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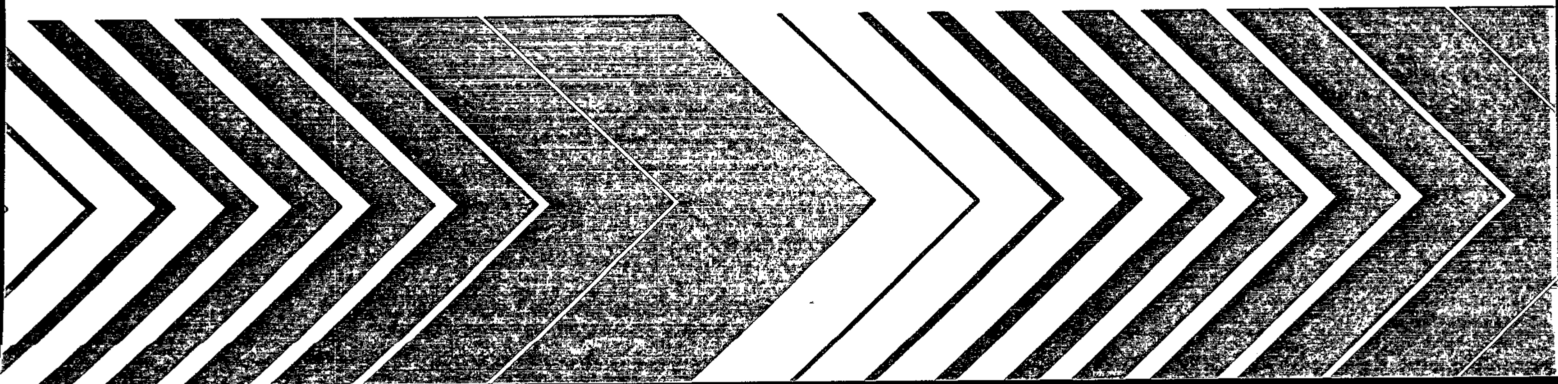
Technology Assessment of Solar Thermal Energy Applications in Wastewater Treatment



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February 1982

TECHNOLOGY ASSESSMENT OF SOLAR THERMAL ENERGY APPLICATIONS IN WASTEWATER TREATMENT

by

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Contract No. 68-03-2775

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities which use wastewater treatment alternatives that reduce costs or energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in this country. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Municipal Environmental Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and economic feasibility of utilizing solar thermal energy to reduce reliance on conventional energy sources for municipal wastewater treatment facilities.

Francis T. Mayo
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ABSTRACT

As a result of the innovative and alternative technology provisions of the Clean Water Act of 1977, the U.S. Environmental Protection Agency (EPA) has initiated a series of technology assessments dealing with the two major objectives of these provisions:

1. To incorporate more cost-effective and energy-efficient systems in publicly owned treatment works (POTW's) than current traditional practice.

2. To encourage the adoption of resource recovery and recycle practices among POTW's.

This technology assessment deals with the use of solar thermal energy as an alternate energy source for POTW's.

Energy is required for both the collection and subsequent treatment of wastewater and, as conventional forms of energy become more scarce and prices rise, energy will become an increasingly large fraction of the POTW's operating budget. This report deals specifically with solar thermal energy usage (heliothermal), and other direct or indirect solar technologies are not discussed.

This document is written for practicing environmental engineers; therefore, a minimal background in solar thermal engineering is assumed. The report discusses the development of the technology including history, theory, available equipment, and conceptual system design. Both passive and active solar thermal energy systems are presented.

Three major areas were identified for which solar thermal energy usage has potential applicability in POTW's. These areas include space and domestic water heating, anaerobic digester heating, and sludge drying. Based on energy usage as a function of facility size, a 3,785 m^3/d (1 mgd) facility could potentially save about 31 percent of its total energy usage by converting these three processes from conventional energy to solar thermal energy. Similarly, a 378,500 m^3/d (100 mgd) facility would save approximately 10 percent of its total energy requirement.

The report contains a detailed analysis of solar heating of anaerobic digesters utilizing an active solar energy (flat-plate collector) system. The analysis was conducted for nine different cities throughout the United States for both a 3,785 m^3/d (1 mgd) and a 37,850 m^3/d (10 mgd) facility. A present worth cost-effectiveness analysis was utilized whereby the present worth of the anaerobic digester gas conserved (in terms of conventional fuels) was compared to the present worth of the solar energy collection system (including both installed capital and operation and maintenance costs). A 4 percent per annum escalation factor was used to account for the increasing value of the conventional fuels saved.

Based on the analysis, solar-aided anaerobic digester heating proved uneconomical at all locations within the United States. A sensitivity analysis was performed to determine which variable had the greatest effect on the cost analysis. Variables considered included collector system price per unit area, annual operations and maintenance cost, fuel escalation cost factor, and percent solids in digester feed. The analysis indicated that the collector system cost was the most sensitive item, and that system costs would have to be reduced to between \$162 and \$323/m^2 (\$15 to \$30/ft^2) in order to make the systems economically viable. Currently, the system costs are in the range of \$538/m^2 (\$50/ft^2).

This report was submitted in fulfillment of Contract No. 68-03-2775 by Roy F. Weston, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period May 1980 to December 1980, and the work was completed as of December 1980.

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TECHNOLOGY DESCRIPTION

INTRODUCTION

The Clean Water Act of 1977 (PL 95-217) requires the inclusion of innovative and alternative treatment techniques during the planning and evaluation of wastewater management alternatives. Section 201(g)(5) of the Act makes that requirement mandatory for planning studies initiated after September 30, 1978. The objectives of this program are twofold (1, 2):

1. To incorporate more cost-effective and energy-efficient systems in publicly owned treatment works (POTW's) than the current traditional practice.
2. To encourage the adoption of resource recovery and recycle practices among POTW's.

As a result of this encouragement through the EPA-administered construction grants program, numerous projects have been funded which use innovative processes and techniques for municipal wastewater treatment. In order to assess the status of development and the capabilities of these new technologies, EPA has initiated a series of emerging technology assessments for evaluating these processes. This technology assessment report is prepared to evaluate the use of solar thermal energy as a potential energy source for POTW's.

TECHNOLOGY DESCRIPTION

Energy is required for both the collection and subsequent treatment of wastewater. As most forms of energy are becoming increasingly scarce, market economics dictate that the prices will rise accordingly. This sharp rise in power costs has made energy an increasingly large part of the operation and maintenance budgets of POTW's. In fact, during the period 1967 to 1978, equipment costs increased 200 percent, labor costs 205 percent, electricity costs 260 percent and fuel oil 295 percent (3). The majority of the electrical and fuel oil cost escalations have occurred since the 1973 oil embargo. Aside from the economic commitment, the wastewater treatment industry has a moral commitment to energy efficiency in order to conserve present resources for future generations.

NATIONAL ENERGY USAGE AND POTW ENERGY USAGE

In terms of the national energy outlook, Figure 1 presents the 1980 energy demand and energy supply for the United States. In 1980, 32 percent of the total energy was used by industry, 26 percent by transportation, 34 percent by residential/commercial uses, and 8 percent by nonenergy uses (primarily chemical feedstocks). For energy supply, fossil fuels contributed over 90 percent of the energy (oil, 46 percent; gas, 26 percent; and coal, 19 percent). Nuclear energy supplied 5 percent and hydro, geothermal, and solar accounted for 4 percent (4). The current contribution of solar energy is due primarily to biomass (wood combustion) and hydropower, and a very small contribution due to active and passive solar energy (5).

Based on an analysis of data presented by Owen (6), the energy requirement for municipal wastewater and sludge treatment for 1980 was estimated to be 0.266 EJ (0.252×10^{15} Btu).[1] This compares to the 1980 U.S. energy usage of 82.7 EJ (78.4×10^{15} Btu). Therefore, in 1980, POTW's accounted for 0.32 percent of the total energy consumed. By way of comparison, industrial wastewater treatment in 1978 consumed 0.37 EJ (0.35×10^{15} Btu) (7), which is 0.45 percent of the total 1980 energy consumption. Therefore, the treatment of wastewater accounted for approximately 0.77 percent of the national energy consumption or 0.636 EJ (0.60×10^{15} Btu) in 1980.

Although wastewater treatment consumed less than 1 percent of the total estimated energy consumption in 1980, both conservation and alternate energy sources can save substantial quantities of conventional fuels. For example, if through conservation and alternate fuels a 10-percent conventional energy reduction of POTW's could be achieved, then approximately 545,000 cubic meters (144 million gallons) of oil equivalent per year could be saved. Assuming a \$330.25 per cubic meter (\$1.25/gallon) cost, this oil is worth \$180 million.

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[1] Note:

$kJ = 10^3 J$

$EJ = 10^{18} J$

$J = 9.46 \times 10^{-4}$ Btu

1 Barrel Oil $= 5.86 \times 10^6$ kJ

$= 5.55 \times 10^6$ Btu

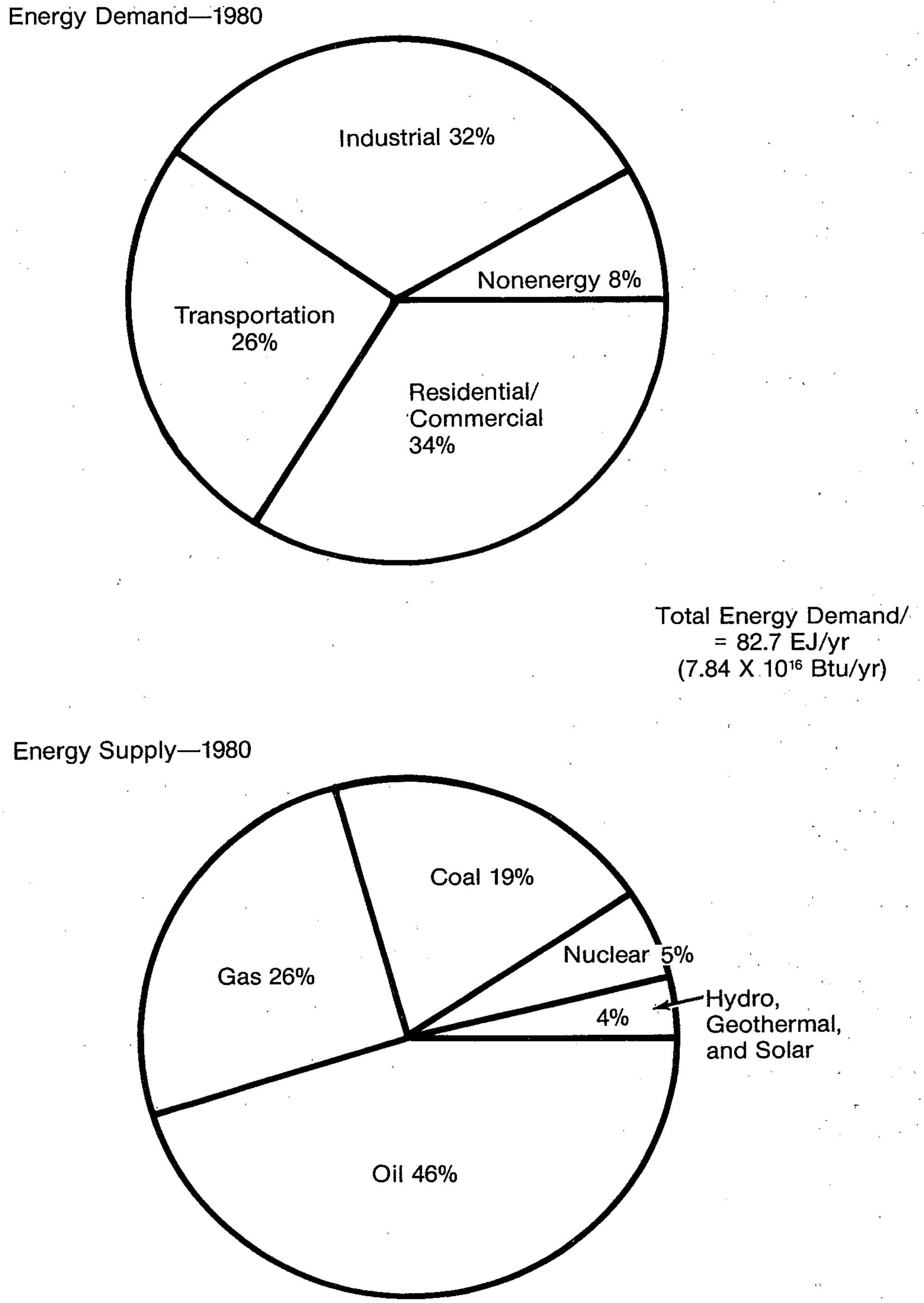


Figure 1. United States energy supply and demand by source, 1980 (4).

Solar energy arrives at the surface of the United States at an average rate of 17,000 kJ/m^2/day (1,500 Btu/ft^2/ day) (8). The estimated requirement for municipal wastewater treatment and sludge disposal in the year 2000 is 0.442 EJ/yr (0.42 x 10^{15} Btu/yr) (6). To meet this requirement, assuming a 40-percent conversion efficiency, 17,800 hectares (ha) (44,000 acres) of solar collectors would be required. Therefore, a great potential source of energy is available; however, solar energy utilization requires a concentrating of this energy prior to usage.

There have been numerous publications which deal with energy conservation, energy recovery, and alternate energy sources in wastewater treatment (3,9,10,11,12,13,14,15,16,17,18). Alternate energy sources include wind, geothermal, low-head hydro, effluent heat recovery, internal combustion engine heat recovery, and solar energy.

This report deals specifically with the use of solar energy applications in wastewater treatment. Furthermore, it considers only direct uses of solar energy, primarily thermal energy usage (heliothermal) with a brief presentation of photovoltaic (helioelectrical) usages. Other solar energy processes such as biomass production, ocean thermal power, or wind power will not be discussed. The use or conversion of fossil fuels is not considered.

POTW ENERGY REQUIREMENTS

In order to acquaint the reader with the energy requirements for a "typical" POTW, the data in Table 1 are presented. The "typical" POTW consists of preliminary treatment, influent pumping, primary sedimentation, activated sludge secondary treatment, and chlorination. The sludge stream is treated by gravity thickening, anaerobic digestion, vacuum filtration, and incineration. In addition, the energy associated with sludge pumping, lighting and miscellaneous power, and building heating is included. The data in the table indicate that, in terms of electrical equivalent, the 3,785, 37,850, and 378,500 m^3/d (1, 10, and 100 mgd) facilities utilize approximately 1,230, 830, and 726 kWh of primary energy per 3,785 m^3 (million gallons) of treated wastewater (16,17). The activated sludge aeration system is by far the largest user (36 to 60 percent), followed by influent pumping (12 to 18 percent).

TABLE 1. ESTIMATED ENERGY CONSUMPTION FOR OPERATION OF A POTW

	Energy consumption kWh/3,785 m^3		
Process	3,785 m^3/d facility	37,850 m^3/d facility	378,500 m^3/d facility
Preliminary Treatment	18.5 (1.5%)	6.6 (0.8%)	2.5 (0.3%)
Influent Pumping	153.0 (12.4%)	145.1 (17.5%)	129.3 (17.8%)
Primary Sedimentation	30.6 (2.5%)	12.2 (1.5%)	7.3 (1.0%)
Activated Sludge with Mechanical Aeration	449.0 (36.4%)	446.3 (53.8%)	435.3 (59.9%)
Secondary Sedimentation	30.6 (2.5%)	12.2 (1.5%)	7.3 (1.0%)
Chlorination	0.7 (0.06%)	0.7 (0.08%)	0.7 (0.1%)
Sludge Pumping	2.7 (0.2%)	2.7 (0.3%)	2.7 (0.4%)
Gravity Thickening	10.2 (0.8%)	2.0 (0.2%)	0.4 (0.06%)
Anaerobic Digestion	123.6 (10.0%)	45.6 (5.5%)	19.1 (2.6%)
Vacuum Filtration	58.5 (4.7%)	34.6 (4.2%)	36.4 (5.0%)
Incineration	65.0 (5.3%)	28.7 (3.5%)	25.9 (3.6%)
Lights and Miscellaneous Power	57.0 (4.6%)	21.0 (2.5%)	24.0 (3.3%)
Building Heating	233.0 (18.9%)	72.2 (8.7%)	35.3 (4.9%)
TOTAL	1,232.4	829.9	726.2

Data compiled from (16) and (17).

In order to determine where solar energy can be effectively used, it is necessary to identify those processes which utilize the majority of the energy associated with municipal wastewater treatment. Based on data presented by Owen (6), the 10 most energy intensive wastewater treatment processes account for over 90 percent of the total annual energy required by POTW's. These processes and their energy requirements are shown in Figure 2. Stabilization processes (activated sludge, incineration, aerated ponds, and aerobic and anaerobic digestion) account for about 70 percent of the total energy usage, whereas sludge conditioning and dewatering account for approximately 10 percent of the total demand.

The most common process for recovering energy from waste biological sludge is anaerobic digestion. Assuming a 50-percent reduction in volatile solids during digestion, 648 kg VSS/3,785 m^3 (1,425 lb VSS/mgd) of wastewater, and 0.94 m^3 digester gas/kg (15 ft^3/lb) of volatile solids destroyed, then approximately 300 m^3 (10,700 ft^3) of digester gas is available per 3,785 m^3 (million gallons) (16). The gas has a heating value of 22,350 kJ/m^3 (600 Btu/ft^3). For a 3,785 m^3/d (1 mgd) treatment facility, this gas when used as fuel in an internal combustion engine (allowing for efficiency) can continuously produce 25 kWh (33 hp-hr) (16). This represents about 46 to 79 percent of the total plant energy requirements as shown in Table 1. Therefore, by utilizing an alternate energy source to heat the digester, the majority of the digester gas generated can be used to operate the treatment facilities. Potential alternate energy sources include waste heat generated by internal combustion engines, waste heat contained in digester effluent, and solar energy. This technology assessment will focus on the utilization of solar thermal energy to supplement or replace conventional energy sources.

SOLAR ENERGY FUNDAMENTALS

Solar energy reaches the earth's surface in two ways - by direct radiation and by diffuse radiation. Diffuse radiation, as opposed to direct radiation, consists of nonparallel radiation which is reflected from clouds and atmospheric dust. In addition, reflected radiation from the ground or building surfaces is also present. The total radiation, therefore, consists of three types (direct, diffuse, and reflected), and the percent of each type varies widely. In hot, dry climates, clear skies enable a large portion of the direct radiation to reach the earth's surface. In temperate and humid climates, up to 40 percent of the incident radiation may be diffuse. In northern climates, the low winter sun results in decreased incident radiation; however, this still may be greater than the radiation received in a warmer but cloudier climate.

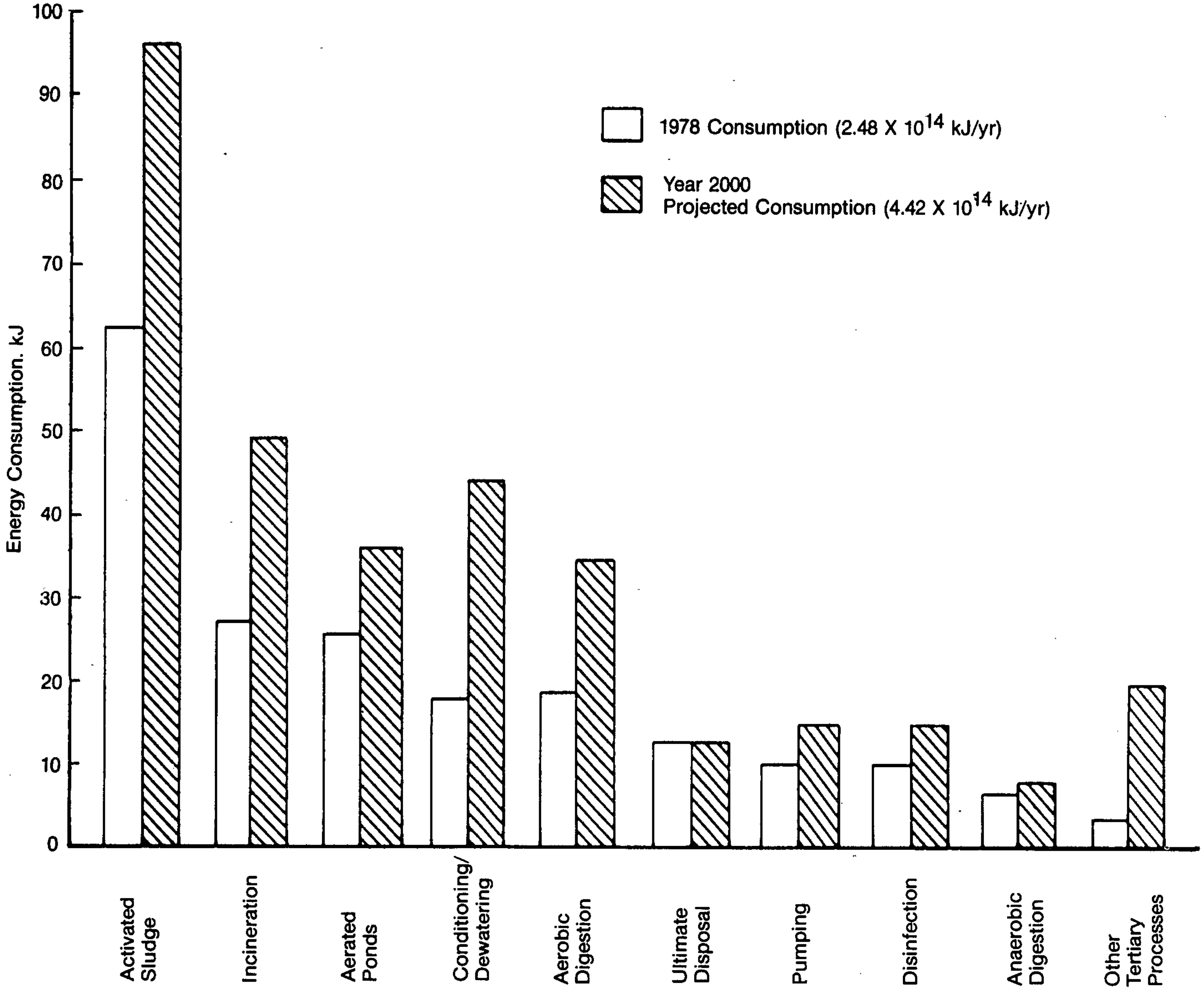


Figure 2. The ten most energy intensive wastewater treatment processes in the United States, 1978 and 2000 (projected) (6).

As a result of differences in type and amount of radiation reaching a surface, climate, time of year, and type of end use, the need for and design of a solar energy system will vary in each locale. Recognition of these various differences is necessary to ensure proper design of a solar energy system.

Regardless of end use, a solar energy system consists of three components: solar energy collection, storage, and distribution. The solar collector converts incident solar radiation (insolation) to usable thermal or electrical energy by absorption on a suitable surface. The storage component of the solar system is utilized as a reservoir which stores energy so that energy can be supplied during evening hours and cloudy days. The distribution component distributes energy from the collector or storage component to the point of consumption.

Three additional components may include transport, auxiliary energy input, and controls. The transport component provides a positive means of moving a fluid containing thermal energy to and from the collector and storage. Passive and active solar energy systems differ in terms of the transport component. In a passive system, a transport component is not required and energy is transported from the collector to the storage component primarily by conduction or naturally induced convection. In the active system, a fluid (liquid or gas) transports heat by convective transport. An auxiliary energy source provides for a supply of energy when insufficient energy is available from either the collector or the storage components. Lastly, the control components perform the sensing, evaluation, and response functions required to operate the system in the desired mode. This system is depicted in Figure 3.

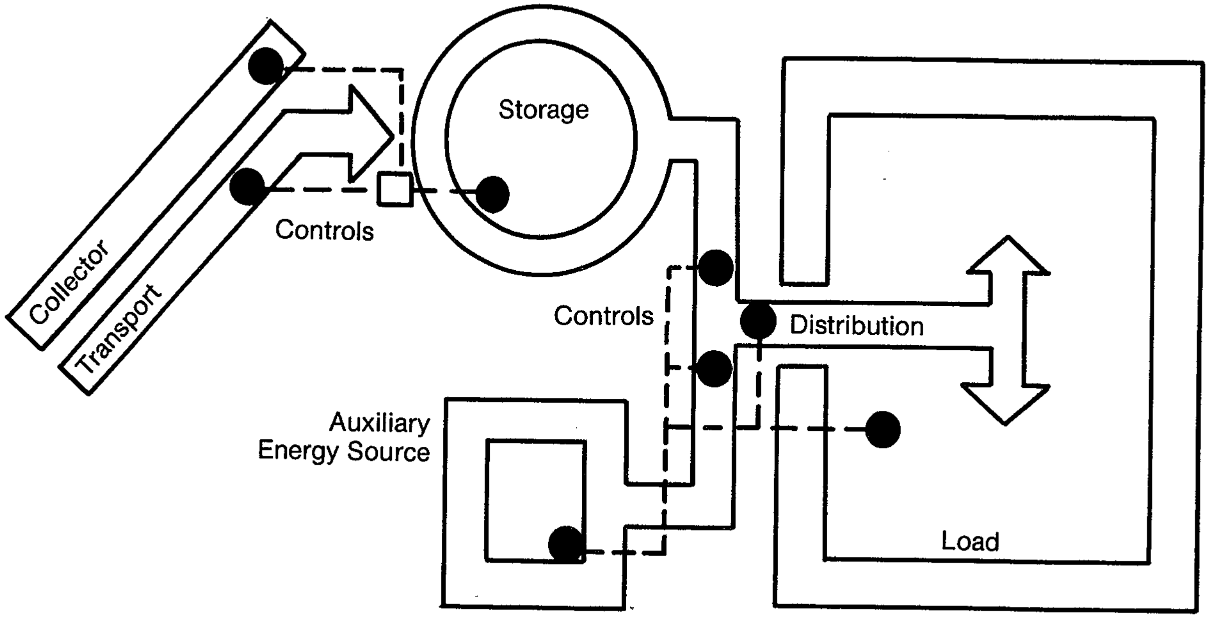


Figure 3. Generalized solar energy system.

SECTION 2

TECHNOLOGY DEVELOPMENT

DEVELOPMENT HISTORY

The sun has been used by man as a source of energy for thousands of years. References exist as to its use for igniting temple fires as far back as 212 B.C. This review is based on information presented in Reference 19. By 1600 A.D., science had begun to consider other uses of solar energy, as Salomon de Caux put the sun to work heating air in a solar engine which he used to pump water. In the late 18th century, the French scientist Antoine Lavoisier began using the sun for research purposes, creating temperatures of 1,650 degrees C (3,000 degrees F) in a solar furnace and, thereby, discovered the nature of carbon and platinum.

In 1866, August Mouchot of France, backed by Napolean III, built several sun-following solar concentrators in Algeria, and used them to drive pumps and distill water. The French government, however, decided that Mouchot's machines could not be made with an economy "sufficient to the demands of commerce." In the United States, John Ericson had invented eight different models of solar engines by 1875. However, none were practical. In 1883, Ericson made a rectangular parabolic collector measuring 3.4 m x 4.9 m (11 ft x 16 ft) which drove a 152 mm (6 in.) bore piston through a 203 mm (8 in.) stroke. Ericson claimed the machine delivered 0.746 kwh/9.3 m^2 (1 hp/100 ft^2) of collector.

In France in the early 1880's, the first flat-plate collector was built by Charles Albert Tellier, and this 20 m^2 (215 ft^2) collector drove an engine utilizing ammonia as a working medium rather than steam, air, or water. In 1885, Scientific American proposed a flat-plate collector which would also serve as a factory roof.

The sun has not been used only to run engines, however; food has been dried for centuries by the sun. The first solar cooker dates back approximately 150 years. In 1878, Mouchot demonstrated a solar cooker with glass lids which was able to cook a half kilogram of beef in twenty minutes. At a copper mine in

Las Salines, Chile in 1871, Charles Wilson, an American engineer, built a solar still to convert locally available salt water to potable water. The still was nearly 0.4 ha (1 acre) in area, produced over 15 m^3 (4,000 gallons) of water per day, and, as in present day stills, consisted of a shallow basin painted with a waterproof black compound and covered with a glass roof. Water, after vaporizing, would condense on the relatively cool glass and trickle down the glass to a collection point.

At the turn of the 20th century, pumping water was the major objective of solar power in the United States. The most spectacular of these devices was built by an English inventor, A.G. Eneos, whose parabolic concentrator was 10.2 m (33.5 ft) in diameter at the top and 4.6 m (15 ft) at the bottom. The device utilized 1,788 mirrors to concentrate the sun's rays on a boiler located at the focal point. The boiler produced steam at pressures up to 1,034 kN/m^2 (150 psi) and the pump was capable of pumping at rates of up to 0.091 m^3/s (1,450 gpm).

In 1907, an engineer named Frank Shuman proposed a huge solar steam plant covering 1.6 ha (4 acres) and having an estimated output of 75 kw (100 hp). A plant built in Pennsylvania never achieved nearly this output as smoke and clouds hampered operation. However, a similar power plant in Cairo, Egypt, which was put into service in 1912, produced 37 kw (50 hp).

In terms of photovoltaic devices, Antoine Becquerel in 1839 found that sunlight produced a weak current in the electrodes of an electrolyte system. Forty years later, Adam and Day observed a similar effect in a solid, selenium. In 1931, Dr. Bruno Land demonstrated the first photovoltaic solar power at Kaiser Wilhelm Institute, consisting of a "sandwich" of copper oxide, silver selenide, and a "secret ingredient."

Solar water heaters were another area for early inventors, and were developed mainly for hot baths. During World War I, many installations were developed for Army bases. Most of these units used natural circulation (or "thermo-siphon"). Currently, thousands of this type of water heater are in use in Australia, Israel, and Japan. Typically these units have an auxiliary immersion heater.

Aside from both a knowledge and technology gap hindering early development, the major drawback against solar energy was the fact that conventional forms of energy were both inexpensive and abundant. The costs to develop and implement solar technology could not compete with other energy forms. With the cost of conventional fuels increasing, interest in solar energy has once again risen.

DEVELOPMENT STATUS

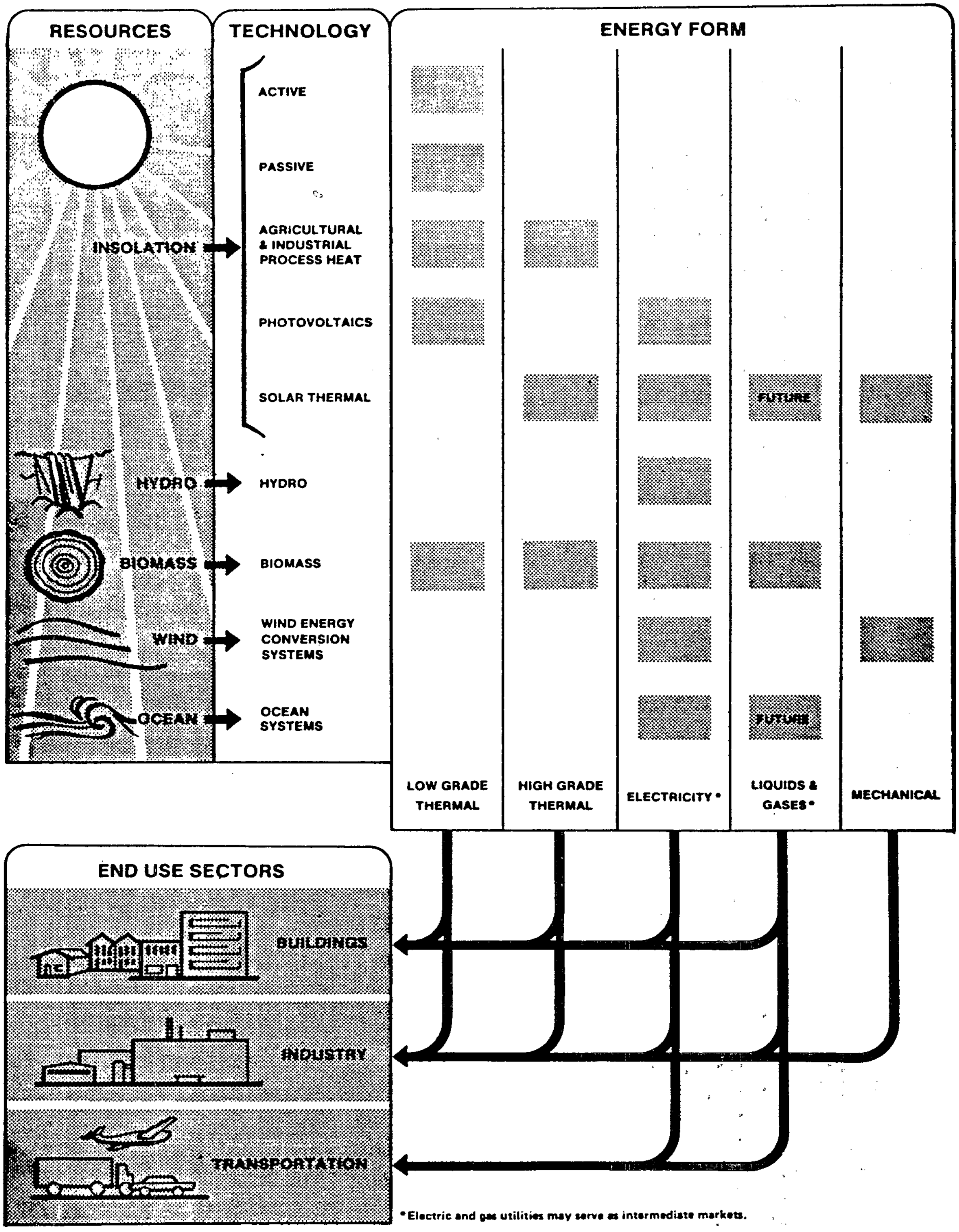
Solar Technology

After the passage of Public Law 93-409, "The Solar Heating and Cooling Act of 1974," and of legislation that established the Energy Research and Development Administration (now the Department of Energy), the national program for the commercialization of solar energy began. In his 20 June 1979 National Solar Message, President Jimmy Carter established a national goal for solar energy of meeting 20 percent of the year 2000 energy requirements with solar and renewable resources.

The current national solar strategy must consider the complexity of the energy markets, the diversity of solar resources, regional needs and environmental factors, plus the rapidly escalating prices of conventional energy. The range of energy needs is broad and includes high-temperature process heat, low-temperature space heat, mechanical power, electricity, fuels for transportation, and chemical feedstocks. Technology is currently available or under development to utilize solar resources by end-use markets. Additional technologies are also available or under development to convert either direct or indirect solar energy into energy forms to meet consumer needs. Solar resources include direct sunlight, as well as indirect resources such as biomass, hydro, wind, and ocean energy. Figure 4 illustrates how the various solar resources and technologies can be linked to end-use energy demands. This technology assessment is limited to considerations involving direct solar radiation conversion. The five technologies for converting and using solar insolation include the following (5):

1. Active Solar Heating and Cooling - Active solar heating and cooling systems employ primarily flat-plate collector technology. Modular or site-built collection systems convert insolation into thermal energy by absorbing radiation. Mechanical subsystems then transfer heat using air or liquids, where it goes directly to heat space or water, or is stored for later use.

2. Passive and Hybrid Solar Heating and Cooling - Passive and hybrid solar buildings employ designs that maximize the benefits of natural energy flows and minimize dependence on conventional energy sources. Passive systems utilize elements of the building to collect, store and distribute energy. When other solar technologies are used in conjunction with passive solar, the result is considered a hybrid application.



*Electric and gas utilities may serve as intermediate markets.

Figure 4. Solar resources, conversion technologies, and end uses (5).

3. Agricultural and Industrial Process Heat - A range of solar collection systems is used to produce hot air, hot water and steam within three temperature ranges: low, less than 100 degrees C (212 degrees F); intermediate, 100 to 177 degrees C (212 to 350 degrees F); and high, greater than 177 degrees C (350 degrees F). Depending on system design and operation, heat is utilized either directly or through the application of heat exchangers. The actual energy use and the range of required temperatures are diverse and require specific process designs.

4. Photovoltaic Energy Systems - Sunlight is converted to electricity by solar cells, which are made from various semi-conductor materials. Research is under way to create improved, high efficiency, lower cost devices.

5. Solar Thermal Power Systems - In these systems, the sun's heat is concentrated and used to heat water or some other fluid to provide industrial process heat or to drive a turbogenerator. Total energy systems applications which supply both heat and electricity are included.

During fiscal year 1980, DOE appropriations in these five areas amounted to approximately $417 million (5).

Solar Applications in POTW's

Based on data from Reference 14 on energy use in POTW's by source (activated sludge secondary treatment with sludge treatment and disposal), the following table is presented showing forms of energy used in wastewater treatment facilities.

Form of Energy Used - Percent of Total

Facility Size	Electrical	Fuel Oil or Gas
3,785 m^3/d (1 mgd)	86%	14%
37,850 m^3/d (10 mgd)	66%	34%
378,500 m^3/d (100 mgd)	63%	37%

Considering the data presented in Section 1 on energy consumption by POTW's, the majority of the electrical energy is consumed by electrical motors on pumps, blowers, drives, etc. Therefore, the greatest potential for solar energy utilization at a POTW would be for photovoltaic conversion to electrical energy. Alternatively, solar energy could be utilized to produce steam to run steam-driven engines.

For smaller plants, heating accounts for a substantial portion of the total energy requirements: 19 percent for the 3,785 m^3/d (1 mgd) facility versus 5 percent for 378,500 m^3/d (100 mgd) facility. Additionally, heating and cooling loads can be substantial for facilities in extreme northern or southern locales. Therefore, there is a potential for active and passive solar heating/cooling at a POTW. The seasonal nature of both heating and cooling, however, decreases the cost-effectiveness of these systems because they are not used year-round. Solar heated hot water with a year-round demand has a greater potential for being cost-effective.

One often overlooked area for solar energy utilization is natural lighting. Natural lighting is an attractive alternative as it is a one-time capital cost expenditure with minimal O&M requirements. Although natural lighting will not be considered further, its utilization in POTW's is recommended.

Additional potential uses of solar energy are for heating aeration basin mixed liquor to improve either carbonaceous or nitrogenous BOD removal kinetics and to eliminate winter freezing problems. For a 3,785 m^3/d (1 mgd) facility, 12,210 kWh (41.7 million Btu) would be required to raise the water temperature 2.8 degrees C (5 degrees F) (neglecting recycle and sidestream inputs). This is approximately ten times the total energy required for treatment and, therefore, is uneconomical. However, the use of a passive device, such as a solar pool heater, to cover the basin (primary or secondary clarifier, aeration basin, trickling filter, etc.) to reduce convective heat transport and increase solar heat gain has greater potential.

Because anaerobic digestion is the most popular method of recovering energy from wastewater treatment facilities, and anaerobic digestion requires a heat source to maintain mesophilic (or possibly thermophilic) conditions within the digester, the possibility of substituting solar-derived heat for combustion of digester gas exists. The advantage of a solar heated digester is that the gas which is conserved (not combusted) can be used to either run motors directly, or to run a generator and operate the process equipment with the generated electricity. The second option is advantageous as only one piece of equipment (the generator) need burn the "dirty" fuel, and the electricity can be directed to the motors utilizing the existing electrical cables. The disadvantage, however, is that the gas must be converted to electricity at a relatively low efficiency, further reducing the energy available at the point of usage.

A final potential use for solar energy is in a sludge drying operation, in which the heat energy could be used with either an active or passive system to evaporate water and dry the sludge either prior to sale as a fertilizer amendment or prior to incineration with energy recovery. Currently, two processes for solar-aided sludge drying are described in the literature. In the first process (20), active flat-plate collectors heat air which is blown into a dryer similar to that used for soybean drying. This system has been proposed for a 11,355 m^3/d (3 mgd) facility in Denver Colorado.

The second concept proposes passive sludge drying on a 20- to 30-degree inclined plane beneath a glazing, thereby creating a greenhouse effect plus a convective air flow (21). A traveling rake on the inclined plane moves the material to expose wet portions and also moves the drying sludge down the incline. Screw conveyors both spread and collect the sludge from the dryer. Evaporative cooling should maintain the sludge temperature below 38 degrees C (100 degrees F) to minimize odors. During February 1979, a 7.6 m (25 ft) long prototype model was tested, and the evaporation rate averaged 0.70 kg/m^2-hr (0.14 lb/ft^2-hr) at an incident radiation of 910 kJ/m^2 (80 Btu/ft^2-hr).

It should be noted that one form of solar-aided sludge drying has been practiced for many years by enclosing sand drying beds with glass to increase sludge drying rates.

The first detailed analysis of utilizing solar energy to heat an anaerobic digester was performed during late 1975 and early 1976 to assess the feasibility of utilizing an active solar system (flat-plate collector) to preheat primary sludge to one of two anaerobic digesters at the 17,000 m^3/d (4.5 mgd) Annapolis, Maryland Wastewater Treatment Plant (18). The authors concluded that the system was feasible and economically justifiable. Furthermore, it was concluded that, where physically possible, all existing anaerobic digesters should be converted to solar heating and all new treatment facilities should utilize solar-heated digesters.

Only one solar-heated anaerobic digester is currently (1980) known to be in operation at a POTW in the United States (Wilton, Maine). However, an anaerobic digester treating dairy manure has been tested utilizing both a passive solar energy "bread box" (tank(s) of water painted flat-black, covered by glass and enclosed in an insulated box which is oriented south) and a solar pond collector (22). Numerous references to the potential use and the feasibility of solar energy in anaerobic digesters are available (6,10,11,14,16,23,24).

The Wilton, Maine facility, which has been operational since September 1978, includes both active and passive solar energy utilization, plus other energy recovery systems including effluent heat recovery, digester gas utilization, electricity generation, and air-to-air heat recovery (25). The 1,700 m^3/d (450,000 gpd) Wilton facility consists of preliminary treatment, primary screening, rotating biological contactors (RBC's), secondary clarification, chlorination, and either surface discharge or land application (spray irrigation). Sludge treatment consists of mesophilic anaerobic digestion followed by sludge dewatering.

The Wilton system is designed as an integrated energy source and utilization system (25). The sources of heat can work either individually or in combination with the basic heat utilization systems. The overall philosophy is that the plant will use solar energy as the primary energy source, digester gas as the secondary energy source, and effluent heat recovery as a back-up and supplementary energy source. A conceptual diagram of the energy systems is presented in Figure 5.

The active solar collectors consist of 139 m^2 (1,500 ft^2) of flat-plate collectors with an ethylene glycol/water collector loop, a heat exchanger, and a storage loop. The collector array consists of 54 double-glazed panels with an effective collection area of 119 m^2 (1,286 ft^2) facing two degrees west of south at an angle of 60 degrees from the horizontal. The active collectors were designed to collect between 232 and 274 GJ/yr (220 to 260 million Btu/yr), and this energy is exchanged to the plant's circulating water system. The active collectors supply heat for domestic hot water, digester heating, and building heating.

The passive solar system utilizes fiberglass panels which allow solar heat and light radiation into the clarifier room. The passive solar array consists of 83 m^2 (896 ft^2) of panels (75 m^2 (812 ft^2) of effective collection area) facing two degrees west of south at an angle of 60 degrees from the horizontal. A building over-hang provides partial shading in the summer and full exposure in the winter, thereby aiding summer cooling and winter heating. The panels are constructed of four layers of fiberglass, with a transmissivity listed as 66 percent by the manufacturer (25). The passive collectors were sized to collect between 106 and 137 GJ/yr (100 to 130 million Btu/yr).

Based on information provided by Fuller, et al.(25) for the period June 1979 through March 1980, the following preliminary conclusions were reported:

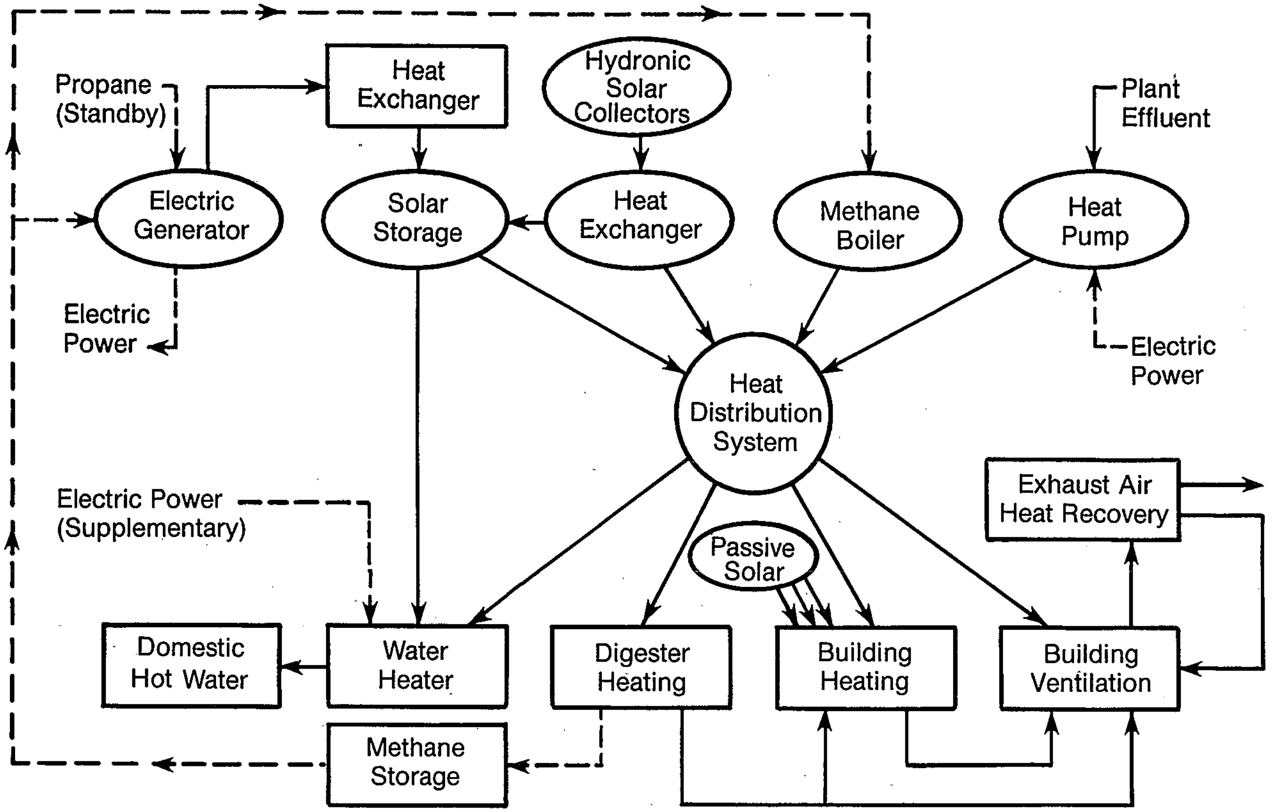


Figure 5. Wilton, Maine energy systems conceptual design.

1. An overall theoretical collector efficiency of 49 percent for the active solar array was calculated. Despite insolation values 13 percent in excess of design, measured efficiency was 23 percent (47 percent of design). The major cause of the discrepancy appeared to be the response of the collectors to actual weather conditions (i.e., the collectors did not efficiently collect the radiation from a short-time duration event) and the lack of a calculation procedure to accurately simulate this interaction. The authors believe that the characteristics of observed performance place the cost-effectiveness of solar-aided anaerobic digestion in question. Based on actual performance, the simple payback period for the active system was 54 years.

2. The passive solar system transmissivity ranged from 35 percent in July to 57 percent in January. Part of the reduction from the 66 percent estimated transmissivity is due to the overhang, whereas the remaining reduction is due to dust and sun-panel angle resulting in surface reflection. The simple payback period for the passive solar system was calculated to be 30 years, based on actual system performance.

At the time of this writing, the design and/or construction of five additional facilities utilizing solar comfort and process heating have been funded under the provisions of the Innovative and Alternative Technology Program as summarized in Table 2.

TABLE 2. PROPOSED SOLAR THERMAL ENERGY APPLICATIONS IN POTW's (14)

Facility	Capacity	Solar Energy Application
Hillsborough, NH	1,800 m^3/d (0.475 mgd)	Space Heating, Passive and Active Anaerobic Digester Heating, Active
Gardiner, ME	6,060 m^3/d (1.6 mgd)	Domestic Hot Water
Jackson, WY	13,250 m^3/d (3.5 mgd)	Space Heating
Pine River, MN	946 m^3/d (0.25 mgd)	Space Heating, Passive and Active
Pella, IA	8,630 m^3/d (2.28 mgd)	Anaerobic Digester Heating, Active

AVAILABLE EQUIPMENT AND HARDWARE

A solar energy system is composed of numerous individual parts such as collectors, storage, distribution network, controls, heat exchangers, etc. The parts are assembled in a variety of combinations depending on function, component compatibility, climatic conditions, required performance, site characteristics, and architectural requirements. Various types of hardware will be discussed in this subsection.

Flat-Plate Collectors

The flat-plate collector is the most common active solar collection device for space and hot-water heating in use today (27). The collector converts the sun's radiation into heat on a simple surface within an enclosure. The collector is designed to utilize either gas (generally air) or liquid (water, water with anti-freeze). Regardless of the thermal transfer medium used, most flat-plate collectors consist of the same components. The purpose of these components is as follows: the cover plate (glazing) is a transparent sheet of glass or plastic, mounted above the absorber plate. The sun's rays penetrate the glass and are transformed to heat energy on the absorber plate. The glazing serves to minimize both convective and radiant heat losses. The absorber plate has an absorptive coating which improves its ability to absorb and not reflect energy. The absorber plate also has heat transfer fluid passages which consist of tubes or fins attached above, below, or integral with the absorber plate for the purpose of transferring thermal energy to storage, or end use. The greatest variation in flat-plate collector design occurs within the heat transfer fluid passage unit and its combination with the absorber plate. Tube on plate, integral tube and sheet, open channel flow, corrugated sheets, deformed sheets, extruded sheet, and finned tubes are some of the types of techniques used for liquid collectors. Air collectors utilize configurations such as gauze or screens, overlapping plates, corrugated sheets, and finned plates and tubes (27).

Since the absorber plate must have a good thermal bond with the fluid passages, an absorber integral with the heat transfer medium is most common and optimum. Insulation is employed to reduce heat loss through the rear of the collector. The insulation must be suitable for the high temperatures that may occur. The final component is the collector housing which contains all of the components and makes the assembly waterproof. Rubber seals or gaskets are used to fasten the cover glazing to the housing. Various materials used for flat-plate collectors are presented in Table 3 (28). The components of typical flat-plate collectors are illustrated in Figure 6.

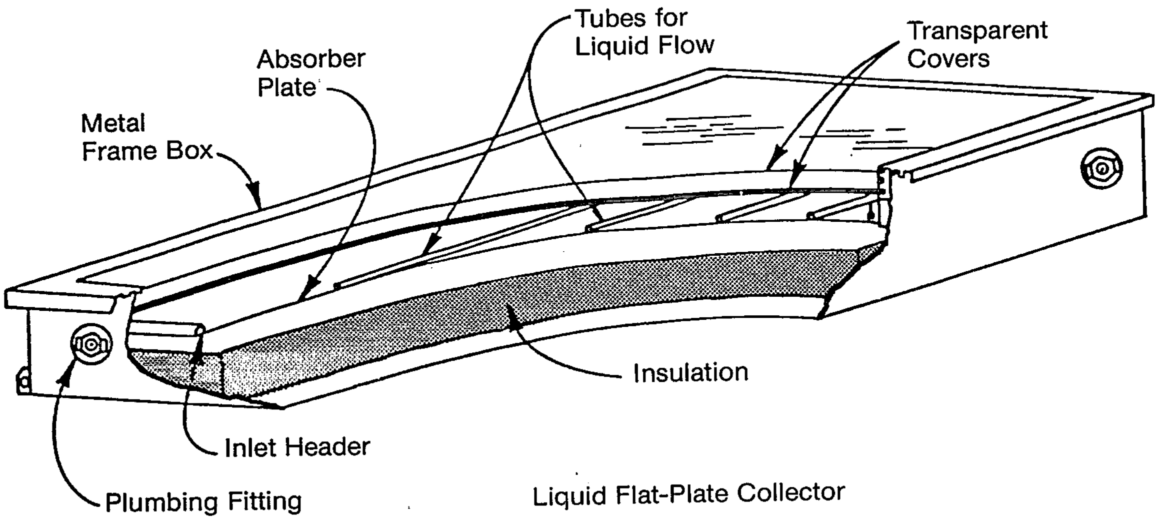
TABLE 3. MATERIALS OF CONSTRUCTION USED FOR TYPICAL FLAT-PLATE COLLECTORS

Collector Component	Materials Used
Cover Plate or Glazing	Glass, fiberglass laminates, thermoplastic sheeting, and film
Absorber Plate Coating	Selective metal oxides, nonselective black paints
Absorber Plate	Copper, aluminum, stainless or carbon steel
Fluid Passages	Aluminum or copper tubes, integral spaces in absorber plate
Insulation	Fiberglass, glass foam, foamed thermoplastics
Housing	Metal, honeycombed concrete, fiberglass laminates, extruded thermoplastics
Gasketing	Silicone, EPDM, butyl, PVC elastomers
Heat-Transfer Medium	Air, water, silicone fluid, hydrocarbon oils, water/glycol mixtures

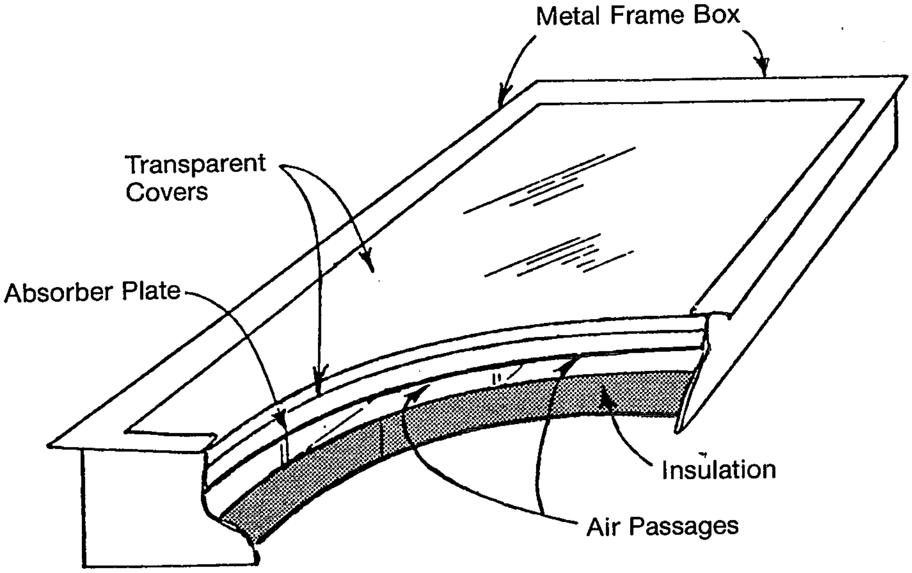
Adapted from Reference 28.

Flat-plate collectors are classified according to the type of heat transfer medium they use. Liquid-type collectors use a liquid such as water, water with glycol silicone fluid, or other liquids, whereas air-type collectors use air as the heat-transfer medium. Liquid-type collectors can be used for both space and water heating, whereas air-type collectors are used primarily for space heating (28).

The operation of a liquid-type flat-plate collector system is relatively simple. Solar radiation passes through the glazing and strikes the absorber plate coating. The absorber plate and coating then convert the radiation to usable heat. The heat is then absorbed by the heat-transfer medium in the plate's fluid passages. A pump in the collector loop circulates the heated fluid to a heat exchanger. The heat exchanger is part of a seconday loop which transfers the heat energy from the fluid and transports the energy to storage or directly to the end use. The system is shown in Figure 7.



Liquid Flat-Plate Collector



Air Flat-Plate Collector

Figure 6. Typical flat-plate collector components.

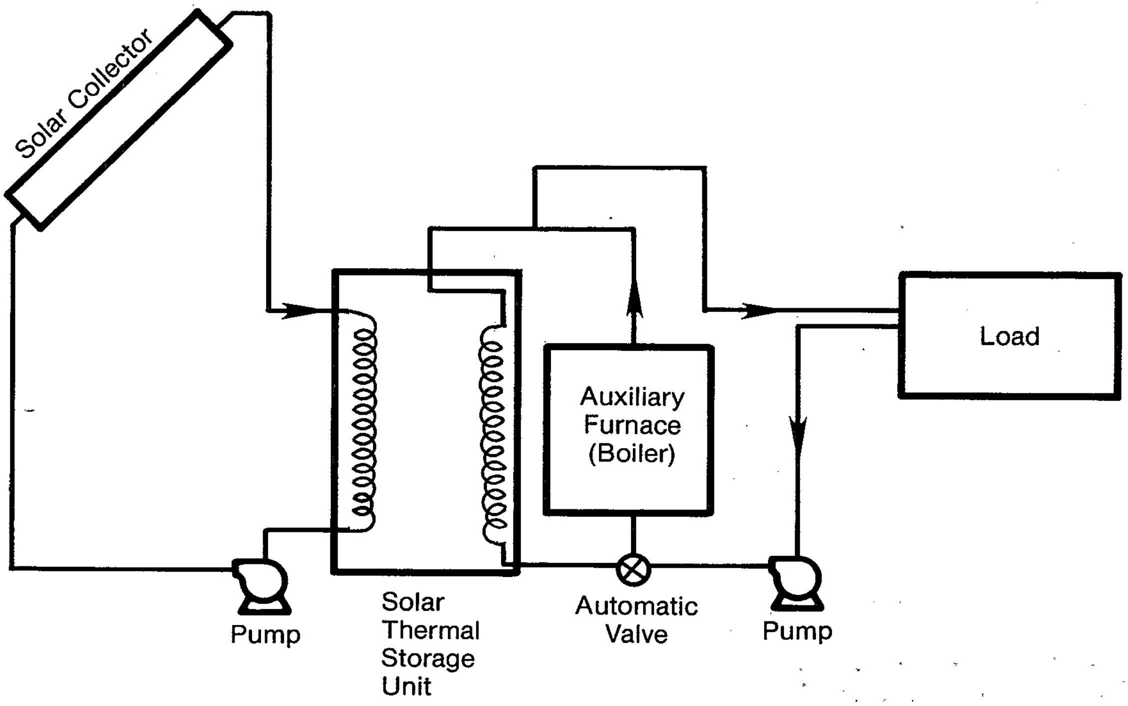


Figure 7. Typical liquid flat-plate solar energy collection system.

In the air-type, flat-plate collector, the operation is similar to the liquid-type collector. However, as air has a lower heat capacity and density than water, approximately 100 m^3 (3,500 ft^3) of air are needed to transport the same amount of heat as 0.028 m^3 (1 ft^3) of water (28). As a result, the air-type collector is usually much larger than the liquid-type collector of comparable capacity. In the air-type collector, the fluid passages are replaced by larger air ducts. The underside of the absorber is usually roughened and made with fins or baffles to promote turbulence and heat transfer. In addition, the pump in the system is replaced by a blower, and the liquid (heat) storage is a much larger rock-pebble storage bed. An air-type collector system is shown in Figure 8.

The design of both types of flat-plate collectors is well known and, unlike other types of collectors, all three types of radiation (direct, diffuse, and reflected) are collected. Both air and water systems are especially efficient at collection temperatures of less than 82 degrees C (180 degrees F) as typically used for water and space heating (29). They are not as efficient as other collectors at the higher temperatures needed for purposes such as industrial uses.

Evacuated-Tube Collectors

In this device, a vacuum is used to insulate and protect the absorber coating from deterioration. The collector itself consists of a vacuum bottle placed over a U-shaped liquid-filled tube as shown in Figure 9. The double walled glass bottle has an absorber coating on its inner glass. During operation, incident radiation travels through the evacuated area, strikes the selective coating, and heats the air within the inner bottle. This heated air in turn heats the liquid in the tube. For the type of absorber shown, both air and water are used for heat transfer. Other designs use all air or all water heat transfer (28).

The evacuated-tube collector collects direct solar radiation very efficiently, and some designs collect both direct and diffuse radiation efficiently. It is most efficient for high temperature applications such as for industrial processing or absorption cooling. Its efficiency for low-temperature applications such as water or space heating is lower than flat-plate collectors (30).

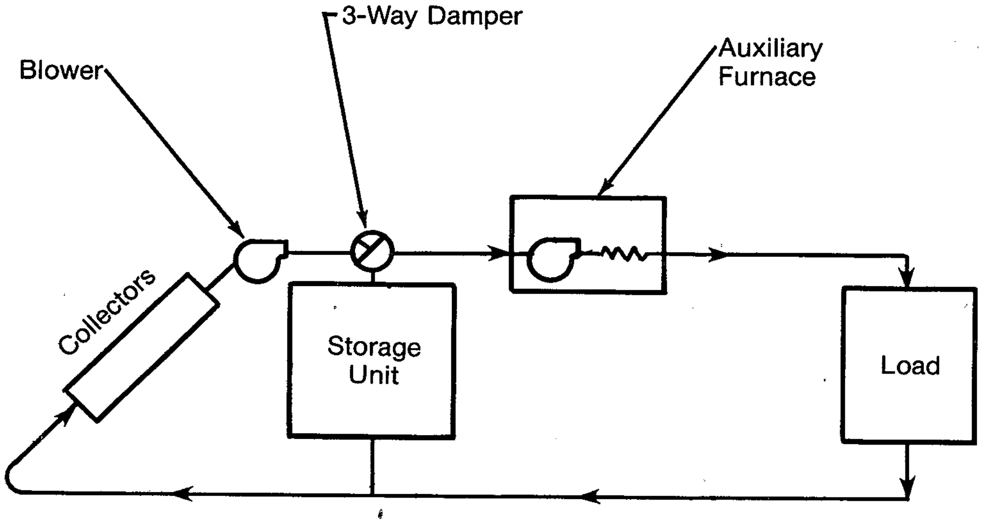


Figure 8. Typical air flat-plate solar energy collection system.

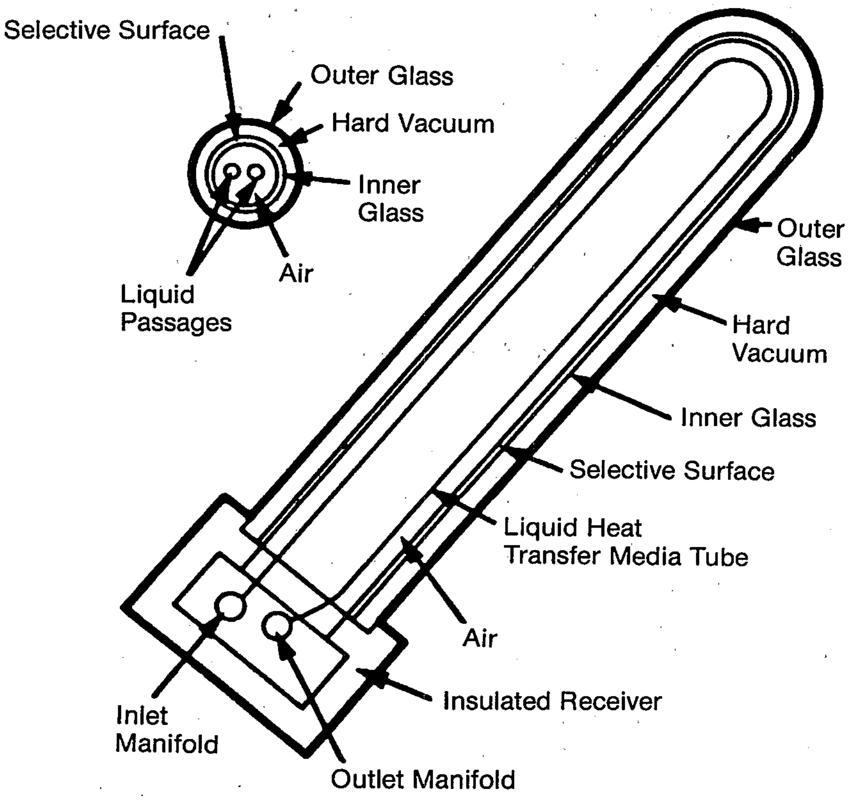


Figure 9. Typical evacuated tube collector.

Concentrating Collectors

Concentrating collectors, which are also known as focusing or tracking collectors, work on the principle that the sun's energy can be concentrated by reflecting it off one or more mirrors to concentrate it onto a smaller absorber. There are numerous types of concentrating collectors, most of which require a mechanical device to shift the collector position to track the sun. In addition, some require special optical lens arrangements to focus the energy. Three of the most promising collectors are the linear concentrating collector; the linear-trough, fresnel lens collector; and the compound parabolic mirror collector. The first two types of collectors only collect direct radiation and track the sun, whereas the parabolic mirror gathers both direct and diffuse solar radiation without tracking the sun (28).

Concentrating collectors show the most promise for industrial-type applications, as they can produce extremely high temperatures efficiently. The costs, however, rule them out for residential space heating. Maintenance of the mirror and tracking mechanism further limits their application (30).

Collector Arrangements

When more than one collector module is used, the functional arrangement is important for effective energy collection and system operation. Three basic configurations for multiple collectors exist: parallel flow, direct return; parallel flow, reverse return; and series flow. Parallel flow-reverse return systems are preferable to direct-return systems since flow balancing through the collectors is easier as the pressure drop (head loss) through each collector is approximately equivalent. Series flow is often used to either reduce the piping requirement or increase temperature output of the collectors. With series flow, either direct or reverse-return systems can be used (27). The configurations are presented in Figure 10.

Energy Storage

Because of the periodic and intermittent character of insolation, storage of thermal energy is important. Heat must be stored when the available solar energy exceeds demand. Storage can be as simple as a concrete wall or floor which re-radiates heat when the ambient temperature drops (sensible heat storage), or as relatively complex as latent heat storage.

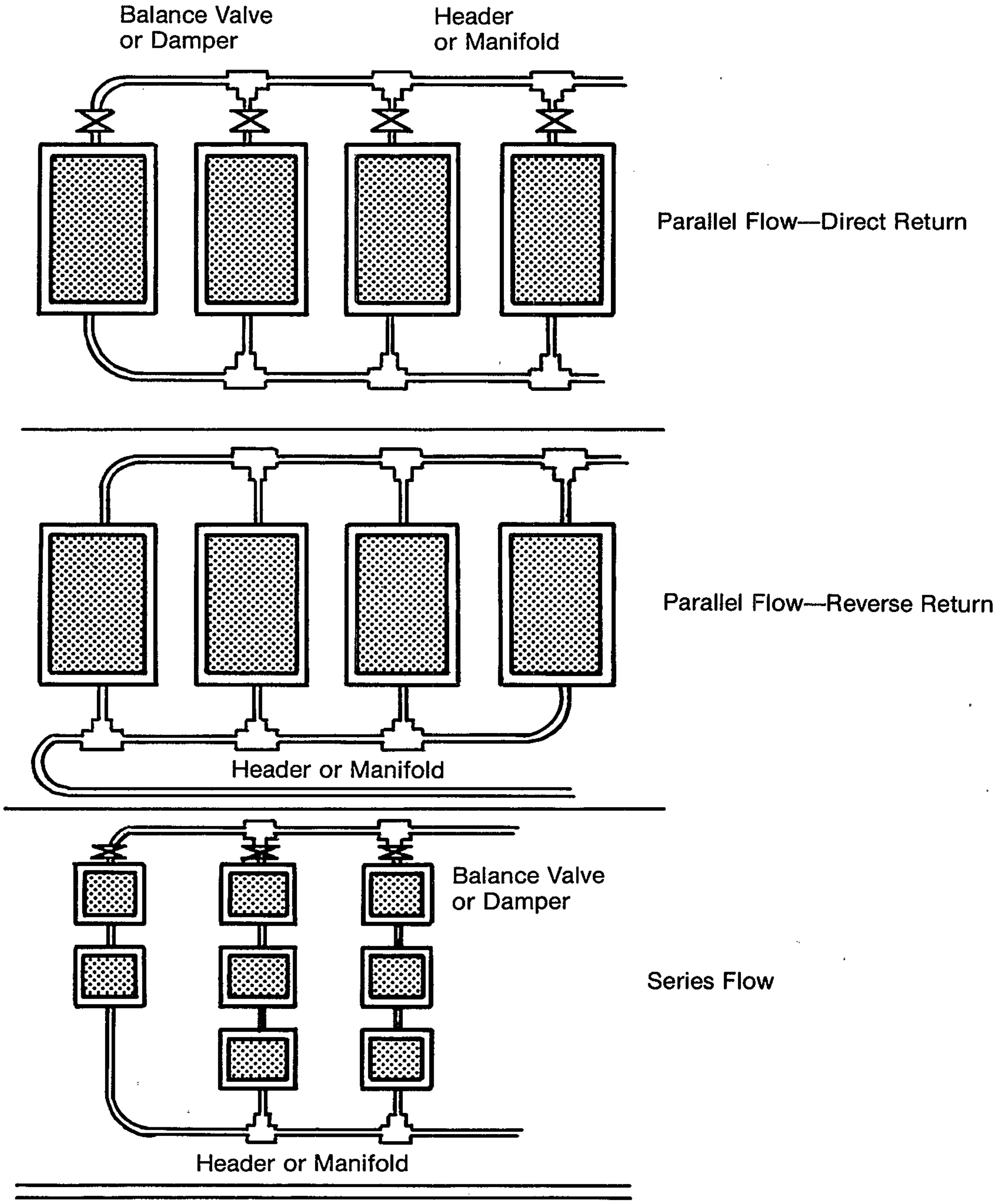


Figure 10. Common arrangements for multiple collector systems.

Sensible heat storage involves raising the temperature of inert substances such as rock, water, and masonry for subsequent release of heat. Various methods are used including room air and/or exposed surfaces, rock storage, and water storage. Rock storage is most often associated with flat-plate collectors which use air as the heat transfer medium (31). The rock is heated with hot air from the collector, and the sensible heat is recovered later by blowing air through the rock pile. Water storage, by comparison, requires only 40 percent of the space required by rock to store an equivalent amount of energy for the same temperature range (28). In addition, water is inexpensive; however, potential disadvantages include leakage, corrosion, and freezing. Heat is generally transferred to and from storage by a working fluid, either directly or by a heat exchanger.

The second type of heat storage involves utilizing the heat of fusion or heat of vaporization associated with changes of state or with chemical reactions. Numerous physical/chemical processes have been investigated and numerous advantages of latent heat storage versus sensible heat storage exist. However, a completely reliable system has yet to be developed. Under consideration, however, are salt hydrates (such as Glauber salt) which, when raised to a specific temperature, release water of crystallization which dissolves the salt. When the temperature drops below the crystallization temperature, the stored heat is released from the solution and the salt recrystallizes. The phase change allows the salt to store a large amount of heat per unit volume (31). Unfortunately, many phase change cycles tend to break down the salt hydrates. A similar storage method is possible using the thermal energy stored by the heat of fusion of paraffin. Unfortunately, waxes tend to shrink upon solidification and lose contact with the heat exchange surfaces (31).

Heat Exchange

By definition, a heat exchanger is a device which transfers heat from one substance to another without mixing the two. Heat exchangers applicable to solar energy may transfer heat from air-to-air, liquid-to-air, and liquid-to-liquid (28). Because the rate of heat transfer is a function of the temperature difference, the heat exchanger must be carefully matched to the system collectors, storage capabilities, and heat load.

There are four basic flow configurations for a liquid-to-liquid exchanger: coil-in-tank, counter-flow, mixed-flow, and parallel-flow. For solar energy systems, the counter-flow designs, which include coil-in-tank exchangers, are the most efficient, followed by mixed-flow and parallel-flow exchangers (28).

Another consideration for heat exchanger specification is whether single or double walled exchangers are required. Double walled heat exchangers are used when non-potable collector fluid must be separated from potable water such as domestic hot water. In a double walled exchanger, the resistance to heat transfer per unit area is greater; therefore, a larger exchanger is required to achieve the same efficiency. In addition, the construction is more complex; both items result in greater costs. A single walled exchanger is used whenever water used for heat storage is not used for potable purposes (27).

Heat Transfer Fluids

Four liquids are in general use: water, water/glycol mixtures, hydrocarbons, and silicone fluids (28). Water is safe, available, and inexpensive. However, it is subject to freezing, supports galvanic corrosion, boils at a low temperature, and promotes scale formation. These limitations require the use of more expensive materials of construction, more complicated controls, and periodic use of corrosion inhibitors.

A water/glycol mixture will not freeze at temperatures greater than -37 degrees C (-35 degrees F), and, although additives can prevent scale and offer some corrosion resistance, it boils at only a slightly higher temperature than water, and does support galvanic corrosion. Because it rapidly decomposes at 138 to 149 degrees C (280 to 300 degrees F), forming sludge and organic acids, the fluid must be replaced frequently. The reliability of a water/glycol system depends on maintenance.

Hydrocarbon heat transfer fluids, typically highly refined mineral oils, are low cost, nonvolatile, relatively nontoxic, and not subject to freezing. Unfortunately, they have relatively poor stability at high temperatures that results in sludge and acid formation. Additional problems include high viscosity at low temperature, incompatibility with copper, and a harmful effect on some roofing materials. Because of their low flashpoint, they should be used in only lower efficiency panels with stagnation temperatures from 121 to 191 degrees C (250 to 375 degrees F).

Silicone fluids have certain advantages in that they do not freeze or boil under operating temperatures, they do not corrode metals including aluminum, and they do not cause scale or sludge build-up. Silicone fluids have disadvantages in lower heat capacity which results in larger heat exchangers, their high viscosity at low temperature, high initial cost, and a propensity to seep at pipe joints (27,28).

Solar roof ponds (also known as thermal storage roofs) are unique for passive solar systems as they are the only passive solar system that can provide both heating and cooling. The most widely employed version of the solar roof pond uses a shallow pond of water (in bags) in thermal contact with a highly conductive flat roof and ceiling structure. In the heating mode the bags are exposed to solar heat gain during the day, and protected (insulated) against heat loss at night. Cooling is accomplished in the reverse manner.

The solar roof pond replaces the ceiling and roof of a conventional structure. The system includes a steel floor deck/ceiling, plastic water bag thermal storage, wood framed glazing, reflective wall, double glazed skylight system and movable insulation sub-system with controls. The movable insulation may consist of a system in which polystyrene beads are blown from a central storage unit between the glazing, and later drawn from the space by a vacuum pump. This system is shown in Figure 16.

Solar roof ponds are characterized by low temperature operation. The daily temperature swing may, in winter, average 2.8 degrees C (5 degrees F), and the average mid-winter temperature of the pond may only be 5.6 degrees C (10 degrees F) over room temperature. The average daily heating contribution by a 25 mm (10 in.) deep pond is in the range of 1,140 to 2,840 kJ/m^2-hr (10 to 20 Btu/ft^2-hr), depending on surface temperature of the pond heated ceiling and the room temperature (17).

PROCESS CAPABILITIES AND LIMITATIONS

In terms of capabilities alone, current solar energy technology could supply the entire energy needs of a POTW if desired. However, applicability must be based on two factors: cost and reliability. The high capital cost and the requirement for and cost of back-up energy make photovoltaic solar energy unattractive given the development status of current technology. A similar conclusion regarding utilization of solar energy to produce process steam is valid.

Aside from the potential use of solar energy systems for sludge drying, the current utilization of solar energy in POTW applications is basically limited to typical applications such as space and water heating.

Space heating can be accomplished utilizing either passive or active solar collectors and either air or liquid flat-plate collectors. The choice between the numerous available technologies is site specific and must be based on a detailed analysis. The potential exists for significant savings in conventional

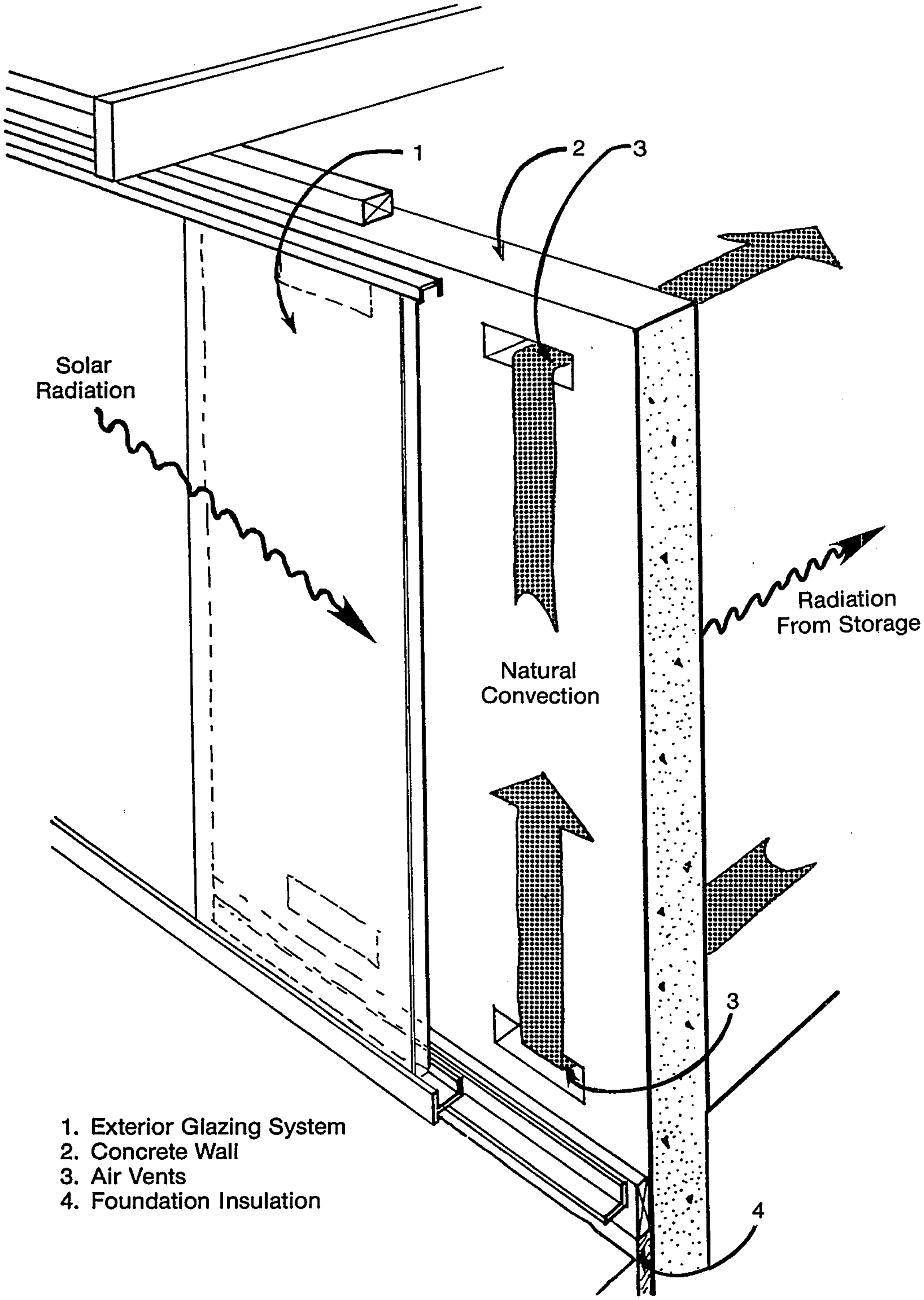


Figure 15. Typical Trombe wall design (19).

The Trombe wall is the most common of the thermal storage walls, and is a south-facing concrete or masonry wall covered on the exterior by light-transmitting glazing (17,34). The recommended design has vents at the top and bottom to permit natural convective air flow as can be seen in Figure 15. The outer window consists of two layers of translucent or semi-transparent low-cost plastic rather than glass. Unlike the direct gain passive system, views out are not possible, and views in showing rough concrete may be undesirable. Maximum system temperatures are in the 66 to 82 degree C (150 to 180 degrees F) range, but more likely at the lower end.

In the Trombe wall, the thermal storage wall is concrete, either cast in place or constructed with blocks and mortar. Dampers are used to prevent air circulation in the "wrong" direction; without proper dampers, the performance can be reduced by as much as 20 percent. On the interior of the Trombe wall, the finish must be such that it does not prevent heat from radiating into the room. Therefore, wood or gypsum should not be used, but rather the concrete should be exposed and finished off. In a typical design, the concrete wall is 0.25 m (10 in.) thick, with vents placed 0.61 m (2 ft) on center along the length. The exterior glazing is mounted 76 to 102 mm (3 to 4 in.) away from the exterior face of the concrete, which is blackened to increase absorption.

The heated air in the Trombe wall generally does not exceed 66 degrees C (150 degrees F) and air delivered to the room does not exceed 32 degrees C (90.9 degrees F). The vertical south wall orientation enables good winter heating, and minimizes summer overheating.

The maximum delivered air temperature tends to occur eight hours prior to the maximum interior wall surface temperature. Total convective and radiant heat transfer from the interior wall is usually not more than 397 kJ/m^2-hr (35 Btu/ft^2-hr) (27). Over a heating season, the Trombe wall will provide enough solar energy to cancel all thermal losses through the wall and thus deliver excess heat to the remaining building load.

A second type of thermal storage wall utilizes water instead of masonry materials for energy storage. Tubes of water, 0.21 m^3 (55 gallon) drums and specially fabricated water walls are typical. Radiant heat rather than natural flow of air is usually the major design consideration (34).

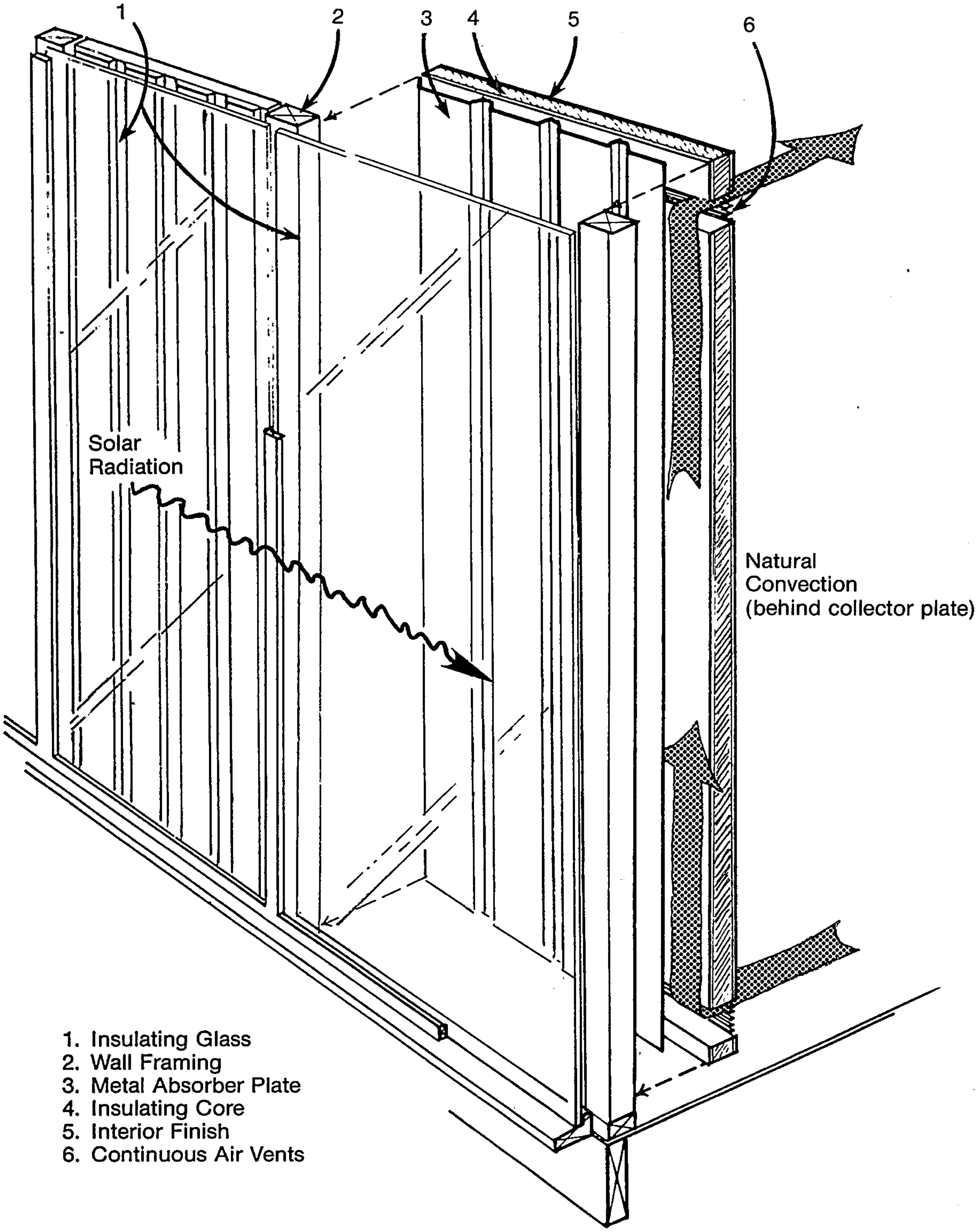


Figure 14. Typical thermosiphon air panel collector.

direct gain area. During the heating season, the south-facing, direct-gain area takes advantage of the sun's low position in the sky. In the summer when the sun is high, the glass is shaded by overhangs, awnings, or trees.

Direct gain systems also utilize sunlight to heat opaque surfaces such as roofs and walls. The color of these surfaces is important and in warm climates the surface should be light in color to reflect sunlight, whereas, in cool and cold climates a dark color should be used. The location of the structure is also important as orientation affects the amount of radiation absorbed. Due south is, in general, the optimal direction for the passive collector. However, the designer must also consider: the type of structure; its method of construction; and the geometry of both the structure and the glass. Sufficient thermal capacity inside the building must be provided so that excess thermal energy can be absorbed and stored for later release (17).

As a fluid increases in temperature, its density decreases and it becomes more buoyant than the cooler fluid. This is the theory behind convective loops. Thermal circulation is a natural convective loop that allows a fluid heated by an absorbing surface to rise and, thereby, draw cooler fluid into the collector area to replace the warm rising fluid.

Figure 14 illustrates the simplest form of a convective loop, the thermosiphoning air collector.

In the thermosiphoning air collector, air flow is provided by the pressure differential created between solar heated air and the lower room air temperature. The air heater consists of exterior glazing, a composite wall element consisting of the thermosiphoning absorber plate, rigid insulation and interior finish, and air grills and dampers. The low mass of the system allows it to undergo greater temperature extremes than the Trombe wall. Double-pane insulating glass is typically used as glazing.

Thermosiphoning air heaters are suited to structures where the heating load is large compared to the panel area. All of the panel output can be absorbed by the building load, as there are no thermal storage provisions. Facilities with intermittent use (schools and office buildings) are well-suited to the thermosiphoning air heater's daily cycle. Thermal performance of the collectors is dependent on the natural convection in the system, and air flow is low to non-existent during periods of little or no sun. A collector, as shown in Figure 14, has an average outlet temperature of 35 degrees C (95 degrees F) at a maximum flow rate of 0.057 m^3/min (2 ft^3/min) resulting in 1,022 kJ/m^2-hr (90 Btu/ft^2-hr) as an average heat gain.

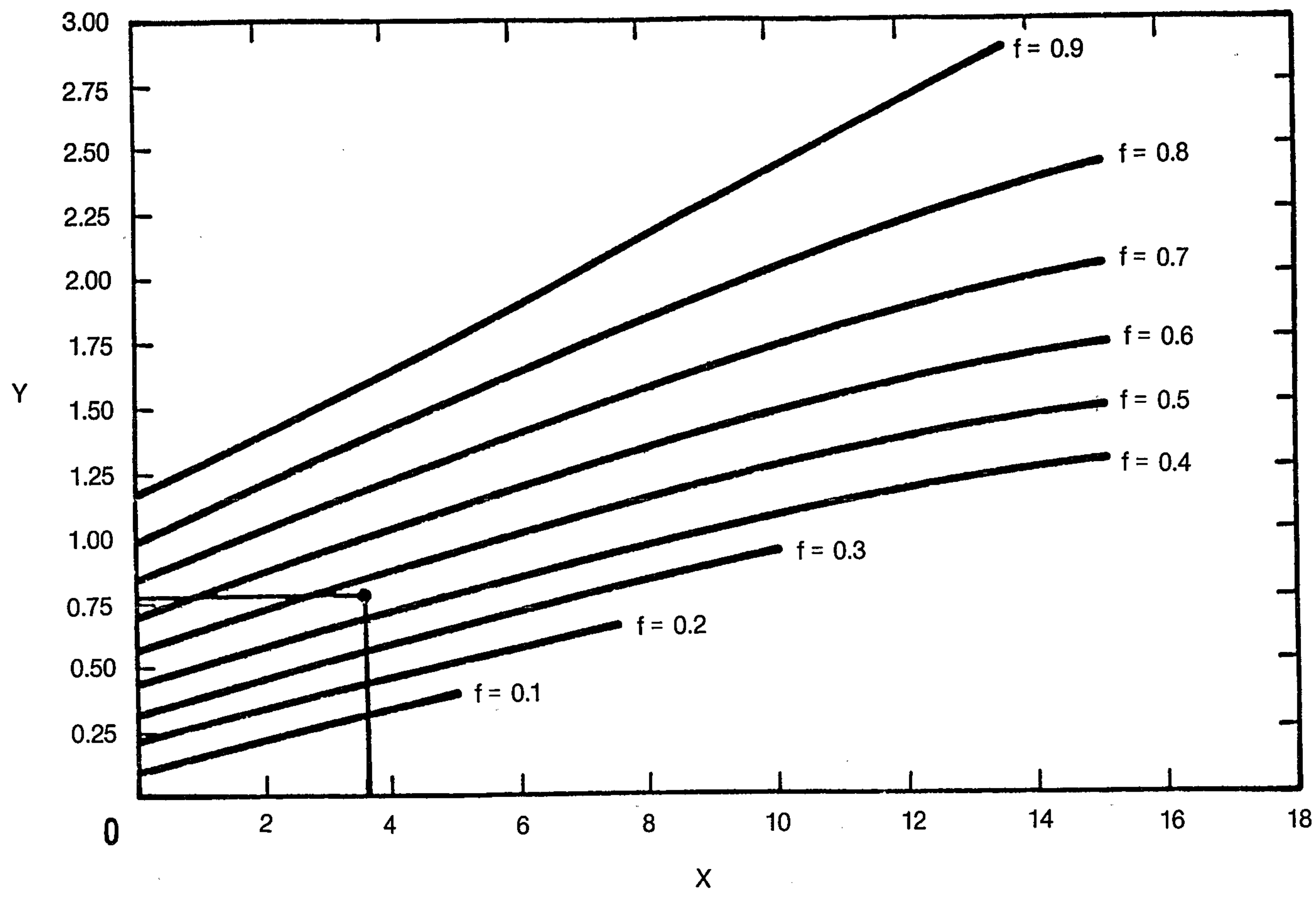


Figure 13. f-chart for liquid-based solar heating systems.

L	is the total monthly load in kJ (Btu)
$^{\tau}/T_n$	is the ratio of the average monthly collector cover transmittance to the transmittance of normal incidence (0.90 - 0.95)
$^{\bar{\alpha}}/{}^{\alpha}{}_n$	is the ratio of the collector surface solar absorptance to the solar absorptance at normal incidence (0.95)
H_T	is the long-term insolation, kJ/m^2-hr (Btu/ft^2-hr)

Once monthly values of X and Y are calculated, the fraction of the monthly energy load supplied by solar energy (f-value) is obtained from graphs such as shown in Figure 13 for liquid based systems. Having obtained f-values for each month, the annual solar fraction is calculated by summation. In summary, the f-chart method is an empirical method based on computer simulations, experiments, and years of experience which can be used to predict flat-plate collector performance.

PASSIVE SOLAR SYSTEM CONCEPTUAL DESIGN

As opposed to the active solar system which requires collectors, thermal storage, and a thermal energy transport system, passive solar energy does not use any mechanical power to transfer energy into and out of a structure. Controls and comfort-regulating devices can be incorporated into the design, but are not required. In certain systems, mechanical energy is utilized to improve energy transfer, and these systems are designated as hybrid. This section is intended to give the reader an idea of the concepts utilized in passive solar design. For a further discussion of concepts, as well as design guidelines, the reader is referred to References 34 and 35 or other similar documents.

Passive solar systems are characterized by the linkage of solar collection, thermal energy storage, the space to be heated/cooled, and the application of energy conservation concepts to the design of the desired structure. Passive systems can be divided into four different types: direct gain, convective loops, thermal storage (Trombe) walls, and thermal storage roofs (34).

Direct gain systems use sunlight entering directly through glass or plastic to the space to be heated, and virtually all the sunlight entering is converted to heat. A thermal mass for storing excess heat (concrete floor, brick wall) is utilized to absorb solar heat. To reduce heat loss at night and, therefore, increase thermal performance, insulation may be applied on the

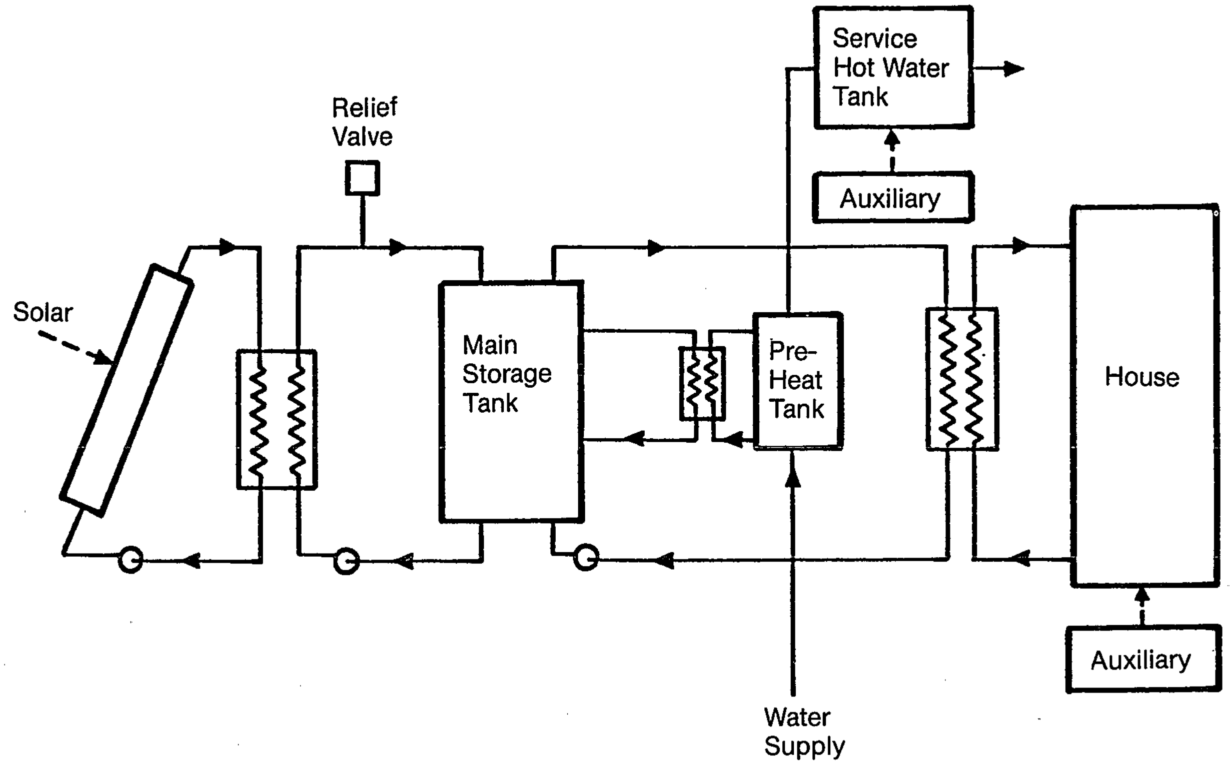


Figure 12. Schematic diagram of the "standard" liquid-based solar space and water heating system utilized for f-chart analysis.

To simplify collector sizing, the Duffie-Beckman-Klein procedure was developed. This general design procedure was developed based on numerous simulations of solar heating systems utilizing a detailed simulation program and a specific system configuration (19,30). This exercise resulted in the empirical "f-chart" method to predict the performance of "standard" solar systems providing space heating and domestic hot water heating. Figure 12 shows the standard active solar heating system utilizing liquid flat-plate collectors. A similar air, flat-plate system is also available. When utilizing the f-chart analysis, meteorological data in the form of long-term monthly temperature and insolation data are required.

A detailed discussion of the f-chart procedure can be found in References 19 and 30, and a brief description is presented below. The thermal efficiency is predicted through the calculation of two dimensionless parameters: X, which represents the ratio of solar collector energy losses at a reference operating condition to the total system heating demands; and Y, which is the ratio of solar energy absorbed by the collector to the total system heating demand. The equations used for calculating X and Y are as follows:

$$X = F_R U_L \left[\frac{F_R'}{F_R}\right] \frac{A\,(T_{ref} - \bar{T}_a)\,\Delta T}{L}$$

$$Y = F_R\,(\tau\alpha)_n \left[\frac{F_R'}{F_R}\right] \frac{\bar{\tau}}{\tau_n}\;\frac{\bar{\alpha}}{\alpha_n}\;\frac{AH_T}{L}$$

where:

$F_R U_L$ and $F_R\,(\tau\alpha)_n$	are parameters describing performance of a flat-plate collector and are the slope and y-intercept, respectively, of the efficiency curve of Figure 11.
F_R'/F_R	is the collector-tank heat exchanger performance efficiency (0.90 - 1.0)
A	is a collector area, m^2 (ft^2)
T_{ref}	100 degrees C (212 degrees F)
$\bar{T}_a$	is the average ambient monthly temperature
ΔT	is the number of hours in the month

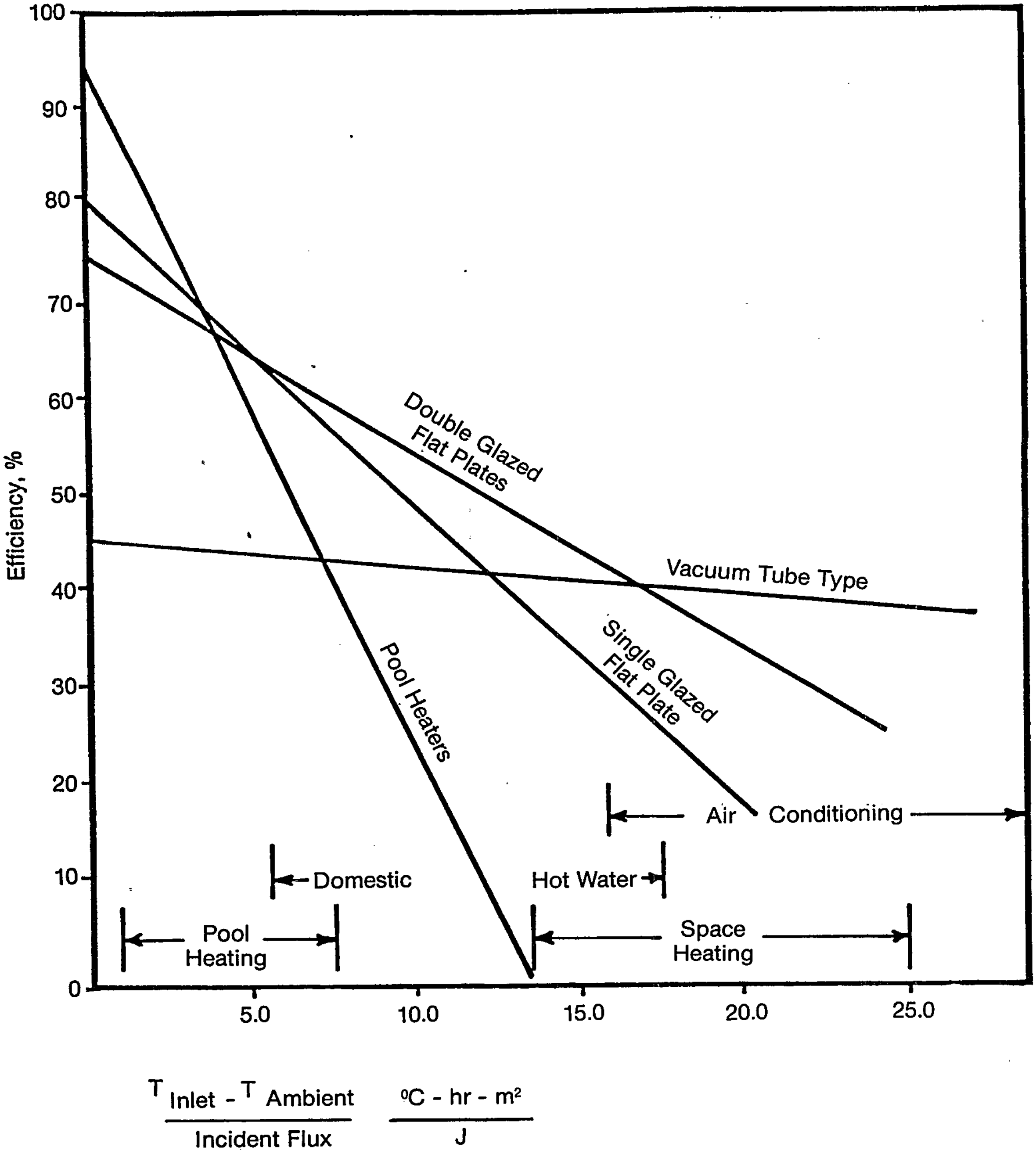


Figure 11. Collector efficiencies for various liquid collectors.

As opposed to conventional systems, solar systems are typically not oversized because the cost of the system is directly related to collector size. In addition, solar systems are not designed to provide 100 percent of the demand, since the collection and storage system would have to be designed for successive sunless days (30). During sunny days, therefore, the system would be overdesigned and the energy wasted. For home heating, sufficient capacity for the evening hours and the few early hours of the following day are typically provided. Concentrating collectors are not currently considered practical for residential usage due to their high capital cost and maintenance requirements. Because flat-plate collectors can provide sufficiently high temperatures for POTW applications, they will be the only active collector considered.

Solar collector efficiency is defined as the ratio of useful heat delivered by the collector to insolation over the same time period. Typical flat-plate efficiencies vary from 20 to 60 percent, depending on fluid and ambient air temperatures. Factors accounting for efficiency losses include emittance or reradiation and convective losses. Low fluid flow and high collector temperatures lead to low efficiency. With a large fluid flow, the fluid and collector temperatures are low, heat losses from the collector are lower, and efficiencies high. At the normal fluid temperatures of from 38 to 60 degrees C (100 to 140 degrees F), efficiencies of 35 to 40 percent are typical (19).

For standardization and convenience, the efficiency of a collector is correlated with the ratio:

$$\frac{\begin{pmatrix}\text{Collector Inlet}\\ \text{Temperature}\end{pmatrix} - \begin{pmatrix}\text{Atmospheric}\\ \text{Temperature}\end{pmatrix}}{\begin{pmatrix}\text{Solar Radiation per Time}\\ \text{per Collector Surface Area}\end{pmatrix}} = \frac{T_{in} - T_a}{H_T}$$

When efficiency is correlated to this ratio, a straight line results, as can be seen in Figure 11 for various collector types. The slope and intercept of the line are used as measures of collector properties and performance in design calculations.

The performance of an active solar system must be related to the climatological conditions which prevail at the site and the specific system design and control strategy. Therefore, only generalized computer simulations are flexible enough to predict system performance of any conceivable system. However, these programs require hour-by-hour meteorological data and the performance predictions only apply to the time period of the input data.

of solar energy is typically required. The solar window will change with geographical area, as the top and bottom of the window depend on latitude while the sides are a function of the longitude (28).

Based on the solar window, the shade caused by interferring objects can be plotted and the optimum location of the collector determined. Based on the sun's path, the collector's surface should be oriented to point due south. Due south should be based on geographical south rather than magnetic south, and compass readings should be corrected by the Isogonic Chart readings which show magnetic deviations from due north.

Due to the site specific conditions such as shading or local weather conditions, a shift in collector direction of 15 degrees east or west of south is acceptable. This shift will reduce, although not drastically, the energy collected. Beyond 15 degrees to 20 degrees east or west of south, energy collection is significantly reduced (30).

The angle between the collector and a horizontal surface is called the collector tilt angle. The collector tilt angle is a function of both the geographical location and the energy use. For domestic hot water heating, the tilt angle should be the same as the latitude of the location. Therefore, at a latitude of 35 degrees N, the collector should be tilted 35 degrees from horizontal to ensure maximum energy collection throughout the year (27).

For space heating applications, however, it is desirable to collect the maximum amount of energy during the winter months when the demand is the greatest. As the sun is lower in the sky during the winter months, the collector must be tilted to latitude plus 15 degrees. Therefore, at 35 degrees N, a collector should be oriented 50 degrees from horizontal. Variations in collector tilt of 10 degrees either side of optimum are acceptable and will not significantly reduce energy collection. In some cases, a different angle may be desirable due to architectural or other reasons (27).

ACTIVE SOLAR SYSTEM CONCEPTUAL DESIGN

This section is intended to present the methodology for the process design (sizing) of an active solar heating system, given a known load. However, it is not intended to give the specific details of design or various system modifications. A methodology for calculating the heat load required for anaerobic digester heating is given in Appendix A. Calculation of building heating loads is available from numerous sources.

The earth rotates on its axis once every 24 hours; the axis of rotation is tilted at an angle of 23.5 degrees to the plane of the earth's orbit. If the earth were not tilted, the equatorial regions of the earth, which are closest to the angle of solar radiation, would always receive the maximum insolation. However, due to the tilt of the earth's axis, the area receiving the maximum solar radiation moves north and south, between the Tropic of Cancer and the Tropic of Capricorn, causing changes in insolation. One other factor affecting insolation rate is the length of the daylight period, which is a function of day of year. Based on these factors, each area of the earth will be affected differently. The total amount of insolation and the distribution of direct and diffuse insolation will vary as a result of these modifying factors.

Numerous models are available to predict the amount of solar radiation reaching the earth's surface as a function of time of year and location. Two of those available include the Liu and Jordan method, and the Klein, Duffie, and Beckman method (30). Both methods involve utilizing long-term solar radiation data to predict the amount of solar radiation which will be converted to usable energy by a solar collector. Owing to the variations in insolation, solar collector sizing cannot be determined by simply choosing the solar radiation data for a particular hour, day, month, or even year. Therefore, solar system sizing must be based on long-term averages for insolation and weather conditions. Long-term averages for insolation as well as air temperature are available in tabular form for numerous locations within the United States.

Collector Positioning

Regardless of the type of solar energy collection system to be used, correct collector positioning is necessary so that the optimum amount of energy can be collected. Typically, the solar window concept, in which one assumes the sky as a transparent dome, is used to pictorally demonstrate the sun's position with respect to the desired solar collector location (28,29,31). In this method, the bottom of the window is formed by the sun's path at the start of winter (December 21) and the top of the window by the sun's path at the start of summer (June 21). The sides of the window are 9 A.M. and 3 P.M. This window outlines the area through which a maximum amount of solar energy could reach the collectors during the year. By plotting the solar window, objects such as trees or buildings which might interfere with solar collection can be identified. Objects which cast a shadow when the sun is low in the sky (winter) are extremely important to identify as this is the time when the maximum amount

SECTION 3

TECHNOLOGY EVALUATION

PROCESS THEORY

Basics of Solar Energy

Sun, wind, temperature, humidity, and various other factors shape the climates of the earth. As far as solar energy is concerned, there are four elements of the climate which are important. These are solar radiation, air temperature, humidity, and air movement.

The sun provides the earth with essentially all of its energy. This energy is received in the form of electromagnetic radiation transmitted in wavelengths varying from 0.29 to 3 microns. By comparison, the human eye can detect visible light at wavelengths between 0.36 and 0.76 microns.

The intensity of radiation reaching the upper surface of the earth's atmosphere (solar constant) varies as much as plus or minus 2 percent due to variation in the sun's energy output and plus or minus 3.5 percent due to changes in the distance between the sun and earth. On a plane perpendicular to the sun's rays, the solar constant is 4,874 kJ/m^2-hr (429.2 Btu/ft^2-hr) (31). The radiation which arrives at the earth's surface (insolation) is less than the solar constant for various reasons. Insolation values are maximum per unit area when solar radiation impacts on a surface perpendicular to the incident radiation. Because of the curvature of the earth, solar radiation strikes the earth at discrete angles varying up to the maximum of 90 degrees. The design intent of tilting solar collectors from a horizontal plane is to compensate for this phenomenon in order to maximize insolation.

Radiation reaching the earth's surface is also affected by the condition of the atmosphere in terms of its vapor, dust, and smoke content because radiation is absorbed and scattered by these elements. In addition, the lower the solar altitude, the greater the path through the atmosphere the radiation must travel, further reducing the amount reaching the earth's surface.

cells are silicon and cadmium sulfide cells. A great deal of research is under way aimed at solar cell development; however, the technology is still in the developmental stage. The primary use of solar cells is to supply small amounts of electricity in remote locations where conventional sources are not available.

EQUIPMENT AVAILABILITY

A total of 223 firms were identified as manufacturers of solar thermal collectors during the first half of 1980 (32). These 223 manufacturers shipped 820,000 m^2 (8.83 x 10^6 ft^2) of solar collectors from January through June 1980; this is an increase of over 20 percent compared to the second half of 1979, and 28 percent over the first half of 1979 (32), indicative of a growth industry.

Of the collectors shipped during the first half of 1980, low-temperature collectors (temperatures below 43 degrees C (110 degrees F), no glazing or insulation, generally plastic or rubber) accounted for 68 percent of total production, with 97 percent of these collectors for swimming pool heating. Medium-temperature solar collectors (typical operating temperatures of 60 to 82 degrees C (140 to 180 degrees F), single or double glazed, metal absorber with integral or attached tubing or ducting, insulated) accounted for 29 percent of the shipments. Of this 29 percent, 238,000 m^2 (91 percent) used liquid heat transfer. Of the medium-temperature liquid heat transfer collectors, 62 percent were used for domestic hot water and 22 percent for space heating. Special collectors (evacuated tube or concentrating/focusing collectors) accounted for 3 percent of the total producer shipments (32).

The residential market accounted for 84 percent of the solar collectors installed in the first half of 1980; the commercial sector accounted for 12 percent of the applications; and industry, agriculture, and other uses accounted for 3 percent. The government sector accounted for 3 percent; however, this sector overlaps the others (32).

Twelve firms manufactured photovoltaic solar collector modules with a capacity of 1,841 peak kilowatts during the first half of 1980. Industry accounted for 63 percent of this market; residential 18 percent; and commercial, agricultural, government, and other uses 19 percent. Of the total, 41 percent was for export.

Numerous publications contain lists of solar collector and system component manufacturers. Publications such as the "Solar Industry Index" (27) or the "Solar Products Specifications Guide" (33) list companies involved in and specifications for solar collector equipment.

Solar Space Cooling

Solar cooling is typically accomplished by using solar heat to operate a thermal absorption type refrigeration system. The system differs from electrically operated refrigeration in that in electrical units a vapor such as ammonia is condensed to a liquid by a motor-driven pump and the released heat is removed by blowing air through the condenser. The liquid is then vaporized and the heat is absorbed by the vaporization, resulting in cooling. In solar refrigeration, the cycle is similar; however, the ammonia (or lithium bromide) is condensed by heating a concentrated solution, thereby causing a high vapor pressure. The details of the complete cycle can be found in numerous references (8,19,29,30).

Solar powered air conditioning is possible also using an organic Rankine cycle engine. In this process, solar heat vaporizes an organic liquid, drives an organic Rankine cycle engine, which in turn drives a conventional compressor of an air conditioner (8,30).

Passive Solar Systems

There are three general passive solar collection concepts. The first concept involves incidental heat traps such as windows, skylights and glass structures. Aside from direct solar heat gain such as lighting and ventilation, these incidental heat traps typically serve a variety of purposes. The second concept is known as thermosiphoning. This approach utilizes the heat absorbed by a wall or roof structure by drawing if off or siphoning it to a room or to storage. The third method of passive solar heating or cooling involves the thermal storage pond or roof concept. In this method, control of solar heat gain or heat loss is controlled by the use of movable insulating panels to expose or conceal the ponds. Solar ponds have found their greatest use where cooling is the principal design condition, and when summer nighttime temperatures are substantially lower than daytime temperatures (31). A further description of passive systems will be presented in Section 3.

Photovoltaic Conversion

Solar cells offer a means of direct conversion of sunlight into electricity with high reliability and low maintenance (8). The present disadvantages are the high capital cost and the difficulty in storing electricity for later use. The cost of photovoltaic cells will hopefully be reduced when the cells are manufactured in large quantities using new production techniques. The two most promising materials for inexpensive solar

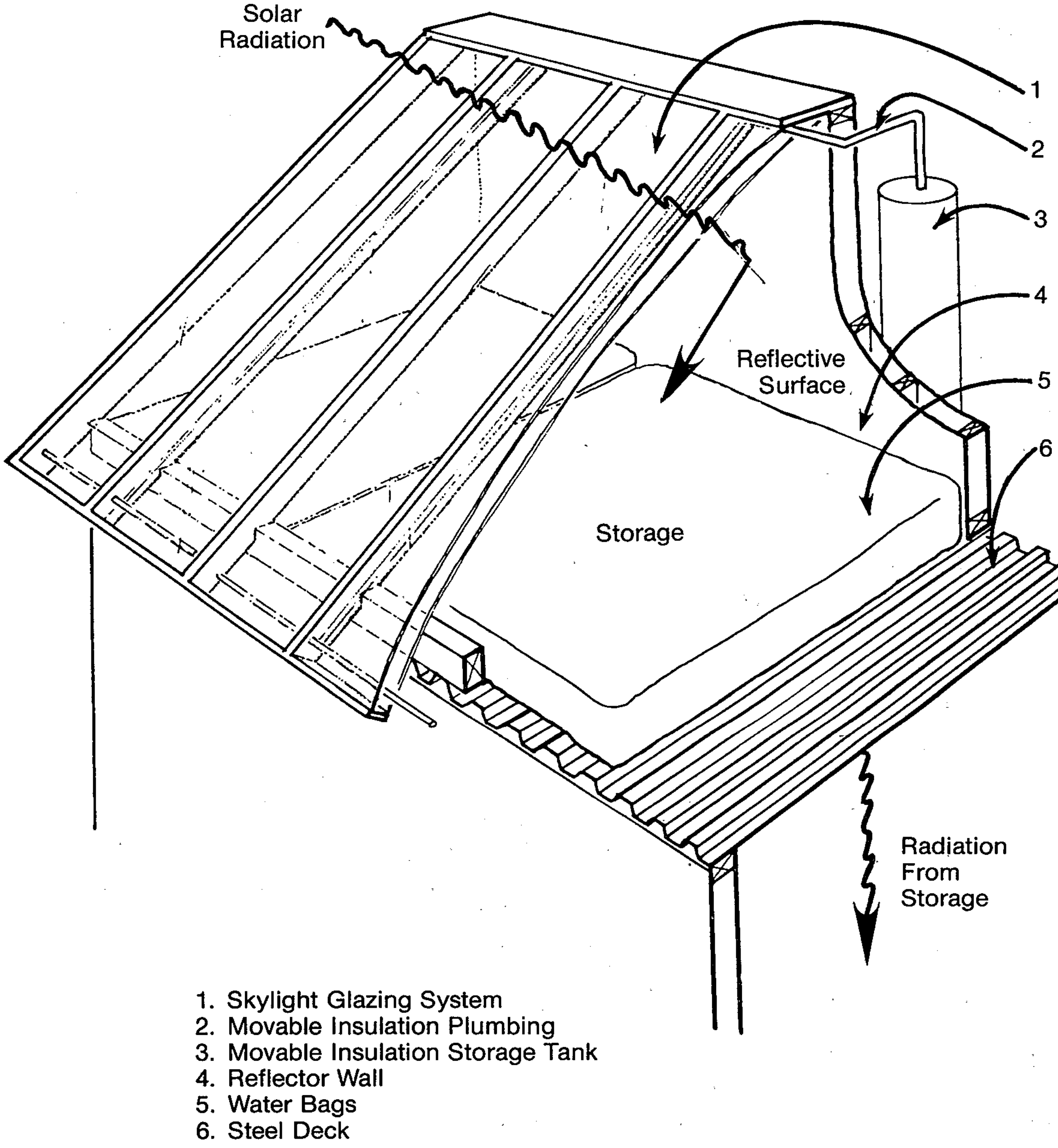


Figure 16. Typical solar roof pond system.

energy at smaller facilities. Space heating accounts for about 19 percent of the total energy requirements at a 3,785 m^3/d (1 mgd) facility, but only 5 percent at a 378,500 m^3/d (100 mgd) POTW (see Table 1). In terms of overall plant energy usage, the installation of a solar domestic hot water heater would have minimal impact, although, if installed in conjunction with an active space heating system, it may prove economical. Solar-aided anaerobic digestion has the potential for energy savings of about 9 percent at 3,785 m^3/d (1 mgd), and 2 percent at 378,500 m^3/d (100 mgd).

In summary, assuming the "typical" wastewater treatment plant of Table 1 and 90 percent solar replacement, the maximum possible energy savings by utilizing solar energy are presented in Table 4.

TABLE 4. MAXIMUM ENERGY REDUCTIONS POSSIBLE BY THE UTILIZATION OF SOLAR THERMAL ENERGY ALTERNATIVES[1].

	3,785 m^3/d (1 mgd)	37,850 m^3/d (10 mgd)	378,500 m^3/d (100 mgd)
Anaerobic Digester Heating	9.0%	5.0%	2.3%
Building Heating	16.9%	7.8%	4.4%
Sludge Drying (instead of incineration)	4.8%	3.2%	3.2%
Total Maximum Savings	30.7%	16.0%	9.9%

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[1] Assuming 90 percent replacement of conventional fuel with solar thermal energy.

OPERATION AND MAINTENANCE CONSIDERATIONS

The installation of an active solar anaerobic digester heating system, or the installation of either active or passive space heating, both require installation of additional equipment at the POTW. However, these systems are not overly complicated, and should not pose an operation or maintenance problem for the plant staff. In fact, such systems are typically automatically controlled, and operation would consist of only occasional monitoring. Operating costs for the active systems (exclusive of labor) are limited to pumping power, whereas the passive systems have near zero operating cost.

In terms of maintenance of an active solar system, 15 items have been identified as requiring maintenance: collector glazing, collector gasketing, collector sealants, absorber plate, absorber plate coating, insulation, heat-transfer fluid, pumps, heat exchangers, piping, valves, expansion tank, connectors, storage tank, and manifolds (28).

Although there is a wide range of items requiring maintenance, the installation of premium grade materials tends to minimize maintenance requirements. A high quality solar system is estimated to last 20 to 25 years. Yearly maintenance costs have been estimated to be about 1 to 3 percent of the installed capital cost (29).

A recent article (36) reviews the results of the Department of Energy's National Solar Heating and Cooling Demonstration Program through September 1980. Of 12 active solar heating systems (both air and liquid based), only one provided the expected solar fraction. Nine problems were reported as causing poor system performance:

1. Air leakage
2. Water leakage
3. Freezing problems
4. Control problems
5. Storage problems
6. Storage heat loss problems
7. Severe weather
8. Lower energy requirements than design load
9. Supplemental heat problems

As opposed to the opeation and maintenance associated with either digester or space heating, the potential operations and maintenance problems with active or passive sludge drying are difficult to assess. The two schemes discussed previously are likely to be operator and maintenance intensive owing to the non-homogeneous properties of and associated difficultues in handling sludge.

COST CONSIDERATIONS

A basic consideration of any solar energy alternative is the installed capital cost. As solar energy is not a continuous, dependable source, back-up equipment to provide supplemental energy is required. In the case of active solar digester heating and space heating, the back-up systems will be approximately the same size as the equipment which would be installed without solar energy. Specifically, for both digester heating and space heating, both a combustion burner and a heat exchanger are required whether or not solar energy is utilized. Therefore, the annual energy savings accrued due to solar energy must be balanced against the higher initial capital cost due to the solar equipment. A similar case for passive solar heating exists.

For the case of solar aided sludge drying, the non-continuous nature of solar energy will cause the required sludge storage facilities to be larger. In addition, the drying facilities may also have to be enlarged over conventional gas fired dryers if the solar heated air is used directly, thereby increasing the capital cost. Once again the energy savings must be compared to this additional capital cost.

The final consideration involves the increased system operation and maintenance costs due to solar energy use which also must be subtracted from the yearly energy savings.

ENERGY CONSIDERATIONS

The energy considerations associated with solar energy are obvious in that, with the exception of energy consumed by system operation, all other energy produced represents a net gain. This does not consider the secondary energy requirements associated with production of the solar energy collection equipment.

SECTION 4

COMPARISON WITH EQUIVALENT TECHNOLOGY

EQUIVALENT CONVENTIONAL CONCEPT

The equivalent conventional concept used in the analysis of solar energy applications in POTW's is the process which utilizes conventional fuel sources in lieu of solar energy. For solar aided anaerobic digestion, an equivalent technology could be digester heating utilizing waste heat from the internal combustion engine which burns the digester gas. However, as this is not considered to be conventional practice, it is not discussed further, and all comparisons are to anaerobic digestion utilizing fossil fuels as a supplemental heat source.

The comparative evaluation of the solar aided anaerobic digestion process with the equivalent technology was conducted primarily with respect to cost and energy requirements. It should be noted that the original intention was to compare solar aided mesophilic and thermophilic digestion as well as sludge drying. However, based on the results and conclusions presented here, and further detailed in Appendices A and B, only solar aided mesophilic anaerobic digestion was considered.

COST COMPARISON

Summary of Available Cost Data

Numerous references present the cost of solar collectors, however, the data are based on estimates rather than on installed capital cost information. Two recent articles (39,40) present data on solar system costs in industrial applications. In Reference 39, it is stated that the widespread use of solar energy has been predicted (by researchers and manufacturers) to allow for a 70 percent cost reduction by 1990. However, experience during the period 1977 to 1980 shows that both cost and performance have failed to meet expectations, leading to lower than expected rates of return on solar investments.

This may be expected of a new technology, however, and is not necessarily indicative of future potential. Of six projects reviewed which utilized solar energy for process heat, annual average efficiencies ranged from 8.1 to 19.7 percent based on insolation rates which is only 25 to 50 percent of the predicted performance (39). From a cost standpoint, there appeared to be no tendency for economies of scale. Although there is reason to be optimistic about future cost reductions, there is no evidence available today to show any reduction in costs, and \$538.21/m^2 (\$50.00/ft^2) of collector area is representative of current (1980) installed costs of solar energy systems.

Reference 40 presents a detailed review of construction costs for 14 facilities within the National Solar Heating and Cooling Demonstration Program, and includes process hot water, space heating (air and liquid), and space cooling systems.

The cost breakdown among system components is presented in Table 5. The costs for solar space heating (considered closest to the digester application), including installation and profit, but excluding design, instrumentation, or auxiliary equipment in 1977 dollars averaged \$527.45/m^2 (\$49/ft^2) (50). System costs showed only a slight economy of scale. The authors then reviewed the data to determine the average and minimum potential cost for the hot water and space heating systems. The cost data, by category, is as follows (40):

TABLE 5. SOLAR SYSTEM COST DATA (40)

	Average Costs			Minimum Cost		
	\$/m^2	(\$/ft^2)	%	\$/m^2	(\$/ft^2)	%
Collector	143.16	(13.30)	33.3	130.25	(12.10)	49.0
Support	80.73	(7.50)	18.8	30.14	(2.80)	11.3
Piping, Duct, and Insulation	117.33	(10.90)	27.3	67.81	(6.30)	25.5
Storage	30.14	(2.80)	7.0	12.92	(1.20)	4.9
Electrical and Controls	37.67	(3.50)	8.8	13.99	(1.30)	5.3
General Construction	20.45	(1.90)	4.8	10.76	(1.00)	4.0
Total	429.49	(39.90)		265.88	(24.70)	

Note: All costs are in 1977 dollars.

Therefore, the actual solar collector accounts for only about 33 to 50 percent of the total system costs. The authors also concluded that retrofit applications could be as much as 15 percent more expensive mainly due to piping, ductwork, and insulation (40).

The second solar system cost item is the annual operations and maintenance cost. Although information regarding maintenance requirements is available, few actual O&M cost data are available. Exclusive of operating costs, a 1 to 3 percent maintenance cost has been presented (29).

Methodology for Cost Analysis

In order to obtain regional conclusions, nine cities in the United States, three in each of the north, central, and southern regions, were selected as shown in Figure 17. Within each region, three locations were chosen so that each site had similar climates in terms of degree-days, yet varying insolation rates (Table A-1, Appendix A). This selection was made so that, for a similar climate, the effect of varying insolation rates could be obtained and the results potentially extrapolated to generalizations for the entire United States.

The methodology for determining the cost-effectiveness of solar aided mesophilic anaerobic digestion consists of comparing the present worth cost of digester gas saved due to solar to the cost associated with producing the solar energy. Costs to produce solar energy include the capital cost of the equipment necessary to capture and transfer the thermal energy, and the operation and maintenance costs associated with the equipment.

In sizing a solar energy collector, various "rules of thumb" exist as to what portion of the total heat load should be supplied by solar energy. For the analysis described within, it was decided that the solar collector system size be based on the most cost-effective solution. Since the anaerobic digester facilities are equivalent whether or not solar energy is used to preheat the sludge, then the cost-effectiveness analysis should compare the additional cost associated with implementation of the solar energy collection system (both initial capital cost and yearly O&M costs) to the value of the digester gas saved (i.e., not combusted). Net present worth costs were calculated and were defined as the total present worth of the solar collection facilities (including O&M), minus the present worth cost of the digester gas saved. Thus, only where net present worth values are negative would there be an economic advantage to utilizing solar energy for digester heating.

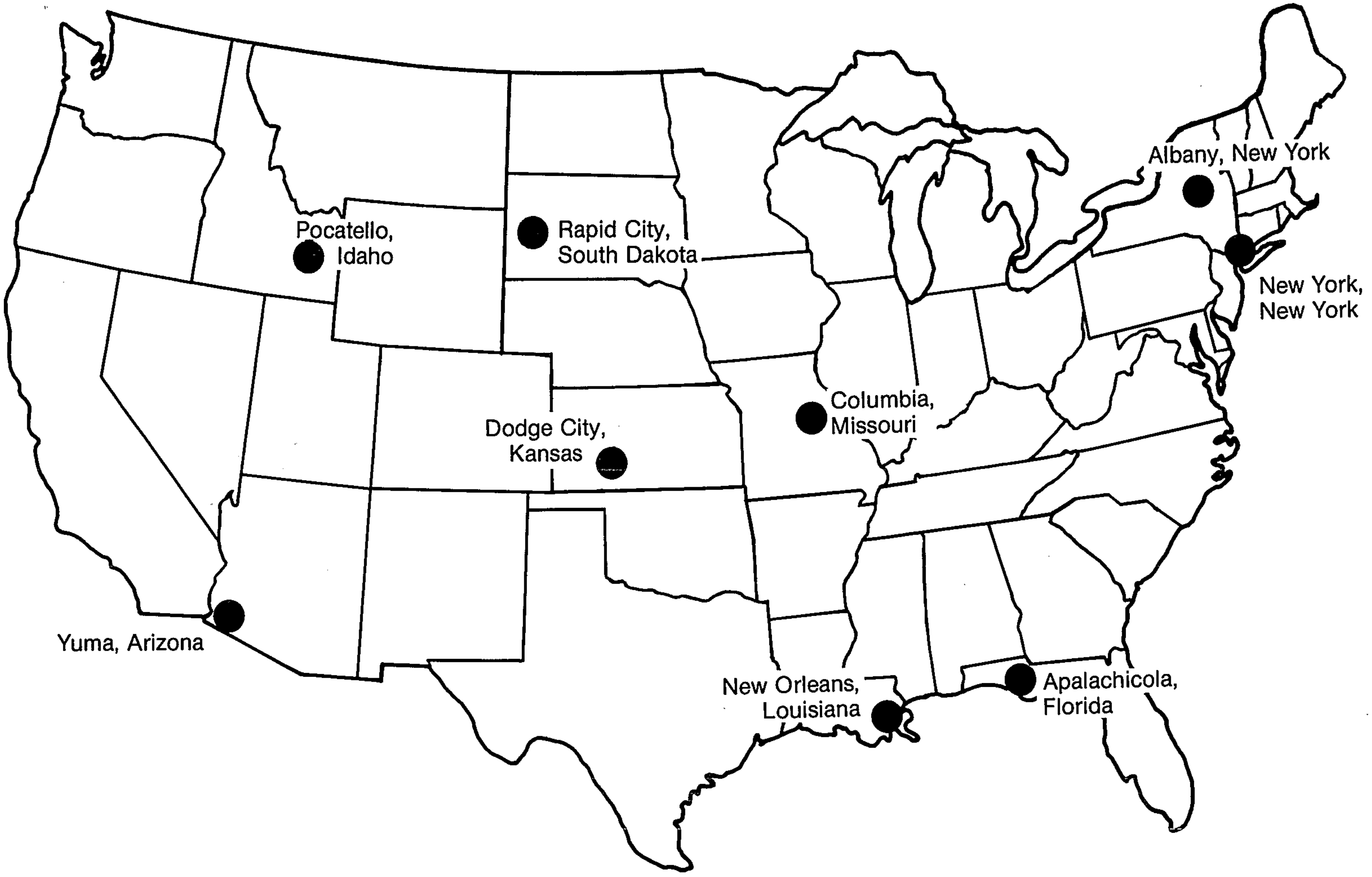


Figure 17. Location of cities in the United States utilized in solar-aided anaerobic digestion calculations.

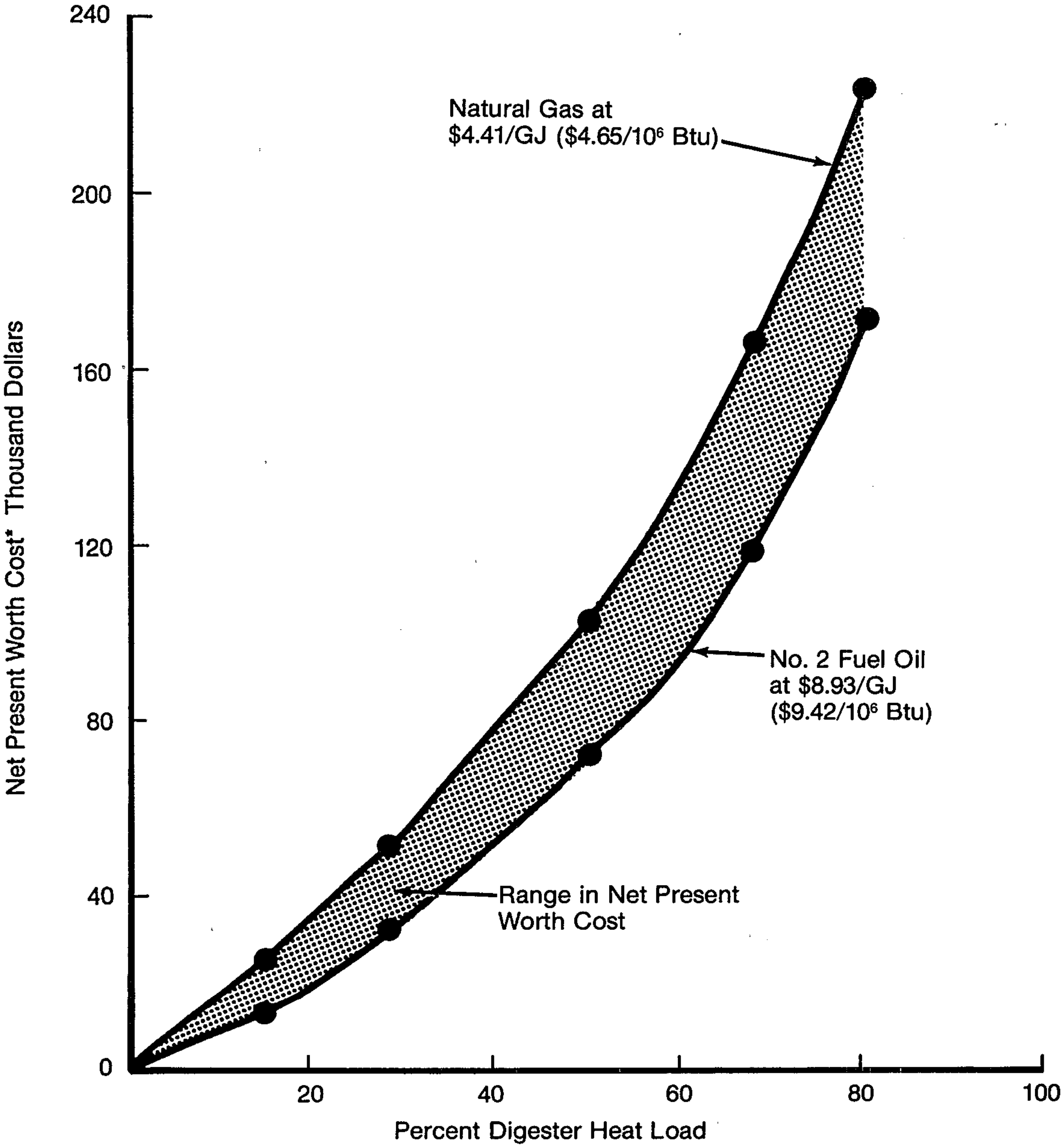
No cost savings are associated with the gas that may be generated in excess of that required for digester heating, as this gas would be available regardless of whether or not the solar energy system is installed.

For this analysis, a solar system cost (including collector, pumps, piping, insulation, heat exchanger, and appurtenances) of \$538.21/m^2 (\$50/ft^2) was used. In addition, a yearly operation and maintenance cost of 4 percent of initial installed capital cost was assumed. The annual maintenance cost (1 to 3 percent of installed capital cost (29)) was revised to 4 percent to include annual operating costs. As No. 2 fuel oil or natural gas is typically utilized for supplemental digester heating, the energy saved by installation of a solar collection system was assigned a cost value based on these two fuels, after consideration of the various energy conversion efficiencies (see Appendix B). Regional energy costs were used to more closely simulate market conditions. Natural gas prices for commercial users for December 1980 were utilized (nationwide average price, \$3.70/GJ; \$3.51/million Btu), as was October 1980 fuel oil costs to industrial customers (nationwide average price, \$226/m^3 (\$0.855/gallon); \$6.45/GJ (\$6.11/million Btu) (38)). For comparison purposes, electricity at \$0.05/kWh is equivalent to \$15.48/GJ (\$14.64/million Btu).

The cost-effectiveness analysis was performed utilizing the EPA-approved discount rate of 7-3/8 percent. The collectors were assumed to have a 20-year life, with zero salvage value after 20 years.

Results of Cost Analysis

Preliminary computations for the Rapid City, South Dakota 3,785 m^3/d (1 mgd) facility indicated that the net present worth cost of the solar collection equipped digester increased with increased size of collector areas. In other words, as the percent utilization of solar energy was increased (collector area), the difference between the total present worth of the solar collection system and the dollar value of the digester gas saved became greater. The calculated range in net present worth costs for various levels of solar energy utilization expressed as a percent of digester heat load is illustrated in Figure 18. A similar economic analysis for the 37,850 m^3/d (10 mgd) capacity plant revealed identical results, indicating that the cost of energy derived from solar collectors is significantly greater than the cost of energy derived from either No. 2 fuel oil or natural gas. In order to confirm these findings and to extrapolate to other geographical areas, the City of Yuma, Arizona, having a higher insolation value and a lower degree-day



*Net Present Worth = (Capital Cost) Collection + (Present Worth of O&M) Collector - Present Worth of Fuel Saved

Figure 18. Effect of incremental solar collector area on solar system net present worth (Rapid City, SD; plant capacity 3,785 m^3/d).

total than Rapid City, was evaluated. The results were found to be similar to the Rapid City site for the 37,850 m^3/d (10 mgd) plant capacity. In fact, the Yuma site was more expensive on the basis of present worth cost, since the overall system efficiency decreased. This reduction in system efficiency is due to the lower heat load requirement per unit area of collector resulting in decreased system performance. Based on these preliminary results, solar aided anaerobic digestion did not appear cost-effective, and a sensitivity analysis was performed to determine the controlling variables. The results of the present worth analysis are summarized in Tables 6 through 8.

Further investigations assessed the effect of feed solids concentration on the economic feasibility of solar aided anaerobic digestion, as feed sludge at a higher concentration has a lower sensible heat requirement and the smaller sludge volume allows for a smaller digester volume. However, as with the Rapid City versus Yuma comparison, the resulting smaller heat load/unit area collector caused the actual system efficiency to decrease, resulting in an increased present worth. The results at 6 percent and 8 percent feed solids are presented in Tables 9 and 10.

Sensitivity Analysis

The results of the economic evaluation indicated that active solar aided anaerobic digestion cannot be recommended for any location or treatment plant size within the United States. Several factors contributed to this conclusion including the unit price for the solar collector, the assumptions relative to the operation and maintenance cost, unit equivalent fuel price, etc. In order to evaluate the sensitivity of these various cost elements on net present worth cost, the cost analysis was repeated incorporating various ranges for these cost elements as follows:

1. Installed Capital Cost for Solar Collector System = \$161.50 to \$538.20/m^2 (\$15 to \$50/ft^2).
2. Annual Operation and Maintenance Cost = 1 to 4 percent of capital cost.
3. Escalation in Fuel Cost (geometric series present worth cost) = 4 to 8 percent.

In general, the cost evaluation results indicated that the most cost sensitive factor affecting the total net present worth of the solar collector system is the initial cost of installing the collector. In order for the technology to be economically viable at the present fuel costs, assuming a 4 percent annual

TABLE 6. NET PRESENT WORTH ANALYSIS, 3,785 m^3/d (1 mgd) FACILITY, RAPID CITY, SD

Solar Panel		Digester Heat Requirement		Available Solar Energy			Equivalent Annual[1] Savings, $/yr		Present Worth[2] Savings, $		Present Worth of Solar Equipment	Net Present Worth, $	
Area, m^2	(ft^2)	GJ	(10^6 Btu/yr)	GJ	(10^6 Btu/yr)	Percent Solar	No. 2 Fuel Oil	Natural Gas	No. 2 Fuel Oil	Natural Gas	$	No. 2 Fuel Oil	Natural Gas
46.5	(500)	1,102	(1,045)	165	(156)	15.0	1,470	725	20,600	10,100	35,300	14,700	25,200
92.9	(1,000)	1,102	(1,045)	312	(296)	28.3	2,790	1,380	39,000	19,300	70,600	31,600	51,300
186.0	(2,000)	1,102	(1,045)	560	(531)	50.8	5,000	2,470	69,900	34,500	141,000	71,300	107,000
279.0	(3,000)	1,102	(1,045)	751	(712)	68.1	6,710	3,310	93,800	46,300	212,000	118,000	166,000
372.0	(4,000)	1,102	(1,045)	895	(848)	81.2	7,990	3,940	112,000	55,100	282,000	170,000	227,000

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[1] Equivalent annual savings were calculated assuming No. 2 fuel oil at $8.93/GJ ($9.42/10^6 Btu) and natural gas at $4.41/GJ ($4.65/10^6 Btu). These numbers are energy costs at end point of use and have a built-in energy conversion efficiency of 65 percent.

[2] 20 years, 7 3/8 percent, 4 percent per annum escalation factor on both oil and gas, GESPWF = 13.98628.

TABLE 7. NET PRESENT WORTH ANALYSIS, 37,850 m^3/d (10 mgd) FACILITY, RAPID CITY, SD

Solar Panel		Digester Heat Requirement		Available Solar Energy			Equivalent Annual[1] Savings, $/yr		Present Worth[2] Savings, $		Present Worth of Solar Equipment	Net Present Worth, $	
Area, m^2	(ft^2)	GJ	(10^6 Btu/yr)	GJ	(10^6 Btu/yr)	Percent Solar	No. 2 Fuel Oil	Natural Gas	No. 2 Fuel Oil	Natural Gas	$	No. 2 Fuel Oil	Natural Gas
697	(7,500)	9,489	(8,994)	2,374	(2,250)	25.0	21,200	10,500	297,000	147,000	529,000	232,000	382,000
1,161	(12,500)	9,489	(8,994)	3,719	(3,525)	39.2	33,200	16,400	464,000	229,000	882,000	418,000	653,000
1,626	(17,500)	9,489	(8,994)	4,889	(4,634)	51.5	43,700	21,500	611,000	301,000	1,235,000	624,000	934,000
2,090	(22,500)	9,489	(8,994)	5,897	(5,590)	62.2	52,700	26,000	737,000	364,000	1,588,000	851,000	1,224,000
2,555	(27,500)	9,489	(8,994)	6,756	(6,404)	71.2	60,300	29,800	843,000	417,000	1,941,000	1,098,000	1,524,000

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[1] Equivalent annual savings were calculated assuming No. 2 fuel oil at $8.93/GJ ($9.42/10^6 Btu) and natural gas at $4.41/GJ ($4.65/10^6 Btu). These numbers are energy costs at end point of use and have a built-in energy conversion efficiency of 65 percent.

[2] 20 years, 7 3/8 percent, 4 percent per annum escalation factor on both oil and gas, GESPWF = 13.98628.

TABLE 8. NET PRESENT WORTH ANALYSIS, 3,785 m^3/d (1 mgd) FACILITY, YUMA, AZ

Solar Panel		Digester Heat Requirement		Available Solar Energy			Equivalent Annual[1] Savings, $/yr		Present Worth[2] Savings, $		Present Worth of Solar Equipment	Net Present Worth, $	
Area, m^2	(ft^2)	GJ	(10^6 Btu/yr)	GJ	(10^6 Btu/yr)	Percent Solar	No. 2 Fuel Oil	Natural Gas	No. 2 Fuel Oil	Natural Gas	$	No. 2 Fuel Oil	Natural Gas
46.5	(500)	762	(722)	154	(146)	20.2	1,350	914	18,900	12,800	35,300	16,400	22,500
92.9	(1,000)	762	(722)	287	(272)	37.7	2,520	1,700	35,200	23,800	70,600	35,400	46,800
186.0	(2,000)	762	(722)	495	(469)	65.0	4,340	2,940	60,700	41,100	141,000	80,500	100,000
279.0	(3,000)	762	(722)	636	(603)	83.5	5,580	3,770	78,000	52,700	212,000	134,000	159,000
372.0	(4,000)	762	(722)	716	(679)	94.0	6,290	4,250	88,000	59,400	282,000	194,000	223,000

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[1] Equivalent annual savings were calculated assuming No. 2 fuel oil at $9.77/GJ ($9.26/10^6 Btu) and natural gas at $6.60/GJ ($6.26/10^6 Btu). These numbers are energy costs at end point of use and have a built-in energy conversion efficiency of 65 percent.

[2] 20 years, 7 3/8 percent, 4 percent per annum escalation factor on both oil and gas, GESPWF = 13.98628.

TABLE 9. NET PRESENT WORTH ANALYSIS, 3,785 m^3/d (1 mgd) FACILITY, RAPID CITY, SD (DIGESTER FEED SOLIDS = 6 PERCENT)

Solar Panel Area, m^2	Solar Panel (ft^2)	Digester Heat Requirement GJ	Digester Heat Requirement (10^6 Btu/yr)	Available Solar Energy GJ	Available Solar Energy (10^6 Btu/yr)	Percent Solar	Equivalent Annual[1] Savings, $/yr No. 2 Fuel Oil	Equivalent Annual[1] Savings, $/yr Natural Gas	Present Worth[2] Savings, $ No. 2 Fuel Oil	Present Worth[2] Savings, $ Natural Gas	Present Worth of Solar Equipment $	Net Present Worth, $ No. 2 Fuel Oil	Net Present Worth, $ Natural Gas
46.5	(500)	749	(710)	160	(152)	21.4	1,430	710	20,000	9,930	35,300	15,300	25,400
92.9	(1,000)	749	(710)	296	(281)	39.6	2,650	1,310	37,100	18,300	70,600	33,500	52,300
186.0	(2,000)	749	(710)	504	(478)	67.3	4,500	2,220	62,900	31,000	141,000	98,300	110,000
279.0	(3,000)	749	(710)	639	(606)	85.3	5,710	2,820	79,900	39,400	212,000	132,000	172,000
372.0	(4,000)	749	(710)	707	(670)	94.4	6,310	3,110	88,300	43,500	282,000	194,000	239,000

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[1] Equivalent annual savings were calculated assuming No. 2 fuel oil at $8.93/GJ ($9.42/10^6 Btu) and natural gas at $4.41/GJ ($4.65/10^6 Btu). These numbers are energy costs at end point of use and have a built-in energy conversion efficiency of 65 percent.

[2] 20 years, 7 3/8 percent, 4 percent per annum escalation factor on both oil and gas, GESPWF = 13.98628.

TABLE 10. NET PRESENT WORTH ANALYSIS, 3,785 m^3/d (1 mgd) FACILITY, RAPID CITY, SD (DIGESTER FEED SOLIDS = 8 PERCENT)

Solar Panel Area, m^2	Solar Panel (ft^2)	Digester Heat Requirement GJ	Digester Heat Requirement (10^6 Btu/yr)	Available Solar Energy GJ	Available Solar Energy (10^6 Btu/yr)	Percent Solar	Equivalent Annual[1] Savings, $/yr No. 2 Fuel Oil	Equivalent Annual[1] Savings, $/yr Natural Gas	Present Worth[2] Savings, $ No. 2 Fuel Oil	Present Worth[2] Savings, $ Natural Gas	Present Worth of Solar Equipment $	Net Present Worth, $ No. 2 Fuel Oil	Net Present Worth, $ Natural Gas
46.5	(500)	475	(450)	153	(145)	32.2	1,365	670	19,100	9,370	35,300	16,200	25,900
92.9	(1,000)	475	(450)	271	(257)	57.1	2,420	1,190	33,800	16,600	70,600	36,800	54,000
186.0	(2,000)	475	(450)	417	(395)	87.8	3,720	1,835	52,000	25,700	141,000	89,200	116,000
279.0	(3,000)	475	(450)	464	(440)	97.8	4,140	2,040	57,900	28,500	212,000	154,000	183,000
372.0	(4,000)	475	(450)	472	(447)	99.3	4,210	2,080	58,900	29,100	282,000	223,000	253,000

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[1] Equivalent annual savings were calculated assuming No. 2 fuel oil at \$8.93/GJ (\$9.42/10^6 Btu) and natural gas at \$4.41/GJ (\$4.65/10^6 Btu). These numbers are energy costs at end point of use and have a built-in energy conversion efficiency of 65 percent.

[2] 20 years, 7 3/8 percent, 4 percent per annum escalation factor on both oil and gas, GESPWF = 13.98628.

fuel cost escalation, the collector system cost would have to be reduced to between \$161.50 and \$322.93/m^2 (\$15 to 30/ft^2). The results of this analysis are shown in Figures 19 and 20.

The second factor considered was the annual operation and maintenance cost for the solar collector system. In this analysis, 4 percent of the installed capital cost was used in the initial evaluation. However, with improvements in the design and construction of these facilities, the O&M costs can be potentially reduced. For this reason, a range of annual O&M costs between 1 and 4 percent were evaluated. These results are presented in Figure 21. In addition, these computations were based on a unit installation cost of \$161.50 m^2 (\$15/ft^2) so that the effects of the reduced O&M costs could be illustrated. Based on these results, it can be concluded that the total costs are sensitive to O&M costs, particularly in marginal applications. However, the capital cost of the collector system is still the major cost consideration.

Current EPA cost-effectiveness analysis guidelines utilize a 4 percent per annum escalation factor on natural gas only. This 4 percent escalation, however, was also applied to fuel oil in this analysis. As the Regional Administrators of EPA can dictate a different escalation factor, and owing to future market uncertainties, escalation rates of 4, 6, and 8 percent at an interest rate of 7-3/8 percent over a 20-year period were considered. The geometric series present worth factor (GESPWF) was utilized to compute present worth values of equivalent energy savings realized from solar collector systems. These results are presented in Figure 22, and indicate that the appreciation of fuel prices at 4, 6, and 8 percent per annum do not, by themselves, make for a cost-effective solution at a solar system cost of \$538.21/m^2 (\$50/ft^2). Therefore, for the range of 4 to 8 percent, the overall analysis is not sensitive to fuel escalation factors.

It should be noted that a fuel escalation rate of 4 percent per annum over the 20-year planning period is higher than DOE projected price increases (41).

Based on the information presented on a net present worth basis, the solar heating of anaerobic digesters is not cost-effective given the current prices for the solar collection system and conventional fuels. This conclusion was identical for the 3,785 m^3/d (1 mgd) and 37,850 m^3/d (10 mgd) facilities. The facility location did not impact the conclusions.

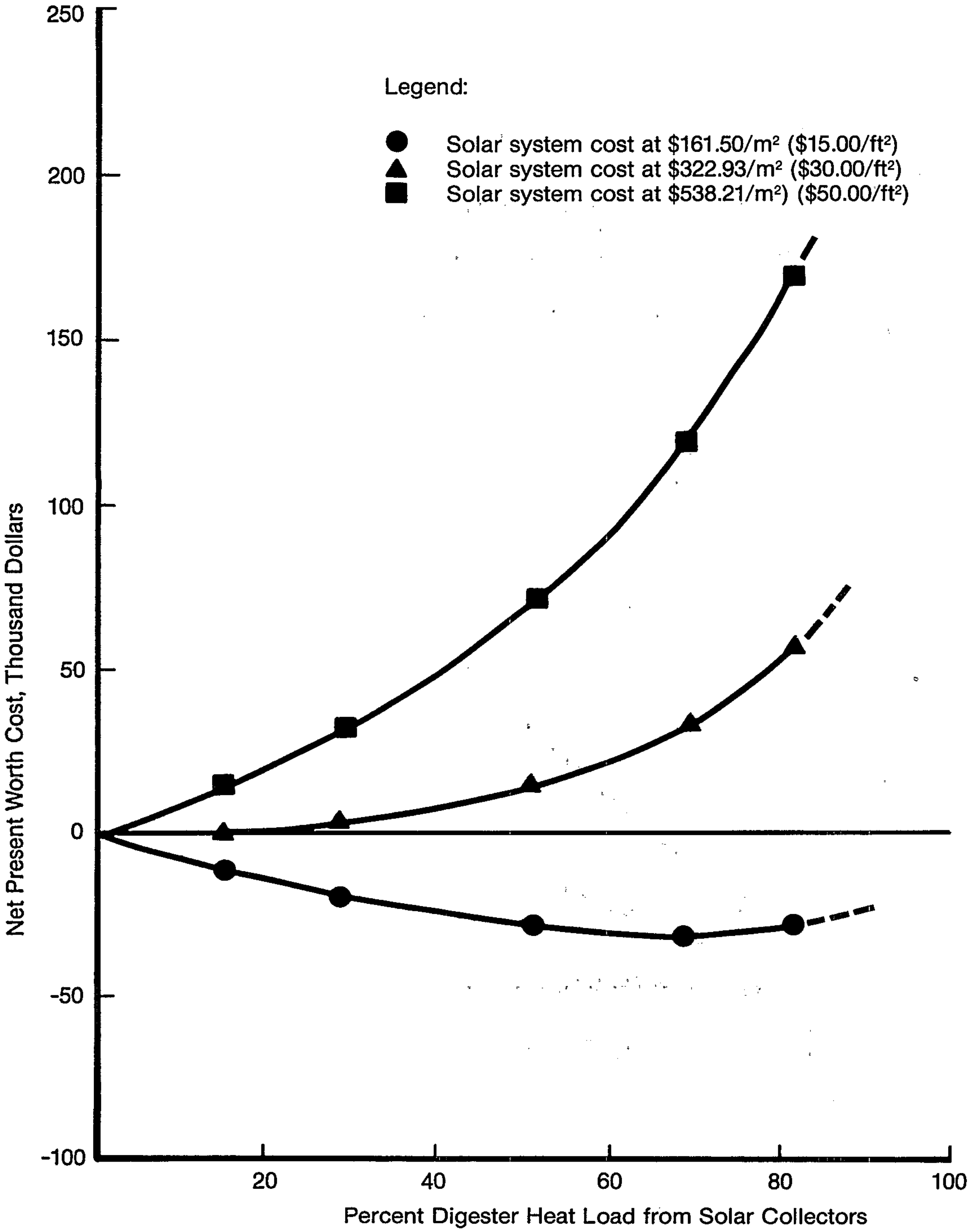

Figure 19. Effect of solar system cost on net present worth cost (Rapid City, SD; plant capacity 3,785 m^3/d; No. 2 fuel oil used as basis for comparison).

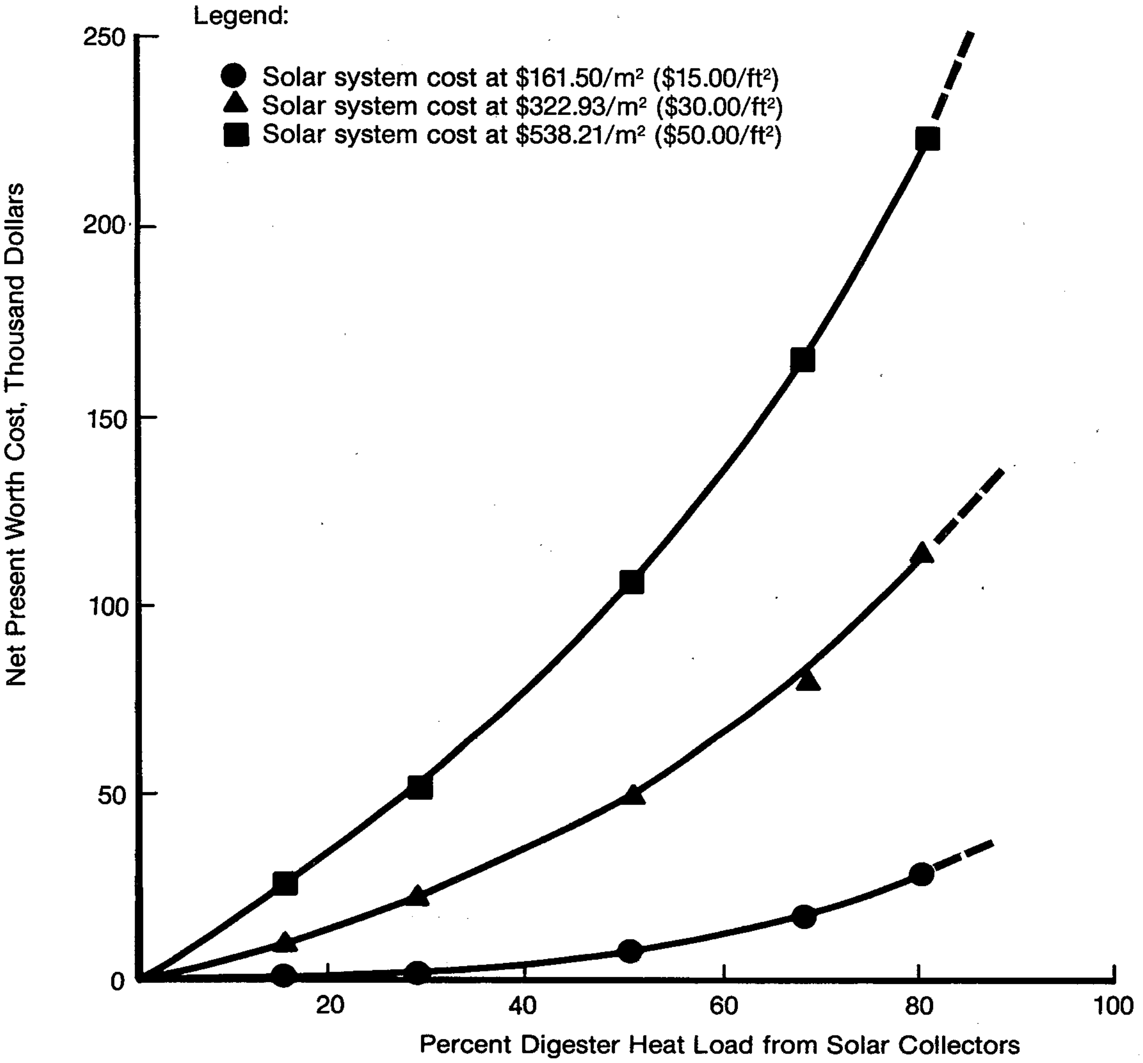

Figure 20. Effect of solar system cost on net present worth cost (Rapid City, SD; plant capacity 3,785 m^3/d; natural gas used as basis for comparison).

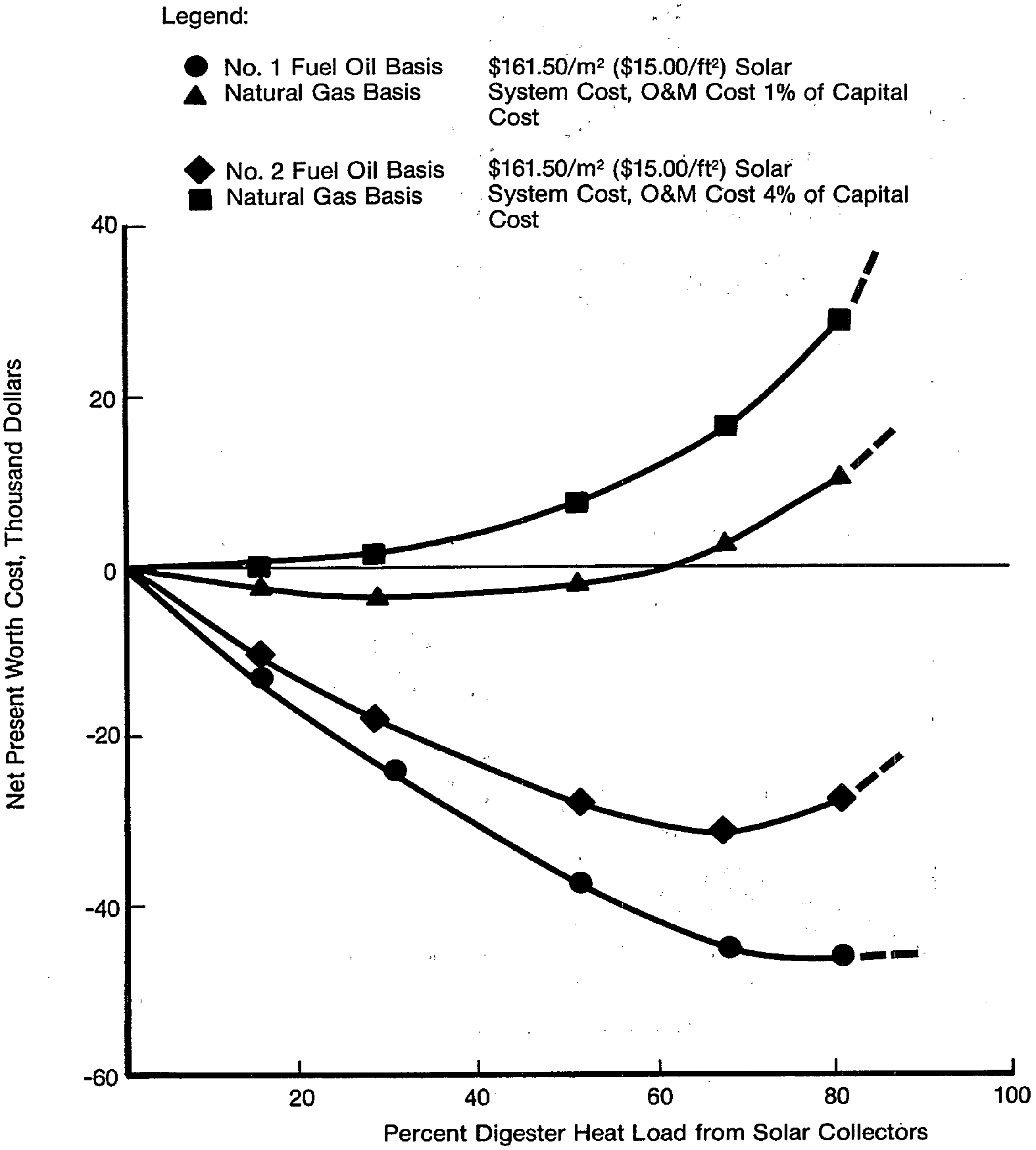

Figure 21. Effect of operations and maintenance cost on net present worth cost (Rapid City, SD; plant capacity 3,785 m^3/d).

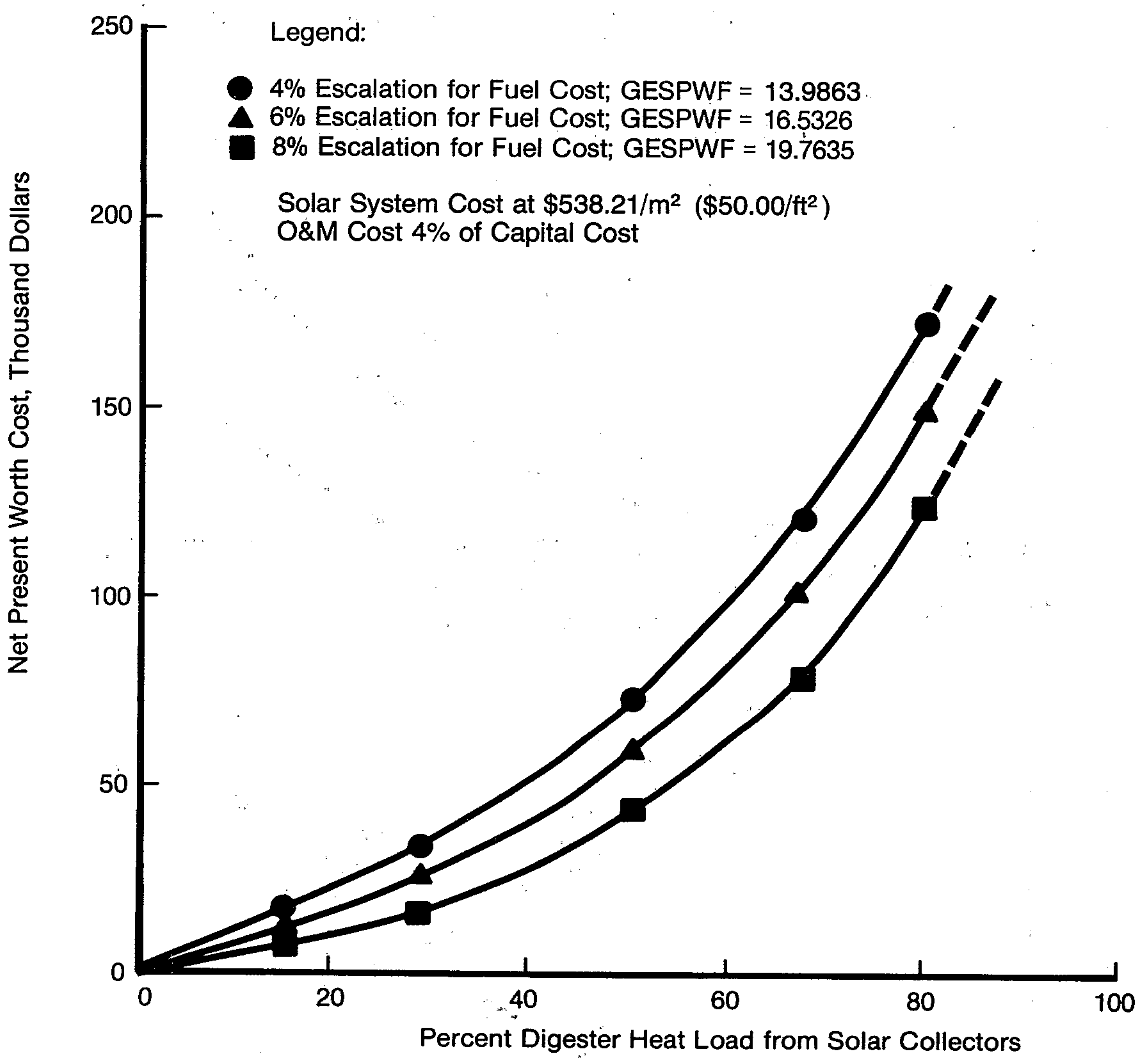

Figure 22. Effect of fuel price escalation factor on net present worth cost (Rapid City, SD; plant capacity 3,785 m^3/d; No. 2 fuel oil used as basis for comparison).

It should be noted that numerous previously referenced articles (25,36,39,40) all discussed the fact that most design procedures have over-estimated the amount of energy actually collected by the system. This places additional doubt on the cost-effectiveness of solar aided anaerobic digestion.

A final comment is in order, as previous research (18) indicated that solar aided anaerobic digestion was cost-effective at every location within the United States. The discrepancy between the previous and current research is due to the questionable cost-effectiveness analysis, as the authors used a 12 percent per annum escalation factor in the cost of natural gas. If the present worth analysis presented in Reference 18 is redone utilizing the geometric series present worth factor at 4 percent escalation for 20 years at 7-3/8 percent, the analysis indicates that the solar system is not cost-effective.

ENERGY CONSIDERATIONS

With the exception of any energy used for pumps or blowers in the solar energy system, all energy produced is a net energy gain. As solar aided anaerobic digestion does not appear cost-effective, there will be minimal use of the technology, and all potential energy savings are associated with POTW space heating.

SECTION 5

NATIONAL IMPACT ASSESSMENT

MARKET POTENTIAL

Because collection of solar energy for heating anaerobic digesters does not appear to be cost-effective given the present cost of collector systems, resulting in a high cost per unit of energy, it is not considered as currently having a market potential. However, if solar collector system costs decrease substantially, or conventional fuel costs increase dramatically, solar-heated digesters may prove cost-effective. (See Section 4 for further details).

Active solar-aided sludge drying is an unproven technology and, given the high costs of solar energy production from active systems, is more than likely not economically attractive. The feasibility of a passive sludge dryer should be investigated further.

Therefore, the only potential market for solar applications at POTW's would appear to be for space/domestic hot water heating. The potential for active and passive space heating should be investigated on a case by case basis. Utilizing data from the 1978 Needs Survey (42), as of 1978, 14,592 treatment plants were in operation, with an additional 8,176 facilities planned by the year 2000. Therefore, a great potential for the application of solar energy technology for space heating exists, with implementation dependent on economic feasibility.

COST AND ENERGY IMPACT

The implementation of solar space heating for retrofitting existing facilities and for construction of new facilities could reduce the conventional energy requirements of POTW's (see Table 1). However, all decisions must be based on firm engineering judgment and engineering economics.

RISK ASSESSMENT

There is a small risk associated with the application of solar space heating in POTW's. The risk involved can be divided into two areas. First, solar collection systems have not typically been operating at their design efficiencies. Second, as the technology is relatively new, there are little data to assess the long-term maintenance requirements and system life.

SECTION 6

RECOMMENDATIONS

FURTHER RESEARCH AND DEVELOPMENT EFFORTS

The only area for which further research efforts appear warranted is passive sludge drying. Efforts could include both conceptual design and pilot testing. There is presently a great deal of research being conducted on space heating and process thermal energy conversion.

Once finalized, the results and conclusions of the Wilton, Maine energy systems monitoring report should be compared to the analysis contained here. If the final report confirms the findings of this study (as the preliminary report results have indicated), then no additional research on active solar energy collection and utilization is warranted.

PROCESS/TECHNOLOGY MODIFICATIONS

Aside from any potential modifications to the conceptual design of the passive sludge dryer, no additional process or technology modifications are required. Precluding any major advances in solar energy technology, there appear to be limited uses of solar thermal energy in POTW's with the exception of building/space heating.

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APPENDIX A[1]

DESIGN AND EVALUATION OF SOLAR AIDED ANAEROBIC DIGESTER HEATING

OBJECTIVES

This appendix describes the methodology utilized for evaluating the economics of digester heating using active solar energy collection. Since the solar energy recovery potential is a function of sunlight hours and geographical location (latitude), three geographical regions were considered for the evaluation, as follows:

1. Northern United States
2. Middle United States
3. Southern United States

Based on the climatological data within each region, nine model cities were selected for evaluating the potential for solar anaerobic digester heating. These model cities were selected on the basis of their total annual degree-days (an indication of the annual heating load) and horizontal incident solar radiation data. The purpose of city selection was to choose three cities in each of the three areas with an equivalent number of degree days, yet with varying insolation rates. In this way, it was hoped that for a given climate (i.e., number of annual degree-days), a correlation could be made between insolation rate and economic feasibility of solar digester heating, and thereby allow for some national or regional conclusions to be derived. The selected cities and their respective data are summarized in Table A-1. Furthermore, to assess the effect of plant size, solar aided anaerobic digestion was investigated for treatment facilities having a design capacity of 3,785 and 37,850 m^3/d (1 and 10 mgd).

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[1] This appendix utilizes both traditional (English) and SI units, as existing equipment specifications and design procedures are based on English units.

TABLE A-1. SUMMARY OF CLIMATOLOGICAL DATA FOR MODEL U.S. CITIES

City	Geographical region	Latitude	Annual degree days	Horizontal[1] radiation (Btu/sq ft)
Apalachiola, FL	Southern	29.45	1,308	1,539
New Orleans, LA	Southern	29.59	1,385	1,316
Yuma, AZ	Southern	32.40	1,217	1,629
Columbia, MO	Middle	38.58	5,046	1,193
Dodge City, KS	Middle	37.46	4,986	1,399
New York, NY	Middle	40.46	5,000	964
Albany, NY	Northern	42.40	6,875	946
Pocatello, ID	Northern	42.55	7,033	1,216
Rapid City, SD	Northern	44.09	7,345	1,156

[1] Horizontal radiation values for month of October have been taken as typical values for this evaluation.

DIGESTER AND HEAT LOAD SIZING

Two-stage high rate mesophilic anaerobic digesters for the 3,785 and 37,850 m^3/d (1 and 10 mgd) facilities were sized by assuming primary and secondary sludge generation rates, sludge solids concentration, and a mass volatile solids loading rate in the first stage. The assumptions utilized for design are presented in Appendix B.

The total heat load associated with digester operations consists of two components:

$$\text{Total Heating Requirement} = \text{Sludge Heating Requirement} + \text{Digester Heat Loss}$$

The sludge heating requirement (sensible heat requirement) to preheat the sludge to 35 degrees C (95 degrees F) was calculated assuming the sludge to have a specific heat of 1.0 Btu/$^{\circ}$F-lb:

$$\text{Sludge Heating Requirement, Btu/yr} = (\text{Sludge Feed Rate, lb/yr}) \; \frac{1\ \text{Btu}}{1^{\circ}\text{F-lb}} \; (95^{\circ}\text{F} - \text{Sludge Temperature, }^{\circ}\text{F}) \; (\text{hr/yr})$$

Sludge temperatures were assumed to vary monthly and different influent temperatures were used for each of the three zones of the United States (Table B-1).

Utilizing typical heat transfer coefficients for digester components (Appendix B), the heat loss due to heat radiation from the digester was calculated:

Heat Loss from Digester, Btu/yr = [Heat Loss Through (Roof + Walls + Floor) Btu/hr] (hr/yr)

The total heat loss from the digester structure was calculated utilizing monthly average weather data (ambient air temperature). A summation of the sensible heat requirement plus the radiant heat requirement yields an equation for the total heat requirement, which is then solved on a monthly basis for the nine different cities.

In order to assess the effect of plant size on the feasibility of solar-aided anaerobic digester heating, the calculations were done for both 3,785 and 37,850 m^3/d (1 and 10 mgd) facilities. The total digester heat load requirements for a 3,785 m^3/d (1 mgd) facility with a digester feed solids concentration of 4 percent (dry weight basis) are summarized in Tables A-2 through A-10 for each of the selected cities. The tables also include the average ambient temperature and average daily insolation data. Similarly, the data for the 37,850 m^3/d (10 mgd) facilities are summarized in Tables A-11 through A-19.

SOLAR COLLECTOR DESIGN

Based on the digester head load requirements, the solar energy which can be potentially utilized from various collector areas was computed from each size and for the two design capabilities. The collector area selected for evaluating the 3,785 m^3/d (1 mgd) plant include: 46.5, 92.9, 186, 279, and 372 m^2 (500, 1,000, 2,000, 3,000, and 4,000 ft^2). The collector areas selected for the 37,850 m^3/d (10 mgd) plant include: 697, 1,161, 1,626, 2,090, and 2,555 m^2 (7,500, 12,500 17,500, 22,500, and 27,500 ft^2). Collector area sizes were selected on the basis of available solar insolation versus heating load after consideration of collector efficiency.

All computations involving solar collector system efficiency were done utilizing the f-chart analysis procedure. All calculations were performed utilizing WESTON's program entitled SOLECO, a computerized f-chart analysis.

TABLE A-2. DESIGN CALCULATIONS - RAPID CITY, SD, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, ^oF	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	23.0	0.141	744	105.0	1,611	31	49,941
February	26.6	0.136	672	91.6	1,850	28	51,800
March	32.0	0.131	744	97.2	1,954	31	60,574
April	44.6	0.120	720	86.7	1,723	30	51,690
May	53.6	0.112	744	83.7	1,546	31	47.926
June	64.4	0.103	720	74.4	1,559	30	46,770
July	71.6	0.097	744	71.8	1,628	31	50,468
August	69.8	0.100	744	74.5	1,757	31	54,467
September	59.0	0.109	720	78.6	1,840	30	55,200
October	48.2	0.118	744	88.0	1,889	31	58,559
November	35.6	0.128	720	92.5	1,646	30	49,380
December	28.4	0.135	744	101.0	1,466	31	45,446

TABLE A-3. DESIGN CALCULATIONS - POCATELLA, ID, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, ^oF	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	24.8	0.140	744	104.0	1,259	31	39,029
February	30.2	0.134	672	90.1	1,521	28	42,588
March	33.8	0.130	744	96.4	1,690	31	52,390
April	44.6	0.120	720	86.7	1,821	30	54,630
May	53.6	0.112	744	83.7	1,640	31	50,840
June	60.8	0.106	720	76.0	1,678	30	50,340
July	69.8	0.098	744	72.7	1,797	31	55,707
August	68.0	0.101	744	75.3	1,886	31	58,466
September	59.0	0.109	720	78.6	2,017	30	60,510
October	48.2	0.118	744	88.0	1,926	31	59,706
November	35.6	0.128	720	92.5	1,533	30	45,990
December	28.4	0.135	744	101.0	1,307	31	40,517

TABLE A-4. DESIGN CALCULATIONS - ALBANY, NY, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	23.0	0.141	744	105.0	828	31	25,668
February	24.8	0.137	672	92.4	995	28	27,860
March	32.0	0.131	744	97.2	1,559	31	48,329
April	46.4	0.119	720	85.9	1,229	30	36,870
May	57.2	0.110	744	82.0	1,252	31	38,812
June	66.2	0.102	720	73.6	1,553	30	46,590
July	71.6	0.097	744	71.8	1,442	31	44,702
August	69.8	0.100	744	74.5	1,403	31	43,493
September	62.6	0.107	720	77.0	1,222	30	36,660
October	50.0	0.117	744	87.2	1,382	31	42,842
November	39.2	0.126	720	90.9	1,677	30	50,310
December	28.4	0.135	744	101.0	1,120	31	34,720

TABLE A-5. DESIGN CALCULATIONS - NEW YORK, NY, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	32.0	0.123	744	91.8	941	31	29,171
February	32.0	0.121	672	81.3	1,133	28	31,724
March	39.2	0.114	744	84.9	1,384	31	42,904
April	50.0	0.105	720	75.6	1,346	30	40,380
May	60.8	0.096	744	71.4	1,402	31	43,462
June	69.8	0.088	720	63.3	1,511	30	45,330
July	75.2	0.082	744	61.2	1,533	31	47,523
August	73.4	0.086	744	63.8	1,657	31	51,367
September	68.0	0.092	720	65.9	1,476	30	44,280
October	57.2	0.101	744	74.9	1,359	31	42,129
November	46.4	0.110	720	79.0	982	30	29,460
December	33.8	0.120	744	89.1	867	31	26,877

TABLE A-6. DESIGN CALCULATIONS - DODGE CITY, KS, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, ^oF	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	30.2	0.124	744	92.6	1,829	31	56,699
February	33.8	0.120	672	80.5	1,851	28	51,828
March	41.0	0.113	744	84.1	1,938	31	60,078
April	53.6	0.103	720	74.0	1,908	30	57,240
May	62.6	0.095	744	70.6	1,677	31	51,987
June	73.4	0.086	720	61.7	1,804	30	54,120
July	78.8	0.080	744	59.4	1,842	31	57,102
August	77.0	0.084	744	62.2	1,910	31	59,210
September	68.0	0.092	720	65.9	2,022	30	60,660
October	55.4	0.102	744	75.7	2,026	31	62,806
November	41.0	0.113	720	81.3	1,875	30	56,250
December	32.0	0.121	744	90.0	1,732	31	53,692

TABLE A-7. DESIGN CALCULATIONS - COLUMBIA, MO, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	30.2	0.124	744	92.6	1,168	31	36,208
February	32.0	0.121	672	81.3	1,353	28	37,884
March	42.8	0.112	744	83.2	1,508	31	46,748
April	53.6	0.103	720	74.0	1,527	30	45,810
May	64.4	0.094	744	69.8	1,602	31	49,662
June	73.4	0.086	720	61.7	1,602	30	48,060
July	77.0	0.081	744	60.4	1,660	31	51,460
August	75.2	0.085	744	63.0	1,740	31	53,940
September	68.0	0.092	720	65.9	1,841	30	55,230
October	57.2	0.101	744	74.9	1,699	31	52,669
November	42.8	0.112	720	80.6	1,429	30	42,870
December	32.0	0.121	744	90.0	1,178	31	36,518

TABLE A-8. DESIGN CALCULATIONS - APALACHICOLA, FL, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	53.6	0.098	744	72.9	1,677	31	51,987
February	55.4	0.094	672	63.5	1,773	28	49,644
March	59.0	0.090	744	66.8	1,756	31	54,436
April	66.2	0.830	720	59.8	1,769	30	53,070
May	73.4	0.076	744	56.7	1,651	31	51,181
June	78.8	0.070	720	50.7	1,494	30	44,820
July	80.6	0.067	744	49.7	1,428	31	44,268
August	80.6	0.069	744	51.6	1,522	31	47,182
September	78.8	0.073	720	52.4	1,679	30	50,370
October	69.8	0.081	744	60.1	1,937	31	60,047
November	60.8	0.089	720	63.9	1,865	30	55,950
December	55.4	0.094	744	70.3	1,568	31	48,608

TABLE A-9. DESIGN CALCULATIONS - NEW ORLEANS, LA, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	51.8	0.099	744	73.7	1,125	31	34,875
February	55.4	0.094	672	63.5	1,174	28	32,872
March	59.0	0.090	744	66.8	1,292	31	40,052
April	68.0	0.082	720	59.0	1,324	30	39,720
May	73.4	0.076	744	56.7	1,256	31	38,936
June	78.8	0.070	720	50.7	1,170	30	35,100
July	80.6	0.067	744	49.7	1,137	31	35,247
August	80.6	0.069	744	51.6	1,259	31	39,029
September	77.0	0.074	720	53.2	1,381	30	41,430
October	68.0	0.082	744	60.9	1,610	31	49,910
November	59.0	0.090	720	64.7	1,490	30	44,700
December	53.6	0.096	744	71.1	1,082	31	33,542

TABLE A-10. DESIGN CALCULATIONS - YUMA, AZ, 3,785 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	51.8	0.099	744	73.7	1,376	31	42,656
February	53.6	0.096	672	64.2	1,486	28	41,608
March	60.8	0.089	744	66.0	1,693	31	52,483
April	66.2	0.083	720	59.8	1,565	30	46,950
May	73.4	0.076	744	56.7	1,515	31	46,965
June	78.8	0.070	720	50.7	1,252	30	37,560
July	80.6	0.067	744	49.7	1,448	31	44,888
August	80.6	0.069	744	51.6	1,623	31	50,313
September	77.0	0.074	720	53.2	1,552	30	46,560
October	68.0	0.082	744	60.9	1,604	31	49,724
November	59.0	0.090	720	64.7	2,140	30	64,200
December	53.6	0.096	744	71.1	1,992	31	61,752

TABLE A-11. DESIGN CALCULATIONS - RAPID CITY, SD, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	23.0	1.164	744	866	1,611	31	49,941
February	26.6	1.129	672	759	1,850	28	51,800
March	32.0	1.091	744	811	1,954	31	60,574
April	44.6	1.032	720	743	1,723	30	51,690
May	53.6	0.983	744	732	1,546	31	47,926
June	64.4	0.930	720	670	1,559	30	46,770
July	71.6	0.886	744	659	1,628	31	50,468
August	69.8	0.915	744	681	1,757	31	54,467
September	59.0	0.969	720	697	1,840	30	55,200
October	48.2	1.022	744	761	1,889	31	58,559
November	35.6	1.081	720	778	1,646	30	49,380
December	28.4	1.124	744	837	1,466	31	45,446

TABLE A-12. DESIGN CALCULATIONS - POCATELLO, ID, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	24.8	1.159	744	862	1,259	31	39,029
February	30.2	1.119	672	752	1,521	28	42,588
March	33.8	1.086	744	808	1,690	31	52,390
April	44.6	1.032	720	743	1,821	30	54,630
May	53.6	0.959	744	714	1,640	31	50,840
June	60.8	0.940	720	677	1,678	30	50,340
July	69.8	0.891	744	663	1,797	31	55,707
August	68.0	0.920	744	685	1,886	31	58,466
September	59.0	0.969	720	697	2,017	30	60,510
October	48.2	1.022	744	761	1,926	31	59,706
November	35.6	1.081	720	778	1,533	30	45,990
December	28.4	1.124	744	837	1,307	31	40,517

TABLE A-13. DESIGN CALCULATIONS - ALBANY, NY, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, ^oF	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	23.0	1.164	744	866	828	31	25,668
February	24.8	1.134	672	762	995	28	27,860
March	32.0	1.091	744	811	1,559	31	48,329
April	46.4	1.027	720	740	1,229	30	36,870
May	57.2	0.974	744	724	1,252	31	38,812
June	66.2	0.925	720	666	1,553	30	46,590
July	71.6	0.886	744	659	1,442	31	44,702
August	69.8	0.915	744	681	1,403	31	43,493
September	62.6	0.959	720	690	1,222	30	36,660
October	50.0	1.017	744	757	1,382	31	42,842
November	39.2	1.071	720	771	1,677	30	50,310
December	28.4	1.124	744	837	1,120	31	34,720

TABLE A-14. DESIGN CALCULATIONS - NEW YORK, NY, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	32.0	1.019	744	758	941	31	29,171
February	32.0	0.995	672	668	1,133	28	31,724
March	39.2	0.950	744	707	1,384	31	42,904
April	50.0	0.896	720	645	1,346	30	40,380
May	60.8	0.843	744	627	1,402	31	43,462
June	69.8	0.794	720	572	1,511	30	45,330
July	75.2	0.755	744	562	1,533	31	47,523
August	73.4	0.784	744	584	1,657	31	51,367
September	68.0	0.823	720	593	1,476	30	44,280
October	57.2	0.877	744	652	1,359	31	42,129
November	46.4	0.930	720	670	982	30	29,460
December	33.8	0.990	744	736	867	31	26,877

TABLE A-15. DESIGN CALCULATIONS - DODGE CITY, KS, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	30.2	1.023	744	761	1,829	31	56,699
February	33.8	0.990	672	665	1,851	28	51,828
March	41.0	0.945	744	703	1,938	31	60,078
April	53.6	0.886	720	638	1,908	30	57,240
May	62.6	0.838	744	623	1,677	31	51,987
June	73.4	0.784	720	565	1,804	30	54,120
July	78.8	0.746	744	555	1,842	31	57,102
August	77.0	0.774	744	576	1,910	31	59,210
September	68.0	0.823	720	593	2,022	30	60,660
October	55.4	0.882	744	656	2,026	31	62,806
November	41.0	0.945	720	680	1,875	30	56,250
December	32.0	0.995	744	740	1,732	31	53,692

TABLE A-16. DESIGN CALCULATIONS - COLUMBIA, MO, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	30.2	1.023	744	761	1,168	31	36,208
February	32.0	0.995	672	668	1,353	28	37,884
March	42.8	0.940	744	699	1,508	31	46,748
April	53.6	0.886	720	638	1,527	30	45,810
May	64.4	0.833	744	620	1,602	31	49,662
June	73.4	0.784	720	565	1,602	30	48,060
July	77.0	0.750	744	558	1,660	31	51,460
August	75.2	0.779	744	580	1,740	31	53,940
September	68.0	0.823	720	593	1,841	30	55,230
October	57.2	0.877	744	652	1,699	31	52,669
November	42.8	0.940	720	677	1,429	30	42,870
December	32.0	0.995	744	740	1,178	31	36,518

TABLE A-17. DESIGN CALCULATIONS - APALACHICOLA, FL, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	53.6	0.838	744	624	1,677	31	51,987
February	55.4	0.810	672	544	1,773	28	49,644
March	59.0	0.775	744	576	1,756	31	54,436
April	66.2	0.731	720	526	1,769	30	53,070
May	73.4	0.687	744	511	1,651	31	51,181
June	78.8	0.649	720	470	1,494	30	44,820
July	80.6	0.620	744	461	1,428	31	44,268
August	80.6	0.644	744	479	1,522	31	47,182
September	78.8	0.673	720	484	1,679	30	50,370
October	69.8	0.721	744	537	1,937	31	60,047
November	60.8	0.770	720	554	1,865	30	55,950
December	55.4	0.810	744	602	1,568	31	48,608

TABLE A-18. DESIGN CALCULATIONS - NEW ORLEANS, LA, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	51.8	0.843	744	627	1,125	31	34,875
February	55.4	0.810	672	544	1,174	28	32,872
March	59.0	0.775	744	576	1,292	31	40,052
April	68.0	0.726	720	523	1,324	30	39,720
May	73.4	0.687	744	511	1,256	31	38,936
June	78.8	0.649	720	467	1,170	30	35,100
July	80.6	0.620	744	461	1,137	31	35,247
August	80.6	0.644	744	479	1,259	31	39,029
September	77.0	0.677	720	488	1,381	30	41,430
October	68.0	0.726	744	540	1,610	31	49,910
November	59.0	0.775	720	558	1,490	30	44,700
December	53.6	0.814	744	606	1,082	31	33,542

TABLE A-19. DESIGN CALCULATIONS - YUMA, AZ, 37,850 m^3/d FACILITY

Month	Average Ambient Temperature, °F	Hourly Heat Load, Btu x 10^6	Hours Per Month	Monthly Heat Load Btu x 10^6	Average Daily Insolation, Btu/sq ft	Days Per Month	Monthly Insolation, Btu/sq ft
January	51.8	0.843	744	627	1,376	31	42,656
February	53.6	0.814	672	547	1,486	28	41,608
March	60.8	0.770	744	573	1,693	31	52,483
April	66.2	0.731	720	526	1,565	30	46,950
May	73.4	0.687	744	511	1,515	31	46,965
June	78.8	0.649	720	467	1,252	30	37,560
July	80.6	0.619	744	461	1,448	31	44,888
August	80.6	0.644	744	479	1,623	31	50,313
September	77.0	0.677	720	488	1,552	30	46,560
October	68.0	0.726	744	540	1,604	31	49,724
November	59.0	0.775	720	558	2,140	30	64,200
December	53.6	0.814	744	606	1,992	31	61,752

APPENDIX B

DESIGN AND EVALUATION OF SOLAR AIDED ANAEROBIC DIGESTER HEATING: ASSUMPTIONS

1. Primary sludge production rate: 0.625 tons (dry weight) of primary sludge per million gallons of wastewater treated. Primary sludge solids concentration at 5 percent by weight.

2. Waste activated sludge production rate: 0.535 tons (dry weight) per million gallons of wastewater treated. Thickened waste activated sludge concentration at 2.8 percent by weight.

3. Total undigested sludge production rate: 1.16 tons (dry weight basis) per million gallons of wastewater treated. Digester feed sludge concentration at 4 percent by weight. Volatile fraction in digester feed is approximately 0.68 by weight.

4. Volatile solids loading to the primary digester is assumed at 0.16 lb VSS/ft^3-day.

5. Digester dimensions for the 1 mgd case were calculated by assuming equal diameter and sidewater depth. This will minimize heat loss from exposed digester surfaces. For 10 mgd facility, a maximum digester depth of 40 feet was used. One digester (including primary and secondary stages) rather than two digesters was used to minimize heat losses.

6. Operating temperature for the primary digester is assumed at 35 degrees C (95 degrees F) (mesophilic conditions). No heating of the secondary digester is provided.

7. The influent sludge temperatures are assumed to vary at the rate of 0.56 degrees C (1 degree F) per month with average temperatures occurring during the months of April and October of each year. The assumed influent sludge temperatures for the three geographical regions are shown summarized in Table B-1.

8. The thermal capacity of digester feed sludge is assumed equal to that of water (specific heat of sludge = 1.0 Btu/^{o}F-lb).

9. The following heat transfer coefficients were used (37):

Floating cover with built-up roof	- 0.24 Btu/hr-ft^2
12-inch thick concrete walls	- 0.25 Btu/hr-ft^2
Floor and surrounding soil	- 0.12 Btu/hr-ft^2

   The soil temperature was assumed equal to the monthly ambient air temperature.

10. The rate of gas production from anaerobic digestion has been assumed at 15 ft^3 per pound of volatile suspended solids destroyed.

11. For evaluating overall process economics, the heating values for digester gas, No. 2 fuel oil, and natural gas have been assumed as 600 Btu/ft^3, 140,000 Btu/gallon, and 1,000 Btu/ft^3, respectively. In addition, a combustion efficiency of 65 percent is assumed for the conversion of either natural gas or fuel oil to energy supplied to the digester contents when calculating the dollar value of digester gas.

12. Facilities to store and utilize the excess digester gas are assumed to be existing and of sufficient capacity to utilize any additional gas saved due to the application of solar digester heating.

TABLE B-1. ASSUMED FEED SLUDGE TEMPERATURES FOR THE THREE GEOGRAPHICAL REGIONS[1]

Month	Northern U.S. °F	Middle U.S. °F	Southern U.S. °F
January	55	60	65
February	56	61	66
March	57	62	67
April	58	63	68
May	59	64	69
June	60	65	70
July	61	66	71
August	60	65	70
September	59	64	69
October	58	63	68
November	57	62	67
December	56	61	66

[1] Average yearly temperatures of sludge for each region from Reference 16.

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