inch	55.0 (881)	0.30[a] (0.021)
8-inch	45.0 (721)	0.25[a] (0.017)
12-inch	49.0 (785)	0.19[a] (0.013)
Fiberglass		
Batt		3.15[b] (0.218)
Rigid, Organic Bonded	4-9.0 (64-144)	4.00[b] (0.277)

[a]Source: R .M. Graven and P. R. Hirsch. *DOE-1 Users' Manual*. Argonne National Laboratory Report ANL/ENG-77-04, November 1977.

[b]Source: American Society of Heating, Refrigerating and Air Conditioning Engineers. *ASHRAE Handbook of Fundamentals*, 1972, pp. 360-363.

Table 1-5 (continued)

Material	Density, lb/ft^3 (kg/m^3)	r-value, °F·ft^2·hr/Btu·in (°C·m^2/W·cm)
Glass Foam	9.0 (144)	2.50[b] (0.173)
Gypsum or Plaster Board	50.0 (801)	0.90[b] (0.062)
Gypsum Plaster		
Light Weight Aggregate	45.0 (721)	0.63[b] (0.044)
Sand Aggregate	105.0 (1680)	0.18[b] (0.012)
Hard Board		
Medium Density Siding	40.0 (641)	1.53[a] (0.106)
Medium Density Other	50.0 (801)	1.37[a] (0.095)
High Density Standard Tempered	55.0 (881)	1.22[a] (0.085)
Insulation Board		
Sheathing	18.0 (288)	2.63[a] (0.182)
Shingle Backer	18.0 (288)	2.52[a] (0.175)
Nail Base Sheathing	25.0 (400)	2.28[a] (0.158)
Mineral Board, Preformed	-	3.47[a] (0.241)
Mineral Wool/Fiber		
Batt	-	3.33[a] (0.231)
Fill	-	3.09[a] (0.214)
Particle Board		
Low Density		1.85[a] (0.128)
Medium Density		0.11[a] (0.0076)
High Density		0.08[a] (0.0055)
Underlayment		0.46[a] (0.032)
Perlite Expanded with Refrigerant-11	5.0-8.0 (80-128)	2.70[b] (0.187)
Polystyrene		
Board, Expanded	1.8 (29)	4.00[b] (0.277)
Molded Beads	1.0 (16)	3.57[b] (0.248)
Boards, Expanded with Refrigerant-12	2.2-3.5 (35-56)	5.00-5.26[b] (0.347-0.365)
Polyurethane Expanded with Refrigerant-11	1.5-2.5 (25-40)	6.25[b] (0.433)
Roof Insulation, Preformed	16.0 (256)	2.78[a] (0.193)
Steel (Mild)	489.0 (7830)	0.00318[b] (0.22x10^{-3})
Urea-Formaldehyde	0.7 (11)	4.17[a] (0.289)
Vermiculite, Expanded	7.0-8.2 (112-131)	2.13[b] (0.148)
	4.0-6.0 (64-96)	2.27[b] (0.157)
Wood, Soft (Fir, Pine, etc.)	32.0 (513)	1.25[b] (0.087)
Wood, Hard (Maple, Oak, etc.)	45.0 (721)	0.91[b] (0.063)

R-value of Multiple Layers

Most insulation consists of multiple layers. The combined R-value is the surface resistance, if any, between solid materials and air plus the sum of the R-values of the layers, or:

$$R = R_s + s_1r_1 + s_2r_2 + s_3r_3 + \ldots \quad (1\text{-}3)$$

where:

R_s is the surface resistance.

s_1, s_2, and s_3 are thicknesses of each insulation layer.

r_1, r_2, and r_3 are the thermal resistances per unit of thickness for each insulation layer.

Surface resistance will only be present when a surface of the insulation is exposed to air. Insulation in contact with earth or water will not have surface resistance; however, exposed air ducts can have surface resistance on the inside as well as on the outside. Surface resistances are tabulated in Table 1-6.

Table 1-6. Surface Resistances for Nonreflective Surfaces

Wind, mph (m/sec)	Position of Surface	Direction of Heat Flow	Surface Resistance, °F·ft^2·hr/Btu (°C·m^2/W)
0	horizontal	upward	0.61 (0.11)
0	45° slope	upward	0.62 (0.11)
0	vertical	horizontal	0.68 (0.12)
0	45° slope	downward	0.76 (0.13)
0	horizontal	downward	0.92 (0.16)
7.5 (3.4)	any	any	0.17 (0.030)
15.0 (6.7)	any	any	0.25 (0.044)

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook of Fundamentals*, 1972, p. 357.

Example 1-2: The vertical wall of a rock bin is constructed with the following layers: 1/2 inch of gypsum board, 3/4 inch of plywood, 5-1/2 inches of fiberglass batt, and 1/2 inch of gypsum board. What is the combined R-value of the insulation?

The r-value for each layer is multiplied by the layer's thickness, and the products are added to the surface resistance on the outer wall, as shown in Figure 1-5. The combined R-value is 19.84 °F·ft^2·hr/Btu (3.50 °C·m^2/W).

Example 1-3: Suppose the cross-section used for Example 1-2 is taken through a 2 by 6 pine stud instead of through the fiberglass insulation. What is the combined R-value, including the stud?

The stud has an r-value of 1.25 °F·ft^2·hr/Btu·in, while the fiberglass had an r-value of 3.15 °F·ft^2·hr/Btu·in. The surface resistance is 0.68 °F·ft^2·hr/Btu, and the combined R-value is:

$$R = 0.50 \times 0.90 + 0.75 \times 1.25 + 5.50 \times 1.25 + 0.50 \times 0.90 + 0.68$$

$$= 9.39\ ^\circ F \cdot ft^2 \cdot hr/Btu\ (1.66\ ^\circ C \cdot m^2/W).$$

This example will be used in the next section to illustrate the effect of parallel heat loss.

Parallel Heat Loss

When heat can escape by several paths, each with a different R-value, it is most convenient to work with the *thermal transmittance* of the insulation. This quality, given the symbol U, has units of Btu/hr·ft^2·°F (W/m^2·°C) and is often called the U-value. Mathematically, the thermal transmittance of insulation is approximately:

$$U = \frac{1}{A}\left[\frac{A_1}{R_1} + \frac{A_2}{R_2} + \frac{A_3}{R_3} + \ldots\right] \qquad (1\text{-}4)$$

where:

R_1, R_2, and R_3 are R-values for each path of heat escape.

A_1, A_2, and A_3 are the cross-sectional areas of each path.

A is the sum of A_1, A_2, A_3, and so on.

The lower the thermal transmittance, the less heat flow through the insulation.

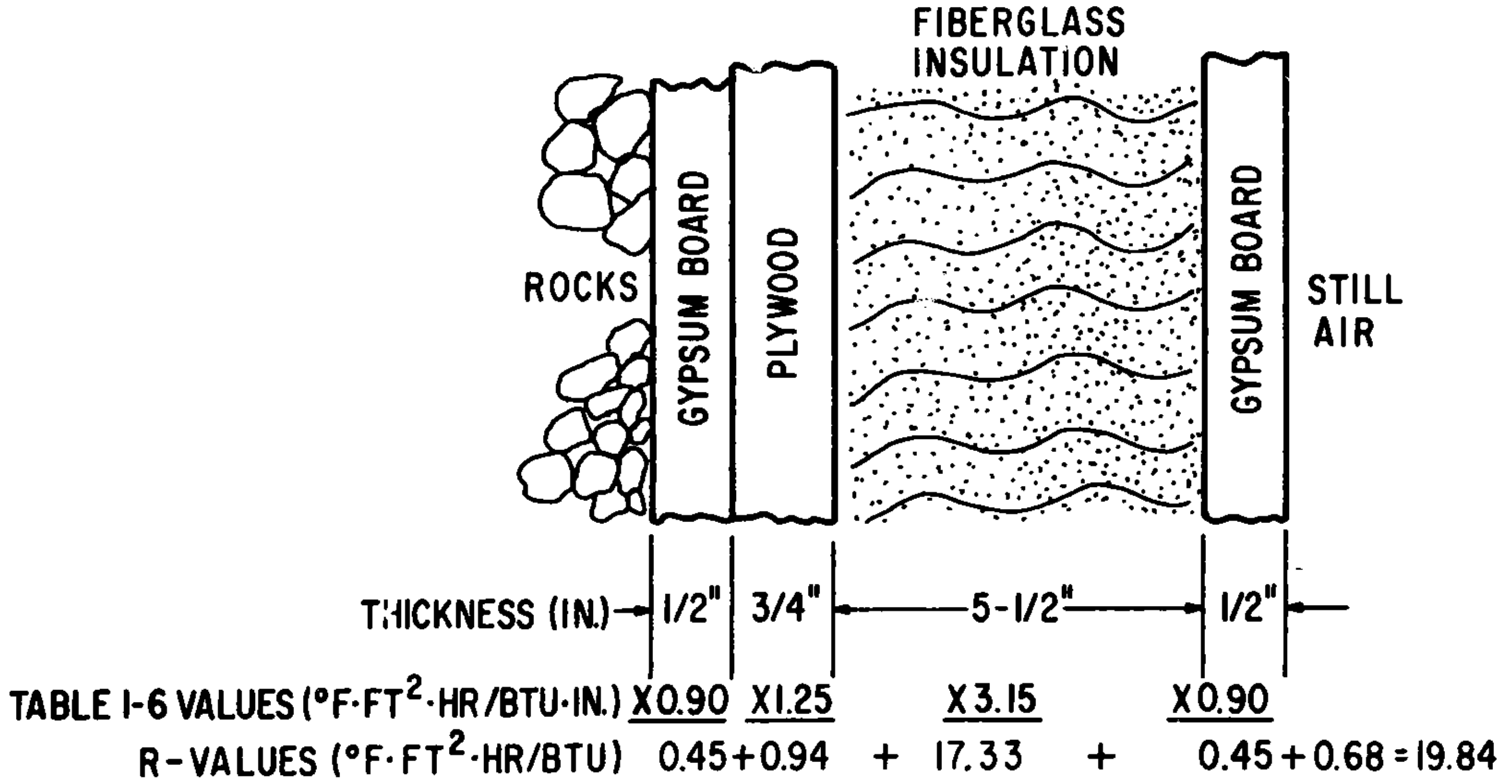

Figure 1-5. R-value of Multilayered Insulation

Example 1-4: Calculate the thermal transmittance of a 4 foot by 4 foot stud wall with layers as shown in Figure 1-5. The 2 by 6 studs are located on 16-inch centers as shown in Figure 1-6.

Path 1 through the fiberglass has an R-value of $R_2 = 19.17$ °F·ft²·hr/Btu (3.38 °C·m²/W) as calculated in Example 1-2 and an area of $A_2 = 13.12$ ft² (1.22 m²) as shown in Figure 1-6. Path 2 through the studs has an R-value of $R_1 = 9.39$ °F·ft²·hr/Btu (1.65 °C·m²/W) as calculated in Example 1-3 and an area of $A_1 = 2.88$ ft² (0.27m²). Substituting these numbers into Equation 1-4 yields the thermal transmittance of the stud wall.

$$U = \frac{1}{16}\left[\frac{13.12}{19.84} + \frac{2.88}{9.39}\right]$$

$$= 0.0605 \text{ Btu/hr·ft}^2\text{·°F } (0.343 \text{ W/m}^2\text{·°C}).$$

Notice that the parallel heat loss through the studs increases the transmittance by 20 percent over the path through the fiberglass alone. This illustrates the importance of accounting for the parallel heat losses.

Brackets, supports, and mountings of storage units, heat exchangers, pipes, and ducts are among the most often neglected paths for parallel heat losses. These losses tend to be significant even in systems that are well insulated in other respects. Some suggestions for reducing the losses are shown in Figure 1-7.

SMACNA and HUD Insulation Standards

The HUD Intermediate Minimum Property Standards specify that the storage device should be insulated so that losses during a 24-hour period do not exceed 10 percent of the storage capacity. Because the energy-saving benefits of insulation are so great, we recommend that storage devices be insulated to comply with the SMACNA (Sheet Metal and Air Conditioning Contractors' National Association) standard of a 2-percent loss in 12 hours and that the HUD standard be used only if all the following conditions are met:

- All the heat that escapes from storage heats the building.
- The solar system is shut down in the summer or the area around the storage device can be ventilated so that heat losses do not add to the air conditioning load.
- The storage device is used only to supply space heating.
- You can tolerate uncontrolled heat losses from storage overheating the building occasionally.

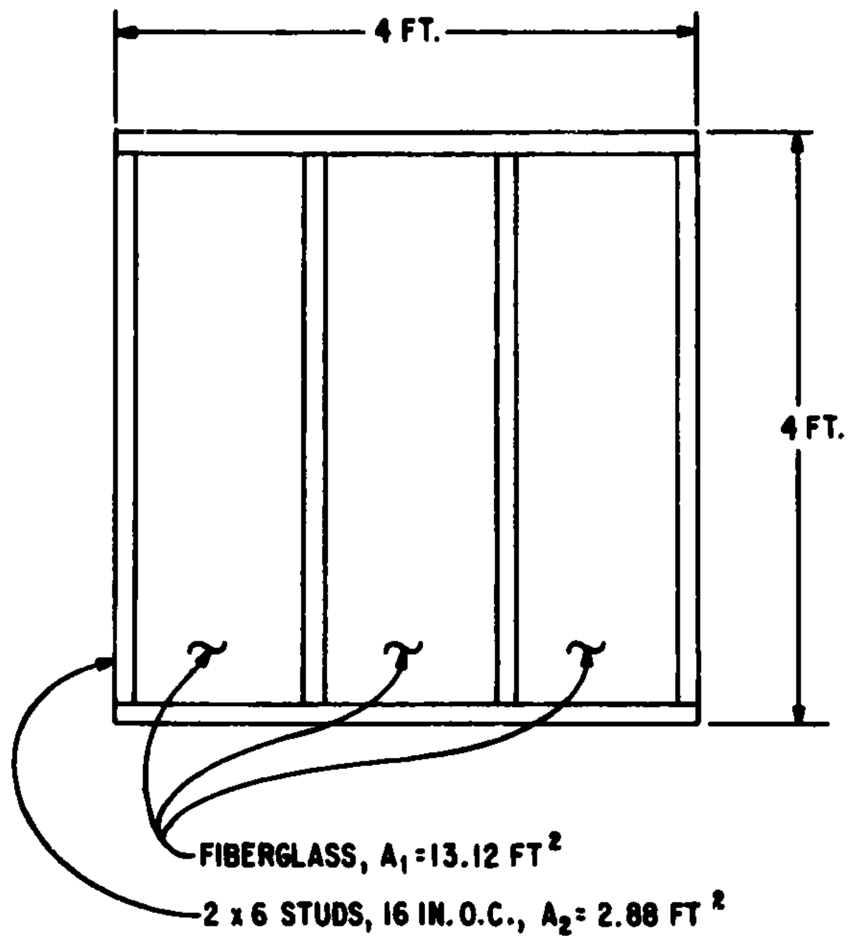

Figure 1-6. Layout of a 4 Foot by 4 Foot Stud Wall

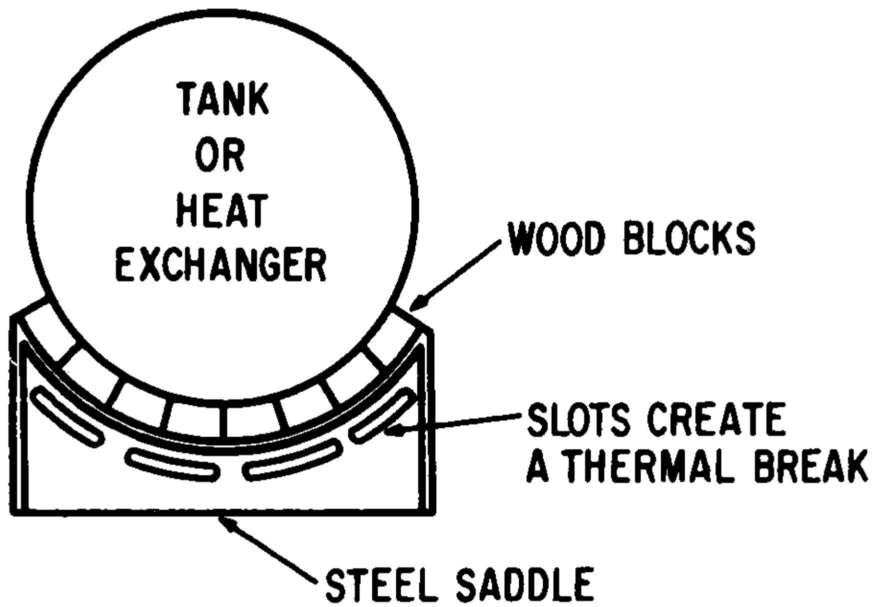

Figure 1-7. Methods for Reducing Parallel Heat Losses

The average rate of heat loss from storage, Q'_{avg}, is given by:

$$Q'_{avg} = UA\ (T_{avg} - T_a) \qquad (1\text{-}5)$$

where:

- U is the overall thermal transmittance of the insulation on the storage unit as calculated in Equation 1-4.
- A is the exposed surface area of the storage unit.
- T_{avg} is the average temperature in the storage unit.
- T_a is the ambient temperature surrounding the storage unit.[1]

The standards require that no more than a specified fraction, f, of the energy stored, Q, can be lost in a certain time period, t. (The energy stored is calculated from either Equation 1-1 or 4-1.) In the form of an equation, this statement is:

$$Q'_{avg}t = fQ\ . \qquad (1\text{-}6)$$

Combining Equations 1-5 and 1-6 and solving yields the maximum allowable thermal transmittance:

$$U = \frac{fQ}{At(T_{avg} - T_a)}\ . \qquad (1\text{-}7)$$

This is a general equation that can be used with all types of storage for either the SMACNA or HUD standards.

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[1] For "ambient temperature," use the average temperature of the storage device's surroundings during the season when the storage device will he heated. Assume an ambient temperature of about 68°F (20°C) for storage devices in heated areas. For unheated locations, find out the average outdoor temperature during the heating season from the nearest weather bureau office. For underground ambient temperature, assume that the ground temperature rises linearly from the average heating season outdoor temperature at the surface to the average annual outdoor temperature at a point 20 feet underground. This is a rough approximation to the ground temperature, but it is sufficiently accurate for our purposes here.

To simplify the calculation of maximum allowable thermal transmittance, we have supplied the insulation factor fQ/At in Tables 1-7 through 1-10. The following assumptions have been used in preparing the tables:

- f = 0.02 (2 percent) and t = 12 hours, per SMACNA standards.
- The daily temperature range (T_{max} - T_{min}) is 60°F (33°C) for water tanks and 50°F (28°C) for rock beds.
- Several container shapes (Tables 1-7, 1-9, and 1-10) have only half as much insulation on the bottom as on the top and sides. The thermal transmittance calculated from the tabulated values of fQ/At apply to the top and sides of the container.
- Rock beds have a 30 percent void fraction and an allowance for the volume of the plena (air spaces) at the top and bottom.

To use the tables, find the vertical column that best represents the shape of your storage unit. Find the insulation factor fQ/At in the row corresponding to the storage unit's size. It may be necessary to interpolate between rows or columns. Divide the insulation factor by the difference between average storage temperature and ambient temperature to obtain the maximum allowable thermal transmittance, U.

Besides controlling thermal losses, insulation also limits the exposed surface temperature to prevent burns. The insulation factors given in Tables 1-7 through 1-10 will limit the temperature on the outer surface of the insulation to 140°F (60°C) or less.

Example 1-5: Calculate the maximum allowable thermal transmittance for the 375-cubic-foot (10.6-cubic-meter) rock bed shown in Figure 1-8. The rock bed will have an average temperature of 115°F (46°C) and will be located in a 68°F (20°C) basement.

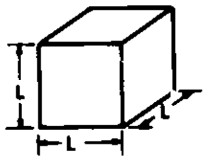
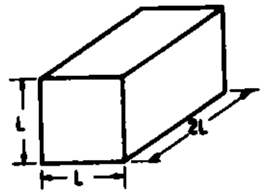
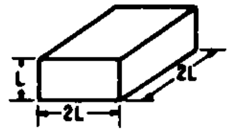
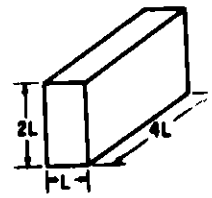
The space occupied by the rocks is 102 inches x 96 inches x 66 inches (2.59 meters x 2.44 meters x 1.68 meters); its shape lies between the shapes listed in the first and fourth columns of Table 1-10. The size lies between the 300- and 400-cubic-foot rows. Interpolating between the rows and columns gives a value of fQ/At = 1.74 Btu/hr·ft^2 (5.48 W/m^2) Substituting these numbers into Equation 1-7 gives the maximum allowable thermal conductance on the top and sides:

$$U = \frac{1.74}{115-68} = 0.0370 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}.$$

The insulation in Example 1-4, with U = 0.0605 Btu/hr·ft^2·°F, would be inadequate in this case.

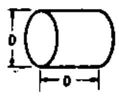
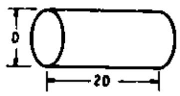
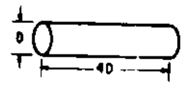
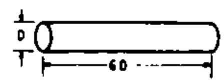
Since the storage unit is to be located in a basement the insulation requirement can be relaxed to a 10 percent loss in 24 hours if the other requirements in this section are satisfied. The maximum allowable thermal conductance can be adjusted by multiplying it by 10/2 to change the fraction lost from 2 percent to 10 percent and by 12/24 to change the time period from 12 hours to 24 hours:

Table 1-7. Insulation Factor fQ/At for Rectangular Water Tanks

Size, gallons (liters)	Shape			
				
250 (946)	2.87 (9.05)	2.66 (8.39)	2.53 (7.98)	2.51 (7.92)
500 (1893)	3.62 (11.4)	3.35 (10.6)	3.19 (10.1)	3.17 (10.0)
750 (2839)	4.14 (13.1)	3.83 (12.1)	3.65 (11.5)	3.62 (11.4)
1000 (3785)	4.56 (14.4)	4.22 (13.3)	4.02 (12.7)	3.99 (12.6)
1500 (5678)	5.22 (16.5)	4.83 (15.2)	4.60 (14.5)	4.57 (14.4)
2000 (7571)	5.74 (18.1)	5.32 (16.8)	5.06 (16.0)	5.02 (15.8)
3000 (11356)	6.57 (20.7)	6.09 (19.2)	5.80 (18.3)	5.75 (18.1)
4000 (15142)	7.24 (22.8)	6.70 (21.1)	6.38 (20.1)	6.33 (20.0)
5000 (18927)	7.79 (24.6)	7.22 (22.8)	6.87 (21.7)	6.82 (21.5)

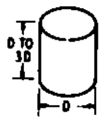
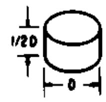
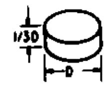
Note: Table values are for a 2-percent loss in 12 hours with an assumed daily temperature range of 60°F (33°C). Table units are Btu/hr·ft^2 (W/m^2). To obtain the maximum allowable thermal transmittance for the side and top insulation, divide the insulation factor by the difference between the average storage temperature and the ambient temperature. The maximum allowable thermal transmittance for the bottom insulation is assumed to be twice that on the top and sides.

Table 1-8. Insulation Factor fQ/At for Horizontal Cylindrical Water Tanks

Size, gallons (liters)	Shape			
				
250 (946)	3.63 (11.5)	3.46 (10.9)	3.05 (9.62)	2.77 (8.74)
500 (1893)	4.57 (14.4)	4.36 (13.8)	4.84 (12.1)	3.49 (11.0)
750 (2839)	5.24 (16.5)	4.99 (15.7)	4.40 (13.9)	3.99 (12.6)
1000 (3785)	5.76 (18.2)	5.49 (17.3)	4.84 (15.3)	4.39 (13.8)
1500 (5678)	6.60 (20.8)	6.28 (19.8)	5.54 (17.5)	5.03 (15.9)
2000 (7571)	7.26 (22.9)	6.92 (21.8)	6.10 (19.2)	5.53 (17.4)
3000	8.31 (26.2)	7.92 (25.0)	6.98 (22.0)	6.33 (20.0)
4000 (15142)	9.15 (28.9)	8.71 (27.5)	7.68 (24.2)	6.97 (22.0)
5000 (18927)	9.86 (31.1)	9.39 (29.6)	8.28 (26.1)	7.51 (23.7)

Note: Table values are for a 2-percent loss in 12 hours with an assumed daily temperature range of 60°F (33°C). Table units are Btu/hr·ft^2 (W/m^2). To obtain the correct maximum allowable thermal transmittance for the insulation, divide the insulation factor by the difference between the average storage temperature and the ambient temperature.

Table 1-9. Insulation Factor fQ/At for Vertical Cylindrical Water Tanks

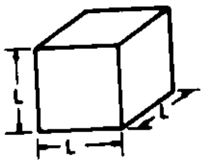
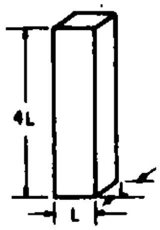
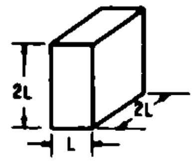
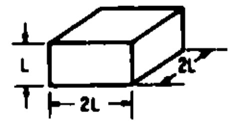
Size, gallons (liters)	Shape			
				
80 (303)	2.10[a,b] (6.62)	1.88[a] (5.93)	2.15 (6.78)	1.97 (6.21)
120 (454)	2.39 (7.54)	2.15 (6.78)	2.46 (7.76)	2.26 (7.13)
250 (946)	3.07 (9.68)	2.74 (8.64)	2.46 (9.91)	2.88 (9.09)
500 (1893)	3.87 (12.2)	3.46 (10.9)	3.96 (12.5)	3.63 (11.5)
750 (2839)	4.43 (14.0)	3.96 (12.5)	4.53 (14.3)	4.16 (13.1)
1000 (3785)	4.87 (15.4)	4.36 (13.8)	4.99 (15.7)	4.57 (14.4)
1500 (5678)	5.58 (17.6)	4.99 (15.7)	5.71 (18.0)	5.24 (16.5)
2000 (7571)	6.13 (19.3)	5.49 (17.3)	6.28 (19.8)	5.76 (18.2)
3000 (11356)	7.03 (22.2)	6.28 (19.8)	7.19 (22.7)	6.60 (20.8)
4000 (15142)	7.73 (24.4)	6.92 (21.8)	7.92 (25.0)	7.26 (22.9)
5000 (18927)	8.33 (26.3)	7.45 (23.5)	8.53 (26.9)	7.82 (24.7)

Note: Table values are for a 2 percent loss in 12 hours with an assumed daily temperature range of 60°F (33°C). Table units are Btu/hr·ft^2 (W/m^2). To obtain the maximum allowable thermal transmittance of insulation, divide the insulation factor by the difference between the average storage temperature and the ambient temperature.

[a] The maximum allowable thermal transmittance of the bottom insulation is assumed to be twice that on the top and sides for tanks specified by the first two columns.

[b] The first column is applicable to all tanks with height of one to three times the diameter. Insulation factors for most domestic hot water tanks can be found in the first column.

Table 1-10. Insulation Factor fQ/At for Rock Beds

Volume of Rock,[b] ft^3 (m^3)	Shape of Rock Bed[a]			
				
100 (2.83)	0.82 (3.82)	0.83 (3.79)	0.80 (3.88)	0.97 (3.22)
150 (4.25)	0.72 (4.35)	0.72 (4.32)	0.70 (4.45)	0.85 (3.69)
200 (5.66)	0.65 (4.79)	0.66 (4.76)	0.64 (4.89)	0.76 (4.07)
300 (8.50)	0.57 (5.49)	0.57 (5.46)	0.56 (5.62)	0.67 (4.64)
400 (11.33)	0.52 (6.03)	0.52 (5.99)	0.51 (6.18)	0.61 (5.11)
500 (14.16)	0.48 (6.50)	0.48 (6.47)	0.47 (6.66)	0.56 (5.52)
600 (16.99)	0.45 (6.91)	0.46 (6.85)	0.44 (7.07)	0.53 (5.87)
800 (22.65)	0.41 (7.60)	0.41 (7.54)	0.40 (7.79)	0.48 (6.44)
1000 (28.32)	0.38 (8.20)	0.38 (8.14)	0.37 (8.39)	0.45 (6.94)

Note: Table values are for a 2-percent loss in 12 hours with an assumed daily temperature range of 50°F (28°C). Table units are in $Btu/ft^2 \cdot hr$ (W/m^2). To obtain the maximum allowable thermal transmittance for the side and top insulation, divide the insulation factor by the difference between the average storage temperature and the ambient temperature. The maximum allowable thermal transmittance for the bottom insulation is assumed to be twice that on the top and sides.

[a,b]The insulation is assumed to cover both plena, but the volume and shapes given are for the rocks only.

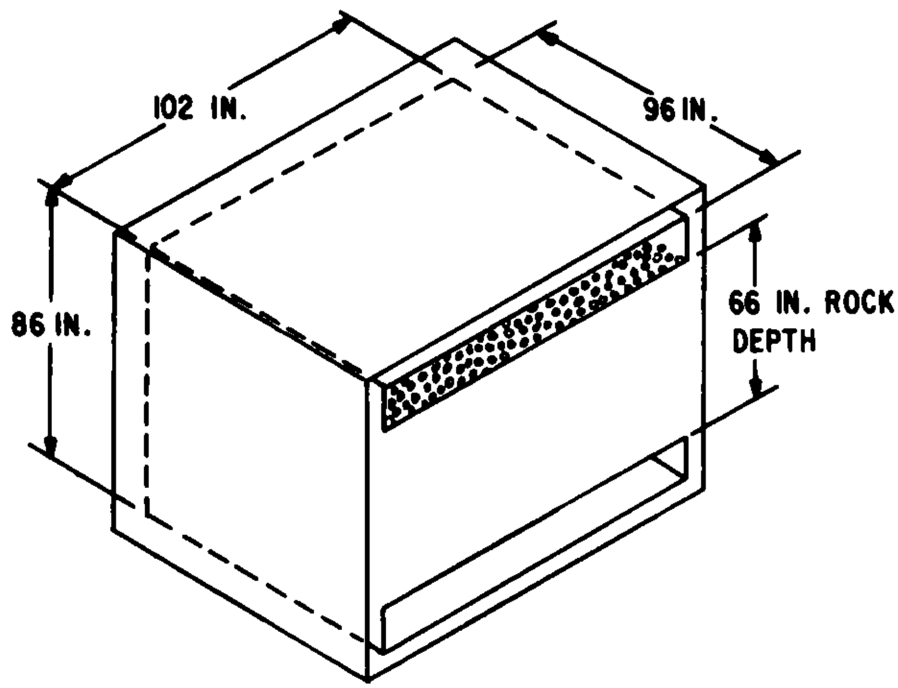


Figure 1-8. Inside Dimensions of a 375-Cubic-Foot Rock Bin

$$U = \frac{10}{2} \times \frac{12}{24} \times 0.0370 = 0.0926 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}.$$

In this case, the insulation calculated in Example 1-4 would be adequate.

Insulating Pipes and Ducts

Heat can be lost not only from the storage device but also as it is moved into and out of storage. These losses include:

- Losses between the collector and the storage unit (charging losses).
- Losses between the storage unit and the heating load (discharging losses).

To minimize these losses, (1) the piping system from collector to storage must be well insulated and have weather protection, and (2) the piping or ductwork from storage to load must be kept as short as possible and be well insulated.

The Polytechnic Institute of New York recommends using R-4 insulation for pipes less than 1 inch in diameter and R-6 insulation for pipes 1 to 4 inches in diameter. The method given in Appendix C for calculating the most economical thickness of insulation can also be used here.

HEAT EXCHANGERS

Heat exchangers are devices that transfer heat from one fluid to another while preventing mixing of the two fluids. Hot fluid flows on one side of a metal barrier and heats a cold fluid flowing on the other side. In order for heat to be transferred the hot fluid must be hotter than the cold fluid directly across the barrier. This necessary temperature difference leads to a loss of overall system efficiency each time a heat exchanger is used. Heat exchangers typically used in solar energy systems are shown in Figures 1-9 through 1-14.

Heat Exchangers in Liquid-based Systems

The collectors must be protected against freezing in the winter. If antifreeze is used for protection, a liquid-to-liquid heat exchanger must be installed as shown in Figure 1-2 to separate the heat transfer fluid from the water in storage, since antifreeze is too expensive to use as a storage medium. Because there must be a temperature difference from the collector side to the storage side of the heat exchanger, the collector must operate at a higher, less efficient temperature than in a system without a heat exchanger between collector and storage. Thus, the heat exchanger imposes a performance penalty on the system.[2]

The collector-to-storage heat exchanger can be as simple as a coiled tube immersed in the storage tank (Figure 1-9) or wrapped around the outside of the tank (Figure 1-10). Figure 1-11 shows a wraparound shell heat exchanger.

The types of heat exchangers represented in Figures 1-9 through 1-11 rely on natural convection to move the water inside the tank past the heat exchange surface. If the tank is large, say several hundred gallons, natural convection is an inefficient means of transferring heat. Shell-and-tube heat exchangers (Figures 1-12 and 1-13) are often used in this case, and a pump circulates the water between the tank and the heat exchanger.

In the simple heating system shown in Figure 1-2, a heat exchanger (liquid-to-air) is needed to transfer heat to the building. This heat exchanger is often a finned-tube unit (Figure 1-14) inserted in an air duct. Another common type of finned-tube heat exchanger is the A-frame type (not shown). Less frequently used alternatives are baseboard convectors, radiant heating coils, and individual fancoil units.

Solar-heated domestic hot water requires a heat exchanger to separate the potable, or drinkable, hot water from either the nonpotable storage fluid or the collector fluid. Heat exchangers for use with potable water are subject to special safety requirements discussed in Chapter 5.

Heat Exchangers in Air-based Systems

In contrast with the liquid-based system, the air-based system (Figure 1-1) does not need separate heat exchangers between the collectors and the heating load. The rock bed is both the storage device and the collector-to-load heat exchanger.

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[2] Another method of protecting the collectors is to drain them whenever there is danger of freezing weather. This method, known as the draindown system, is one of the most efficient solar collection systems available. Details of the draindown system and its many variations are available in systems design manuals such as ITT's *Solar Systems Design Manual*.

A draindown system must be totally foolproof. Pipes must be carefully pitched and collectors carefully selected to ensure that all of the water will drain when it should. A single failure can ruin the collectors. Many designers prefer to use antifreeze in the collectors rather than risk this catastrophe. The designer must decide whether to pay the penalties of lower performance and higher first cost for an antifreeze system in return for less risk of an expensive failure.

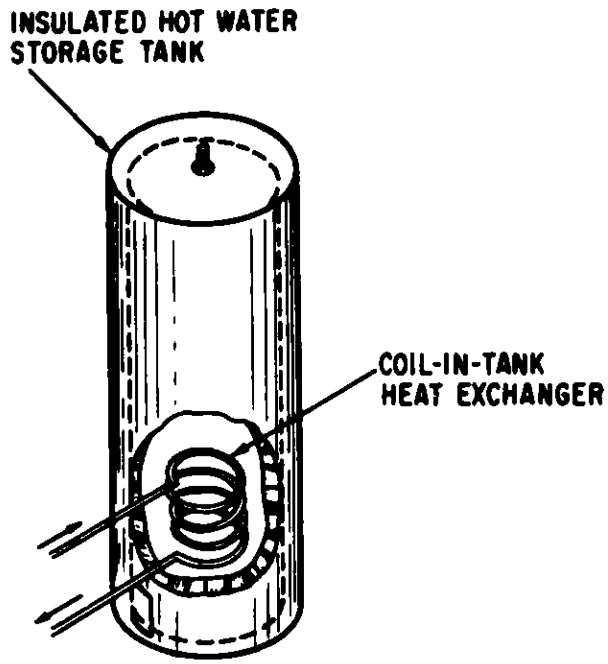


Figure 1-9. Typical Coil-in-Tank Heat Exchanger

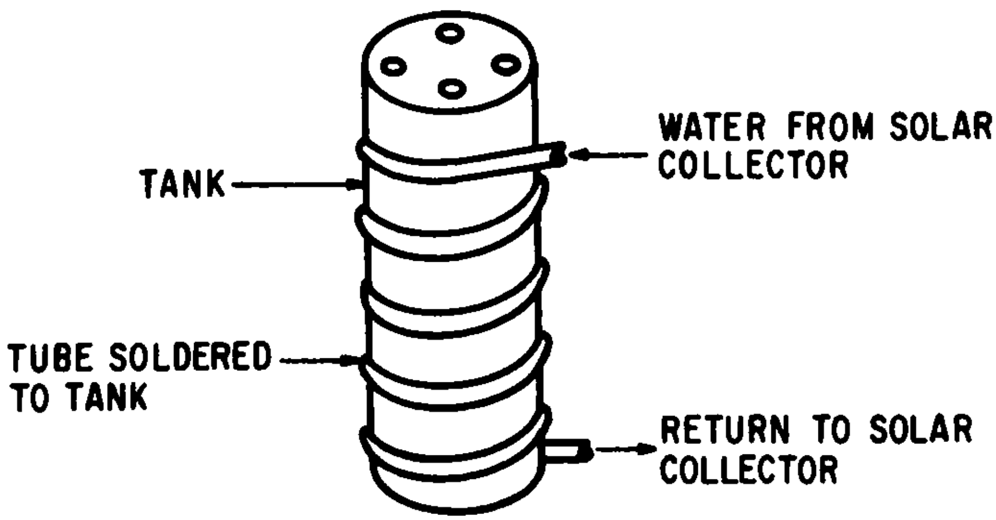


Figure 1-10. Schematic Drawing of Wraparound (Traced Tank) Heat Exchanger

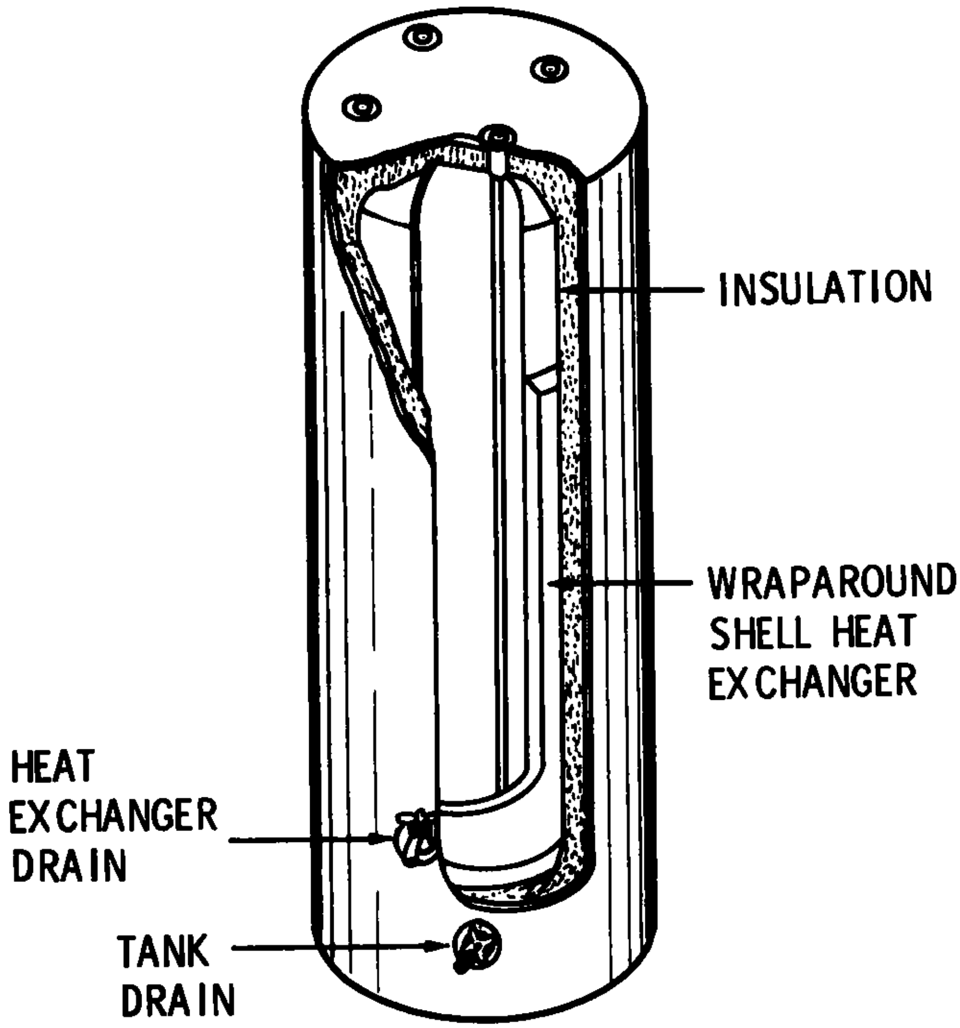


Figure 1-11. Wraparound Heat Exchanger

A pressure-bonded metal plate with integral fluid passageways is clamped around the outside of the storage tank.

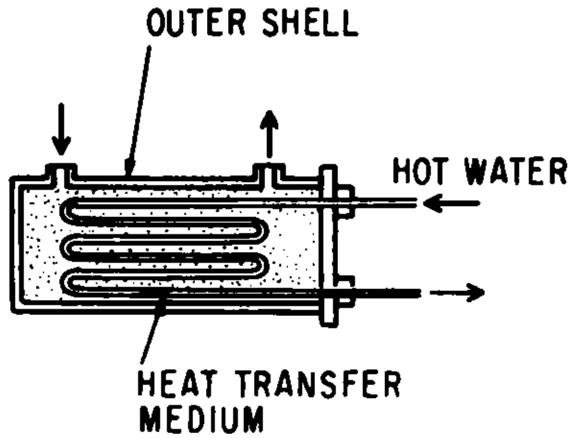


Figure 1-12. Shell-and-Tube Heat Exchanger

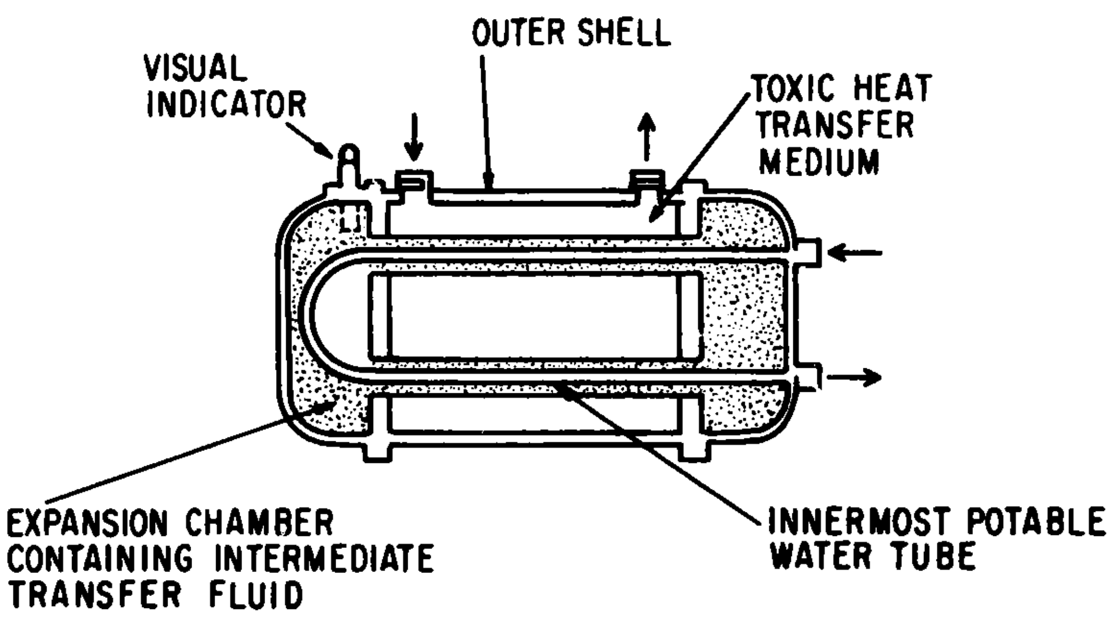


Figure 1-13. Shell-and-Double-Tube Heat Exchanger

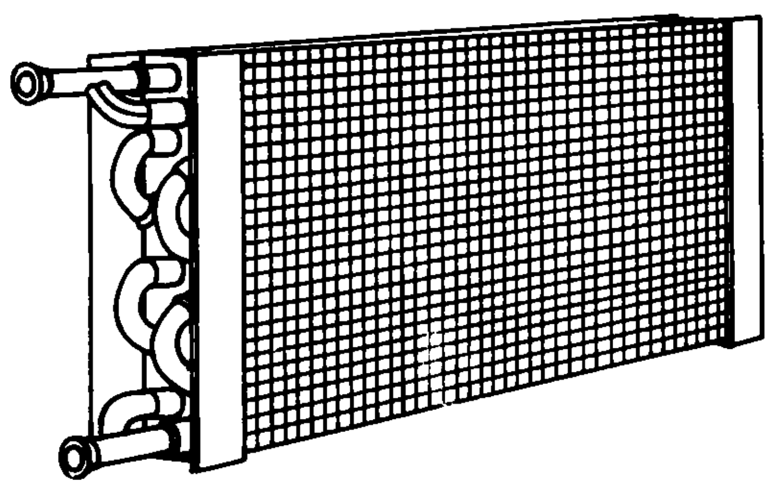


Figure 1-14. Typical Liquid-to-Air or Air-to-Liquid Heat Exchanger

Drawing courtesy of Bohn Heat Transfer Division, Gulf-Western Manufacturing Company, Danville, Illinois

Air-based collector systems used to heat domestic hot water must use an air-to-liquid heat exchanger. Such a heat exchanger usually consists of finned water tubing in the air-handling duct (Figure 1-14) similar to the finned tube heat exchanger used in air ducts of liquid-based systems.

Heat Exchanger Effectiveness

As we said earlier, using heat exchangers imposes a penalty on the solar space heating system. A collector-to-storage heat exchanger forces the collector to operate at a higher temperature than in a system without the heat exchanger. Similarly, the storage-to-load heat exchanger forces the storage system to operate at a higher temperature than would be required if that heat exchanger could be eliminated.

In order to calculate how efficiently a system with heat exchangers will perform, you must be able to determine the penalty imposed on the system by the heat exchangers. This penalty, called heat exchanger effectiveness, is defined as the actual rate of heat exchange divided by the rate of heat exchange of a perfect, infinitely large heat exchanger.

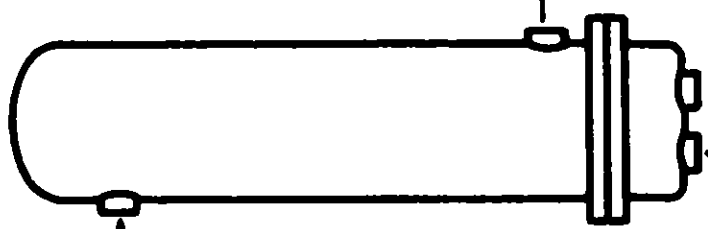
Since there is no perfect, infinitely large heat exchanger, the designer's task is to choose the size of heat exchanger that will minimize the overall cost of the system. This relatively complex task is described in Appendix D. Alternatively, most heat exchanger manufacturers can select the properly sized heat exchanger given the following information about the system:

- The physical characteristics of the two fluids in the heat exchanger. (See Appendix B.)
- The amount of heat to be transferred.
- The flow rates on both sides of the heat exchanger.
- The approach temperature difference, defined as the difference between the temperatures of the hot fluid entering the heat exchanger and the heated fluid leaving the heat exchanger.

A form for specifying heat exchangers is provided in Table 1-11.

Appendix E gives sample specifications for heat exchangers that are not integral parts of a storage tank. Appendix G, Part 2, gives sample specifications for domestic hot water tanks with integral heat exchangers.

Table 1-11. Heat Exchanger Specification Form



	FLUID A	FLUID B
Description	________	________
Heat Capacity (Btu/lb·°F) (J/kg·°C)	________	________
Density (lb/ft^3) (kg/m^3)	________	________
Thermal Conductivity (Btu/hr·ft·°F) (W/m·°C)	________	________
Viscosity (lb/ft·hr) (Pa·sec)	________	________
Flow Rate (gpm) (liters/sec)	________	________
Inlet Pressure (psi) (MPa)	________	________

Rate of Heat Transfer (Btu/hr) (W) ________

Approach Temperature Difference (°F) (°C)
(Temperature of heating fluid inlet minus temperature of heated fluid outlet) ________

SYMBOLS USED IN CHAPTER 1

Main Symbols

A	area, ft^2 (m^2)
C_p	heat capacity, Btu/lb·°F (J/kg·°C)
f	fraction of energy stored
m	mass, lb (kg)
Q	amount of heat stored, Btu (J)
$\dot{Q}$	rate of heat flow, Btu/hr (W)
R	thermal resistance to flow of heat, °F·ft^2·hr/Btu (°C·m^2/W)
r	resistance to flow of heat per unit thickness, °F·ft^2hr/Btu·in (°C·m^2/W·cm)
s	thickness of an insulation layer, in. (cm)
T	temperature, °F (°C)
t	time, hr (sec)
U	thermal transmittance, Btu/hr·ft^2·°F (W/m^2·°C)

Subscripts

a	ambient condition
avg	an averaged quantity
max	a maximum quantity
min	a minimum quantity
s	surface condition
1,2,3	first, second, third, (and subsequent) layers of insulation or paths for heat flow

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CHAPTER 2
THERMAL ENERGY STORAGE IN AIR-BASED SYSTEMS

INTRODUCTION

When rocks are used as the heat storage medium, they are placed in a container (a rock bin) that provides enough room for the loose rocks and for air spaces, called plena, that distribute the flow of air through the rocks. When solar-heated air is forced into the rock bin, the plenum allows the air to spread out and pass evenly through the rocks. The hot air gives up its heat to the rocks, and cool air is drawn off and returned to the collectors. When space heating is needed, the air flow is reversed and warm air is delivered into the building.

Air Flow Direction and Rock Bed Shape

In this manual we assume the rock bed is vertically oriented--that is, the direction of the air flow through the rocks is from top to bottom when charging and bottom to top when discharging. A vertical bed provides the best thermal characteristics, since it can best take advantage of warm air's natural tendency to rise. Vertical rock beds tend to be tall, however, and must be designed carefully to fit into the space available.

Besides the vertical rock bed, two other types have been used: the U-shaped bed and the horizontal bed.

The U-shaped rock bed requires less vertical space than the vertical one and is sometimes preferred for that reason. (Figure 2-1 shows a typical design.) Because not much data on the performance of this type of rock bed is available, it should be considered an experimental design. We do not recommend it, because of the following potential problems.

- More air flows near the center baffle than around the outer walls, resulting in uneven charging.
- Air flow tends to bypass the bottom corners so that they contribute little to storage.
- At the exit side, the tendency for warm air to rise reduces or even reverses the thermal stratification in that section of the rock bed. As a result, the air that is returned to the solar collector will be warmer than it would be in a vertical bin, and the collector will operate less efficiently.

The horizontal rock bed, shown in Figure 2-2a, also requires less vertical space than the vertical one. However, the horizontally oriented rock bed has two major disadvantages, both caused by its air flow travelling from side to side. First, as the rocks settle, an air space is opened between the top of the rocks and the top of the bin. Air will flow horizontally through this space, bypassing the rocks.

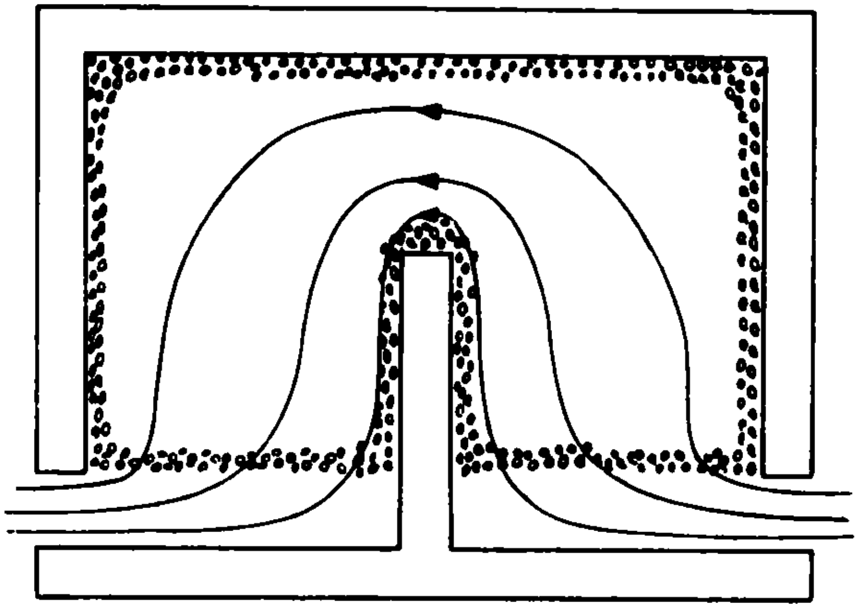

Figure 2-1. U-Shaped Rock Bed

Second, as the warm air flows through the rocks, it will rise and heat the rocks on the top of the bin more than those on the bottom. When the flow is reversed for space heating, part of the air will pass through the warmer rocks at the top while the rest of the air passes through the cooler rocks at the bottom. The mixed warm and cool air will be delivered to the building at a temperature lower than that of the warmest rocks.

Research on improved designs for horizontal rock beds is being conducted in Japan and the United States. One experimental design is shown in Figure 2-2b.

Rocks

The ideal rocks to use in a rock bed are the rounded ones typically found in river beds, but crushed rock will work nearly as well. Rocks that conform to ASTM C 33, "Specifications for Concrete Aggregates," are generally acceptable and have been washed to remove dust and dirt.

Several types of rock are unacceptable for use in rock beds. Rocks that crumble, such as schist and softer varieties of limestone and sandstone, should not be used. Marble, limestone, and dolomite, which are acceptable for heating systems, react with water and carbon dioxide and may therefore cause problems in systems that are used for nighttime cooling in the summer. In addition, some rocks of volcanic origin will smell of sulfur when they are cracked. Test for this before you buy the rocks by breaking several open.

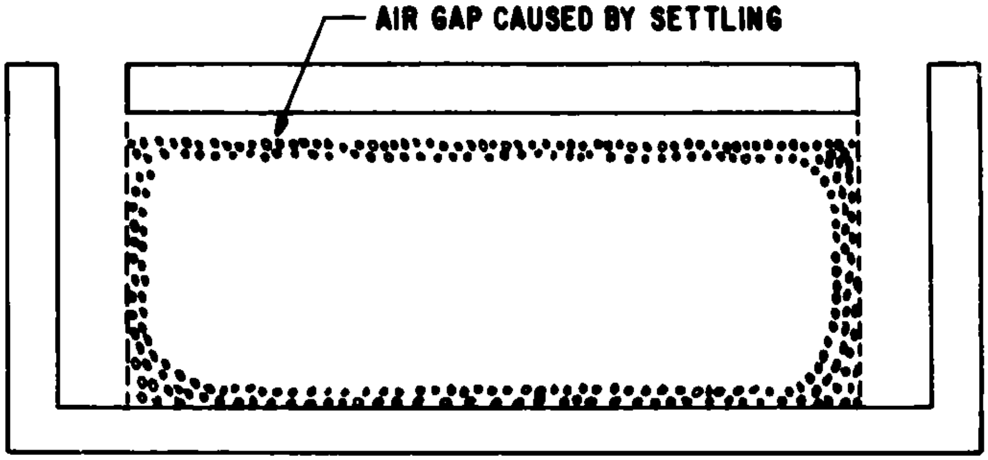

Figure 2-2a. Horizontal Rock Bed

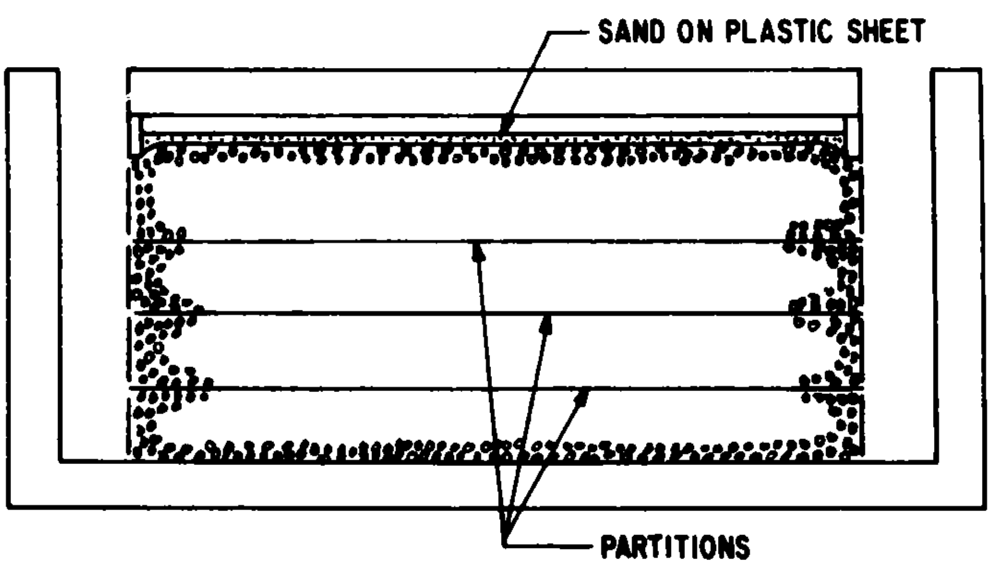

Figure 2-2b. Horizontal Rock Bed with Partitions and Floating Cover

The rocks should be about the same size--within 3/4 to 1-1/2 times the nominal, or average, rock diameter. Rocks are usually sorted into specific sizes by being passed through a screen mesh. We recommend screening the rocks twice--once to eliminate rocks that are too large and again to eliminate rocks that are too small.

When the rocks are delivered, the smaller ones may have settled to the bottom of the truck, leaving the larger ones on top. You may want to mix them before filling the bin. Since, even if the rocks have been washed, they may have picked up dirt and dust during handling, you may have to wash them again. Some installers dry the rocks in the bin by using the system's fan. If you do that, be sure the moisture will not harm the materials in the bin.

Rock Bin

Rock bins must be strong enough to withstand the outward pressure of the rocks. This pressure, already great when the bin is first filled, increases as the rocks expand, contract, and settle with the heating and cooling of the bed. Typical materials for rock bins include wood, concrete, and cement blocks. Appendix F shows details for construction of a wooden bin. Construction of a poured concrete bin is similar to that of the cast-in-place water tank described in Appendix H, except that no lining is needed and air inlet and outlet openings must be provided.

Plena

The function of the plena, as we have said, is to distribute the air uniformly over the top and bottom of the rocks. To do this, the plena must resist air flow much less than the rocks do. We recommend that the cross-sectional area of each plenum, as shown in Figure 2-3, be at least 8 percent of the cross-sectional area of the rock bin. That is, the plenum height times the plenum width should be at least 8 percent of the rock bin's width times its length. If a plenum is partially obstructed by supports for the rock bed, the plenum area should be increased to 12 percent of the cross-sectional area of the rock bed.

The pressure drop across the rock bed is also important in ensuring proper air distribution. This characteristic will be discussed in the next section.

PERFORMANCE CHARACTERISTICS

Of primary importance to the performance of the rock bed are its volume, the face velocity, the pressure drop across the rock bed, and the size of the rocks in relation to the depth of the rock bed.

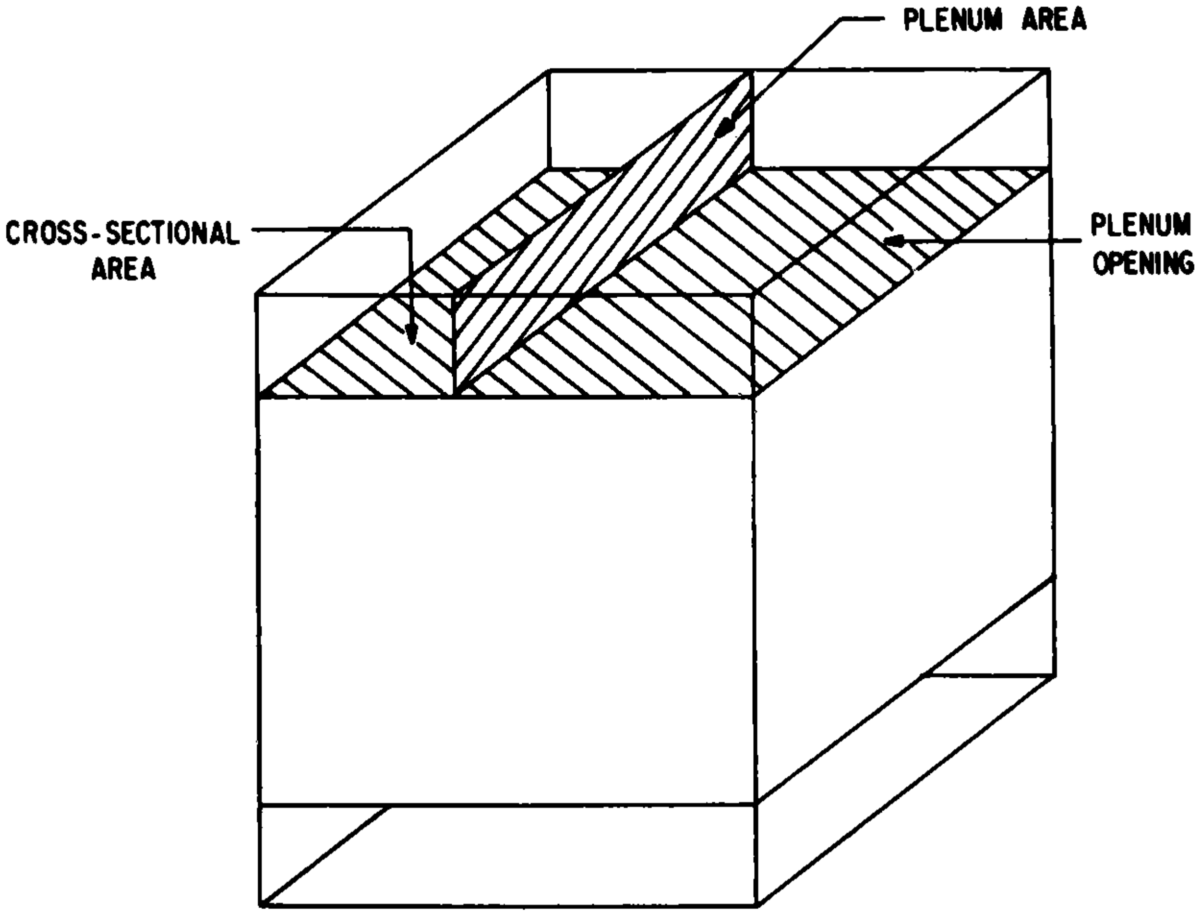

Figure 2-3. Definition of Plenum Area and Cross-Sectional Area in a Rock Bed

Volume

The method of determining the required rock bed volume was given in Chapter 1. Either the rule of thumb--0.50 to 0.75 cubic feet of rock per square foot (0.015 to 0.020 cubic meters per square meter) of collector--or the calculation method can be used, but we prefer the calculation method. Having determined the correct volume, you can use the methods shown in this chapter's design examples to determine the dimensions of the rock bed.

Face Velocity

The face velocity is defined as the volumetric air flow rate divided by the cross-sectional area of the rock bed. It measures the air's velocity immediately before it enters the rocks. (Some texts call it the superficial velocity.) The volumetric air flow rate is determined by the collector manufacturer and the size of the collector. Increasing the face velocity increases the pressure drop across the rock bed.

Pressure Drop

Designing the rock bed for a minimum pressure drop of 0.15 inches of water (38 pascals) will help the plena distribute the air by ensuring that they resist air flow much less than the rock bed does. We also recommend designing the rock bed for a maximum pressure drop of 0.30 inches of water (75 pascals) so that the fan does not consume an excessive amount of power. Figure 2-4 shows the air flow patterns that occur with proper and improper design.

Dividing the pressure drop by the rock depth (for a vertical-flow rock bed) yields the *pressure gradient*, which will be used in later calculations.

Rock Diameter

The fourth parameter affecting performance is the rock diameter. Increasing the rock diameter decreases the pressure drop across the rock bed, because the larger spaces between large rocks have less resistance to air flow than the spaces between small rocks.

Another, more subtle effect of increasing the rock diameter is that it increases the time required for each rock to reach its equilibrium temperature with the air. If this time is more than the time required for air to traverse the rock bed, the rocks will be unable to absorb all of the heat in the air by the time the air leaves the rock bed. Thus, air will be returned to the collector at a temperature that is warmer than the coolest rocks, and the benefit of thermal stratification will be lost.

If the rocks' equilibration time is much less than the time required for air to traverse the rock bed, however, the air will give up nearly all of its heat to the rocks and will emerge from the rock bed at the temperature of

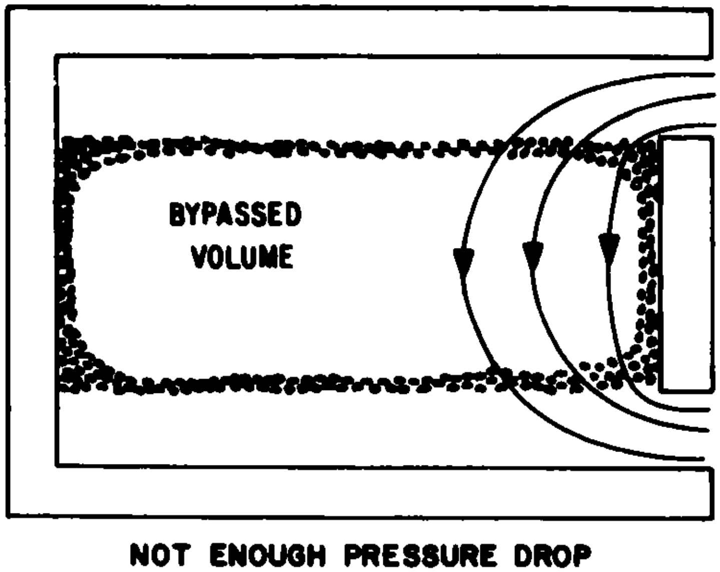

Figure 2-4a. Air Flow Pattern When the Pressure Drop is Too Low or the Plena Are Too Small

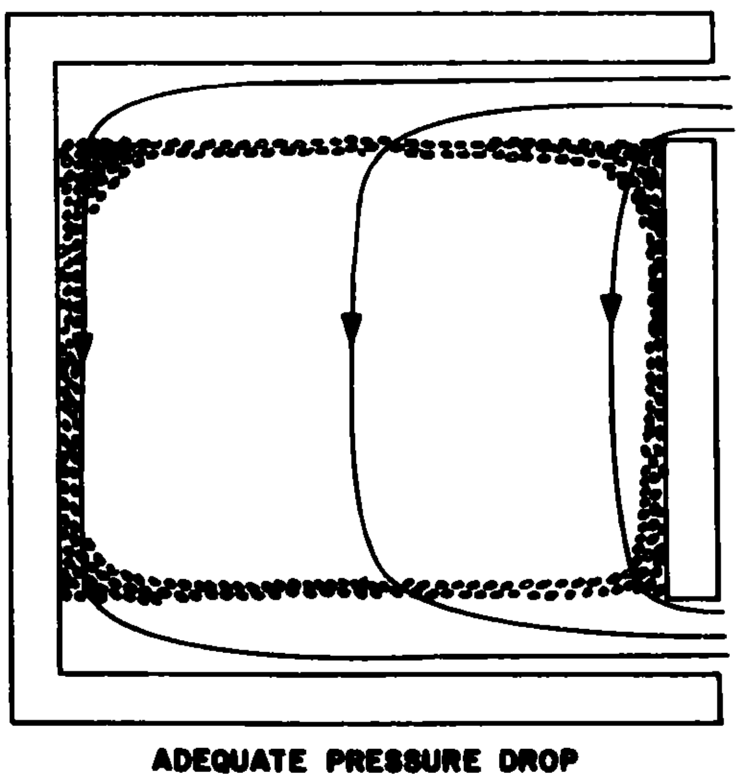

Figure 2-4b. Air Flow Pattern When the Pressure Drop and Plenum Size Are Adequate

the coolest rocks. The rock bed will remain thermally stratified, with hot rocks at the top and cool rocks at the bottom. As heat is added to the rock bed, the interface between hot and cool rocks moves downward, but air leaves the rock bed at the temperature of the coolest rocks until the rock bed is almost fully charged. To maintain thermal stratification in this manner, you should make the rock depth at least twenty times the rock diameter if the rocks are less than 4 inches (10 centimeters) in diameter or by at least thirty times the rock diameter if the rocks are larger than 4 inches in diameter.

Rock Bed Performance Map

The rock bed performance map shown in Figure 2-5[1] gives the relationship among face velocity, pressure gradient, and rock diameter. The vertical axis represents the pressure gradient in inches of water per foot of depth (pascals per meter) and the horizontal axis represents the face velocity in feet per minute (meters per second). The curved lines show the relationship between pressure gradient and face velocity for various rock diameters. Two typical calculations using the rock bed performance map are:

- Given the air flow rate and the rock bin dimensions, determine the rock size necessary for adequate performance.
- Given the air flow rate and the available rock size, determine the necessary dimensions of the rock bin.

Use of the performance map will be demonstrated in the rock bed design example.

ROCK BED DESIGN

Most rock bed designs are subject to several constraints. Typical constraints include sizes of rocks that are available and floor-to-ceiling height available for the bin, as well as the rules of thumb given earlier, which are summarized below.

- Volume of the Rock Bed
  The volume of the rock bed should be between 0.5 and 0.75 cubic feet of rock per square foot of collector (between 0.015 and 0.020 cubic meters per square meter of collector).

---

[1]The information used to make this performance map was derived from: R. V. Dunkle and W. M. Ellul. Randomly-packed particulate bed regenerators and evaporative cooling. *Mechanical and Chemical Engineering Transactions of the Institution of Engineers, Australia*, MC8(2):117-121, 1972.

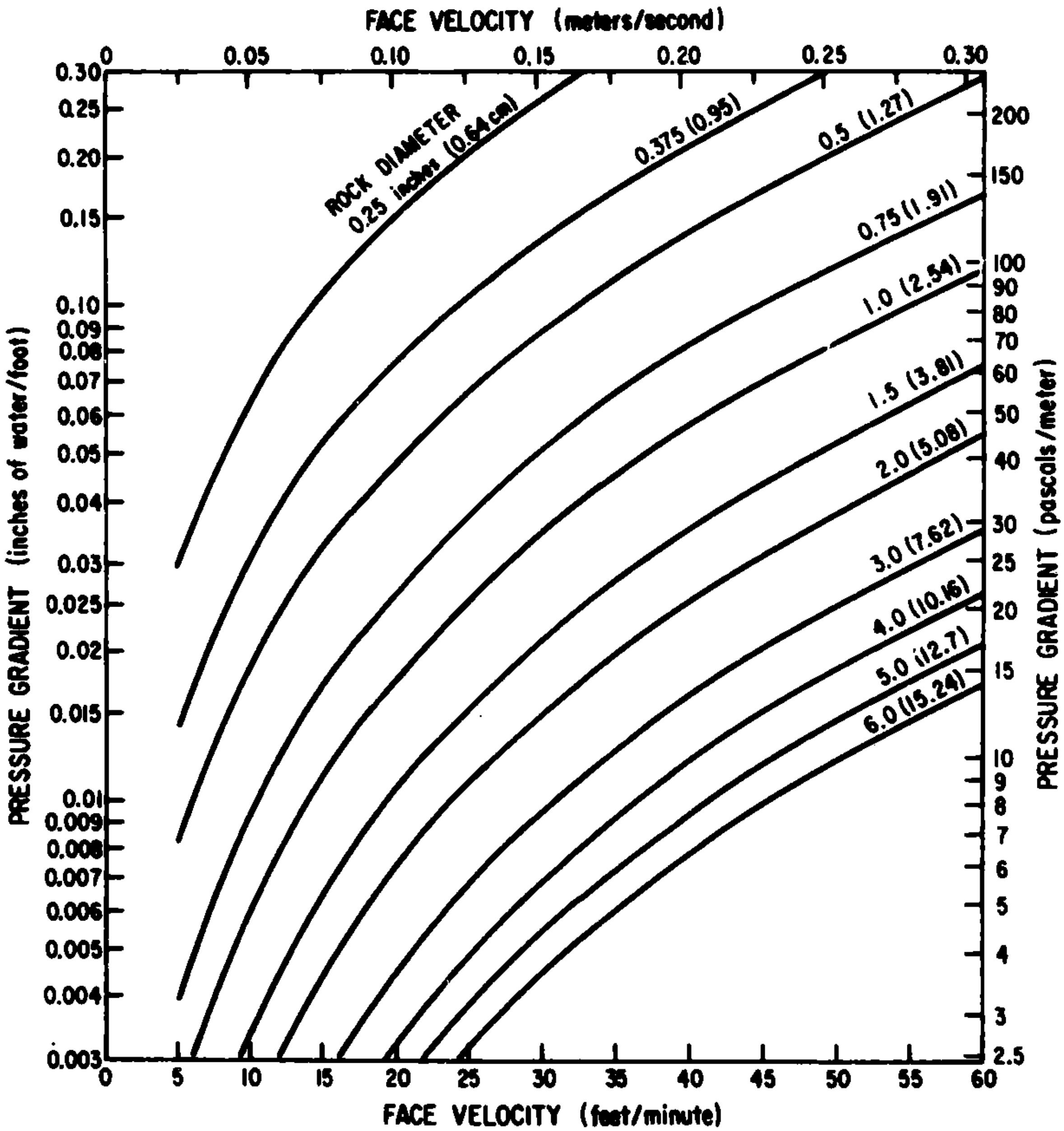

Figure 2-5. Rock Bed Performance Map

- Pressure Drop across the Rock Bed
  The total pressure drop across the rock bed should be between 0.15 and 0.30 inches of water (between 37 and 75 pascals).
- Plenum Size
  The area of the plenum perpendicular to the air flow should be at least 8 percent of the cross-sectional area of the rock bed. (See Figure 2-3.) If a plenum contains rock bed supports such as bond beam blocks, then its area should be increased to 12 percent of the rock bed cross section.
- Rock Size and Rock Bed Depth
  The rock bed's depth should be at least twenty times the nominal rock diameter if the rocks are less than 4 inches (10 centimeters) in diameter, or thirty times the nominal rock diameter if the rocks are more than 4 inches in diameter.

Other Considerations

Common sense and building codes dictate a number of considerations that a designer should keep in mind when designing a rock bed.

- Do a thorough job in designing the first few systems. Many of the details of these designs can be incorporated in later systems.
- Be sure the rock bin walls can hold not only the pressure of the rocks when the bin is first filled but also the additional pressure that will develop as the rocks expand, contract, and settle when the bed is in use. Have a structural engineer design a rock bed foundation that will meet building code requirements and ensure the safety of the building.
- Choose materials that can withstand high temperatures for the life of the system. Fire codes generally outlaw placing flammable materials in contact with the hot air system, so sheet metal or fire-retardant gypsum board must be specified as the interior lining of wooden rock bins.
- Consider such constraints as space restrictions and available rock sizes.
- Use standard materials and dimensions. This will save both time and labor.
- Use flexible silicone caulk for sealing the rock bin. Silicone caulk will not dry out and crack and will therefore minimize leaks.
- Design for easy maintenance. All components (blowers, filters, and so on) must be accessible for repair and maintenance.
- Install a drain that is not trapped to a sewer. The drain will allow any water in the bed (from accidents or condensation in nighttime cooling systems) to escape. A trap in the drain will dry out in normal use, so the drain cannot be connected directly to a sewer.
- Design to reduce summer cooling loads. For rock beds located within the heated area, provide a bypass for summer domestic hot water heating so the rock bed can be kept cool. Install the rock bed in a room that can be manually vented when heat is needed at night but not during the day.

ROCK BED DESIGN EXAMPLE

We are going to install an air-based solar space heating system in a new house. We have already determined the following:

- We need 400 square feet (37 square meters) of solar collector.
- The collector manufacturer recommends an air flow rate of 2 cubic feet per minute per square foot (0.01 cubic meters per second per square meter) of collector area, for a total air flow rate of 800 cubic feet per minute (0.38 cubic meters per second).
- We are going to install the rock bed in the basement of the house, which has a floor-to-joist height of 7 feet (213 centimeters).
- We can pour a recessed floor for the rock bed no lower than 1 foot (30 centimeters) below the nominal basement floor level in order for the rock bed drain to go to the sump well.
- We will line the wooden rock bin with sheet metal for fire protection.

From that information we calculate the following design parameters:

A. Depth

The total height of the rock bed, including insulation and plena, is limited to 96 inches (243.8 centimeters). Because we will need room to put on the cover, we will allow 2 inches (5 centimeters) of working space, limiting the height to 94 inches (238.8 centimeters).

We plan to make the cover of 2 x 6 studs (to allow room for insulation) with 1/4-inch (0.64-centimeter) plywood sheathing, so the cover will be 6 inches (15.2 centimeters) thick.

Because the bond beam blocks we will use to support the rocks come in a standard 7-5/8-inch (19.3-centimeter) size, we will assume that the bottom plenum, which will contain the bond beam blocks, will be 7-5/8 inches high and that the top plenum will be 5-1/8 inches (13.0 centimeters) high.

We plan to place the bond beam blocks on a piece of 2-inch (5.1-centimeter) rigid fiberglass insulation.

The total height of all of these components is 20.75 inches (52.7 centimeters), which leaves 94 inches - 20.75 inches = 73.25 inches (186.1 centimeters) for the rocks. For convenience we will assume that we will use 72 inches, or 6 feet (182.9 centimeters), of rocks.

B. Volume Limits

Using the rule of thumb for the volume of the rock bed, we find that for 400 square feet of collector the minimum rock volume is:

$$400 \times 0.5 = 200 \text{ ft}^3 \ (5.66 \text{ m}^2)$$

and the maximum rock volume is:

$$400 \times 0.75 = 300 \text{ ft}^3 \ (8.50 \text{ m}^2).$$

Therefore, any volume between 200 and 300 cubic feet will satisfy the rule of thumb requirement.

If f-Chart or some other design tool is available to you, use it at this point to calculate the optimum storage volume before proceeding with the following calculations.

C. Cross-sectional Area

The cross-sectional area of the rock bed is its volume divided by its height. Using the volume limits from Step B and the height from Step A, we find that the minimum cross-sectional area is:

$$\frac{200 \text{ ft}^3}{6 \text{ ft}} = 33.3 \text{ ft}^2 \ (3.09 \text{ m}^2)$$

and the maximum cross-sectional area is:

$$\frac{300 \text{ ft}^3}{6 \text{ ft}} = 50 \text{ ft}^2 \ (4.65 \text{ m}^2) \ .$$

To get one of the dimensions (the length as defined in Figure 2-6) we will use the rule of thumb regarding plenum sizing. The rule of thumb for the bottom plenum, which will contain bond beam blocks, says that the plenum area must equal at least 12 percent of the cross-sectional area. The minimum plenum area then, is:

Minimum Plenum Area = 0.12 x Cross-sectional Area,

which can be written as:

Plenum Height x Width = 0.12 x Maximum Length x Width.

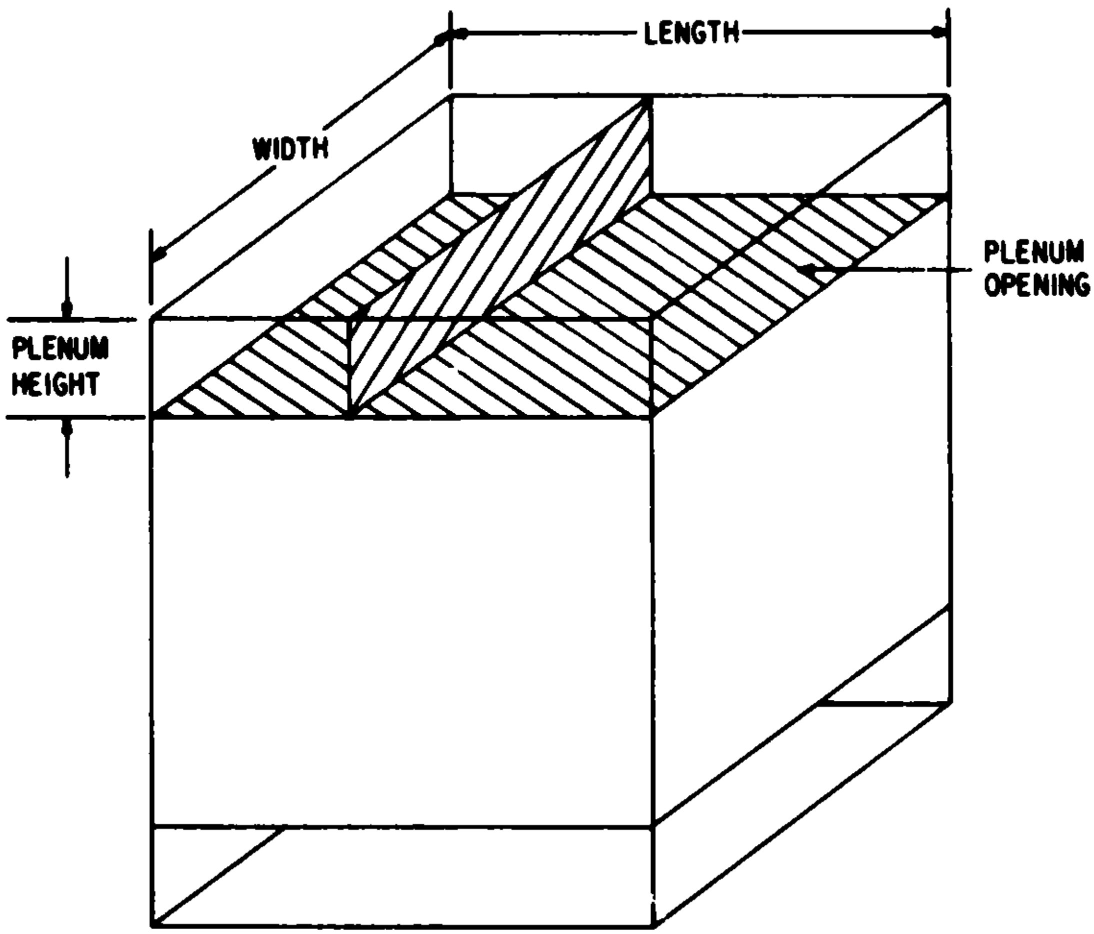

Figure 2-6. Definition of Length and Width for Design Example

Since "Width" is common to both sides of the equation, it can be factored out, leaving:

Plenum Height = 0.12 x Maximum Length.

Therefore, since we have already specified a plenum height of 7-5/8, or 7.62, inches (19.4 centimeters), we can calculate thus:

$$\text{Maximum Length} = \frac{7.62}{0.12}$$

$$= 63.5 \text{ in } (161.3 \text{ cm}).$$

We will therefore choose a length of 63 inches (160.0 centimeters), which is less than the maximum length permitted by the rule of thumb. The top plenum is correctly sized, since we chose its height to be about two-thirds (8 percent/12 percent) of the size of the bottom plenum to satisfy the rule of thumb.

Anticipating that the walls will be made from 2 x 6 studs with 1-inch (2.5-centimeter) plywood inside and half-inch (1.3-centimeter) gypsum board outside, we choose the other dimension to be 82 inches (208.3 centimeters).

The cross-sectional area is then:

$$\frac{63 \times 82}{144} = 35.9 \text{ ft}^2 \ (3.33 \text{ m}^2),$$

which is within the limits of 33.3 to 50.0 square feet as calculated above.

D. <u>Face Velocity</u>

The face velocity is the velocity of the air immediately before it enters the rocks. It is calculated by dividing the air flow rate by the cross-sectional area of the rock bin. In this case the face velocity will be:

$$\frac{800 \text{ ft}^3/\text{min}}{35.9 \text{ ft}^2} = 22.3 \text{ ft/min } (0.11 \text{ m/s}).$$

We will later use this number to help determine the rock size and the pressure drop in the rock bed.

E. Pressure Gradient Limits

The pressure gradient is the pressure drop per unit length through the rock bin. It is calculated by dividing the total pressure drop by the depth of the rocks. Using the second rule of thumb given earlier, we find that the minimum pressure gradient is:

$$\frac{0.15 \text{ inches of water}}{6 \text{ ft}} = 0.025 \text{ inches of water/ft } (20.4 \text{ Pa/m})$$

and the maximum pressure gradient is:

$$\frac{0.30 \text{ inches of water}}{6 \text{ ft}} = 0.05 \text{ inches of water/ft } (40.8 \text{ Pa/m}).$$

These limits will now be used to help determine the rock size and the pressure drop in the rock bed.

F. Rock Size

We will use the rock bed performance map in Figure 2-7 and the numbers that we calculated in Steps D and E to determine the rock size suitable for our system.

First, we draw a vertical line at the face velocity of 22.3 feet per minute (0.11 meters per second). Next, we draw two horizontal lines at the pressure gradient limits of 0.025 and 0.05 inches of water per foot (20.4 to 40.8 pascals per meter).

Any of the curved lines corresponding to various rock sizes that cross the face velocity line between the pressure gradient limit lines is a suitable choice. In this case, only the curve that corresponds to 3/4-inch-diameter (1.9-centimeter-diameter) rock is indicated, so that is the rock size we will use. We will accept washed rocks whose average diameter varies from 3/4 to 1-1/2 times the nominal diameter, or from 5/8 inch to 1-1/8 inches (1.6 to 2.8 centimeters).

To check the fourth rule of thumb, we note that 20 x 3/4 inch = 15 inches (38.1 centimeters), which is much less than the rock bed depth. That means thermal stratification in the rock bed will be good.

G. Pressure Drop

The design point of our rock bed is the point on the rock bed performance map where the line representing the pressure gradient

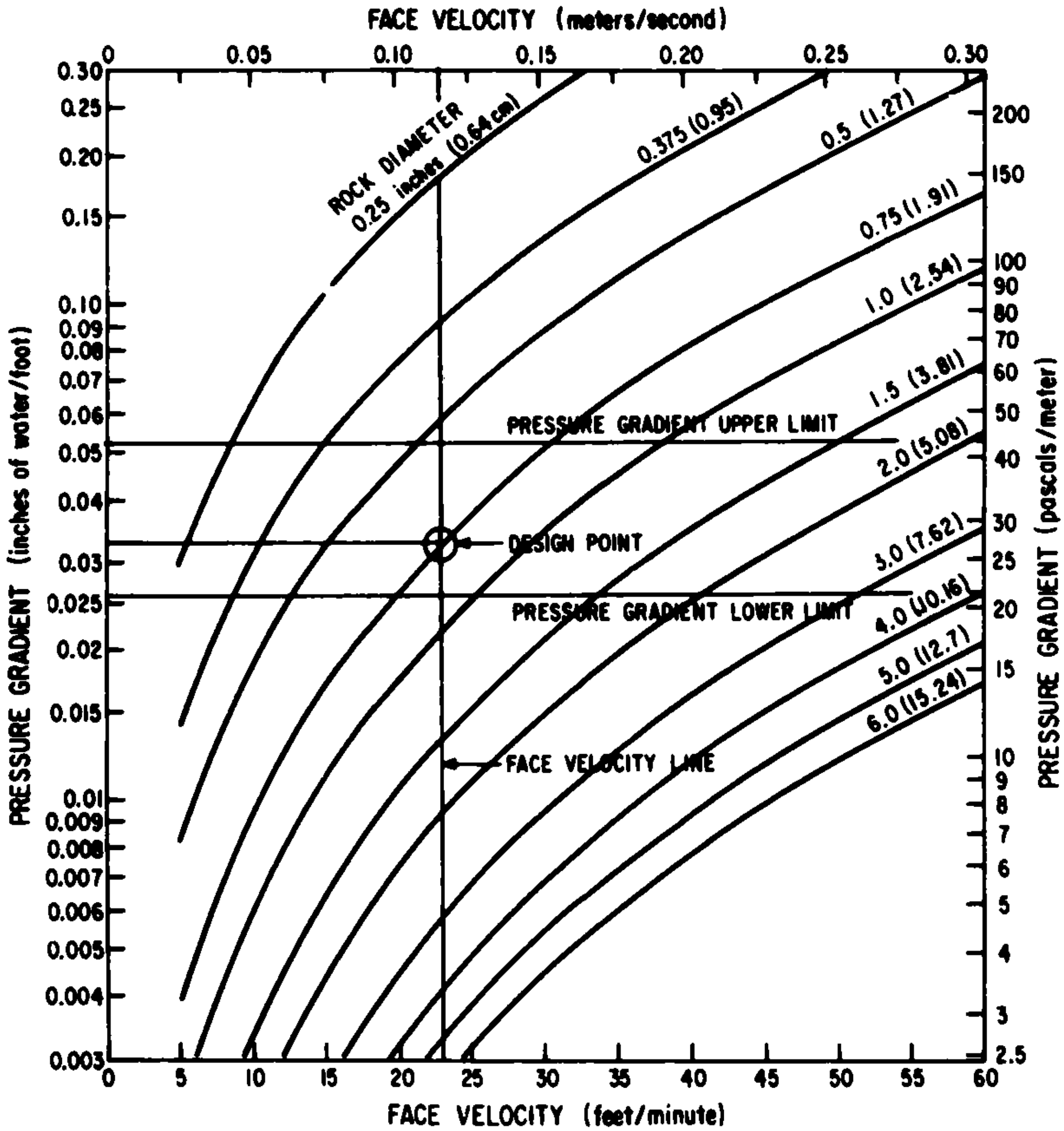

Figure 2-7. Rock Bed Performance Map for Design Example

crosses the curve representing the rock size. In our case, the design point is at a pressure gradient of 0.032 inches of water per foot (26.1 pascals per meter). Multiplying this value by the rock bed depth gives a total pressure drop of:

$$0.032 \times 6 = 0.19 \text{ inches of water } (47.3 \text{ Pa}).$$

This number will be used along with the other pressure drops in the system to size the blower.

H. Volume and Floor Loading

The total volume of rocks will be:

$$6 \text{ ft} \times 35.9 \text{ ft}^2 = 215 \text{ ft}^3 \ (6.09 \text{ m}^3).$$

If the rocks have a 30-percent void fraction, they will weigh:

$$0.7 \times 167 \frac{\text{lb}}{\text{ft}^3} \times 215 \text{ ft}^3 = 25{,}234 \text{ lb } (11{,}470 \text{ kg}),$$

or almost 13 tons. The loading on the floor will be:

$$\frac{25{,}134 \text{ lb}}{35.9 \text{ ft}^2} = 700 \text{ lb/ft}^2 \ (3{,}425 \text{ kg/m}^2).$$

Since most basement floors can support only 150 to 400 pounds per square foot (734 to 1,957 kilograms per square meter), we must have a structural engineer determine the load capacity and design reinforcements if necessary. Failure to do this may lead to a building code violation and structural damage to the building.

Note that the design point we have selected is not unique. If we calculate the maximum and minimum values of the face velocity by using the minimum and maximum values of the area, respectively, from Step C, we find that the face velocity can be anywhere between 16.0 and 24.0 feet per minute (0.081 to 0.122 meters per second). Lines corresponding to these values as well as the pressure gradient limits are shown in Figure 2-8. Any point within the allowable design area is a valid design point in that it falls within the limits set by the rule of thumb for volume and pressure drop corresponding to the rock bed depth we initially chose. We could change the allowable design area by using a different rock bed depth.

FAN SELECTION

When you select a fan for the system your main concern will be matching the fan's pumping characteristics to the system's pressure drop characteristics. The fan's diameter, type (axial flow or centrifugal), blade angles, and

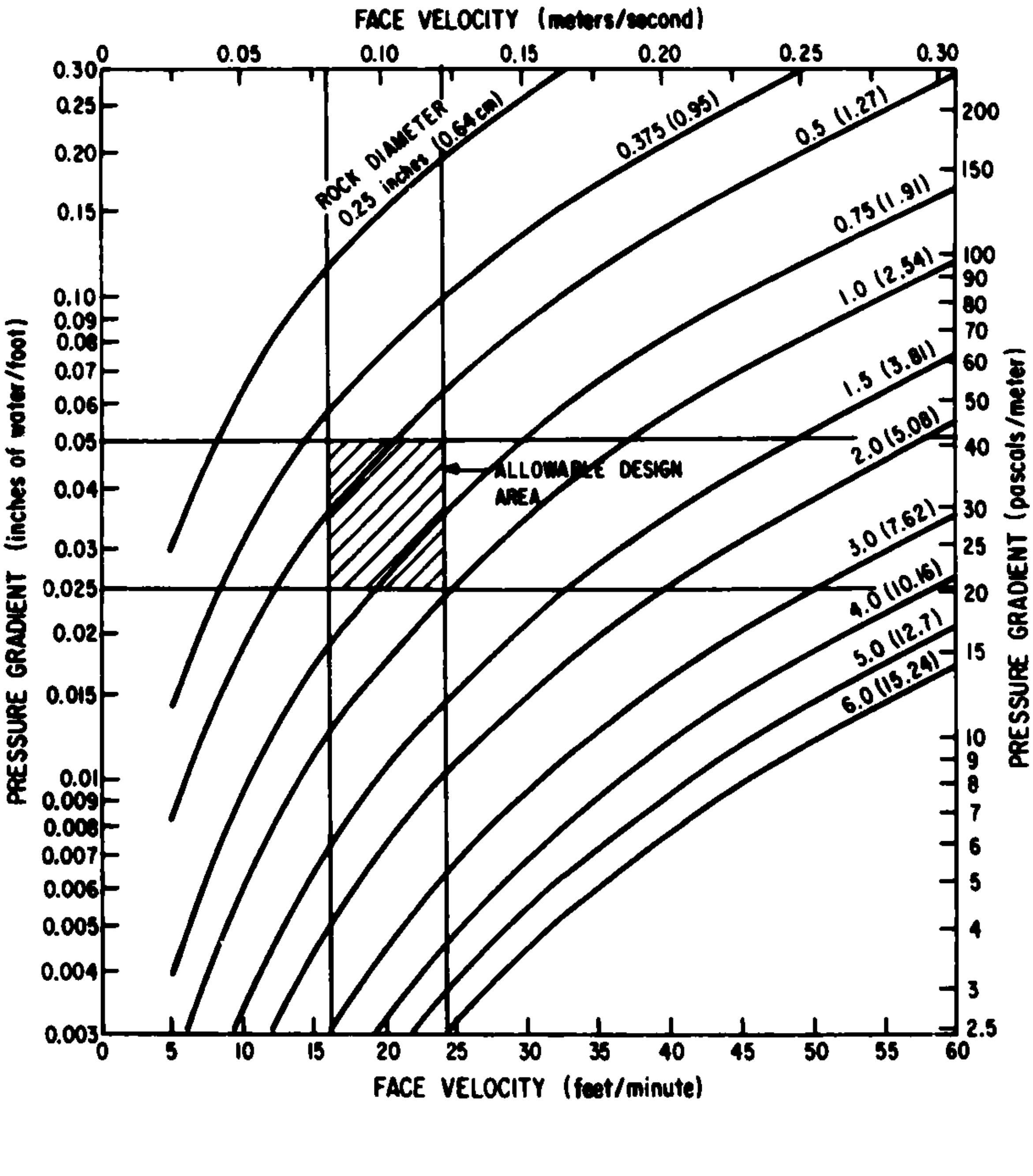

Figure 2-8. Allowable Design Area on the Rock Bed Performance Map

operating speed (RPM) all affect its pumping characteristics. Fan manufacturers publish data giving flow rate versus static pressure for their products. If the fan can operate at more than one speed, data for several speeds will be published. Typical curves for three different fan speeds are shown in Figure 2-9.

The designer must calculate the system's pressure drop at the operating flow rate and select a fan and operating speed that will give a static pressure equal to the system's pressure drop at the operating flow rate. (Figure 2-9 shows the operating flow rate.) For the fan data shown in the figure, the fan should operate at 1100 RPM to provide the operating flow rate required by the system.

To illustrate what will happen if the designer makes the wrong choice of fan or fan speed, a curve labeled "system pressure drop" has been drawn on Figure 2-9. If the fan is too large or the fan speed too fast, the system will operate at Point A. Both the air flow rate and the system pressure drop will be greater than planned for, and the fan will consume more electric power than a properly sized fan.

If the fan is too small or the fan speed too slow, the system will operate at Point B. The system pressure drop will be lower than it should be for normal operation; but, more importantly, the air flow rate will be lower than it should be. The low air flow rate will degrade the system's performance.

System Pressure Drops

The system pressure drop is the sum of several component pressure drops:

- Rock bed pressure drop.
- Collector pressure drop.
- Filter and damper pressure drops.
- Duct losses, including allowance for bends, branch ducts, and expansions or contractions.

We have already discussed rock bed pressure drop. Information about collector, filter, and damper pressure drops should be obtained from the various manufacturers. Detailed procedures for calculating duct losses can be found in the *ASHRAE Handbook of Fundamentals*, Chapter 25, "Air Duct Design Methods." The pressure drops caused by expansion from the air duct into the plenum of the rock bed and the corresponding contraction at the opposite end of the rock bed should not be overlooked. The method for calculating these pressure drops is also given in the *ASHRAE Handbook of Fundamentals*.

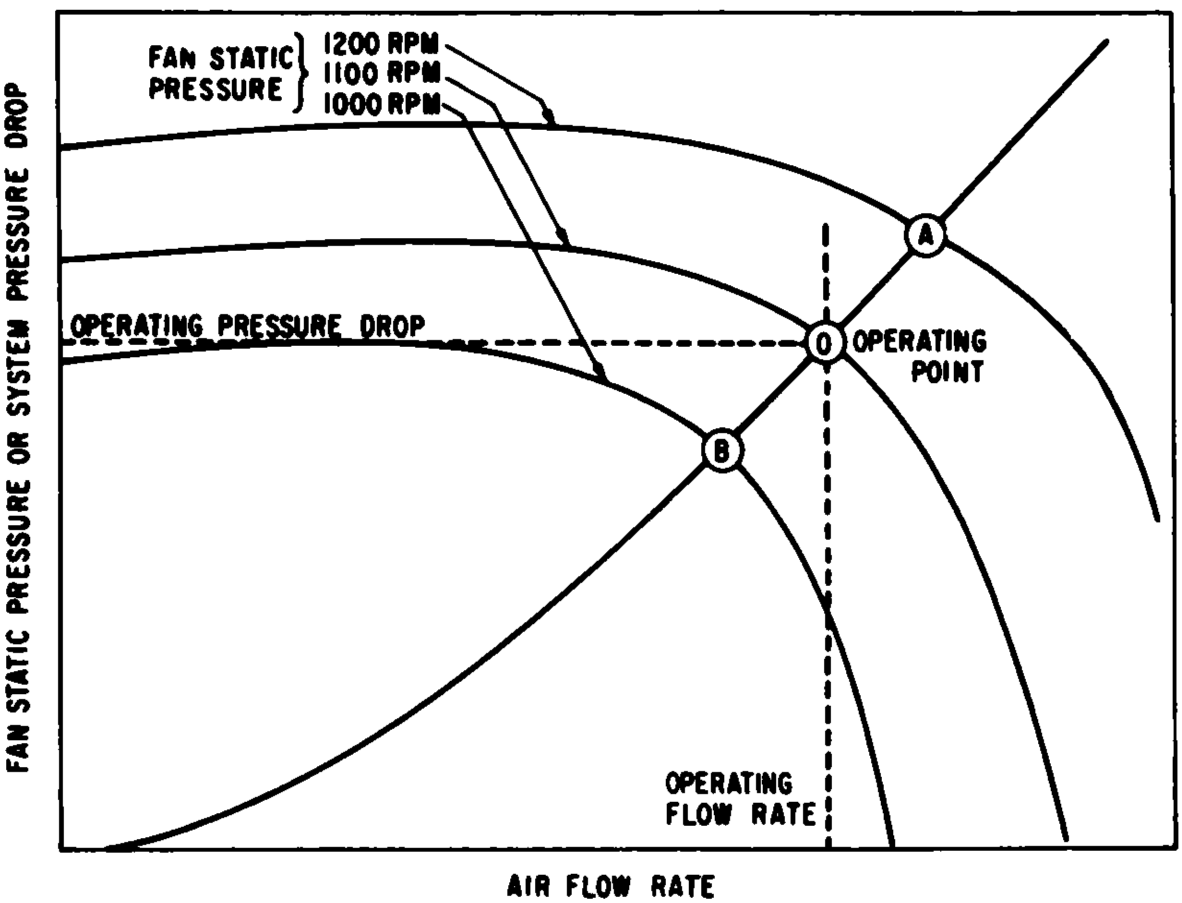

Figure 2-9. Typical Fan and System Characteristics

Power Requirements

Having selected the fan, the designer must choose a motor to power it. If the motor is too small, the fan will not be able to pump the necessary amount of air, and frequent motor burnouts will be likely. An oversized motor will draw only slightly more power than a motor of exactly the proper size (unless the motor is grossly oversized). Thus, it is better to select a slightly oversized motor than an undersized one. Belt drives must be rated for one and a half times the motor power and should include an adjustable sheave on the motor.

Many fan manufacturers publish the motor requirements with the fan performance curves, as shown in Figure 2-10a. If the manufacturer's data is presented in this way, select the larger of the two motors indicated by the dashed lines on either side of the operating point. For example, in Figure 2-10a dashed lines corresponding to 3/4 and 1 horsepower lie on either side of the operating point (Point O). Choose the 1 horsepower motor.

Sometimes the manufacturer presents fan efficiency, as shown in Figure 2-10b, instead of motor horsepower. A short calculation is required to determine the minimum motor power, P_{min}, in horsepower (kilowatts):

$$P_{min} = \frac{1.25\ q\ \Delta p}{c\eta} \qquad (2\text{-}1)$$

where

q = volumetric air flow rate in cubic feet per minute (cubic meters per second).

Δp = system pressure drop in inches of water (pascals).

η = fan efficiency in percent.

c = a unit conversion constant. Use c = 63.46 to convert cubic feet per minute, inches of water, and percent to horsepower; use c = 10 to convert cubic meters per second, pascals, and percent to kilowatts.

Fan Installation

The temperature of the air a fan must handle in a solar system can sometimes present a problem not often encountered in conventional heating systems. Study your system carefully and determine the maximum air temperature the fan will encounter. If that temperature exceeds 100°F (38°C), the fan must meet the following specifications.

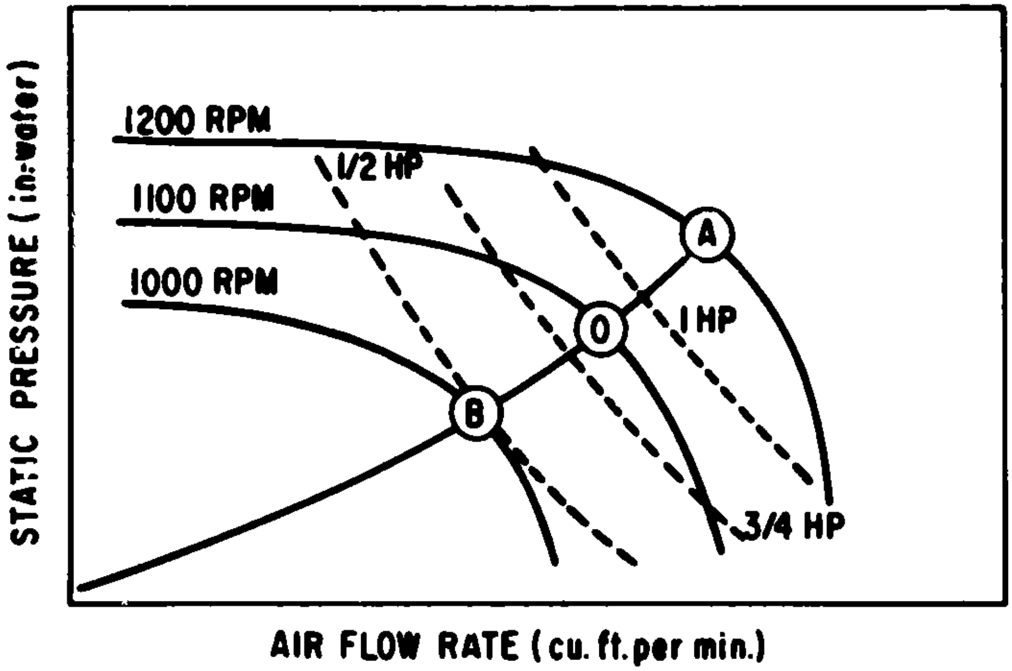

Figure 2-10a. Typical Fan Performance Curves Showing Motor Power Requirements

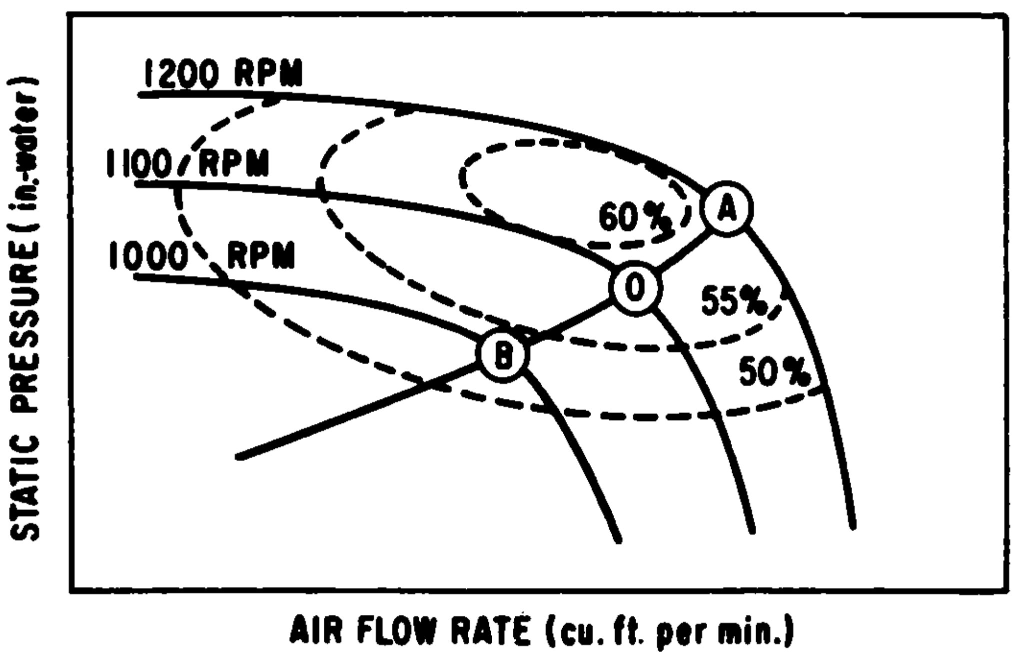

Figure 2-10b. Typical Fan Performance Curves Showing Fan Efficiency

- The fan bearings must be able to operate continuously at the maximum air temperature. Special bearings may be required. Alternatively, the bearings can be located outside the stream of hot air and shaft seals specified to minimize leakage.
- The motor and drive belts must be outside the stream of heated air or a Type B motor connected directly to the fan must be used.
- The fan should be selected on the basis of a modified operating point (Point M in Figure 2-11) instead of the previously defined operating point (Point O). To find the modified operating point multiply both the air flow rate and the fan static pressure at the operating point by the factor F.

$$F = \frac{T + T_o}{T_r + T_o} \qquad (2\text{-}2)$$

where

T = air temperature in the duct in degrees Fahrenheit (degrees Celsius).

T_o = conversion to absolute temperature scale. Use T_o = 460°F for Fahrenheit scale or T_o = 273°C for Celsius scale.

T_r = room temperature. Use T_r = 70°F or T_r = 20°C.

The modified operating point applies only to fan selection and should not be used for other calculations.

Since the major operating expense of an air-based system is the cost of electricity, it is important to install the fan so that it will operate at its highest efficiency. We recommend connecting the inlet of the fan to the ductwork with a straight section of duct at least five duct diameters long. The duct should match the diameter of the fan inlet so that there will not be a sudden contraction or expansion as the air enters the fan. If a transition from a rectangular duct to a round fan inlet must be made, the transition slope should not exceed 4 in 12 inches (18°). It is especially important to avoid using bends or elbows near the fan inlet, because the turbulence they cause reduces fan efficiency. Use similar care in designing the outlet ductwork.

OTHER COMPONENTS

Filters

Filters for the air-based solar system should be located at both the rock bin inlet and outlet where they are easily accessible for service or replacement. Filter mounts must minimize the amount of leakage bypassing the filter and leakage escaping the duct.

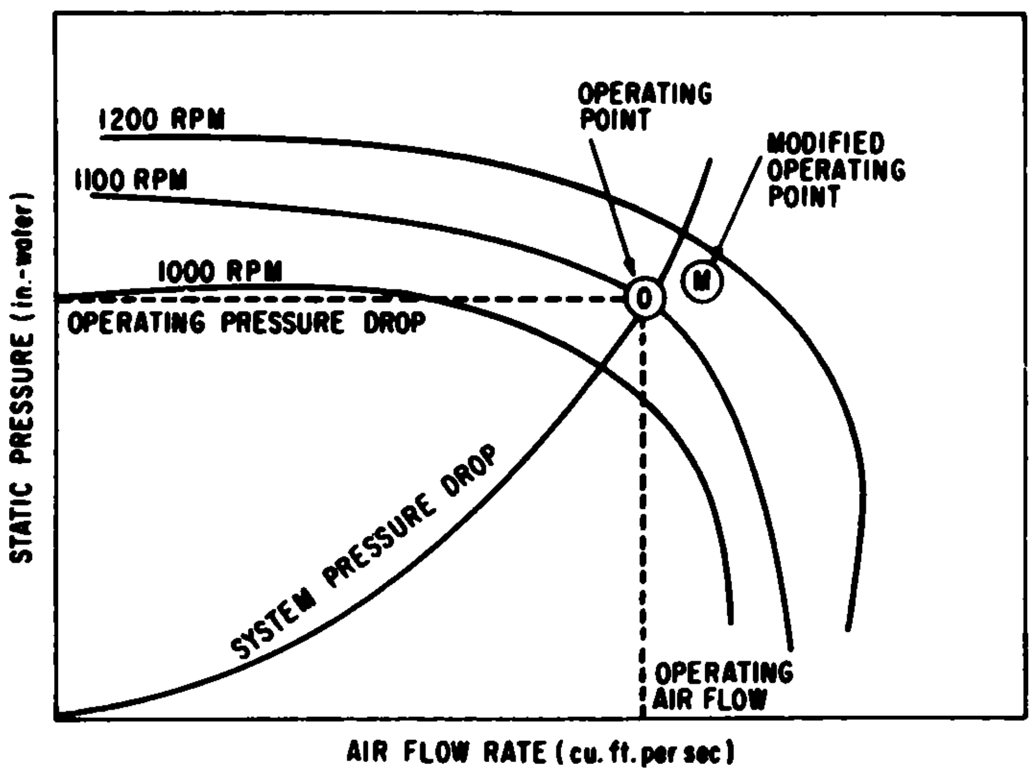

Figure 2-11. Modified Operating Point

The face velocity of the filter (air flow rate divided by filter area) should not exceed 300 feet per minute (1.5 meters per second). If the filter is larger than the cross-section of the duct, a transition to the full filter size, with a slope not exceeding 4 in 12 inches (18°), must be made.

Install a filter replacement indicating gauge at each filter. The gauge can be self-indicating or remote-indicating, but in either case the indicating part of the gauge must be located where it will be easy to see.

Dampers

Since dampers have proven to be the least reliable component in existing air-based systems, it is worthwhile to invest in high-quality dampers for your system. Automatically controlled dampers are essential to control the direction of air flow through the rock bed and to control the collector and space heating loops. A spring-loaded, motor-driven damper can provide fail-safe operation in case of a power failure. Backdraft dampers should be installed in the ducts between the collectors and the rock bed to prevent thermosyphoning at night--a major source of heat loss to the system. Choose a good backdraft damper with seals made of felt or other resilient material such as silicone rubber. The backdraft dampers must close by either gravity or springs and must remain tightly closed until the blower opens them.

Air Handlers

Air handlers, including a fan and as many as four motorized dampers in one package, are available. The main advantages of an air handling unit are:

- Air handlers require less installation labor than separate components.
- Air handlers specifically designed for solar applications can be purchased.

We recommend choosing an air handler in preference to individual components if an air handler that meets your system's flow rate and control requirements is available.

Temperature Sensors

Use the type of temperature sensor recommended by the controller manufacturer.

Two temperature sensors should be placed in the rock bed, one 6 inches (15 centimeters) below the top of the rocks and the other 6 inches (15 centimeters) above the bottom of the rocks. Low temperature readings by both sensors indicate that little heat remains in the rock bed, and the auxiliary heater must supply heat. High temperature readings by both sensors indicate that the rock bed is fully charged. A high temperature reading at the top and a low temperature reading at the bottom indicate that the rock bed is partially charged.

To avoid damaging temperature sensors and to make replacement simple, we recommend that the sensors be placed inside pipes that extend from outside the rock bin's inner wall to the center of the rock bed. The sensor leads are then run from the pipe out through the insulation to an electrical box for connection to the controller.

Air-to-Water Heat Exchanger

If the solar system is to provide domestic hot water, an air-to-water heat exchanger is usually installed in the collector return duct. Although it is possible to bury a water tank in the rock bed, using an air-to water heat exchanger in the duct offers the advantages of (1) good heat transfer characteristics and (2) the ability to bypass the rock bed during the summer while providing solar-heated water. (Bypassing the rock bed in summer will reduce the air conditioning load if the rock bed is located in an air conditioned part of the building.)

Install a low-leakage automatic damper between the heat exchanger and the collector to protect the heat exchanger from freezing. The damper should close automatically when the collector is not collecting. In several instances heat exchangers have frozen when cold air from the collector settled around the heat exchanger where there was no damper to separate them, or where the damper leaked. The preferred type of actuator uses a 24-volt motor to open the damper and a spring to close it, so that the heat exchanger will be protected even during a power failure.

Auxiliary Heating System

Every solar-heated building must have an auxiliary heating unit to furnish heat when the sun is not shining or the thermal storage device is depleted. The auxiliary heater must be able to supply 100 percent of the heating load without any assistance from the solar system. Such a unit should be located as close as possible to the storage device to minimize the length and cost of the connecting ducts. Almost all air-based solar systems use forced-air auxiliary heaters, which can be placed in the duct following the rock bed, as shown in Figure 2-12a, or in parallel with the rock bed, as shown in Figure 2-12b.

The configuration shown in Figure 2-12a has a minimum rock bed operating temperature of about 65 to 70°F (18 to 21°C). Studies have shown that people find circulating air at 70°F chilling. To ensure that the air will circulate at a comfortable temperature, the auxiliary heater is turned on whenever solar energy is unable to maintain a duct temperature of about 95°F (35°C) or more. While the auxiliary heater is operating, solar energy

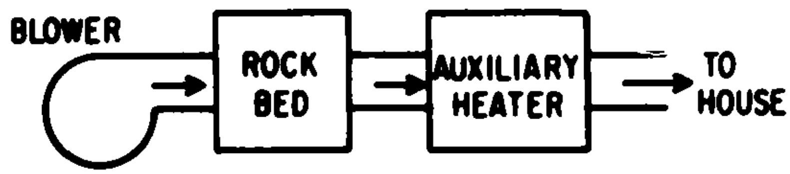

Figure 2-12a. Rock Bed in Series with Auxiliary Heater

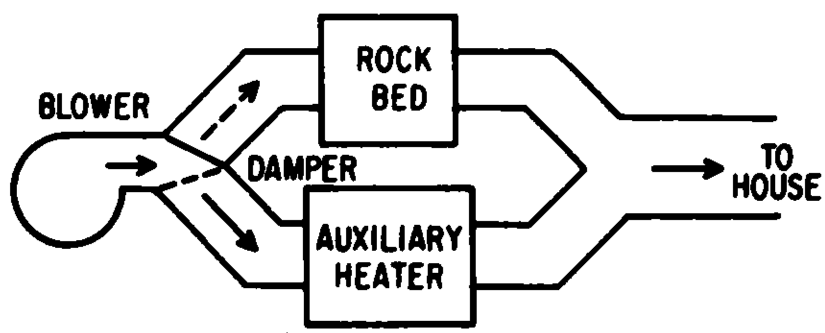

Figure 2-12b. Rock Bed in Parallel with Auxiliary Heater

preheats the air entering the auxiliary heater. This system is usually used with an electric heater. Because the solar-heated air must pass through the auxiliary furnace's heat exchanger, some solar heat may be lost up the flue of a gas or oil furnace. If the auxiliary furnace has an automatic flue damper to prevent this loss, the solar preheat arrangement is feasible with a gas or oil furnace.

The configuration shown in Figure 2-12b is usually used with gas or oil auxiliary heaters without flue dampers or for situations where there is not room to install the rock bed between the blower and the auxiliary heater. The auxiliary heater is turned on whenever solar energy cannot maintain a duct temperature of about 95°F (35°C) or more. If the rock bed cannot maintain a 95°F outlet temperature, a motorized damper switches the air flow to the auxiliary heater, and the auxiliary heater is turned on. Thus, if the rock bed and auxiliary heater are installed in parallel, the minimum usable rock bed temperature is 95°F.

In some solar heating installations the design air flow rate through the collectors does not match the residential space air flow requirements. For example, if the building is to be cooled as well as heated, the air flow requirements will normally be based on the cooling load and will be higher than the air flow required for heating. In areas where the design temperatures and the amount of available sunshine are low, it is possible that the solar collector's flow rate requirements will exceed the conventional heating system's flow specifications.

In those systems where the collector and the conventional heating system air flows are essentially balanced, the solar system blower can provide the total air movement. A second blower is necessary when an air imbalance exists or when constant air circulation through the building is required for ventilation or filtration. This second blower may be a component of a standard furnace, a roof-top unit, or an air handling system. When air movement requirements of the conventional system exceed those of the solar system, a duct must be installed to bypass the rock bed, and air balance between the two systems must be adjusted with a damper.

ROCK BED COSTS

The costs of rock beds vary widely from region to region. The cost of rocks at the quarry typically ranges from three to ten dollars per ton, although "ornamental rock" may cost as much as sixty dollars per ton. You will need to carefully specify the type of rocks you want, and you should inspect them before they are delivered. In locations distant from suitable quarries, delivery is a major expense.

The cost of the rock bin will, of course, depend upon the type that you build. Wooden containers are the least expensive, followed by cinder block and concrete. Figure 2-13 shows the relative cost per cubic foot of these three types of containers in one area of the United States. The relative

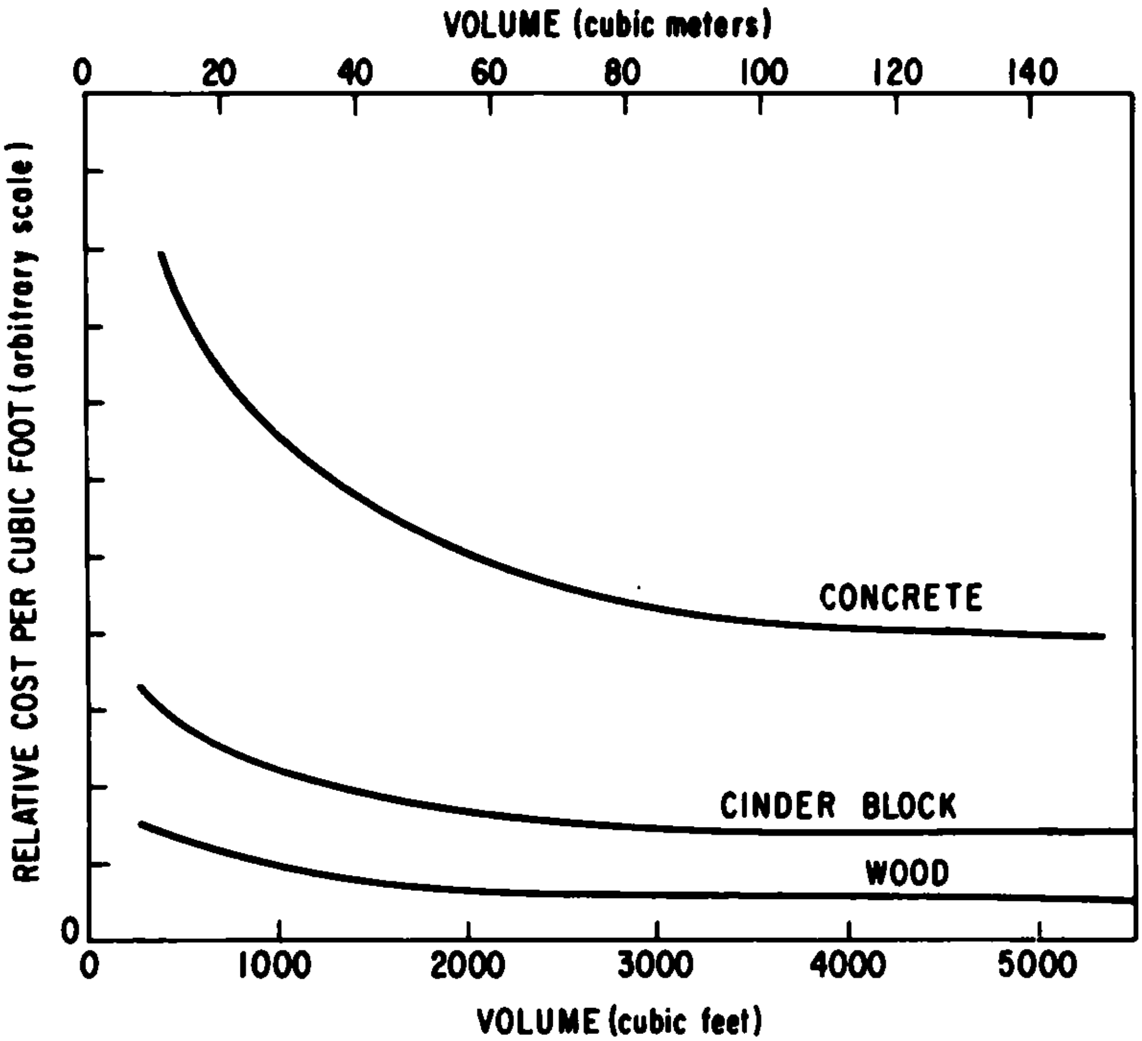

Figure 2-13. Relative Cost of Rock Bed Containers

Source: United States Energy Research and Development Administration, Division of Solar Energy. *Inter-Technology Corporation Technology Summary, Solar Heating and Cooling.* ERDA Report no. COO/2688-76-10, 1976.

costs are for complete rock beds--that is, they do not reflect such possible savings as using a basement corner as two walls of a concrete or cinder block rock bin. The cost per cubic foot for larger containers is less than for smaller ones, because the volume goes up faster than the surface area, and it is the surface area that determines the amount of material and labor involved in constructing the container.

OPERATION AND MAINTENANCE

Design for Maintainability

Maintenance must be considered as the system is being designed. Many solar systems fail or perform poorly because they cannot be properly maintained. For example, a component that cannot be easily replaced should last the lifetime of the system. Even better, the system should be redesigned so that the component can be repaired or replaced. Before installing any components the designer should consider how each component will be repaired or replaced and provide for working room around the components.

Simple systems are usually easier to maintain than complicated systems. The relative advantages of simple systems are:

- Initial cost is lower.
- Installation errors are less likely.
- There are fewer components to fail.
- Controls and operation are easier to understand.
- Defective components can be more easily found and replaced.

Answering three questions will help you decide whether the system is too complicated or too simple.

- If a feature were deleted from the system, how much energy collection would be lost?
- If a feature were deleted from the system, would a mode of failure be introduced?
- If a feature were deleted from the system, would human safety be degraded?

A system analysis method (such as f-Chart, SOLCOST, DOE-1, or TRNSYS) is required to estimate the extra amount of energy collection attributable to a particular feature. If the value of the extra energy collected over the life of the system is less than the cost of the feature, the feature cannot be justified economically. If, in addition, the answers to the second and third questions are "no," the feature should be deleted from the system.

Startup

Before applying insulation to the ducts and the rock bin, carefully inspect and test the system. Begin by checking all ducts, dampers, and wiring against the system drawings. Typical problems that might be encountered include:

- Inlet and outlet connections to rock bed, fans, heat exchanger, or collector reversed.
- Normally open automatic dampers installed in place of normally closed automatic dampers.
- Fan rotation reversed.

Leak detection is more difficult in air-based systems than in liquid-based systems. Check your system for leaks before installing the insulation by disconnecting the ducts going to the collectors and the building and sealing the ends of these ducts. Connect the blower so that it will pressurize the system and then introduce smoke from a nontoxic smoke candle into the blower inlet. Carefully inspect the rock bin and all ducts and connections for smoke leaks.

If you find a leak, try to repair it permanently before applying duct tape and insulation. Leaks are most likely to occur at the seams of the rock bin, at joints between duct sections, and at connections between ducts and other equipment.

This is a good time to test the system in all operating modes to ensure that it functions as intended. Since systems vary greatly in their operating modes, only general guidelines can be given here. Most controller manufacturers make testing devices and publish data on how to use the testers. You may need a set of jumper wires to operate the system in its various modes. CAUTION, DANGEROUS VOLTAGE MAY BE PRESENT AT CONTROLLER TERMINALS. Flows in ducts can usually be determined by feeling a temperature change and by observing temperature changes with the temperature sensors installed in the ducts, rock bed, and collectors.

Install the insulation on the ducts, rock bed, and other components. As you install the insulation you should label the ducts according to air flow direction. Tag the dampers, fans, filters, and so on to correspond with the numbers on the system drawings. Automatically controlled two-way dampers should be labelled "normally open" or "normally closed," and the legs of automatically controlled three-way dampers should be labelled "common," "normally open," and "normally closed."

Operate the system in its heating, noncollecting mode to fully discharge the rock bed. With the rock bed discharged, its temperature sensors should indicate low temperatures. Change to the collecting, nonheating mode to charge the rock bed. As it charges, its top temperature sensor should indicate a high temperature, its bottom temperature sensor a low temperature. When the rock bed is fully charged, both temperature sensors should indicate high temperatures. Replace defective sensors.

Inspect the air filters. If they are excessively dirty, find the cause and repair it before you install clean air filters. The system is now ready for operation.

Periodic Inspection and Maintenance

The following tasks should be performed monthly during the heating season or at intervals specified by component manufacturers.

- Replace air filters.
- Inspect fan belts.
- Lubricate motor and fan bearings.

Before each heating season, inspect the system for leaks and check fans, dampers, sensors, and controllers for proper function.

Owner's Manual

The contractor should provide the owner with a manual that includes the following:

- A summary description of how to operate the controls.
- Instructions on how to do periodic maintenance.
- A detailed description of how the system operates.
- Schematics of ducting and wiring with labels that correspond to the labels attached to the hardware.
- Component and system warranties.

SYMBOLS USED IN CHAPTER 2

Main Symbols

c	unit conversion factor
F	correction factor
P	power in horsepower (kilowatts)
q	volumetric flow rate in cubic feet per minute
T	temperature in degrees Fahrenheit (degrees Celsius)
ΔT	system pressure drop in inches of water (pascals)
η	fan efficiency in percent

Subscripts

min	a minimum quantity
o	conversion to absolute scale
r	room temperature

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CHAPTER 3
THERMAL ENERGY STORAGE IN LIQUID-BASED SYSTEMS

INTRODUCTION

Before selecting a particular type of storage tank, you must consider a number of variables:

- Size and shape.
- Material.
- Location.
- Insulation.
- Corrosion.
- Cost.
- Leak protection.
- Protective coating.
- Installation.
- Pressure and temperature limits.

Each individual liquid-based storage system has different requirements. The temperatures listed below are subject to variation and are intended only as a general guide. Direct space heating usually requires storage temperatures no higher than 160°F (71°C), although some hydronic heating systems require higher temperatures. Most direct space heating systems use unpressurized tanks. Solar-assisted heat pump systems typically operate at less than 100°F (38°C), which dramatically reduces the amount of insulation required on the tank. Absorption air conditioning systems use hot storage at temperatures above 170°F (77°C) or cold storage at temperatures below 55°F (13°C). A pressure vessel may be required for the hot storage.

Storage for load management may resemble storage for direct space heating systems if the tank is heated electrically at off-peak rates. If a load management system uses heat pumps to move heat from one part of the building to another or to air condition during the day and heat at night, the temperature requirements will be similar to the temperature requirements for a solar-assisted heat pump.

Direct heating of potable water usually requires temperatures of less than 140°F (60°C) and a pressurized tank. Preheating the water usually requires temperatures under 120°F (49°C). The preheat tank may be pressurized or unpressurized, depending on the system configuration. It is not unusual for domestic hot water systems to operate at higher temperatures than those listed here.

Various tank materials that can meet these temperature and pressure requirements are available. Use tested materials, such as steel, fiberglass, concrete, or wood with plastic lining, to avoid the risks inherent in using materials that have not been proven. Advantages and disadvantages of each type of tank are shown in Table 3-1. All types of tanks can be purchased or constructed in any size likely to be used in storage systems.

Normally, only one tank is used for storage in space heating systems. Where the properly sized tank is unavailable, or where space restrictions dictate the use of smaller tanks in place of a larger one, two or more

Table 3-1. Advantages and Disadvantages of Tank Types

ADVANTAGES

Steel Tank	Fiberglass Tank	Concrete Tank	Wooden Tank with Liner
Steel tanks can be designed to withstand pressure.	Factory-insulated tanks are available.	Cost is moderate.	Cost is low.
Much field experience is available.	Considerable field experience is available.	Concrete tanks may be cast in place or may be precast.	Indoor installation is easy.
Connections to plumbing are easy to make.	Some tanks are designed specifically for solar energy storage.		
Some steel tanks are designed specifically for solar energy storage.	Fiberglass does not rust or corrode.		

DISADVANTAGES

Steel Tank	Fiberglass Tank	Concrete Tank	Wooden Tank with Liner
Complete tanks are difficult to install indoors.	Maximum temperature is limited, even with special resins.	Careful design is required to avoid cracks, leaks, and excessive cost.	Maximum temperature is limited.
Steel tanks are subject to rust and corrosion.	Fiberglass tanks are relatively expensive.	Concrete tanks must not be pressurized.	Wooden tanks must not be pressurized.
Steel tanks are relatively expensive.	Complete tanks are difficult to install indoors.	Connections to plumbing are difficult to make leaktight.	Wooden tanks are not suitable for underground installation.
	Fiberglass tanks must not be pressurized.		

storage tanks can be used. Two small tanks cost more than a large one, however, and a multiple tank system requires more insulation because it exposes a larger surface area than a single tank.

TANK TYPES

Steel Tanks

The principal advantages of steel tanks are the relative ease of fabricating them to ASME Pressure Vessel Code requirements, the ease of attaching pipes and fittings, and the amount of experience available with steel tanks. The main problem with steel tanks is corrosion, although the difficulty of installing them in enclosed buildings and their cost are also problems.

Table 3-2. Corrosion Inhibitors

Generalized Categories	Metals Protected	Specific Compounds	Acute Oral Toxicity[a]
Nitrate Salts	Iron, Aluminum	Lithium Nitrate, Sodium Nitrate	High
Sulfate Salts	All Metals	Sodium Sulfate	?
Sulfite Salts	All Metals	Sodium Sulfite	Mod
Borate Salts	Iron and Iron Alloys	Sodium Borate	Mod
Phosphate Salts	Iron, Aluminum	Potassium Hydrogen Phosphate, Trisodium Phosphate	Mod Low
Silicate Salts	Copper, Iron, Aluminum	Sodium Metasilicate	Mod
Triazoles	Primarily Cuprous Metals	Benzoltriazole	?
Benzoate Salts	Iron	Sodium Benzoate	Mod

[a] Source: N. Irving Sax. *Dangerous Properties of Industrial Materials.* Van Nostrand Reinhold Company, New York, 1979.

Four types of corrosion present the greatest threat to steel tanks: electrochemical corrosion, oxidation (rusting), galvanic corrosion, and pitting. Six methods of protection, which can be used singly or in combination, are sealing the system, adding chemical corrosion inhibitors (see Table 3-2), using protective coatings or liners, using cathodic protection, increasing the metal's thickness, and using noncorroding alloys. Since corrosion rates double with each 20°F (10°C) increase in temperature, limiting the maximum temperature will prolong the tank's life.

Electrochemical Corrosion

Electrochemical corrosion of a metal is mainly governed by two conditions: the pH of the liquid (electrolyte) and the electric potential of the metal. The pH is a measure of acidity or alkalinity of the liquid; an acid solution has a pH lower than 7, an alkali has a pH higher than 7, and a neutral solution has a pH of 7. The electric potential of the metal is usually given relative to that of hydrogen, which is always present in water.

Marcel Pourbaix has produced diagrams showing corrosion conditions for various metals as functions of pH and electric potential. Figure 3-1 is the Pourbaix diagram for iron at 77°F (25°C). In addition to corrosion conditions for the metal, the figure shows two lines, a and b. Below Line a, decomposition of water and evolution of hydrogen is possible; above Line b, decomposition of water and evolution of oxygen is possible.

Under normal conditions the pH is 7, and iron has an electric potential of -0.44 volts relative to hydrogen. This state is shown as Point X in Figure 3-1. As you can see, Point X is in a region where corrosion can take place.

Three methods of preventing corrosion can move Point X. Cathodic protection can move it down, alkalinization can move it to the right, and anodic protection can move it up.

The most reliable method is cathodic protection, which can be used effectively to protect either the inside or the outside of the tank. The steel tank is given a negative electric potential by being connected either to a source of direct current or to a bar of a more reactive metal.

If a source of direct current is used, the tank must be connected to the negative (-) terminal, and an electrode in contact with the water but insulated from the tank must be connected to the positive (+) terminal. Pourbaix recommends using the following voltages:

- For pH less than 10, $E = -0.62$ volts.
- For pH between 10 and 13, $E = -0.08 - pH \times 0.059$ volts.

The electrode should be an inert material such as carbon. This type of cathodic protection has the disadvantage of requiring electrical equipment and a power source that must be checked periodically.

A more common method of cathodic protection is using a sacrificial anode. This method has the advantage of not requiring an external power source. The anode must be submerged in the water and electrically connected to the tank. Since protection ends when the anode has completely dissolved, the anode should be inspected annually and replaced if necessary.

In choosing a sacrificial anode, you must choose a metal that is more reactive than the steel tank as shown in Table 3-3. The most commonly used anodes are made of magnesium, aluminum, or zinc. We recommend choosing a magnesium bar as the anode for most storage tanks. Aluminum has a tendency to form a protective coating over itself, reducing the effectiveness of the protection. Zinc, whether as a metal bar, as galvanizing, or as an additive to epoxy or paint, is not recommended for most thermal energy storage applications. At temperatures above approximately 155°F (68°C), the roles of zinc and steel reverse, so that the steel is sacrificed instead of being protected. Zinc can provide effective protection if the maximum allowable tank temperature is kept below about 140°F (60°C), however.

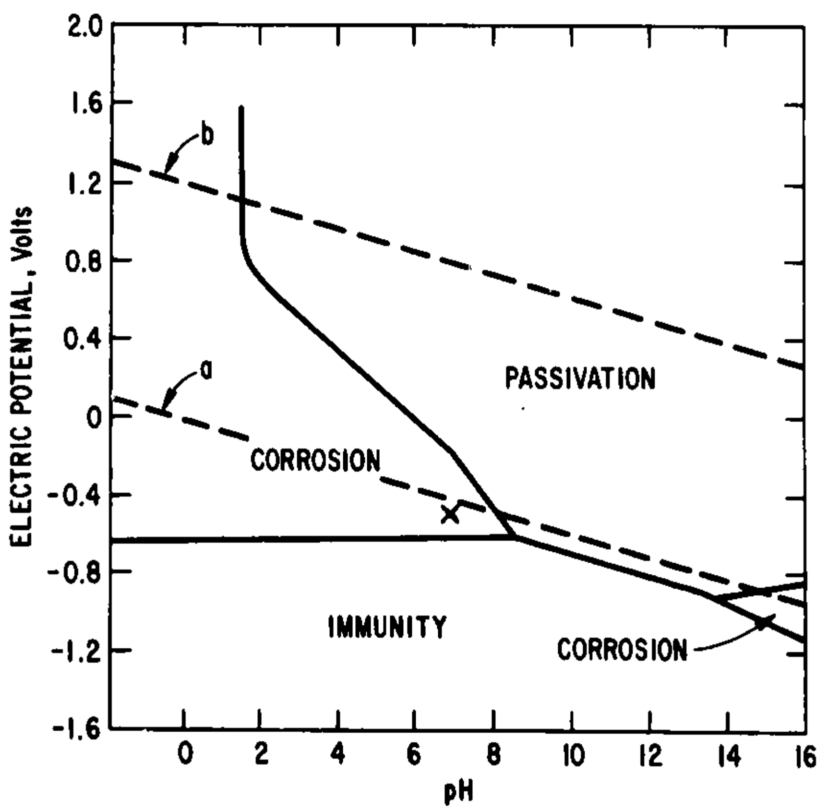

Figure 3-1. Pourbaix Diagram for Iron at 77°F (25°C)

Adapted from Marcel Pourbaix, translated from the French by James A Franklin. *Atlas of Electrochemical Equilibria in Aqueous Solutions*. Pergamon Press, 1966.

Either method of cathodic protection works particularly well if the tank is lined with epoxy, glass, or hydraulic stone. The coating protects most of the steel and leaves only a few small uncoated areas. Since the current required for cathodic protection is proportional to the area of the exposed steel, the coating allows a smaller current source to be used or allows the anode to last longer.

In most situations, cathodic protection should not be combined with strong alkalinization. In one case the alkalinization may cause a protective coating to form over the anode, but in another it may cause rapid consumption of the anode. In both cases the effectiveness of the protection will be decreased.

Table 3-3. Electromotive Force Series of Metals

MOST REACTIVE	Magnesium
	Beryllium
	Aluminum
	Manganese
	Zinc
	Chromium
	Iron
	Cadmium
	Nickel
	Tin
	Lead
	Hydrogen
	Copper
	Mercury
	Silver
	Palladium
	Platinum
LEAST REACTIVE	Gold

Source: Theodore Baumeister and Lionel S. Marks, editors. *Standard Handbook for Mechanical Engineers*. McGraw-Hill, seventh edition 1967.

The relative positions of the metals depend on the electrolyte solution in which they are immersed, the temperature, and the surface condition of the metals.

Steel is relatively inactive in an alkaline environment; adding lime, caustic soda, or trisodium phosphate to maintain a pH of 9.5-12 will protect steel from electrochemical corrosion. Increasing the pH of the water also moves iron into the region of passivation, in which a protective film forms over its surface. The pH of the water must be tested periodically to maintain the required alkalinity. Alkalinization cannot ordinarily be used to protect domestic hot water tanks, but it works well for vented or sealed tanks in other applications. Do not use alkalinization if aluminum parts will be exposed to the water, since aluminum corrodes quickly in a alkaline environment.

Anodic protection is rarely used, because it does not stop corrosion completely, because increased corrosion rates can occur if the potential of the steel is raised too high, and because imperfections in the passivated surface can lead to pit corrosion. For these reasons, we do not recommend anodic protection.

Oxidation

Oxygen can enter a tank in two ways: It can be dissolved in water that enters the tank, or it can enter through the tank's air vent. Besides causing rust, oxygen tends to catalyze other types of corrosion.

One method of stopping oxidation is to seal the system so that no air or water can enter it. The oxygen initially present in the system will quickly be removed as it reacts with parts of the system. Although minor rusting may occur at that time, no further rusting can take place after the oxygen has reacted. Sealing the system requires that all of the components be able to withstand the pressure generated when the system is heated. You must design the tank to the American Society of Mechanical Engineers' (ASME) Pressure Vessel Code or local code requirements and provide it with a pressure relief valve. With some system configurations, an expansion tank may also be required. The main disadvantage of a sealed system is its cost; but if the system must operate close to or above the normal boiling point, sealing it provides effective protection from oxidation.

Oxygen dissoved in water flows continuously into domestic hot water tanks. Thus, even though the tank is pressurized, oxygen cannot be excluded from it. Linings of glass or hydraulic stone limit the contact of steel and oxygen, thus limiting the extent of rusting. In tanks larger than 120 gallons (454 liters), glass or hydraulic stone can be expensive. For these tanks, we recommend four interior coatings of baked-on phenolic epoxy.

Vented tanks are exposed to oxygen from the air that enters the vent. We recommend four coats of baked-on phenolic epoxy to protect the tank interior. If a baked-on treatment is unavailable, four coats of two-part epoxy can be specified, although it is less effective than the baked-on coating. Sodium sulfite added to the water will scavenge oxygen; it must be periodically tested and replenished.

If the tank is to be located underground, we recommend two coats of coal-tar epoxy on the outside. For indoor or aboveground locations, a coat of primer followed by two coats of enamel provides adequate outer protection.

Galvanic Corrosion

Galvanic corrosion occurs when dissimilar metals in an electrolyte are in electrical contact with each other. This often occurs when a copper fitting is screwed into a steel tank. The water in the tank serves as the electrolyte. The more reactive metal (steel) dissolves in the vicinity of the less reactive metal (copper), and the usual result is a leak in the system.

Galvanic corrosion can be minimized by electrically insulating dissimilar metals from each other. Use dielectric bushings to connect pipes to tanks, and gaskets or pads to insulate other components. Be careful to eliminate other electrical connections between dissimilar metals. A common ground, for example, would defeat the effort to insulate dissimilar metals from each other. Use a volt-ohm meter (VOM) to measure the electrical resistance between components before the system is filled with water. A resistance of more than 1000 ohms indicates adequate insulation, but a resistance of less than 100 ohms means that an electrical connection still exists. Because the dissimilar metals plus the electrolyte form a battery, testing after the system has been filled with water will give false resistance measurements.

The dissimilar metal combinations encountered most frequently in solar systems are iron-copper (or brass), aluminum-iron, aluminum-copper (or brass), and zinc-iron. The more reactive metal is listed first in each case except for the zinc-iron combination. Zinc is more reactive than iron below about 155°F (68°C) but less reactive above that temperature.

Pitting

Pitting is a localized form of corrosion in which small-diameter holes penetrate the base metal. One type of pitting is believed to be caused by ions or particles of a less reactive metal plating onto a more reactive metal. Localized galvanic corrosion produces a pit that can quickly penetrate the more reactive metal. In a storage system, a typical source of the less reactive metal ions is a copper pipe. The copper ions circulate in the water until they plate out on the steel tank and cause a pit.

Another type of pit corrosion is believed to be caused by small imperfections in a passivated surface. As the pit grows, the chemistry of the solution changes locally so that the passivating agents become deficient within the pit, accelerating pit growth. A similar type of corrosion occurs in crevices and screw threads. Cathodic protection is more effective against pitting than alkalinization or anodic protection. The presence of some ions, especially chloride ions, tends to encourage this form of pitting.

Other Methods of Protection

Occasionally, the thickness of the walls in steel tanks is increased for corrosion protection. Although the use of thicker metal does not stop corrosion, it does increase the length of time before the corrosion causes system failure. Use of thicker metal is often combined with alkalinization.

Stainless steel alloys are rarely encountered in solar energy storage systems, because of their high first cost. Stainless steels form a passivated surface condition that protects the metal from corrosion. Cathodic protection will destroy that surface condition and should not be used with stainless steel.

Recommendations for Steel Tanks

We recommend the following for most steel tanks used in space heating applications:

- Use four coats of baked-on phenolic epoxy on the inside of the tank.
- Use a magnesium bar as cathodic protection.
- Electrically insulate dissimilar metals, except the magnesium anode, with dielectric bushings, gaskets, or pads.
- Use sodium sulfite to scavenge oxygen.
- Do not use chromate-type corrosion inhibitors. They are highly toxic, carcinogenic, cause damage to a common type of pump seal, and are difficult to dispose of properly. Since chromates act by passivating the steel surface, their effectiveness is much reduced when combined with cathodic protection.
- If possible, limit the maximum tank temperature to 160°F (71°C) or less.
- Protect the outside of a buried tank with two coats of coal-tar epoxy and a magnesium anode. Use a coat of primer and two coats of enamel to protect the outside of aboveground tanks.
- If the tank will be pressurized, it must comply with Section VIII of the ASME Boiler and Pressure Vessel Code or local codes.
- Do not install large steel tanks in basements, crawl spaces, or other locations where building modifications would be necessary to replace them.

Fiberglass-Reinforced Plastic Tanks

Both factory-insulated and on-site-insulated fiberglass-reinforced plastic (FRP) tanks are available and have been successfully used in solar energy installations. The main advantage of FRP tanks is that they do not corrode.

We recommend that you use factory-insulated FRP tanks, which are designed specifically for solar energy storage and are available in convenient sizes and shapes. A typical factory-insulated FRP tank consists of an inner FRP shell covered with 2 to 4 inches (5 to 10 centimeters) of urethane insulation. An outer FRP shell protects the insulation. Factory-insulated FRP tanks can be used outdoors above or below grade or in a garage. Do not install an FRP tank in a location where major building modifications would be necessary to replace it.

Installation of on-site-insulated FRP tanks requires much more care than that of factory-insulated FRP tanks. Since the fiberglass is thin, the tanks must be protected from punctures and must be carefully supported to prevent rupture.

The extra labor required to insulate and install an on-site-insulated tank may make a factory-insulated tank less expensive. Some installations, however, can benefit from the greater variety of sizes and shapes that are available in on-site-insulated tanks.

Nearly all FRP tanks have two limitations.

- They must not be pressurized or subjected to a vacuum inside the tank unless they are specifically designed for it. A vent will ensure that the tank is not subjected to these conditions.
- Their temperatures must never exceed the limit specified by the manufacturer. Exceeding the limit will void the warranty and damage the tank. Since the temperature limit is nearly always below the boiling point, the system controller must stop heat addition to the tank before the manufacturer's temperature limit is reached. Adjust the cutoff point on the controller to 5°F (3°C) below the temperature limitation on the tank. Since many controllers do not have a provision for limiting the tank temperature, you must select the controller carefully.

The temperature limitation is determined by the type of resin used to make the tank. Ordinary polyester resins have a limitation of 160°F (71°C) -- suitable only for low-temperature tanks. With premium quality resins, the temperature limitation can be raised to 180-200°F (82-93°C). Consult the tank manufacturer for details.

Before accepting delivery of an FRP tank you should inspect it carefully. Do not accept delivery of a tank that has been dropped or shows any signs of physical damage. Before installing the tank, inspect the gel coat on its inner surface. If the gel coat is cracked or if fibers are exposed, hot water can break the bond between the glass fibers and the resin, which will lead to premature tank failure.

A sample specification for FRP tanks is shown in Appendix I.

Concrete Tanks

Concrete tanks for solar energy storage can be divided into two categories: cast-in-place tanks and precast tanks, including tanks designed primarily to be used as septic tanks and utility vaults. Major advantages of concrete tanks are that they are relatively inexpensive as long as their shape is kept simple, the mass of concrete becomes part of the storage system, and concrete is a readily available construction material. Concrete also has considerable resistance to underground loads. Because concrete can be cast in almost any shape, it is a good material for retrofit installations. Concrete is also fireproof and corrosion resistant.

Concrete does have several disadvantages, however. It is subject to capillary action, so water can seep through cracks and joints unless the tank is lined. Leakproof connections through the tank walls are often difficult to make. Plaster coatings, which are adequate for cisterns, have a tendency to crack with the fluctuating temperatures of thermal storage materials. Seepage that can be tolerated in a cistern or swimming pool will degrade the insulation around a tank. We recommend using either a spray-on butyl rubber coating 30 to 50 mils (0.75 to 1.25 millimeters) thick on the inside of the tank or a replaceable liner of the type used for wooden tanks.

The weight of a concrete tank may be either an advantage or a disadvantage, depending on the situation. Special footings may be required to carry the weight, particularly if the tank is close to a load-bearing wall. It is possible to design the tank into a corner of a basement wall if the foundation and wall are designed to carry the added load. This technique is more amenable to new construction than to retrofitting.

The weight of concrete is an advantage in underground storage containers, since it can help prevent the tank from being buoyed out of the ground by high groundwater.

Do not install precast concrete tanks in locations where major building modifications would be required to install or replace them. Cast-in-place tanks can be installed in some locations that do not permit installation of precast tanks.

Detailed specifications for concrete tanks are given in Appendix H.

Wooden or Multicomponent Tanks with Plastic Liners

Wooden or multicomponent tanks can be purchased as kits or can be custom designed. Their main advantages are low cost and easy indoor installation. The disadvantages are that the plastic liners have temperature limitations and the tanks are usually intended for indoor locations only.

One available kit makes a vinyl-lined, 2000-gallon (7600-liter) cylindrical tank.[1] According to the manufacturer's instructions, the tank, made of 3/8-inch CDX plywood and reinforced with steel bands, can be installed with simple hand tools. The kit includes insulation for the bottom, sides, and cover, as well as a 1-inch PVC compression fitting. The maximum allowable temperature inside the tank is 160°F (71°F).

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[1] Acorn Structures, Inc., Concord, Massachusetts 01742.

Another type of kit uses lock-together panels of 4-inch-thick (10-centimeter-thick) urethane foam sandwiched between steel facings.[2] The plastic liner is rated for 180°F (82°C) continuous service, and an aluminum roof is available for outdoor containers. Sizes from 500 to 2000 gallons (1900 to 7600 liters) are available.

You can make your own wooden tank by modifying the rock bin described in Chapter 2 and Appendix F. The gypsum board or sheet metal lining, tie rods, caulking, and openings for air ducts can be deleted from the design, but otherwise construction of a water tank is similar to construction of a rock bin. Custom fabricators of plastic linings can be found in most major U.S. cities, since the technology is similar to that used for water beds and swimming pools. Consult the yellow pages of your telephone book or the *Thomas Register* for names of fabricators.

Liners should be about 1 to 3 percent larger than the inside of the container to avoid the possibility of stressing the seams. With some types of plastic, it may be difficult to fabricate corners; but they can be folded from a flat sheet, if necessary. When installing the liner, you must be careful to remove all sharp edges, burrs, splinters, and debris that might puncture it. Avoid working inside the tank with the liner in place; if you must work there, remove shoes, belt buckles, tools, and other objects that could puncture the liner. Properties of several plastics are listed below.

Polyvinyl Chloride (PVC)

PVC is one of the least expensive and easiest liner materials to work with, and there is considerable experience with it in solar systems, industrial hot water processes, swimming pools, and water beds. Seams can be made by dielectric sealing, a more reliable process than heat sealing or cementing. Repairs can be made with patches and adhesives.

Specify a material thickness in the range of 30 to 60 mils (0.75 to 150 millimeters), and make liners slightly oversized to avoid stressing the seams. Maximum tank temperature should be limited to 160°F (71°C), although a few special compositions can tolerate a water temperature of 180°F (82°C). Lifetime varies from 6 to 15 years, with about 8 years being typical. Failure is finally caused by leaching of plasticizers. When this occurs, the plastic becomes brittle and cracks appear, usually at the corners.

Ethylene Propylene Diene (EPDM)

EPDM is a rubber-like material that can withstand boiling water. It is more expensive than PVC and more difficult to fabricate, since dielectric sealing cannot be used. You may have difficulty finding a fabricator who will make corners, although flat EPDM sheets are available. EPDM can be patched with adhesives, but patching is more difficult than for PVC. You should specify a thickness in the 30 to 60 mil (0.75 to 1.50 millimeter) range.

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[2] Bally Case and Cooler, Inc., Bally, Pennsylvania 19503.

Butyl Rubber

Butyl rubber is a reasonably durable material that is less expensive than EPDM but more expensive than PVC. Seams can be vulcanized, but the process is more difficult than dielectric sealing. Butyl rubber can be patched with adhesives. Its sheet form is more durable than its spray-on form.

Polyethylene and Polypropylene

Polyethylene and polypropylene are inexpensive in flat sheets, but joints are difficult to fabricate, and patching is difficult at best. Adhesives perform poorly on polyethylene and polypropylene because they are unaffected by most ordinary solvents. The materials tend to be stiff if their thickness is more than 30 mils (0.75 millimeters). Polypropylene is capable of withstanding higher temperatures than polyethylene, but there is little experience with using these materials in solar systems.

Chlorosulfonated Polyethylene

Chlorosulfonated polyethylene is usually laminated with a scrim (a mesh fabric) of another material to give it dimensional stability. Flat sheets are generally available, but fabricated corners may be difficult to obtain. Some users have reported separation of the material from the scrim.

Chlorinated Polyvinyl Chloride (CPVC)

Like PVC, CPVC is normally rigid, but it can be made flexible by adding plasticizers. The plasticizers are subject to leaching, as they are with PVC; therefore, CPVC has no advantages over PVC.

TANK COSTS

Factors that affect tank installation costs include the tank's size, whether it is being installed in a new building or has to be built into an existing one, its location, its temperature requirements, its insulation requirements, and the materials used.

Size

Tank size is the most important factor affecting cost. Generally, the cost per gallon decreases as the size of the tank increases, as shown in Figure 3-2. Because system performance is not extremely sensitive to tank size (unless the tank is considerably undersized) the best approach is to select a standard size close to the optimum size as determined in Chapter 1.

New Building or Existing Building

Whether the tank is to be installed in a new or an existing building limits the choice of tank materials and location. It may be possible to design

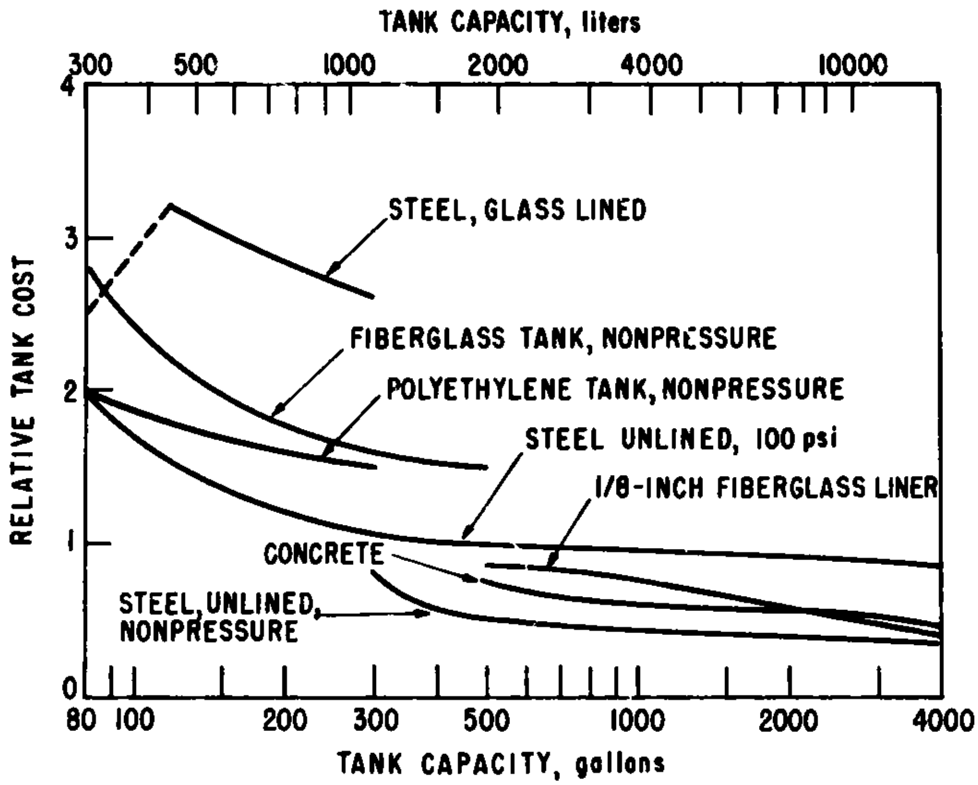


Figure 3-2. Relative Cost of Tanks in the Los Angeles Area, June 1975

Cost of steel tanks includes supports and fittings. Add 0.1 unit to the cost of unlined steel tank for phenolic lining.

Source: E. J. Beck, Jr., and R. L. Field. *Solar Heating of Buildings and Domestic Hot Water*. Civil Engineering Laboratory Technical Report R835, Naval Construction Battalion Center, Port Hueneme, California, April 1976.

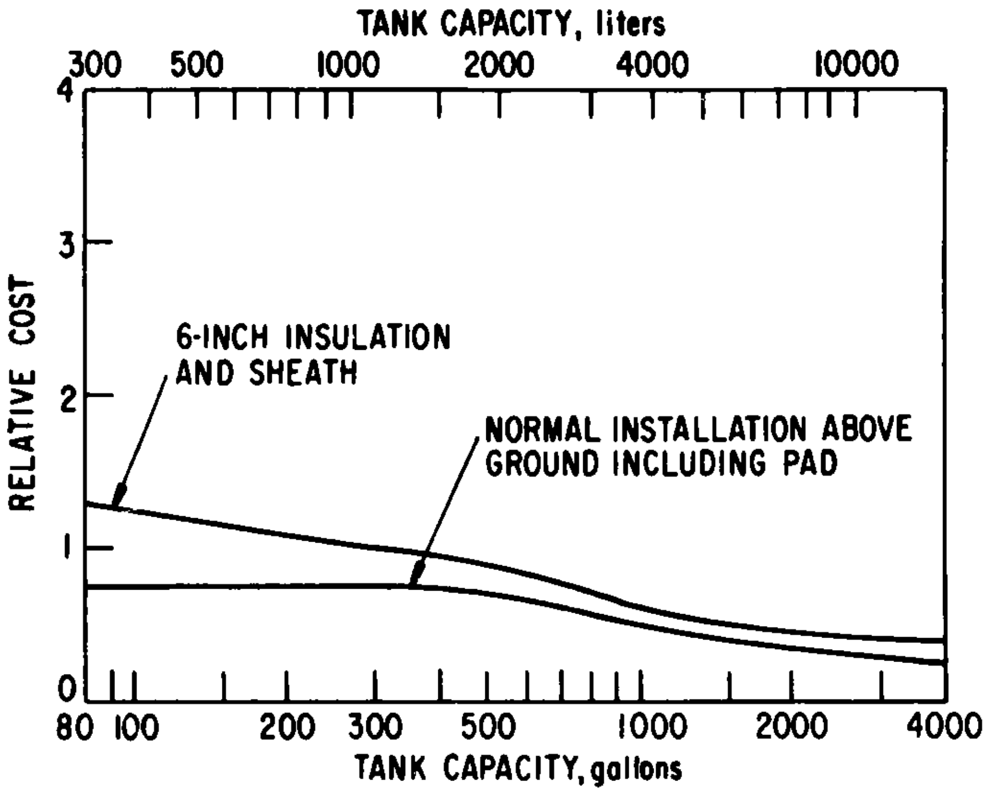


Figure 3-3. Relative Cost of Insulation and Installation for Tanks in the Los Angeles Area, June 1975

Relative cost scale is the same as in Figure 3-2.

Source: E. J. Beck, Jr., and R. L. Field. *Solar Heating of Buildings and Domestic Hot Water*. Civil Engineering Laboratory Technical Report R835, Naval Construction Battalion Center, Port Hueneme, California, April 1976.

access to a steel, fiberglass, or precast concrete tank into a new buillding, but the lack of access in an existing building may require choosing an outdoor location or a different tank material.

Reinforcements to the foundation can be specified before a new building is built, but in an existing building part of the basement floor may have to be removed before a reinforced section of floor can be installed. The greater flexibility in choosing tank materials, tank location, and foundation reinforcement generally gives a solar system in a new building a cost advantage over a solar system in an existing building.

Location

Tank location affects the special requirements for tanks shown in Tables 1-4 and 1-5. These requirements include waterproof insulation, extra-thick insulation, freeze protection, protection from groundwater (tie-down straps, exterior corrosion protection, provisions for drainage of groundwater, and so on), long-lifetime components, and limitations on materials that can be used. Each special requirement adds to the system's cost.

Underground tanks generally have the most special requirements. The insulation should be waterproof and should have extra thickness because of the possible presence of groundwater, which reduces its insulating value. Tie-down straps are required to prevent flotation of a partly filled tank. Provisions for draining groundwater and rainwater away from the tank and exterior corrosion protection for steel tanks should also be included. Because access to them is difficult, underground tanks should be designed for a long lifetime. Steel, fiberglass, and concrete can be used for underground tanks, but wood is not recommended because of its short lifetime when in contact with earth.

Basement locations generally impose few special requirements on the storage tank. Weatherproof and extra-thick insulation, freeze protection, and protection from groundwater are not needed when the tank is indoors. Steel and fiberglass tanks are not recommended for existing buildings because they ordinarily will not fit through the doors. If a steel or fiberglass tank is to be installed in a new building it should last the lifetime of the building. Both wooden and cast-in-place concrete tanks are suitable for basement installation.

The requirements for tanks in basements also apply to tanks in crawl spaces. In addition, since most crawl spaces are unheated, extra insulation and a means of protecting the tank from freezing are needed.

Garages are excellent locations for steel or fiberglass tanks. The large door allows for easy installation or replacement of the complete tank. Since most garages are unheated, extra insulation and a means of protecting the tank from freezing are needed.

The requirements for outdoor, aboveground storage tanks are the same as for those in garages, except that the tank must also be protected from the weather. Some factory-insulated fiberglass tanks are adequately protected against weathering and do not need additional protection.

Temperature Requirements

High storage temperatures are undesirable for the following reasons.

- High temperatures decrease collector efficiency.
- High temperatures increase insulation requirements.
- High temperatures require better quality lining and material for all types of tanks.
- High temperatures increase corrosion rates.

Each of these effects of high storage temperature tends to increase costs.

Insulation Requirements

Insulation requirements are primarily determined by the tank's location. Indoor tanks in heated areas require the least insulation, and protection of the insulation can consist of a simple cover. Typical insulation costs for indoor tanks are shown in Figure 3-3. Tanks in unheated indoor locations need extra insulation thickness, but a simple cover is sufficient protection for the insulation. Outdoor tanks have the most severe insulation requirements. Aboveground tanks require extra insulation thickness and protection from the weather. Underground tanks require waterproof insulation and extra thickness to compensate for the presence of groundwater. The cost of insulating an outdoor tank is about two to four times the cost of insulating an indoor tank. The costs of materials and labor frequently make a factory-insulated tank less expensive than an on-site-insulated tank.

Materials

Steel tanks rated for 100 psi (690 kPa) are generally the most expensive type of tank. When the tank, lining, insulation and sheath, and installation costs are added, you can expect the total to be about $2.50 per gallon ($0.66 per liter) for an indoor, 1000- to 2000-gallon (3800- to 7600-liter) tank. This figure should be considered a rough guide and not a precise estimate, since shipping, labor cost and skill, inflation, and availability of tanks influence the total cost. The premium for a pressure-rated tank is generally about $0.50 per gallon ($0.13 per liter), although in some areas the premium can be much less.

The installed cost for a 1000- to 2000-gallon (3800- to 7600-liter) FRP tank without a high-temperature resin for direct space heating is about $1.75 per gallon ($0.53 per liter). On-site-insulated and factory-insulated tanks are similar in cost, since the more difficult and labor-intensive installation procedure for the on-site-insulated tank tends to bring its installed cost up to the installed cost of a factory-insulated tank. As with steel tanks, the choice of manufacturer, shipping, labor cost and skill, inflation, and availability of tanks can significantly affect the installed cost. The cost of high-temperature resin (recommended for direct space heating; unnecessary for a solar-assisted heat pump) is about $0.25 to $1.25 per gallon ($0.07 to $0.33 per liter), varying widely from manufacturer to manufacturer.

The installed cost of a 1000- to 2000-gallon (3800- to 7600-liter) precast concrete tank is about $1.50 per gallon ($0.40 per liter). Shipping costs can add a significant amount if the distance to the manufacturer is more than 100 miles (160 kilometers). Because of the difficulty of shipping these large, heavy objects, manufacturers tend to be local, and prices and availability vary from one part of the country to another. Installed costs of cast-in-place concrete tanks are highly variable, and there is a tendency to neglect cost considerations when designing tanks. With careful design the installed cost of a 1000- to 2000-gallon (3800- to 7600-liter) tank can be less than about $1.50 per gallon ($0.40 per liter). If the tank can be designed into a corner of a building and the tank is poured at the same time the building walls are poured, lower cost is possible. Since this type of construction is labor intensive, costs will vary from one part of the country to another.

Plastic-lined wooden or multicomponent tanks installed in sheltered locations are the least expensive type of tank. The installed cost of a 1000- to 2000-gallon (3800- to 7600-liter) tank of this type can be less than $1.00 per gallon ($0.26 per liter), although some may cost about $1.50 per gallon ($0.40 per liter). Some liner types require periodic replacement, which increases costs.

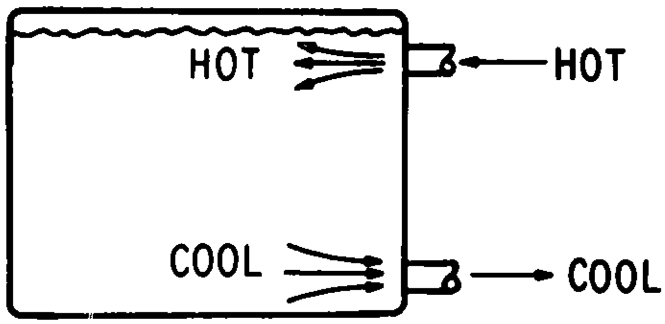
THERMAL STRATIFICATION IN TANKS

In Chapter 1 we said that a storage system with perfect thermal stratification can perform 5 to 10 percent better than a thermally mixed system. Although perfect stratification cannot be achieved in a liquid-based system, partial stratification can be encouraged by the methods shown in Figures 3-4a, b, and c. Using a horizontal inlet and outlet and low-velocity flows (Figures 3-4a and b) is so easy to do that it should be standard practice in liquid-based systems. Baffles (Figure 3-4c) are most easily installed by the manufacturer. Avoid the design mistakes illustrated in Figures 3-5a, b, and c.

PUMPS

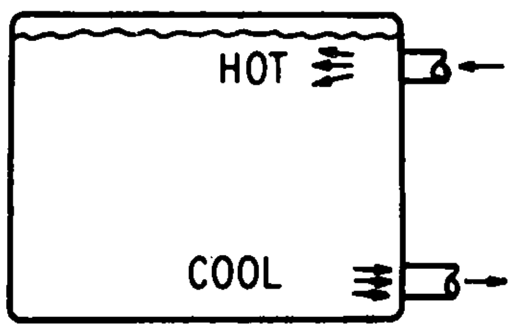
Pumps are used to circulate heat transfer fluids in all liquid-based solar systems except thermosyphon systems. This section discusses the types of pumps available and how to select a pump for a specific application.

Two types of pumps are readily available on the market. One is the positive displacement pump, characterized by a low flow rate and high head. (Head,

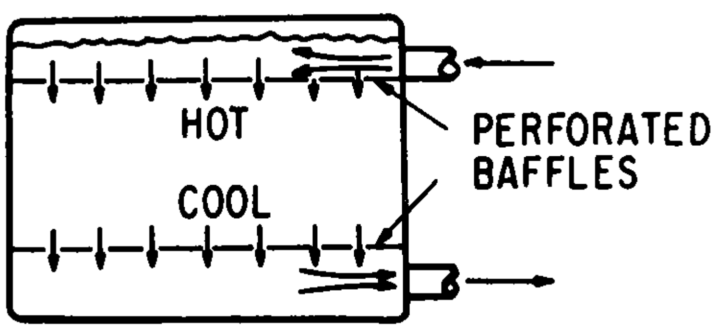


a. Horizontal Flow

Hot water should enter or leave at the top; cold water should enter or leave at the bottom.

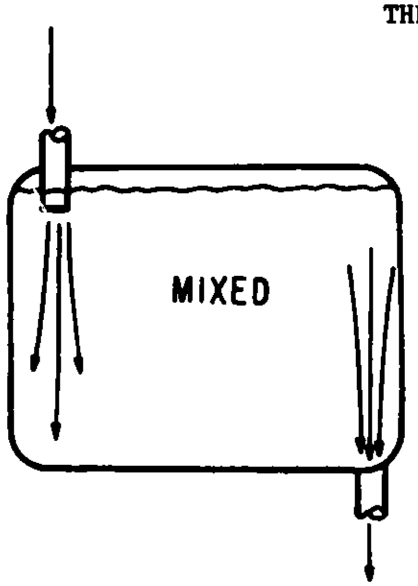


b. Low-Velocity Flow

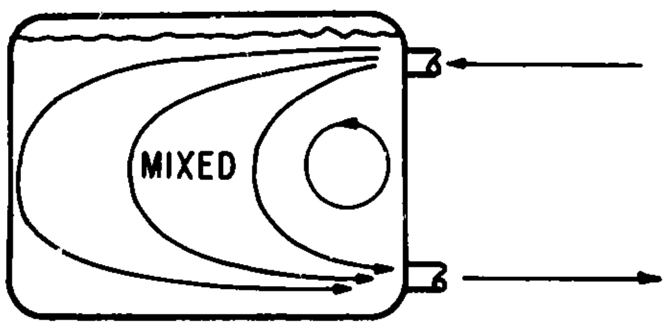


c. Baffles to Direct Flow

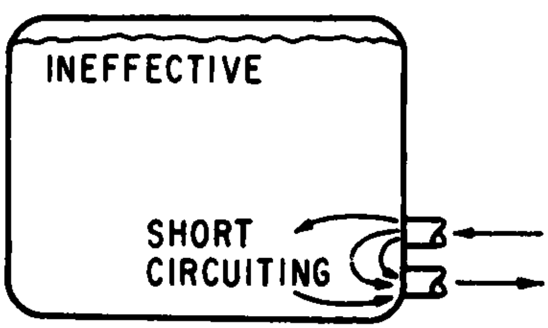
Figure 3-4. Methods of Promoting Thermal Stratification in Water Tanks



a. Vertical flow disrupts thermal stratification.



b. High-velocity flow causes turbulence, mixing, and short-circuiting.



c. Inlet and outlet close together causes short-circuiting. Parts of storage medium far from inlet and outlet may be ineffective.

Figure 3-5. Water Tank Design Mistakes

a term used throughout this section, is another word for pressure, which can be measured in the height of liquid that the pressure can support in a vertical pipe.) The positive displacement pump is rarely used in solar systems, which do not need a high head. If you use a positive displacement pump you will need a relief valve on the output side to prevent excessive pressure from mounting if a pipe becomes plugged.

Centrifugal pumps, characterized by a low head and high flow rate, are used in most solar systems and are available with a wide variety of flow rates. These pumps can be sealed against leaks in three ways: with adjustable packing, with a mechanical seal, or with a magnetic coupling.

The adjustable-packing seal, shown in Figure 3-6, is the least desirable sealing system because it requires frequent inspection and adjustment. This type of seal uses a packing gland to squeeze the packing between the pump housing and the pump shaft. If the packing-gland adjustment is too tight, the packing will bind the pump shaft, but if the packing-gland adjustment is too loose, the seal will leak. As the packing wears, the packing gland must be tightened. Adjustable-packing seals should not be used where access to the pump is difficult, where leakage from the seal could cause system failure, where leakage could create a hazard to people, or where antifreeze fluids are used. Antifreeze solutions, especially silicon oils and, to a lesser extent, glycol solutions, have an affinity for leaks.

The mechanical (or face) seal, shown in Figure 3-7, consists of two carefully polished surfaces pressed together by a spring. One of the surfaces is part of the pump shaft, and the other is sealed against the pump housing with an O ring A minute amount of leakage, so small that it evaporates before becoming visible, lubricates the polished surfaces.

Considerable experience with hydronic heating systems has shown that mechanical seals can last the lifetime of the system without requiring adjustments. The system must be kept clean, for grit in the water can easily scratch the polished surfaces. Chromate-type corrosion inhibitors have caused failures when the leakage evaporated and deposited hard chromate crystals between the polished surfaces. High temperatures and pressures also cause premature failure. Some antifreeze fluids, such as silicon oils, tend to leak excessively with mechanical seals.

A pump that uses a magnetic coupling, shown in Figure 3-8, has no troublesome rotating seals. Instead, the rotor of the electric motor and its bearings are placed entirely inside an extension of the pump housing. The stator of the electric motor fits outside the pump housing and drives the rotor with a rotating magnetic field. In some designs a set of rotating magnets replaces the stator, and an external electric motor turns a shaft that rotates the magnets. Magnetically-coupled pumps can be expected to last the lifetime of the system.

Figure 3-9 shows typical performance data for a large (140 gallons per minute or 8.8 liters per second) pump. Performance data for each pump model

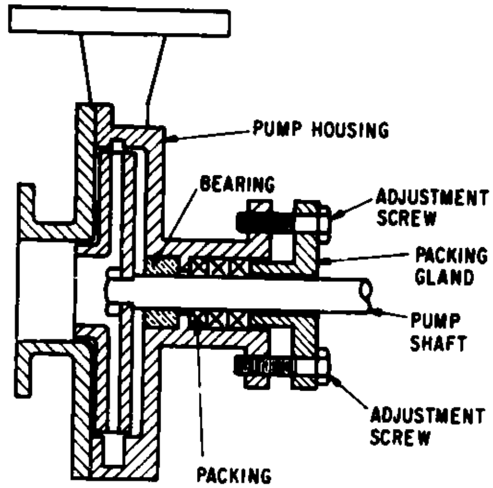


Figure 3-6. Cross-section through an Adjustable-packing Seal

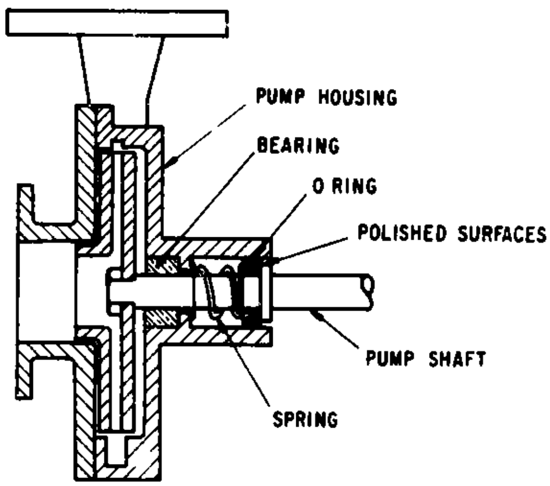


Figure 3-7. Cross-section through a Mechanical Seal

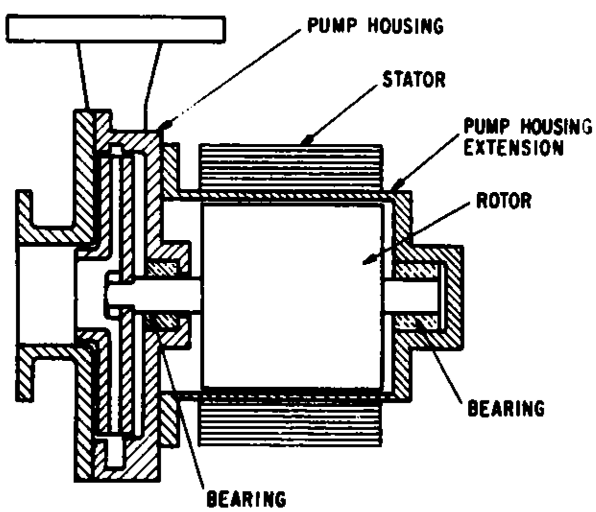


Figure 3-8. Cross-section through a Magnetically Coupled Pump

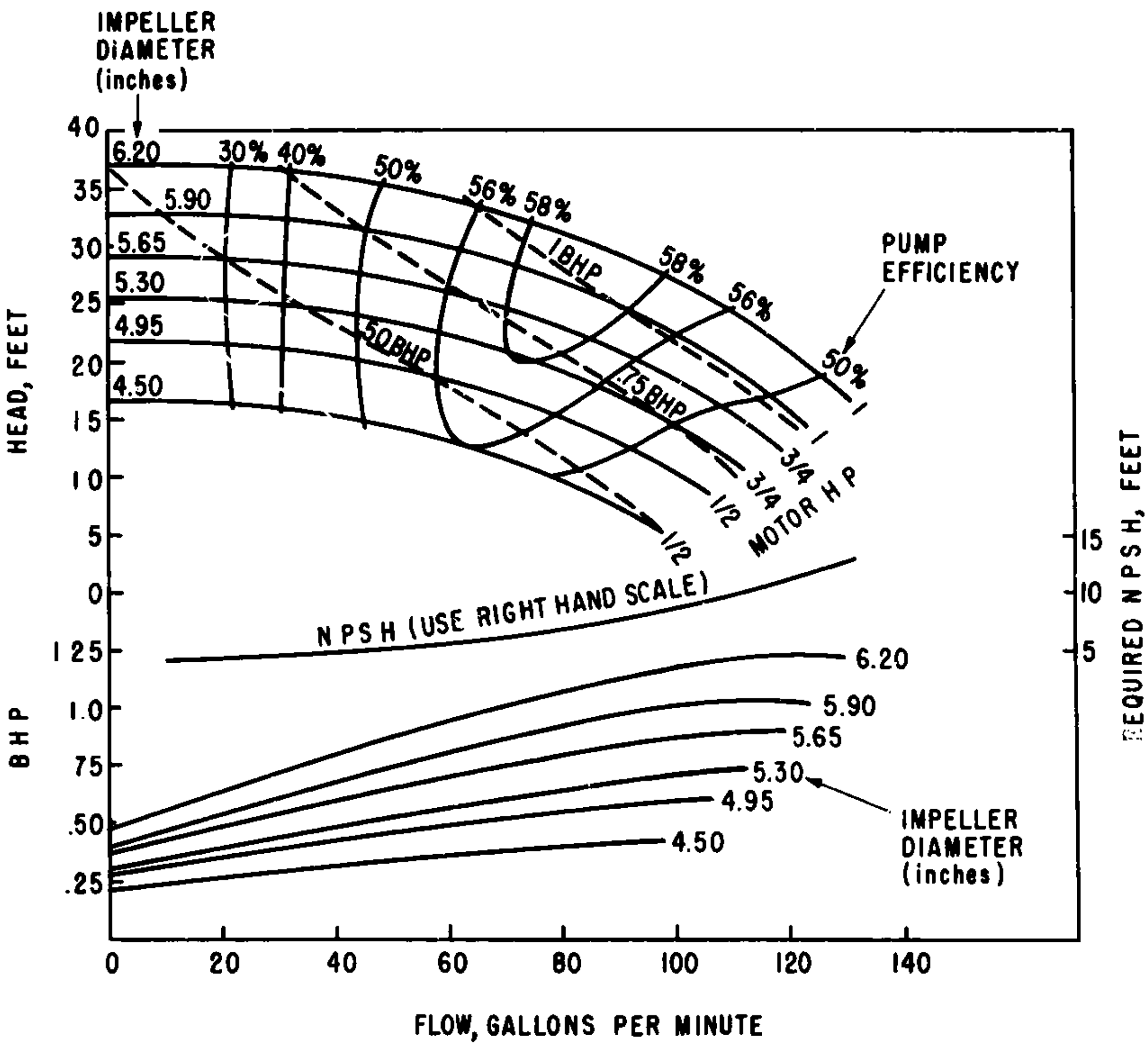


Figure 3-9. Pump Performance Data

Based on a drawing supplied by Taco, Inc., Cranston, Rhode Island.

are available from manufacturers and distributors. Although complete data such as that in Figure 3-9 is useful to the designer, data for pumps of the size used in residential systems (less than 10 gallons per minute or 0.63 liters per second) often lack information on net positive suction head (NPSH) requirements and power consumption. Figure 3-9 will be used to illustrate how the complete set of curves, if available, is used.

The designer must first consider the upper set of curves, which gives the head versus flow. Figure 3-9 shows six head-versus-flow-rate curves corresponding to six impeller diameters. Manufacturers of large pumps can supply several impeller sizes to fit each pump model in order to match the pump characteristics to the system characteristics. Usually only one size of impeller is available for small pumps. Also shown on the upper set of curves are the pump efficiency and the required motor horsepower.

To use the upper set of curves in selecting a pump, you must first determine the flow rate and the head loss (pressure drop) at which the system must operate. Data on flow rate and head loss through the collectors is available from the collector manufacturer. For a heat exchanger loop, the flow rate, q, in cubic feet per hour (cubic meters per second) is:

$$q = \frac{Q'}{\rho\ C_p\ \Delta T} \qquad (3\text{-}1)$$

where:

Q' is the heating rate in Btu per hour (watts).

C_p is the heat capacity of the heat transfer fluid in Btu per pound per degree Fahrenheit (joules per kilogram per degree Celsius).

ρ is the fluid density in degrees Fahrenheit (degrees Celsius).

ΔT is the temperature change of the heat transfer fluid in degrees Fahrenheit (degrees Celsius).

Divide q in cubic feet per hour by 8.02 to obtain q in gallons per minute. (Multiply q in cubic meters per second by 1000 to obtain q in liters per second.) Data on head loss through heat exchangers are available from the manufacturer.

You will also need to estimate the head loss caused by friction in pipes,[3] and if the system is the open-drop draindown type,[4] you will need to determine the difference in height between the top of the collector and the water.

[3]Details of pipe friction calculations can be found in Appendix B of this manual and are available from several other sources, including the *ASHRAE Handbook of Fundamentals*, Chapter 26, "Pipe Sizing"; *Flow of Fluids* by the Crane Company; and textbooks such as *Fluid Mechanics* by Victor Streeter and Benjamin Wylie.

[4]An open-drop draindown system is vented at the highest point in the system by having a vent valve at the highest point or by having the collector to storage return pipe larger than the pump to collector pipe.

level in the tank. The required pumping head, H_p, is equal to the sum of the head losses around the loop.

$$H_p = Z + H_f + H_x + H_c \qquad (3\text{-}2)$$

where:

Z is the difference in height between the top of the collector and the liquid level in the tank (for open-drop draindown systems only).

H_p is the head loss caused by friction in the pipe.

H_x is the head loss in the heat exchanger.

H_c is the head loss in the collector.

All terms in Equation 3-2 are expressed in feet (meters).

By plotting the required flow rate and pumping head on performance curves of several different pump models, you can choose the pump that meets or exceeds the pumping head requirements at the required flow rate.

The second consideration in selecting a pump is that it should be capable of filling the initially empty system. That is, the pump head at zero flow rate should exceed the difference in height between the top of the loop and the level of the liquid in the reservoir. By plotting this height difference on the vertical axis of the pump performance curves, you can determine whether a pump will meet this requirement.

Pump Power

The lower set of curves in Figure 3-9 gives the power consumed by the pump versus flow rate and impeller diameter. After selecting a pump, an impeller diameter, and a flow rate, you can use the lower set of curves to determine the size of the motor required by the pump. In a well-designed system, the total pumping power for the system should not exceed 1-1/2 percent of the solar power being collected. (1 HP = 2546 Btu per hour; 1 watt = 3.41 Btu per hour.)

Net Positive Suction Head

The middle curve in Figure 3-9 gives the pump's net positive suction head (NPSH) requirement. Net positive suction head is the absolute head at the pump inlet minus the vapor head of the liquid being pumped. If the available NPSH does not exceed the pump's NPSH requirement, cavitation can destroy the pump in a short time. Most systems have sufficient NPSH, but all systems must be checked for this requirement.

The available NPSH for your system can be calculated from Equation 3-3.

$$NPSH = Z - H_f - H_v + H_a + H_p \qquad (3\text{-}3)$$

where:

- Z is the difference in height in feet (meters) between the liquid level in the reservoir and the pump inlet. If the pump inlet is above the level of the reservoir, Z will be a negative number.
- H_f is the head loss in feet (meters) caused by friction in the pipe leading to the pump inlet.
- H_v is the vapor pressure head of the liquid in the reservoir in feet (meters) at the maximum allowable temperature. The relationship between H_v and temperature for water is shown in Figure 3-10. Vapor pressures for other fluids can be found in Appendix B, Figure B-5. Multiply pressure in psi by 0.43 to obtain feet of water. (Multiply pressure in Pa by 1.02×10^{-4} to obtain meters of water.)
- H_a is the atmospheric pressure in feet (meters) of water. Figure 3-11 gives the relationship between H_a and altitude.
- H_p is the minimum pressure in the tank in feet (meters) of water if the system is not vented to the atmosphere.

Pump Materials

Pumps are usually made from iron, bronze, or stainless steel. Iron will quickly rust in an open system, but it can be used in a closed system with corrosion inhibitors. Both bronze and stainless steel pumps can give long service life.

OTHER COMPONENTS

Hand-Operated Valves

Solar systems generally use the same types of hand-operated valves commonly found in residential water systems. There are two common types of valves, the globe valve and the gate valve. The globe valve (Figure 3-12) controls the amount of flow. Globe valves do not permit complete draining of lines when they are placed in a horizontal position, and they offer more resistance to flow than do gate valves. Gate valves (Figure 3-13) are not suitable for controlling the amount of flow but are used to open or close a line. When open, gate valves have only small resistance to flow. They can be used as isolation valves. Most valves used in solar systems are of this type.

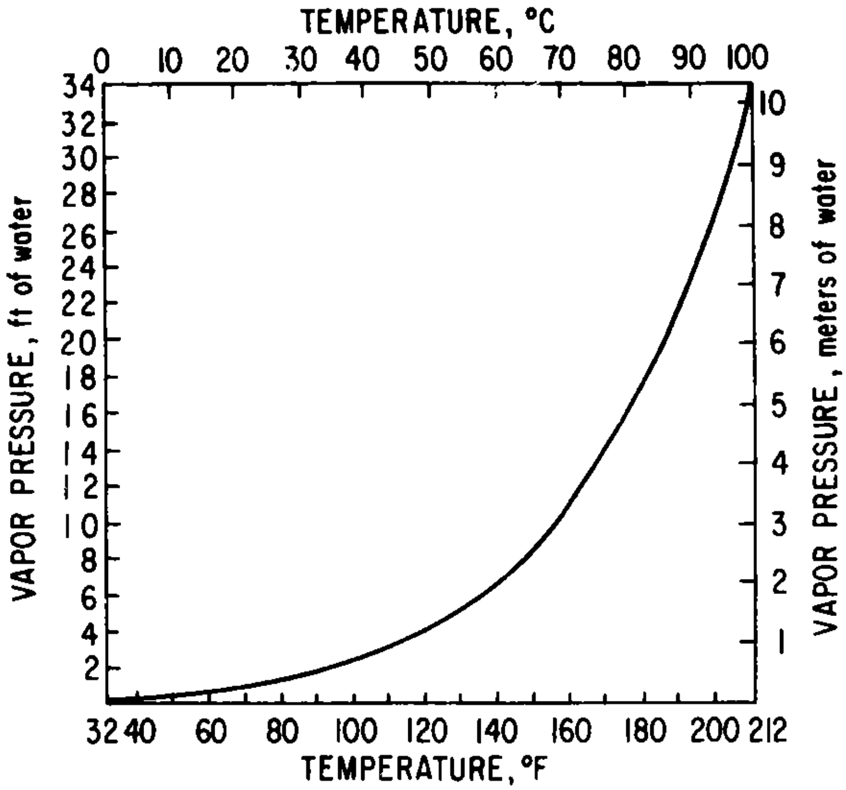


Figure 3-10. Vapor Pressure of Water versus Temperature

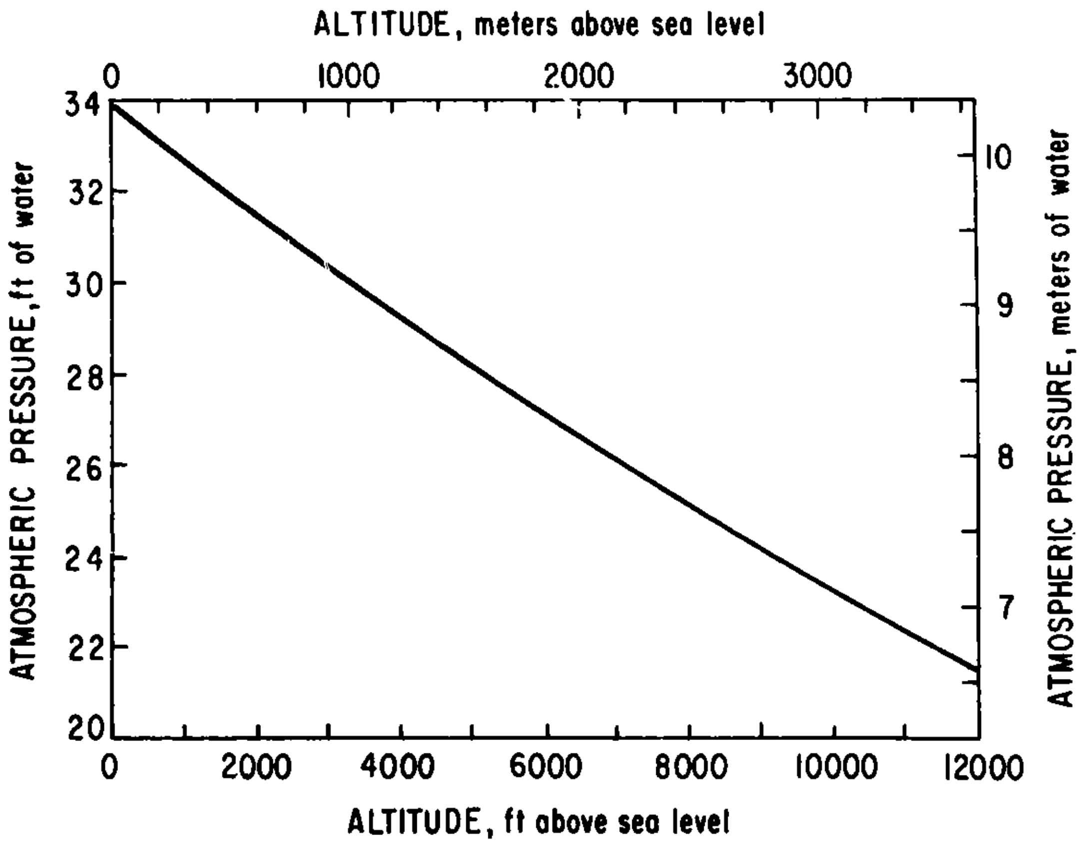


Figure 3-11. Atmospheric Pressure versus Altitude

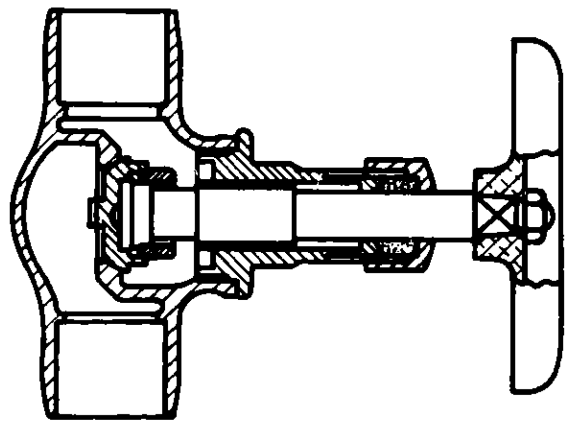


Figure 3-12. Typical Section through a Globe Valve

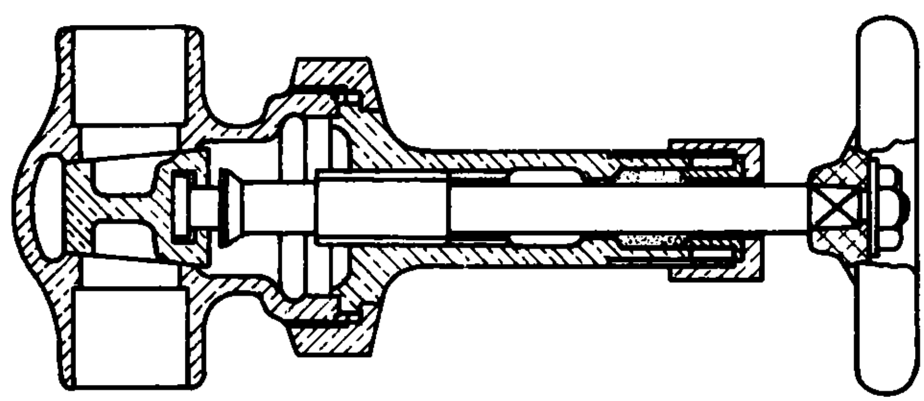


Figure 3-13. Typical Section through a Gate Valve

Check Valves

Most antifreeze systems require at least one check valve installed between the pump outlet and the collector inlet to prevent thermosyphoning on cold nights. Failure to install the check valve has caused heat exchanger failure because of freezing in several installations.

Two other causes of check-valve problems are installing the check valve backwards and selecting the wrong type of check valve. The backwards installation problem can be avoided by using care during installation, comparing the system as installed to the plans before startup, and testing the system to be certain that it functions properly.

There are two basic types of check valves, those that are closed by gravity and those that are closed by a spring. The gravity-operated swing-check and lift-check valves must be installed in the proper orientation with respect to gravity. If they are installed upside down or at 90° to their intended orientation, they will not block a backward flow. The gravity-operated check valves usually have hard seats that allow a small amount of leakage. In some cases, there is enough leakage to cause a thermosyphoning problem.

Spring-operated check valves can be installed in any position with respect to gravity. Resilient seats combined with the spring-operated closure assure complete stoppage of backward flow. Spring-operated check valves are more expensive and have a higher pressure drop than gravity-operated check valves, but these disadvantages are outweighed by their greater reliability.

Temperature and Pressure Relief Valves

Any closed subsystem must contain a temperature and pressure (T&P) relief valve to prevent damage to the system from excessive temperature or pressure. T&P valves for domestic hot water tanks usually have 210°F (99°C) temperature and 150 psi (1 MPa) pressure settings. Temperature and pressure settings for other types of tanks will differ from settings for domestic hot water tanks. All T&P valves must meet ASME Boiler and Pressure Vessel Code requirements.

Expansion Tanks

The liquids in a solar system expand when they are heated. The pipes and other components also expand, but not enough to contain the increased volume of the liquid in a closed system. To allow room for this excess volume in closed systems, an air space must be provided. The air space may be part of the main tank in the system or a separate expansion tank.

Incorrect sizing of expansion tanks has been a frequent cause of trouble in solar systems. A method of determining expansion tank size is given in the *ASHRAE Handbook and Product Directory, 1976 Systems*, Chapter 15, "Basic Water System Design." Since the volumetric expansion of antifreeze solutions is greater than the volumetric expansion of water, systems using antifreeze require a larger expansion tank than do systems using water. For these systems, the method of calculating expansion tank size given in the *ASHRAE Handbook and Product Directory* must be modified as follows.

- From the distributor or manufacturer of the fluid, obtain data on how the fluid's density changes with changes in temperature. (This information for water and some other heat transfer fluids can be found in Figure B-4, Appendix B of this manual.)
- Multiply the volume of fluid in the system by the fluid's density at the lowest temperature that you expect and divide the result by the fluid's density at the highest temperature that you expect. The result will be the total expansion of the fluid in the system (Part E in Equation 7 of the ASHRAE handbook mentioned above). All other parts of the ASHRAE method of sizing expansion tanks can be used without modification.

Two types of expansion tanks are available. One is a simple tank with an air space; the other uses a flexible diaphragm to separate the water from the air in the tank, thus preventing the water from absorbing the air. Both are effective, but the diaphragmless tank requires periodic replacement of the air absorbed by the water in the tank.

Vacuum Relief Valves

As a solar system cools, the volume of the liquid in the system decreases. Vacuum relief valves must be installed in closed systems to prevent vacuum damage to tanks. For example, if a tank with a 4-foot (1.2-meter) diameter cools until the pressure in the tank is 1 psi (7 kPa) below atmospheric pressure, the force on the top of the tank will be more than 1800 pounds (8000 newtons).

Temperature Sensors

Temperature sensors in storage tanks serve three purposes:

- To tell the controller when to turn the collector pump on. This temperature sensor should be installed in the tank near the bottom connection to the tank. When the collector temperature is warmer than the temperature at the bottom of the tank, the system controller turns on the collector pump.

- To tell the controller when heat is available for heating. This temperature sensor should be installed in the tank near the top connection to the tank. When the tank is warm enough to supply heat to the load, the controller will take heat from storage to satisfy the load. Otherwise, the controller will turn on the auxiliary heater.
- To limit the temperature in the tank to a safe maximum. Some controllers use the same temperature sensor to indicate when heat is available for the load and to limit the tank temperature, while other controllers use separate temperature sensors for these functions. Unfortunately, many of the controllers that are commercially available do not have provisions for limiting tank temperatures. Limiting the tank temperature is essential if the tank has a rubber or plastic liner or if it is made of fiberglass-reinforced plastic. Even metal tanks can benefit from a temperature limit, for corrosion rates approximately double with each 20°F (10°C) increase in tank temperature.

Thermistors and silicon transistors are the easiest to use, most reliable, and most commonly used types of temperature sensors, although thermocouples, bimetallic elements, and liquid or vapor expansion units have been used. Because its signal is linear with respect to temperature, the silicon transistor is easier to calibrate than the thermistor. The type of temperature sensor selected is less important than its compatibility with the control unit.

The electrical leads of the temperature sensor must be protected from immersion in water. Some temperature sensors are equipped with a protective sheath, while others must be installed in a temperature sensor well (a capped pipe immersed in the water). If a temperature sensor well is used, it should have provisions for good thermal contact between the temperature sensor and the metal.

If the tank is metal, the temperature sensor can be attached to the outside of the tank provided that certain cautions are observed.

- Cover the temperature sensor with insulation so that it reads the tank temperature and not the ambient temperature.
- Clamp or bolt the temperature sensor to the tank so that they are in firm contact. Taping or cementing the sensor to the tank is not adequate.
- Some types of sensors must be electrically insulated from the tank; otherwise, a short circuit can cause false readings.

In addition to the temperature sensors, thermometers should be installed to measure the water temperature at the upper and lower connections to the tank. These thermometers will help the installers start up and adjust the system. After the system is in operation, the thermometers can help detect malfunctions. For example, a failure of the collector circuit would be indicated by an abnormally low tank temperature in the afternoon of a sunny day.

Auxiliary Heating System

As we stated in the preceding chapter, solar space heating systems must have auxiliary heaters that are able to supply 100 percent of the heating load. Liquid-based systems are often combined with forced air heating systems, requiring a liquid-to-air heat exchanger in a forced-air duct to transfer heat to the building air. The heat exchanger can be installed either upstream of the auxiliary heater as shown in Figure 3-14a or downstream of the auxiliary heater as shown in Figure 3-14b.

The configuration shown in Figure 3-14a has a minimum operating temperature of about 70 to 75°F (21 to 24°C). The minimum operating temperature is a few degrees above the return air temperature because of the temperature drop caused by the heat exchanger. Studies have shown that people find 70°F (21°C) circulating air chilling. To ensure that the air will circulate at a comfortable temperature, the auxiliary heater is turned on whenever solar energy is unable to maintain a duct temperature of about 95°F (35°C) or more. While the auxiliary heater is operating, solar energy preheats the air entering the auxiliary heater. This system is usually used with an electric heater. Because the solar-heated air must pass through the auxiliary furnace's heat exchanger, some solar heat may be lost up the flue of a gas or oil furnace. If the auxiliary furnace has an automatic flue damper to prevent this loss, the solar preheat arrangement is feasible with a gas or oil furnace.

The configuration shown in Figure 3-14b is usually used with gas or oil auxiliary heaters without flue dampers or for situations where there is no room to install the heat exchanger between the blower and the heater. As in the previous configuration, the auxiliary heater is turned on whenever solar energy cannot maintain a duct temperature of about 95°F (35°C) or more. In this configuration the pump that circulates water from storage to the heat exchanger must be turned off when the auxiliary heater is turned on so that the auxiliary energy heats the building instead of recharging the storage unit.

The solar space heating system can also be combined with hydronic heating systems (Figure 3-14c) using baseboard heaters, fancoil units, ceiling panels, or floor panels. Each type of hydronic system has a minimum operating temperature that varies with the outdoor temperature. If the temperature in storage is less than the minimum operating temperature of the system, the automatic valves must shut off the storage loop, and the boiler must be turned on.

TANK INSTALLATION

Proper installation of storage tanks is essential. The foundation under the tank must be strong enough to support the weight of the tank and the water that the tank will hold. Water weighs about 8.3 pounds per gallon (1 kilogram per liter), so the water in a 1000-gallon (3800-liter) tank will

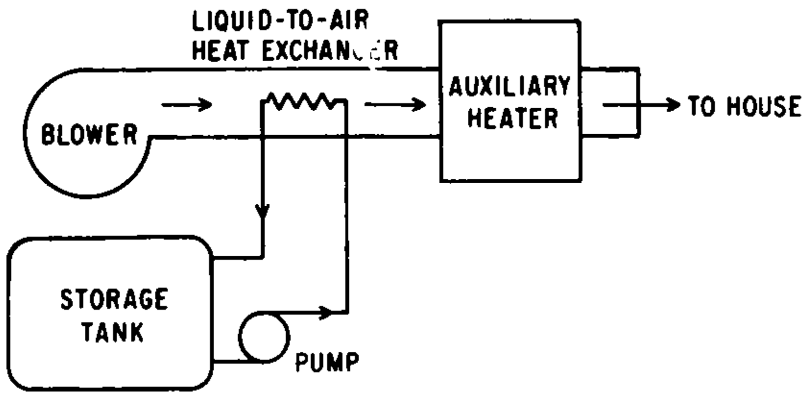


Figure 3-14a. Liquid-to-Air Heat Exchanger Installed Upstream of Auxiliary Heater

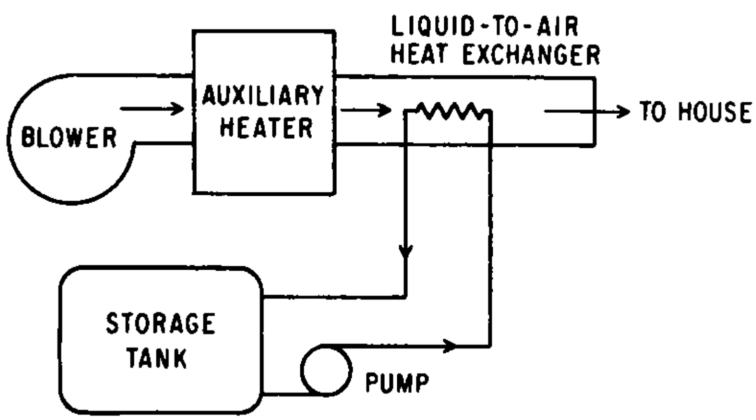


Figure 3-14b. Liquid-to-Air Heat Exchanger Installed Downstream of Auxiliary Heater

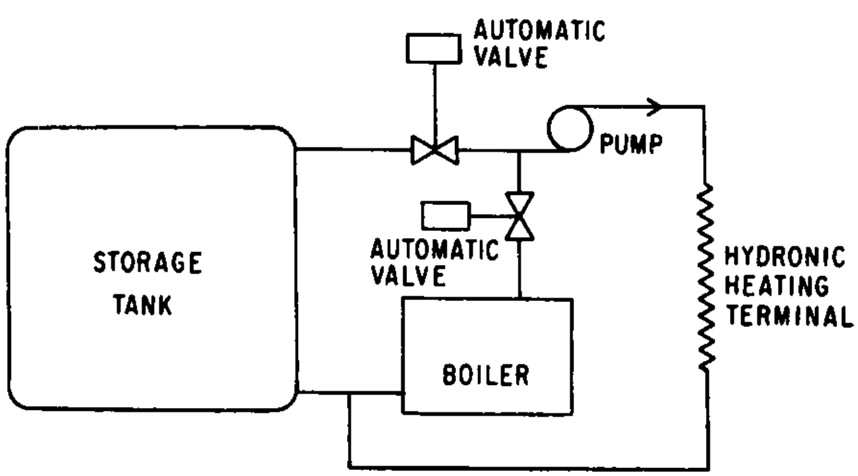


Figure 3-14c. Combined Solar and Hydronic Heating Systems

weigh 8300 pounds (3800 kilograms) -- more than four tons. If the foundation is not built to hold this weight, the tank may settle and cause leaks in the connected piping or in the tank itself. We recommend that you have a structural engineer review the foundation design for any storage tank. Local building codes will specify the type of footings required.

Vertical steel tanks that are not buried need a concrete ring-wall foundation. Horizontal steel tanks above ground should be supported on concrete saddles with appropriate foundations. The tank manufacturer will tell you the tank's weight to help you determine how much support it needs.

Fiberglass tanks are designed to be installed with full bottom support. If an aboveground tank is mounted on a concrete pad, the concrete must be smooth and have enough reinforcement to support the weight of the full tank. Underground tanks are usually supported by the backfill. In both cases, the manufacturer's installation instructions must be followed carefully to avoid damaging the tank and to preserve the warranty.

For tanks installed underground, anchorage must be provided to prevent bouyant uplift when the tank is empty. The tank should be anchored to a concrete pad at least 6 inches (15 centimeters) thick and weighing at least as much as the water the tank can hold. The concrete should be covered with a layer of fine pea gravel, sand, or number 8 crushed stone at least 6 inches (15 centimeters) deep and spread evenly over the concrete to separate it from the tank. Fiberglass or steel hold-down straps should be anchored 1 foot (30 centimeters) beyond the sides of the tank. The hold-down straps should pass over the top of the tank and should be tightened with turnbuckles to give a snug fit. Use at least a 5 to 1 safety factor when you calculate the strength of the hold-down straps and turnbuckles.

Backfill with pea gravel, sand, or number 8 crushed rock at least 2 inches (5 centimeters) all around the tank. The remainder of the backfill may be clean tamped earth or sand to a depth of 24 to 36 inches (60 to 90 centimeters) above the tank. Provide concrete pads for nozzles and manholes extending to grade. See Figure 3-15 and Appendices G and I for additional details.

In areas with a high water table, the tank insulation must be impervious to water or the tank must be installed in a vault provided with a sump pump.

Design for Maintainability

Maintenance must be considered as the system is being designed. Many solar systems fail or perform poorly because they cannot be properly maintained. If a storage tank cannot be easily replaced, it should last the lifetime of the building. Before installing any components the designer should consider how each component will be repaired or replaced and provide for working room around the components. All tanks and heat exchangers must have a means of being drained for inspection and repairs.

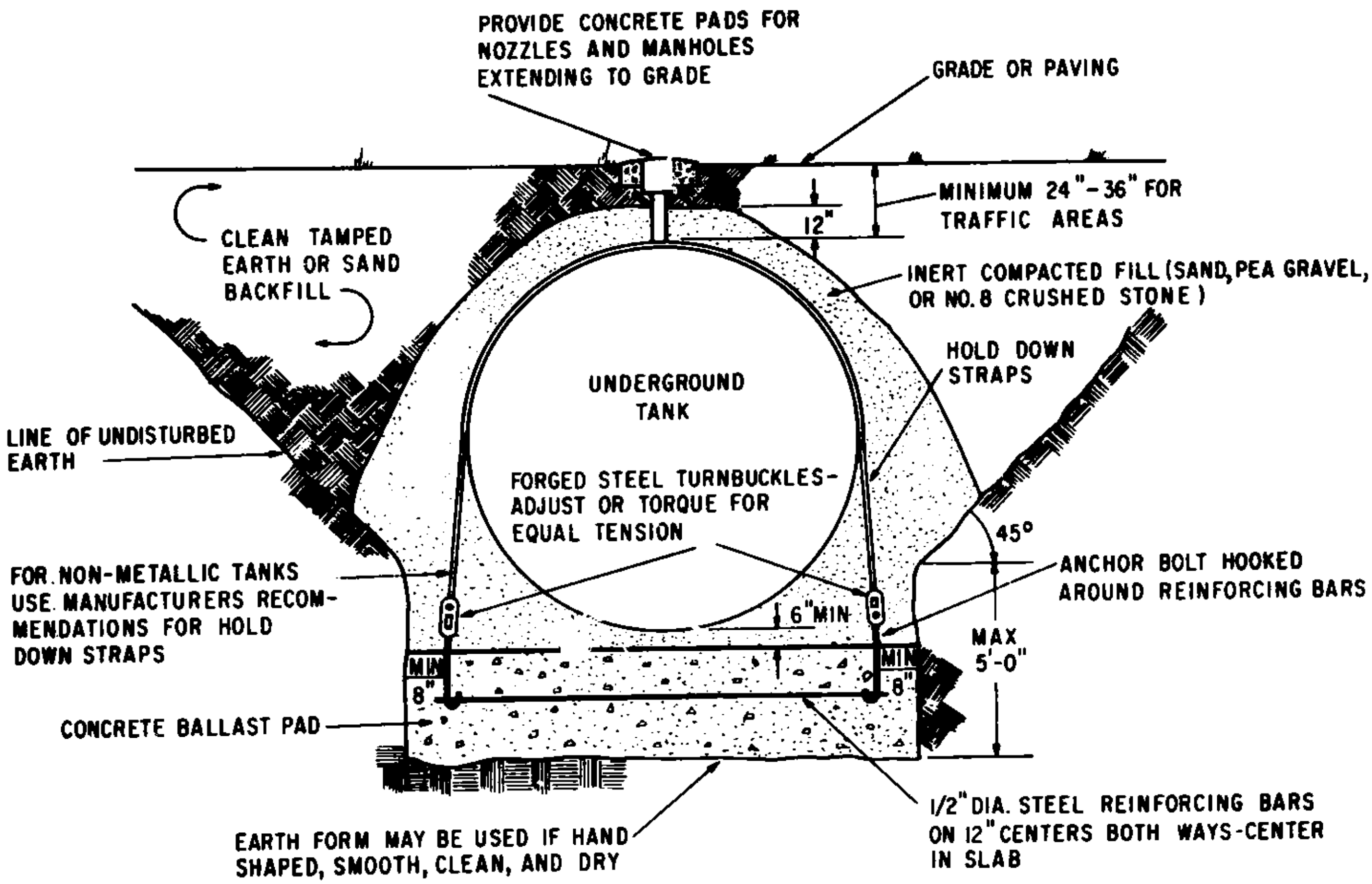


Figure 3-15. Installation of an Underground Tank

Simple systems are usually easier to maintain than complicated systems. The advantages of a simple system over a complicated system are:

- Initial cost is lower.
- Installation errors are less likely.
- There are fewer components to fail.
- Controls and operation are easier to understand.
- Defective components can be more easily found and replaced.

Answering three questions will help you decide whether the system is too complicated or too simple.

- If a feature were deleted from the system, how much energy collection would be lost?
- If a feature were deleted from the system, would a mode of failure be introduced?
- If a feature were deleted from the system, would human safety be degraded?

You can use a system analysis method (such as f-Chart, SOLCOST, DOE-1, or TRNSYS) to estimate the extra amount of energy collection attributable to a particular feature. If the value of the extra energy collected over the life of the system is less than the cost of the feature, the feature cannot be justified economically. If, in addition, the answers to the second and third questions are "no," the feature should be deleted from the system.

Startup

Before insulation is applied to the pipes, the system must be carefully inspected and tested. Begin by checking all piping, valving, and wiring against the system drawings. Typical problems that might be encountered include:

- Pumps or valves reversed.
- Inlet and outlet connections to tanks, heat exchangers, or collectors reversed.
- Normally open valves installed in place of normally closed valves, or vice versa.
- Lines in drain-down systems improperly sloped.
- Check valves improperly oriented.

This is a good time to begin labeling the piping, although some parts must be labeled after the insulation is installed. The contents (air, water, ethylene glycol, and so on) should be tagged on each major line, along with the notation for liquids "potable" or "nonpotable." Potable water is fit for human consumption. Toxic substances, such as ethylene glycol and many corrosion inhibitors, are, of course, nonpotable; however, a substance need not be toxic to be nonpotable. Water that resides in a storage tank for several weeks is nonpotable, even if it has no toxic additives. A color code can be used for labeling (see the *ASHRAE Handbook of Fundamentals*).

Safe fluids should be labeled with green, white, gray, black, or aluminum; dangerous fluids with orange or yellow. Pipes should be labeled with flow direction.

Valves, pumps, heat exchangers, and so on should be tagged to correspond to the identification mumbers on the system drawings, and flow directions should be marked on the parts. Automatically controlled two-way valves should be labeled "normally open" or "normally closed." The legs of three-way valves should be labeled "common," "normally open," and "normally closed." Labeling components in this way will often disclose installation errors.

Before installing insulation and before backfilling an underground storage tank, test the entire system for leaks. If the system can be pressurized, the best way to test for leaks is:

> Close the vent valves if necessary. Attach an air compressor to the system through a valve and fill the system to the normal operating pressure of the weakest component. Turn off the air compressor and close the valve. If the air pressure drops more than 20 percent in twenty-four hours, the system leaks. Test all pipe joints and packings with soapy water. Bubbles will appear at the leak. Do not forget to open the vent valves if you have had to close them before testing.
>
> THIS TEST IS ONLY FOR FINDING LEAKS IN THE SYSTEM; IT IS NOT A REPLACEMENT FOR THE ASME PRESSURE VESSEL CERTIFICATION TEST. PERFORM ASME PRESSURE VESSEL CERTIFICATION TESTS OF COMPONENTS BEFORE YOU PERFORM THIS LEAK TEST TO BE CERTAIN THAT ALL COMPONENTS CAN WITHSTAND THE TEST PRESSURE.

If the system is not designed for pressure or if it has already been leak-tested with compressed air, fill it to the proper levels with the appropriate fluids. If the fluids are warm when the system is filled, the inspection will not be confused by moisture condensing on the tank and pipes. Inspect all pipe joints and packings for leaks and remove any trapped air pockets.

Trapped air pockets can be removed in several ways.

- Fill the system at its highest point.
- If the system is designed for pressure, pressurize it and open the air bleed valves at the high points.
- Turn the pumps on and allow the liquid to sweep the air from the system.

Check and refill the system to the proper levels.

Test the system in all operating modes to ensure that it functions as intended. Since systems vary greatly in their operating modes, only general guidelines can be given here. Most controller manufacturers make testing devices and publish data on how to use the testers. You may need a set of jumper wires to operate the system in its various modes.

CAUTION: DANGEROUS VOLTAGE MAY BE PRESENT AT CONTROLLER TERMINALS. Flows in pipes usually can be determined by feeling a temperature change and by observing temperature changes with the thermometers installed in the tank and collectors.

A special test is required for draindown systems. After operating the system in the collecting mode and then in the draindown mode, shut off the system and temporarily disconnect the piping, as shown in Figure 3-16a. Apply compressed air as shown in Figure 3-16b to blow trapped water, if any, into buckets. If more than a few drops of water fall into the buckets, the system does not drain properly and could be damaged by freezing. Do not operate the system until the cause of faulty draining has been corrected and the system has been retested. If the system passes the draindown test, reconnect the pipes.

Several final operations should be performed before the system is put into operation. Inspect the filters. If you find dirt or grit, or if the fluid is discolored, do not start the system until the cause has been found and corrected. Test the fluid pH and measure the antifreeze or corrosion inhibitor concentration. If test results are not within the manufacturer's specifications, do not continue until the cause has been found and corrected. Inspect and repair leaks, if any. Finally, install the insulation on tanks and piping and complete the labeling of components. The system is now ready for operation.

Periodic Inspection and Maintenance

The following tasks should be performed twice each year, when the system is switched between winter and summer modes.

- Inspect for leaks.
- Check fluid levels in tanks.
- Clean or replace fluid filters.
- Examine fluid samples for grit, sludge, dirt, or discoloration.
- Test the fluid pH.
- Measure the concentration of antifreeze or corrosion inhibitors.
- Check pumps, valves, sensors, and controllers for proper function.

At an interval (usually two to five years) specified by the tank manufacturer, the collector manufacturer, the antifreeze manufacturer, or the corrosion-inhibitor manufacturer, drain and replace the fluids in the system. (For some systems this is unnecessary.)

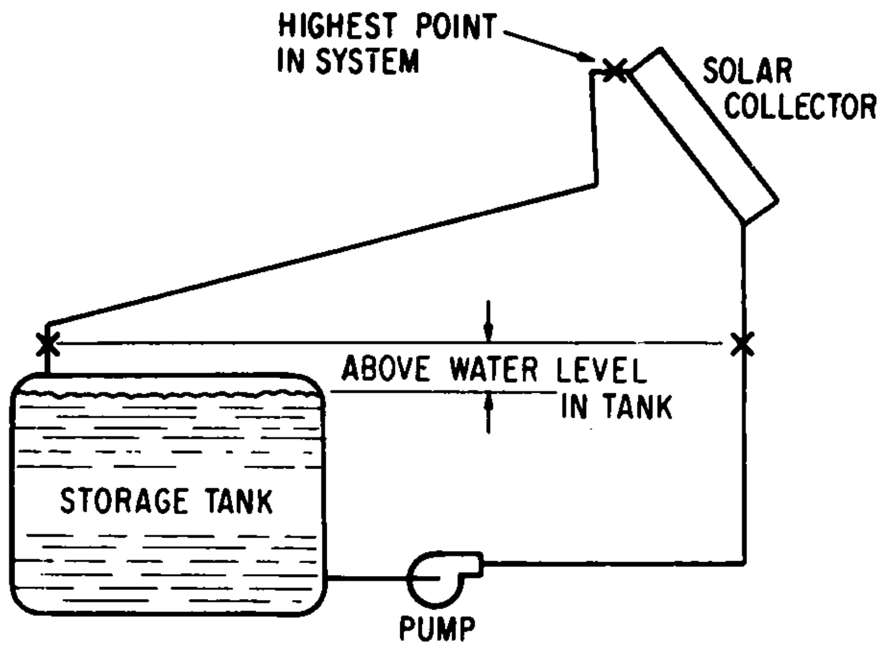


Figure 3-16a. Temporarily disconnect piping at points marked "X" for draindown test.

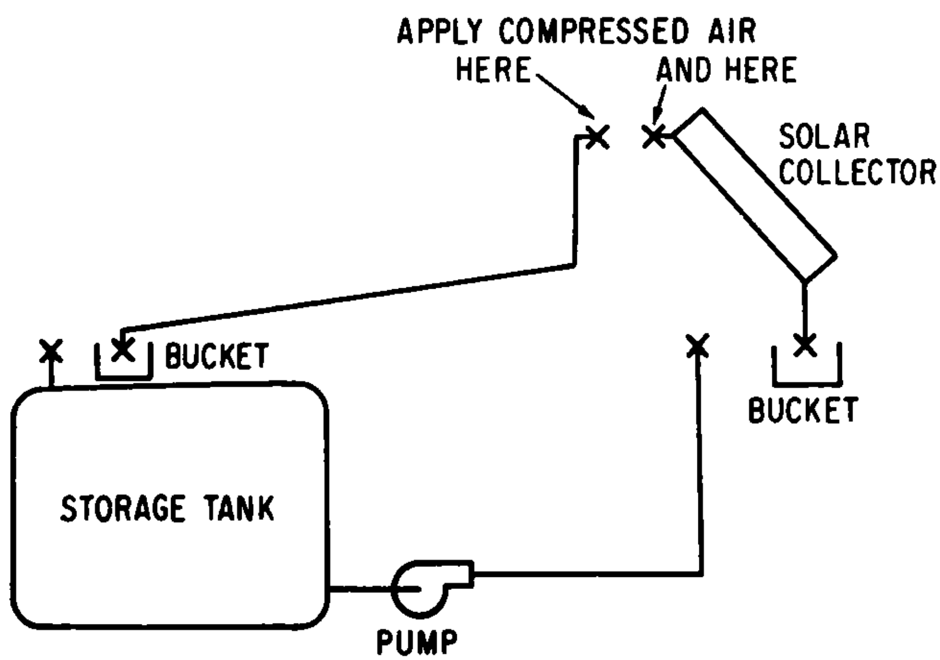


Figure 3-16b. Draindown Test

Owner's Manual

The contractor should provide the owner with a manual that includes the following information:

- A summary description of how to operate the controls.
- Instructions on how to do periodic maintenance.
- A detailed description of how the system operates.
- Schematics of plumbing and wiring with labels that correspond to the labels attached to the hardware.
- Component and system warranties.

SYMBOLS USED IN CHAPTER 3

Main Symbols

C_p	liquid density in Btu/lb·°F (kg/m^3)
E	electrical potential in volts
H	head (pressure) in feet (m) of water
NPSH	net positive suction heat in feet (m) of water
pH	measure of acidity or alkalinity of an aqueous solution
q	volumetric flow rate in ft^3/hr (m^3/sec)
Q'	heating rate in Btu/hr (W)
Z	difference of elevation in feet (m)
ΔT	temperature difference in °F (°C)
ρ	liquid density in lb/ft^3 (kg/m^3)

Subscripts

a	atmospheric pressure
c	collector
f	friction
p	pressure relative to atmospheric pressure
v	vapor pressure
x	heat exchanger

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CHAPTER 4
LATENT HEAT STORAGE SYSTEMS

Chapters 1, 2, and 3 dealt with sensible heat storage; this chapter will discuss latent heat storage. Latent heat storage systems can be designed to replace both rock beds and water tanks. In latent heat storage systems the storage medium undergoes a phase change in which it absorbs heat without changing temperature; in the type of phase change we will be discussing, the heat flowing into storage melts the storage material. When space heating is needed, heat is removed from storage and the storage material refreezes.

The storage medium is called a phase change material (PCM). Four types of phase changes have been investigated for use in thermal energy storage systems. They are:

- Melting-freezing.
- Boiling-condensing.
- Changing from one solid crystalline structure to another.
- Changing from one liquid structure to another.

Of the four, only melting-freezing latent heat storage systems have reached the marketplace, and that is the type that will be discussed further in this chapter. The vapor in boiling-condensing phase change occupies so much space that no practical system of using it has been found. The other two types of phase change listed are under experimental investigation.

The amount of heat that a PCM absorbs at a constant temperature as it melts is called the latent heat of fusion, h_f, and has units of Btu per pound of material (joules per kilogram of material). In this manual, the term "latent heat of fusion" is shortened to "latent heat," since it is the only type of latent heat being discussed.

Characteristics of Latent Heat Storage

An outstanding feature of latent heat storage systems is the compactness of the storage unit compared with sensible heat storage units. The volume of PCM required to store a given amount of heat is less than the volume of sensible heat storage material required to store the same amount of heat. This allows much greater flexibility in choosing a location for the storage unit. Further, since the unit is small, much less insulation is required to maintain reasonable thermal losses.

Thermal stratification does not occur in phase change storage systems, because their temperatures remain nearly constant throughout the charge-discharge cycle. If the melting point is chosen so that the storage unit provides heat at slightly above the minimum temperature required by the system, then the output from the collector need be only a few degrees warmer than the minimum temperature regardless of whether the storage unit is charged or discharged. By contrast, a sensible heat storage system typically operates at 40 to 60°F (22 to 33°C) above its minimum operating temperature when it is fully charged. Thus, a collector coupled to a phase change storage system can operate at a lower, more efficient average temperature than a collector coupled to a sensible heat storage system.

PHYSICAL PROPERTIES OF PHASE CHANGE MATERIALS

Several physical properties of PCMs are important in latent heat storage systems. They are:

- Melting point.
- Latent heat of fusion.
- Melting behavior.
- Heat capacity of the liquid and solid materials.
- Thermal conductivity of the liquid and solid materials.
- Corrosiveness.

The first four of these properties are summarized in Table 4-1. Also summarized in the table is the density of solid PCM, which can be used to calculate the volume of PCM after the required mass has been calculated.

Melting Point

The melting point has a strong influence on the type of system that can be used with a particular PCM. In heating systems, the melting point must be several degrees warmer than the delivered temperature because of the temperature drop in the heat exchanger. Studies have shown that people find 70°F (21°C) air chilling in a forced-air heating system. Accordingly, about 90°F (32°C) is the lowest practical melting point for use in an air-based direct solar heating system. A liquid-based system, which has one more heat-exchange process than an air-based system, has a minimum practical melting temperature of about 100°F (38°C). Solar-powered cooling systems would require a minimum melting temperature of about 200°F (93°C) for hot-side storage. For cold-side storage, a delivered temperature of less than 55°F (13°C) is necessary to achieve dehumidification. This means that a maximum melting temperature of about 45-50°F (7-10°C) would be required for cold-side storage. Solar-assisted heat pumps have considerable flexibility in their storage temperature and can use materials with melting points between 50 and 90°F (10-32°C).

There are commercially available latent heat storage systems applicable to liquid- and air-based direct solar heating and solar-assisted heat pump systems. But at present, there are no known commercially available latent heat storage systems applicable to either hot-side or cold-side storage in solar-powered cooling. The PCMs used in the commercially available systems include calcium chloride hexahydrate, sodium sulfate decahydrate, sodium thiosulfate pentahydrate, and several waxes. Although the inorganic salt hydrates have fairly well-defined melting points, there is considerable variation in the melting points of the waxes. Some, being mixtures of several waxes, do not have a constant melting temperature but melt over a small temperature range.

Latent Heat of Fusion

The latent heat of fusion given in Table 4-1 tells how much heat can be stored per unit mass of PCM. Materials with a large latent heat will generally make a compact storage unit. Water has the highest latent heat, but its low melting point makes it useful only for cold-side storage. The hydrated inorganic salts generally have a slightly larger latent heat than the organic substances. Both types of materials are used in commercially available systems.

Melting Behavior

The four types of melting behavior listed in Table 4-1 are congruent melting, semicongruent melting, incongruent melting, and supercooling.

Congruent melting is desirable in a PCM because the material will readily change from its liquid state back to its solid phase as heat is withdrawn and will therefore give up all its heat of fusion. Materials that do not change their chemical nature when they melt, such as water and paraffin wax, melt congruently. Unfortunately, none of the congruently melting salt hydrates make suitable storage materials because of cost or safety considerations.

When a salt hydrate melts, some or all of the water of hydration separates from the salt molecules. If the salt is completely soluble in its water of hydration, it will rehydrate easily when heat is removed from it. In this case, the salt melts congruently. If, however, the salt is not completely soluble in its water of hydration, the undissolved salt can settle to the bottom (precipitate) where it cannot be easily rehydrated. After the salt has melted completely in this manner, it will accept sensible heat and increase its temperature as heat is added. If the precipitated material becomes fully soluble at a few degrees above the melting point, the material is said to melt semicongruently. If the precipitated material does not become fully soluble as the temperature is raised, the material is said to melt incongruently.

Materials that melt incongruently or semicongruently can cause problems in latent heat storage systems, because as the salt precipitates out of the solution it is not available to recombine with the water. The problem can be overcome by actively mixing the system when it is in its liquid state, by storing the material in extremely small volumes (microencapsulation), or by fixing the material in a gel so that the salt cannot settle to the bottom. Because some of these remedies are not completely effective, an efficiency is assigned to latent heat storage devices. This efficiency is defined as the fraction of latent heat recoverable from the system.

Table 4-1. Latent Heat Storage Materials

Material	Melting Point, °F (°C)	Heat of Fusion, Btu/lb (kJ/kg)
Calcium Chloride Hexahydrate[c,d]	84.9 (29.4)	73.1 (170)
Sodium Carbonate Decahydrate[c,d]	91.0 (33)	108.0 (251)
Disodium Phosphate Dodecahydrate[c,d]	97.0 (36)	114.0 (280)
Sodium Sulfate Decahydrate[c,d]	90.3 (32.4)	109.0 (253)
Sodium Thiosulfate Pentahydrate[c,d]	120.0 (49)	86.0 (200)
N-Octodecane[d]	82.4 (28.0)	105.0 (243)
N-Eicosane[d]	98.1 (36.7)	106.0 (247)
Polyethylene Glycol 600[d]	68-77 (20-25)	63.0 (146)
Stearic Acid[d]	156.9 (69.4)	85.5 (199)
Water[d]	32.0 (0.0)	143.1 (333.4)
Tristearin[d]	133.0 (56)	82.1 (190.8)
Sunoco 116 Paraffin Wax[e]	116.0 (47)	90.0 (209.2)
Sodium Sulfate Decahydrate/Sodium Chloride/Ammonium Chloride Eutectic[e]	55.0 (13)	78.0 (181.3)

[a]C = congruent, S = semicongruent, I = incongruent, SC = tendency to supercool.

[b]liquid.

[c]Source: M. Telkes. Solar energy storage. *ASHRAE Journal* 16:44, September 1974.

[d]Source: United States National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Alabama. *Phase Change Materials Handbook*. NASA CR-61363. Prepared by D. V. Hale, M. J. Hoover, and M. J. O'Neill, Lockheed Missiles and Space Company, Huntsville, Alabama, September 1971.

[e]Source: Charles Lee, Lawrence Taylor, John DeVries, and Stephen Heibein. *Solar Applications of Thermal Energy Storage*. H-C0199-79-753F, Hittman Associates, Inc., Columbia, Maryland, January 1979. (Prepared for *Solar Energy Storage Options Workshop*, San Antonio, Texas, March 19-20, 1979.)

[f]Source: Frank Baylin. *Low Temperature Energy Storage: A State-of-the-Art Survey*. SERI/RR-54-164D, Solar Energy Research Institute, Golden, Colorado, March 1979.

Table 4-1 (continued)

Melting Behavior[a]	Solid Density, lb/ft^3 (kg/m^3)	Heating Capacity--Solid, Btu/lb·°F (kj/kg·°C)	Heating Capacity--Liquid, Btu/lb·°F (kJ/kg·°C)
S[f], SC[g]	102.0 (1630)	0.320 (1340)[i]	0.552 (2310)[i]
I[g], SC[g]	89.9 (1440)	-	-
C[d], S[f], SC[g]	95.0 (1520)	0.404 (1690)	0.464 (1940)
I[f]	91.2 (1460)	0.459 (1920)[h]	0.779 (3260)[h]
SC, S[f]	106.0 (1690)	0.60 (2510)[e], 0.346 (1450)[i]	- 0.570 (2389)[i]
C	50.8 (814)	0.515 (2160)	-
C	53.4 (856)	0.528 (2210)	0.481 (2010)
C	69.0 (1100)	0.54 (2260)	-
C	52.9[b] (847)	0.399 (1670)[i]	0.550 (2300)[i]
C, SC	57.24 (916.8)	0.487 (2040)	1.00 (4210)
C	53.8 (862)	-	-
C	49.0 (785)	0.691 (2890)[h]	-
	-	-	-

[g]Source: United States Energy Research and Development Administration. *Solar Energy Subsystems Employing Isothermal Heat Storage Materials.* ERDA 117. Prepared by George A. Lane et al., Dow Chemical Company, Midland, Michigan, May 1975.

[h]Source: J. J. Jurinak and S. I. Abdel-Khalik. Sizing phase-change energy storage units for air-based solar heating systems. *Solar Energy* 22 (4): 355-359, 1979.

[i]Source: Charles D. Hodgeman, editor. *Handbook of Chemistry and Physics.* Chemical Rubber Publishing Company, Cleveland, Ohio, thirtieth edition 1946.

Supercooling is another problem that occurs with some PCMs. As heat is drawn out of such a material, its temperature can drop below its normal melting point without a change in phase. The temperature will continue to drop until a crystal of solid PCM forms. At that point, rapid crystal growth accompanied by an increase in temperature to the melting point will occur, and the unit will revert to its normal freezing behavior. Two problems arise from supercooling: the system may cool below the point at which useful heat can be extracted, and the supercooled condition may give the controller a false signal that storage is completely discharged when, in fact, it is almost fully charged. The problems can be solved in two ways. A tube called a "cold finger" can be brought outside the insulation to a point where the PCM in the cold finger will freeze. (Room temperature is cold enough to freeze most PCMs.) The frozen material in the cold finger provides the first crystal on which other crystals can grow as the PCM freezes. Another solution is to introduce another material such as borax into the system. These materials, called "nucleating agents," provide sites for crystal growth.

Heat Capacity

Besides storing latent heat, some latent heat storage systems are allowed to store a small amount of sensible heat by cooling below or heating above the melting temperature. For these systems, you will need to know the heat capacities of the solid and liquid PCM so that you can calculate the amount of PCM required to store a given amount of heat. The amount of sensible heat stored in these systems is usually small compared with the latent heat stored. Determining the size of the latent heat storage system is covered in another section of this chapter.

Thermal Conductivity

A high thermal conductivity in both the liquid and solid phases of the PCM is desirable to achieve good heat exchange during charging and discharging. The thermal conductivity of the liquid phase is usually high enough that it does not create a problem, but the thermal conductivity of the solid phase tends to limit the rate at which heat can be removed from storage. The two methods used to overcome this limitation are:

- To package the PCM in thin containers with a large surface area.
- To stir the liquid phase.

Corrosiveness

The inorganic salt hydrates and the organic acids tend to be corrosive. Several of the salt hydrates react violently with aluminum or magnesium, and calcium chloride is particularly corrosive. These substances can be held in plastic containers, however. Waxes are generally inert unless they contain impurities.

SIZING LATENT HEAT STORAGE SYSTEMS

Although most of the heat stored in latent heat storage systems is stored as latent heat, some systems store a portion of it as sensible heat. The advantages of doing so are:

- The system can store more heat in a given amount of PCM.
- The temperature change associated with storing sensible heat gives an indication of when the system is fully charged or discharged.

Since the heat capacities of the solid and the liquid material differ, you must use three terms to calculate the heat that can be stored in the PCM:

- Sensible heat stored in the solid PCM.
- Latent heat stored in the PCM.
- Sensible heat stored in the liquid PCM.

The amount of heat, Q, in Btu (joules), stored is:

$$Q = m \quad C_{ps} \left(T_m - T_{min}\right) + \eta h_f + C_{p\ell} \left(T_{max} - T_m\right) \qquad (4\text{-}1)$$

where:

m is the amount of PCM in pounds (kilograms).

C_{ps} and $C_{p\ell}$ are the heat capacities in Btu per pound per degree Fahrenheit (joules per kilogram per degree Celsius) of the solid and liquid PCM, respectively.

T_m, T_{max}, and T_{min} are the melting point temperature, the maximum storage temperature, and the minimum storage temperature in degrees Fahrenheit (degrees Celsius).

h_f is the latent heat of fusion in Btu per pound (joules per kilogram).

η is the fraction of theoretical latent heat that can be recovered.

Sizing by Rule of Thumb

In Chapter 1, we gave a rule of thumb requiring that storage capacity be about 600 Btu per square foot (6.8 megajoules per square meter) of collector. The rule of thumb is valid for latent heat storage systems and can be used with Equation 4-1 to approximate the amount of PCM required.

Example 4-1: Suppose you want to store 400,000 Btu in Glauber's salt (sodium sulfate decahydrate) operating between 80 and 100°F (27 and 38°C). For your particular storage unit, it has been determined that after thirty heating and cooling cycles, 90 percent of the latent heat is recoverable. How much Glauber's salt is required for storage?

Rearranging Equation 4-1 and substituting the values from Table 4-1 gives the required mass of Glauber's salt.

$$m = \frac{Q}{C_{ps}\ (T_m - T_{min}) + \eta h_f + C_{p\ell}\ (T_{max} - T_m)}$$

$$= \frac{400,000}{0.459 \times (90.3-80) + 0.90 \times 109 + 0.779 \times (100-90.3)}$$

= 3624 lb (1647 kg) of Glauber's salt.

Compare this weight with the necessary weight for water--10,000 pounds--calculated in Example 1-1.

Dividing the mass of Glauber's salt by its density yields its required volume--39.7 cubic feet. Once again, compare this volume with the 160 cubic feet (1200 gallons) of water needed for sensible heat storage in Example 1-1. This comparison of volume does not tell the entire story, since heat transfer devices, stirring devices, and encapsulation tend to add bulk to the latent heat storage unit; nevertheless, it is clear that the potential for saving space is one of the main advantages of latent heat storage systems.

Sizing by Calculation

The method of sizing by calculation described in Chapter 1 can be used for latent heat storage systems, except that the simplified methods of analysis such as f-chart and SOLCOST have not been adapted to latent heat storage systems. More elaborate methods of analyzing system performance, such as DOE-1 and TRNSYS, can be used.

INSULATING LATENT HEAT STORAGE CONTAINERS

The compactness of latent heat storage containers means that they need less insulation than sensible heat storage containers. This actually represents a double saving, for having less surface area to insulate also implies that the insulation can be thinner. For example, if the same type of insulation is used for latent and sensible heat storage containers of equal storage capacity and the latent heat storage container has half as much surface area as the sensible heat storage container, the thermal loss from the latent heat storage unit will be half as much as the thermal loss from the sensible heat storage unit. If both types of storage must meet the same insulation standard for maximum loss in a given time period, the insulation on the latent heat storage unit would need to be only half as thick as the insulation on the sensible heat storage unit. Thus, the latent heat storage unit has a double saving in the amount of insulation required compared with the sensible heat storage unit--first, there is only half as much surface area to insulate; and second, the insulation need be only half as thick.

In addition to reduced surface area and thickness, the lower average temperature at which the latent heat storage unit operates makes it possible to use less insulation.

While these combined savings mean that latent heat storage devices require substantially less insulation than sensible heat storage devices, they also mean that Tables 1-7 through 1-10 cannot be used to calculate the amount of insulation they require. Equation 1-9, however, is completely general and can be used to calculate the maximum allowable thermal transmittance, U, in Btu/hr·ft^2·°F (W/m^2·°C), for latent heat storage containers.

$$U = \frac{fQ}{At\,(T_{avg} - T_a)} \qquad (1\text{-}9)$$

where:

Q is the amount of heat stored in Btu (joules).

f is the fraction of heat lost in time t.

A is the surface area of the storage unit in square feet (square meters).

T_{avg} is the average storage temperature in degrees Fahrenheit (degrees Celsius).

T_a is the average ambient temperature in degrees Fahrenheit (degrees Celsius).

t is the length of time in hours (seconds) used for specifying the maximum heat loss from storage.

Q should be calculated from Equation 4-1, and T_{avg} can be approximated as the melting temperature of the PCM.

AVAILABLE SYSTEMS

At this writing (September 1979), only a few latent heat storage systems are available on the market. The market is in a state of flux, however, with new systems appearing frequently. This section will describe some available systems; their inclusion in this manual is for information only, however, and should not be construed as an endorsement or recommendation.

Two companies, Pipe Systems Incorporated (Fenton, Missouri) and Texxon Corporation (Omaha, Nebraska), manufacture plastic pipes filled with calcium chloride hexahydrate and stabilizing ingredients, which have a melting temperature of 81°F (27°C). The pipes are 6 feet (1.8 meters) high with a 3-1/2-inch (8.9-centimeter) outside diameter. They have 4-inch (10-centimeter) flanges at each end so that when they are stacked together in an insulated bin, there is adequate room for air flow around them (see Figure 4-1). Each pipe contains 30 pounds (14 kilograms) of PCM with a heat of fusion of 82 Btu per pound (190 kilojoules per kilogram) and a sensible heat capacity of 0.53 Btu/lb·°F (2.22 kJ/kg·°C) in the liquid state.

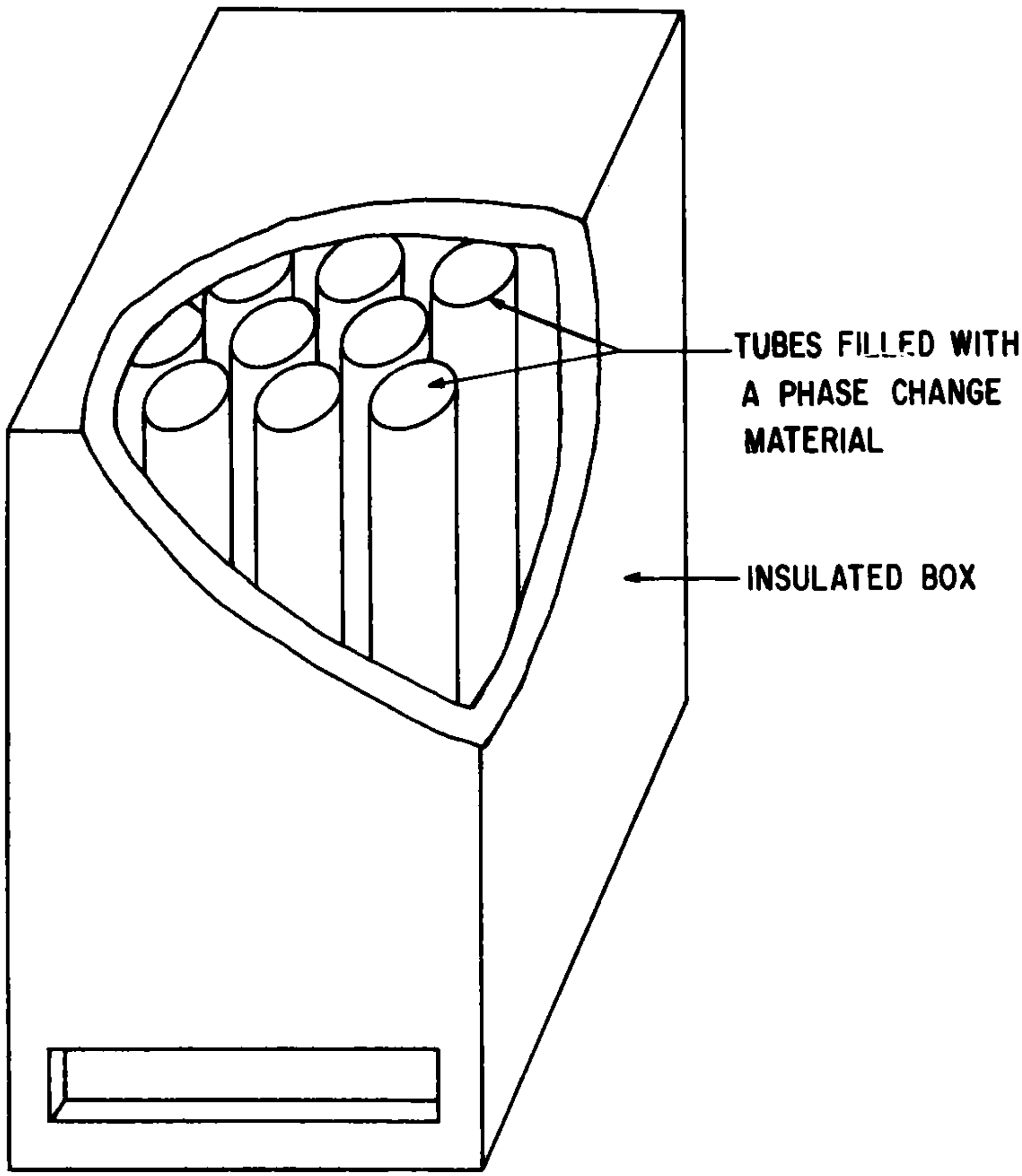

Figure 4-1. Plastic Pipes Containing Calcium Chloride Hexahydrate

Another type of air-based system uses flat plastic trays containing PCM (see Figure 4-2). "Suntainer" trays, manufactured by Solar, Inc., (Mead, Nebraska), each contain 13 pounds (5.9 kilograms) of Glauber's salt, with thickening agents to overcome the incongruent melting problem, and have a volume of 0.125 cubic feet (0.0035 cubic meters). The Glauber's salt mixture will store 10,600 Btu per cubic foot (395 megajoules per cubic meter) at 120°F (49°C) including both latent and sensible heat. Valmont Industries (Omaha, Nebraska) also sells a system using Glauber's salt in plastic trays.

A third type of air-based system uses a paraffin wax in canisters. Addison Products Company (Addison, Michigan) uses a paraffin wax that melts at between 115°F (46°C) and 120°F (49°C) and has a heat of fusion of 80 Btu per pound (186 kilojoules per kilogram). In this system the canisters are stacked on shelves that also act as baffles to force the air to travel the full length of each shelf before passing to the shelf below (charging) or above (discharging).

The three systems described above need extra space within the storage bin for air flow. There are three systems on the market that need less volume, because they use the PCM in bulk form rather than in individual containers. These systems are designed for use with liquid-based solar collectors.

The Solarmatic™ Division of OEM Products, Inc., (Tampa, Florida) produces a storage device called the Heat Battery™, as shown in Figure 4-3. The Heat Battery™ consists of an insulated tank containing a heat exchanger, Glauber's salt, a heat transfer fluid in which the salt will not dissolve or mix, a floating fluid segregator, and a series of pressure-controlled outlets for the heat transfer fluid.

When the system is being charged, an external pump forces the heat transfer fluid through the top outlets, which are located above the segregator, until the salt has melted down to the next level of outlets, freeing them for fluid flow. There is less pressure drop across the spring-loaded valve in this lower outlet than across the spring-loaded valve in the top outlet, so the fluid now flows out the lower outlet. The process can continue level by level until the entire tank is melted. For heat extraction, the process is reversed.

The movement of the heat transfer fluid keeps the Glauber's salt solution mixed, and because the two fluids are immiscible, the salt solution remains in small drops. Both of these effects minimize the incongruent melting problem. The fluid segregator keeps the Glauber's salt solution from being carried along with the heat transfer fluid, where it could foul the pump. The Heat Battery™ is being developed as part of a solar-assisted heat pump system.

Calmac Manufacturing Corporation (Englewood, New Jersey) produces a latent heat storage system in which a tank contains both the PCM, which can be any of several materials, and a plastic tubing heat exchanger. The heat exchanger tubes are placed close enough together so that they will effectively transfer heat into the solidified PCM. The PCM in its liquid state is kept stirred by a pump; when the PCM is solidified, the pump motor stalls without harm.

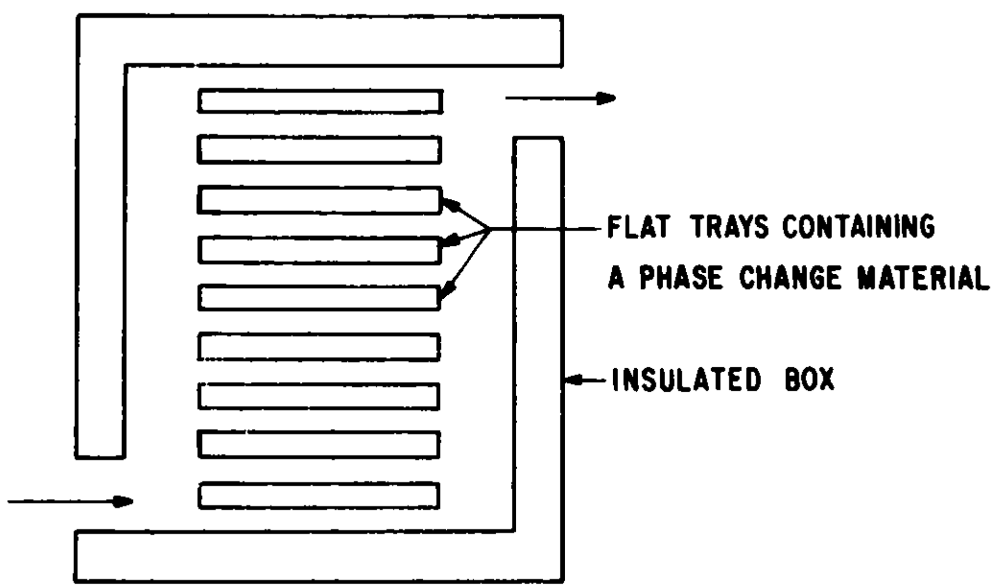

Figure 4-2. Plastic Trays Containing Glauber's Salt

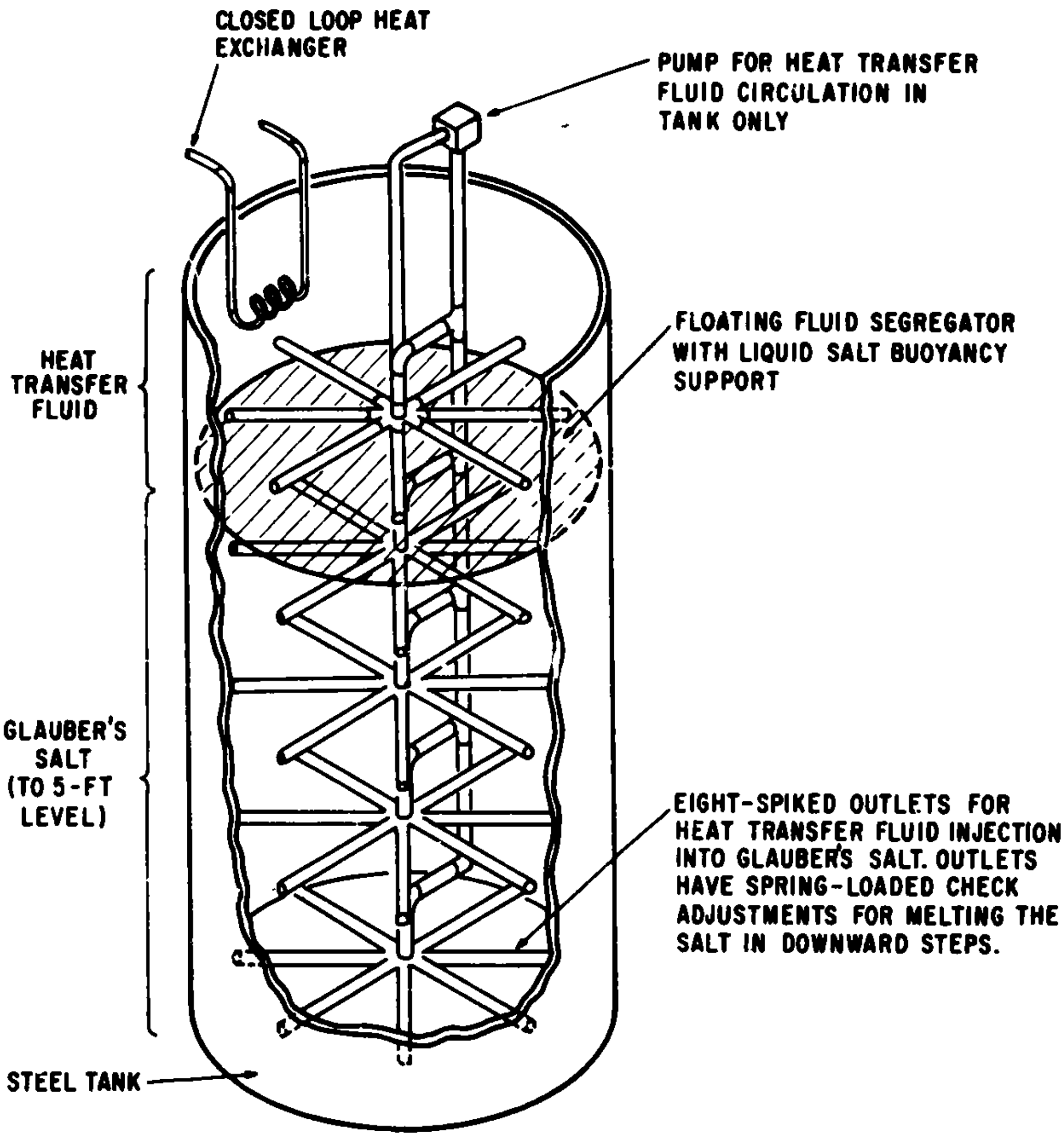

Figure 4-3. Heat Battery™, Produced by Solarmatic™ Division of OEM Products, Inc., Tampa, Florida

Another system, developed by Thermal Energy Storage Systems, Inc., (La Jolla, California), is similar to the Calmac system except that it uses less heat exchanger tubing and uses chemicals to keep the sodium thiosulfate pentahydrate (hypo) from supercooling. An advantage of both systems is that as heat escapes through the insulation some of the PCM will solidify on the walls, in effect creating more insulation and reducing heat losses.

COST OF LATENT HEAT STORAGE SYSTEMS

At present (September 1979), the costs of latent heat storage systems vary considerably. Lee, Taylor, DeVries, and Heibein list costs that vary from $5,000 to $18,500 per million Btu ($4.75 to $17.55 per million joules). These costs cover a range from partially complete, unassembled units to complete storage systems. By comparison, sensible heat storage in a water tank costs about $2,000 to $7,500 per million Btu ($1.90 to $7.10 per megajoule).[1] More recent contact with manufacturers suggests a clustering of several systems at about $10,000 to $12,000 per million Btu ($9.50 to $11.40 per megajoule), but the overall range is still large. As companies gain experience and competition, the range of costs can be expected to decrease.

Latent heat storage systems for heating and cooling applications are unlikely to compete in the near future with sensible heat storage systems on the basis of cost. Instead, the compactness of latent heat storage systems and their ability to enhance collector performance will be emphasized. Compactness will allow installation of latent heat storage containers in locations where sensible heat storage containers would be difficult or expensive to install.

Enhancing collector performance by maintaining a low average collector temperature may lead to an overall reduction in system cost in some systems. The choice of latent versus sensible heat storage systems can only be made after analysis of the entire system's performance with each type of storage system. Unfortunately, the simplified analysis methods such as f-chart and SOLCOST do not have provisions for analyzing systems with latent heat storage, although the more elaborate simulation methods such as TRNSYS and DOE-1 can analyze these systems. In the near future, new simplified analysis methods and modifications to existing ones can be expected as latent heat storage systems become more readily available.

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[1] The costs were calculated for a water tank cost of $1.00 to $2.50 per gallon ($0.26 to $0.66 per liter) and an operating temperature range of 40 to 60°F (22 to 33°C).

SYMBOLS USED IN CHAPTER 4

Main Symbols

A	surface area of the storage unit in ft^2 (m^2)
Cp	heat capacity in Btu/lb·°F (J/kg·°C)
f	fraction of heat lost in time t
h_f	latent heat of fusion in Btu/lb (j/kg)
m	mass of phase change material (kg)
Q	amount of heat stored in Btu (J)
T	temperature in °F (°C)
t	a time period in hours (seconds) during which no more than a specified fraction, f, of the heat stored can be lost
η	fraction of theoretical latent heat that can be recovered

Subscripts

a	ambient condition
avg	average condition
ℓ	liquid PCM
m	melting point
max	maximum condition
min	minimum condition
s	solid PCM

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CHAPTER 5
THERMAL ENERGY STORAGE IN DOMESTIC HOT WATER SYSTEMS

The most common and economical use of solar energy in the United States is heating hot water in homes and other buildings. Because hot water is the product of the system, water is the natural thermal energy storage medium.

SAFETY CONSIDERATIONS

Solar hot water heating systems differ from conventional hot water heating systems mainly in two areas, both related to safety. First, the potable water must be separated from nonpotable water and from the toxic substances used in many solar systems. Second, overheating of the system must be guarded against.

Separation of Potable and Nonpotable Liquids

The Department of Housing and Urban Development has published standards for property receiving federal financing in their Solar Initiative programs. The HUD Intermediate Minimum Property Standards lists the following requirements:

"S-615-10 PLUMBING

"S-615-10.1 Handling of Nonpotable Substances

Potable water supply shall be protected against contamination in accordance with the prevailing model plumbing code having jurisdiction in the area, as well as the requirements which follow.

"S-615-10.1.1 Separation of Circulation Loops

Circulation loops of subsystems utilizing nonpotable heat transfer fluids shall either be separated from the potable water system in such a manner that a minimum of two walls or interfaces is maintained between the nonpotable liquid and the potable water supply or otherwise protected in such a manner that equivalent safety is provided.

"Commentary: Double wall heat exchanger designs are one way of meeting the intent of this criterion. When double wall heat exchanger designs consisting of two single wall heat exchangers in combination with an intermediary potable heat transfer liquid are used, leakage through one of the walls would result in a single wall configuration.

Although this design is considered to meet the intent of this criterion, there are several other designs that avoid this problem.

"The use of single wall configurations which solely rely upon potable water pressure to prevent contamination is not considered to be an acceptable solution. Similarly, extra thick single walls are not considered to meet the intent of this criterion.

"For approval of other than double wall designs, the procedures described in S-101 should be utilized.[1]

"S-615-10.1.2 Identification of Nonpotable and Potable Water

In buildings where dual fluid systems, one potable water and the other nonpotable fluid, are installed each system may be identified either by color marking or metal tags as required in ANSI A13.1-1956 [*Scheme for the Identification of Piping Systems*, American National Standards Institute] or other appropriate method as may be approved by the local administrative code authority. Such identification may not be required in all cases.

"S-615-10.1.3 Backflow Prevention

Backflow of nonpotable heat transfer fluids into the potable water system shall be prevented in a manner approved by the local administrative code authority.

"Commentary: The use of air gaps and/or mechanical backflow preventers are two possible solutions to this problem."

At present (1979), the Uniform Plumbing Code (UPC) published by the International Association of Plumbing and Mechanical Officials (IAPMO), the Standard Building Code (SBC) published by the Southern Building Code Congress International (SBCCI), and the National Standard Plumbing Code (NSPC) published by the National Standard Plumbing Code Committee (NSPCC) require double-walled heat exchangers having separated walls to separate potable water from nonpotable fluids. If one wall of such a heat exchanger leaks, the heat exchanger is then considered single-walled. To meet these codes, then, the heat exchanger must incorporate some form of leak detection, either visual, electrical, or mechanical. Most local building code authorities adopt one of these codes.

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[1] S-101, "Variations to Standards," is an earlier section of the *HUD Intermediate Minimum Property Standards*. It lists some general goals and refers to Section 101-4 of MPS 4900.1, *Minimum Property Standards for One- and Two-Family Dwellings*, which contains details for approval of one-time-only and multiple-occurrence variations.

Because of the severe performance penalty imposed by double-walled heat exchangers, the American Society of Mechanical Engineers (ASME) under the auspices of the American National Standards Institute (ANSI) is working on less restrictive standards for heat exchangers. When they are finished, probably in 1980, they may be adopted by the organizations listed above.

Of the various types of heat exchangers, only the double-walled heat exchanger is rarely encountered in conventional plumbing practice. Some types of heat exchangers which may be double walled are:

- Wraparound shell (Figure 1-11).
- Two single-walled heat exchangers with an intermediate loop.
- Coil-in-tank (Figure 1-9).
- Coil-around-tank--also called traced tank (Figure 1-10).
- Shell-and-double-tube (Figure 1-13).

A wraparound shell heat exchanger can be single walled as shown in Figure 5-1a or it can be double walled as shown in Figure 5-1b. The bleedhole provides visual leak indication, but it must, of course, be able to drain to a location where the fluid will be visible.

Two single-walled heat exchangers with an intermediate loop may satisfy code requirements if the fluid in the loop is potable. That can be a problem, because water in a closed system such as a thermal energy storage tank is often considered nonpotable even if it contains no additives.

The coil-in-tank heat exchanger is considered double walled if the coil is made of double-walled tubing. Figure 5-2a shows a type of double-walled tubing that is considered an extra-thick single wall according to most interpretations of the HUD Intermediate Minimum Property Standards; Figure 5-2b shows a type that may meet the requirements. External leak indication may be a problem with the latter type.

A heat exchanger that consists of a coil wrapped around a tank may also be considered either single or double walled. If the coil is not soldered to the tank, it is definitely double walled; but soldered coils may be considered single walled if the soldered area is large enough to sustain a leak without any fluid leaking outside.

The shell-and-double-tube heat exchanger is double walled and will satisfy most code requirements.

Overheating

Overheating is the second area of concern in domestic hot water heating by solar energy. Conventional hot water heaters are regulated by thermostats that do not allow water temperatures to exceed the thermostat setting (usually 140°F, or 60°C). It is quite possible, especially in summer, for solar-heated water to reach scalding temperatures that can cause serious

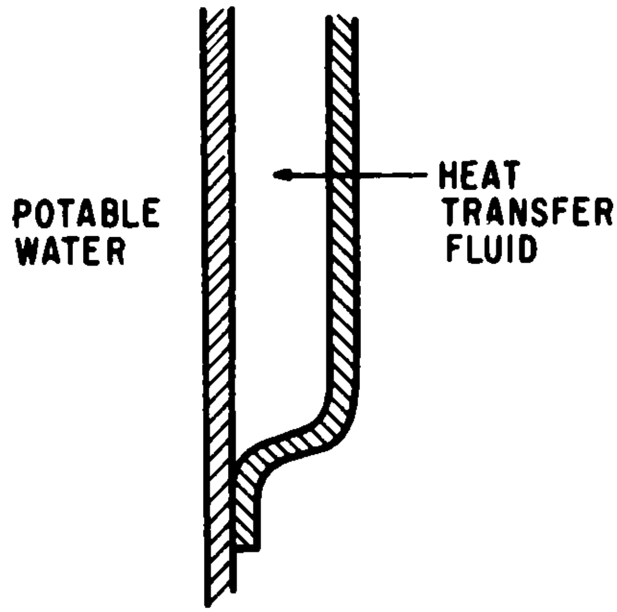

Figure 5-1a. Single-Walled Wraparound Shell Heat Exchanger

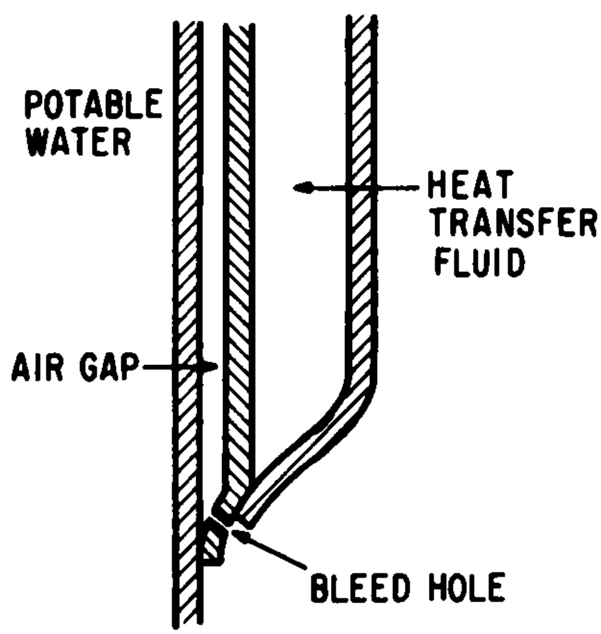

Figure 5-1b. Double-Walled Wraparound Shell Heat Exchanger

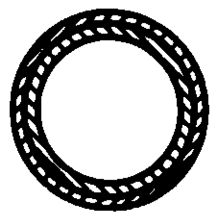

Figure 5-2a. Double-Walled Tubing
(May Not Meet Requirements)

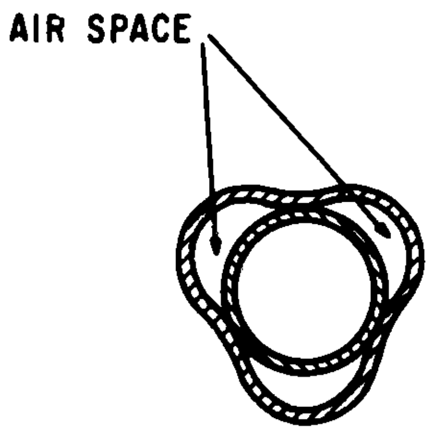

Figure 5-2b. Double-Walled Tubing
(May Meet Requirements)

burns. For this reason all the hot water should pass through a tempering (mixing) valve that adds enough cold water to keep the temperature of water delivered to the taps below 140°F (60°C). Figure 5-3 shows a typical tempering valve installation. If the tempering valve is soldered in place, the temperature-sensing element must be removed during soldering to prevent its being damaged. The tempering valve must not be mounted directly above a hot water tank, because heat from the tank would affect the calibration of the sensing element.

All domestic hot water tanks must be equipped with temperature and pressure relief valves as specified in local building codes. In addition, the tank must comply with the ASME Boiler and Pressure Vessel Code if any of the following conditions are exceeded:

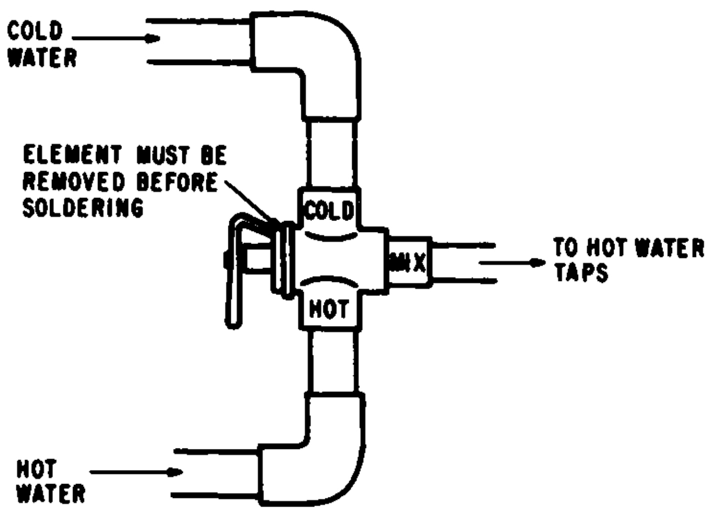

Figure 5-3. Typical Tempering Valve

- 120-gallon-capacity (454-liter-capacity) tank.
- 200,000-Btu-per-hour (60-kilowatt) heating rate.
- 210°F (99°C) water temperature in tank.

Since most single-family residential domestic hot water tanks do not exceed these conditions, they are exempt from ASME Boiler and Pressure Vessel Code requirements.

SIZING DOMESTIC HOT WATER STORAGE SYSTEMS

The storage system should be large enough to supply approximately 100 percent of the daily hot water load from storage. The HUD Intermediate Minimum Property Standards recommend the following guidelines for determining the load:

- For one- and two-family residences and apartments up to twenty units, each unit requires 20 gallons (76 liters) each for the first two persons plus 15 gallons (57 liters) for each additional person.
- For apartments of 20 to 200 units, each unit requires 40 gallons (150 liters).
- For apartments of more than 200 units, each unit requires 35 gallons (130 liters).

In most cases there is no conflict between these storage sizes and the rule of thumb of 1.25 to 2 gallons per square foot (50 to 75 liters per square meter) of collector given in Chapter 1.

If there is a small conflict between the rule of thumb and the HUD recommendations, choose the larger of the two. In the rare instance that the conflict between the two methods is substantial, only computer methods such as TRNSYS or DOE-1 can resolve the conflict.

AUXILIARY HEATING SYSTEMS

To provide hot water on cloudy days you will need auxiliary heat, which can be provided by gas, oil, or electricity. There is considerable controversy about whether the auxiliary heat should be added to the solar-heated tank (a one-tank system, shown in Figure 5-4) or the auxiliary tank should be separate from the solar-heated tank (a two-tank system, shown in Figure 5-5).

With gas or oil auxiliary heat the flue is a major source of heat loss. This heat loss can be minimized in two ways, which can be used separately or in combination: (1) by using a small auxiliary heating tank which has relatively small flue loss, or (2) by installing an automatic flue damper. The use of a small auxiliary heating tank implies a two-tank system. The small heater does not provide enough hot water for heavy demand by itself, but preheating the water from the solar storage tank allows the auxiliary heater to recover quickly. Retrofit solar systems can use an existing gas or oil water heater as the auxiliary unit, although the tank and its corresponding flue losses will be larger than necessary. Automatic flue dampers are recommended for gas and oil auxiliary heaters, but they may be prohibited or very strictly regulated by local building codes, and they may cost too much compared with the value of the energy they save. If you want to use an automatic flue damper, be sure it is approved by the American Gas Association (AGA), Underwriters Laboratories (UL), and your local building codes.

With electric auxiliary heat there are no flue losses, and one-tank systems are usually specified, since the cost of providing an electric heater in the tank is very low compared with the overall cost of another tank. Electric heaters are usually installed in the upper part of the tank to take advantage of temperature stratification. In retrofit applications, storage tanks with electric heaters are frequently ordered where the source of auxiliary heat is an existing gas or oil water heater. The electric element is left unconnected until the gas or oil water heater fails, at which time the electric element is connected and the system is converted to one-tank operation.

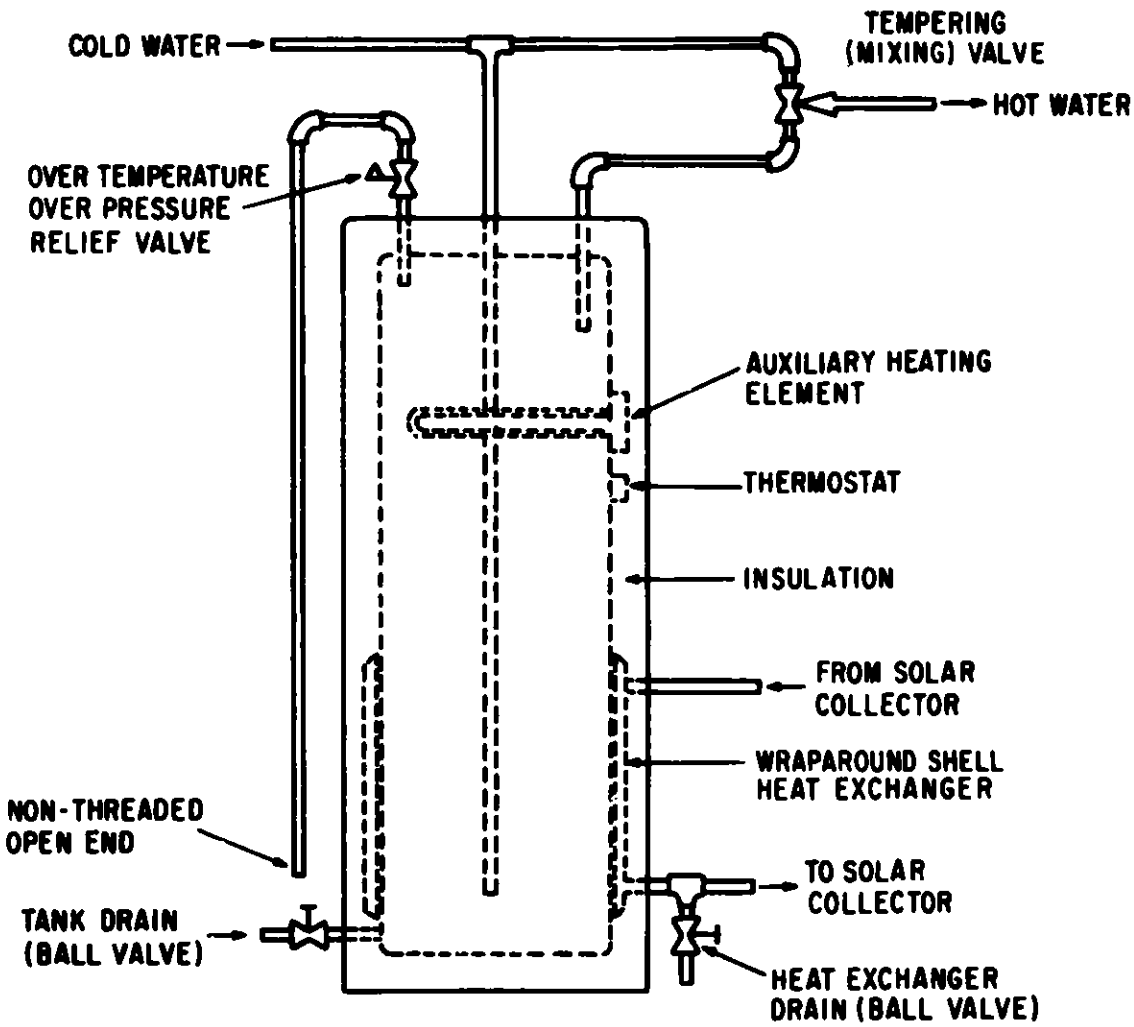

Figure 5-4. Typical One-Tank Installation

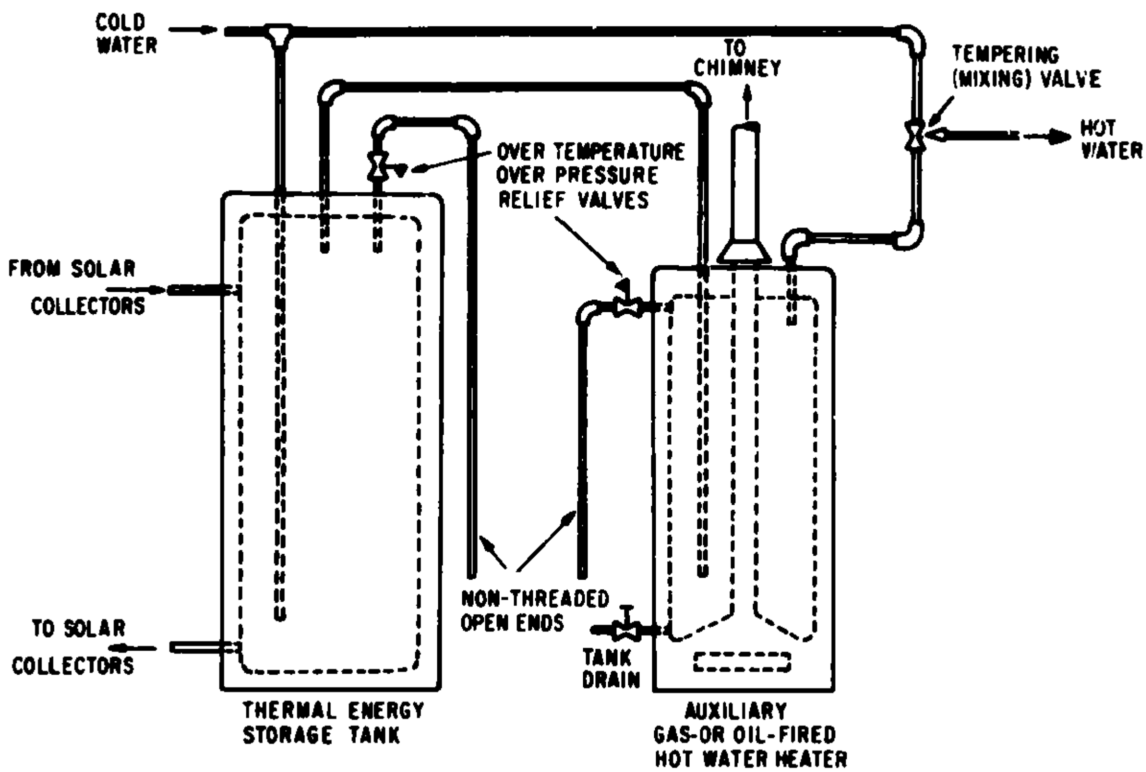

Figure 5-5. Typical Two-Tank Installation

TANK INSULATION

Typical domestic hot water tank insulation has a thermal conductance of 0.10 Btu/hr·ft^2·°F (0.57 W/m^2·°C) or more. By comparison, following the method described in Chapter 1 of this manual would require a thermal conductance of 0.030 to 0.033 Btu/hr·ft^2·°F (0.17 to 0.19 W/m^2·°C) to limit heat loss to 2 percent in 12 hours (assuming a tank temperature of 140°F and an ambient temperature of 70°F). Even if the insulation requirements were lowered to limit losses to 10 percent in 24 hours as specified by the HUD Intermediate Minimum Property Standards, a thermal conductance of 0.071 to 0.083 Btu/hr·ft^2·°F (0.40 to 0.47 W/m^2·°C) would be required. Clearly, then, most domestic hot water tanks can benefit from added insulation, and insulation kits are available. The added insulation is very effective on electric- and solar-heated storage tanks, but it cannot reduce the flue losses in gas- or oil-fired tanks. If you install additional insulation, be careful not to obstruct air vents on gas- or oil-fired tanks, controls, pressure and temperature safety valves, or water temperature tempering valves.

DOMESTIC HOT WATER WITH LIQUID-BASED SPACE HEATING

A domestic hot water heating system can be used with a liquid-based space heating system in several ways. A separate stand-alone hot water system that can operate throughout the year independent of the space heating system can be used. This type of installation allows the space heating system to be shut down in the summer with no effect on the hot water system.

Two variations of a system in which domestic hot water is preheated by a heat exchanger in the storage tank are shown in Figure 5-6. The main advantage of this type of system is that it does not require a separate tank for storing preheated domestic hot water. However, the space heating storage tank must be heated in the summer to provide year-round solar-heated domestic hot water. Furthermore, most corrosion inhibitors could not be used in the storage tank without violating the HUD Intermediate Minimum Property Standards for double-walled heat exchangers.

A system in which hot water from the main storage tank is pumped through the domestic hot water heat exchanger is shown in Figure 5-7. The spring-check valve prevents thermosyphoning when the domestic hot water tank is warmer than the main storage tank. The chief advantage of this system is that corrosion inhibitors can be used in the main storage tank, since domestic hot water tanks with double-walled heat exchangers are available. Disadvantages include the system's mechanical complexity and the necessity of heating the main storage tank in summer.

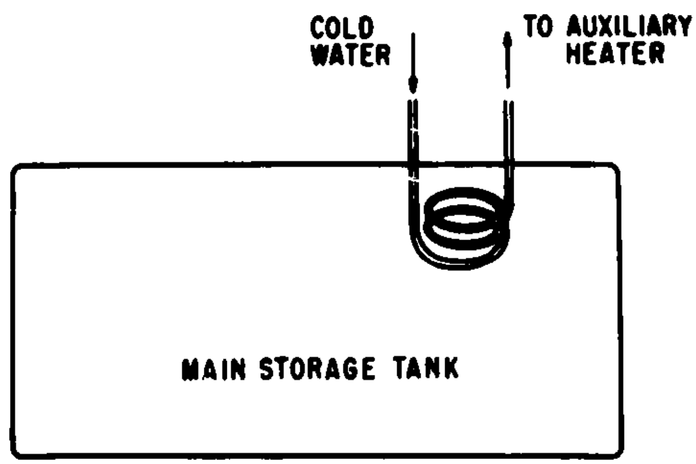

Figure 5-6a. Coil Immersed in Main Storage Tank to Heat Domestic Hot Water

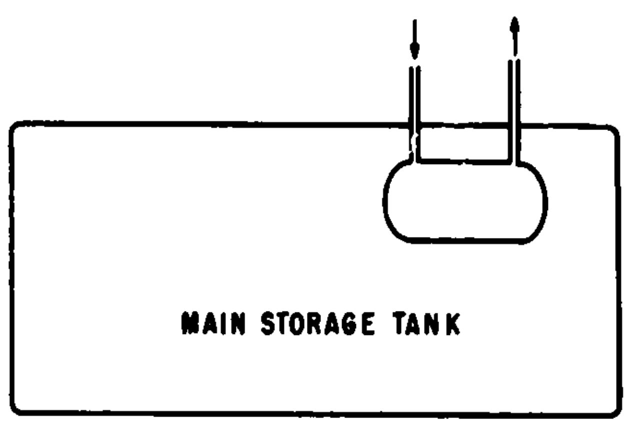

Figure 5-6b. Tank Immersed in Main Storage Tank to Heat Domestic Hot Water

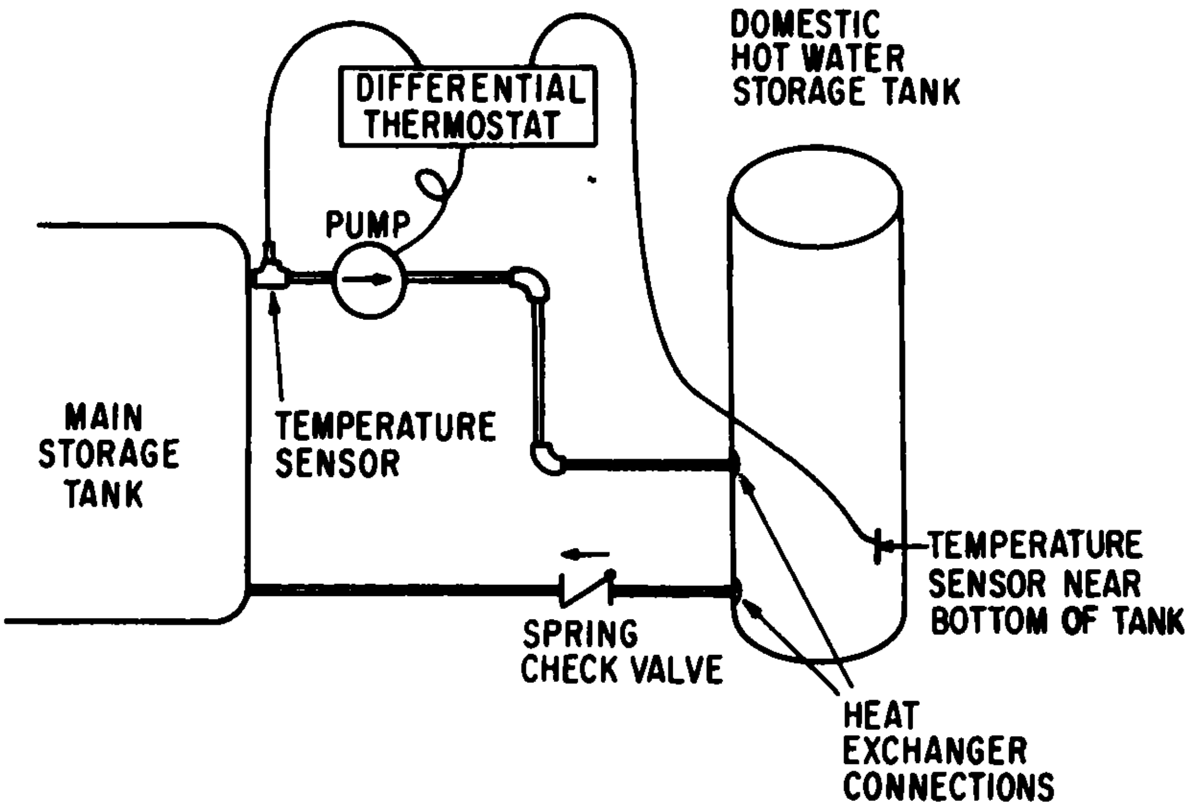

Figure 5-7. Water Pumped from Main Storage Tank to Heat Domestic Hot Water

DOMESTIC HOT WATER WITH AIR-BASED SPACE HEATING

An air-to-liquid heat exchanger (Figure 1-14) installed between the air handler and the rock bin is commonly used to heat domestic hot water in air-based systems. The heat exchanger must be capable of withstanding watermain pressure, since it will contain potable water. A pump circulates water from the domestic hot water tank to the air-to-liquid heat exchanger.

The heat exchanger can be placed between the air handling unit and the rock bed as shown in Figure 5-8. If heat leakage from the rock bed will not add to the summer air conditioning load, then the bypass duct and the manually operated dampers shown in Figure 5-8 are not necessary. The dampers in the air handling unit must close the collector loop when the power is off to prevent freezing the heat exchanger in the winter. These dampers must have good seals of felt or silicon rubber to prevent leakage.

STAND-ALONE DOMESTIC HOT WATER SYSTEMS

The most common type of solar system being installed today is the stand-alone domestic hot water system. Since the purpose of these systems is to heat water, most are liquid based, although a few are air based.

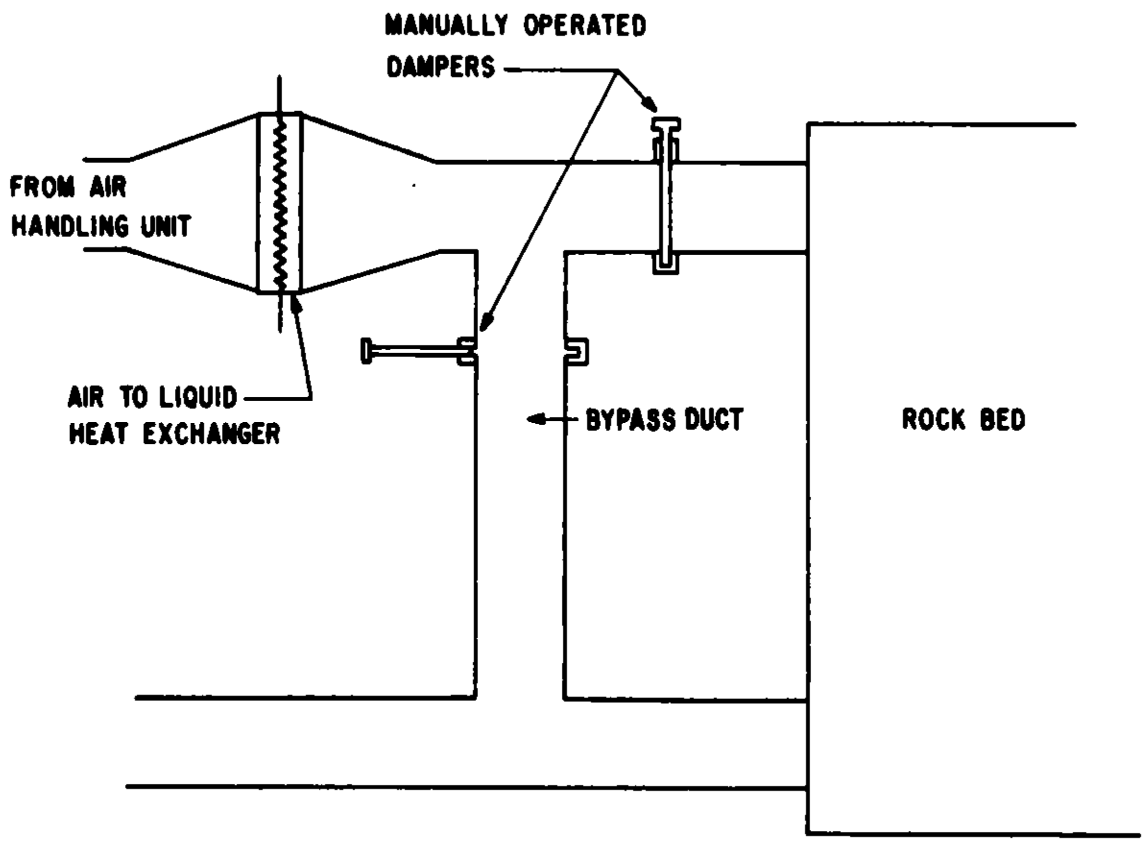

Figure 5-8. Air-to-Liquid Heat Exchanger Installation

For single-family residential systems, many companies sell kits that include specialized solar system components such as collectors, storage tanks, heat exchangers, controllers, pumps, valves, and temperature sensors, as well as installation instructions. The installer must supply standard hardware such as electrical wire, pipe and fittings, and nuts and bolts. We recommend using such a kit in preference to individual components because the kit manufacturers have selected components and controls that work together and have tested and modified the systems to eliminate problems.

If you use a kit there are several things you should do before beginning to install it. Read the manufacturer's instructions carefully so that you will know what order the steps of the installation must follow, what specialized skills are necessary, and whether any steps require special care or precautions. Determine exactly what materials you must supply--this requirement varies from one manufacturer to another. Also, determine what type of heat exchanger is supplied in the kit, whether the heat exchanger fluid to be used is toxic, and whether local building officials will approve the installation.

Systems larger than 120-gallon (454-liter) capacity are not available as kits. If you choose to design a domestic hot water system using components from different sources, you should be thoroughly familiar with the material in Chapters 1, 3, and 5 of this manual and the appendices referred to in those chapters. We also recommend that a professional engineer be a member of the design team. An important difference between large and small systems is that domestic hot water tanks larger than 120-gallon (454-liter) capacity must have an ASME Pressure Vessel Certification. A sample specification for a large domestic hot water tank is given in Appendix G.

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APPENDIX A
COMMON PROBLEMS OF STORAGE SYSTEMS

The following table presents some examples of problems actually experienced with solar energy storage systems, what caused the problems, and how they were dealt with.[1]

PROBLEM	DESCRIPTION	RESOLUTION
Stratification in Liquid Tank Not Accomplished.	High velocity input prevented stratification and reduced efficiency.	Diffusers were installed to minimize velocity.
High Thermal Loss in Buried Tank	Water getting into insulation of buried tank increased heat loss.	Provide ground drainage, provide waterproof insulation, or locate above ground.
Heat Loss	High heat loss at night was thought to be caused by heat escaping through the tank insulation because of high groundwater. Further investigation showed a faulty thermocouple that allowed pump to run all night, rejecting tank heat to atmosphere.	Thermocouple was replaced and replacement also failed. It was then found that the thermocouples used were not suitable for the temperatures experienced. They were replaced with high temperature thermocouples.
Heat Loss	Groundwater around tank caused high heat loss.	Additional insulation and stones were placed under and around tank to improve drainage.

[1] United States Department of Commerce, National Technical Information Service. *Hardware Problems Encountered in Solar Heating and Cooling Systems*, prepared by Mitchell Cash, George C. Marshall Space Flight Center. N78-25539, May 1978.

PROBLEM	DESCRIPTION	RESOLUTION
Bypass of Rock Bed	A rock bed designed for horizontal flow had an air space at the top, which permitted the air to bypass the rocks.	Redesign to use vertical flow through the rock bed. (Horizontal flow also reduces the desired stratification effect.)
Leakage	Leakage existed at joints of fiberglass tank after tank was assembled on site from two halves.	Carefully assemble following the manufacturer's recommendations and using the recommended sealing materials.
Leakage	Fiberglass tanks leaked through wicking action in some fiberglass threads that extended through the tank.	Seal all exposed fiberglass threads.
Sewer Gas in the House	A sewer drain was installed under a rock bin to remove any water. The heat in the bin evaporated the water in the drain trap, letting sewer gas into the house.	Changed drain to a location outside rock bin.
Heat Loss through Insulation	Buried concrete tank leaked water through the tar seal, soaking the insulation and increasing the heat loss.	Changed to aboveground storage tank.
Heat Loss	Heat loss from domestic hot water tanks exceeded manufacturer's specifications. Investigation showed the added solar piping and instrumentation provided an increased heat leak path.	Adequately insulated all exposed piping and instrumentation connected to the storage tank.

PROBLEM	DESCRIPTION	RESOLUTION
Oversized Storage Tank	Tank was too large for collector area and tank temperature never exceeded 57°C (135°F).	Replaced tank with one that provided 7.6 liters (2 gallons) of storage for each square foot of collector.
Contaminated Heat Exchangers	Heat exchangers supposedly of refrigeration quality were contaminated with machine oil and metal filings.	Units were returned to vendor for cleaning.
Heat Transfer Losses	Heat transfer from collector loop through the heat exchanger into the storage tank was not as good as assumed.	A parallel heat exchanger was added. (This was considered less expensive than replacing with a more desirable larger single heat exchanger.)
Corrosion	Investigation indicated that the corrosive condition of the ground itself might create problems with the underground storage tank.	Installed cathodic protection for the tank (sacrificial magnesium anodes) and coated tank with a rubberized vapor barrier.
Heat Loss	Underground tank insulation was damaged by lack of proper support in rocky soil. Maintaining water-tight insulation on underground storage tanks is difficult. Water in insulation increased heat transfer.	Check waterproofing prior to installing, provide proper support, install carefully, patch any bad spots in insulation, and backfill carefully.

PROBLEM	DESCRIPTION	RESOLUTION
Incorrect Inlet and Outlet	Flow from collector to tank entered at bottom of tank. Flow back to collector was also from bottom of tank, causing short circuit in flow path and eliminating benefit of stratification.	Flow from collector to tank should enter tank at top where water is hottest. Flow back to collector should be from bottom of tank (on opposite end from inlet if no distribution manifold is used).
Materials	Material planned for inside coating of storage tank melted at 82°C (180°F).	Changed to a compound stable at 145°C (250°F).
Saturation of Insulation	An open-cell foam was applied to the tank. This acted as a sponge, collected water, and increased heat loss.	Use closed-cell foam.
Too Many Tank Penetrations	The fiberglass storage tank had all feed and return pipes for the solar collector loop, house loop, and domestic hot water loop through the tank below the water level. This resulted in leaks that were difficult to seal.	Two of the three loops were pressurized with positive pressure to the pump suction. Only suction line to the unpressurized loop needed to be below the water level to provide positive suction to the pump. All others could be brought into the tank above the waterline, and even the one suction line tank penetration could be above the water level if a foot valve was added.

PROBLEM	DESCRIPTION	RESOLUTION
High Pressure Drop in Heat Exchanger	Heat exchanger tubes extended completely through manifold to far side of manifold and restricted flow.	Reworked manifold header to provide internal clearance.
Loss of Heat from Storage	A heat exchanger for collector-to-storage heat transfer was installed too high in the storage tank. Under some conditions (particularly when solar radiation was low), the collector pump would start when collector temperatures were below storage tank top temperatures, resulting in transfer of heat from storage to collector.	Ensure proper location of heat exchangers and proper location and setting of controls.
Trash in Tank	Tank covers were difficult to remove to check water level, and loose tank insulation was dislodged and dropped into tank.	Covered source of loose insulation and used care in opening.

APPENDIX B
HEAT TRANSFER FLUIDS AND PRESSURE DROPS

Heat transfer fluids are used in solar systems to transfer heat from the solar collector to the storage medium and from the storage medium to the building. They are sometimes called "collector coolants" because they cool the collector as they absorb its heat. Mention of specific products in this appendix is for information only, and does not constitute an endorsement or recommendation.

COMPARISON OF HEAT TRANSFER FLUIDS BY GENERAL CHARACTERISTICS

Air

Air is one of the most commonly used transfer fluids in solar systems. It is free and will operate at any temperature the solar system will reach. Moreover, a leak in an air-based system will cause no damage, although it will degrade system performance. Since air has a low volumetric heat capacity, its flow rate through the system must be high. The power used to transfer a given amount of energy is higher for air than for most liquids. The major disadvantage of air is that it requires large duct size, which makes retrofitting difficult and provides more area for thermal losses. Air handling systems are also generally noisier than liquid-based systems.

Water

Water is a readily available fluid with good heat transfer properties (high heat capacity, high thermal conductivity, and low viscosity). Its major drawbacks are its high freezing temperature, its expansion upon freezing, and its corrosive effect on common engineering materials (except copper). Its low boiling point can cause high pressures within the collector system under zero flow conditions. Water has no adverse biological or environmental effects.

Ethylene Glycol

Other than water, the most commonly used heat transfer liquids in flat plate collectors are water/ethylene glycol solutions. These common, colorless, odorless antifreeze solutions are also used in many other applications. Ethylene glycol is relatively inexpensive and available from many manufacturers. (See listings in the *Thomas Register*.) With corrosion inhibitors, aqueous ethylene glycol solutions can reduce the corrosive action and freezing temperature of water. These solutions are usually available in a wide range of concentrations and inhibitor levels. The thermal properties of the solutions (heat capacity, thermal conductivity, and viscosity) are poorer than those of water.

The boiling and flash points of aqueous ethylene glycol mixtures are low and can be easily reached under zero flow conditions. Glycols can oxidize to organic acids (such as glycolic acids) when exposed to air near boiling temperatures. The inhibitors used are designed to neutralize these extremely corrosive acids. Periodic maintenance and addition of inhibitors must be done if these fluids are used. Another major drawback to the use of ethylene glycol is its high toxicity.[1] Most plumbing codes require that ethylene glycol solutions be separated from potable water by double-walled heat xchangers.

Propylene Glycol

Propylene glycol has properties similar to those of ethylene glycol, except that propylene glycol has higher viscosity and is less toxic. With inhibitors, propylene glycol can be used with most common engineering materials. Periodic maintenance must be performed and inhibitors must be added to limit corrosion. Propylene glycol will also form acids at high temperatures in oxygen-rich atmospheres. Because of its lower toxicity, propylene glycol has been widely used in the food industry. Most manufacturers who produce ethylene glycol also market propylene glycol. The higher viscosity of propylene glycol makes the heat transfer properties of aqueous propylene glycol mixtures poorer than those of ethylene glycol.

Other Glycols

Other glycol solutions have been used as heat transfer fluids in industrial applications. These include diethylene and triethylene glycol. With inhibitors, both of these fluids can be used with higher boiling points than ethylene glycol. The thermal properties of these aqueous solutions are similar to those of ethylene glycol at similar concentrations. The vapor pressure of each is slightly higher than that of ethylene glycol. Their toxicity is between that of ethylene and propylene glycol; their cost is slightly higher than that of ethylene and propylene glycol.

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[1] The U.S. Food, Drug and Cosmetic Act of 1938, a step in the formation of the U.S. Food and Drug Administration (FDA), was prompted mainly by a poisoning episode in 1937 involving at least 73 deaths and perhaps as many as 107 deaths caused by diethylene glycol contained in a drug known as "Elixir Sulfanilamide" (according to W. G. Campbell). Diethylene glycol is somewhat <u>less</u> toxic than ethylene glycol.

Other glycol heat transfer compounds include polyalkylene glycols such as Ucon[2] brand fluids and Jeffox[3] brand fluids. With inhibitors, the corrosive action of these compounds upon common engineering materials can be reduced. They are low in toxicity and are available in a wide range of viscosities. Fluids of this type that are applicable to heat transfer purposes cost more than the other glycol compounds.

Petroleum (Mineral) Oils

Petroleum oils are also used as heat transfer fluids in industrial applications. They generally are designed to operate at high temperatures, although some are able to offer lower temperature operation. As a group, they have poorer heat transfer properties than water, with lower heat capacity and thermal conductivity and higher viscosity. The flash point and boiling point lie below possible zero flow temperatures of a collector. Upon exposure to air at high temperatures, these fluids are subject to oxidation and cracking, forming tars and other by-products that will reduce collector performance and increase corrosion. The toxicity of these fluids is generally low, and their prices are relatively low. Mobiltherm[4] Light brand fluid was chosen in this appendix as a good representative of this class of fluids for low temperature applications.

Silicone Fluids

Some flat plate collector installations have used silicone fluids for heat transfer. They are produced by Dow Corning and General Electric, among others. These fluids have low freezing and pour points, low vapor pressure, low general corrosiveness, good long term stability, and low toxicity. Their major drawbacks are high cost and high viscosity, causing poor heat transfer and requiring higher flow rates. Also, leakage through fittings can create problems because silicone fluids have lower surface tension than aqueous solutions. Joints and fittings must be tight to ensure that leakage is minimal.

Other Fluids

Another fluid for possible use in flat plate collectors is Dowtherm[5] J brand fluid. It is an alkylated aromatic compound with low viscosity, low heat capacity, and low thermal conductivity. It is relatively inexpensive but has low flash and fire points. Oxidation of Dowtherm J at high temperatures

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[2] Ucon is a trademark of Union Carbide Corporation.

[3] Jeffox is a trademark of Jefferson Chemical Company, Inc.

[4] Mobiltherm is a trademark of Mobil Oil Corporation.

[5] Dowtherm is a trademark of Dow Chemical Company.

upon exposure to air can lead to formation of insoluble materials and increased fluid viscosity When the fluid is overheated, the flash point can be lowered and vapor pressure increased. If it is contaminated by other fluids (such as water), corrosion can be enhanced

(as in the case of water and steel). The toxicity of Dowtherm J is high. As with aqueous ethylene glycol solutions, double walls would be required to separate the potable water from the Dowtherm J.

Some other possible heat transfer fluids include Therminol[6] 44 brand ester-based fluid, Therminol 55 brand alkylated benzene fluid, and Therminol 60 brand hydrogenated aromatic fluid. They have low heat capacity, low thermal conductivity, high viscosity, and low freezing temperature. The flash points of these fluids are at the upper range of possible zero flow temperatures. The costs of Therminol 44 and 60 are relatively high, while Therminol 55 is much less costly.

Sun-Temp[7] brand fluid, a saturated hydrocarbon, is another possible heat transfer fluid available to flat plate collector users. It has low heat capacity, low thermal conductivity, high viscosity, a low freezing temperature, a high boiling temperature, low toxicity, low corrosiveness with aluminum, and low vapor pressure. It is relatively inexpensive. Because of its high viscosity, higher flow rates are required to produce turbulent flow and to increase heat transfer.

Inorganic aqueous salt solutions have recently been proposed for use as heat transfer fluids. According to K. W. Kauffman, 23-percent sodium acetate and 38-percent sodium nitrate aqueous solutions with suitable additives can be used as heat transfer fluids. These solutions have low toxicity. Their cost is comparable to that of ethylene glycol, and their heat transfer properties are similar to those of the glycols. Pumping costs for these fluids would be low. Like other aqueous solutions, they are subject to boiling at lower temperatures with high vapor pressures. These fluids are still being investigated for solar energy applications.

COMPARISON OF HEAT TRANSFER FLUIDS BY PHYSICAL PROPERTIES

The preceding discussion of heat transfer fluids pointed out general characteristics of each fluid studied. The following sections will discuss the following physical properties:

- Thermophysical properties.
- Cost.
- Toxicity.
- Flammability.
- Vapor pressure.
- Freeze protection.

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[6]Therminol is a trademark of Monsanto Company.

[7]Sun-Temp is a trademark of Research Technology Corporation.

The heat transfer fluids discussed earlier will be compared to offer a quantitative description of probable performance in double-loop heat exchanger collector systems. In some sections, representative fluids are chosen for the comparison. For ethylene and propylene glycol a 50-percent aqueous solution with inhibitors is used, since this allows adequate freeze protection for most cases. For some applications, lower concentrations might be plausible; in such cases, the results found here will be slightly conservative for heat transfer and flow rate properties. Also, since the properties of diethylene and triethylene glycol are close to those of ethylene glycol, we did not consider it necessary to compare these fluids in every section.

Thermophysical Properties

The thermophysical properties of the fluids were found from the manufacturers' specifications over the operating temperature range of flat plate collectors. For heat transfer, water is the best fluid. It has a high heat capacity, high thermal conductivity, and low viscosity. Water and the other heat transfer fluids are compared in Figures B-1 through B-4 for the following thermophysical properties:

- Absolute viscosity.
- Heat capacity.
- Thermal conductivity.
- Density.

Generally, aqueous solutions (such as ethylene and propylene glycol) have better thermophysical properties than do the rest of the heat transfer fluids except Dowtherm J. Dowtherm J has a lower viscosity than glycol solutions but also has lower heat capacity and thermal conductivity. Other simple comparisons of the heat transfer fluids can be made from Figures B-1 through B-4.

Cost

In some applications, more expensive fluids can be competitive with less costly ones. In order to determine the relative cost of a heat transfer fluid, you must know the volume of fluid required for a particular application. For some applications (such as domestic hot water heating), the amount of heat transfer fluid required will be small, since the collector area needed is small. In traced tank systems more costly fluids can be used if their other properties are desirable.

Table B-1 shows the 1978 costs of many heat transfer fluids in single 55-gallon drum quantities. Note that the final costs will generally be lower for the glycol solutions, since it is not necessary to use them in 100-percent solutions. Thus Mobiltherm Light and the glycols are the least expensive heat transfer fluids for initial installation, while the silicone fluids are the most expensive.

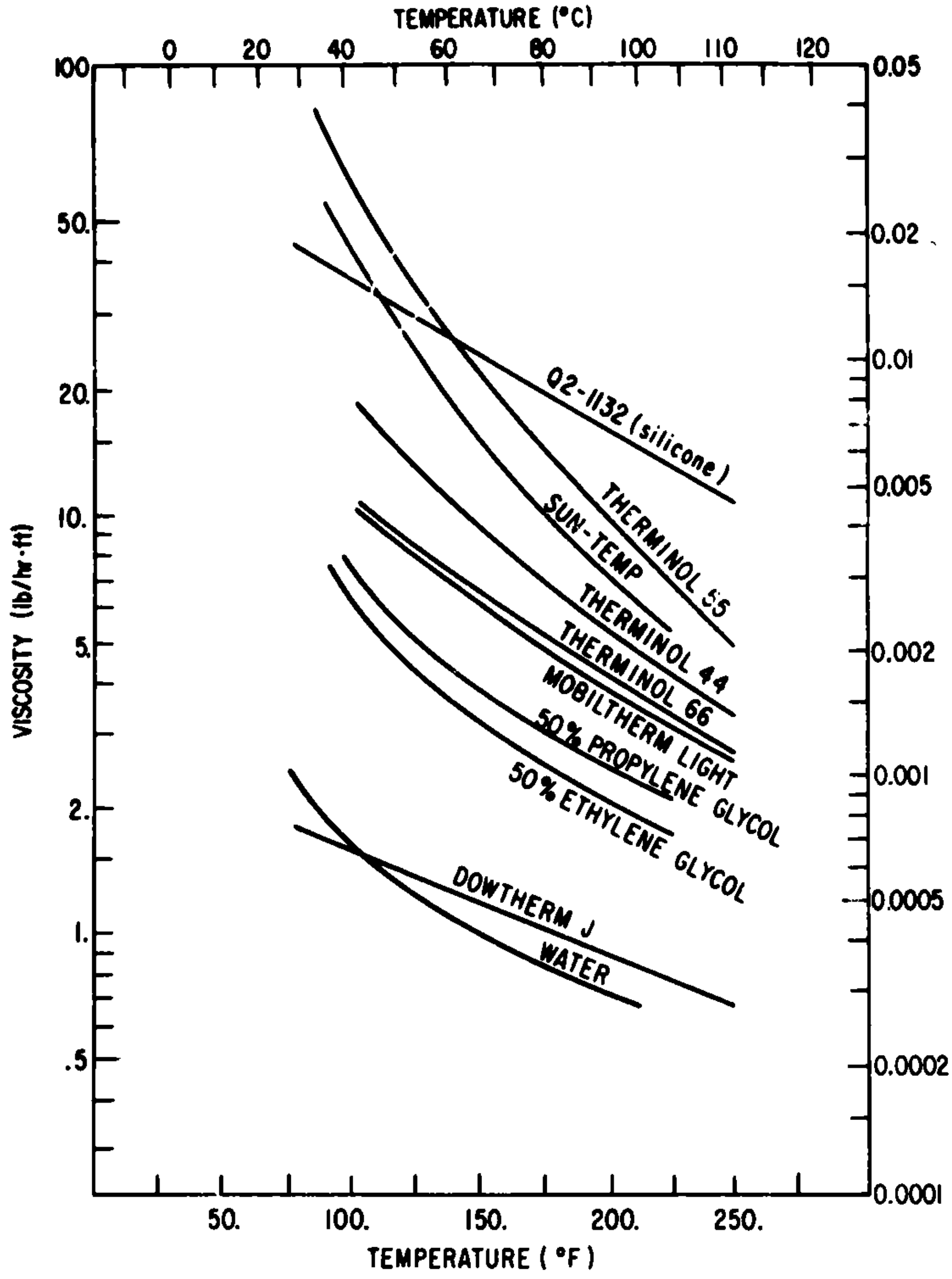

Figure B-1. Viscosity of Heat Transfer Fluids versus Temperature (Multiply viscosity in centipoise by 2.419 x 10^{-4} to get viscosity in lb/ft·hr.)

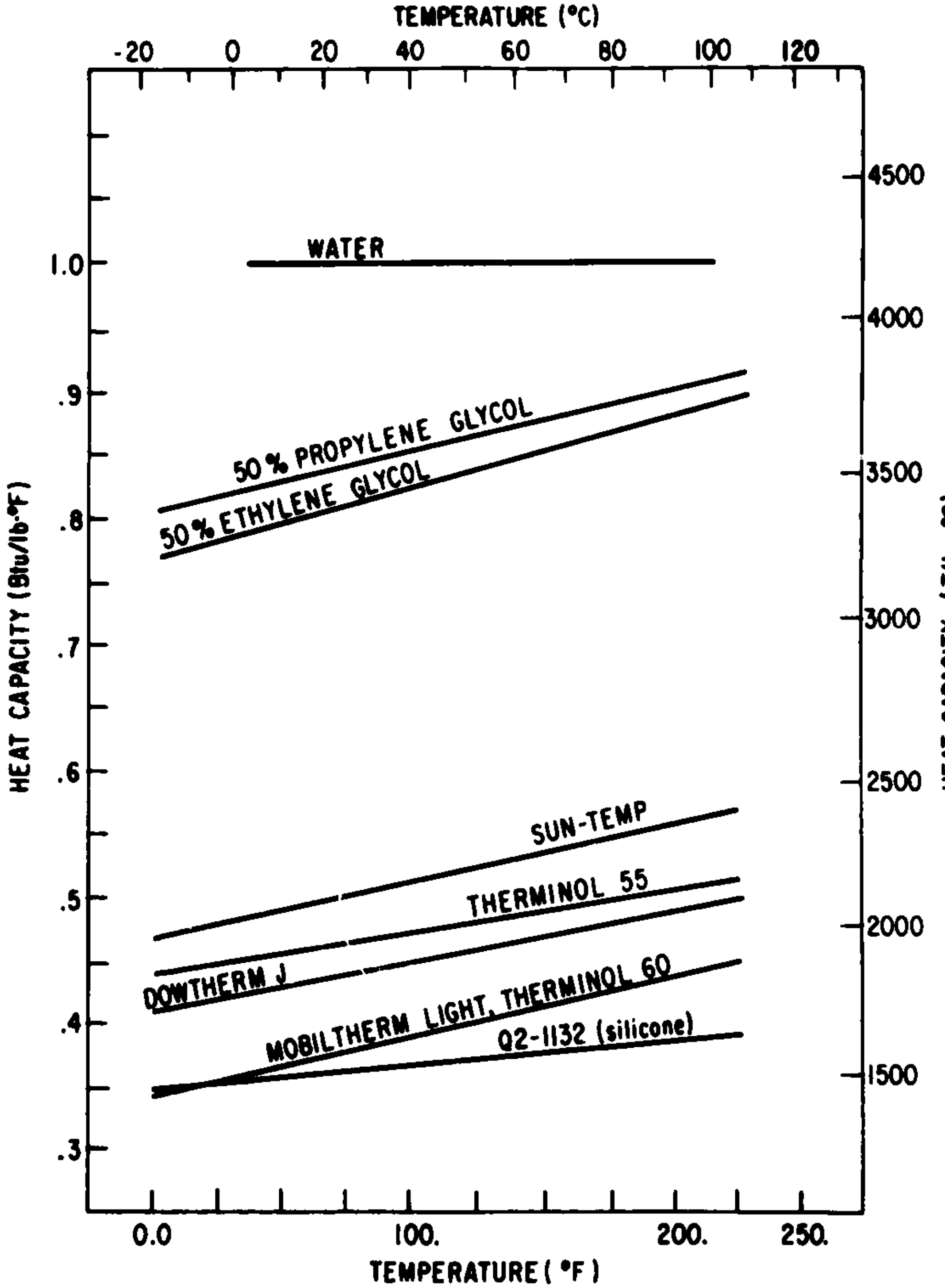

Figure B-2. Heat Capacity of Heat Transfer Fluids versus Temperature

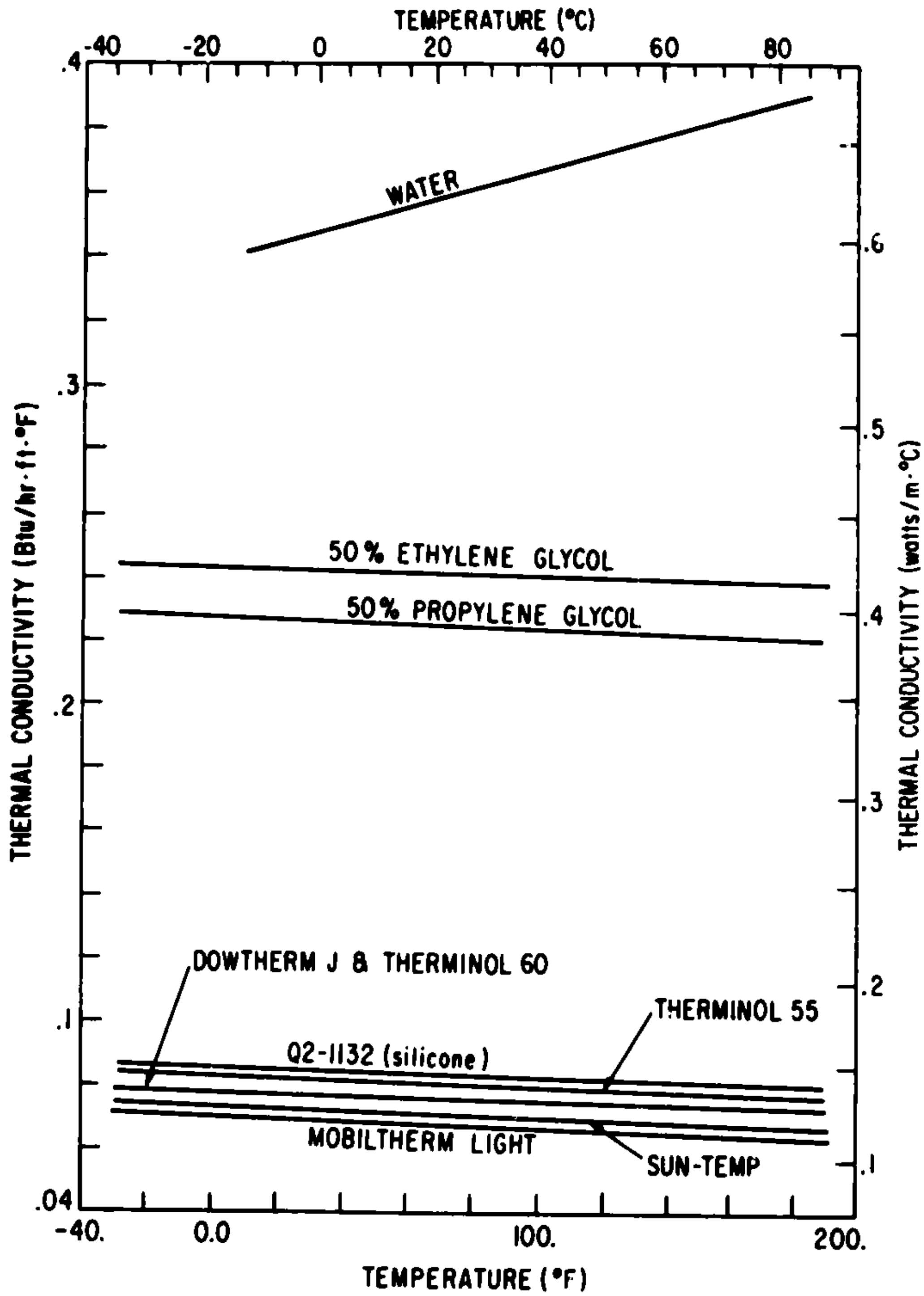

Figure B-3. Thermal Conductivity of Heat Transfer Fluids versus Temperature

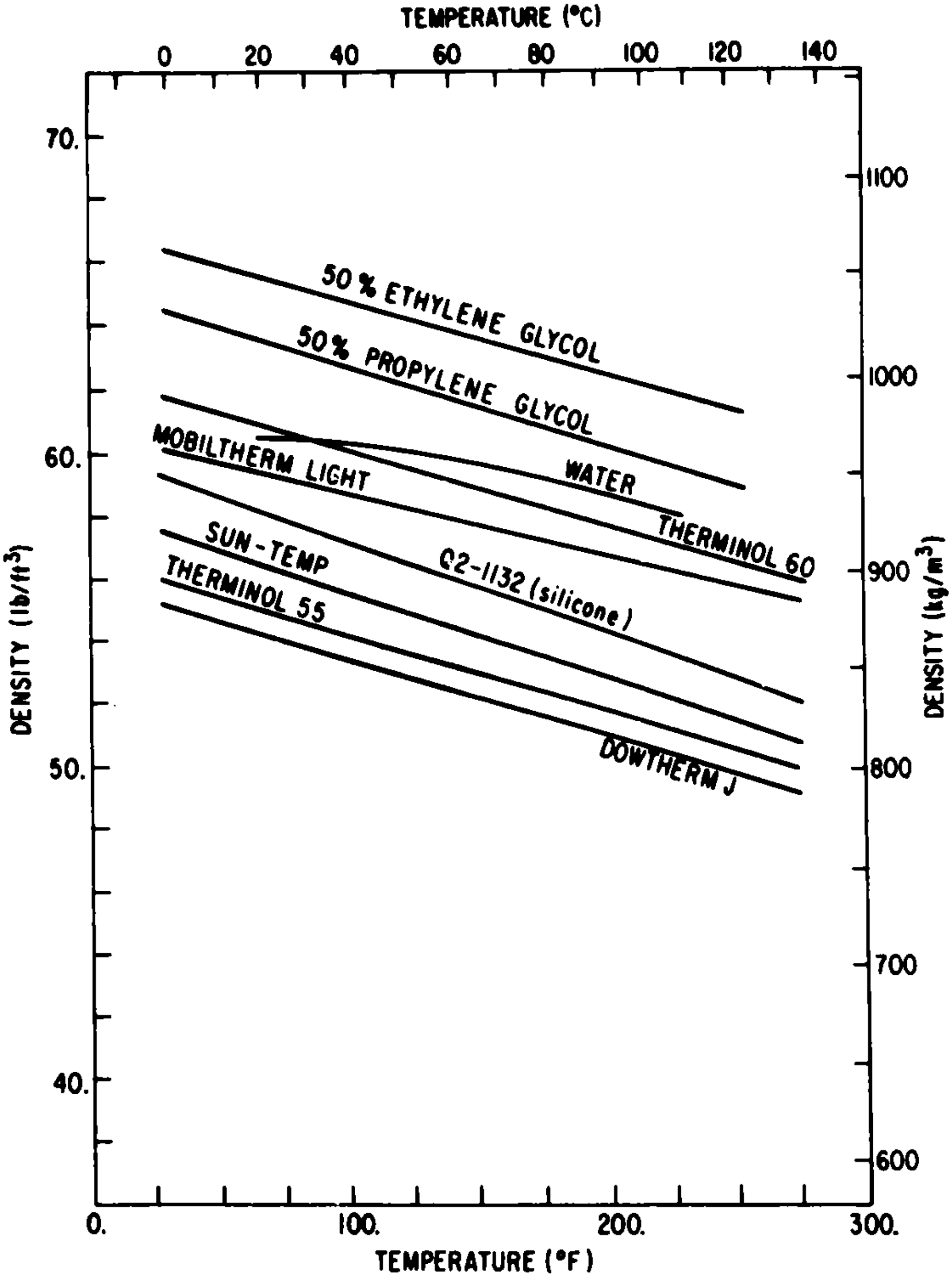

Figure B-4. Density of Heat Transfer Fluids versus Temperature

Table B-1. Initial Fillup Cost of Heat Transfer Fluids

Fluid	Cost per Gallon (single 55-gallon drum quantities)	Manufacturer
Water	--	--
100% Ethylene Glycol	$ 2.56	Union Carbide
100% Propylene Glycol	2.45	Union Carbide
100% Diethylene Glycol	2.82	Union Carbide
100% Triethylene Glycol	3.70	Union Carbide
100% Ucar[a] Thermofluid (ethylene glycol and inhibitors)	3.81	Union Carbide
100% Ucar Foodfreeze (propylene glycol and inhibitors)	3.63	Union Carbide
100% Dowtherm[b] SR-1 (ethylene glycol and inhibitors)	3.65	Dow Chemical
100% Dowfrost[b] (propylene glycol and inhibitors)	3.45	Dow Chemical
Mobiltherm[c] Light	1.29	Mobil Oil
SF-96(50) (silicone)	14.00	General Electric
Q2-1132 (silicone)	23.00	Dow Chemical
Dowtherm J	4.50	Dow Chemical
Therminol[d] 44	7.65	Monsanto
Therminol 55	2.80	Monsanto
Therminol 60	6.80	Monsanto
Sun-Temp[e]	3.50	Resource Technology Corporation

[a]Ucar is a trademark of Union Carbide Corporation.

[b]Dowtherm and Dowfrost are trademarks of Dow Chemical Corporation.

[c]Mobiltherm is a trademark of Mobil Oil Corporation.

[d]Therminol is a trademark of Monsanto Company.

[e]Sun-Temp is a trademark of Resource Technology Corporation.

There are other costs besides those of the initial fillup. Periodic maintenance and inhibitor addition, if needed, can add to the total cost of the fluid over a specific time period. Where inadequate corrosion and freeze protection might lead to collector failure, this additional cost must be considered. Also, more viscous fluids will require higher flow rates and increased pumping costs. The total investment in fluid over a given time period is equal to the sum of the initial cost of the fluid plus any additional costs of added fluid or inhibitor, increased pumping costs, maintenance, cost of replaced parts needed because of inadequate freeze or corrosion protection, or cost of reserve draindown or expansion tanks needed for some fluids.

Toxicity

The toxicity of a heat transfer fluid can greatly affect the design and operation of a double-loop flat plate collector system. Most plumbing codes require that double walls or vented surfaces separate a toxic fluid from potable water supplies. The possibility of poisonous fumes escaping from the heat transfer fluid must also be considered. These problems require the use of heat exchangers that transfer heat less optimally than those that can be used with nontoxic fluids. The following discussion describes the toxicity of the heat transfer fluids studied. The information was obtained from the manufacturers.

In a discussion of toxicity, the following definitions (from *United States Codes Annotated, 1974*) are useful.

A hazardous substance is any substance or mixture of substances that:

- Is toxic.
- Is corrosive (will cause destruction of living tissue by chemical action).
- Is an irritant.
- Is a strong sensitizer.
- Is flammable or combustible.
- Generates pressure through decomposition, heat, or other means.

A toxic substance is any substance that has the capacity to produce injury or illness to man through ingestion, inhalation, or absorption through any body surface.

A highly toxic substance is any substance that produces death within 14 days in half or more than half of a group of ten or more laboratory white rats, each weighing between 200 and 300 grams, at a single dose of 50 milligrams or less per kilogram of body weight when orally administered or when inhaled continuously for a period of 1 hour or less at an atmospheric concentration of 200 parts per million by volume or less of gas or vapor or 2 milligrams per liter by volume or less of dust or mist.

LD_{50} refers to the quantity of chemical substance that kills 50 percent of dosed animals within 14 days. Dosage is expressed in grams or milliliters per kilogram of body weight.

Single dose (acute) oral LD_{50} refers to the quantity of substance that kills 50 percent of dosed animals within 14 days when administered orally in a single dose.

Because the primary hazard in using heat transfer fluids is the possibility that they may leak into a potable water supply and be ingested, acute oral toxicity is the primary concern in this section. Table B-2 lists the LD_{50} values for selected fluids for acute oral toxicity. No substance listed is highly toxic according to the preceding definition, but several are quite toxic. Dowtherm J is the most toxic fluid listed in Table B-2, with the ethylene glycol mixture second. The least toxic fluids are silicone fluids, Sun-Temp, and propylene glycol.

Flammability

The possibility of the heat transfer fluid being a fire hazard must be considered. In a discussion of the flammability of a heat transfer fluid, the following definitions are useful.

Boiling point is the temperature at which the vapor pressure of a liquid equals the absolute external pressure at the liquid-vapor interface.

Flash point is the lowest temperature at which a combustible vapor above a liquid ignites and burns when ignited momentarily in air.

Fire point is the lowest temperature at which a combustible vapor flashes and burns continuously.

Self-ignition point is the temperature at which self-sustained ignition and combustion in ordinary air take place independent of a heating source.

Extremely flammable describes any substance that has a flash point at or below 20°F as determined by the Togliabue Open Cup Tester (TOCT).

Flammable describes any substance that has a flash point between 20°F and 80°F as determined by the TOCT.

Combustible describes any substance that has a flash point between 80°F and 150°F as determined by the TOCT.

Table B-3 lists the fluids and their boiling or flash points, whichever were supplied by the manufacturers. None of the fluids listed are extremely flammable or flammable. Only Dowtherm J is combustible, with a flash point of 145°F. With the exception of the silicone fluids, Sun-Temp, and Therminol

Table B-2. Acute Oral Toxicities of Heat Transfer Fluids

Fluid	LD_{50} (grams/kilogram of body weight)
Water	--
100% Ethylene Glycol (no inhibitors)	8.0
100% Propylene Glycol (no inhibitors)	34.6
100% Diethylene Glycol (no inhibitors)	30.0
100% Triethylene Glycol (no inhibitors)	30.0
100% Dowtherm SR-1	4.0
Mobiltherm Light	20.0
SF-96(50) (silicone)	50.0
Q2-1132 (silicone)	50.0
Dowtherm J	1.1
Therminol 44	13.5
Therminol 55	15.8
Therminol 60	13.0
Sun-Temp	No test information available

Table B-3. Flammability of Heat Transfer Fluids

Fluid	Boiling Point °F (°C)	Flash Point, °F (°C) (Cleveland Open Cup)
Water	212 (100)	--
100% Ethylene Glycol	388 (198)	240 (116)
50% Ethylene Glycol	225 (107)	--
100% Propylene Glycol	370 (188)	225 (107)
100% Diethylene Glycol	475 (246)	290 (143)
100% Triethylene Glycol	550 (288)	330 (166)
100% Dowtherm SR-1	325 (163)	240 (116)
50% Dowtherm SR-1	230 (110)	--
100% Dowfrost	--	214 (101)
Mobiltherm Light	250 (121)	--
SF-96(50)	--	600 (316)
Q2-1132	--	450 (232)
Dowtherm J	--	145 (63)
Therminol 44	425 (218)	405 (207)
Therminol 55	600 (316)	355 (179)
Therminol 60	650 (343)	310 (160)
Sun-Temp	500 (260)	310 (160)

44, most of the fluids have flash points below possible stagnation temperatures, a potential hazard.

The HUD Minimum Property Standards for FHA eligibility, according to K. W. Kauffman, preclude the use of fluids whose flash points are not at least 100°F higher than the highest temperature to which they might be exposed. Thus the use of fluids with low flash points is limited unless adequate safeguards limit the exposure of these fluids to high temperatures and exposure to the atmosphere.

Vapor Pressure

Under zero flow conditions within the collectors, temperatures may exceed 300°F. For aqueous solutions the vapor pressure under stagnation conditions can reach several atmospheres. Some collectors cannot withstand these pressures. Figure B-5 shows the absolute vapor pressure versus temperature for several of the fluids. The vapor pressures of the fluids are quite low, even under zero flow conditions, except for the aqueous solutions and Dowtherm J.

Freeze Protection

One of the major drawbacks of using water as a heat transfer fluid is its high freezing temperature. In the continental United States, few locations have had no recorded below-freezing temperatures.

Antifreeze solutions have been commonly added to water to lower its freezing temperature. In some cases these solutions can retard the expansivity of the water and create a slush that will not rupture the fluid vessel. Most nonaqueous fluids do not expand upon freezing and thus will reduce the risk of damaged piping.

Because some fluids become so viscous that their freezing temperatures are not easily measured, the pour point temperatures of the fluids are used as their lower operating limits. The pour point temperature is the temperature of the fluid at which it fails to flow when the container is tilted to horizontal and held for 5 seconds.

Freeze protection temperatures can best be obtained from the manufacturer for the particular fluid in question.

PRESSURE DROPS IN PIPES AND HEAT EXCHANGERS

One of the important parameters to be considered in selecting a heat transfer fluid is the operating pressure drop caused by friction in the fluid loop. This parameter will determine what size pump you buy and how much power will be needed to circulate the fluid.

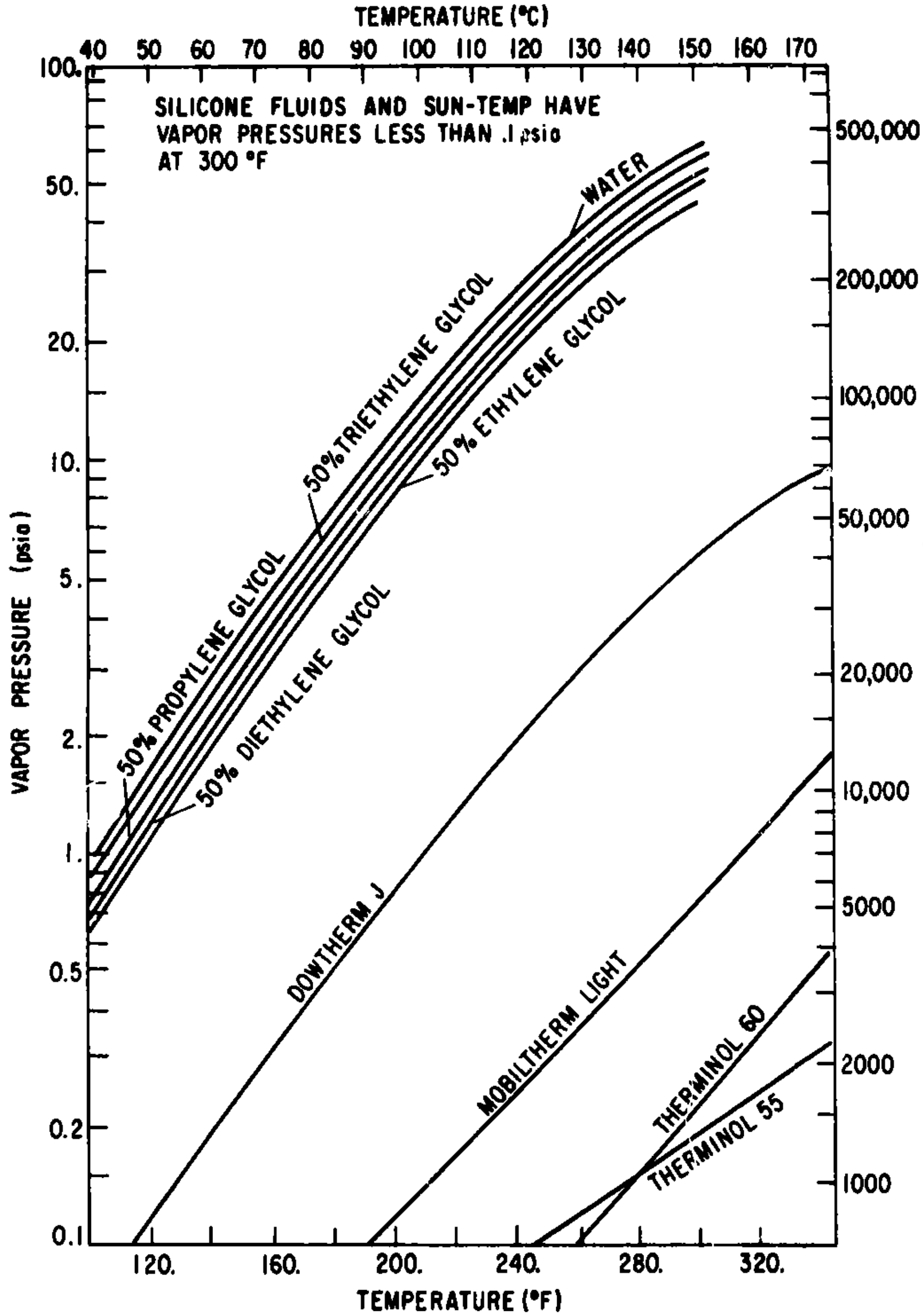

Figure B-5. Vapor Pressure of Heat Transfer Fluids versus Temperature

The Darcy-Weisbach equation gives the pressure drop per unit length in a tube:

$$\Delta p = f\frac{L}{D_i}\frac{\rho V^2}{2g} \tag{B-1}$$

where:

Δp is the pressure drop in lbf/ft^2 (Pa).

L is the length of the tube in feet (meters).

D_i is its inside diameter in feet (meters).

ρ is the density of the fluid in lb/ft^3 (kg/m^3).

V is the fluid velocity in ft/hr (m/s).

g is the unit conversion factor,[8] 4.17×10^8 $lb \cdot ft/lbf \cdot hr^2$ (1.0 when metric units are used).

f is the friction factor, which is related to the Reynolds number. Re, in the following way:

$$f = \begin{cases} 16/Re < 2500 \text{ (laminar flow).} \\ 0.0014 + 0.125/Re^{0.32} \text{ for } Re > 2500 \text{ (turbulent flow).} \end{cases}$$

The Reynolds number is:

$$Re = \frac{\rho V D_i}{\mu} \tag{B-2}$$

where μ is the fluid's absolute viscosity in $lb/ft \cdot hr$ ($Pa \cdot s$).

The fluid velocity, V, is equal to the volume flow rate divided by the cross-sectional area of the tube:

$$V = \frac{4\,q}{\pi\,D_i^2} \tag{B-3}$$

where q is the volume flow rate in ft^3/hr (m^3/s).

---

[8] See Appendix J for a discussion of units and conversions. Notice that the problem of converting pounds mass to pounds force is avoided in the metric system.

Combining Equations B-1 and B-3 gives the following equation:

$$\Delta p = \frac{8}{\pi^2} \frac{f \rho L q^2}{g\ D_i^5} \quad . \tag{B-4}$$

This equation shows that the inside tube diameter, D_i, greatly affects the pressure drop per unit length within the tube. Replacing 1-inch pipe with 3/4-inch pipe will give more than four times the pressure drop in the pipe for a given flow rate.

When calculating the pressure drop in a system, add together the pressure drops of each component to get the total pressure drop. *Flow of Fluids* by the Crane Company and the *ASHRAE Handbook of Fundamentals* give the pressure drops in equivalent lengths of pipe for elbows and other types of pipe joints and for valves.

For shell and tube heat exchangers, the tube side pressure drop can be calculated by using the formulas given above. The shell side pressure drop can be calculated by using the following equation from D. Q. Kern:

$$\Delta p = \frac{8\ f \rho q_{max}^2\ (n_{baf} + 1)}{\pi^2 g\ D_s^3\ D_o} \tag{B-5}$$

where:

q_{max} is the maximum volumetric flow rate in ft^3/hr (m^2/s) as defined in Appendix D.

n_{baf} is the number of baffles within the heat exchanger.

D_s is the inside diameter of the shell in feet (meters).

D_o is the outside diameter of the tubes in feet (meters).

The rest of the symbols are as defined previously.

SYMBOLS USED IN APPENDIX B

Main Symbols

D	tube diameter, ft (m)
f	friction factor
g	unit conversion factor, 4.17×10^8 lb·ft/lbf·hr^2 (1.0 if metric units are used)
L	length, ft (m)
n	number
q	volume flow rate, ft^3/hr (m^3/s)
Re	Reynolds number
V	fluid velocity, ft/hr (m/s)
ρ	fluid density, lb/ft^3 (kgm/m^3)
Δp	pressure drop, lb/ft^2 (Pa)
μ	absolute fluid viscosity, lb/ft·hr (Pa·s)

Subscripts

baf	baffles
i	inside of tube
max	maximum of several possible quantities
o	outside of tube
s	shell of heat exchanger

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APPENDIX C
CALCULATING INSULATION REQUIREMENTS FOR STORAGE DEVICES

This appendix shows how you can calculate the economic thickness of insulation as an alternative to the SMACNA or HUD standards described in Chapter 1. To use the method, you must determine the collector and storage unit size by calculation as outlined in Chapter 1, and you should understand elementary calculus. In many cases, the thickness determined by this method will not differ greatly from the thickness required by the SMACNA standard limiting the loss of heat to 2 percent in 12 hours.

The basis of the method is to compare the cost of collecting an additional unit of energy with the cost of saving an equal unit of energy. If the cost of collecting energy is more than the cost of saving it, you should add insulation; but if the cost of collecting energy is less than the cost of saving it, you have too much insulation. The economic thickness of insulation is the one that makes the cost of saving energy equal to the cost of collecting it.

COST OF COLLECTING ENERGY

When you calculate the optimum collector area for your system using f-Chart, SOLCOST, or other methods, it is relatively easy to add an increment of collector area, ΔA_c, to the optimum collector area and determine the increment of useful energy ΔQ_c, the added collector area adds over a year's time. Since you supplied the cost data necessary to calclate the optimum collector area, you can easily determine the added cost to the customer, ΔC_c, of the added collector area. An economic factor, E_c, uses mortgage rates, inflation rates, length of service, tax rates, and the like to convert the customer's initial cost for the solar collector to an annual equivalent cost basis.

The ratio $E_c \Delta C_c / \Delta Q_c$ is the incremental cost of collecting energy in units of dollars per Btu (dollars per joule). It is the quantity that will be compared with the cost of saving energy. Later we will assume that the cost of saving energy will be calculated on the same economic basis (that is, the same mortgage rate, inflation rate, length of service, and so on) as the cost of collecting energy so that the economic factor can be ignored.

INSULATION ON FLAT SURFACES

Heat Loss

If the surface to be insulated is flat or its radius of curvature is large compared to the insulation thickness (a large tank, for example), the following analysis can be used. The energy lost from the surface, Q_L, is approximately:

$$Q_L = - \frac{At\ (\bar{T} - \bar{T}_a)}{R^* + sr^*} \quad . \qquad \text{(C-1)}$$

In Equation C-1, R^* is the thermal resistance of the fixed layers of insulation in °F·ft²·hr/Btu (°C·m²/W), s is the thickness in inches (centimeters) of the layer of insulation, and r^* is the thermal resistance per unit thickness of that layer in °F·ft²·hr/Btu·in (°C·m²/W·cm). The asterisks on R^* and r^* are a reminder that these quantities must be adjusted for parallel heat losses. A is the area of the surface to be insulated, and t is the total time in hours (seconds) the system will be heated during a year. If the storage unit is used for heating domestic hot water, it will probably be hot for the entire year, or 8760 hours (31.5×10^6 seconds); but if the system is used only for space heating, the storage unit will probably be hot only during the heating season. Ducts, pipes, and heat exchangers will be hot only while the collector is operating or while the building is being heated from storage.

$\bar{T}$ is the average storage, heat exchanger, pipe, or duct temperature during time t. The bar over the T indicates that it is averaged over the time the unit is operating. A reasonable estimate for $\bar{T}$ is the average of the maximum temperature, T_{max}, and the minimum temperature, T_{min}, while the unit is operating. $\bar{T}_a$ is the ambient temperature averaged during the time the unit is operating. The minus sign preceeding Equation C-1 indicates that the heat is lost from the system.

The derivative of the heat loss equation with respect to the thickness of the insulation layer will be used in a later step:

$$\frac{dQ_L}{ds} = \frac{Atr^*\ (\bar{T} - \bar{T}_a)}{(R^* + sr^*)^2} \quad . \qquad \text{(C-2)}$$

Cost of Insulation

The cost of the insulation, C_I, is assumed to include a fixed cost, C_1, and a cost that is proportional to the amount of insulation used:

$$C_I = C_1 + sAc \quad . \qquad \text{(C-3)}$$

The factor s is the thickness of the insulation layer, A is the area covered, and c is the installed cost to the customer per unit of area per unit of thickness (dollars per square foot per inch or dollars per square meter per centimeter). Differentiating Equation C-3 with respect to insulation layer thickness yields

$$\frac{dC_I}{ds} = Ac \quad . \qquad \text{(C-4)}$$

The incremental cost of saving energy which must be compared to the incremental cost of collecting energy is

$$E_I \frac{dC_I}{dQ_L} = \frac{E_I \; dC_I/ds}{dQ_L/ds} = \frac{E_I \; c(R^* + sr^*)^2}{(\bar{T} - \bar{T}_a)tr^*} \; . \qquad \text{(C-5)}$$

E_I is an economic factor that converts the customer's initial cost for the insulation to an annual equivalent cost basis. Since the insulation and the collectors are part of the same solar system, they will have the same mortgage rate, inflation rate, tax rate, and length of service; therefore, we can assume that E_I is equal to E_c. When the incremental cost of collecting energy is equated to the incremental cost of saving energy, the two economic factors will cancel and can be neglected. If we had wanted to compare the cost of saving energy with the cost of conventional energy, it would not have been possible to neglect the economic factors in this manner.

The last step in deriving of the most economic thickness of an insulation layer is to equate the incremental cost of collecting energy with the incremental cost of saving energy and solve for the thickness:

$$s = \left[\frac{t(\bar{T} - \bar{T}_a)\Delta Cc}{c \; r^* \; \Delta Qc}\right]^{1/2} - \frac{R^*}{r^*} \; . \qquad \text{(C-6)}$$

Example C-1: Determine the economic insulation thickness for a rock bed with walls similar to those described in Examples 1-4 and 1-5. Assume the collector sizing calculations show that by adding 53.8 square feet (5 square meters) to the collector at an added cost of $1076 you can collect an additional 5.05×10^6 Btu (5.32×10^9 joule) of usable energy per year. Since the heating season is 8 months long, the rock bed will be in use 5840 hours (21.0×10^6 seconds) per year. The average rock bed temperature is 115°F (46°C), and the rock bed is located in a basement where the ambient temperature is 68°F (20°C).

The thicknesses of gypsum board and plywood given in Example 1-4 contribute only to the fixed cost of the insulation, since they will be present regardless of the stud width. The method of changing the amount of insulation for this example is to change the width of the studs and the corresponding thickness of the fiberglass.

A 5-1/2-inch thickness of fiberglass has an R-value of

$$R_1 = 5.5 \times 3.15 = 17.33\ ^\circ F \cdot ft^2 \cdot hr/Btu\ (3.05\ ^\circ C \cdot m^2/W),$$

and a 2 x 6 stud has an R-value of

$$R_2 = 5.5 \times 1.25 = 6.88\ ^\circ F \cdot ft^2 \cdot hr/Btu\ (1.21\ ^\circ C \cdot m^2/W).$$

With the stud layout shown in Figure 1-6, the fiberglass-and-stud layer has a thermal transmittance (see Example 1-6) of

$$U = \frac{1}{17.33} + \frac{2.88}{13.12 \times 6.88}$$

$$= 0.0896\ Btu/hr \cdot ft^2 \cdot {}^\circ F\ (0.508\ W/m^2 \cdot {}^\circ C).$$

The adjusted thermal resistance per unit thickness, r^*, is

$$r^* = \frac{1}{Us} = \frac{1}{5.5 \times 0.0896}$$

$$= 2.03\ ^\circ F \cdot ft^2 \cdot hr/Btu \cdot in\ (0.141\ ^\circ C \cdot c^2/W \cdot cm).$$

The plywood, gypsum board, and surface resistance contribute $R^* = 2.52\ ^\circ F \cdot ft^2 \cdot hr/Btu\ (0.444\ ^\circ C \cdot m^2/W)$ to the insulation.

We assume that the difference in cost between using 2 x 6 studs and using 2 x 8 studs with thicker insulation is \$0.36 per square foot, which gives a cost for the insulation layer of

$$c = \$0.18/ft^2 \cdot in\ (\$0.76/m^2 \cdot cm).$$

Substituting these figures into Equation C-7 gives the economic thickness of the stud-and-insulation layer:

$$s = \left[\frac{5840 \times (115-68) \times 2076}{0.18 \times 2.03 \times 5.05 \times 10^6}\right]^{1/2} - \frac{2.52}{2.03}$$

$$= 11.4\ in\ (29.0\ cm).$$

It is interesting to notice that 12.1-inch-wide studs satisfy the SMACNA standard as calculated in Example 1-6.

You should also notice that two of the four prerequisites for relaxing the insulation requirement to the HUD standard have been satisfied in the statement of the example. That is, the rock bed is located inside a building, and collected heat will not be added to storage in the summer. If the rock bed will not be used to heat domestic hot water, and occasional overheating near the rock bed in Spring and Fall can be tolerated, you can use the HUD standard allowing a 10 percent loss in 24 hours. This will allow you to use a 2 x 6 stud wall as shown in Example 1-6.

INSULATION ON A CYLINDRICAL SURFACE

Calculating the optimum insulation thickness for a cylindrical surface is more complicated than calculating for a flat surface, because both the heat loss equation and the insulation cost equation have more terms. Although we could not find a closed-form solution, we have included an equation that can be solved by trial-and-error or by numerical methods.

Heat Loss

The insulation is assumed to have three parts--an inside surface resistance, R_i, in °F·ft²·hr/Btu (°C·m²/W); a layer of insulation whose thickness, s inches (centimeters), we want to determine; and an outside surface resistance, R_o, in °F·ft²·hr/Btu (°C·m²/W). The heat loss is

$$Q_L = \frac{\pi L t \, (\bar{T} - \bar{T}_a)}{\dfrac{R_i}{D} + \dfrac{r^* \ln\left(1 + \frac{2s}{D}\right)}{2} + \dfrac{R_o}{D\left(1 + \frac{2s}{D}\right)}} \qquad \text{(C-7)}$$

where:

L is the length of the surface to be insulated in feet (meters).

t is the annual amount of time the cylinder will be hot in hours (seconds).

$\bar{T}$ is the average temperature of the cylinder in °F (°C).

$\bar{T}_a$ is the average ambient temperature surrounding the cylinder in °F (°C).

D is the diameter of the cylinder in inches (centimeters).

r^* is the thermal resistance of the insulation per unit thickness in °F·ft²·hr/Btu (°C·m²/W) adjusted for parallel heat loss.

Taking the derivative of the heat loss with respect to insulation thickness yields an equation which will later be combined with the derivative of the cost:

$$\frac{dQ_L}{ds} = \frac{\pi L t(\bar{T} - \bar{T}_a)\left[\dfrac{r^*}{D\left(1 + \frac{2s}{D}\right)} - \dfrac{2\,R_o}{D^2\left(1 + \frac{2s}{D}\right)^2}\right]}{\left[\dfrac{R_i}{D} + \dfrac{r^*\ln\left(1 + \frac{2s}{D}\right)}{2} + \dfrac{R_o}{D\left(1 + \frac{2s}{D}\right)}\right]^2}. \tag{C-8}$$

Cost of Insulation

The cost of the insulation, C_I, is assumed to have three terms--a fixed cost, a cost that is proportional to the outer surface area of the insulation, and a cost that is proportional to the amount of insulation used:

$$C_I = C_1 + \pi(D + 2s)\,LC_2 + \frac{\pi}{4}\left[(D + 2s)^2 - D^2\right] Lc \tag{C-9}$$

where:

- C_1 is the fixed cost of the insulation in dollars.
- C_2 is the cost of applying a cover to the insulation in dollars per square foot (dollars per square meter).
- c is the cost of the insulation in dollars per square foot per inch (dollars per square meter per centimeter).

The derivative of insulation cost with respect to insulation thickness is

$$\frac{dC_I}{ds} = \pi L\left[2C_2 + D\ 1 + \frac{2s}{D}\right] c\ . \tag{C-10}$$

Combining Equations C-8 and C-10 yields the incremental cost of saving energy:

$$E_I\frac{dC_I}{dQ_L} = \frac{E_I\ dC_I/ds}{dQ_L/ds}$$

$$= \frac{E_I\left[C_2 + D\left(1 + \frac{2s}{D}\right)\frac{c}{2}\right]\left[R_i\left(1 + \frac{2s}{D}\right) + \frac{r^*D}{2}\left(1 + \frac{2s}{D}\right)\ln\left(1 + \frac{2s}{D}\right) + R_o\right]^2}{\left[\frac{r^*D}{2}\left(1 + \frac{2s}{D}\right) - R_o\right]t(\bar{T} - \bar{T}_a)}. \tag{C-11}$$

Since the incremental cost of saving energy, $E_I \frac{dC_I}{dQ_L}$, must equal the incremental cost of collecting energy, $E_I \frac{\Delta C_c}{\Delta Q_c}$, at the optimum insulation thickness, and since we assume that the economic factors are equal, Equation C-11 can be rewritten as follows:

$$\left[C_2 + \frac{cD}{2} Y\right]\left[R_i Y + \frac{r^* D}{2} Y \ln Y + R_o\right]^2$$

$$- \left[\frac{r^* D}{2} Y - R_o\right] t(\bar{T} - \bar{T}_a) \frac{\Delta C_c}{\Delta Q_c} = 0 \qquad \text{(C-12)}$$

where $Y = 1 + \frac{2s}{D}$.

Equation C-12 can be solved for Y in terms of C_2, $\frac{cD}{2}$, $\frac{r^* D}{2}$, R_i, R_c, and $t(\bar{T} - \bar{T}_a) \frac{\Delta C_c}{\Delta Q_c}$, either by trial and error or by more advanced methods such as the Newton-Raphson method. A program for a Hewlett-Packard HP-25 calculator is shown in Table C-1. The program solves Equation C-12 by the interval-halving method.

To use the program, load the six constants into registers 0 through 5, a high guess at Y in register 7, and a low guess in register 6. We recommend using 10 for the high guess and 1 for the low guess. Calculate (high guess-low guess)/2 and leave the result showing in the display. Press the following key sequence:

f, clear PRGM, R/S .

When the calculator stops running, after about a minute, the plus-or-minus accuracy of the Y calculation will be in the display. Press the rolldown key twice to obtain Y.

Example C-2: A one-inch pipe (with an actual outside diameter of 1.315 inches, or 3.34 centimeters) carries antifreeze solution at an average temperature of 130°F (54°C) from the collectors into a building. The average ambient temperature is 40°F (4°C), and the pipe will pass through an uninsulated attic. The pipe will be insulated with foam rubber costing \$1.92 per square foot per inch of thickness (\$8.14 per square meter per centimeter of thickness), and the cost of installing the insulation is \$2.09 per square foot (\$22.50 per square meter). Adding 53.8 per square foot (5 square meters) of collector will cost \$1076 and will result in collection of 5.05×10^6 Btu (5.32×10^9J) of additional energy per year. The pipe will be hot an average of 6 hours per day during the 8-month heating season for a total of 1460 hours (5.26×10^6 seconds) per year.

Table C-1. HP-25 Calculator Program for Insulation Thickness

Register	Contents	Register	Contents	Register	Contents
0	C_2	3	R_o	6	low guess
1	$\frac{cD}{2}$	4	$\frac{r^*}{2}$	7	high guess
2	R_i	5	$t(\bar{T} - \bar{T}_a)\frac{\Delta C_c}{\Delta Q_c}$		

Step	Key	Step	Key	Step	Key
1	RCL 6	16	X	31	STO 6
2	+	17	RCL 0	32	GTO 35
3	ENTER ↑	18	+	33	R↓
4	ENTER ↑	19	X	34	STO 7
5	f ln	20	x⇄y	35	RCL 7
6	RCL 4	21	RCL 4	36	RCL 6
7	X	22	X	37	-
8	RCL 2	23	RCL 3	38	2
9	+	24	-	39	÷
10	X	25	RCL 5	40	EEX
11	RCL 3	26	X	41	CHS
12	+	27	-	42	5
13	g x^2	28	g $x \geq 0$	43	x⇄y
14	x⇄y	29	GTO 33	44	f $x \geq y$
15	RCL 1	30	R↓	45	GTO 01

The insulation's thermal resistance per unit of thickness is $r^* = 4.90$ °F·ft²·/Btu·in (0.340 °C·m²/W·cm). The thermal resistance on the inside of the pipe, R_i, is negligible, and the thermal resistance on the outside of the pipe, R_o, from Table 1-7, is 0.68 °F·ft²·hr/Btu (0.120 °C·m²/W). The six constants required for the calculation are

$$C_2 = \$2.09/\text{ft}^2 \ (\$22.50/\text{m}^2) \ .$$

$$\frac{cD}{2} = \frac{1.92 \times 1.315}{2} = \$1.26/\text{ft}^2 \ (\$13.59/\text{m}^2) \ .$$

$$\frac{r^*D}{2} = \frac{4.90 \times 1.315}{2} = 3.22 \ {}^\circ\text{F}\cdot\text{ft}^2\cdot\text{hr/Btu} \ (0.568 \ {}^\circ\text{C}\cdot\text{m}^2/\text{W}).$$

$$R_i = 0 \ .$$

$$R_o = 0.68 {}^\circ\text{F}\cdot\text{ft}^2\cdot\text{hr/Btu} \ (0.120 \ {}^\circ\text{C}\cdot\text{m}^2/\text{W}) \ .$$

$$t(\bar{T} - \bar{T}_a) \frac{\Delta C_c}{\Delta Q_c} = \frac{1460 \times (130-40) \times 1076}{5.05 \times [illegible]}$$

$$= \$28.0 \ {}^\circ\text{F}\cdot\text{hr/Btu} \ (\$53.1 \ {}^\circ\text{C/W}) \ .$$

Using the calculator program in Table C-1 produces the solution $Y = 2.160$, and the outside diameter of the insulation is $DY = 1.315 \times 2.160 = 2.84$ inches (7.21 centimeters). The thickness of the insulation is

$$s = \frac{D}{2}(Y - 1) = 0.76 \text{ in } (1.94 \text{ cm}).$$

Standard-sized 3/4-inch-thick insulation would be close to the economic thickness and would provide a thermal resistance of approximately 4.4 °F·ft²·hr/Btu (0.775 °C·m²/W) including the surface resistance. This is close to the Polytechnic Institute of New York recommendation of 4°F·ft²·hr/Btu (0.705 °C·m²/W) for 1-inch pipe.

Example C-3: A hot air duct passing through an uninsulated attic has the following parameters associated with it:

D = 12 in (30.5 cm).

$\bar{T}$ = 120°F (49°C).

$\bar{T}_a$ = 40°F (4°C).

R_i = 0.17°F·ft²·hr/Btu (0.030°C·m²/W).

R_o = 0.68°F·ft²·hr/Btu (0.120°C·m²/W).

r^* = 3.15°F·ft²·hr/Btu·in (0.219°C·m²/W·cm).

c = \$1.65/ft²·in (\$6.99/m²·cm).

C_2 = \$1.30/ft² (\$13.99/m²).

ΔC_c = \$1076.

ΔQ_c = 5.05×10^6 Btu (5.32×10^9 J).

t = 1460 hr (5.26×10^6 sec).

The solution is Y = 1.263, and the outside diamater of the insulation is

$$DY = 12 \times 1.263 = 15.16 \text{ in } (38.5 \text{ cm}) .$$

The economic thickness of insulation is

$$s = \frac{D}{2}(Y-1) = 1.58 \text{ in } (4.0 \text{ cm}) .$$

A 1-1/2-inch-thick wrapping of fiberglass would have a thermal resistance of approximately 5.8 °F·ft²·hr/Btu (1.03 °C·m²/W) including the inside and outside surface resistances.

SYMBOLS USED IN APPENDIX C

Main Symbols

A	area, $ft^2 (m^2)$
C	cost, $
c	unit cost insulation, $\$/ft^2 \cdot in$ ($\$/m^2 \cdot cm$)
D	storage unit, pipe, or duct diameter, in (cm)
E	economic factor to convert initial cost to annual equivalent cost
L	length of storage unit, pipe, or duct, ft (m)
Q	thermal energy, Btu (J)
R	thermal resistance of insulation, $°F \cdot ft^2 \cdot hr/Btu$ ($°C \cdot m^2/W$), not corrected for parallel heat loss
R^*	thermal resistance of insulation, $°F \cdot ft^2 \cdot hr/Btu$ ($°C \cdot m^2/W$), corrected for parallel heat loss
r^*	thermal resistance of insulation per unit thickness, $°F \cdot ft^2 \cdot hr/Btu \cdot in$ ($°C \cdot m^2/W \cdot cm$), corrected for parallel heat loss
s	insulation thickness, in (cm)
$\bar{T}$	temperature, °F (°C), averaged over time t
t	time, hr (sec)
U	thermal conductance of insulation, $Btu/hr \cdot ft^2 \cdot °F$ ($W/m^2 \cdot °C$)
Y	ratio of outside diameter of insulation to diameter of storage unit, pipe, or duct
ΔA	increment of area, ft^2 (m^2)
ΔC	increment of cost, $
ΔQ	increment of energy, Btu (J)

Subscripts

a	ambient condition
c	collector
I	insulation
i	inside surface
L	loss
max	maximum condition
min	minimum condition
o	outside surface
1, 2, etc.	first, second, etc.

APPENDIX D
DETERMINING HEAT EXCHANGER SIZE

Using a heat exchanger either as a means of separating antifreeze solution from the storage water or as a means of separating potable water from non-potable water requires choosing a heat exchanger of the proper size. For purposes of calculating heat exchanger size there are two main types of heat exchanger systems, double-loop and single-loop. A double-loop system, illustrated in Figure D-1, requires two pumps (forced convection) to maintain positive control of the flow on both sides of the heat exchanger. A single-loop system has only one pump and typically features either a coil inside the tank or a coil fastened to the outside of the tank. Single-loop systems rely on buoyancy of the heated water to maintain flow on the tank side of the heat exchanger (natural convection). Forced convection is maintained on the other side of a single-loop system by a pump.

The use of a heat exchanger leads to a collection penalty, as shown in Figure D-1. The efficiency of collection decreases with increasing collection temperature, as shown in the curve in the lower part of the figure. The presence of the heat exchanger increases the collection temperature and hence produces the collection penalty.

There are two areas of interest in heat exchanger calculations. The first is calculation of the heat exchanger penalty, which is expressed either in terms of heat exchanger effectiveness, ε, or in terms of the reduced collector heat removal factor, F_R'. Either heat exchanger effectiveness or reduced collector heat removal factor can be used to calculate the optimum collector and storage size by f-Chart, TRNSYS, or other methods.

The second area of interest is calculation of the economic heat exchanger size. Both heat exchanger penalty and economic heat exchanger size calculations require calculation of the heat transfer coefficient for the heat exchanger, U_X.

HEAT EXCHANGER PENALTY AND ECONOMICS

Heat Exchanger Effectiveness

In heat exchanger calculations, it is convenient to define the capacity rate, W, in Btu/hr·°F (W/°C), as the product of the mass flow rate, $\dot{m}$, in lb/hr (kg/sec), and the heat capacity, C_p, in Btu/lb·°F (J/kg·°C). The capacity rates for the collector loop and storage loop, respectively, are:

$$W_c = \dot{m}_c \; C_{pc} \tag{D-1a}$$

and

$$W_s = \dot{m}_s \; C_{ps} \; . \tag{D-1b}$$

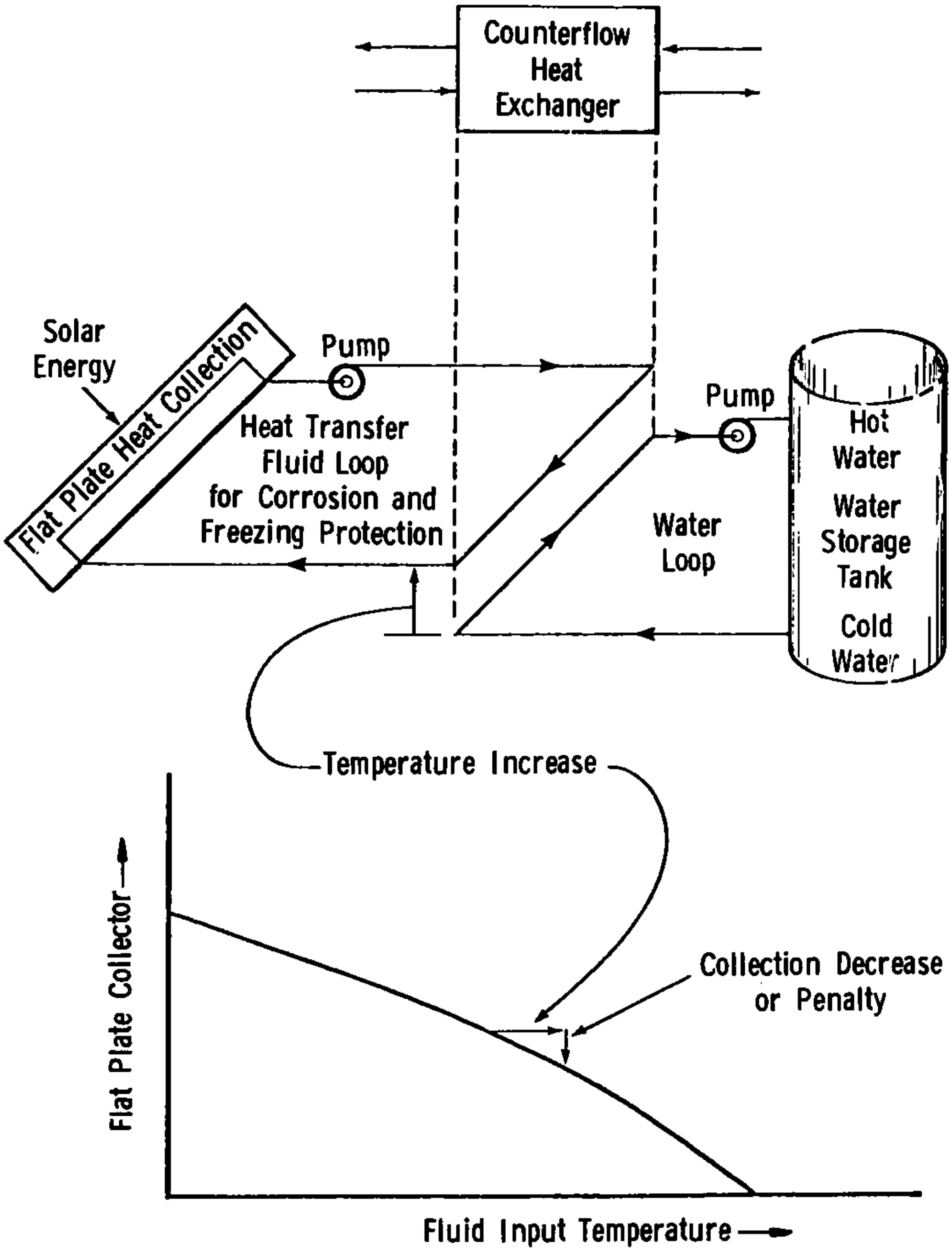

Figure D-1. Heat Collection Decrease Caused by a Double-Loop Heat Exchanger

The amount of heat transferred, Q, in Btu/hr (W), is the same for both sides of the heat exchanger:

$$Q = W_c(T_{c,in} - T_{c,out}) = W_s(T_{s,out} - T_{s,in}) \ . \qquad \text{(D-2)}$$

The subscripts in Equation D-2 refer to the inlet and outlet temperatures in °F (°C) of the collector and storage sides of the heat exchanger.

If the heat exchanger were perfect, it would operate between the highest temperature, $T_{c,in}$, and the lowest temperature, $T_{s,in}$; and the heat transferred would be:

$$Q_{max} = W_{min}(T_{c,in} - T_{s,in}) \ . \qquad \text{(D-3)}$$

W_{min} is the smaller of W_c and W_s. It must be used in Equation D-3 because the fluid that has the smaller capacity has the larger temperature change rate.

The heat exchanger effectiveness is defined as the ratio of the amount of heat transferred, Q, to the amount of heat transferred by a perfect heat exchanger, Q_{max}. Using this definition leads to the following equations for effectiveness:

$$\varepsilon = \frac{T_{c,in} - T_{c,out}}{T_{c,in} - T_{s,in}} \text{ when } W_c \leq W_s \ . \qquad \text{(D-4a)}$$

$$\varepsilon = \frac{T_{s,out} - T_{s,in}}{T_{c,in} - T_{s,out}} \text{ when } W_c \geq W_s \ . \qquad \text{(D-4b)}$$

For a counterflow heat exchanger, the heat transferred is the product of the heat transfer coefficient for the heat exchanger, U_x, in Btu/hr·ft^2·°F (W/m^2·°C); for the heat exchange area, A_x, in ft^2 (m^2); and the log-mean temperature difference in °F (°C).

$$Q = U_x A_x \frac{(T_{c,in} - T_{s,out}) - (T_{c,out} - T_{s,in})}{\ln\left[\dfrac{T_{c,in} - T_{s,out}}{T_{c,out} - T_{s,in}}\right]} \ . \qquad \text{(D-5)}$$

Equation D-5 would be true for a parallel-flow heat exchanger if $T_{s,in}$ and $T_{s,out}$ were interchanged.

Using Equations D-2, D-4, and D-5 leads to a general equation for effectiveness that is true for all values of W_c and W_s and counter- and parallel-flow heat exchangers:

$$\varepsilon = \frac{1 - \exp\left[-N_{TU}(1-W_{min}/W_{max})\right]}{1 - \frac{W_{min}}{W_{max}} \exp\left[-N_{TU}(1-W_{min}/W_{max})\right]} \text{ if } W_c \neq W_s \qquad \text{(D-6a)}$$

$$\varepsilon = \frac{N_{TU}}{N_{TU}+1} \text{ if } W_c = W_s \qquad \text{(D-6b)}$$

where the number of heat transfer units, N_{TU}, is defined as:

$$N_{TU} = \frac{U_x A_x}{W_{min}} \;. \qquad \text{(D-7)}$$

Reduced Collector Heat Removal Factor

DeWinter analyzed the case of a double-loop heat exchanger system with $W_c \leq W_s$. In that case the collector heat removal factor, F_R, of the Hottel-Whillier flat-plate collector model is reduced by the ratio:

$$\frac{F_R'}{F_R} = \frac{1}{1 + \frac{F_R U_c A_c}{W_c}\left[\frac{1}{\varepsilon} - 1\right]} \qquad \text{(D-8)}$$

where F_R' is the reduced collector heat removal factor. U_c and F_R are available from the collector manufacturer or from independent tests.

Beckman, Klein, and Duffie extended the analysis summarized by Equation D-8 and produced a result that is valid for all values of W_c and W_s:

$$\frac{F_R'}{F_R} = \frac{1}{1 + \frac{F_R U_c A_c}{W_c}\left[\frac{W_c}{\varepsilon W_{min}} - 1\right]} \;. \qquad \text{(D-9)}$$

Equation D-9 shows that the reduced heat removal factor is a function of $W_c/F_RU_cA_c$ and $\epsilon W_{min}/W_c$. This result has been plotted in Figure D-2. The effectiveness increases with heat exchange area (A_x) and reduces the collection penalty by bringing F_R'/F_R closer to 1. On the other hand, increasing the heat exchanger size increases the system cost. This tradeoff of system performance versus heat exchanger cost indicates that an optimum heat exchanger size might be found. That an optimum heat exchanger size can, indeed, be found is illustrated in Figure D-3.

For the specific case in which $W_c = W_s$ deWinter found that:

$$\frac{F_R'}{F_R} = \frac{1}{1 + \frac{F_RU_cA_c}{U_xA_x}} \; . \qquad \text{(D-10)}$$

When the cost per unit area of the collector, c_c, in \$/ft^2 (\$/m^2), and the cost per unit area of the heat exchanger, c_x, are constant, deWinter further found that if the heat transfer coefficient, U_x, did not vary with the area, A_x, the optimum heat exchanger, A_x, could be calculated from the equation:

$$A_x = A_c \left[\frac{F_RU_cc_c}{U_xc_x} \; .\right]^{1/2} \qquad \text{(D-11)}$$

According to Horel and deWinter, with a given average W, the optimum heat exchanger invariably has a storage capacity rate, W_s, higher than its collector capacity rate, W_c, so that Equation D-8 applies. For typical values of the collector capacity rate, W_c, they found that the value of W_c/W_s ranges from 0.5 to 0.6 and that, for all practical purposes, Equation D-11 can still be used to find the optimum heat exchanger area, since its result is only about 1 percent different from that found for the optimum (unmatched capacity rate) case.

Single-Loop Systems

The previous discussion of the reduced collector heat removal factor has been directed toward double-loop systems. The discussion of heat exchanger effectiveness, including Equations D-1 through D-7, is applicable to both single-loop and double-loop systems. Horel and deWinter analyzed a single-loop system and determined that Equation D-8 can be used to calculate the reduced collector heat removal factor. The main difficulty with single-loop systems is that neither calculation of the heat transfer coefficient, U_x, nor of the capacity rate on the storage side, W_s, is straightforward because of natural convection on the storage side. Methods of calculating the heat transfer coefficient for both double- and single-loop systems are discussed in the next section.

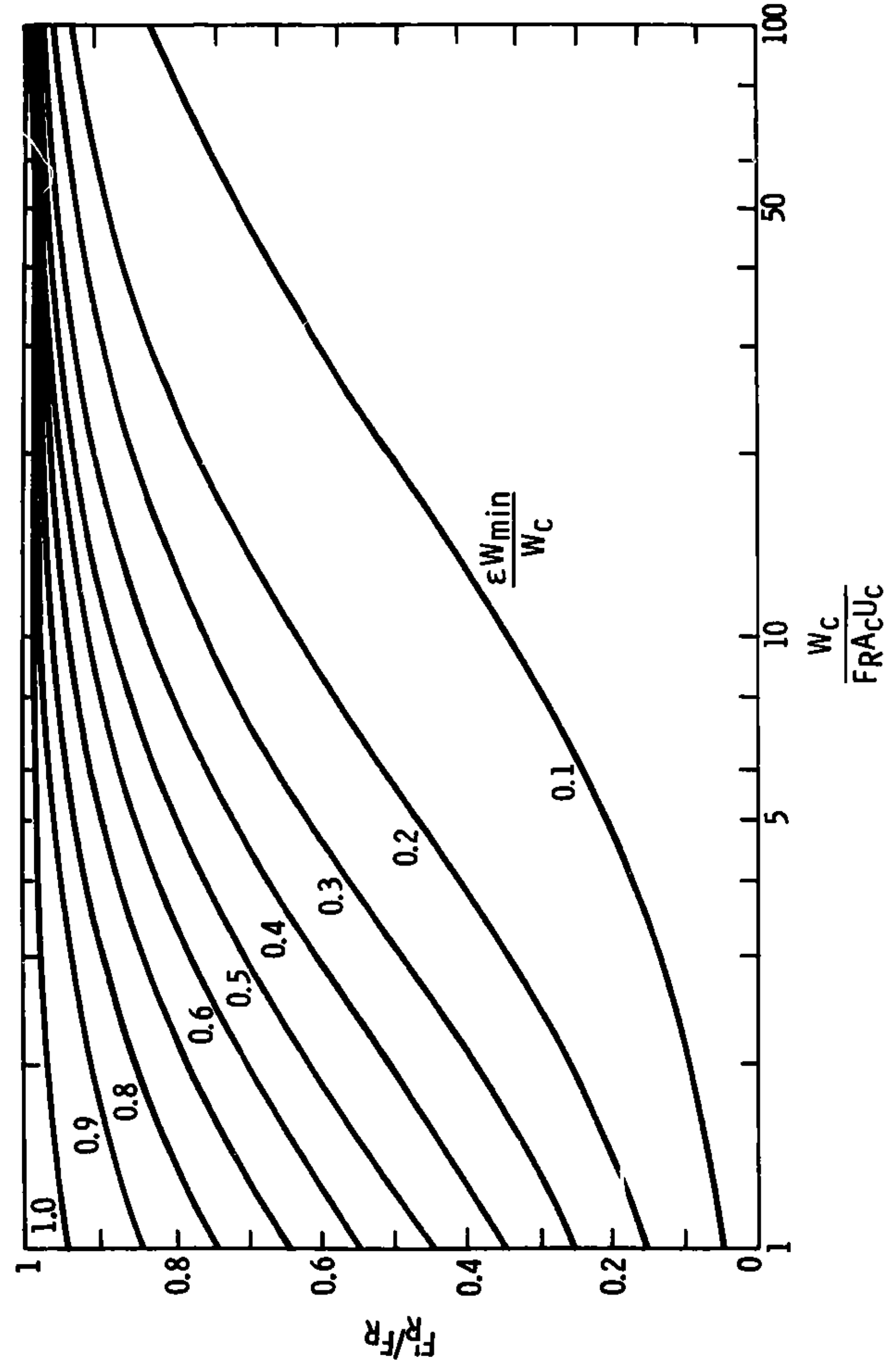

Figure D-2. Reduced Collector Heat Removal Factor F'_R/F_R

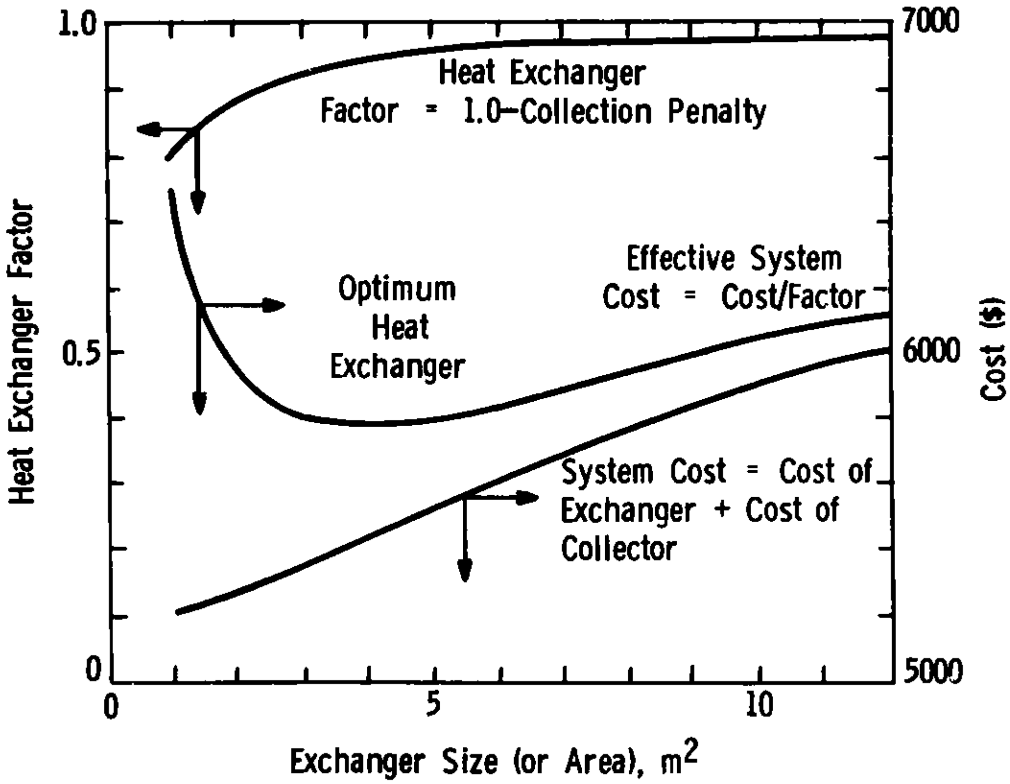

Figure D-3. Typical Heat Exchanger Optimization Plot, Showing the Heat Exchanger Factor $1-F_R'/F_R$, Total System Cost, and Effective System Cost as a Function of Heat Exchanger Size or Area

HEAT TRANSFER COEFFICIENT

This section summarizes the important relationships and equations which are derived in the references listed at the end of this appendix. The first subsection contains information that is necessary for an understanding of the other two. The second and third subsections show how to calculate the heat transfer coefficient, U_x, for shell-and-tube heat exchangers and for natural convection heat exchangers.

Forced Convection inside a Tube

The inside tube heat transfer coefficient, h_i, depends upon:

- Flow rate through the tube.
- Size of the tube.
- Temperature of operation.
- Properties of the fluid at the operating temperature.

These characteristics are summarized by two dimensionless numbers: the Reynolds number, Re_i, and the Prandtl number, Pr_i.

$$Re_i = \frac{4\rho_i q_i}{\pi \mu_i D_i n} = \frac{4\dot{m}_i}{\pi \mu_i D_i n} \qquad \text{(D-12)}$$

$$Pr_i = \frac{C_{pi}\mu_i}{k_i} \qquad \text{(D-13)}$$

where:

ρ_i is the fluid density in lb/ft^3 (kg/m^3).

q_i is the volumetric flow rate in ft^3/hr (m^2/sec).

μ_i is the absolute viscosity of the fluid in lb/ft·hr (Pa·sec).

D_i is the inside diameter of the tube in ft (m).

n is the number of tubes in parallel flow.

$\dot{m}_i$ is the mass rate of flow in lb/hr (kg/sec).

C_{pi} is the fluid heat capacity in Btu/lb·°F (J/kg·°C).

k_i is the fluid thermal conductivity in Btu/hr·ft·°F (W/m·°F).

The density, absolute viscosity, heat capacity, and thermal conductivity for several common fluids can be found in Appendix B.

The fluid flow in the tube may be laminar, transitional, or turbulent. The Reynolds number is used to differentiate these three types of flow. A different empirical correlation for the heat transfer coefficient on the inside of the tube, h_i, in Btu/hr·ft^2·°F (W/m^2·°C), applies for each type of flow. For laminar flow ($Re_i < 2500$), the following correlation from McAdams can be used:

$$h_i = \frac{k_i K_1}{D_i} \quad \text{(D-14)}$$

where:

$$K_1 = 1.75 \left[\frac{\pi}{4}\frac{L}{D_i} Pr_i Re_i\right]^{1/3} \text{ for } 1.75 \left[\frac{\pi}{4}\frac{L}{D_i} Pr_i Re_i\right]^{1/3} > 3.66 \quad \text{(D-15a)}$$

$$K_1 = 3.66 \text{ for } 1.75 \left[\frac{\pi}{4}\frac{L}{D_i} Pr_i Re_i\right]^{1/3} \leq 3.66 \quad \text{(D-15b)}$$

and L is the tube length in ft (m).

For transitional flow ($2500 < Re_i < 7100$), the heat transfer coefficient is given by:

$$h_i = 0.116 \frac{k_i}{D_i} Pr_i^{1/3} (Re_i^{2/3} - 125) \ . \quad \text{(D-16)}$$

For turbulent flow ($Re_i > 7100$ and $L/D_i > 60$), the heat transfer coefficient is:

$$h_i = 0.023 \frac{k_i}{D_i} Pr_i^{0.4} Re_i^{0.8} \ . \quad \text{(D-17)}$$

Since, in general, the transitional region should be avoided, it was included only to provide continuity from the laminar to the turbulent regimes. Also note that, at the interface between transitional and turbulent (Re = 7100) and the interface between laminar and transitional (Re = 2500), the equations do not predict similar inside tube heat transfer coefficients. For Re = 7100 there is a 10-percent difference between the two equations, and around Re = 2500 the error is larger. The selection of the transitional region between Reynolds numbers 2500 and 7100 was completely arbitrary. It was chosen to minimize the errors at the two boundaries and to allow reasonable heat transfer in the lower turbulent region. Heat exchangers operating in laminar flow have much lower effectiveness than those operating in the turbulent regime.

Shell-and-Tube Heat Exchangers

The shell-side heat transfer coefficient, h_o, is a function of:

- Flow rate through the shell.
- Operating temperature.
- Fluid properties at the operating temperature.
- Dimensions of the heat exchanger.

Since we are considering forced convection, the Reynolds and Prandtl number are:

$$Re_o = \frac{\dot{m}_o D_o}{\mu_o A_{min}(n_{row}+1)} \quad . \qquad \text{(D-18)}$$

$$Pr_o = \frac{C_{po}\mu_o}{k_o} \quad . \qquad \text{(D-19)}$$

where: $$A_{min} = S_{baf}\, S_{min} \qquad \text{(D-20)}$$

In these equations: $\dot{m}_o$ is the mass rate of flow on the shell side.

D_o is the outside diameter of the tubes in ft (m).

μ_o is the absolute viscosity on the shell side.

n_{row} is the number of tube rows across the diameter of the shell (see Figure D-4).

C_{po} is the heat capacity of the shell-side fluid.

k_o is the thermal conductivity of the shell-side fluid.

S_{baf} is the baffle spacing in ft (m) (see Figure D-4).

S_{min} is the spacing between tubes in ft (m) (see Figure D-4).

A_{min} is the minimum cross-sectional area between tubes.

$n_{row}+1$ is a factor that gives a conservative estimate of the number of tube openings for the fluid to flow through.

Based on the above Reynolds and Prandtl numbers, Kreider and Kreith give the following correlation for shell-side heat transfer coefficient:

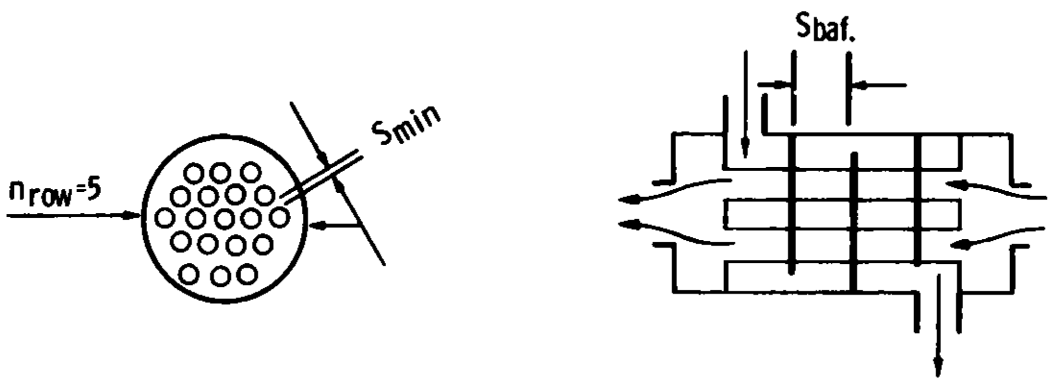

Figure D-4. Shell-Side Heat Exchanger Dimensions

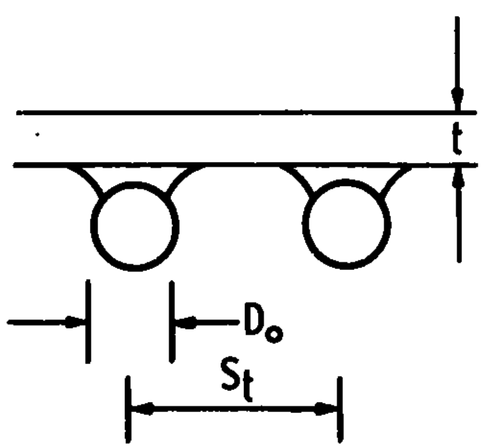

Figure D-5. Traced Tank Heat Exchanger Dimensions

$$h_o = 0.33 \frac{k_o}{D_o} Pr_o^{0.33} Re_o^{0.6} \quad . \tag{D-21}$$

The overall heat transfer coefficient of the heat exchanger, U_x, can be determined from the following equation by Kays and London. This is the heat transfer coefficient to be used for calculating the effectiveness, reduced heat removal factor, and optimum heat exchanger area for shell-and-tube heat exchangers:

$$U_x = \frac{1}{\frac{1}{h_o} + \frac{1}{h_{so}} + \frac{D_o}{D_i}\left(\frac{1}{h_i} + \frac{1}{h_{si}}\right) + R_t} \tag{D-22}$$

where:

$$R_t = \frac{D_o}{2k_t} \ln \frac{D_o}{D_i} \quad . \tag{D-23}$$

R_t is the thermal resistance of the tube wall in °F·ft²·hr/Btu (°C·m²/W), which can generally be neglected if the tube is copper. The numbers h_{so} and h_{si} are scaling coefficients on the shell side and the inside of the tube respectively. The scaling coefficient can be assumed constant for nearly all fluids and tube sizes and equal to 1000 Btu/hr·ft²·°F (5700 W/m²·°C). If the water is very hard (over 15 grains/gallon), a scaling coefficient of 330 Btu/hr·hr·ft²·°F (1900 W/m²·°C) can be specified. The reciprocal of the scaling coefficient, known as the fouling factor, is frequently used instead of the scaling coefficient. Normally, scaling coefficients decrease with time because of deposits if periodic maintenance is not performed. Lack of maintenance can reduce the performance of the heat exchanger as well as increase the possibility of corrosion.

Natural Convection in a Tank

Although forced convection heat transfer coefficients are determined entirely from the flow conditions, natural convection coefficients are determined by the geometry of the heating or cooling surface, the temperature difference between the surface and the fluid, and the fluid properties. This makes determination of heat transfer coefficients considerably more difficult for natural convection than for forced convection. This section considers two tank configurations, a vertical cylindrical tank in which a length L in ft (m) of the vertical surface is heated and a tank with a helical coil immersed in the water.

As in forced convection, two dimensionless parameters govern the heat transfer. They are the Prandtl number (Equatio. D-19) and the Grashof number, Gr_o, given below. (The subscript o refers to the water in the tank.)

$$Gr_o = \frac{\rho_o^2 g \ \beta_o}{\mu_o^2} L^3 \Delta T \qquad \text{(D-24)}$$

where:

ρ_o is the fluid density in the tank, in lb/ft^3 (kg/m^3).

g is the acceleration of gravity (4.17×10^8 ft/hr^2 = 9.81 m/sec^2).

β_o is the volumetric thermal expansion coefficient in $ft^3/ft^3 \cdot {}^\circ F$ ($m^3/m^3 \cdot {}^\circ C$).

μ_o is the absolute viscosity of the fluid in the tank in lb/ft·hr (Pa·sec).

ΔT is the log-mean temperature difference between the tank wall or the coil and the fluid in the tank.

L is the length of the heated portion of the wall in ft (m).

If the heat exchanger is a coil of tubing, the length, L, can be replaced by half the tube perimeter:

$$L = \frac{\pi}{2} D_o \quad . \qquad \text{(D-25)}$$

In laminar flow ($10^4 < Gr_o Pr_o < 10^9$), the heat transfer coefficient, h_o, between the wall or tube and the water in the tank is:

$$h_o = 0.59 \frac{k_o}{L} (Gr_o \ Pr_o)^{1/4} \quad . \qquad \text{(D-26)}$$

The factor composed of fluid properties $\frac{\rho^2 g \ \beta \ C_p}{\mu k}$ in the product of the Grashof and Prandtl numbers is given for water in Table D-1.

In turbulent flow ($10^9 < Gr_o \ Pr_o < 10^{12}$), the heat transfer coefficient is:

$$h_o = 0.13 \frac{k_o}{L} (Gr_o \ Pr_o)^{1/3}. \qquad \text{(D-27)}$$

The heat transfer coefficient for the heat exchanger, U_x, is given by the following equation:

$$U_x = \frac{1}{\frac{S_t}{\pi D_o}\left(\frac{1}{h_i} + \frac{1}{h_{si}}\right) + \frac{S_t}{D_o + (S_t - D_o)E}\left(\frac{1}{h_o} + \frac{1}{h_{so}}\right) + \frac{S_t}{C}} \qquad \text{(D-28)}$$

where:

S_t is the spacing between tubes (see Figure D-5).

h_{si} and h_{so} are scaling coefficients defined in the shell-and-tube heat exchanger section.

E is the conduction efficiency for the wall between the tubes.

C is the conductance of the tank to coil bond given approximately below:

$$C \approx \frac{4tk_t}{D_o} \quad . \qquad \text{(D-29)}$$

where:

t is the thickness of the tank wall in ft (m).

k_t is the thermal conductivity of the tank wall in Btu/hr·ft·°F (W/m·°C).

Table D-1. Convection Factors for Water

Temperature, °F (°C)		$\frac{\rho^2 g\ \beta\ C_p}{\mu k}$, 10^9 $ft^{-3} \cdot {}^\circ F^{-1}$ (10^9 $m^{-3} \cdot {}^\circ C^{-1}$)	
60	(16)	0.337	(21.42)
80	(27)	0.557	(35.41)
100	(38)	0.959	(60.96)
120	(49)	1.453	(92.36)
140	(60)	2.189	(139.1)
160	(71)	2.785	(177.0)
180	(82)	3.660	(232.7)

Recommended Iteration Procedure

Since the natural convection heat transfer coefficient is a function of temperature difference, it is necessary to iterate to determine the heat transfer coefficient. The scheme recommended below will converge to within about 1 percent after four or five iterations. The iteration scheme assumes that $W_c = W_s$, because otherwise there would be too many unknowns for the number of equations available.

(1) Calculate the heat transfer coefficient on the inside of the tube, h_i, (usually Equation D-17 but possibly Equation D-14 or D-16).

(2) Assume a natural convection heat transfer coefficient, h_o, of 100 Btu/hr·ft^2·°F (570 W/m^2·°C) to start the calculation process.

(3) Calculate the heat exchanger coefficient, U_x, using Equation D-28 and the conduction geometry.

(4) Calculate the heat removal factor reduction, F_R'/F_R, using Equation D-10.

(5) Calculate the collected heat, Q, from the collector performance map.

(6) Calculate the log-mean temperature difference, $\Delta T = \frac{Q}{U_x A_x}$.

(7) Calculate the natural convection heat transfer coefficient, h_o, using the ΔT calculated above and Equation D-26 or D-27.

(8) Repeat Steps 3 through 7 using the latest h_o until the numbers in successive iterations no longer change appreciably.

(9) If necessary, calculate the heat exchanger effectiveness, ϵ, using Equations D-7 and D-6b.

The results of this procedure are the heat exchanger coefficient, U_x; the heat exchanger effectiveness, ϵ; and the collector heat removal factor reduction, F_R'/F_R, which can be used for other calculations. Equation D-11 gives the economic heat exchanger size.

SYMBOLS USED IN APPENDIX D

Main Symbols

A	area, ft^2 (m^2)
C	conductance, Btu/hr·ft^2·°F (W/m^2·°C)
c	cost per unit area, \$/ft^2 (\$/m^2)
C_p	heat capacity, Btu/lb·°F (J/kg·°F)
D	tube diameter, ft (m)
E	conduction efficiency
F_R	collector heat removal factor
F_R'	reduced collector heat removal factor
g	acceleration of gravity, 4.17 x 10^8 ft/hr^2 (9.8 m/sec^2)
Gr	$\frac{\rho^2 g\ \beta}{\mu^2} L^3 \Delta T$ = Grashof number
h	heat transfer coefficient, Btu/hr·ft^2·°F (W/m^2·°C)
K	coefficient
k	thermal conductivity, Btu/hr·ft·°F (W/m·°F)
L	length, ft (m)
$\dot{m}$	mass flow rate, lb/hr (kg/sec)
n	number of tubes
N_{TU}	number of heat transfer units
Pr	$\frac{C_p \mu}{K}$ = Prandtl number
q	volume flow rate, ft^3/hr (m^3/sec)
R	thermal resistance, °F·ft^2·hr/Btu (°C·m^2/W)
Re	$\frac{4\rho q}{\pi \mu D_i} = \frac{4\ \dot{m}}{\pi \mu D_i}$ = Reynolds number
S	spacing, ft (m)

Main Symbols (continued)

t	thickness, ft (m)
U	heat transfer rate or heat loss coefficient, Btu/hr·ft^2·°F (W/m^2·°C)
W	capacity rate, Btu/hr·°F (W/°C)
ΔT	log-mean temperature difference, °F (°C)
β	thermal expansion coefficient, ft^3/ft^3·°F (m^3/m^3·°C)
ε	heat exchanger effectiveness
μ	absolute viscosity, lb/ft·hr (Pa·sec)
ρ	fluid density, lb/ft^3 (kg/m^3)

Subscripts

baf	baffles
c	collector
i	inside of tube
in	inlet
max	maximum of several possible quantities
min	minimum of several possible quantities
o	outside of tube or inside of tank
out	outlet
row	per row
s	shell of heat exchanger or storage
si	scaling on inside of tube
so	scaling on outside of tube or inside tank
t	tube or tank
x	heat exchanger
1, 2	first, second

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APPENDIX E
SAMPLE SPECIFICATIONS FOR HEAT EXCHANGERS

In this appendix, comments and other material that is not a part of the sample specifications are written in italics.

1.0 WORK INCLUDED (Provide)

1.1 All materials, parts, and work related to heat exchangers as indicated on drawings or specified herein.

1.2 Heat exchanger accessories such as bleed valves, supports, pressure relief valves, etc.

1.3a Heat exchangers used to heat water for thermal energy storage.

1.3b Heat exchangers used to heat potable water.

Choose item 1.3a or 1.3b as appropriate to your system. In some cases both 1.3a and 1.3b will be required.

1.4 Heat exchangers designed to operate at temperatures between 35°F and 300°F.

2.0 RELATED WORK

2.1 Cast-in-place concrete.

2.2 Anchor bolts.

2.3 Piping and pipe connections.

2.4 Tanks.

2.5 Pumps.

3.0 DETAILS

3.1 All details shall be in accordance with the ASME Code, American Water Works Association, TEMA Standards, etc., as applicable to heat exchangers.

3.2 Contractor shall be responsible for all dimensions and shall check structural drawings in relation with other work and existing field conditions. Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 APPLICABLE CODES AND STANDARDS

4.1 HUD Intermediate Minimum Property Standards, Solar Heating and Domestic Hot Water Systems, 1977 edition.

4.2 ASME Code.

4.3 TEMA Standards.

5.0 CONSTRUCTION

Choose section 5.1a, 5.1b, or 5.1c as applicable to your particular installation.

5.1a Type

The heat exchanger should be a 4-pass shell-and-tube type with a removable U-tube bundle constructed to meet ASME Code and TEMA Standards.

This is a general purpose heat exchanger. Since it separates the two fluids by only a single wall, this type of heat exchanger should not be used to separate toxic fluids from potable water. Consult the heat exchanger manufacturer regarding the number of passes versus performance of heat exchangers.

5.1b Type

The heat exchanger shall be a U-tube bundle for installation in a storage tank. The heat exchanger shall be constructed to meet ASME Code and TEMA Standards.

This type of heat exchanger requires a flange on the tank to mate with the flange on the heat exchanger. Since this type of heat exchanger separates the two fluids by only a single wall, it should not be used to separate toxic fluids from potable water. This type of heat exchanger relies on natural rather than forced convection to transfer heat to or from the water in the tank.

5.1c Type

The heat exchanger shall be a double-walled type constructed to meet ASME Code and TEMA Standards and shall meet HUD Intermediate Minimum Property Standards for separation of toxic fluids from potable water and applicable local building codes.

Specify this type of heat exchanger if your system requires heating potable water with a toxic fluid.

5.2 Materials

Other less easily corroded materials can be specified at extra cost. Consult the heat exchanger manufacturer for availability.

5.2.1 Shell--Seamless Steel.

U-tube bundle heat exchangers do not include a shell.

5.2.2 Baffles--Steel.

5.2.3 Heads--Steel.

5.2.4 Tube Sheets--Steel.

5.2.5 Tubes--3/4-inch O.D. copper.

5.3 Pressure and Proof Test

Shell and tubes shall be designed for 150 psi operating pressure and shall be tested at 225 psi per ASME Code requirements.

Do not specify a shell pressure if you specified a U-tube bundle in Section 5.1.

6.0 <u>ACCESSORIES (Optional)</u>

6.1 The heat exchanger shall have mounting saddles welded to the shell as shown on the drawings.

6.2 The heat exchanger shall be equipped with a replaceable zinc plug in the head to resist corrosion. 6.3 An automatic air-bleed valve shall be installed on the shell.

7.0 INSULATION

7.1 After the system has been installed and pipes and equipment have been tested and proven tight, install 2 inches of fibergl s insulation all over the heat exchanger except at flanges and valves.

7.2 Adjacent pieces of insulation shall be closely and tightly fitted to eliminate voids. Cut and miter insulation to fit the shape and contour of surfaces to be insulated. Band insulation with straps on 9-inch centers on round surfaces and wire or strap in place as required at heads of other flat or irregularly shaped surfaces, using galvanized steel wire and strapping.

7.3 Apply a 1/2-inch-thick coat of mineral fiber cement smoothly troweled over insulation. Finish with field-applied 8-ounce canvas jacket neatly pasted on.

8.0 CAPACITY AND DIMENSIONAL REQUIREMENTS

8.1a Capacity

The following specification is applicable to shell-and-tube and double-walled heat exchangers. Fill in the flow rates and temperatures with numbers that you calculated in designing your system. (Refer to sections on heat exchangers in Chapters 1 and 5 and Appendix D, "Determining Heat Exchanger Size.")

You must also specify the fluids to be used in the heat exchanger. In this example, water and propylene glycol solution have been specified, but you may require different fluids. You must also specify fouling factors appropriate to the fluids used. For the water found in most solar energy systems a fouling factor of 0.001 hour-square foot-°F per Btu is adequate. For hard water (over 15 grains per gallon) use a fouling factor of 0.003 hour-square foot-°F per Btu.

The heat exchanger shall have the capacity to heat ________ gpm of water (in the tubes) from _____°F when supplied with _____gpm of propylene glycol solution (50 percent) at _____°F (at the inlet end of the shell). Fouling factors shall be 0.001 hour-square foot-°F per Btu for both tube side and shell side.

8.1b Heat Exchanger Area

The following type of specification should be used in place of 8.1a if you specified a U-tube bundle heat exchanger in Section 5.1. Since the U-tube bundle uses natural convection, you cannot specify the flow rate on the exterior of the tubes. Instead you must calculate and specify the required heat exchange area. Refer to Appendix D for a method of calculating heat exchange area.

The heat exchanger shall have a minimum heat exchange area of _____square feet. The heat exchanger will be supplied with _____gpm of propylene glycol solution (50 percent) at _____°F and will be used to heat water.

8.2 Pressure Drops and Velocities

For most systems maximum pressure drops should be specified to ensure that the pumps will be able to maintain the required flow rates and that the cost of energy for the pumps does not become excessive.

8.2.1 The maximum pressure drop on the shell side shall be _____psi with the fluid, flow rate, and temperature specified in Section 8.1.

8.2.2 The maximum pressure drop on the tube side shall be _____psi with the fluid, flow rate, and temperature specified in Section 8.1.

8.2.3 The maximum tube velocity shall be _____ feet per second.

8.3 Dimensions

If you have special dimensional requirements, such as maximum heat exchanger length, heat exchanger diameter, or location of inlet and outlet, state your requirements in this section.

9.0 DRAWINGS

Include drawings appropriate to your system. Sample drawings of a shell-and-tube heat exchanger and a U-tube bundle are shown in Figures E-1 and E-2. A sample mounting detail is shown in Figure E-3.

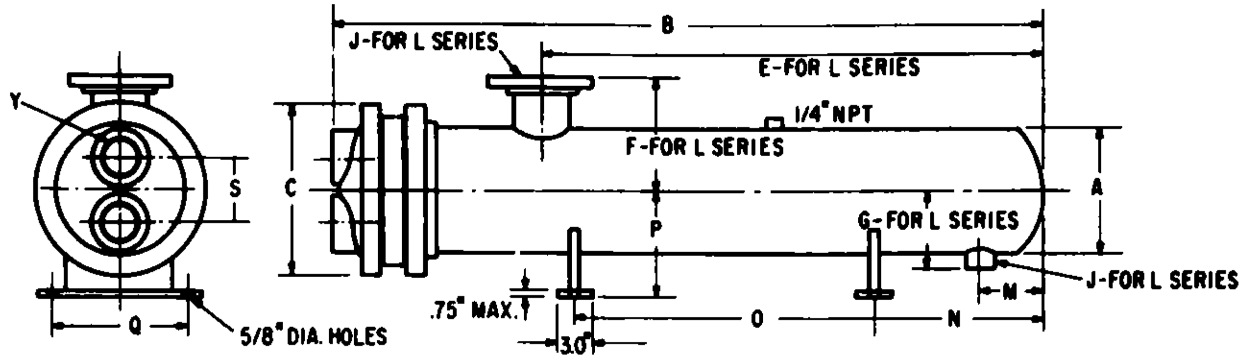

Figure E-1. Typical Shell-and-Tube Heat Exchanger

Based on drawings supplied by Taco, Inc., Cranston, R.I.

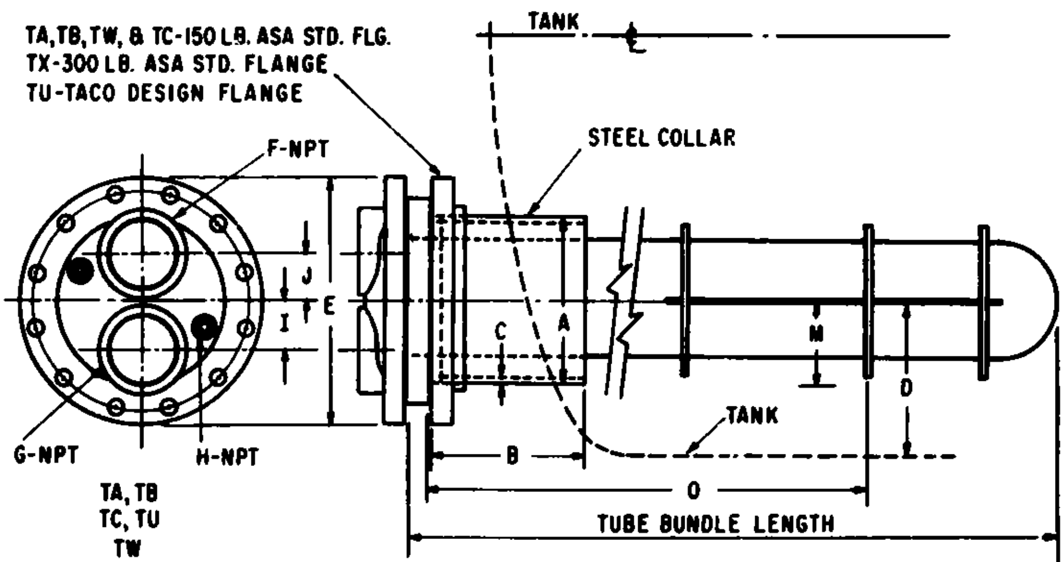

Figure E-2. Typical U-tube Heat Exchanger

Based on Drawings supplied by Taco, Inc., Cranston, R.I.

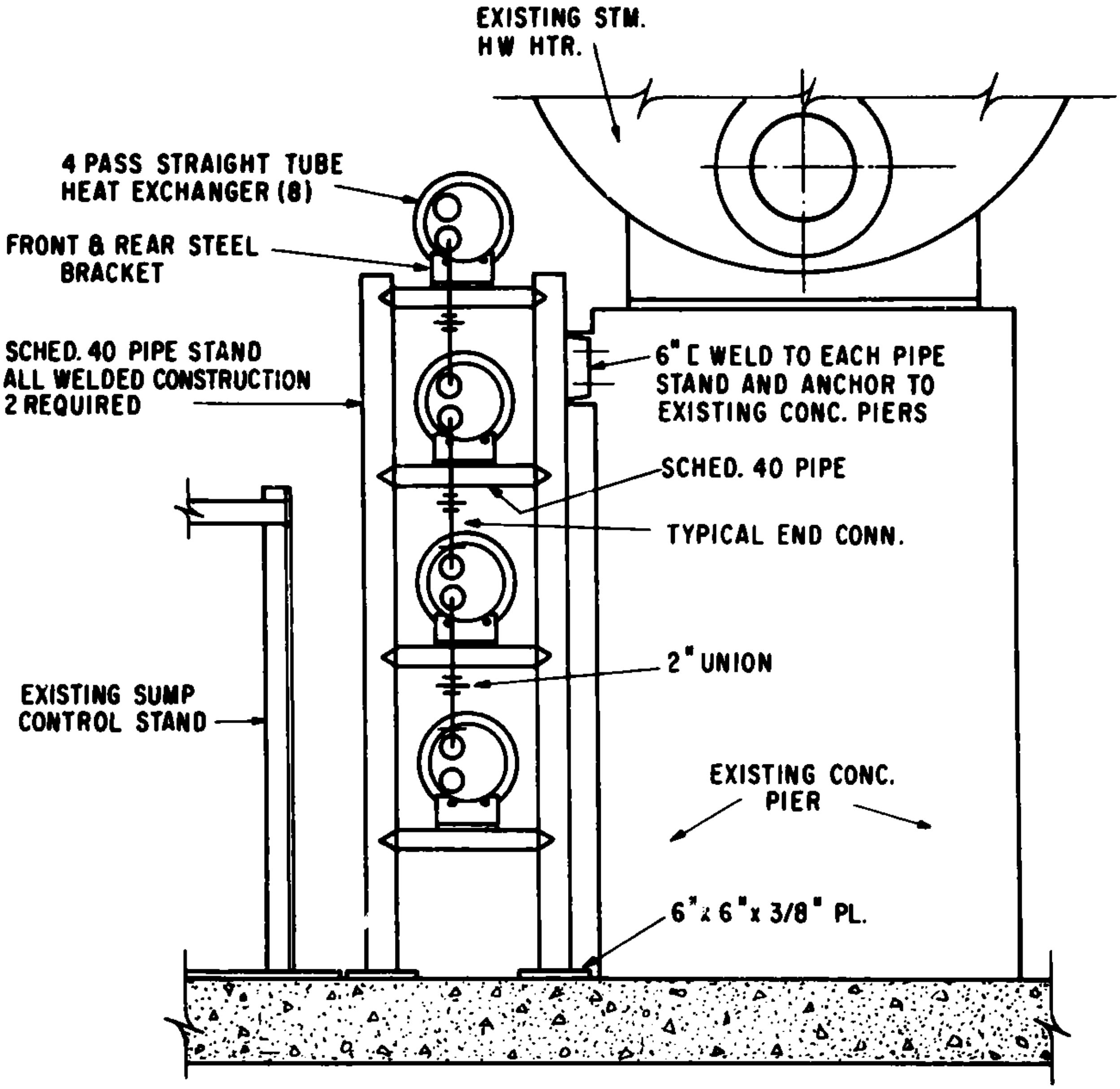

Figure E-3. Mounting Detail for Multiple Shell-and-Tube Heat Exchangers in a Large System

APPENDIX F
CONSTRUCTION DETAILS FOR A WOOODEN ROCK BIN

The wooden rock bin described in this appendix is based on the design example in Chapter 2. This appendix is intended only as a general guide to rock bin design; there are many designs in use which will work equally well. For rock bins of other sizes, you must go through the design process described in Chapter 2 to be sure that the design parameters, such as plenum sizing and the like, will fit your particular needs. By omitting the tie rods, sheet rock or sheet metal lining, and inlet and outlet and by adding a plastic liner you can use this rock bin as a water tank.

The rock bin shown in Figures F-1 through F-11 is intended for installation in a basement, but it could be adapted to outdoor, aboveground service by providing thicker insulation, weatherproof siding, and a roof. Wood should not be used for underground rock bins. If you must have an underground rock bin, one of the concrete tanks described in Appendix H can be modified for that use. (Concrete can also be used for aboveground or basement rock bins.)

FOUNDATION

Since the rock bed is heavy, it must be built on an adequate foundation. Most basement floors are inadequate to support the rock bed; ask a structural engineer to design a proper foundation. We recommend a 2-1/2-foot clearance between the rock bin and any load-bearing wall to avoid overloading the wall foundation. The 2-1/2-foot clearance also provides access for maintenance. Do not place the rock bed over sewer lines, drain lines, or water lines, because the weight of the rock bed can disrupt these lines and block access to them.

If the floor slab must be modified (to provide a stronger foundation or to provide clearance for a deep bin, for example), use the following procedure:

(1) Remove the required area of the existing concrete slab, remove all poor-quality soil, check the soil-loading capacity, and excavate to the proper depth.
(2) Smooth out the supporting soil and cover with pea gravel or coarse sand. To prevent water seepage, cover the gravel or sand with a tough plastic film.
(3) Provide supports for the slab reinforcing bars.
(4) Provide 1/2-inch asphalt joints all around the new section of floor to minimize differential settling problems.
(5) Use pre-mixed concrete and trowel the surface smooth.
(6) Install 1/2-inch anchor bolts in the unhardened concrete or install self-drilling tubular expansion shield anchors after the concrete has hardened. The storage container's base frame can be used as an anchor template.

ROCK BIN

The following material and construction specifications should be used:

(1) All reinforcing ribs shall be dense, Number 1 Douglas Fir or Southern Yellow Pine.
(2) Exterior grade plywood with the bonding glue capable of continuously withstanding a temperature of 140°F for a 20-year period shall be used.
(3) All vertical and all horizontal structural support members shall be nailed and glued to the exterior grade plywood. All bonding glues shall meet the temperature specification in Item 2.
(4) Timber Engineering Company (TECO)[1] connectors or equivalent shall be used to join all vertical ribs to the bottom connecting members.
(5) All timber in contact with concrete shall be coated with asphalt paint.
(6) The bond beam blocks (lintel blocks) should be placed not less than 2 inches apart, to ensure adequate airflow, and not more than 4 inches apart, to provide enough support.
(7) All joints, all timber-concrete contacts, and all cracks shall be caulked with a silicone caulk. A 3/8-inch caulk bead is recommended.
(8) Test for leaks before installing the rocks and insulation. Finding and repairing the leaks will be much more difficult after the rocks and insulation have been installed. With the top cover in place, block the rock bin outlet and use the blower to blow air into the bin. Use a nontoxic smoke candle to show the leaks, or feel the leaks with a hand along joints and seams.

FILLING THE BIN

Select the rocks carefully. The requirements detailed in Chapter 2 are summarized as follows:

- Rounded river rocks are preferred, but crushed rocks that conform to ASTM C 33, "Standard Specification for Concrete Aggregates," are generally acceptable.
- Rocks must be washed as specified in ASTM C 33 to remove all dirt, sand, dust, and foreign material.
- Rocks that react with components of the air, such as limestone, marble, and dolomite, should not be used for nocturnal cooling applications.
- Rocks that crumble or make dust are unacceptable.
- Rocks that have an unpleasant odor are unacceptable.
- The range of rock sizes must be no smaller than 75 percent and no larger than 150 percent of the size you calculated according to the design procedure in Chapter 2.

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[1] 5530 Wisconsin Avenue, Washington, D.C. 20015

You should reject any load of rock that does not conform to all these requirements.

Fill the bin carefully in 6-inch layers. Spread the rocks evenly in each layer before adding the next one. Use a chute to distribute and to break the fall of the rocks or place the rocks by hand. Do not simply dump the rocks from a truck or allow the falling rocks to strike the walls of the bin. After spreading the first layer of rock, carefully pack the rocks under the pipe protecting the temperature sensor. (Not all control systems require a temperature sensor at the bottom of the bin.) Add the remaining layers carefully to avoid damaging the bin walls and the pipe protecting the upper temperature sensor.

Lay the top cover on the rock bin. Using wedges to temporarily raise the cover, run a continuous bead of caulking around the top of the walls. Remove the wedges and allow the top cover to seal against the top of the walls. Use either weights or wedges against the ceiling joists to force the cover tightly in place and then run another bead of caulking around the outside of the cover joint. Cover this joint with duct tape and then secure the cover to the rock bin with 1/8-inch x 3/4-inch x 6-inch steel straps and four number 10 x 2 inch wood screws per strap. (Not shown on drawings.) Space the straps approximately 2 feet apart around the cover.

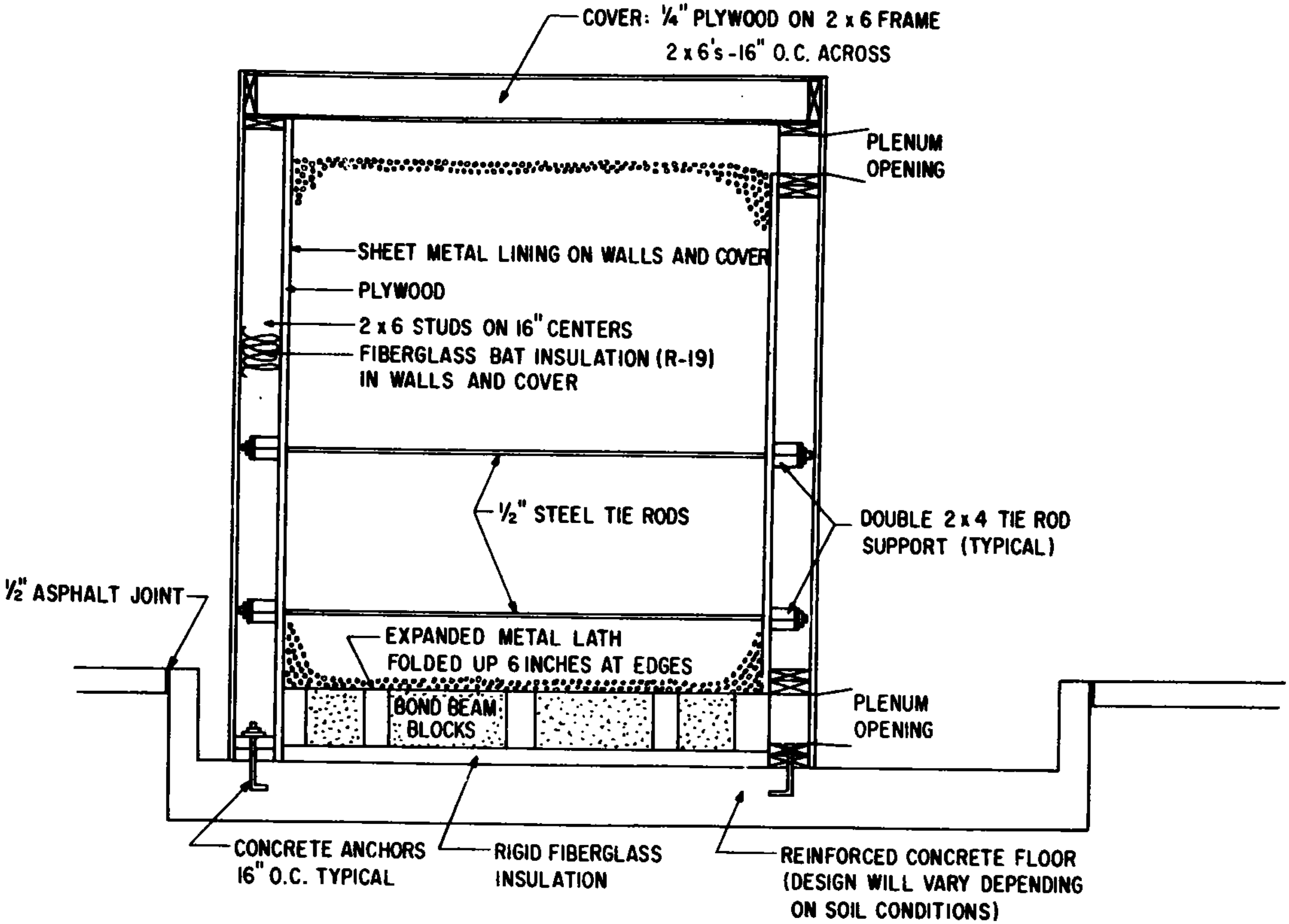


Figure F-1. Elevation of Wooden Rock Bin

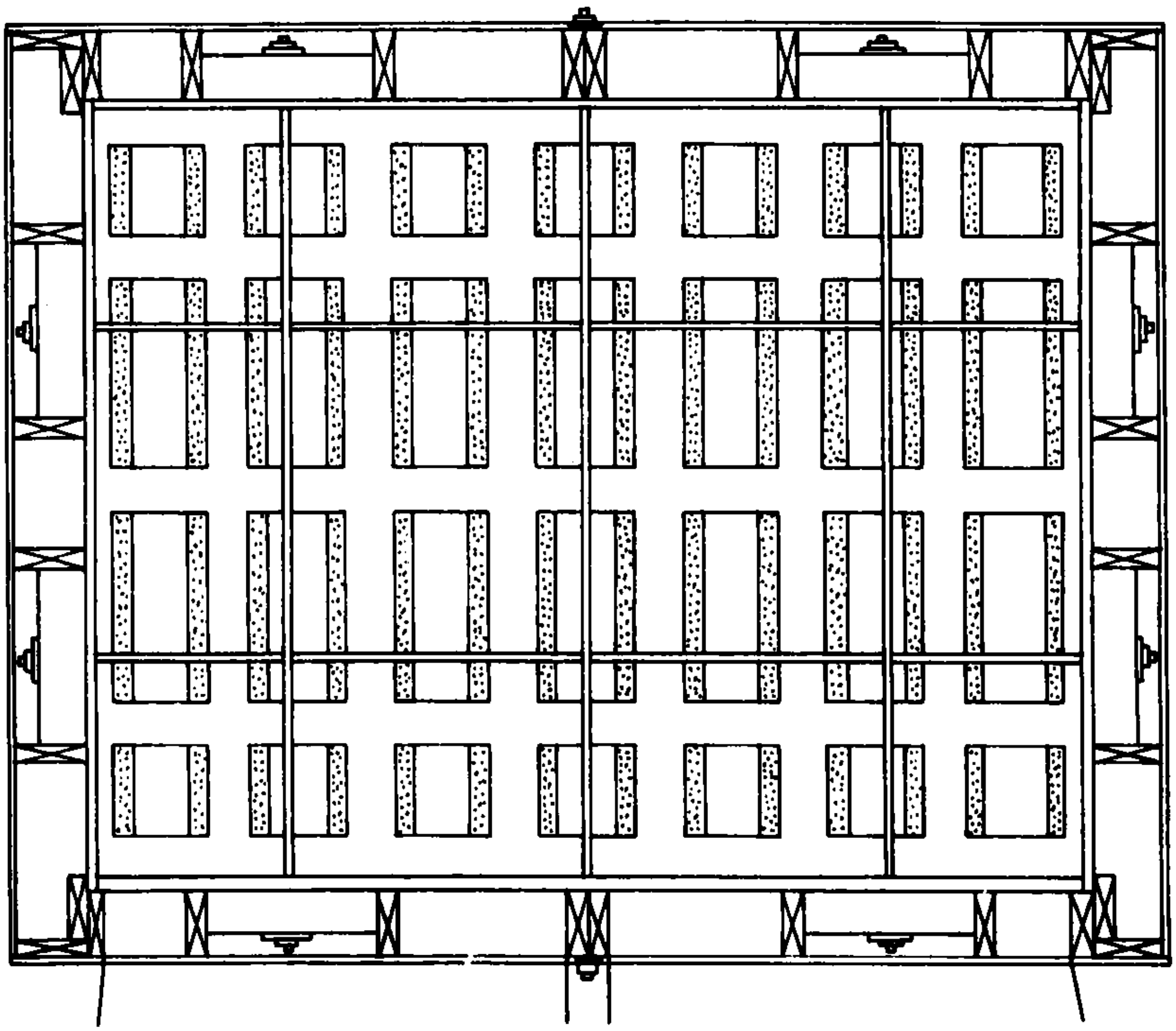


Figure F-2. Plan View of Wooden Rock Bin

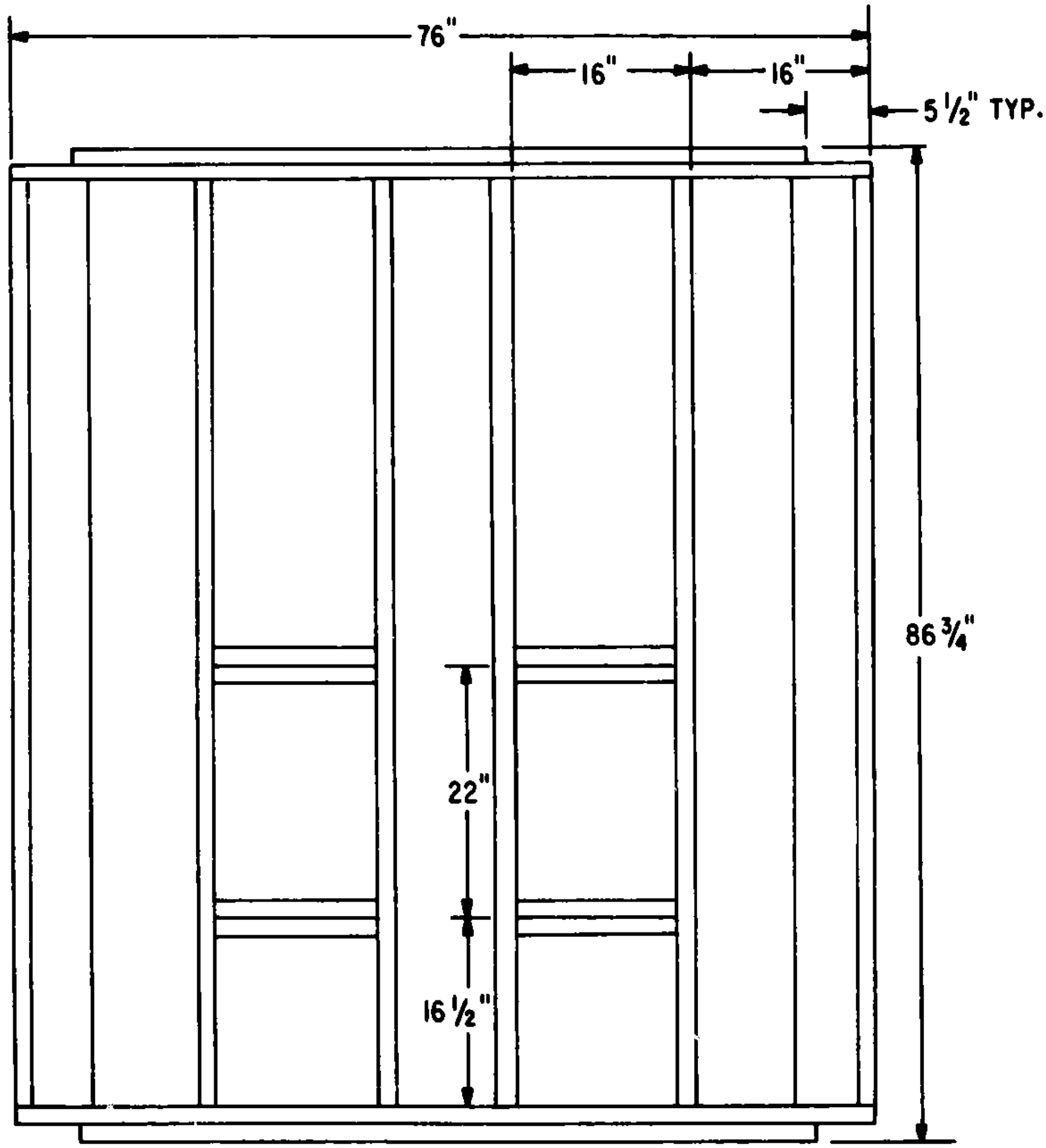


Figure F-3. Detail of Side Wall 2 x 6 Frame

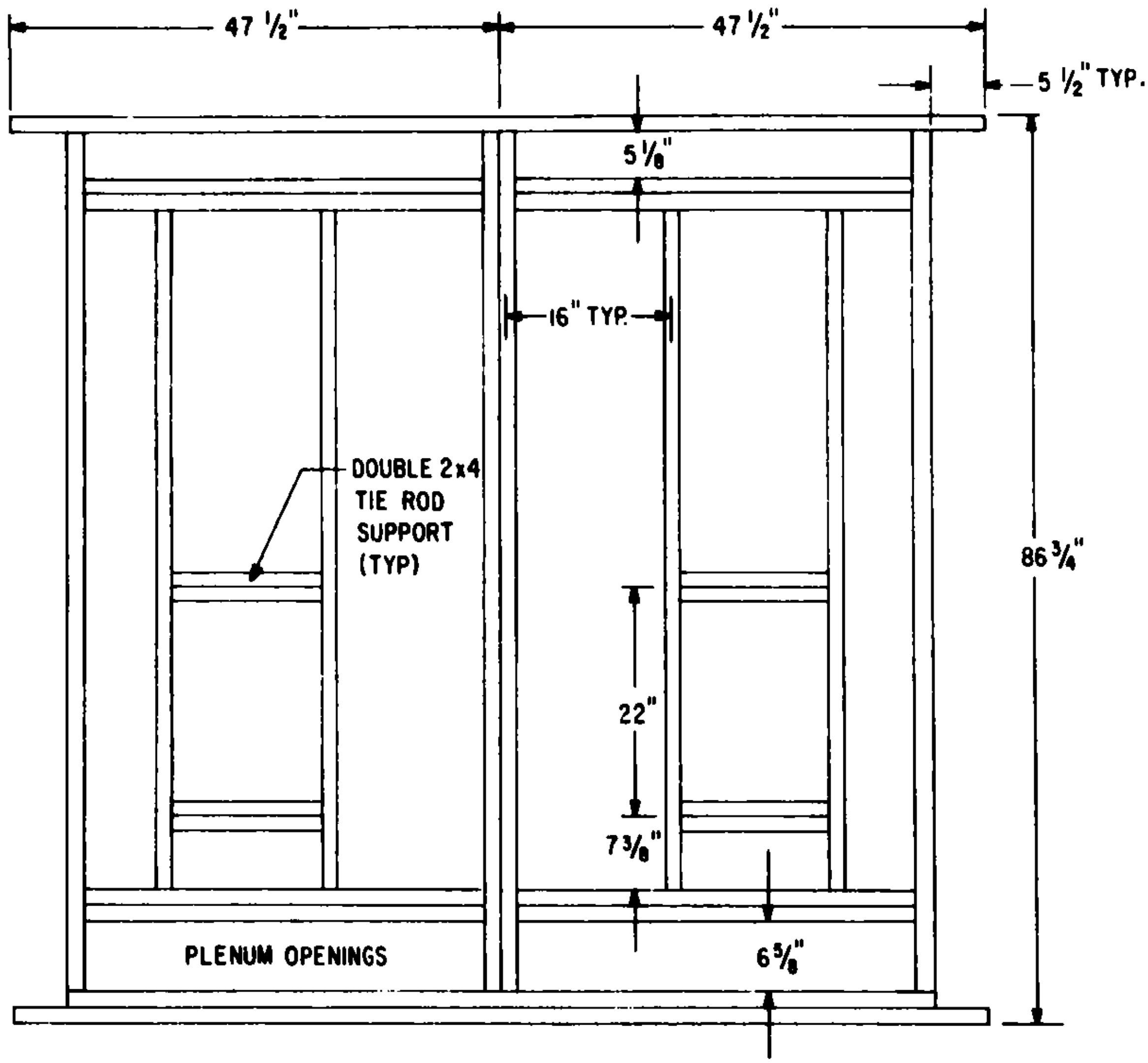


Figure F-4. Detail of Front Wall 2 x 6 Frame

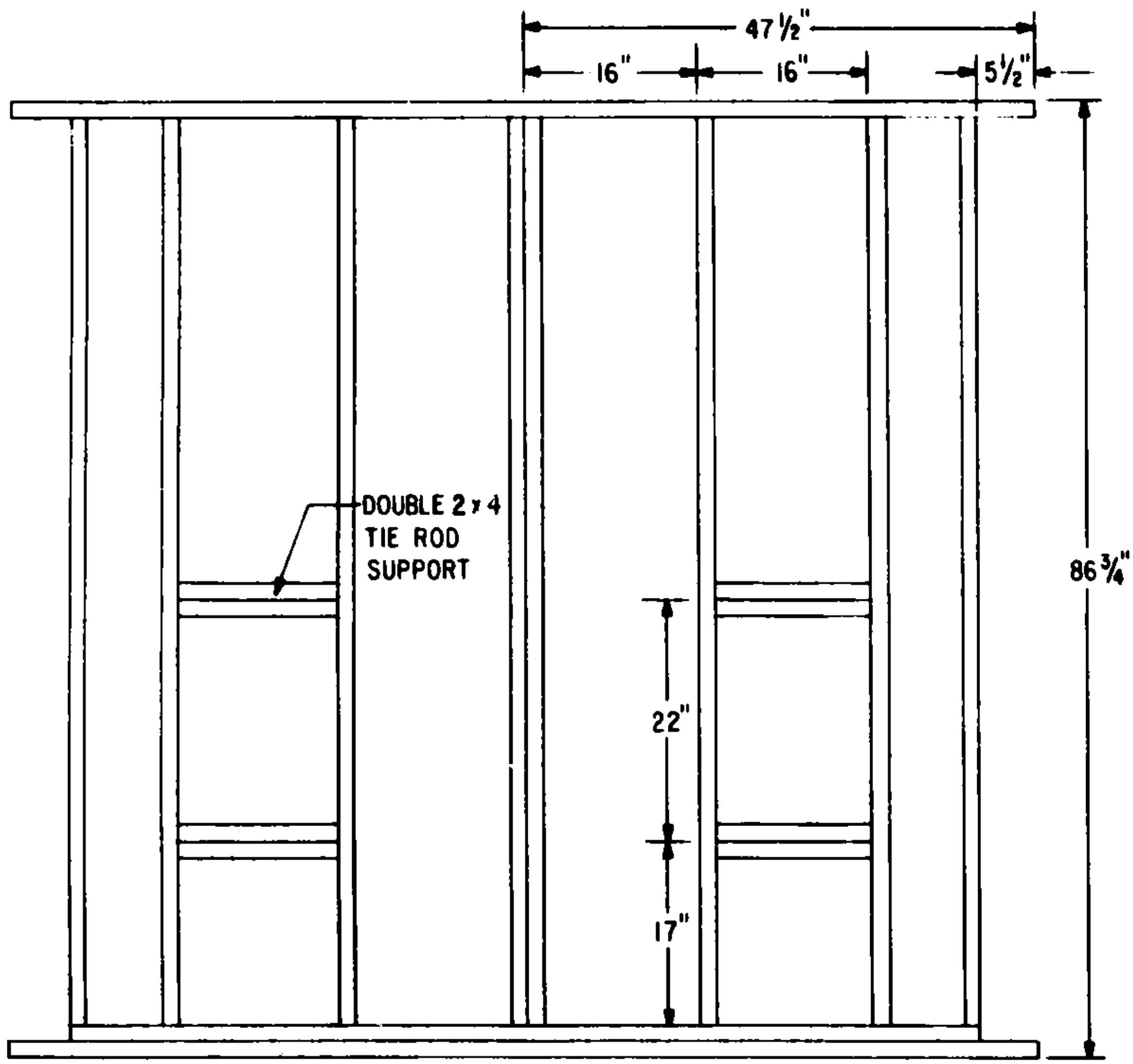


Figure F-5. Detail of Back Wall 2 x 6 Frame

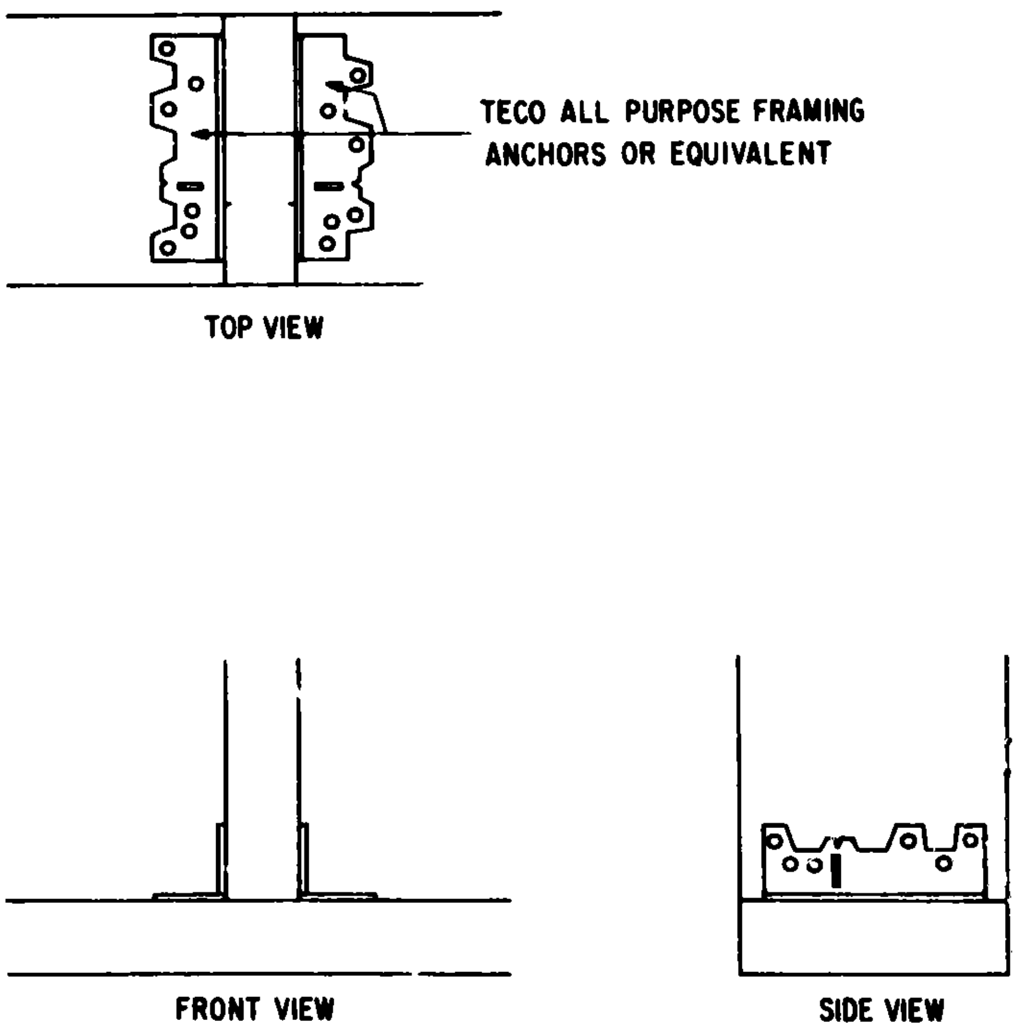


Figure F-6. Detail of Connection of Single 2 x 6 to Other Frame Members

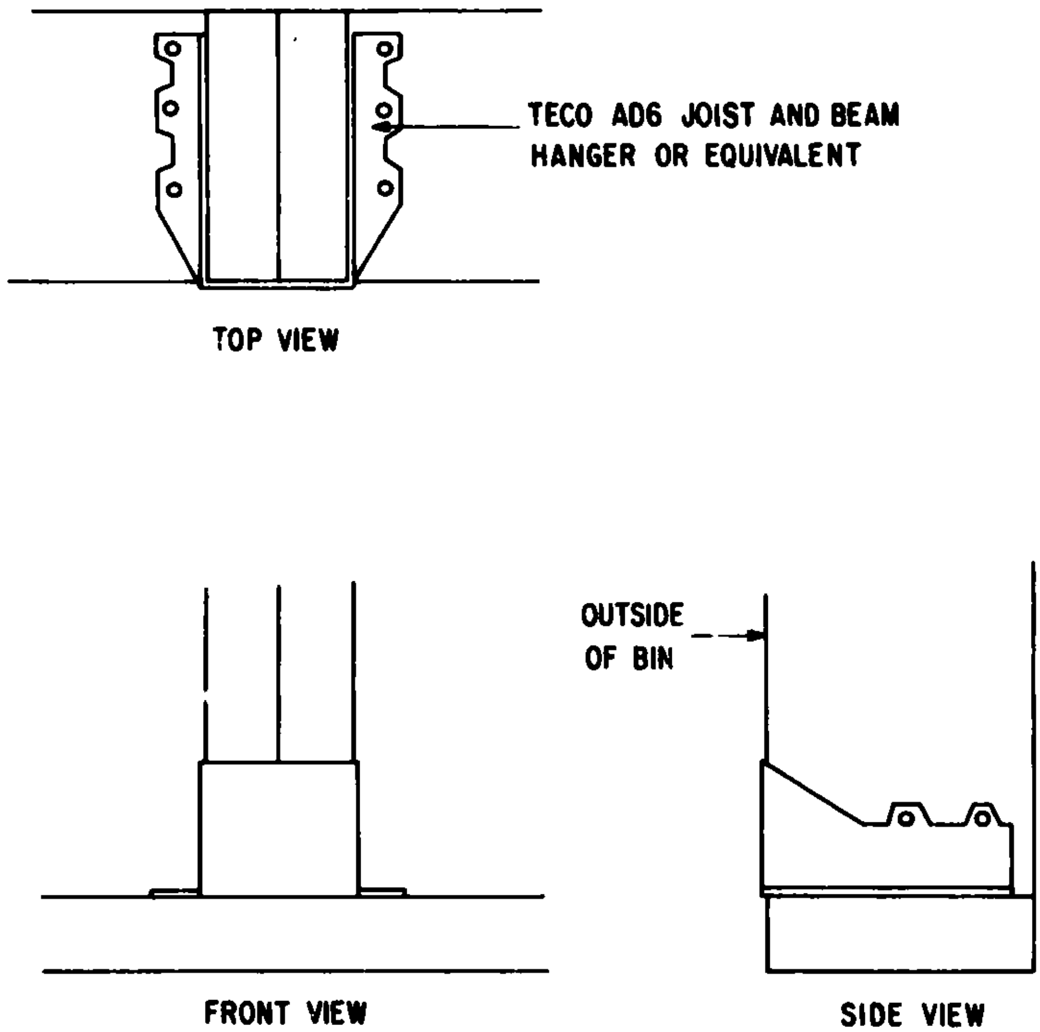


Figure F-7. Detail of Connection of Double 2 x 6 and Double 2 x 4 Tie Rod Support to Other Frame Members

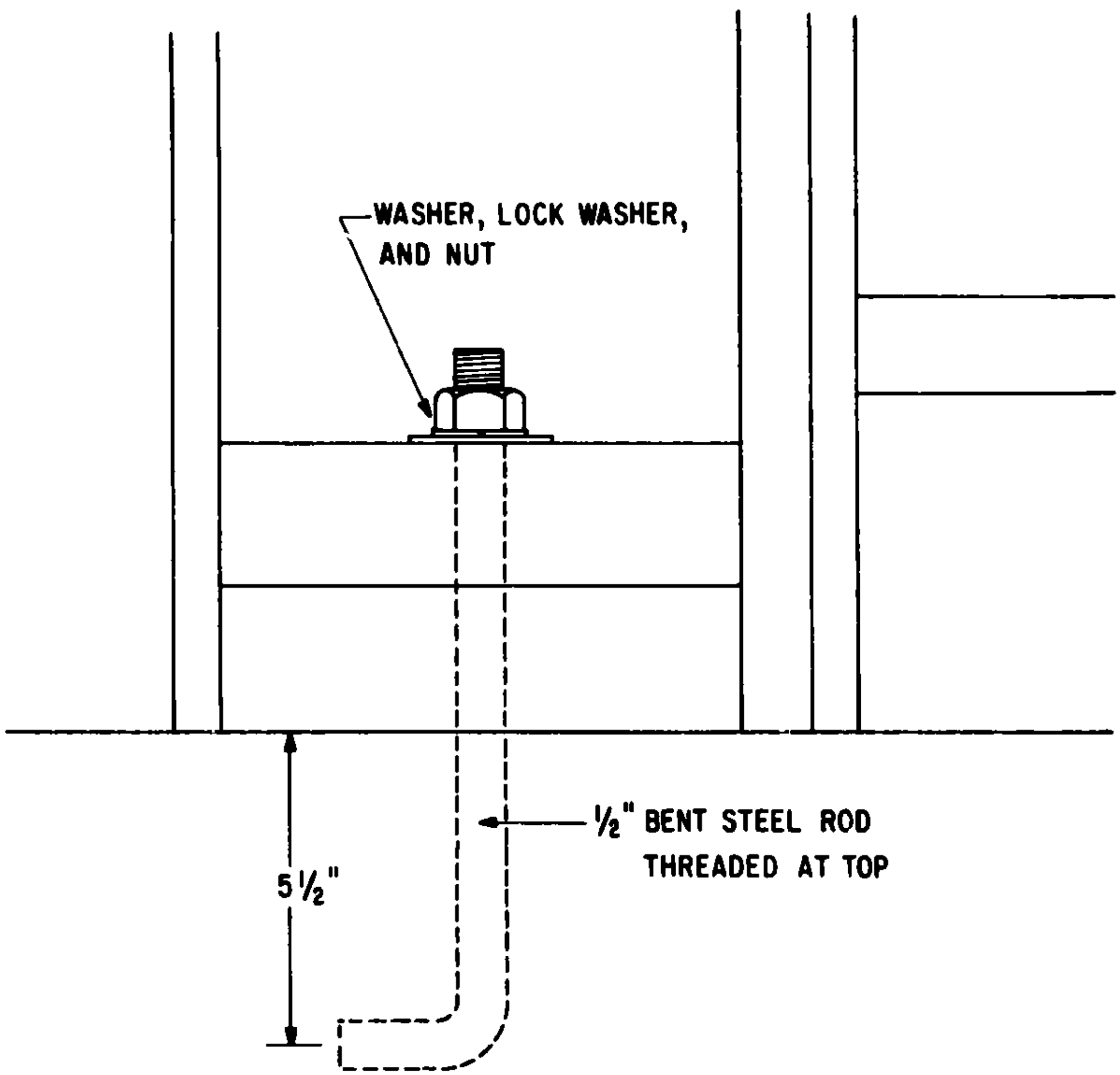


Figure F-8. Detail of Concrete Anchor

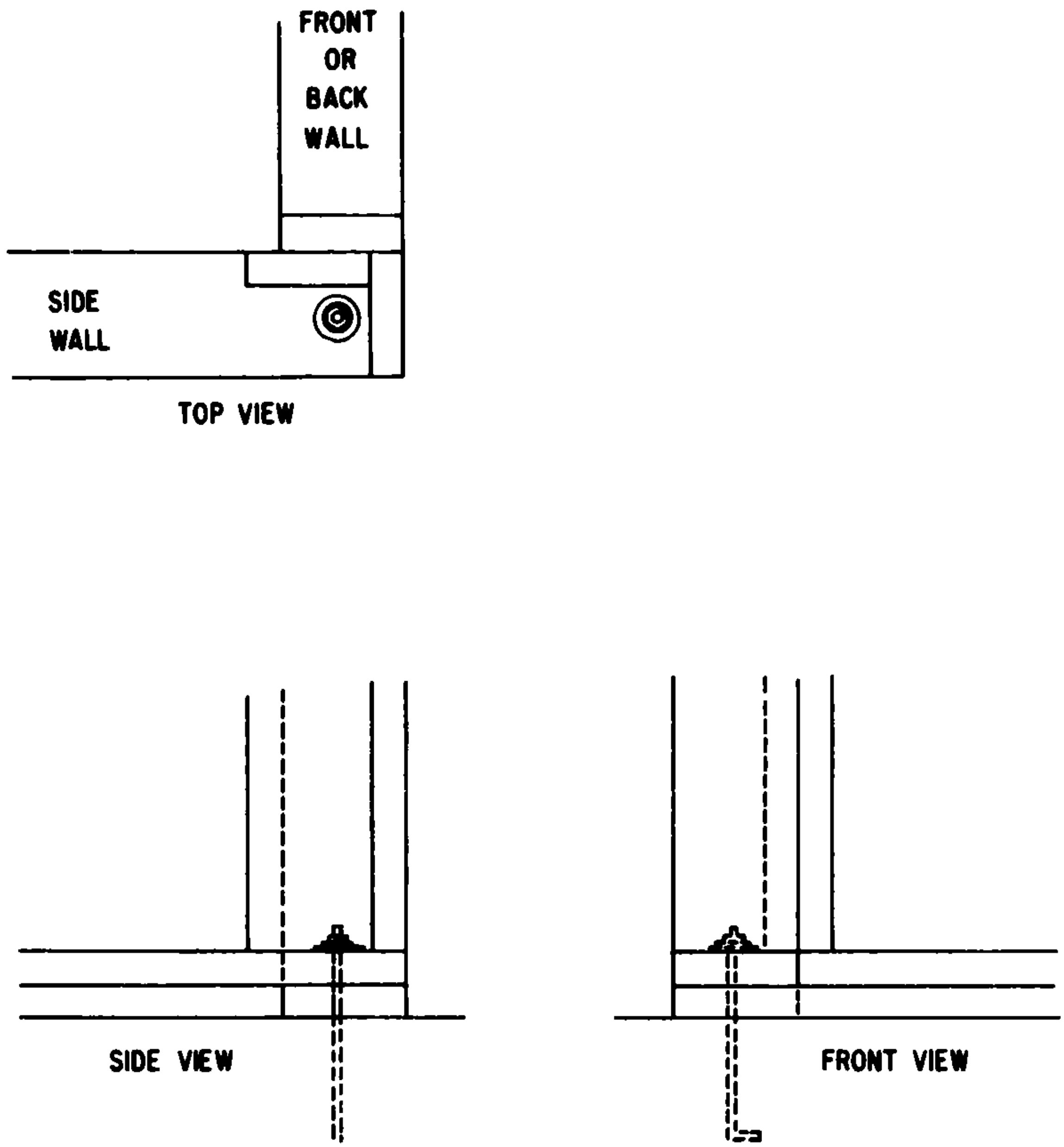


Figure F-9. Detail of Bottom Corner Joints

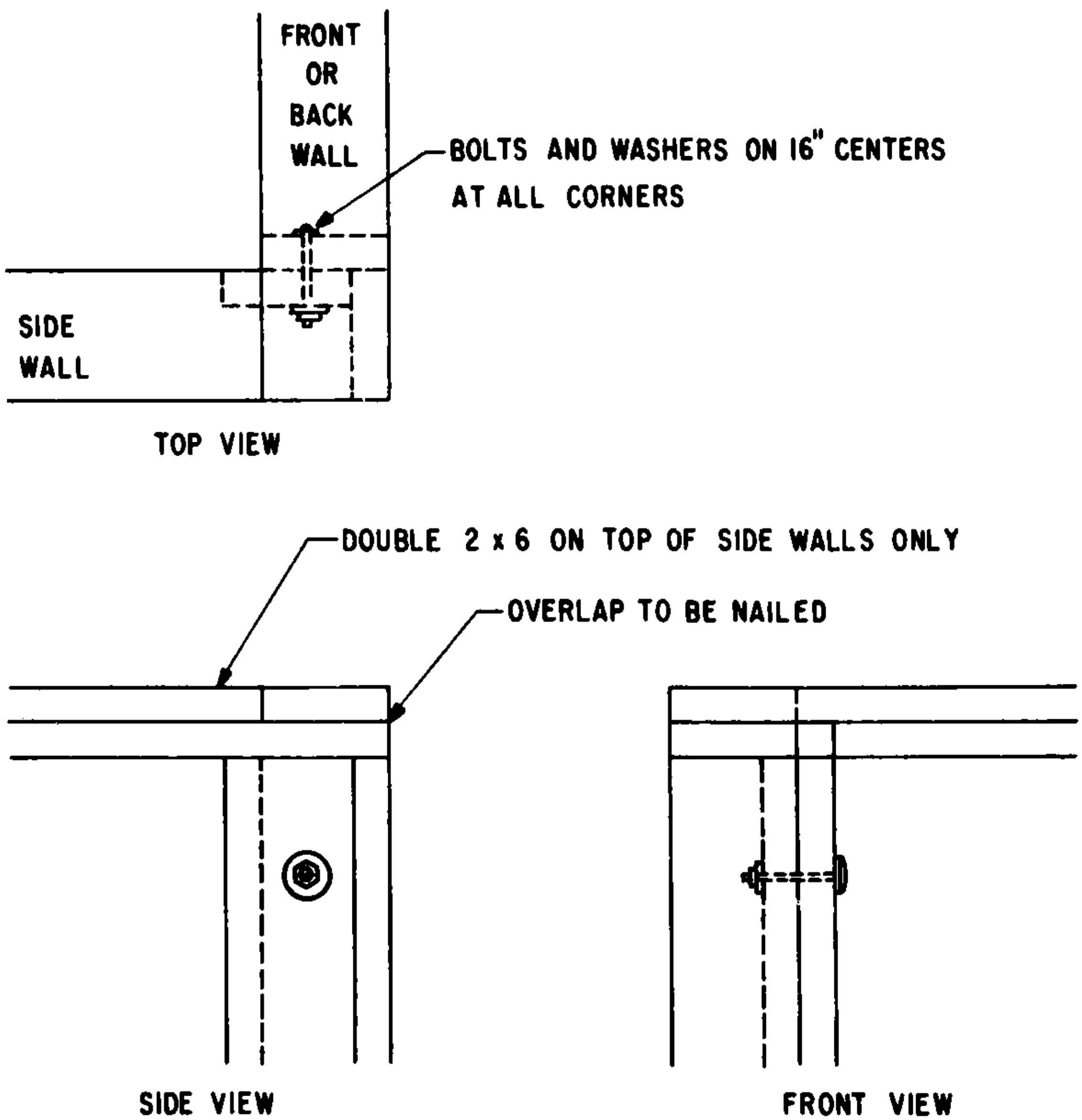


Figure 10. Detail of Top Corner Joints

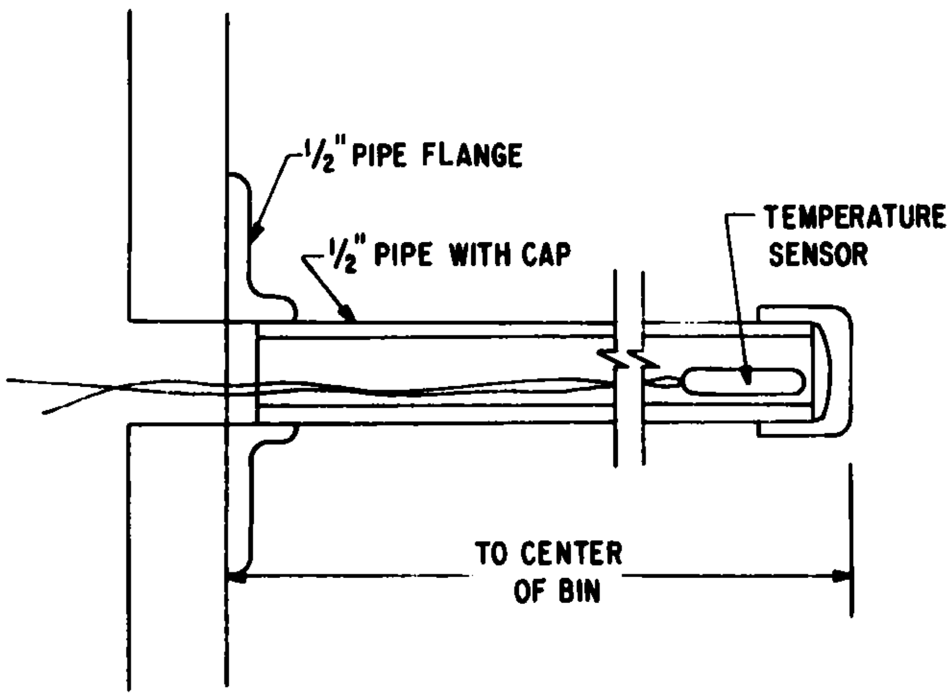


Figure F-11. Detail of Pipe to Protect Temperature Sensor

APPENDIX G
SAMPLE SPECIFICATIONS FOR STEEL TANKS

In this appendix, comments and other material that is not part of the sample specifications are written in italics.

Part 1. SPECIFICATIONS FOR STEEL TANKS WITH CAPACITY BETWEEN 120 GALLONS AND 5000 GALLONS

1.0 WORK INCLUDED (Provide)

1.1 All materials, parts, and work related to steel tanks as indicated on drawings or specified.

1.2 Steel tanks with capacities between 120 gallons and 5000 gallons.

1.3a Steel tanks located inside the building.

1.3b Steel tanks suitable for underground burial.

Choose 1.3a or 1.3b as appropriate to your installation.

1.4 Steel tanks that will have a minimum service life of 20 years.

If the tank is located so that it will be difficult to repair or replace, 30 years may be more appropriate.

1.5 Steel tank accessories such as manholes, extensions, couplings, ladders, hold-down straps, supports, saddles, etc.

1.6 Steel tanks with coatings that will protect them against corrosion.

1.7 Steel tanks that will be able to withstand thermal cycling temperatures between 50°F and 200°F.

1.8 Steel tanks that will be capable of withstanding an operating pressure of 125 psig.

Item 1.8 is required only if the tank will operate at above-atmospheric pressure. Specify a pressure appropriate to your installation.

1.9 Steel tanks that will be used for storage of potable hot water.

Item 1.9 is required for large domestic hot water systems.

2.0 RELATED WORK

2.1 Cast-in-place concrete.

2.2 Anchor bolts.

2.3 Piping.

2.4 Liquid-level gauges, temperature sensors, thermometers, and pressure gauges.

2.5 Excavation and compacted fill.

Item 2.5 is required for underground tanks only.

3.0 DETAILS

3.1 All details shall be in accordance with the standards of the National Board of Fire Underwriters, Underwriters Laboratories, Inc., the ASME Boiler and Pressure Vessel Code, American Water Works Association, etc., as applicable to steel tanks.

Include other standards-writing organizations and state and local governments as necessary.

3.2 Contractor shall be responsible for all dimensions of the steel work and shall check structural drawings in relation with other work and existing field conditions. Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 APPLICABLE CODES AND STANDARDS

4.1 HUD Intermediate Minimum Property Standards, Solar Heating and Domestic Hot Water Systems, 1977 edition.

4.2 The ASME Boiler and Pressure Vessel Code.

Item 4.2 is required if the tank will operate at above-atmospheric pressure and is recommended for other steel tanks.

5.0 CONSTRUCTION

5.1 Materials

All tanks shall be fabricated from Class A open hearth or basic oxygen steel. Thickness of shells and head shall be in strict accordance with Underwriters' specifications. All heads and shell rings shall be of one-plate construction. Plates should be gauged and inspected by an Underwriters' representative before fabrication. The plates shall be free from physical imperfections such as laminations, cracks, mill scale, etc. All steel must be in good condition and free from rust.

5.2 Fabrication

Tanks shall be lap-welded continuously on the inside and outside according to Underwriters' specifications. Nozzles for manholes and outlets for pipe connections shall also be continuously welded inside and outside.

5.3 Welding

All welding for tanks shall be done electrically by qualified welders in strict accordance with the latest edition of the ASME Unfired Pressure Vessel Code and Underwriters' specifications.

5.4 Openings and Accessories

All openings except those for vents or for valves or pipe connections communicating with the interior of the tank shall be equipped with substantial covers. Thieving and gauging openings shall have approved self-closing covers, but manhole covers may be of either bolted or approved self-closing type.

5.4.1 Pipe Connections

Pipe connections shall be supplied by welding standard threaded flanges or studs to the tank, all to be steel of good welding quality. All openings in the tank shall be protected by metal covers, or their equivalent, while tank is in storage or in transit. The size of the opening for each pipe connection should be of the size of the pipe connected, except if noted otherwise. Tank openings shall be plugged until pipe connections are made. All couplings for pipe connections shall be continuously welded inside and outside the tank and plates.

5.4.2 Manhole

Each manhole shall have a 3/8-inch-thick or heavier steel cover plate with two 1/2-inch-diameter steel lift handles welded to plate and shall be provided with 1/8-inch-thick oil resistant ring gasket, etc. Provide in manhole cover plate a 3-inch half coupling with brass plug welded to a 3-inch I.P.S. hole in plate. The cover plate and gasket shall be secured by 5/8-inch-diameter brass bolts and nuts.

Manholes can vary with individual tank manufacturers, and manhole turrets are available as options. A manhole is required only on tanks of 500 gallon capacity or larger.

5.4.3 Vent

Provide a vent to the atmosphere for the tank. The vent shall be at least _______inches in diameter.

A vent is required only for unpressurized tanks. The breather vent permits the proper outflow and inflow of air during filling and emptying operations. Venting prevents the development of dangerous interior pressure or possible collapse of the tank due to vacuum and permits the normal expansion and contraction of the contents caused by varying temperatures. Sizes are as follows: 120 gallons to 500 gallons, 1-inch diameter; 500 gallons to 3000 gallons, 1-1/2-inch diameter; 300 gallons to 5000 gallons, 2-inch diameter.

5.4.4 Ladder

Provide a ladder from the manhole opening to the bottom of each tank. The ladder shall have 3/8-inch x 2-1/2-inch bar steel sides not less than 16 inches apart and 3-inch-diameter steel rod rungs spaced on about 12-inch centers. Rungs shall go through the sides and be welded in place. The ladder shall be properly fastened to tank with angles, etc.

5.4.5 Hold-Down Straps

Provide hold-down straps according to details and schedule of straps as shown on drawings.

5.4.6 Lifting Lugs

Provide lifting lugs as detailed on drawings.

6.0 TESTING

For unpressurized tanks, specify the following leak test:

Before they are painted, all unpressurized steel tanks shall be tested and proved tight against leakage under a test pressure of not less than 5 nor more than 7 psi. In the event of leakage, tanks shall be made tight as approved and the test repeated.

For pressurized tanks, specify the following leak test:

Before they are painted, all pressurized steel tanks shall be tested and proved tight against leakage as specified in the ASME Unfired Pressure Vessel Code. The ASME Unfired Pressure Vessel Code requires leak tesing at a pressure of not less than 1-1/2 times the design operating pressure. In the event of leakage, tanks shall be made tight by methods approved in the ASME Unfired Pressure Vessel Code and the test repeated.

7.0 COATINGS

7.1 Exterior Painting

Where exterior corrosion is not a problem, the following exterior coatings can be specified:

Storage tanks shall be thoroughly sandblasted and painted on the outside at the factory with two coats of approved red lead and oil paint and with one coat of black asphaltum paint. The red lead coatings shall be of different shades to facilitate inspection of the painting. All damaged spots shall be touched up.

For underground tanks, where conditions are generally more corrosive, good protection can be provided by the asphaltic paints or bituminous coatings applied either hot or cold. The Steel Tank Institute P3 method provides good exterior protection under severe conditions. A nominal 1/8-inch-thick coating of fiberglass-reinforced polyester also provides protection under severe conditions.

Sandblasting to remove all of the rust and mill scale is important to ensure adhesion of the paint. If the mill scale is not removed before the paint is applied, the scale will begin to flake off--taking the paint with it--after an exposure of a few months to about three years. The exact time will depend on the humidity and corrosive conditions as well as the thickness and permeability of the paint film.

7.2 Interior Coatings

Storage tanks shall be thoroughly sandblasted and coated on the inside with four coats of baked-on phenolic epoxy. The thickness of each coat shall be 5 to 7 mils.

To complete the protection of the tank interior we recommend installing a replaceable zinc, aluminum, or magnesium bar in the tank. The bar must be in electrical contact with the tank and must be submerged in water. Electrical currents flowing between the tank and the bar protect small areas of the tank where the coating has chipped or cracked.

8.0 PROVISIONS FOR DRAINAGE

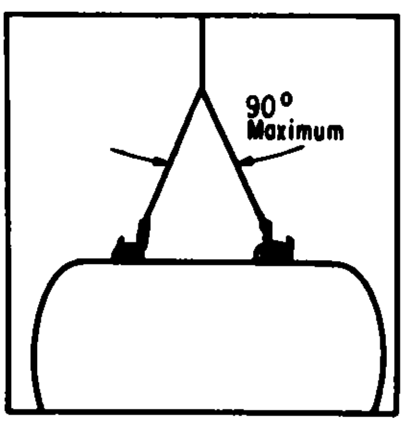
Openings for drains shall be as specified in the ASME Boiler and Pressure Vessel Code.

9.0 INSULATION

Storage tanks shall be insulated with 6 inches of fiberglass and 2 inches of polyurethane foam, vapor sealed to prevent ingress of moisture.

You must calculate the required thickness of insulation as shown in Chapter 1 of this manual and insert the correct numbers in the section above. The insulation specified above is not adequate if groundwater should ever rise above the bottom of the insulation. If the tank must be installed where groundwater could be a problem, you should specify the entire thickness of the insulation to be closed-cell polyurethane or closed-cell polystyrene foam. You should also increase the thickness of the insulation exposed to groundwater, since water can halve the resistance to the flow of heat of closed-cell foams.

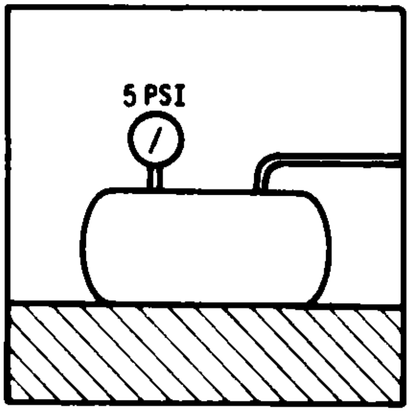
10.0 INSTALLATION



10.1 Lifting Tanks

Handle the tank carefully. Use cables or chains of adequate length (not more than 90° between the chains) attached to lift lugs. Use shackles if necessary.

10.2 Testing

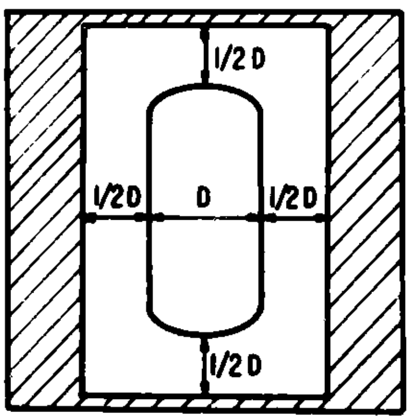


To ensure compliance with applicable codes and regulations, tank and piping should be retested at job site before being covered, enclosed, or placed in use, using 5 psig air pressure as soap solution is brushed over weld seams. Replace tin caps with pipe plugs or capped piping before test. Keep away from manholes or ends of tanks that are under test. Do not leave tanks under pressure unattended. This test is not a substitute for the ASME pressure vessel certification test.

When pressure testing piping, isolate the tank from the piping.

If tanks are dropped or subjected to an impact, retest the tanks.

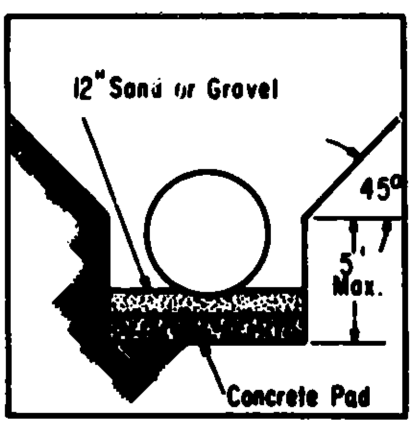
10.3 Hole Size



Hole must be large enough to allow clearance equal to half the tank diameter on all sides.

Observe OSHA regulations regarding supporting the walls of the hole and slanting the sides if the hole is deeper than 5 feet.

10.4 Hole Depth

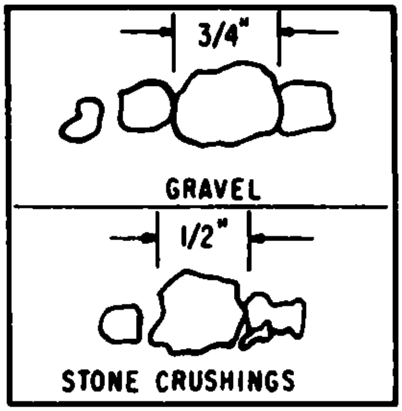


Unsupported vertical wall height shall not exceed 5 feet with ideal soil conditions. Slope upper walls of the hole at 45°. For less than ideal soil conditions reduce the vertical wall height.

The bottom of the excavation shall be level and firm. A full-length concrete pad shall be used. At least 12 inches of clean sand or gravel, suitably graded or leveled, shall be placed before installation of the tank.

Caution: Do not place steel tanks directly on concrete slab or grout tanks in wet concrete. Do not place tanks on timbers, beams, or cradles.

10.5 Bed and Backfill Material

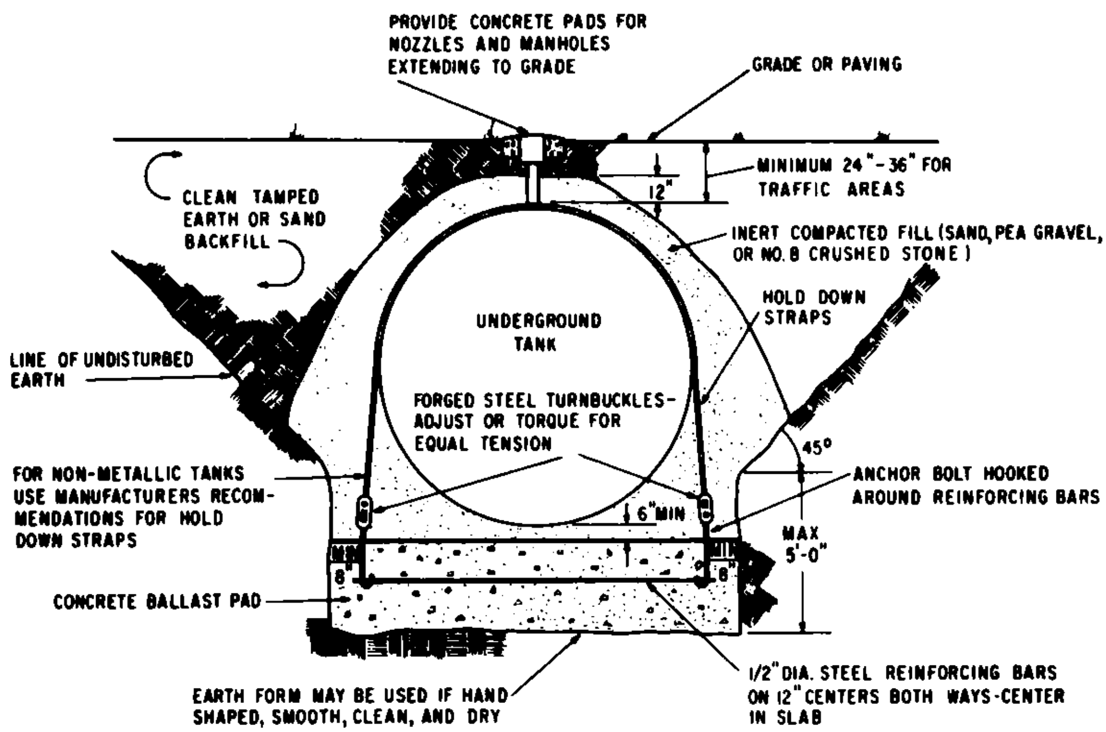


The tanks shall be surrounded with at least 12 inches of non-corrosive inert material such as clean sand, earth, or gravel well tamped in place. Do not allow ashes or other corrosive material to come into contact with tank.

Washed and free-flowing stone or gravel crushings with angular particle size between 1/8 inch and 1/2 inch in diameter are acceptable alternate bed and backfill materials.

10.6 Anchoring

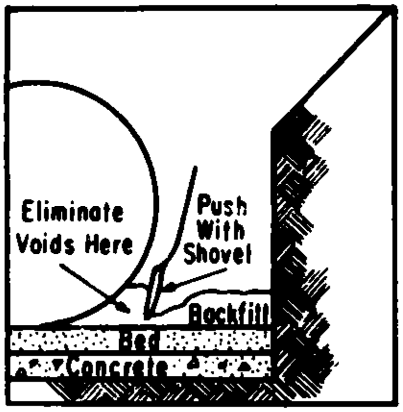
Tanks must be anchored where high water tables exist. Surface water could flow into hole or other water conditions could exist in a dry hole. Strap size shall be selected from the table below. The turnbuckles shall be tightened until the hold-down straps are snug against the tank. Caution: Excessive tightening can distort the tank.



Hold-down Strap Size

Turnbuckle Size	3/4"	7/8"	1"	1-1/8"	1-1/4"	1-3/8"	1-1/2"
Strap Size	1/4" x 3"	3/8" x 3"	3/8" x 3"	3/8" x 3"	3/8" x 4"	1/2" x 4"	1/2" x 4"
Maximum Load Per Strap	9,500 lb.	13,000 lb.	17,000 lb.	22,000 lb.	28,000 lb.	33,000 lb.	40,000 lb.

10.7 Backfilling



Use the same materials as for bedding. Push backfill under the tank with a board or shovel to eliminate all voids beneath the tank.

The bottom sides of the tank should be fully and evenly supported. This can be accomplished only by hand shoveling and tamping. Use hand-guided power equipment and place fill in 6-inch layers until the bottom quadrant is complete.

The use of saddles or "chock blocks" of any sort interferes with the proper distribution of the load to the backfill and may cause failure due to high stress concentrations. They should not be used.

Backfill the top of the tanks with clean sand, earth, or gravel. Backfill must be free of large rocks, debris, or corrosive material that could damage tanks. Do not allow tanks to be impacted during backfilling.

10.8 Barricade

Barricade the tank area to prevent vehicular travel over the tanks until installation is complete.

10.9 Filling Tanks

Do not fill tanks until backfill is to the top of tanks. Since tanks are held down by straps, it is neither necessary nor desirable to add water for hold down.

10.10a No Traffic Loads

Tanks not subjected to traffic loads need a minimum cover of 24-inch backfill or 12-inch backfill plus 4-inch reinforced concrete to meet NFPA 30 requirements.

10.10b Traffic Loads

Tanks subjected to traffic loads must have a cover depth of 36 inches backfill plus 8 inches of asphalt or a minimum of 18 inches backfill plus 6 inches of concrete reinforced with steel rebars.

Use either Section 10.10a or 10.10b as required by your particular installation.

11.0 CAPACITY AND DIMENSIONAL REQUIREMENTS

Fill in the blanks to complete this section. This example applies to horizontal cylindrical tanks. If your installation requires another tank shape or if you have special dimensional requirements (such as special locations for pipe fittings), state your requirements in this section.

11.1 Nominal capacity of the tank shall be __________ gallons.

11.2 Nominal outside diameter of the tank shall be _________ feet.

11.3 Approximate overall length of the tank shall be _______ feet.

12.0 DRAWINGS

Include drawings that are applicable to your particular installation in this section. A sample drawing is shown in Figure G-1.

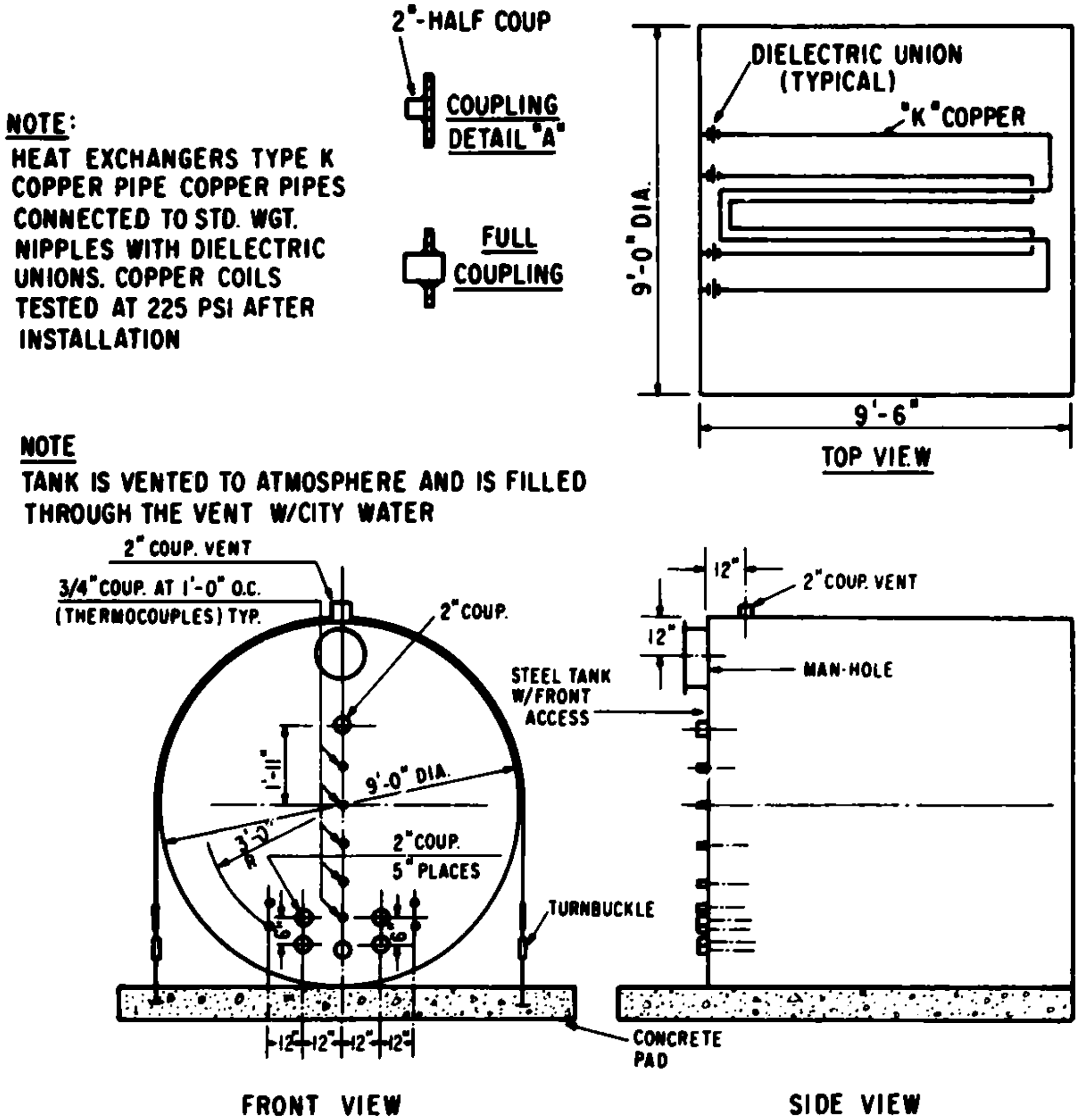


Figure G-1. Sample Drawing of a Steel Tank 9'6" Long x 108" O.D.

Part 2. SPECIFICATIONS FOR DOMESTIC HOT WATER TANKS WITH CAPACITY UP TO 120 GALLONS

1.0 WORK INCLUDED (Provide)

1.1 All materials, parts, and work related to steel tanks as indicated on drawings or specified.

1.2 Steel tanks with capacities up to 120 gallons.

1.3 Steel tanks located inside the building.

1.4 Steel tanks that have a minimum service life of 20 years.

1.5 Steel tanks that can withstand thermal cycling between 50°F and 200°F.

1.6 Steel tanks that will be capable of withstanding an operating pressure of 125 psig.

1.7 Steel tanks that will be used for storage of potable hot water.

1.8 Steel tanks that include an integral heat exchanger capable of meeting the requirements of the HUD Intermediate Minimum Property Standards.

2.0 RELATED WORK

2.1 Plumbing make-up water supply connection.

2.2 Standard 115-volt AC wiring to the control unit and standard 230-volt AC wiring to the electric immersion heater.

3.0 DETAILS

3.1 All details shall be in accordance with the HUD Intermediate Minimum Property Standards, 1977 edition, and HUD Intermediate Standards for Solar Domestic Hot Water Systems, July 1977.

3.2 Contractor shall be responsible for all dimensions of the steel work and shall check structural drawings in relation to all other drawings and shall verify all dimensions in relation with other work and existing field conditions. Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 APPLICABLE CODES AND STANDARDS

HUD Intermediate Minimum Property Standards, 1977 edition, and HUD Intermediate Standards for Solar Domestic Hot Water Systems, July 1977.

Indicate applicable state and local building, plumbing, and electrical codes.

5.0 MATERIALS

5.1 Steel tank uniformly lined with 1/2 inch of seamless hydraulic stone.

5.2 Fiberglass insulation.

5.3 Internal heat exchanger.

5.4 Tank exterior of heavy-gauge steel finished with baked enamel.

6.0 PRESSURE RATINGS

6.1 The tank shall be designed to withstand a maximum operating pressure of 125 psig.

6.2 The tank shall be designed to withstand a maximum operating temperature of 200°F and thermal cycling temperatures between 50°F and 200°F.

7.0 COATINGS

7.1 The interior of the tank shall be uniformly lined with 1/2 inch of seamless hydraulic stone.

7.2 The exterior of the tank shall be heavy-gauge steel finished with baked enamel.

8.0 TANK PROTECTION

A 125-psig, 200°F ASME pressure-temperature safety valve shall be fitted to the tank. The discharge from the valve shall be directed to within 12 inches of the floor or as required by local codes.

9.0 INTEGRAL HEAT EXCHANGER

9.1 The tank shall be fitted with a double-walled heat exchanger. If either wall of the heat exchanger leaks, the leak shall be visible from the outside of the tank so that the tank can be replaced or repaired before contamination of the potable water by toxic heat exchange fluid is possible.

The above specification is necessary to comply with the HUD Minimum Property Standards and most plumbing codes if a nonpotable fluid (such as ethylene glycol-water solution) is used to heat the potable water. A heat exchanger that uses two concentric tubes coextruded or pressure bonded together does not satisfy the HUD Minimum Property Standards for a double-walled heat exchanger, because leaks cannot be detected before the potable water is contaminated.

9.2 The heat exchanger shall have a minimum heat exchange surface of __________ square feet.

One of the most common mistakes in solar system design is the failure to provide enough heat exchange surface. A method of calculating the required heat exchange surface is given in Appendix D of this manual.

10.0 ELECTRIC IMMERSION HEATER

The tank shall include a 4500-watt electric immersion heater located approximately one-third of the distance down from the top of the tank.

An electric immersion heater is usually specified for a one-tank DHW system. You may need to specify a different wattage to suit your system. Gas and other forms of auxiliary heat are rarely specified for a one-tank system.

Since the auxiliary heat enters the second tank of a two-tank system, the first tank does not need an auxiliary heater.

11.0 TEMPERING VALVE

A tempering valve shall be installed at the hot-water outlet of the tank. The tempering valve shall limit the temperature of the water delivered to the house to 140°F by mixing cold water with the hot water.

12.0 CAPACITY AND DIMENSIONAL REQUIREMENTS

The tank shall have a capacity of _______ gallons.

Specify a size to suit your installation. If you require special locations for the potable water inlet and outlet and heat exchanger connections, specify them in this section.

13.0 DRAWINGS

Include drawings appropriate to your system. A sample drawing of one type of system is shown in Figure G-2.

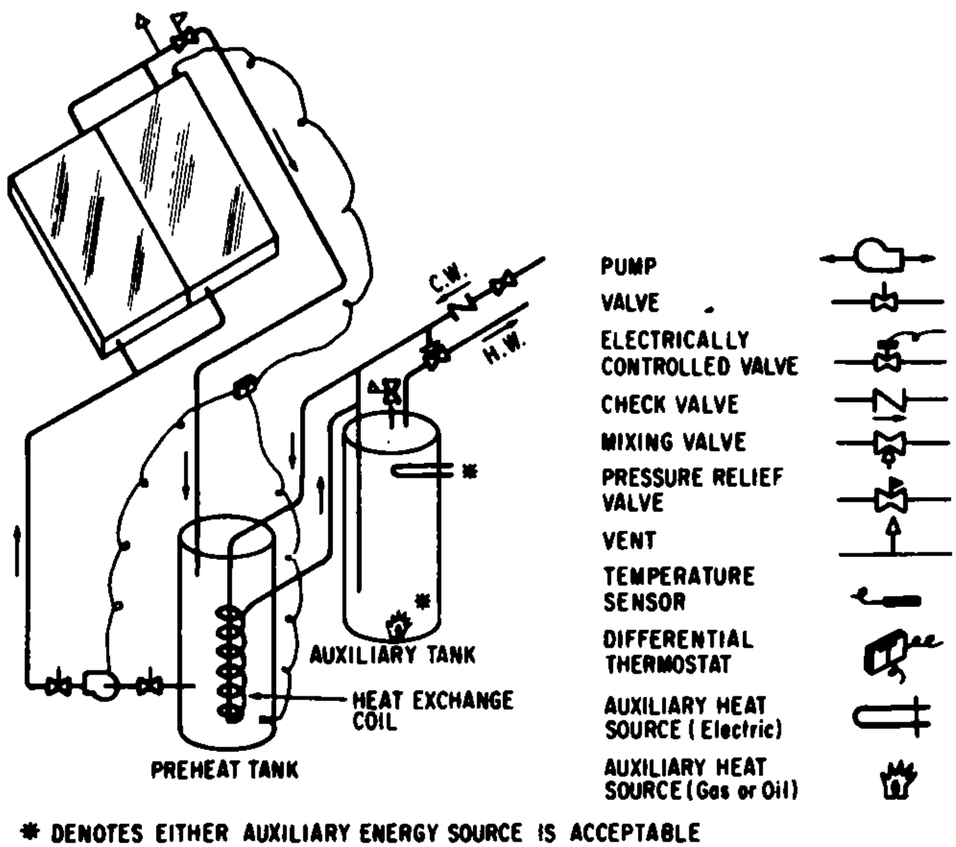


Figure G-2. Sample System Schematic

A vented (low pressure) draindown system is shown.

APPENDIX H
SAMPLE SPECIFICATIONS FOR CONCRETE TANKS

Part 1. Sample Specifications for Cast-in-Place Concrete Tanks

Part 2. Precast Concrete Tanks

- A. Sample Specifications for Precast Concrete Tanks
- B. Sample Specifications for Using Utility Vaults for Thermal Energy Storage
- C. Sample Specifications for Using Septic Tanks for Thermal Energy Storage

Part 3. Waterproofing Concrete Tanks

- A. Sample Specifications for Plastic Liners for Concrete Tanks
- B. Sample Specifications for Rubber Liners for Concrete Tanks

Part 4. Sample Specifications for Insulation of Concrete Tanks

In this appendix, comments and other material that is not part of the sample specifications are written in italics.

Part 1. SAMPLE SPECIFICATIONS FOR CAST-IN-PLACE CONCRETE TANKS

1.0 WORK INCLUDED (Provide)

1.1 All concrete and cement work as indicated in these specifications and shown on drawings.

1.2 Dovetail anchor slots.

1.3 Reinforcing, forming, and accessories.

1.4 Pockets for installation of items required by other trades using templates provided by trades requiring same.

1.5 Concrete for supports or pits required by other trades.

1.6 Grouting.

1.7 Setting anchor bolts.

1.8 Expansion joint filler.

1.9 Protection of all slabs being installed.

1.10 Recesses as shown on drawings.

1.11 Cutting, patching, repairing, and pointing up around sleeves, pipes, and hangers.

1.12 Floor hardeners.

2.0 RELATED WORK

2.1 Porous or compacted fill below slabs on ground.

2.2 Anchor bolts and other items requiring building into concrete will be furnished by others and installed under this contract.

2.3 Waterproofing and vapor barrier.

2.4 Rigid insulation on slabs and against foundation walls.

3.0 DETAILS

3.1 All details shall be in accordance with the American Concrete Institute Standards "Building Code Requirements for Reinforced Concrete" (ACI 318) and "Manual of Standard Practice for Detailing Concrete Structures" (ACI 315), except as qualified.

3.2 The Contractor shall be responsible for all dimensions of the concrete work and shall check structural drawings in relation to all other drawings and shall verify all dimensions in relation with other work and existing field conditions. The Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 APPLICABLE CODES

4.1 The "Building Code Requirement for Reinforced Concrete" (ACI 318-71) shall be applicable.

Include applicable state and local building codes.

5.0 MATERIALS

5.1 Cement

All cement shall conform to the "Standard Specifications for Portland Cement," ASTM Designation C150. No cement that has become lumpy or has in any way deteriorated shall be used.

5.2 Water

Water used in mixing concrete shall be clean and free from deleterious amounts of acids, alkalies, or organic materials.

5.3 Aggregates

Concrete aggregates shall conform to the "Standard Specifications for Concrete Aggregates" (ASTM C 33).

5.3.1 The maximum size of coarse aggregates shall not be larger than 1/5 of the narrowest dimension between forms nor larger than 3/4 of the minimum clear spacing between reinforcing bars.

(The mixture should possess sufficient workability that the concrete can be placed without honeycombs or voids.)

5.3.2 Fine aggregate shall be natural sand for stone concrete.

5.3.3 All aggregates that are frozen or contain frozen particles must be completely thawed before they are used.

5.4 Reinforcing Steel

Reinforcing steel must be correctly rolled to section and free from surface defects, scale, or oil that will destroy or reduce the bond and shall be stored on the job in such a manner as to be kept clean and free of scale. Thin powdery rust is not considered detrimental and need not be removed. Reinforcing steel shall comply with ASTM A 615-68. Bars shall be Grade 40 or Grade 60 as required. Raised markings on bars should identify manufacturer and sizes and distinguish the grade.

5.4.1 Welded wire fabric reinforcing shall meet the requirements of ASTM Specification A 185, current edition, and shall be tagged so as to identify the type and grade of steel and the size.

5.5 Placing of Reinforcement

All reinforcement shall be rigidly wired in place with adequate spacers and chairs.

5.5.1 All reinforcement within the limits of a day's pour shall be rigidly wired in place before concreting starts.

5.5.2 In all concrete surfaces exposed to the weather, bars including ties shall be a minimum of 2 inches clear of forms.

5.5.3 The Contractor shall conform with "C.R.S.I. Recommended Practice for Placing Reinforcing Bars," latest edition.

5.6 Design of Concrete Mixtures

5.6.1 All concrete, unless otherwise specified, shall be controlled concrete and shall be proportioned as outlined in Section 4.2.3, the Building Code of the American Concrete Institute (ACI 318-71), except as otherwise required by these specifications. The allowable design stresses are based on the minimum 28-day compressive strength. The laboratory trial mixtures shall develop concrete of compressive strength 25 percent higher than the required minimum to be acceptable for use in the field. Laboratory tests shall include the admixtures to be used.

5.6.2 All concrete except in footings shall contain Plastiment Retarding Densifier as manufactured by the Sika Chemical Corp., Lyndhurst, New Jersey, or equal. For low temperature conditions, Plastocrete 161 HE or equal may be used instead of Plastiment in walls and slabs. Proportions of all admixtures shall be as recommended by manufacturer's representative. Admixtures must be by same manufacturer as air-entraining agent.

5.6.3 The proportions of aggregate to cement for any concrete shall be such as to produce a non-segregating plastic mixture of such consistency as will give the required finish and can be worked readily into corners and angles of forms and around reinforcement with the method of placement employed. Required changes in consistency must be accomplished by changes in the proportioning of the mix without changing the W/C ratios established for the job.

5.6.4 For concrete exposed to the elements, "SIKA AER" by Sika Chemical Corp. or equal shall be added to the concrete mix in the amount and manner recommended by the manufacturer in order to obtain an air content of 5.0 percent, plus or minus 1.5 percent of the volume of the concrete, for 1-inch maximum stone aggregates and 6.0 percent, plus or minus 2.0 percent, for 3/4-inch maximum stone aggregate. Air-entraining agent must be by the same manufacturer as other additives.

5.6.5 The slump of concrete shall be 5 inches maximum.

5.7 Testing and Inspection

5.7.1 Services Required

5.7.1.1 The Owner will retain at his expense the services of an independent testing laboratory.

5.7.1.1.1 Analysis and testing of all aggregate to be used on the project in accordance with this specification and applicable ASTM specifications.

5.7.1.1.2 Design of concrete mixtures to produce specified strength from aggregates as delivered.

5.7.1.1.3 Inspection of mixing and placing, air content control, slump testing of all concrete, and obtaining specimen cylinders.

5.7.1.1.4 Compression testing of specimen cylinders taken from the concrete actually placed in the work.

5.7.1.1.5 Checking of mix, moisture content of aggregates, additives, gradation of aggregates, cement, temperature of cement during summer months, etc.

5.7.1.1.6 Checking that reinforcing is rigidly secured and mesh raised to proper position.

5.7.2 Preliminary Tests of Controlled Concrete

5.7.2.1 The Contractor shall furnish the laboratory with sufficient material to make the required tests indicated under "Design of Concrete Mixes."

5.7.2.2 The source of supply of the aggregate and cement shall not be changed during the course of the job without previous notice to the Owner, and the material from any new source shall be subject to acceptance or rejection as based on appearance for exposed concrete and on tests to be made by the testing laboratory at the Contractor's expense.

5.7.3 Testing of Concrete

5.7.3.1 During the progress of the work, for every class of concrete placed or for any amount of concrete placed or for any amount of concrete placed on any one day, four test cylinders shall be made and stored in accordance with ASTM C 31. One of the specimens shall be tested after 7 days and three after 28 days. The 7-day strength will be assumed to have 65 percent of the 28-day strength. Compression tests shall be conducted in accordance with ASTM C 39. The method of sampling fresh concrete shall be in accordance with ASTM C 143.

5.7.3.2 Slump tests shall not exceed the maximum recommended by the American Concrete Institute.

5.7.3.3 All test cylinders shall be marked with date they were made, together with full information on materials, proportions, water, air, and cement content, and other pertinent data.

5.7.3.4 The Owner has the authority to order, at Contractor's expense, for any class of concrete, increase in cement content and mix redesign for remaining work, if either:

5.7.3.4.1 Average 7-day strength of any two tests representing class is less than 65 percent of specified strength; or

5.7.3.4.2 Average 28-day strength of any two tests representing class is less than 90 percent of specified strength.

5.7.4 Additional Field Tests

The Owner shall have the right to order the making of load tests, compression tests on specimens taken from the concrete in place or any other part thereof at any time during the course of construction. If the tests show that concrete tested is not in accordance with specifications, the Owner may condemn such concrete and the Contractor, at his own expense, shall remove such condemned concrete and replace same with new concrete to the satisfaction of the Owner.

5.7.4.1 Whenever such tests are ordered because original field tests have failed to comply with the requirements, or there is evidence of faulty workmanship, violation of specifications or likelihood of concrete having been frozen, the cost of the tests shall be borne by the Contractor. Whenever these tests are ordered for any other reason, the costs of the test shall be borne by the Contractor if the concrete test is not up to specifications; otherwise, the cost of the same will be borne by the Owner.

5.7.4.2 Should the Owner incur additional engineering fees or should additional work other than tests be required because original field tests have failed to comply with the requirements, the additional fees and the additional work shall be charged to the Contractor.

5.8 Mixing of Concrete

5.8.1 Ready-mixed concrete shall be mixed and delivered in accordance with the requirements set forth in the "Standard Specifications for Ready-Mixed Concrete" (ASTM C 94).

5.8.2 All measurement of materials shall be done by weight with allowance for moisture content of aggregates. Admixtures shall be dispensed by automatic, metered devices with at least plus or minus 5 percent accuracy. These dispensers shall be regularly inspected and certified as to accuracy by the manufacturer of the admixture.

5.8.3 The concrete shall be mixed until there is a uniform distribution of the materials and shall be discharged completely before the mixer is recharged. For job-mixed concrete, the mixer shall be rotated at the speed recommended by the manufacturer and mixing shall be continued for at least 1-1/2 minutes after all materials are in the mixer. For mixers larger than 1 cubic yard capacity, the minimum mixing time shall be increased 15 seconds for each additional 1/2 cubic yard of concrete or fraction thereof.

5.8.4 The driver of each transit mix truck shall supply the Contractor's superintendent at the building with a certificate stating the time he left the plant and the mix of the concrete he is delivering. The certificate shall also state the amount of water and cement in the concrete. Failure to comply with these requirements shall be sufficient grounds for rejecting the concrete.

5.8.5 The certificates mentioned above must be written and signed by an authorized official of the transit mix company. Time at completion of each load of transit mix concrete shall be inserted on certificate by the Contractor's superintendent. Contractor's superintendent shall retain all certificates at the job for the inspection of the testing laboratory.

5.8.6 Not more than 1 hour shall elapse from the time water is introduced into the drum until it is discharged. No water shall be added to a mix that has stiffened to increase its workability. Retempering of partly set concrete shall not be permitted.

5.8.7 The Owner shall have the right to have the Contractor discontinue the services of the concrete supplier if, in his opinion, the supplier is not providing satisfactory continuity of delivery and cooperation.

5.9 Preparation of Equipment and Place of Deposit

5.9.1 Before placing concrete, all equipment for mixing and transporting the concrete shall be cleaned, all debris and ice shall be removed from the spaces to be occupied by the concrete, forms shall be thoroughly wetted (except where the surrounding atmosphere is below 40°F) or oiled, and reinforcement shall be thoroughly cleaned of ice or other coatings. Water shall be removed from place of deposit before concrete is placed. All reinforcement, forms, and ground with which the concrete is to come in contact shall be free from frost. Concrete shall not be deposited during rain unless adequately protected, and in any case preparations shall be on hand to protect newly placed concrete from the rain until it has hardened sufficiently so that it will not be damaged.

5.10 Conveying and Depositing

5.10.1 Concrete shall be conveyed to the place of final deposit by methods which will prevent segregation or loss of materials. Concrete shall be deposited as near as practicable in its final position to avoid segregation due to handling and flowing. No concrete that has partially hardened or been contaminated by foreign materials shall be deposited nor shall retempered concrete be used.

5.10.2 Concrete shall be placed directly and as near the final position as possible and in layers not exceeding 18 inches in depth to avoid inclined planes or the piling up of the concrete in the forms in such a manner as to permit the escape of water or the free flow of the concrete.

5.10.3 No cold joints resulting from the stoppage of concreting for lunch or other reasons shall be permitted when the temperature is high and an early set may occur.

5.10.4 Concrete shall be placed through canvas, wood, rubber, or metal elephant trunks (6 inches minimum diameter) in order to avoid a free fall of over 3 feet below the chutes or hopper. The maximum rate of placement shall be 2 feet 6 inches per hour. Concrete shall not be allowed to ricochet against forms that have exposed surfaces. Concrete shall be deposited directly to the center of forms. Drop chutes shall be spaced at approximately 10 feet on centers maximum. The use of drop chutes longer than 12 feet shall be prohibited. For inspection purposes adequate illumination in the interior of the forms shall be provided.

5.10.5 An excess of water will accumulate at the top as the result of a poor mix, insufficient fines, or too-rapid placing. This shall be watched and corrected. When this does occur, the water can be removed by boring 1-inch holes in the nonexposed side of the form.

5.10.6 Vibration

5.10.6.1 Vibrate the entire depth of each new layer of concrete and penetrate a few inches into the layer below to ensure a consolidation of layers, providing this layer has not partially hardened, since a wavy line between layers may result. Do not use vibrators to move concrete laterally. Penetrate the concrete with the vibrator vertically and not at an angle. Make sure the concrete is placed against the face of previously placed concrete; otherwise, segregation and air pockets will occur.

5.10.6.2 Thoroughly vibrate the new concrete close to the joint of hardened concrete.

5.10.6.3 Contractor shall not permit internal vibrators to come in contact with the forms. This will mar the face of the form and show up as a defect.

5.10.6.4 Special attention with the vibrators should be paid to such locations as corners, cutouts, places with large number of bars, etc.

5.10.6.5 Internal vibrators may also be supplemented at different locations by the use of form vibrators, rubber or wooden mallets, or hand spading to ensure good results.

5.10.6.6 Contractor shall not place concrete until he has sufficient vibrators on hand, including spares, to suit the particular design.

5.10.6.7 Avoid over-vibration. Prolonged vibration may reduce the initial air content of the air-entrained concrete by more than half.

5.10.7 Once concreting is started, it shall be carried on as a continuous operation until the placing of the panel or section is completed. The locations of construction joints shall be at point of minimum shear. The top surface shall be generally level.

5.10.8 Where new concrete is to be bonded to existing concrete, the forms shall be tightened and the surfaces of the existing concrete shall be swept with a stiff brush or scraped to remove laitance and roughened. The bonding surface shall be cleaned, wet, and covered with a thin layer of mortar 1:1-1/2 mix just before the new concrete is placed.

5.11 Curing and Protection

5.11.1 Curing

5.11.1.1 The top surface of all slabs shall be sprayed with an approved liquid membrane-forming compound in accordance with the directions of the manufacturer as soon as the newly placed surface has been finished and will not be marred by such application.

5.11.1.2 The liquid membrane-forming compound shall meet the requirements of "Specifications for Liquid Membrane-Forming Compounds for Curing Concrete" (ASTM C 309) and shall contain a fugitive dye.

5.11.1.3 The Contractor shall submit test reports from an independent testing laboratory or other acceptable data including a manufacturer's guarantee proving compatibility with all types of adhesives as well as separate cement toppings.

5.11.1.4 Acuricon, manufactured by Anti-Hydro Waterproofing Company, Newark, New Jersey, or other sodium silicate compounds meeting the above requirements, are acceptable.

5.11.1.5 Surfaces subject to heavy rainfall within 3 hours of compound application shall be resprayed.

5.11.1.6 Where practicable, forms shall be kept in place for a 7-day curing period. The top exposed wood forms shall be kept moist. In order that the curing water may reach the surfaces of walls, the forms shall be loosened to allow the water to be poured over the top and thus run down between the concrete and the forms.

5.11.1.7 If it is not practicable to keep forms on for 7 days, cover concrete with fabrics which have moisture retaining properties. Such covers also shall be kept continuously moist to ensure a film of water on the surface.

5.11.2 Hardening

5.11.2.1 Exposed concrete floors after thorough wet curing shall be allowed to dry and then be hardened with Lapidolith as manufactured by Sonneborn Div. of Countech, Inc., or equal. Hardener shall be applied in strict accordance with manufacturer's printed directions, under the direct supervision of manufacturer's representative, in no fewer than <u>three</u> coats. Surplus allowed to remain on the surfaces after third coat dries shall be removed by scrubbing or buffing.

5.11.3 Protection

5.11.3.1 Protect concrete from construction traffic and action of sun, rain, flowing water, frost, snow, or mechanical injury for a period of 2 weeks after placing. Traffic areas shall be provided with raised runways.

5.11.3.2 Reinforcement left exposed to the weather before the next concrete placing shall be coated with a wash of cement and water to prevent the staining of the concrete due to rusting. This coating shall be removed prior to the next concreting. If the exposed concrete finish becomes stained due to rusted reinforcing steel, the surface shall be cleaned.

5.11.4 Cold Weather Protection

All concrete shall be maintained at a temperature of at least 50°F for not less than 4 days after it is deposited. During the next 3 days it should be protected from freezing. The housing, covering, or other protection used shall remain in place and intact at least 24 hours after artificial heating is discontinued. No dependence shall be placed on calcium chloride or other chemicals for the prevention of freezing. The Contractor shall follow "Recommended Standards for Cold Weather Concrete," ACI 604. Calcium chloride shall not be used to prevent freezing or to accelerate concrete set.

5.11.5 Hot Weather Protection

During hot weather, forms, reinforcing steel, and subgrade shall be sprayed periodically with water. The placing temperature of concrete shall not be more than 90°F. Special care shall be taken to place the concrete as quickly as possible after mixing. After finishing, concrete shall be cured as quickly as possible without marring the surface to prevent moisture evaporation. The Contractor shall follow "Recommended Standards for Hot Weather Concrete," ACI 605.

5.12 Forms and Centering

5.12.1 All forms shall conform to the lines, dimensions, and shapes of the concrete as indicated on the drawings. They shall be watertight to prevent leakage of mortar and shall be smooth except where otherwise required and shall be free from defects where the concrete is to be left exposed. The forms shall be in such condition and have ample supports so that they will not bulge or get out of line or level as concrete is placed. For exposed work, the maximum tolerance in line and level will be 1/16 inch at the joints. It will be the concrete contractor's responsibility to see that forms are supported well enough to ensure the safety of workmen and the public. Design of form-work shall comply with ACI 347.

5.12.2 Form lumber shall be moisture-resistant concrete form plywood not less than 5/8 inch thick in accordance with Department of Commerce Product Standard PS 1-66 for softwood plywood, Plyform Class 1, B-B, exterior, or structural equivalent.

5.12.3 For surfaces exposed to view in the finished work, use new, clean, smooth plywood free from blemishes, in sizes as large as practicable and square cut. Handle, store, place, and fit forms in an approved manner.

5.12.4 As the forms for exposed concrete become worn or damaged, they shall be replaced as often as necessary to obtain a smooth finish.

5.12.5 Corners of exposed slabs, walls, etc., shall be sharp and square. 5.12.6 Coat forms with a concrete releasing agent at each use. Form coatings shall not be of material that will leave stains on the concrete or that might cause injury to paint that is applied to exposed concrete. Magic Kote by Symons Corporation, or equal, will be acceptable for exposed concrete.

5.12.7 All keys shall be securely held in position by continuous wood blocking rigidly secured to forms of reinforcing.

5.12.8 All slabs and wall forms shall be cambered 1/8 inch for each 8 feet of span, unless otherwise required. Camber shall be 1/2 inch for each 8 feet of cantilever span. The camber shall be checked and forms adjusted if necessary to maintain the camber before the initial set takes place.

5.12.9 Provide temporary clean-out openings at the base of all forms and other points where necessary to facilitate cleaning and inspection for placing concrete.

5.12.10 In exposed work, metal tools shall not be placed against the concrete to wedge forms loose. Only wood wedges shall be used.

5.12.11 Proper shoring shall be provided under the forms for concrete work to support all construction loads, and reshoring shall be provided for all floor wall slabs before stripping. Supports for forms shall consist of wood or steel posts or of hung units of a size and spacing as required to support the weight of the forms, concrete, and construction live load. Each post shall be secured against horizontal movement by bracing or other means at the top and bottom. Forms shall not be removed until a thorough exmamination indicates that the floor walls have developed ample strength to carry the load put upon them.

5.12.11.1 This shall not be interpreted as permitting the removal of forms under slabs in less than the following periods:

66 hours when the average air temperature is 60°F or higher.

90 hours when the average air temperature is below 60°F.

Attention of the Contractor is called to the statement that the above requirements are minimum requirements and that the shores and reshores shall be kept in place for sufficient length of time to assure the safety of the structure.

5.12.11.2 The average temperature is defined as the average of the daily temperature for the period from the time of pouring to the time of stripping. Temperatures recorded by the local weather bureau are to be used.

If artificial heat and protection are provided for the concrete, the average temperatures of the concrete shall be used instead of the air temperatures. It will be acceptable to assume that the temperature of the concrete slabs is the average temperature of the air directly above the slab at a representative location midway between heaters.

5.12.11.3 Forms shall be left in place and the shorings not disturbed for a longer period than above stated if so required by the condition of the concrete, by severe weather conditions, or by lack of adequate heating and protection.

5.13 Finishes Other Than for Floors

5.13.1 All interior and exterior walls and other concrete surfaces shall be left as they come from the forms. Deep voids and honeycombs which are structurally unacceptable may be filled following the procedure given under patching.

5.13.2 In all foundation walls below grade and tank walls the ties and spreaders shall be cut back to a depth of approximately 1-1/2 inches. Any honeycombed concrete or voids shall be cut back to sound concrete. All cuts shall be to a depth of at least 1-1/2 inches with the edges perpendicular to the surface. All holes resulting from cutting back for scale pockets, honeycomb, surface voids, and the removal of form wires or spreaders shall, however, be filled with cement mortar.

5.13.3 In all concrete exposed to view, cone-shaped snap ties are to be used. Ties are to be placed in horizontal lines in a regular pattern. Voids created by cone-shaped snap ties are to remain exposed.

5.13.4 Patching

5.13.4.1 Any concrete that is not formed as shown on the drawings or for any reason is not of alignment or level or shows a defective surface shall be considered as not conforming with the intent of these specifications and shall be removed from the job by the Contractor at his expense unless the Owner grants permission to patch the defective area.

5.13.4.2 After forms are removed, all concrete shall be inspected and any deep voids, honeycombing, or other defective areas shall be patched when so directed. Where necessary, defective areas shall be chipped away to a depth of not less than 1 inch with edges perpendicular to the surface. For extensive repairs, the Contractor shall use an epoxy mixture as per manufacturer's instructions to obtain better adhesion to the existing surface. The area to be patched and a space at least 6 inches wide entirely surrounding it shall be wetted to prevent absorption of water from the patching mortar.

5.13.4.3 A grout of equal parts Portland cement and sand, with sufficient water to produce a brushing consistency, shall then be well brushed into the surface, followed immediately by patching mortar.

The mortar shall not be richer than 1 part cement to 2 parts sand. The amount of mixing water shall be as little as consistent with the requirements of handling and placing. The mortar shall be retempered without the addition of water by being allowed to stand for a period of 1 hour, during which time it shall be mixed with a trowel to prevent setting.

5.13.4.4 The mortar shall be thoroughly compacted into place and screened off so as to leave the patch slightly higher than the surrounding surface. It shall be left undisturbed for a period of 1 to 2 hours to permit initial shrinkage before being finished. All patches shall be thoroughly cured.

5.14 Floor and Slab Finishes

5.14.1 General

5.14.1.1 Finished concrete slabs shall be worked so that large aggregate will not be visible in the top surface.

5.14.1.2 All slabs must be protected during construction to prevent marring and defacement.

5.14.1.3 Where the allowable tolerances in surface elevation of slabs are exceeded, the Owner may direct the Contractor to grind or patch the floor to bring the surface within the requirements. Grinding shall be done as soon as possible but not before 3 days of cure. Patching material shall be Epolith Patcher as manufactured by Sonneborn Div. of Countech, Inc., or equal. Patching shall be done as soon as possible but not before 28 days of cure.

5.14.2 Finishes

After the concrete has been struck off, consolidated, and leveled, the surface shall be roughened with stiff brushes or rakes before final set.

5.15 Concrete Slabs on Ground

5.15.1 All non-framed concrete slabs on ground shall be placed on 6-inch clean sand or bankrun gravel fill, well tamped. Cover fill with vapor barrier in wide rolls with joints lapped. Slabs shall be reinforced.

5.15.2 Where a working slab is indicated as a base for construction, the working slab may be placed directly on existing soil and the vapor barrier omitted.

5.16 Joint Fillers and Sealants

5.16.1 Expansion joint fillers shall be of preformed, non-extruding resilient type, such as cork or sponge rubber (not a fill containing asphalt or tar), and conforming to ASTM D 1752. Joint fillers shall be used for the full depth of slab to within 1/2 inch of the finished slab and shall be of 1/2 inch thickness.

5.16.2 All expansion joints shall be sealed with Sonolastic NP2 as manufactured by Sonneborn Div. of Countech, Inc., or equal, installed in accordance with manufacturer's instructions.

5.17 Provisions for Work of Other Trades and Contractors

5.17.1 Contractors for other trades requiring slots, chases, recesses, or openings in concrete work will be required to furnish information regarding the size and location of same before concrete forms have been erected.

5.17.2 All slots, chases, recesses, or openings indicated on the contract drawings that are not formed by sleeves, frames, boxes, or other equipment furnished by other trades shall be provided in locations shown by this Contractor as part of his contract.

5.17.3 The Contractor shall do all grouting and filling with concrete as required throughout except as otherwise specified, including frames in concrete walls and openings after pipes are in place. Confine the grout vertically. Grouting exposed to weather shall be an epoxy grout, Colma-Dur Grout with Colma Quartzite aggregate (Sika Chemical Corporation) or equals, installed in accordance with manufacturer's instructions.

5.17.4 When pipes embedded in slabs are larger than 1-1/2 inches O.D., or when they come closer than 1-1/2 inches from either upper or lower surface of the slab, expanded metal of 6-inch x 6-inch #10 welded wire mesh shall be laid and extended beyond such conduit or piping at least 8 inches on all sides. Minimum 1-1/2 inch concrete cover is required for any pipes. Pipes or conduits having an outside diameter larger than one third the slab thickness shall not be placed in the slab.

5.17.5 Pipes shall be spaced not closer than three diameters on centers, and where possible they must be so placed as to avoid changing the locations of the reinforcement from that shown on the drawings.

5.17.6 Sleeves, boxes, and other openings shall not be permitted unless shown on a drawing submitted to and approved by the Structural Engineer.

5.17.7 The Contractor shall carefully point around all pipe sleeves where carried through slabs and concrete walls to present a neat finish.

5.17.8 The Contractor shall furnish and install all inserts as required.

5.17.9 Inserts and anchors carrying pipe and equipment loads shall be rated by manufacturer for safe allowable loads. Submit details and location drawings for approval and for possible additional reinforcement in concrete at insert.

5.17.10 All inserts at exposed surfaces shall be rust and stain proof.

6.0 DRAWINGS

Include drawings that are applicable to your particular installation in this section. Sample drawings are shown in Figures H-1 through H-7.

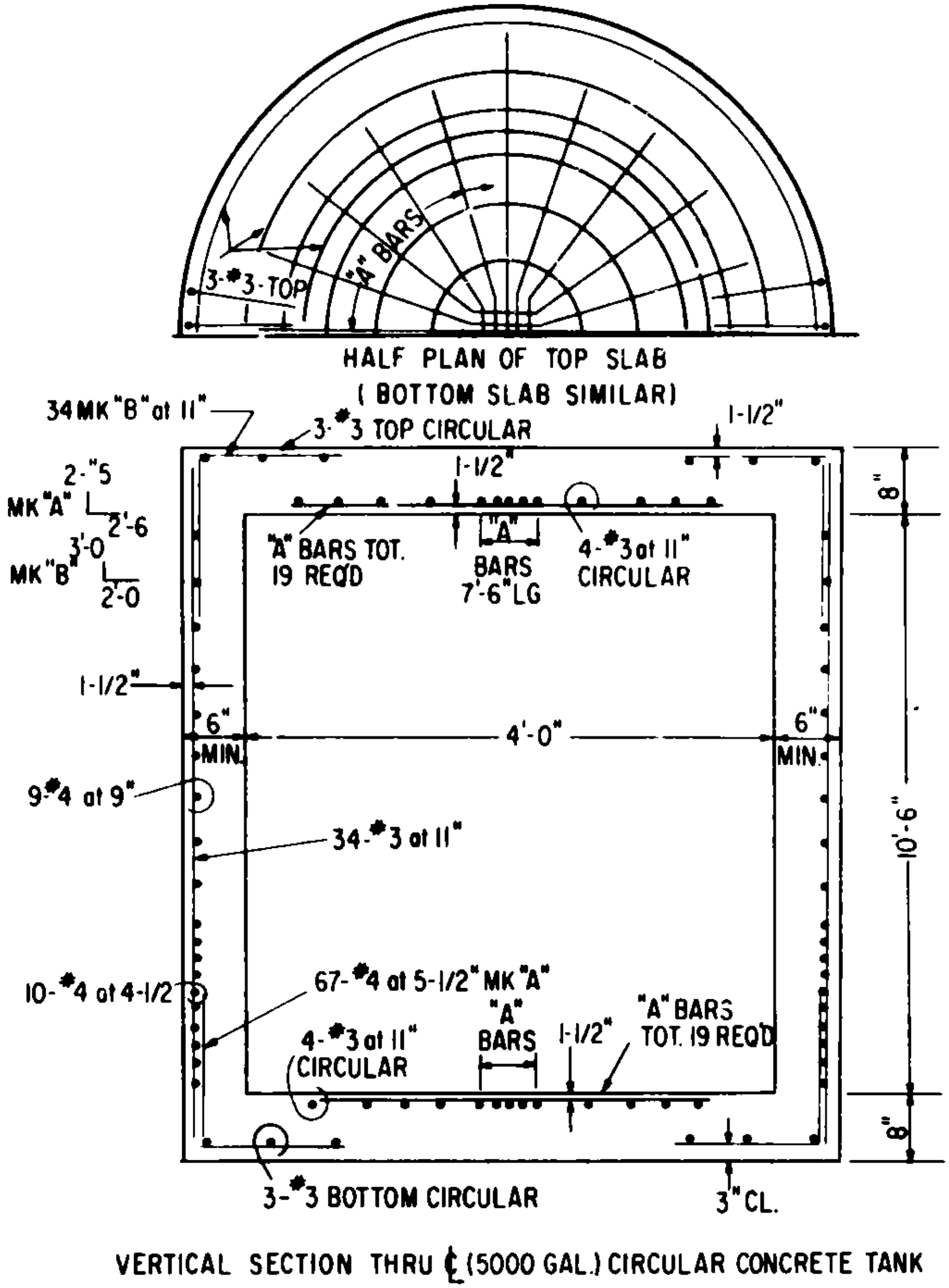
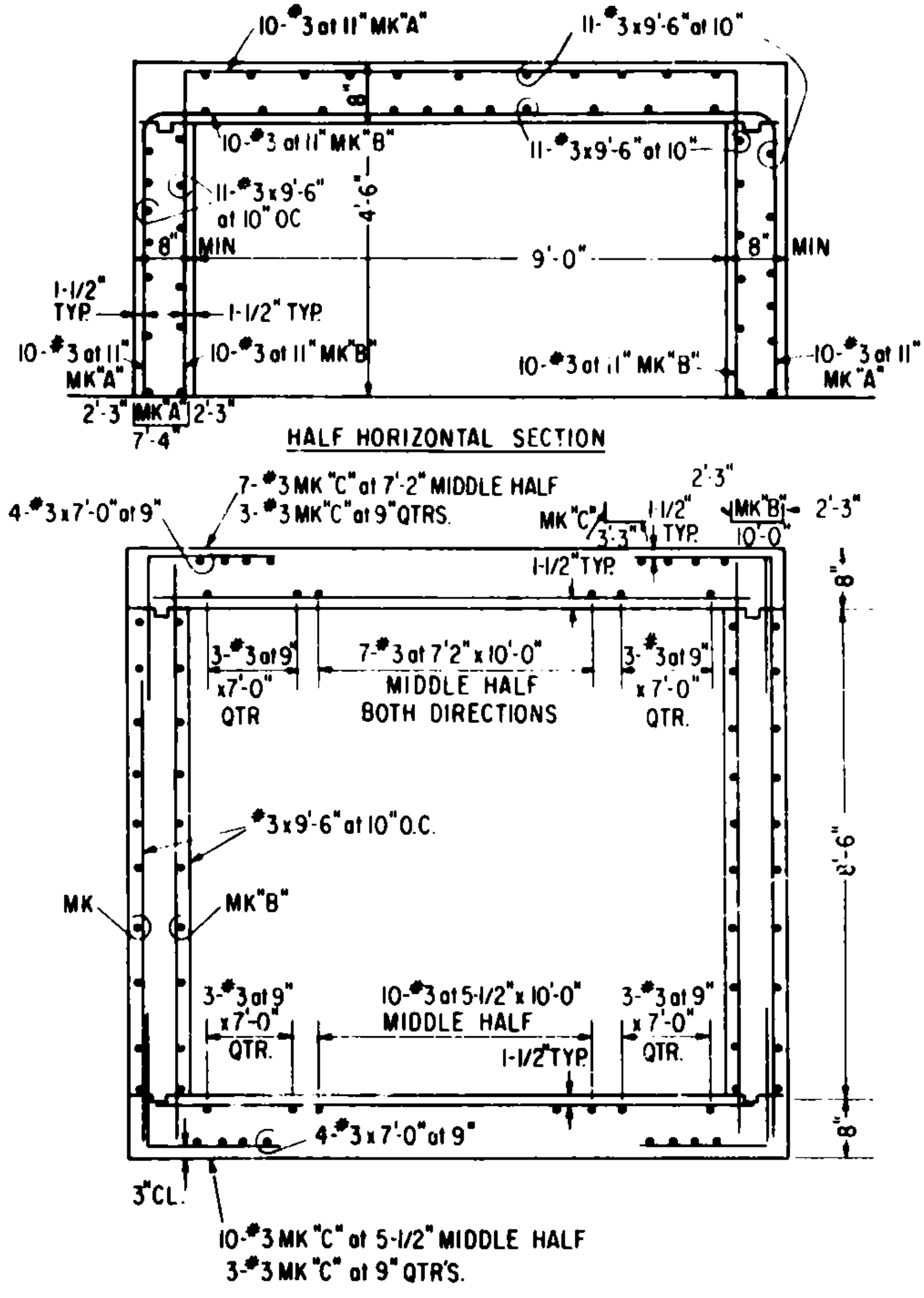


Figure H-1. Sample Drawing of a Circular Concrete Tank



VERTICAL SECTION THRU ℄ (5000 GAL.) RECTANGULAR CONCRETE TANK

Figure H-2. Sample Drawing of a Rectangular Concrete Tank

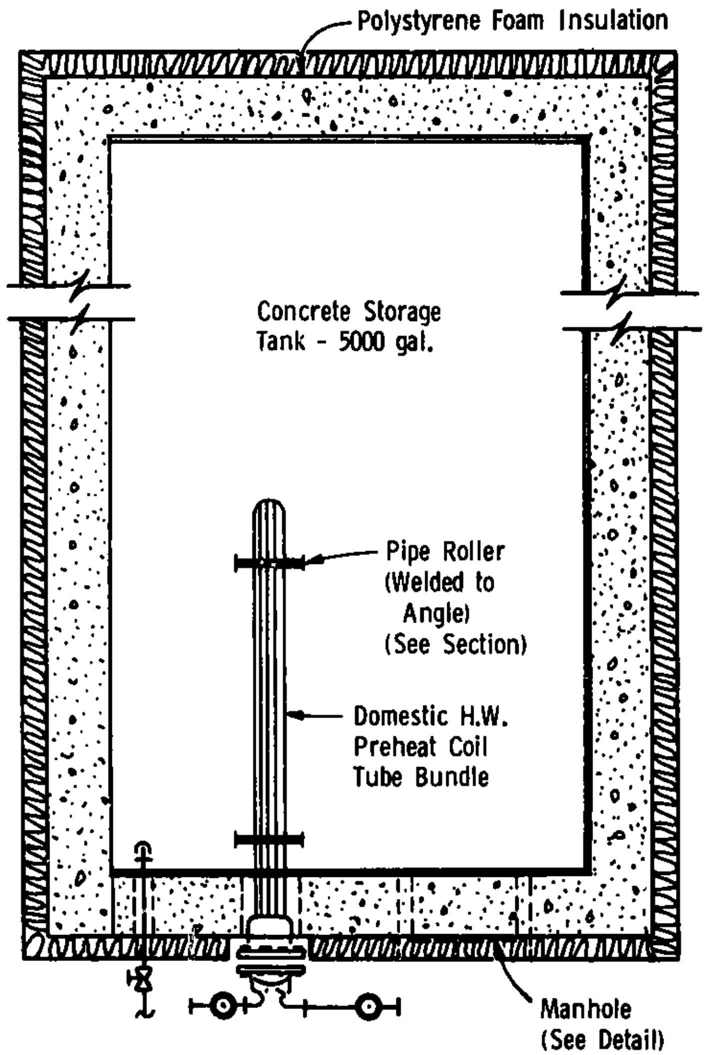


Figure H-3. Plan View of a Rectangular Concrete Tank (not to scale)

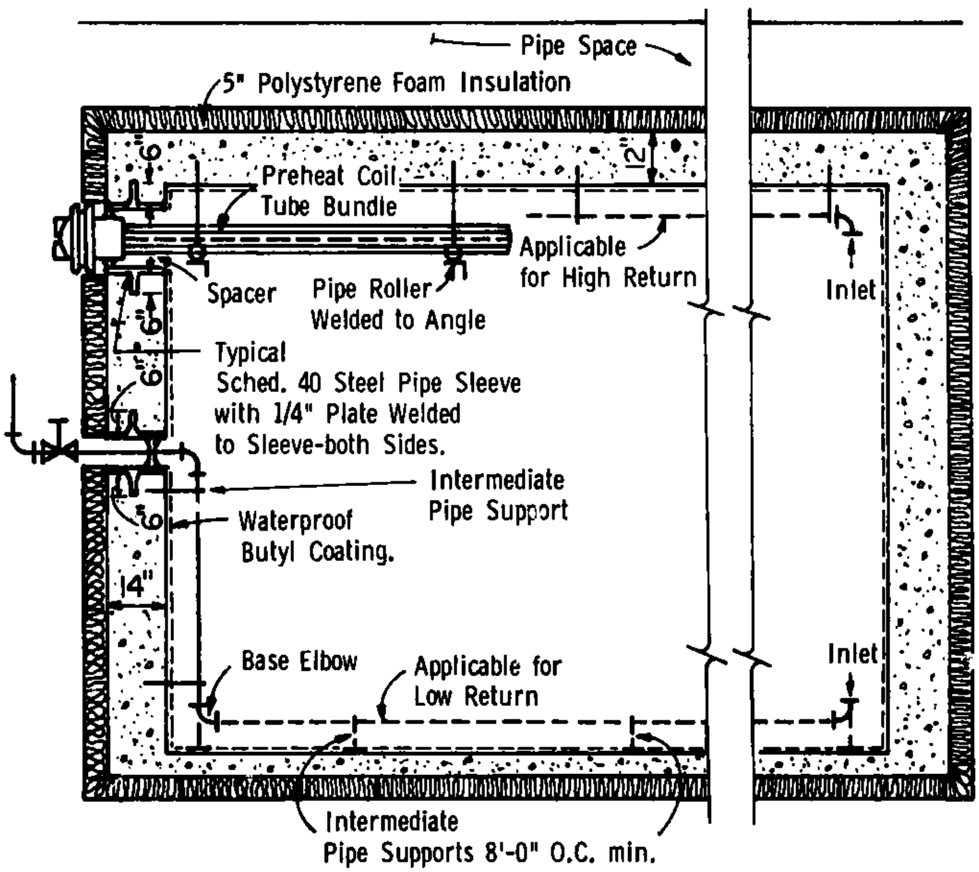


Figure H-4. Section through Rectangular Concrete Tank (not to scale)

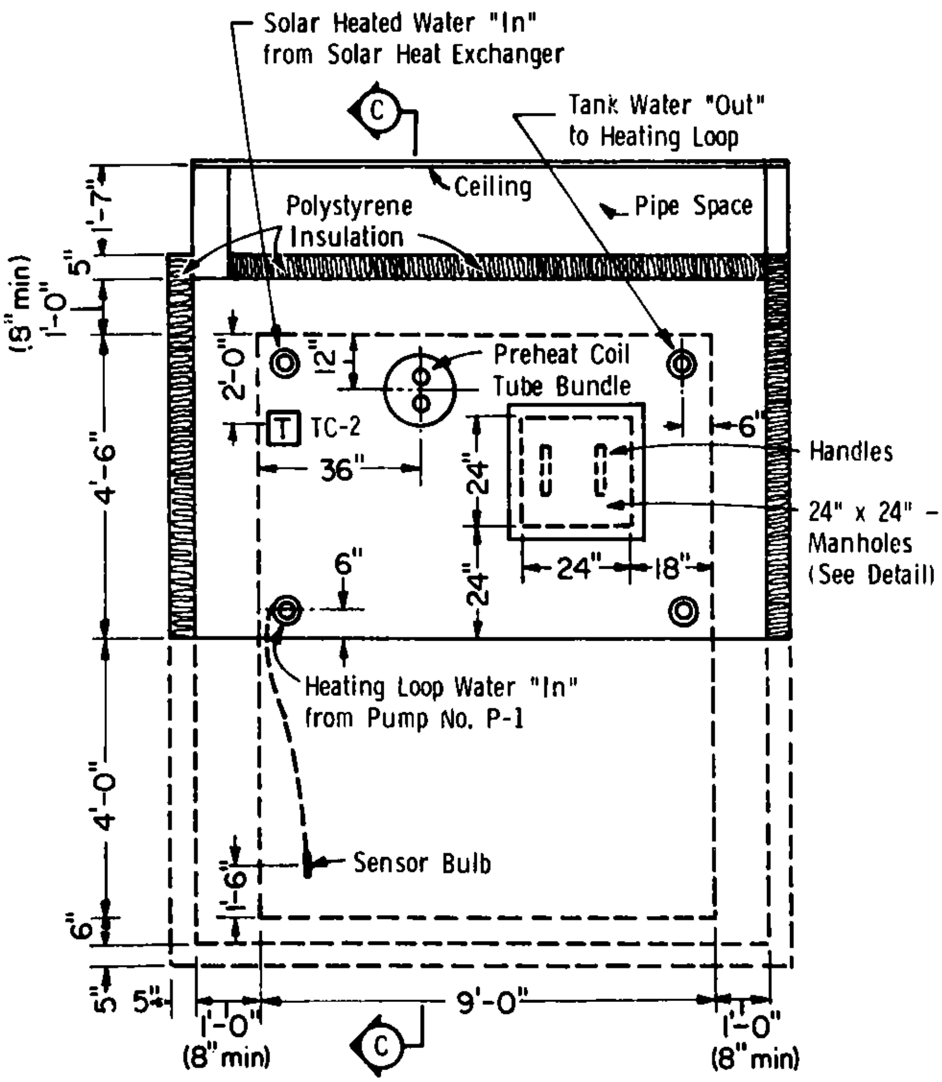
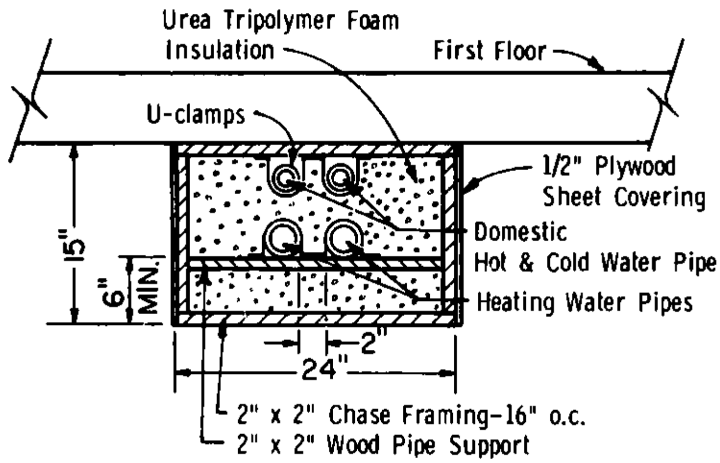
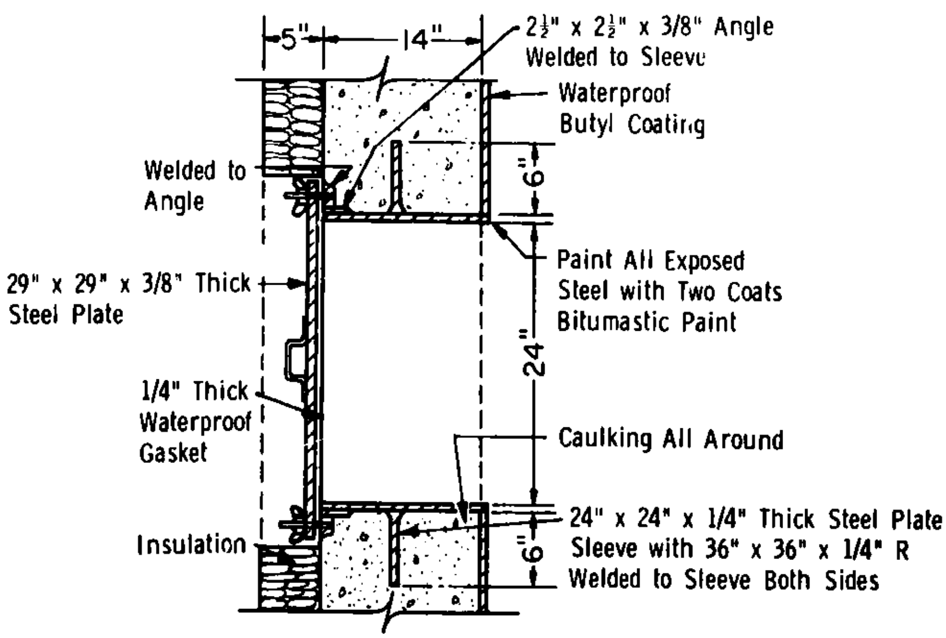


Figure H-5. Front View of Rectangular Concrete Tank
(not to scale)



DETAIL OF PIPE CONDUIT



DETAIL OF MANHOLE

Figure H-6. Details of Rectangular Concrete Tank

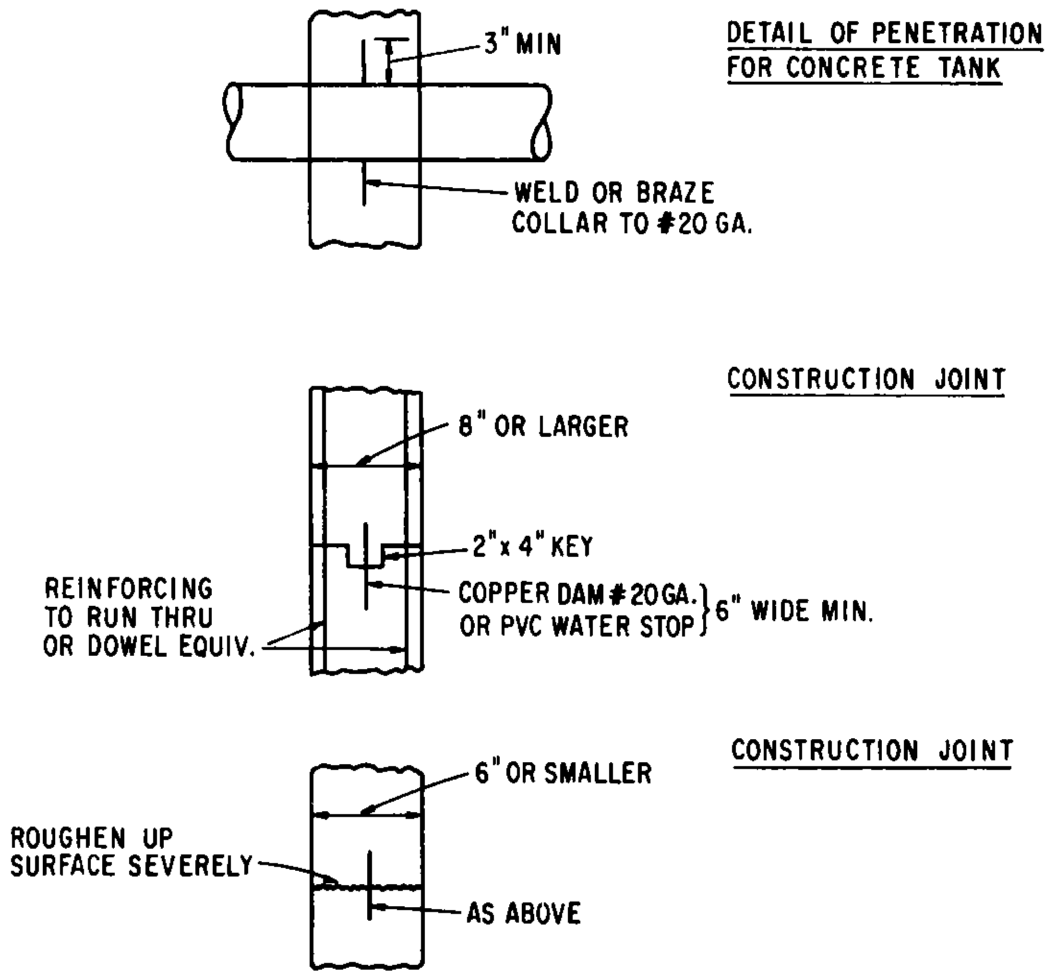


Figure H-7. Details of Penetrations and Joints for Concrete Tanks

Part 2. PRECAST CONCRETE TANKS

Section A. SAMPLE SPECIFICATIONS FOR PRECAST CONCRETE TANKS

1.0 WORK INCLUDED (Provide)

1.1 Precast concrete solar energy storage tanks as indicated in these specifications and shown on the drawings.

1.2 Installation of precast concrete solar energy storage tanks.

1.3 All fittings, connections, and internal piping.

1.4 All internal heat exchangers.

1.5 Insulation.

1.6 Waterproof liners.

2.0 RELATED WORK

2.1 Excavation and grading.

2.2 Solar system piping external to tanks.

2.3 Electrical wiring.

3.0 DETAILS

3.1 All details shall be in accordance with HUD Intermediate Minimum Property Standards for Solar Heating and Domestic Hot Water Systems, Vol. 5 (1977).

3.2 The Contractor shall be responsible for all dimensions of the work and shall check tank drawings in relation to all other drawings and shall verify all dimensions in relation with other work and existing field conditions. The Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 APPLICABLE CODES

4.1 HUD Intermediate Minimum Property Standards for Solar Heating and Domestic Hot Water Systems, Vol. 5 (1977).

Include applicable state and local codes.

5.0 MATERIALS

5.1 Tank Construction

5.1.1 The external precast shell shall be 3500 psi, minimum, concrete with steel reinforcing.

5.1.2 A 2-inch-thick layer of urethane foam insulation shall cover the interior of the tank.

Refer to Chapter 1 and Appendix C for discussion of insulation thickness. Other insulation thicknesses can be specified.

5.1.3 A waterproof liner shall be provided on the sides and bottom to prevent water loss by leakage and prevent insulation degradation by water absorption. The liner shall be capable of withstanding temperatures of at least 160°F.

The 160°F temperature limit can be increased, if necessary. Consult tank manufacturers for availability of liners that can withstand high temperatures.

5.2 Piping and Connections

5.2.1 Two fitting plate(s) shall be provided in 1/4-inch painted steel over two 18-inch x 18-inch port(s) at opposite ends of tank with fittings.

5.2.2 Special: Sixteen 1-1/2-inch copper fittings.

5.2.3 Plates shall be bolted in place and sealed with an elastomeric sealant to prevent entry of groundwater.

5.2.4 Internal piping shall be provided in copper as follows: deep pipe, shallow pipe, collector suction, sensor well, etc.

5.2.5 Internal heat exchangers shall be provided as follows: One shallow heat exchanger and piping in series of smooth copper coils 60 feet x 1/2 inch in diameter.

Refer to Appendix D, "Determining Heat Exchanger Size," before specifying heat exchangers.

5.2.6 An atmospheric vent (1-inch minimum diameter) shall be provided for preventing pressure or vacuum build-up inside tank.

5.2.7 Access shall be provided by means of one 18-inch x 18-inch top port with sealable cover.

6.0 INSTALLATION

6.1 Tanks shall be installed in an excavated hole on minimum of 4 inches crushed and leveled stone with 2 feet clearance all around tank. Hand-tamp backfill in place. CAUTION, DO NOT COMPACT WITH MACHINERY OR ALLOW MACHINERY OVER BACKFILLED TANK. Grade earth cover to drain away from tank.

6.2 Direct and unobstructed access to excavated hole with a minimum of 14 feet head clearance shall be provided for tank carrier approaching long side of hole. Hole shall be no wider than 9 feet, 6 inches at top.

6.3 Provide a concrete casing 30 inches in diameter x 2 feet, 2 inches thick, with cover, sealed to tank top for access from grade. Seal cover to casing with elastomeric sealant to prevent entry of water.

7.0 CAPACITY AND DIMENSIONAL REQUIREMENTS

Fill in the blanks to complete this section. This example applies to rectangular tanks. If your installation requires another tank shape or if you have special dimensional requirements (such as special locations for pipe fittings), state your requirements in this section.

7.1 Nominal capacity of the tank shall be ____________ gallons.

7.2 Width of the tank shall be ________ feet, __________ inches.

7.3 Length of the tank shall be ________ feet, ________ inches.

7.4 Height of the tank shall be ________ feet, ________ inches.

8.0 OPERATION

8.1 Water level inside tank shall not exceed 6 inches below inside top of tank.

8.2 Debris, chemicals, sharp objects, or other items which may damage or degrade tank liner shall be prevented from entering tank.

9.0 DRAWINGS

Include drawings that are applicable to your particular installation in this section. A sample drawing is shown in Figure H-8.

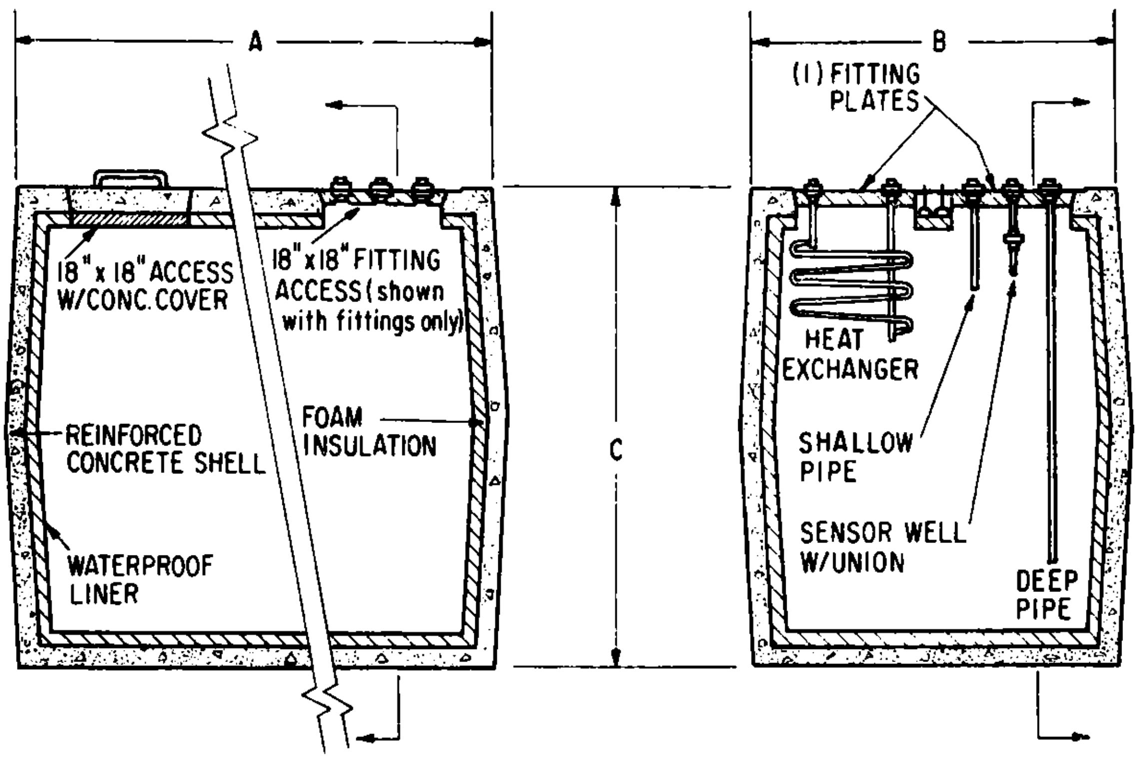


Figure H-8. Precast Concrete Tank

Drawings courtesy of Solatherm Corporation, 1255 Timber Lake Drive, Lynchburg, Virginia 24502.

Because of the difficulty of shipping heavy objects, you should consult the manufacturer for availability of tanks, liners, and components.

Section B. SAMPLE SPECIFICATIONS FOR USING UTILITY VAULTS FOR THERMAL ENERGY STORAGE

Sections 1.0 through 4.0 of this sample specification are the same as for Section A, "Sample Specifications for Precast Concrete Tanks."

5.0 MATERIALS

5.1 Tank Construction

Thermal storage shall be provided by adapting a precast concrete transformer vault. Modify tank to provide three access holes in the top of the tank -- one 30-inch manhole with cover in the center and two 8-inch-diameter holes in diametrically opposite corners as shown on the drawings.

5.2 Tank Insulation

To prevent thermal losses to the ground, the tank shall be insulated as follows:

5.2.1 Bottom

- 10-inch concrete pad.
- Two layers of pentachlorophenol-treated 2-inch x 12-inch boards.
- One layer of 4-inch foam glass.
- Epoxy sealer coating.

5.2.2 Sides

- 4 inches of polyurethane foam, with a water-proof barrier of fiberglass and mastic.
- One layer of pentachlorophenol-treated 2-inch by 12-inch boards.
- Epoxy sealer coating.

5.2.3 Top

- 4 inches of polyurethane foam, with a waterproof barrier of fiberglass and mastic.
- Two layers of pentachlorophenol-treated 2-inch x 12-inch boards.

5.3 Lining

A waterproof liner shall be provided on the sides and bottom to prevent water loss by leakage. The liner shall be capable of withstanding temperatures of at least 160°F.

The 160°F temperature limit can be increased, if necessary. Since this is a non-standard application, the liner must be specially fabricated.

5.4 Piping

Ordinary black steel, schedule 40 pipe shall be used throughout the system.

5.5 Pipe Insulation

5.5.1 Underground

Either of two types of insulation material shall be used for underground insulation.

- 1-1/2-inch foam glass, covered with mastic.
- 1-1/2-inch polyurethane foam, covered with fiberglass and mastic.

5.5.2 Aboveground

- The aboveground piping shall be insulated with 1-1/2-inch fiberglass pipe insulation.
- The hose connections shall be insulated with 3/8-inch foamed plastic insulation.

6.0 <u>INSTALLATION</u>

Place the transformer vault below ground upon a 10-inch slab of concrete after covering the slab with two layers of pentachlorophenol-treated 2-inch x 12-inch boards and 4 inches of foam glass insulation. The periphery of the tanks shall be insulated with 4-inch waterproofed polyurethane. The polyurethane insulation shall be protected by a layer of pentachlorophenol-treated 2-inch x 12-inch boards. The boards shall extend above the ground level. The top of the tank shall be insulated with waterproofed polyurethane and two layers of pentachlorophenol-treated 2-inch x 12-inch boards.

7.0 CAPACITY AND DIMENSIONAL REQUIREMENTS

Fill in the blanks to complete this section. This example applies to rectangular tanks. If your installation requires another tank shape or if you have special dimensional requirements (such as special locations for pipe fittings), state your requirements in this section.

7.1 Nominal capacity of the tank shall be ________ gallons.

7.2 Width of the tank shall be _________ feet, _________ inches.

7.3 Length of the tank shall be __________ feet, ________ inches.

7.4 Height of the tank shall be _________ feet, __________ inches.

8.0 DRAWINGS

Include drawings that are applicable to your particular installation in this section. Sample drawings are shown in Figures H-9 through H-11.

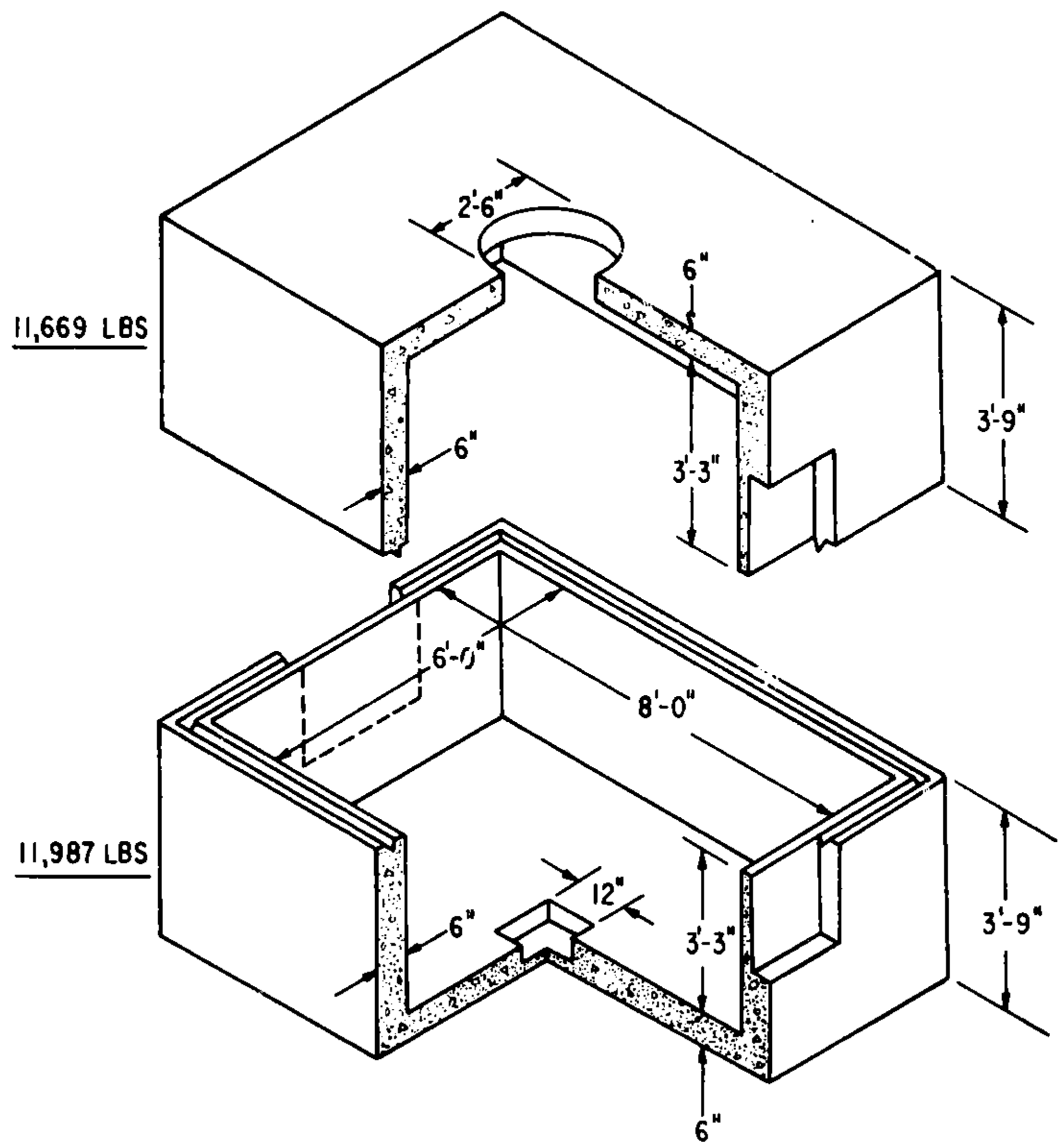


Figure H-9. Typical Utility Vault

Drawing courtesy of Smith Cattleguard Co., Midland, Virginia.

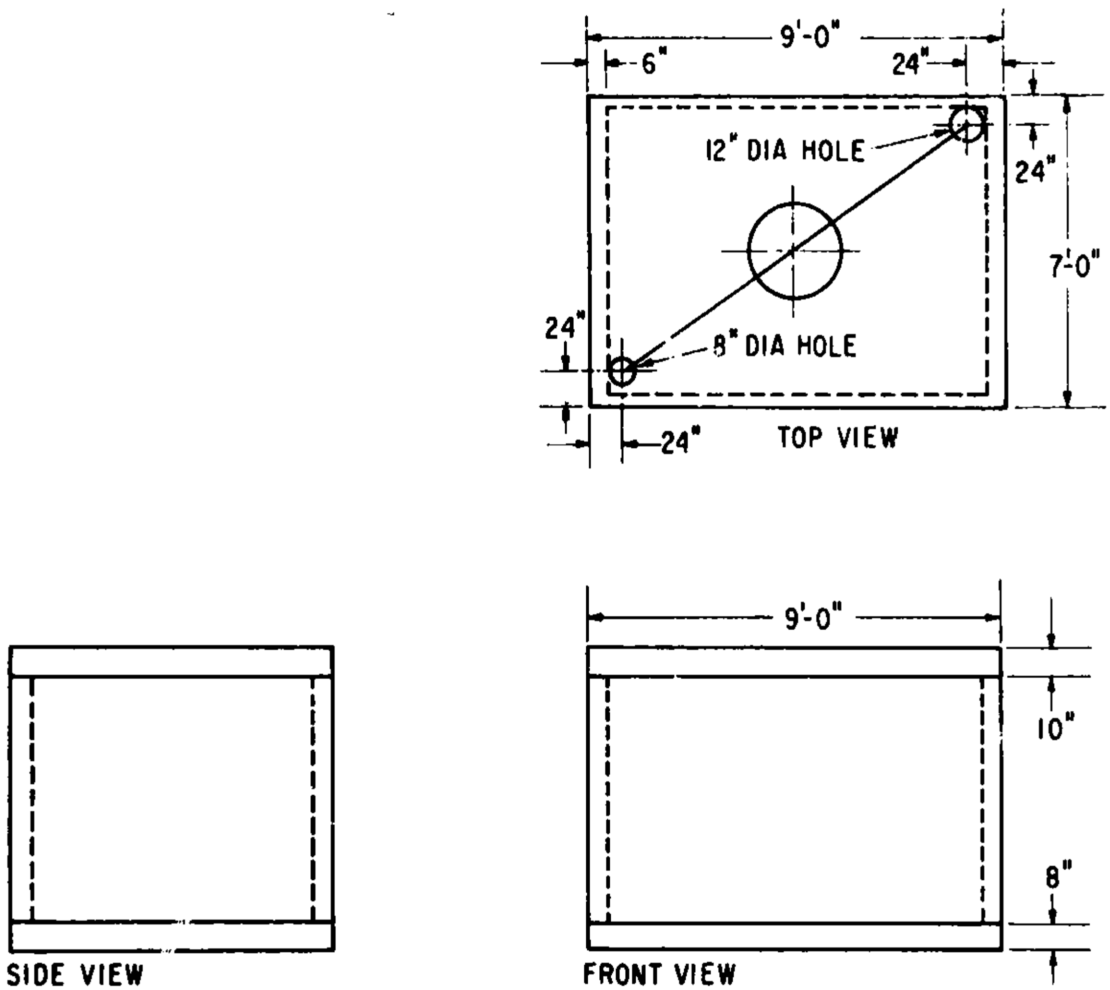


Figure H-10. Modified Utility Vault

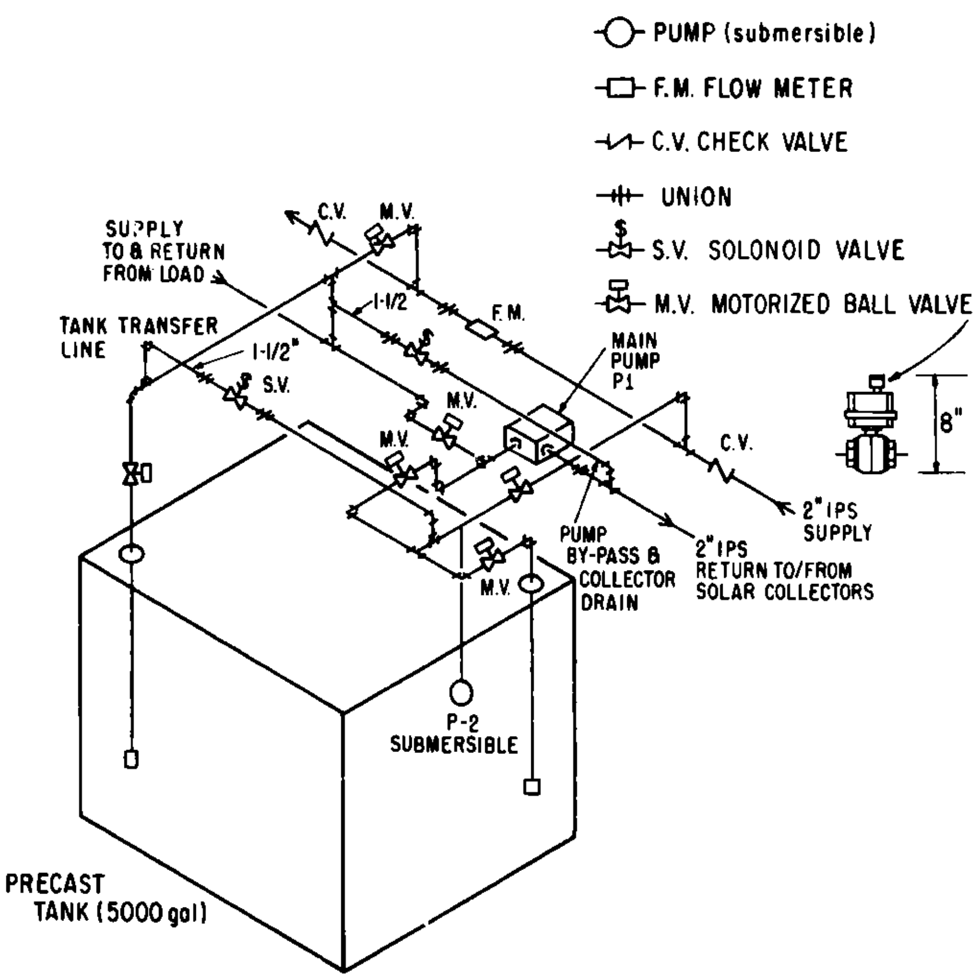


Figure H-11. Piping Schematic

Section C. SAMPLE SPECIFICATIONS FOR USING SEPTIC TANKS FOR THERMAL ENERGY STORAGE

Sample specifications for using septic tanks for thermal energy storage are similar to those in Section B, "Sample Specifications for using Utility Vaults for Thermal Energy Storage." The following specifications, taken from the Uniform Plumbing Code, can be used to specify the tank construction.

5.1 Tank Construction

5.1.1 Plans shall show all dimensions, reinforcing, structural pertinent data as may be required.

5.1.2 Septic tanks shall be constructed of sound durable materials, concrete not subject to excessive corrosion or decay and shall be watertight. Each such tank shall be structurally designed to withstand all anticipated earth or other loads.

5.1.3 The walls and floor of each poured-in-place concrete septic tank shall be monolithic; the maximum length of any section of unreinforced concrete septic tank wall shall be 6 feet, and no cross-section of any such unreinforced concrete wall or floor shall be less than 5 inches in thickness. The minimum compressive strength of any concrete septic tank wall, top and covers, or floor shall be 2500 pounds per square inch.

5.1.4 Concrete septic tank covers shall be reinforced and shall have a minimum compressive strength of 2500 pounds per square inch.

5.1.5 All septic tank covers shall be capable of supporting an earth load of not less than 300 pounds per square foot when the maximum coverage does not exceed 3 feet.

5.1.6 Access to each septic tank shall be provided by at least two manholes 20 inches in minimum dimension or by an equivalent removalbe cover slab.

5.1.7 All concrete septic tanks shall be protected from corrosion by being coated inside with an approved bituminous coating or by other acceptable means. The coating shall extend to at least 4 inches below the water line and shall cover all of the internal area above that point.

5.1.8 To facilitate placement of a precast septic tank that is to be placed outside, dig the hole before the tank is delivered. The hole should be 1 foot larger than the outside measurements or diameter of the tank. The bottom of the hole must be level. In installing a two-section tank, the bottom section containing the floor is set in place with the aid of a derrick. An asphalt material as in paragraph 5.1.7 should be spread on the top edge to seal it to the top section which is then placed.

Part 3. WATERPROOFING CONCRETE TANKS

Section A. SAMPLE SPECIFICATIONS FOR PLASTIC LINERS FOR CONCRETE TANKS

1.0 WORK INCLUDED (Provide)

Furnish all labor, materials, and equipment and install in place all liners for concrete tanks as shown on the drawings and as specified herein.

2.0 RELATED WORK

Concrete tank installation.

3.0 DETAILS

All work shall be done in strict accordance with the drawings and these specifications and subject to the terms and conditions of the contract.

4.0 APPLICABLE CODES AND STANDARDS

ASTM D 1593.
ASTM D 792-A.
ASTM D 882, Method B.
ASTM D 1992.
ASTM D 1004.
ASTM D 1790.
ASTM D 1239.
ASTM D 1203, Method A.
ASTM D 1204.

5.0 MATERIALS

5.1 General

The materials supplied under these specifications shall be first-quality products, designed and manufactured specifically for the purposes of this work, which have been satisfactorily demonstrated by prior use to be suitable and durable for such purposes.

5.2 Description of Materials

The plastic lining shall consist of widths of calendered plastic sheeting fabricated into large sections by means of special factory-sealed seams to fit the jobsite.

5.3 Polyvinyl Chloride, Physical Characteristics

PVC materials shall be manufactured from domestic virgin polyvinyl chloride resin and specifically compounded for use in tank. Reprocessed material shall not be used. It shall be produced in a standard minimum width of at least 76 inches (193 cm).

Certification test results showing that the sheeting meets the specification shall be supplied on request.

The PVC material shall have the following physical characteristics:

Property	Test Method	30 Mil
Thickness	ASTM D 1593	$\underline{+}$5%
Specific Gravity	ASTM D 792A	1.23
Tensile Strength, lbs./in. width	ASTM D 882, Method B	66
Modulus @100% Elongation, lbs./in.	ASTM D 882, Method B	30
Ultimate Elongation, %	ASTM D 882, Method B	325
Oven Aging (Wt. Loss, % max.)	2" x 4" sample 16 hrs. in a forced air circulating over @ 212°F	0.4
Tear Resistant:		
A. Elmendorf, grams	ASTM D 1922	6000
B. Graves Tear, lbs. min.	ASTM D 1004	8.25
Low Temperature Impact, °F	ASTM D 1790	-20
Water Extraction (% loss max. 104°F for 24 hrs.)	ASTM D 1239	.15
Volatility % loss max.	ASTM D 1203, Method A	.75
Dimensional Stability (@ 212°F, 15 min.) % max. change	ASTM D 1204	5
Resistant to Soil Burial:		
Tensile Strength Loss	Par. 4c. (1) per Bureau of Reclamation procedure	5.0
Elongation Loss		20.0

5.4 Chlorinated Polyethylene, Physical Characteristics

The CPE materials shall be manufactured from domestic chlorinated polyethylene resin and shall be specifically compounded for use in concrete tanks. Reprocessed materials shall not be used.

(Similar to PVC above)

5.5 Splicing Materials

Splicing materials shall be supplied by the fabricator of the lining material. These materials shall be used according to instruction supplied by the fabricator of the lining material. The Contractor shall be responsible for the proper splicing of all materials in the field.

6.0 FACTORY FABRICATION

Individual calender widths of CPE and PVC materials shall be factory fabricated into large panels. Lap joints with a minimum width of 1/2 inch (13mm) shall be used. Factory made splices shall have a strength of 80 percent of the specified sheet strength. If reinforced CPER is used in the combination liner, the splice used to seal the CPER to PVC shall be a dielectric seal. Panels shall be as large as can be conveniently handled on the jobsite. The panels shall be fabricated as shown on the shop drawings. After fabrication, the lining shall be folded in both directions and packaged for minimum handling in the field. Packaging shall be substantial enough to prevent damage to the contents.

7.0 SHOP DRAWINGS

Furnish shop drawings for the approval of the engineers and obtain such approval before proceeding with the work. These drawings shall show extent sizes and complete details of the CPE/PVC lining including recommendations for terminating the membrane.

8.0 PREPARATION OF SURFACES

The surface to receive the liner shall be smooth and free of sharp objects that could puncture the lining. All holes and hollow areas shall be filled in and compacted. Before the application of the lining material begins, the surface shall be examined and found satisfactory for installation of the lining material.

9.0 INSTALLATION OF LINING MATERIALS

9.1 General

Installation shall be performed by a contractor that has previously installed a minimum of 500,000 square feet of this material or by a contractor that has a fabricator field representative in attendance. The lining material shall be placed over the prepared surfaces to be lined in such a manner as to assure minimum handling. It shall be sealed to all concrete structures and other openings through the lining in accordance with details shown on the shop drawings. The lining shall be closely fitted and sealed around inlets, outlets, and other projections through the lining. Any portion of lining damaged during installation shall be removed or repaired with an additional piece of lining as specified hereinafter.

9.2 Field Joints

Lap joints shall be used to seal factory fabricated panels together in the field. Lap joints shall be formed by lapping the edges of panels a minimum of 2 inches. The contact surfaces of the panels shall be wiped clean to remove all dirt, dust, or other foreign materials. Sufficient cold-applied bonding adhesive as recommended by the fabricator shall be applied to the contact surfaces in the joint area and the two surfaces pressed together immediately. Any wrinkles shall be smoothed out. Field-made splices shall have a strength of 80 percent of the specified sheet strength.

9.3 Joints to Structures

All curing compounds and coatings shall be completely removed from the joint area. Attachment of the plastic to concrete shall be made by adhesive as recommended by the manufacturer. Unless otherwise shown on the drawings, the minimum width of concrete to liner joint shall be 8 inches.

9.4 Pressure rolling the overlap seam will accelerate bond, and rolling or brooming the entire surface will smooth the membrane and assure complete bond.

9.5 Corners

All inside and outside corners shall be double covered by using an additional strip of the membrane centered on the axis of the corners.

9.6 Joints

Control joints should be treated same as corners. Expansion joints are triple covered by placing a strip of membrane over the joint with the protective film intact and facing the surface. The membrane is then applied in the normal manner.

9.7 Repairs to PVC

Any necessary repairs to the PVC or CPE shall be patched with the lining material itself and cold applied bonding adhesive. The bonding adhesive shall be applied to the contact surface of both the patch and lining to be repaired and the two surfaces pressed together immediately. Any wrinkles shall be smoothed out.

9.8 Quality of Workmanship

All joints, on completion of the work, shall be tightly bonded. Any lining surface showing injury due to scuffing, penetration by foreign objects, or distress from rough subgrade shall, as directed by the Engineer, be replaced or covered and sealed with an additional layer of PVC or CPE of the proper size.

9.9 Guarantee

The Contractor shall guarantee the installation to be waterproof and free of defective materials and faulty workmanship for a period of 5 years and shall replace at his expense all other materials disturbed as originally placed, all in a first-class and workmanlike manner at no additional cost to the owner.

10.0 <u>LEAK TEST</u>

Before continuing with the work and placing of concrete or masonry wearing surface, the membrane installation shall be given a 24-hour test. Drains, if any, shall be plugged to contain the water. Leaks, if any, shall be repaired and surface retested. Cost of such tests shall be included in the contract price. Unusual loss of water will indicate failure of waterproofing application.

11.0 <u>PROTECTION</u>

11.1 As soon as membrane surfaces are dry after the leak test, membrane surfaces shall be covered with the specified protection board.

11.2 In case of delays that result in the accumulation of dirt, dust, construction debris, or other foreign matter, the following procedure shall be performed:

- All loose debris shall be removed, and an additional coating of the liquid membrane formulation of a 50-mil thickness shall be applied.

- Completed work of this section shall be protected from damage by subsequent building operation. Any damage to membrane or protection board shall be repaired immediately to the Owner's satisfaction.

Section B. SAMPLE SPECIFICATIONS FOR RUBBER LINERS FOR CONCRETE TANKS

The sample specifications for rubber liners are similar to the sample specifications for plastic liners given in Section A. Since butyl rubber is usually a 30- to 50-mil coating of spray-on liquid instead of a sheet material, the following modification of Sections 5.0, "Materials," and 9.0, "Installation of Lining Materials," is required. Section 6.0, "Factory Fabrication," is not applicable to butyl rubber liners and should be deleted.

5.0 MATERIALS

The lining material shall be a solvent-based spray-on coating of liquid butyl rubber. Before starting work, the Contractor shall provide the Owner with a letter stating that the lining material will not deteriorate under the water temperatures anticipated in the tank. Temperature information can be obtained from the Mechanical Engineering Consultant.

9.0 INSTALLATION OF LINING MATERIALS

9.1 General

Installation shall be performed by a contractor who has previously installed a minimum of 500,000 square feet of this material or by a contractor that has a manufacturer's field representative in attendance. The lining material shall be sprayed onto the concrete under very strict safety conditions with an airless spraygun so that its thickness when dry is 50 mils. It shall be sealed to all concrete structures and other openings in accordance with the details shown on the shop drawings. Any portion of the lining that is damaged during installation shall be repaired as specified hereinafter.

9.2 Repairs

Any necessary repairs shall be made by cleaning and respraying the damaged area. The resprayed area shall extend a minimum of 8 inches beyond the damaged area.

9.3 Quality of Workmanship

All lining materials, on completion of the work, shall be tightly bonded to the concrete. There shall be no evidence of peeling or looseness at tank penetrations. Any lining surface showing injury due to scuffing, penetration by foreign objects, or distress from rough subgrade shall, as directed by the Engineer, be replaced or resprayed with an additional layer of lining materials.

9.4 Guarantee

The Contractor shall guarantee the installation to be waterproof and free of defective materials and faulty workmanship for a period of 5 years and shall replace at his expense all other material disturbed as originally placed, all in first-class and workmanlike manner at no additonal cost to the Owner.

Part 4. SAMPLE SPECIFICATIONS FOR INSULATION OF CONCRETE TANKS

1.0 <u>WORK INCLUDED (Provide)</u>

All materials, labor, tools, and supplies necessary to insulate concrete tanks as described herein and on the drawings.

2.0 <u>RELATED WORK</u>

Construction of concrete tanks.

3.0 <u>DETAILS</u>

3.1 All details shall be in accordance with local fire and building codes and NFPA standards.

3.2 The Contractor shall be responsible for all dimensions of the concrete work and shall check structural drawings in relation to all other drawings and shall verify all dimensions in relation with other work and existing field conditions. The Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 <u>APPLICABLE CODES</u>

4.1 National Fire Codes: Volume 4, Building Construction Facilities.

4.2 Federal Specification HH-I-524b, Type II, Class B.

4.3 ASTM C 36.

Include applicable state and local building and fire codes.

5.0 MATERIALS

5.1 Rigid Insulation Boards

Rigid polystyrene foam insulation boards (STYROFOAM[1]SM brand insulation or equal) shall be used. Insulation shall have a minimum compressive strength of 25 psi,maximum conductivity (k) of 0.185 Btu per hour per square foot per inch of thickness at 40°F, and shall conform to Federal Specification HH-I-524b, Type II, Class B. Insulation shall be _____ inches thick.

See Chapter 1 to determine insulation thickness.

5.2 Gypsum Wallboard

Gypsum wallboard a minimum of 1/2 inch thick conforming to ASTM C 36 shall be applied over insulation on top and sides of tank.

Since the polystyrene foam is flammable, gypsum wallboard is necessary for fire portection if the tank is installed inside a building. If the tank is installed outside above ground, wood or aluminum siding can be substituted for the gypsum board. An underground tank requires no siding material.

5.3 Wood Nailers

Use wood nailer strips of exterior grade hardwood 2 inches wide (nominal) by the thickness of the rigid insulation.

Nailers are required to support wallboard or siding.

5.4 Fasteners

5.4.1 Wood Nailers to Concrete Wall

Use masonry nails, lead plugs with screws or bolts, powerdriven mechanical fasteners, or pneumatic nailers. Penetration of the fasteners into the concrete wall shall be 1/2 to 3/4 inch.

5.4.2 Gypsum Wallboard to Wood Nailers

Use annularly threaded drywall nails or self-tapping drywall screws having 5/8 to 3/4 inch wood nailer penetration.

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[1] Trademark of The Dow Chemical Company.

5.5 Adhesive

Use STYROFOAM #11 brand mastic or equal for bonding polystyrene insulation to concrete. CAUTION: Adhesive solvents are highly flammable. Follow manufacturer's instructions carefully.

5.6 Roofing

Roofing is required only for outdoor tanks. Cover the top of indoor tanks with gypsum wallboard.

Use complete elastomeric roofing system, 1/16 inch thick. Include flashing and sealing at all penetrations as specified by the roofing manufacturer. The Contractor shall submit a written report to the Owner stating that all roofing work was done in accordance with the manufacturer's requirements.

6.0 INSTALLATION

6.1 Installation of Wood Nailers

Install wood nailers on 16-inch centers on sides and top and along floor, ceiling, and corner junctures of the concrete tank. Use the specified fasteners and the specified adhesive in beads or spots to fasten the nailers to the concrete.

6.2 Installation of Insulation

6.2.1 Remove old paint, dirt, and loose material from the tank walls and top.

6.2.2 Use adhesive applied in spots or strips to secure insulation to the concrete. Uniformly press the insulation against the tank to insure a good bond. Two or more layers of insulation can be laminated together with adhesive to provide the required thickness.

6.3 Installation of Gypsum Wallboard

6.3.1 Check the fit of the wallboard panel. Trim wallboard if necessary to fit corners, etc.

6.3.2 Apply adhesive to the wallboard in spots or beads. Wallboard must be installed within 10 minutes after application of the adhesive.

6.3.3 Install the wallboard over the insulation. Use firm hand pressure over the entire surface of the wallboard to press the wallboard against the insulation, level the board, and close up the butt joints.

6.3.4 Shim the wallboard 1/4 inch off the floor to provide a relief gap and nail the wallboard to the wood nailers.

6.3.5 Tape and spackle the wallboard.

APPENDIX I

SAMPLE SPECIFICATIONS FOR FIBERGLASS-REINFORCED PLASTIC (FRP) TANKS

In this appendix, comments and other material that is not part of the sample specifications are written in italics.

1.0 WORK INCLUDED (Provide)

1.1 All materials, parts, and work related to fiberglass-reinforced plastic (FRP) tanks as indicated on drawings or specified.

1.2 FRP tanks that will have a capacity range between 500 gallons and 5000 gallons.

1.3 FRP tanks suitable for underground burial or location inside a building.

1.4 FRP tanks that will have a minimum service life of 20 years.

If the tank is located so that it will be difficult to repair or replace, 30 years may be more appropriate.

1.5 FRP tanks that will be able to withstand thermal cycling temperatures between 90°F and 180°F.

Adjust these temperature limits to suit your particular installation.

1.6 FRP tank accessories such as manways, ladders, piping, lifting lugs, fittings, etc.

1.7 Installation of items required by other trades in the installation of the tank.

2.0 RELATED WORK

2.1 Cast-in-place concrete.

2.2 Anchor bolts.

2.3 Piping.

2.4 Liquid-level gauges, pressure gauges, temperature sensors, and thermometers.

2.5 Excavation and compacted fill.

3.0 DETAILS

3.1 All details shall be in accordance with the standards of the National Board of Fire Underwriters, Underwriters Laboratories, Inc., ASTM.

Include other standards-writing organizations and state and local governments as necessary.

3.2 Contractor shall be responsible for all dimensions of the work and shall check structural drawings in relation to all other drawings and shall verify all dimensions in relation with otner work and existing field conditions. Contractor shall be responsible for proper arrangement and fit of the work; and, if discrepancies are noted between the various drawings and work, the Contractor shall notify the Owner immediately in writing and shall not proceed until so directed.

3.3 The omission of any material shown on the drawings or called for by these specifications shall not relieve the Contractor of the responsibility for furnishing and installing such materials, even though such drawings may have been approved.

4.0 APPLICABLE CODES AND STANDARDS

4.1 HUD Intermediate Minimum Property Standards, Solar Heating and Domestic Hot Water Systems, 1977 edition.

4.2 Proposed ASTM Standard Draft No. 10, dated September 15, 1977.

4.3 Underwriters Laboratories, Inc. (U.L.), File MH7991, dated October 13, 1965, for storage of flammable liquids as updated under U.L. follow-up service in letter of January 15, 1976.

4.4 National Fire Protection Association, NFPA 30, "Flammable and Combustible Liquids Code" and NFPA 31, "Standard for Installation of Oil Burning Equipment."

Include other standards and state and local building codes as required.

5.0 CONSTRUCTION, FIBERGLASS-REINFORCED POLYESTER TANKS

The tank shall be equal to fiberglass-reinforced polyester underground storage tanks suitable for use with potable water and shall bear the NSF label. Tank shall be constructed and reinforced with bisphenol resins to withstand temperatures of 180°F.

Consult manufacturers for information on temperature limits and resin types. Most manufacturers offer several resin types with different temperature limits. Specify a temperature limit that cannot be exceeded by your system.

6.0 WATER STORAGE REQUIREMENTS

6.1 All tanks must be vented, as tanks are designed for operation at atmospheric pressure only.

6.2 Tanks shall be capable of storing liquids with specific gravity up to 1.1.

6.3 Tanks shall be capable of storing liquids up to maintained temperature of 180°F at the tank's interior surface.

Use a temperature limit appropriate to your system.

7.0 ACCESSORIES

7.1 Fiberglass Flanged Manway

The manway shall have a 22-inch inside diameter and shall be furnished complete with U.L. approved gasket, bolt, and cover, and at locations indicated on the drawings.

7.2 Suction Line

The suction line shall be installed on site by the Contractor. Pipes shall be terminated a minimum of 4 inches from the bottom of the tank.

7.3 Lifting Lugs

Provide lifting lugs on each tank at location indicated on the drawings. Lugs shall be capable of withstanding weight of tank with a safety factor of 3:1.

7.4 Ladders

Ladders shall be standard carbon steel supplied by the tank manufacturer. Refer to drawings for locations.

7.5 Fittings-Threaded NPT

All threaded fittings on U.L.-labeled tanks shall be of a construction material consistent with the requirements of the U.L. label. All fittings shall be supplied with cast iron plugs.

7.5.2 All standard threaded fittings are 4 inches in diameter and shall be half couplings. Reducers are to be used for smaller sizes where specified and provided by Contractor.

7.5.3 All threaded fittings shall have machine tolerances in accordance with the ANSI standard for each fitting size.

7.5.4 Fittings shall be able to withstand a minimum of 300 foot-pounds of torque and 2000 foot-pounds of bending.

Consult the tank manufacturer for availability of accessories. Add accessories to or delete accessories from the specifications as required by your installation.

8.0 LOADING CONDITIONS

8.1 External Hydrostatic Pressure

Tank shall be capable of being buried in ground with 3 feet of overburden over the top and with the hole fully flooded with a safety factor of 3:1 against general buckling.

Specification 8.1 is applicable only to underground tanks.

8.2 Internal Load

Tank shall be able to withstand 5 psi air pressure test with 5:1 factor. Test for leakage prior to installation.

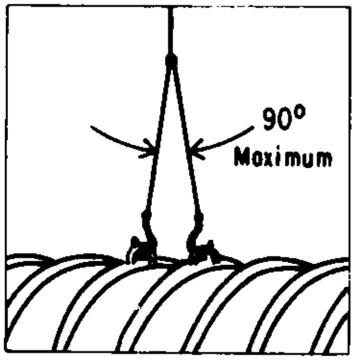
9.0 INSTALLATION

Items 9.4 through 9.11 apply to unpressurized underground tanks only. For aboveground installations and for tank temperatures exceeding 150°F, consult the tank manufacturer for installation instructions. The specifications for installing FRP tanks are based on information supplied by Owens-Corning Fiberglas Corporation, Toledo, Ohio.

Tanks shall be tested and installed with pea gravel or approved alternate backfill material according to the manufacturer's installation instructions.

9.1 Handling

9.1.1 Lifting Tanks

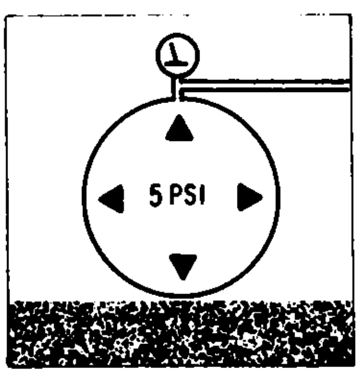


Use installation lift lug(s) to lift tank. Larger tanks have multiple lift lugs; all must be used. Do not use chains or cables around tanks. If tanks have to be moved (do not roll), set on smooth ground, free of rocks and foreign objects, and rechock. Capacity of lifting equipment must be checked before moving tank.

9.1.2 Chocking Tanks

Tanks should not be dropped, rolled, or impacted. Chock the tanks until ready for installation and tie them down if high winds are expected. Use minimum 1/2-inch diameter nylon or hemp rope over each tank and tie to wooden stakes of adequate size to prevent tanks from being moved by high winds.

9.2 Testing



Before installing tanks, tighten and soap fittings and pressure test tank at 5 psi for minimum of one hour. Isolate tank from piping when pressure testing piping. Do not approach ends of tanks or manways that are under test. Tanks under pressure should not be left unattended.

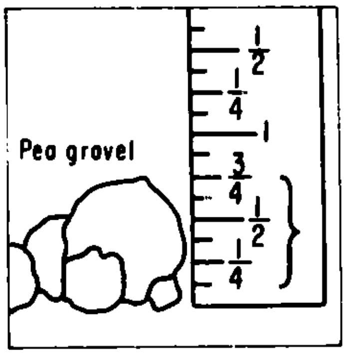
If tanks are dropped or impacted after initial test, retest tanks and soap areas of impact to check for tank damage. If damage has occurred, do not attempt repairs.

After completing the testing all tanks must be vented, as tanks are designed for operation at atmospheric pressure only.

9.3 Insulation

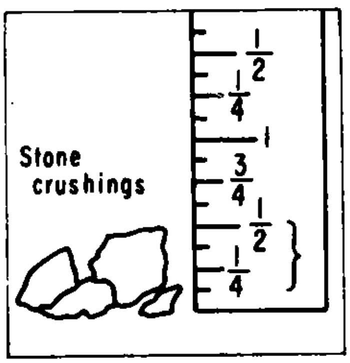
Because underground FRP tanks derive support from their surroundings and many types of insulation deteriorate in the presence of soil or water, you should consult with the tank manufacturer before writing this section on insulation. Refer to Chapter 1 of this manual for maximum permisible thermal conductance of insulation.

9.4 Bed and Backfill Material



9.4.1 Gravel

Use a naturally rounded, clean aggregate with particle size not less than 1/8 inch or more than 3/4 inch in diameter. Use this description when specifying or ordering, because material is known by different names in different areas. This material is commonly called pea gravel.

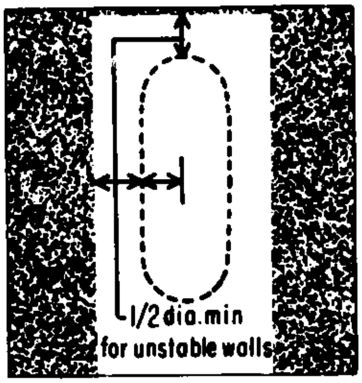


9.4.2 Washed stone or gravel crushings with angular particle size between 1/8 inch and 1/2 inch in diameter are acceptable alternate bed and backfill materials. This material must meet ASTM-33 paragraph 9.1 requirements for quality and soundness.

Caution: In freezing conditions backfill must be dry and free of ice. Do not use other backfill materials.

The tank warranty will be automatically voided if other than approved (above) bed and backfill materials are employed without approval.

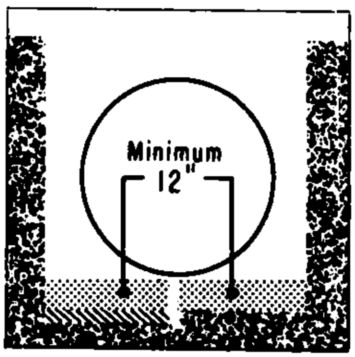
9.5 Hole Size



Hole must be large enough to allow a distance equal to a minimum of half the tank diameter from the ends and sides of tanks to hole walls. A qualified soil-testing laboratory can provide data and recommendations for soils having less than 750 pounds per square foot cohesion as calculated from an unconfirned compression test or for soils with an ultimate bearing capacity of less than 3500 pounds per square foot.

Observe OSHA regulations regarding supporting the walls of the hole and slanting the sides if the hole is deeper than 5 feet.

9.6 Burial Depth and Cover



9.6.1 Hole Depth

Burial holes must be deep enough to allow a minimum of 12 inches required backfill bed over the hole bottom or concrete slab.

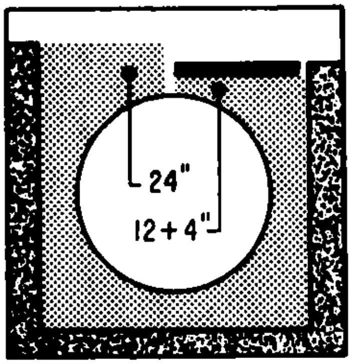
Cover depth is determined by type of pavement on surface.

9.6.2 Traffic Loads

Tanks subjected to traffic loads must have a cover depth of 36 inches backfill plus 8 inches of asphalt or a minimum of 18 inches backfill plus 6 inches of concrete reinforced with steel rebars.

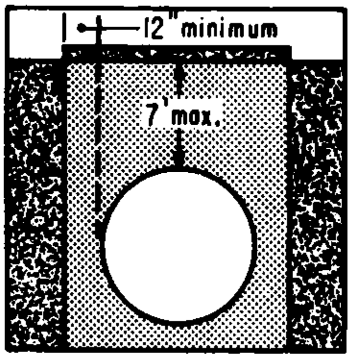
9.6.3 Hillside Installation

Tanks may be buried on moderate slopes providing the downhill side consists of undisturbed native soil and is at least as high as the top of the tank in the installed condition. The maximum slope permitted is 10°. Fill dirt on the downhill side of the tank hole is not permitted.



9.6.4 No Traffic Loads

Tanks not subjected to traffic loads need a minimun cover of 24 inches backfill or 12 inches backfill plus 4 inches reinforced concrete to meet NFP 30 requirements.



9.6.5 Pad Dimensions

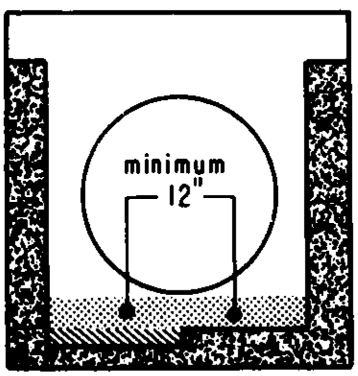
Reinforced concrete paving must extend at least 12 inches beyond tank outline in all directions.

9.6.6 Maximum Burial Depth

Depth of cover for tanks 10 feet or less in diameter in both traffic and no-traffic conditions must not exceed 7 feet over tank top.

9.7 Installation Procedure--Dry Hole

9.7.1 Bed

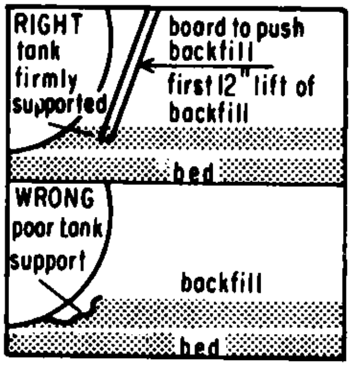


Provide a 12-inch minimum level backbed over hole bottom or concrete slab. Bed must be smooth and level. Place tanks in hole on backfill bed.

Caution: Do not place fiberglass tanks directly on concrete slab or grout thanks in wet concrete. Do not place tanks on timbers, beams, or cradles.

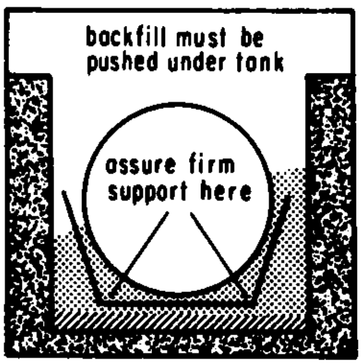
9.7.2 High Water

<u>Tanks, whether strapped or not, must never be left on the bed without backfill to the top of tank if there is any chance that there will be more than 12 inches of water in the hole.</u>



9.7.3 Backfilling

Use the same materials as for bedding. At start of backfilling, care must be taken to push approved backfill material completely beneath tank bottom, between ribs, and under end caps to provide necessary support. A board or similar device should be used to push backfill under the tank.

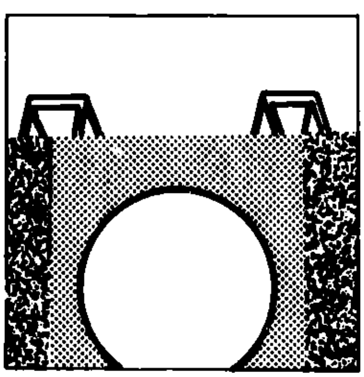


Unanchored tanks installed with backfill to the top of the tank but without backfill to grade should be filled with water or product as ballast. Do not add water or product in tank before backfill material is even with top of tank.

Complete backfilling to top of tank with approved backfill. Be sure backfill is free of large rocks, debris, or foreign materials that could damage the tank. Avoid impacting tanks during the backfilling.

9.7.4 Leveling to Grade

Excavation should be brought to grade with stone or gravel crushings meeting the specifications shown in Section 9.4 if blacktop is used. Otherwise either approved backfill may be used to grade.



9.7.5 Barricade

Tank area must be barricaded to prevent any vehicle travel over the tanks until installation is complete.

9.8 Installation Procedure--Wet Hole

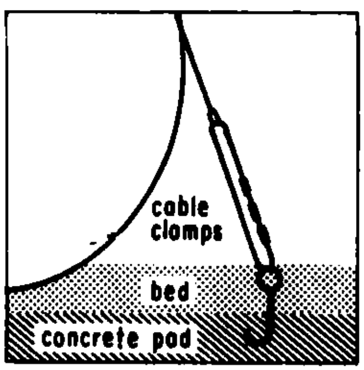
Do not install the tank in a wet hole until the cause of the wetness has been determined. If the cause of the wetness is a high water table, the storage system must be redesigned to prevent excessive heat loss due to wet insulation.

If the wetness in the hole is not caused by a high water table, consult the tank manufacturer for instructions on installing the tank.

9.9 Anchoring

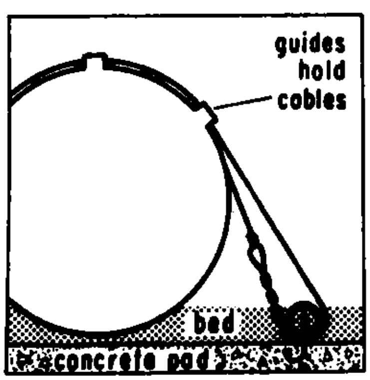
9.9.1 Hold-down Straps

Use fiberglass hold-down straps on top of all designated ribs. Anchor points should be equal to tank diameter plus 1 foot on each side of tank, regardless of diameter of tank. Anchor points at bottom of hole must be aligned with designated rib ± 1 inch. Do not use straps or cables between ribs of tanks. All straps should be mechanically tightened to give snug fit of strap to tank.



9.9.2 Concrete Pad

Anchor the bolts in concrete and attach them to ends of straps with wire cable (see table in Section 9.9.4) and triple clamp with at least three clamps. (Be sure there is a 12-inch bed between concrete pad and tanks).



9.9.3 Alternate Cable System

Triple clamp cable to strap. Thread cable around anchor and bring to top of tank. Repeat procedure with anchor on other side and triple clamp cables together at top of tank.

9.9.4 All Anchoring Methods

Minimums per anchor location

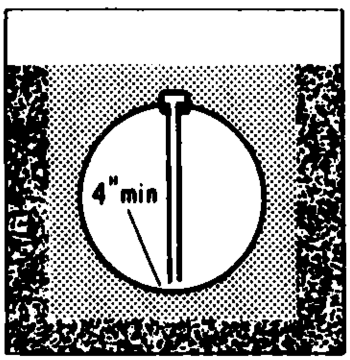
Tank Diameter	6' or less	8'	10'
Wire Rope	(6 x 19 plow steel)		
Diameter	3/8"	1/2"	1/2"
Tensile St., lbs.	9,000	12,500	16,000
Turnbuckle Diameter			
Hook Type	3/4"	1-1/8"	1-1/8"
Eye Type	1/2"	3/4"	3/4"

9.9.5 Turnbuckles (not illustrated)

Hook or eye type turnbuckles may be used in place of all or part of the cable described in this section.

9.10 Piping and Sump

9.10.1 Suction Pipe

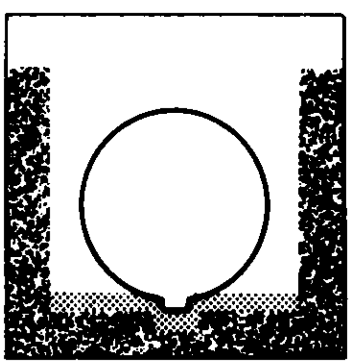


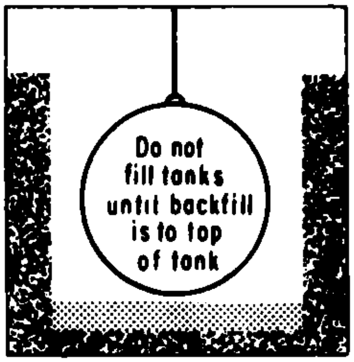
The length of storage-to-load suction pipe shall be selected to provide a minimum of 4 inches clearance between the bottom of the pipe and the bottom of the tank.

The pump and attached piping must be free to move with the tank. Use fill box around fill pipe at grade where asphalt or concrete pad is used. Do not place brick or other spacing material on top of tanks.

9.10.2 Tanks with Sumps

When installing a tank equipped with a sump, modify excavation and bedding to provide a 12-inch-deep by 24-inch-diameter hole centered at the sump location. After the tank is placed, the void surrounding the sump is to be hand backfilled and hand tamped before backfilling is added around the tank.





9.11 Filling Tanks

Do not fill tanks until backfill is to top of tank. Never add product or water for hold down in dry hole conditions until backfilling is completed.

9.12 Adding Tanks to Existing Installations

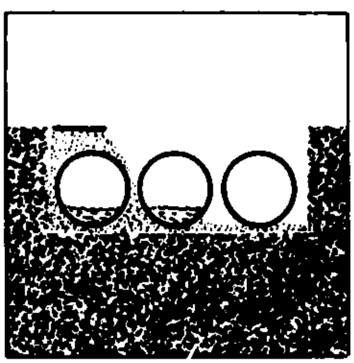
Tanks can be added to existing installations. It is important to remember that fiberglass tanks require good foundation support from surrounding soil.

9.12.1 Isolated Burial (Preferred)

Install tanks in a separate hole that is a minimum of 3 feet from edge of original tank installation hole. Undisturbed soil between new excavation and original hole must be maintained. Keep surface loads off existing tanks.

9.12.2 Burial in Same Hole (Alternate)

Lower water level in existing tanks to less than one-fourth tank capacity.



Remove surface pad, if one exists, to lower backfill.

Excavate for new tanks, leaving as much backfill as possible around existing tanks.

During installation, existing tanks must not be allowed to move. Shoring may be required to retain backfill.

Install new tanks as described earlier in these instructions, leaving a minimum of 24 inches between new tanks and existing tanks.

10.0 CAPACITY AND DIMENSIONAL REQUIREMENTS

Fill in the blanks to complete this section. This example applies to horizontal cylindrical tanks. If your installation requires another tank shape or if you have special dimensional requirements (such as special locations for pipe fittings), state your requirements in this section.

1. Nominal capacity of the tank shall be __________ gallons.

2. Nominal outside diameter of the tank shall be __________ feet.

3. Approximate overall length of the tank shall be _________ feet.

11.0 DRAWINGS

Include drawings that are applicable to your particular installation in this section. Sample drawings for a typical on-site-insulated tank, typical manway and NPT fitting details, and a typical factory-insulated tank are shown in Figures I-1, I-2, and I-3.

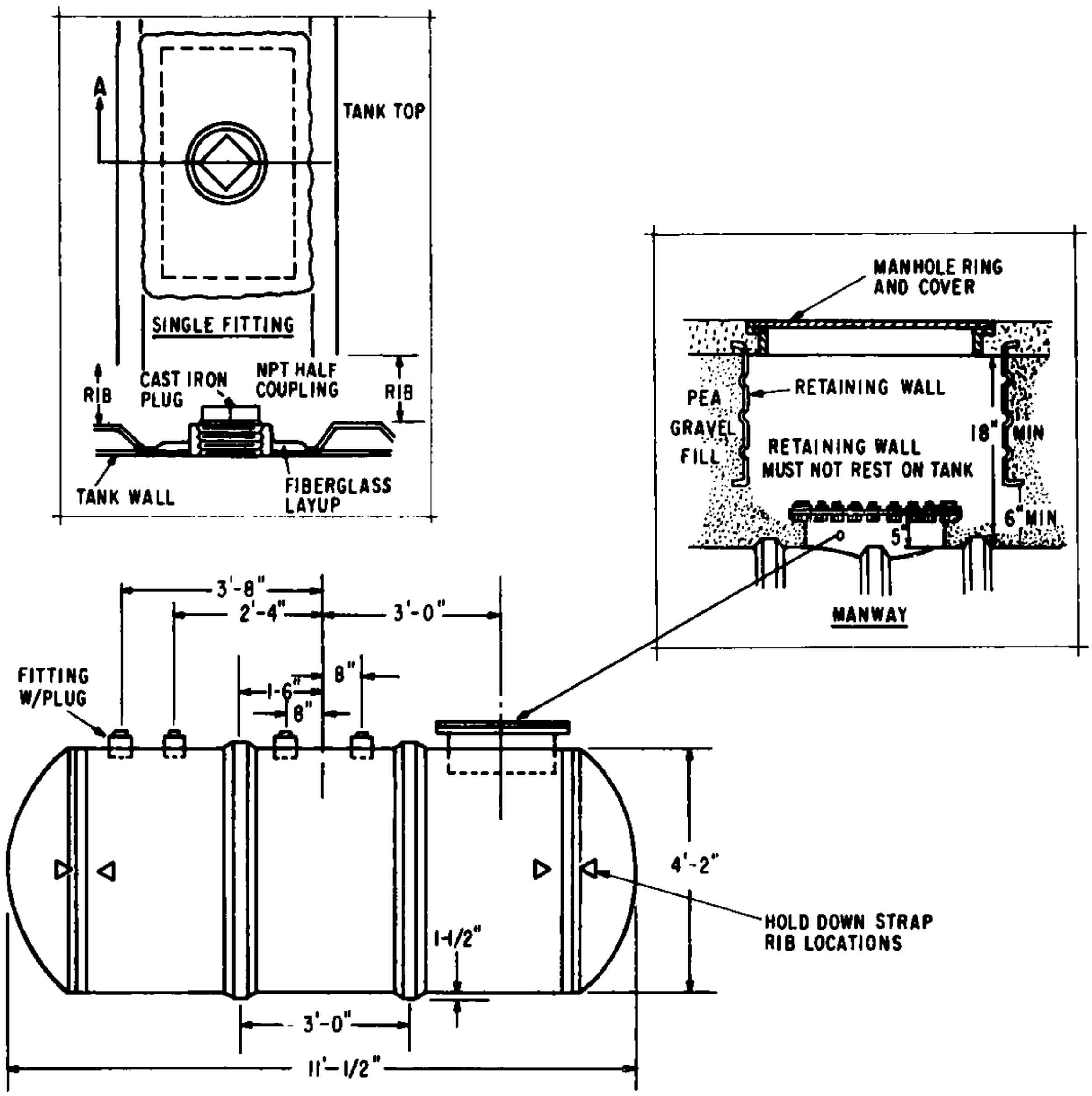


Figure I-1. Sample Drawing of FRP Tank before Installation of Insulation

Courtesy of Owens-Corning Fiberglas Corporation, Toledo, Ohio

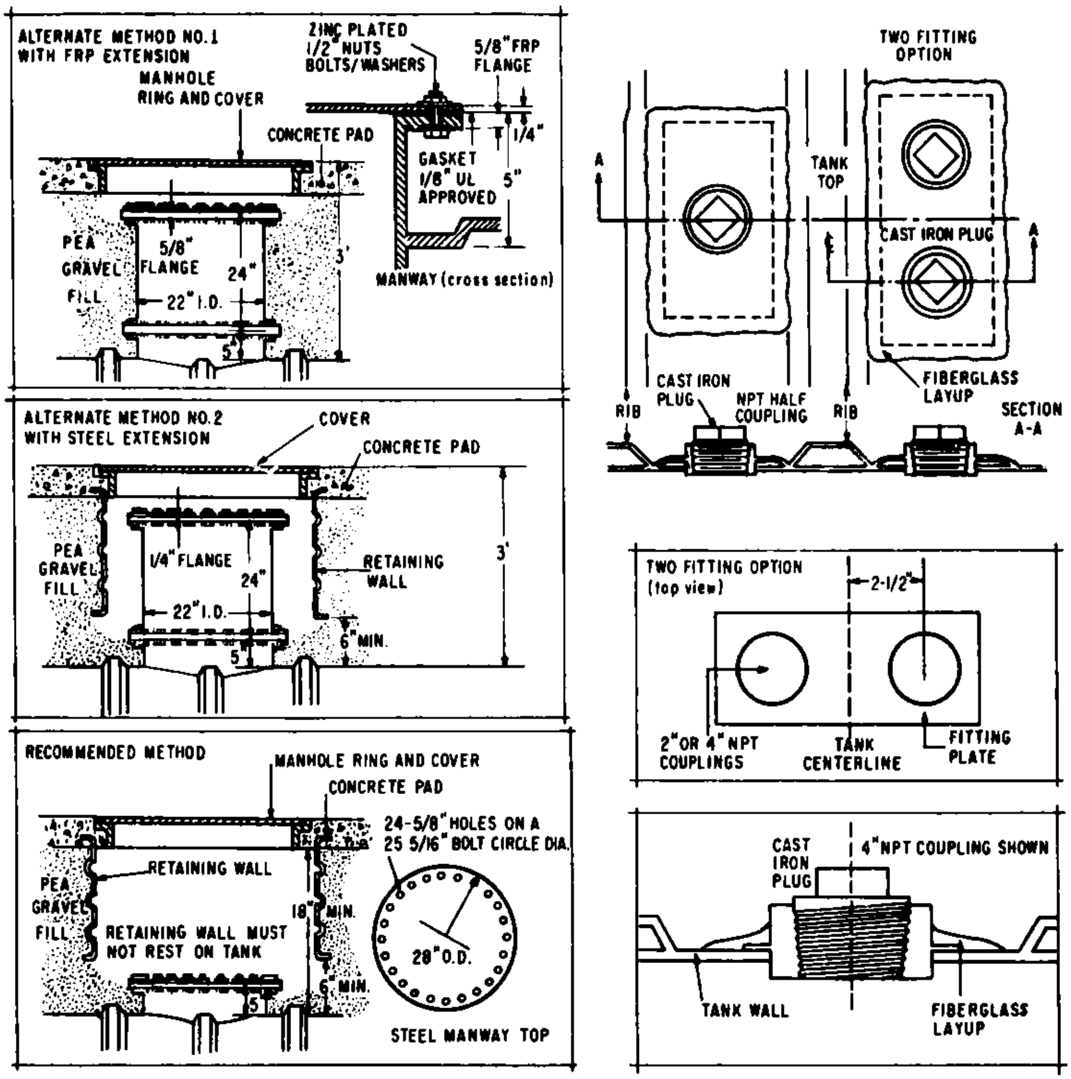


Figure I-2. Typical Manway and NPT Fitting Details for FRP Tanks

Courtesy of Owens-Corning Fiberglas Corporation, Toledo, Ohio

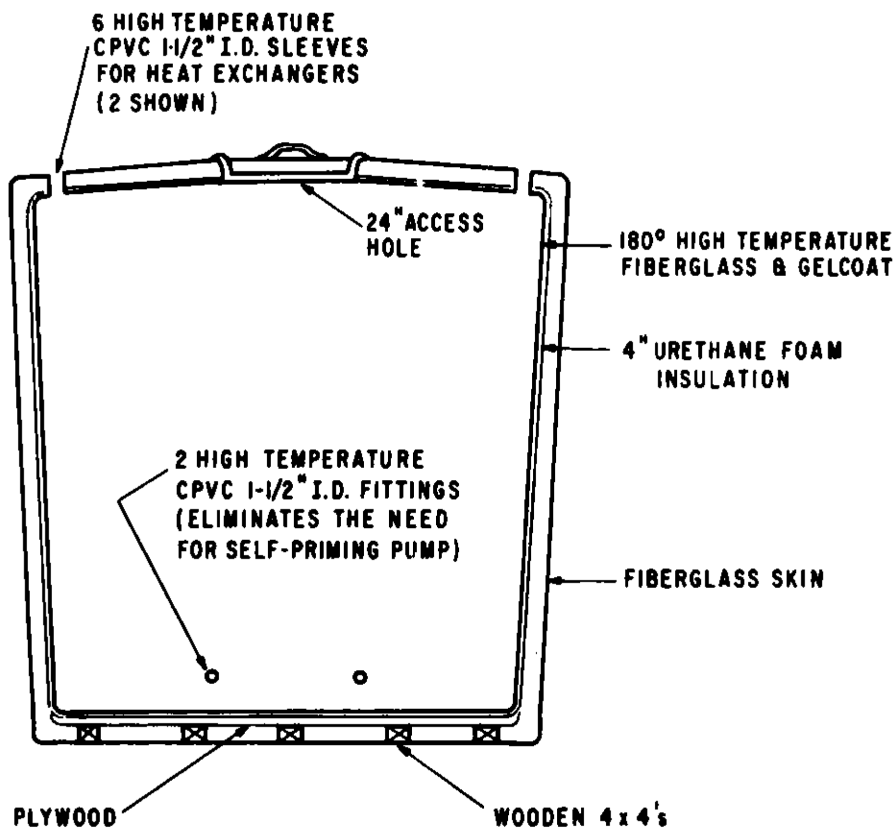


Figure I-3. Sample Drawing of a Factory-Insulated FRP Tank

Courtesy of Solar Systems, Novato, California

APPENDIX J
UNITS AND CONVERSION FACTORS

This appendix contains brief descriptions of the International System of Units (SI) and the English system of units, along with tables for converting from one set of units to another. Discussions of some problem units are also included.

THE METRIC SYSTEM OF UNITS

The SI system is based on seven base units: a unit of length, the meter; a unit of mass, the kilogram (kg); a unit of time, the second (s); a unit of temperature, the kelvin (K); a unit of electric current, the ampere (A); and two units not used in this manual, the mole and the candela.

Many other units are used with these basic ones. The degree Celsius (°C) is more commonly used than the kelvin to measure temperature; it is frequently used in this manual. A temperature interval of one degree Celsius is exactly equal to one kelvin. The difference in the two units is that zero kelvins is absolute zero, while zero degrees Celsius is the freezing point of water which is equal to 273.15 kelvins.

The base units can be combined to form derived units. Density, for example, is given in kilograms per cubic meter (kg/m^3). Some derived units have their own names; those of importance in this manual are listed in Table J-1. Prefixes representing multipliers can be attached to SI units to provide convenient-sized units. Table J-2 lists the most important prefixes, their symbols, and the multiplication factor they represent.

A unit of liquid volume often used with SI units but not defined in the SI system is the liter (ℓ), which is equal to one thousandth of a cubic meter.

THE ENGLISH SYSTEM OF UNITS

The base units of the English system are the foot (ft), a unit of length; the second (sec), a unit of time; the pound-force (lbf), a unit of force; and the degree Fahrenheit (°F), a unit of temperature. The base unit of electrical current is the ampere, which is taken from the SI system. Volts, watts, and ohms are also taken from the SI system.

Some derived units in the English system are single combinations of the base units--for example, pressure is given in pound-force per square foot (lbf/ft^2) --but others are more complicated. A commonly used unit of mass is the pound-mass (lb), which is defined as the amount of mass which exerts a force of one pound-force in the earth's gravitational field.

Table J-1. Some Derived SI Units

Quality	Unit	In Terms of Other Units
Frequency	hertz (Hz)	1/s
Force	newton (N)	$kg \cdot m/s^2$
Pressure	pascal (Pa)	N/m^2
Energy (also heat and work)	joule (J)	$N \cdot m$
Power	watt (W)	J/s
Electric Potential	volt (V)	W/A
Electrical Resistance	ohm (Ω)	V/A

It is worth noting that all of the derived units in the SI system are derived with a multiplier of exactly one. Thus, one joule is exactly one newton meter. The SI system is said to be coherent for this reason.

Table J-2. Some SI Prefixes

Prefix	Symbol	Multiplication Factor
mega	M	1 000 000. = 10^6
kilo	k	1 000. = 10^3
centi	c	0.01 = 10^{-2}
milli	m	0.001 = 10^{-3}
micro	μ	0.000 0001 = 10^{-6}

The unit of energy is the foot-pound-force (ft·lbf), but the British thermal unit (Btu) is more commonly used in thermal calculations. One Btu is defined as the amount of energy needed to raise the temperature of one pound-mass of water by one degree Fahrenheit. It is approximately equal to 778.1693 ft·lbf.[1] The unit of power is the foot-pound-force per second, but, again, another unit, the horsepower (hp), is more commonly used. One horsepower is equal to 550 ft·lbf/sec.

A commonly used unit of volume is the U.S. liquid gallon (gal), which is approximately equal to 0.1337 cubic feet. Other units of time include the hour (hr), which is convenient for heat transfer calculations, and the minute (min), which is often used in flow rate calculations.

PROBLEM UNITS

The Pound

The term pound can cause confusion because the pound is a unit of both force and mass, and its symbol, lb, is often used to stand for both types of pound. In this manual we use lbf to stand for pound-force and lb to stand for pound-mass.

Confusion can also arise when the symbol g is encountered in equations. In some equations it represents the standard acceleration of gravity, and in others it is a unit conversion factor that converts lb to lbf or vice versa. g has the same numerical value in both uses, but its meaning is different.

In this manual, we have defined g wherever it appears in an equation.

Viscosity

The term viscosity can refer to two kinds of viscosity--absolute, or dynamic, viscosity (used in this manual) and kinematic viscosity, which is defined as the absolute viscosity divided by the density of the fluid.

The units of absolute viscosity are pound-mass per hour per foot (lb/hr·ft) in the English system and pascal second (Pa·s) in the SI system. The units of kinematic viscosity are square foot per hour (ft^2/hr) in the English system and square meter per second (m^2/s) in the SI system.

---

[1]These numbers are not exact because the English units are defined in terms of the metric SI units. For instance, one Btu is exactly equal to 1055.05585262 Joules.

Two other units, the poise for absolute viscosity and the stoke for kinematic viscosity, are the most commonly used. These metric units are not part of either the English or the SI system but are used with both. Because poise and stoke are fairly large compared with the viscosities of most liquids, centipoise and centistoke are often used. These units must be converted to the appropriate units in the English or SI system when they are to be used in equations. One centipoise is equal to one thousandth of a pascal second and one centistoke is equal to one millionth of a square meter per second.

You will often have to check the units in order to determine which type of viscosity data is being presented. The factors for converting from one set of units to another are given in Table J-4.

Pressure

Several different units are used to describe pressure. In the English system, its units are pound-force per square foot (lbf/ft^2); in the SI system, its units are pascals (Pa).

Pressure is often given in terms of pound-force per square inch (psi). Two other units which you may encounter are psia and psig. The "a" in psia stands for absolute. A pressure given in psia is the pressure above an absolute vacuum. The "g" in psig stands for gauge. A pressure given in psig is the pressure relative to the atmospheric pressure on the gauge which is measuring the pressure. Gauge pressure can be either positive or negative but absolute pressure can only be positive.

Other units of pressure are inches of water, feet of water, and meters of water. These units are defined as the pressure at the base of a column of water whose height is measured in inches, feet, or meters. To convert these units, multiply them by the density of water. In the SI system, the result, which is in kg/m^2, must be multiplied by the acceleration of gravity, $g = 9.8\ m/s^2$ to get pressure in pascals. In the English system, the result of multiplying the height of water by the density is pound-mass per square foot (or square inch). But, because one pound-mass exerts a force of one pound-force, the pressure at the base of the column is an equal number of pounds-force per square foot.

Head

Head is a term used to describe the output of centrifugal pumps. It is given in units of length or height without a liquid being specified. The operating properties of centrifugal pumps ensure that at a given flow rate they will exert enough pressure at their output to raise a column of the liquid being pumped to a fixed height no matter what liquid is being used. In other words, centrifugal pumps have the same head at a given flow rate regardless of what type of liquid they are pumping. To calcuate the pressure at the pump output, you must multiply the head by the density of the liquid.

Again, for metric units you must multiply this result by the acceleration of gravity.

Quite often, as in Chapter 3 of this manual, all of the pressure drops in a system are described in terms of head losses. If you wish to convert pressure drops to head losses, you must divide the pressure by the density of the liquid. For metric units, you must also divide the result by the acceleration of gravity.

UNIT CONVERSION

Temperature Conversion Table

Converting temperatures from one set of units to another is somewhat different from other conversions; so temperature conversion equations appear in a separate table, Table J-3.

It is important that you know whether you are working with an actual temperature or with a temperature difference before using these equations, since actual temperature and temperature difference are not converted in the same way. In this manual when temperature units are presented within a set of units such as $°F \cdot ft^2 \cdot hr/Btu$, the temperature unit always represents temperature difference.

Unit Conversion Table

Table J-4 contains numerical factors needed to convert quantities expressed in one set of units to quantities expressed in another set of units. Where these factors are very large or very small, scientific notation is used.

The units in Table J-4 are grouped according to type. Conversion factors that are followed by an asterisk (*) are exact. The other factors have been rounded off to five decimal places.

To use Table J-4, find the units that you wish to convert from in the left column opposite the units that you wish to convert to in the right column. Multiply the quantity of those units that you have by the conversion factor in the center column to convert the quantity to the units in the right column.

Example J-1:

Suppose you want to find the number of square meters in an area of 144 square inches. Under the heading Area in Table J-4 find the line:

square inches (in^2) 6.4516×10^{-4}* square meters (m^2)

The conversion is:

$$144\ in^2 \times 6.4516 \times 0.000\ 1 = 0.092903\ m^2.$$

Example J-2:

Suppose you have some isulation with an R-value of 19°F·ft^2·hr/Btu and you wish to know its value in the SI units of °C·m^2/W. To perform the conversion use conversion factors from Tables J-3 and J-4:

The temperature unit, °F, represents a temperature interval in this value; so from Table J-3 you find that:

$$1°\text{C} = 1.8°\text{F} \qquad \text{(J-1)}$$

The other units can be found in Table J-4:

$$1 \text{ m}^2 = 10.764 \text{ ft}^2.$$

$$1 \text{ s} = 2.7778 \times 10^{-4} \text{ hr} = \frac{1}{3600} \text{ hr}. \qquad \text{(J-2)}$$

$$1 \text{ Btu} = 1055.1 \text{ J}.$$

These conversions can be written in another way:

$$1 = \frac{1°\text{C}}{1.8°\text{F}} .$$

$$1 = \frac{1 \text{ m}^2}{10.764 \text{ ft}^2} . \qquad \text{(J-3)}$$

$$1 = \frac{3600 \text{ s}}{1 \text{ hr}} .$$

$$1 = \frac{1 \text{ Btu}}{1055.1 \text{ J}} .$$

The conversion is made by multiplying the original value, 19°F·ft^2·hr/Btu, by the various factors of 1 given in Equation J-3.

$$19 \frac{°\text{F}\cdot\text{ft}^2\cdot\text{hr}}{\text{Btu}} \times \frac{1°\text{C}}{1.8°\text{F}} \times \frac{1 \text{ m}^2}{10.764 \text{ ft}^2} \times \frac{1 \text{ Btu}}{1055.1 \text{ J}} \times \frac{3600 \text{ s}}{\text{hr}} .$$

Now the various units which appear both on the top and bottom of this expression can be cancelled:

$$\frac{19 \times 3600}{1.8 \times 10.764 \times 1055.1} \times \frac{\cancel{°\text{F}} \times °\text{C}}{\cancel{°\text{F}}} \times \frac{\cancel{\text{ft}^2}\ \text{m}^2}{\cancel{\text{ft}^2}} \times \frac{\cancel{\text{hr}}\ \text{s}}{\cancel{\text{hr}}} \times \frac{\cancel{\text{Btu}}}{\cancel{\text{Btu}}\cdot\text{J}}$$

giving: $3.3 \ °\text{C}\cdot\text{m}^2\cdot\text{s/J}$,

which, by definition of the watt, is equivalent to 3.3 °C·m^2/W.

Table J-3. Temperature Conversion Equations[a]

TEMPERATURE

$$T_c = \frac{5}{9}(T_f - 32)$$

$$T_f = \frac{9}{5}T_c + 32$$

$$T_c = T_k - 273.15$$

$$T_f = \frac{9}{5}T_k - 459.67$$

TEMPERATURE DIFFERENCE[b]

$$\Delta T_c = \frac{5}{9}\Delta T_f$$

$$\Delta T_f = \frac{9}{5}\Delta T_c$$

$$\Delta T_c = \Delta T_k$$

$$\Delta T_f = \frac{9}{5}\Delta T_k$$

[a] T_c, T_f, and T_k stand for temperature in degrees Celsius, degrees Fahrenheit, and kelvins.

[b] The symbol Δ represents temperature difference in the following terms.

Table J-4. Conversion Factors

Multiply	By	To Obtain
Area		
cm^2	0.0010764	ft^2
cm^2	$1.0 \times 10^{-4*}$	m^2
ft^2	0.092903	m^2
in^2	0.0069444	ft^2
in^2	$6.4516 \times 10^{-4*}$	m^2
m^2	10.74	ft^2
Density		
kg/ℓ	1000.0 *	kg/m^3
kg/ℓ	62.428	lb/ft^3
kg/m^3	.062438	lb/ft^3
lb/ft^3	16.018	kg/m^3
lb/gal	119.83	kg/m^3
lb/gal	7.4805	lb/ft^3
Energy, Heat, and Work		
Btu	1055.1	J
ft·lbf	0.077817	Btu
ft·lbf	1.3558	J
J	9.4782×10^{-4}	Btu
kWh	3412.1	Btu
kWh	$3.6 \times 10^{6*}$	J

Table J-4. (continued)

Multiply	By	To Obtain
	Force	
N	0.22481	lbf
lbf	4.4482	N
	Heat Capacity	
J/kg·°C	2.3885×10^{-4}	Btu/lb°F
Btu/lb·°F	4186.8*	J/kg·°C
	Heat Capacity, Volumetric	
Btu/ft^3·°F	6.706×10^{4}	J/m^3·°C
Btu/gal·°F	7.4805	Btu/ft^3·°F
Btu/gal·°F	5.0169×10^{5}	J/m^3·°C
J/ℓ·°C	0.014911	Btu/ft^3·°F
J/ℓ·°C	1000.0*	J/m^3·°C
J/m^3·°C	1.4911×10^{-5}	Btu/ft^3·°F
	Length	
cm	0.032808	ft
cm	0.01*	m
ft	0.3048*	m
in	0.083333	ft
in	0.0254*	m

Table J-4. (continued)

Multiply	By	To Obtain
	Length (cont.)	
m	3.2808	ft
mil	8.3333×10^{-5}	ft
mil	2.54×10^{-5}*	m
mm	010032808	ft
mm	0.001*	m
yd	3.0*	m
yd	0.9144*	m
	Mass	
kg	2.2046	lb
lb	0.45359	kg
	Mass Flow Rate	
lb/h	1.2600×10^{-4}	kg/s
lb/min	60 0*	lb/h
lb/min	0.0075599	kg/s
lb/s	3600.0*	lb/h
lb/s	0.45359	kg/s
kg/h	2.2046	lb/hr
kg/h	2.7778×10^{-4}	kg/s
kg/min	132.28	lb/h
kg/min	0.01667	kg/s
kg/s	7936.6	lb/h

Table J-4. (continued)

Multiply	By	To Obtain
	Power	
Btu/h	778.17	ft·lbf/hr
Btu/h	0.29307	W
ft·lbf/h	0.0012851	Btu/h
ft·lbf/h	3 7662 x 10^{-4}	W
ft·lbf/s	4.6262	Btu/h
ft·lbf/s	3600.0*	ft·lbf/h
ft·lbf/s	1.3558	W
hp	2544.4	Btu/h
hp	1.98 x 10^{6}*	ft·lbf/h
hp	745.70	W
W	3.4121	Btu/h
W	2655.2	ft·lbf/h
	Pressure	
cm of water	2.0481	lbf/ft^2
cm of water	98.064	Pa
ft of water	62.426	lbf/ft^2
ft of water	2989.0	Pa
in of water	5.2022	lbf/ft^2
in of water	249.08	Pa
lbf/ft^2	47.880	Pa

Table J-4. (continued)

Multiply	By	To Obtain
	Pressure (cont.)	
psi (lbf/in^2)	144.0*	lbf/ft^2
psi	6894.8	Pa
m of water	204.81	lbf/ft^2
m of water	9806.4	Pa
Pa	0.020885	lbf/ft^2
	Thermal Conductance (U-Value)	
$Btu/ft^2 \cdot h \cdot °F$	5.6783	$W/m^2 °C$
$W/m^2 °C$	0.17611	$Btu/ft^2 \cdot h \cdot °F$
	Thermal Resistance (R-Value)	
$ft^2 \cdot h \cdot °F/Btu$	0.17611	$m^2 °C/W$
$m^2 \cdot °C/W$	5.6782	$ft^2 \cdot h \cdot °F/W$
	Thermal Resistance per Unit Thickness (r-Value)	
$ft^2 \cdot h \cdot °F/Btu \cdot in$	$0.069335\ 10^{-2}$	$m^2 \cdot °C/W \cdot cm$
$m^2 \cdot °C./W \cdot cm$	14.423	$ft^2 \cdot h \cdot °F/Btu \cdot in$
	Time	
day	24.0*	h
day	8.64×10^{4}*	s

Table J-4. (continued)

Multiply	By	To Obtain
	Time (cont.)	
h	3600.0*	s
min	0.016667	h
min	60.0*	s
s	2.7778×10^{-4}	h
y	8760.0*	h
y	3.1536×10^{7}*	s
	Velocity	
ft/h	8.4667×10^{-5}	m/s
ft/min	60.0*	ft/h
ft/min	0.00508*	m/s
ft/s	3600*	ft/h
ft/s	0.3048*	m/s
m/s	1.1811×10^{4}	ft/h
	Viscosity (Absolute or Dynamic)	
lb/ft·h	4.1338×10^{-4}	Pa·s
centipoise	2.4191	lb/ft·h
centipoise	0.001*	Pa·s
Pa·s	2419.1	lb/ft·h

Table J-4. (continued)

Multiply	By	To Obtain
	Viscosity (Kinematic)	
ft^2/h	2.5806×10^{-5}	m^2/s
centistokes	0.038750	ft^2/h
centistokes	1.0×10^{-6}	m^2/s
m^2/s	3.8750×10^{4}	ft^2/h
	Volume	
cm^3	3.5315×10^{-5}	ft^3
cm^3	1.0×10^{-6}*	m^3
ft^3	0.028317	m^3
gal	0.13368	ft^3
gal	0.0037854	m^3
in^3	5.7870×10^{-4}	ft^3
in^3	1.6387×10^{-5}	m^3
ℓ	0.035315	ft^3
ℓ	0.001*	m^3
m^3	35.315	ft^3
yd^3	27.0*	ft^3
yd^3	0.76455	m^3

Table J-4. (continued)

Multiply	By	To Obtain
	Volume Flow Rate	
ft^3/h	7.8658×10^{-6}	m^3/s
ft^3/min (cfm)	60.0*	ft^3/h
ft^3/min	4.7195×10^{-4}	m^3/s
ft^3/s	3600.0*	ft^3/h
ft^3/s	283.17	m^3/s
gal/min (gpm)	8.0208	ft^3/hr
gal/min	6.3090×10^{-5}	m^3s
ℓ/min	2.1189	ft^3/h
ℓ/min	1.6667×10^{-5}	m^3/s
ℓ/s	127.13	ft^3/h
ℓ/s	0.001*	m^3/s
m^3/s	1.2713×10^5	ft^3/h

ABBREVIATIONS USED IN TABLES

Btu	British thermal unit (international table)
°C	degree Celsius (sometimes incorrectly called degree centigrade)
cm	centimeter
°F	degree Fahrenheit
ft	foot
gal	U.S. liquid gallon
h	hour (often abbreviated hr in English system)
hp	horsepower (550 ft·lbf/s)
in	inch
J	joule
K	kelvin
kg	kilogram
kWh	kilowatt-hour
ℓ	liter (also spelled litre)
lb	pound-mass
lbf	pound-force
m	meter (also spelled metre)
mil	one thousandth of an inch
min	minute
mm	millimeter
N	newton
Pa	pascal
psi	pound-force per square inch
s	second (often abbreviated sec. in English system)
W	watt
y	year (365 days)
yd	yard

GLOSSARY

absolute pressure	Also called absolute head. Pressure measured relative to vacuum. Absolute pressure is the gauge plus the atmospheric pressure.
active system	A solar system that uses pumps or fans to circulate a heat transfer fluid through solar collectors and to distribute heat to the building; the opposite of a passive system.
air-type collector	A solar collector that uses circulating air as a heat transfer fluid.
ambient temperature	The temperature of the surroundings as measured by a dry-bulb thermometer.
antifreeze loop	A circuit, consisting of the solar collectors, a pump, and a heat exchanger through which an antifreeze solution is pumped.
aqueous solution	A mixture of a substance (such as ethylene glycol) with water.
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, 345 East 47th Street, New York, New York 10017.
ASME	American Society of Mechanical Engineers, 345 East 47th Street, New York, New York 10017.
auxiliary system	A system that provides heat when solar energy alone is insufficient, a backup system.
Btu	British thermal units. The amount of heat required to raise 1 pound of water 1 degree Fahrenheit; the basic unit of heat in the English system of units.
cathodic protection	A method of corrosion protection in which a highly reactive metal bar is placed in the system liquid. To be effective the metal bar must be more reactive than the most reactive metal component in the system and must have a continuous electrical path to the most reactive metal component.

centrifugal pump	A type of pump in which a fluid is flung outward by the rotation of an impeller. See positive displacement pump.
coil-in-tank heat exchanger	A coil of tubing submerged inside a tank. One heat transfer fluid is pumped through the tubing while the other flows over the outside of the tubing by natural convection.
collector	A device constructed to absorb solar energy and convert it to useful heat.
collector coolant	A heat transfer fluid used in solar collectors.
convection, forced	A means of transferring heat in which the heat transfer fluid is moved by external means such as a pump or fan.
convection, natural	A means of transferring heat in which the heat transfer fluid is moved by the buoyancy of its warmer parts.
convector	A heat exchanger that uses natural convection of air to transfer heat from water or steam to a building.
cooling season	The time of year (usually June to September, but varying with climate) when air conditioning is desirable to maintain comfortable room temperatures.
daily temperature range	The difference between the warmest storage temperature attained in a day and the coolest storage temperature reached on the same day.
DHW	Potable domestic hot water.
dielectric bushing	An electrically insulating pipe connector used to connect dissimilar metals in plumbing.
differential thermostat	A device that uses a measured temperature difference (such as the temperature difference between the collectors and storage) to control a device (such as a pump or fan).
drainback system	A method of protecting the solar collectors against freezing by draining the collector water into the storage tank on cold nights.

draindown system	A method of protecting the solar collectors against freezing by draining the collector water into the sewer on cold nights.
effectiveness	The ratio of actual heat transferred in a heat exchanger to the maximum possible heat that could be transferred in a perfect heat exchanger.
electrolytic solution	A liquid that conducts electricity via ions and electrons. When dissimilar metals are in contact with an electrolytic solution, galvanic corrosion can occur. See dielectric bushing.
expansion tank	A device used to limit the pressure increase caused by thermal expansion of the liquid in a sealed system. The expanding liquid compresses air in the expansion tank.
f - Chart	A method devised at the Univeristy of Wisconsin for calculating the performance of solar energy systems.
flow rate	The volume or mass of fluid that flows past a point in a pipe or duct per unit of time. In the English system the units of volumetric flow rate are typically gallons per minute or cubic feet per minute, and the units of mass flow rate are typically pounds per minute.
fluid	A substance that cannot retain its shape without an external container; a gas or a liquid.
forced convection	See convection, forced.
fouling factor	A factor ($°F \cdot ft^2 \cdot hr/Btu$) that expresses the degradation of heat exchanger performance caused by scaling or biological fouling. The fouling factor is the inverse of the scaling coefficient.
FRP	Fiberglass-reinforced plactic.
gauge pressure	Pressure measured relative to atmospheric pressure.
head	The maximum distance a liquid can rise in a pipe. Head is used as a measure of pressure.

heat capacity — The amount of heat (Btu) required to raise the temperature of 1 pound of a substance 1 degree Fahrenheit. Heat capacity is measured in units of Btu per pound per degree Fahrenheit. Compare the definition of heat capacity with the definition of specific heat.

heat distribution — As used here, heat distribution refers to transport of heat from storage to the parts of a building where heat is required.

heat exchanger — A device for transferring heat from one fluid to another while preventing mixing of the two fluids.

heating season — The time of year (usually October to May, but varying with climate) when heating is required to maintain comfortable room temperatures.

heat of fusion — The amount of heat per unit mass that must be removed from a liquid to freeze it when the liquid is initially at its freezing temperature.

heat storage device — A device that absorbs heat and holds it until the heat is needed to warm a building or domestic hot water.

heat transfer coefficient — The amount of heat that can be transferred across a unit area of surface per unit of time per unit of temperature difference between one side of the surface and the other ($Btu/hr \cdot {}^\circ F \cdot ft^2$).

heat transfer fluid — A liquid or gas used to transport heat from one location to another. Typical heat transfer fluids include air, water, and antifreeze solution.

hybrid system — A solar energy system that combines features of active and passive systems.

hydronic system — A heating system in which water is heated by solar energy or by a boiler and distributed to heat exchangers located at various points in the building. The heat exchangers in a hydronic system are typically radiators, baseboard convectors, fancoil units, floor panels, or ceiling panels.

insolation	The amount of solar energy incident on a unit of surface area per unit of time (Btu/hr·ft^2). Notice the differences in spelling and meaning between insolation and insulation. Insolation is an acronym from incoming solar radiation.
insulation	A material used to restrict the flow of heat or electricity.
iteration	A method of solving mathematical equations that do not have closed-form solutions. Iteration involves making an initial guess at the solution and refining the guess by repeated application of the mathematical formulas until the change in the refined guess becomes negligible.
laminar flow	Fluid flow in which little mixing between fluid layers occurs. Laminar flow occurs at low Reynolds numbers. Compare with turbulent flow and transitional flow.
latent heat	The amount of heat per unit of mass required to change phase. Heat of fusion is an example of latent heat.
life-cycle cost analysis	A method of comparing the cost of a solar energy system with the cost of a conventional system by totaling the costs of each system over the lifetime of the solar system. Items usually included are first cost, mortgage interest, fuel, electricity, repairs, and other taxes.
liquid-type collector	A solar collector that uses a circulating liquid as a heat transfer fluid.
maximum operating temperature	The highest temperature at which the storage system can operate. Maximum operating temperature may be determined by the maximum temperature that the collectors can attain, the temperature limitations of materials in the system, the boiling point of water, or the pressure limitation of a sealed system.
minimum operating temperature	The lowest temperature at which useful heat can be extracted from storge.
natural convection	See convection, natural.

net positive suction head	The absolute head (pressure) available at the inlet to a pump, abbreviated NPSH. Pumps will be damaged by cavitation if the NPSH does not exceed the pump's requirement.
nonpotable fluid	A fluid which does not meet Public Health Service standards for drinking water or state or local standards for drinking water.
operating temperature range	The difference between maximum operating temperature and minimum operating temperature for a specified length of time. See daily temperature range.
Pacific Regional Handbook method	A method devised at Los Alamos Scientific Laboratory for calculating the performance of solar systems.
parasitic losses	The power required to circulate heat transfer fluids and operate controls.
passive system	A solar system that does not use pumps or fans to circulate a heat transfer fluid through solar collectors or to distribute heat to the building; the opposite of an active system.
payback period	The length of time until the fuel savings of a solar system begin to exceed the difference in cost between a solar system and a conventional system. See life-cycle cost analysis.
phase change system	A type of thermal energy storage system in which heat is stored by melting a substance and released by freezing the substance.
plenum (plural plena)	A space at the inlet or outlet of a rock bed used to distribute the air uniformly to the rocks.
positive displacement pump	A pump in which the fluid is squeezed between solid parts such as a piston and cylinder. Compare with centrifugal pump.
potable water	Water that meets federal, state, and local quality and safety standards for human consumption.
pressure gradient	A change of pressure per unit of length.

psi	Pounds per square inch; a unit of pressure. Unless otherwise specified, pressure is measured relative to atmospheric pressure. Compare with psig and psia.
psia	Pounds per square inch, absolute pressure. Absolute pressure is always measured relative to vacuum; that is, it is larger than gauge pressure by the atmospheric pressure. Compare with psi and psig.
psig	Pounds per square inch, gauge pressure. Gauge pressure is always measured relative to atmospheric pressure. Compare with psi and psia.
resistance heating	A method of heating with electricity in which electricity passing through a resistor is converted directly to heat.
retrofit	As used here, retrofit means to install a solar energy system in an existing building or in a building not originally designed for solar energy.
Reynolds number	The dimensionless number $\rho vd/\mu$ where ρ = fluid density, v = fluid velocity, and d = a characteristic distance or diameter, and μ = fluid viscosity. The Reynolds number is closely related to the ratio of inertial force to viscous force in the fluid. Laminar flow occurs at low Reynolds numbers, and turbulent flow occurs at high Reynolds numbers.
rock bed face velocity	The volumetric air flow rate divided by the gross cross-sectional area of the rock bed. The face velocity is an abstract quantity that does not equal the actual air velocity in the small passageways between the rocks.
R-value	Resistance of insulation to heat conduction given in units of $°F \cdot ft^2 \cdot hr/Btu$.
scaling coefficient	A factor ($Btu/hr \cdot °F \cdot ft^2$) that expresses the degradation of heat exchanger performance due to formation of scale on the heat exchange surfaces. The scaling coefficient is the inverse of the fouling factor.

sealed system	A solar system that excludes oxygen by closing all vents and inlets and outlets for liquids. Exclusion of oxygen in this manner limits one type of corrosion, but requires an expansion tank to limit pressure.
sensible heat	Heat that, upon flowing into a storage medium, increases the temperature of the medium. The constant of proportionality between the flow of heat and the temperature increase is the heat capacity of the medium.
sensor	A device that measures pressure or temperature and relays the information to a controller.
shell-and-tube heat exchanger	A type of heat exchanger consisting of a bundle of tubes within an outer shell and baffles to direct the fluid flow. One heat transfer liquid is pumped through the space between the tubes and the shell.
SMACNA	Sheet Metal and Air Conditioning Contractors' National Association, 8224 Old Court House Road, Vienna, Virginia 22180.
solar house	A house that derives a substantial portion of its heat from the sun.
space heating	Heating a building to maintain a comfortable indoor temperature.
specific heat	The ratio of the heat capacity of a substance to the heat capacity of water (1 Btu per pound per degree Fahrenheit). Unlike heat capacity, specific heat is a dimensionless (unitless) quantity. Compare the definition of specific heat with the definition of heat capacity.
storage medium	As used here, a storage medium is a substance that stores heat in a solar system.
storage system	The part of a solar system that includes a storage medium in a container with heat exchangers, pumps, valves, and other components necessary to transfer heat into and out of the storage medium.

tank-in-tank heat exchanger	A tank containing a heat transfer liquid submerged in a tank containing another heat transfer liquid. Natural convection occurs on both sides of the inner-tank wall.
temperature stratification	Thermal stratification.
tempering valve	A valve that limits the temperature of water flowing from a domestic hot water tank by mixing it with cold water.
TES	Thermal energy storage.
thermal stratification	Separation of hot and cool parts of the storage medium within the storage unit.
thermistor	A type of temperature sensor.
thermosyphoning	Motion of a fluid caused by buoyance of its warmer parts; natural convection.
thermosyphon system	A pumpless solar system in which buoyancy, acting on water heated by the collector, causes the water to rise into the storage tank. Thermosyphon systems are usually limited to domestic hot water systems in the tropics because the storage tank must be mounted above the collectors and there is no protection against freezing.
toxic fluid	A gas or liquid that is poisonous, irritating and/or suffocating, as classified in the Hazardous Substances Act, Code of Federal Regulation, Title 16, Part 1500.
traced tank	A type of heat exchanger in which the heat transfer fluid is carried in a tube wrapped around the storage tank; a wraparound heat exchanger.
transitional flow	Fluid flow that is on the borderline between laminar flow and turbulent flow.
turbulent flow	Fluid flow in which mixing between adjacent layers is prevalent. Turbulent flow occurs at high Reynolds numbers. See laminar flow and transitional flow.
void fraction	The ratio of air space volume in a rock bed to the total volume of the rock bed.

volumetric heat capacity	The amount of heat a unit volume of a storage medium contains per unit change of temperature, expressed as $Btu/ft^3 \cdot °F$.
wraparound heat exchanger	A tank that has fluid passages wrapped around it. The fluid passages are typically a tube soldered to the outside of the tank (a traced tank) or a metal panel with integral fluid passageways clamped around the tank.

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  Contains the minimum standards developed for the HUD solar demonstration programs. Strict adherence to these standards generally ensures a safe system, but does not necessarily ensure adequate thermal performance. A summary of the f-Chart method of sizing a system is given with English units (lb., ft., sec.) in an appendix.

- United States Department of Housing and Urban Development. *Intermediate Standards for Solar Domestic Hot Water Systems/HUD Initiative*.
  NBSIR 77-1272, July 1977. Available from NTIS, U.S. Department of Commerce, Springfield, Virginia 22161.
  Contains the standards for solar domestic hot water systems in the HUD solar initiative program. These standards are derived in many cases from experience.

- United States Energy Research and Development Administration. *Interim Performance Criteria for Solar Heating and Cooling in Commercial Buildings*, prepared by the National Bureau of Standards.
  NBSIR 76-1187, November 1976. Available from NTIS, U.S. Department of Commerce, Springfield, Virginia 22161.
  Performance criteria and standards for solar systems in the HUD solar demonstration program.