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ACTIVE SOLAR HEATING SYSTEMS DESIGN MANUAL

American Society of Heating, Refrigerating,
and Air-Conditioning Engineers, Inc.

in cooperation with

Solar Energy Industries Association

ACEC Research & Management Foundation

ISBN 0-910110-54-9



Published 1988 by the American Society of Heating,
Refrigerating, and Air-Conditioning Engineers, Inc.,
1791 Tullie Circle, N.E., Atlanta, GA 30329

in cooperation with



Solar Energy Industries Association
1730 N. Lynn St., Suite 610, Arlington, VA 22209-2009



ACEC Research & Management Foundation
1015 Fifteenth St., N.W., Washington, DC 20005

ACKNOWLEDGMENTS

The Energy Technology Engineering Center (ETEC), Rockwell International, has prepared this manual as a task in the Department of Energy's Solar in Federal Buildings Program (SFBP) with the advice and assistance of consultants from the solar community.

The manual was conceived and sponsored by the U.S. Department of Energy (DOE), Division of Solar Heat Technologies, Dr. Frederick H. Morse, Director. The following organizations were instrumental in the planning and review of the manual: The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Research Division, William Seaton, Manager; the Solar Energy Industries Association (SEIA), Scott Sklar, Executive Director; and The American Consulting Engineers' Council (ACEC) Research and Management Foundation, Jack Warner, Program Director.

Particular recognition is due the members of the Industry Working Group (listed below) for their direction in defining the manual's format and for their detailed review of several drafts; to a large extent, the manual reflects the comments and experience of these reviewers.

Robert Aresty
Wayne Bryan
Terry Buffum
William Dokus
Richard Evans
William Fleming
Rob Gorham
Robert Hassett
Jeffery Hatman
Don Kazimir
Thomas King
Willard King
Charles Kutscher
George Lof
Norman Lutkefedder
Gene Meyer
Frederick Morse
Arlen Reimnitz
Al Rich
Dick Rittlelmann
William Seaton
Scott Sklar
Jack Warner

Contributors from the solar community included George Lof, Colorado State University (CSU), on air-cooled collectors and systems; Dick Rittelmann, Burt Hill Kosar Rittelmann Associates, on conceptual system sizing and cost estimation; Bill Duff, CSU, and M. Chandrashekar, University of Waterloo, on evacuated collectors; Charles Smith, CSU, and Jack Duffie, University of Wisconsin, on application of system simulation computer programs; and James Senn on instrumentation and controls. Joseph Conrad reviewed the manual's technical language and terminology for conformance with industry practice.

The Managing Editor of the manual was Glen Schmidt. Major contributors as authors and editors of the technical sections were Keith Balkwill (Project Engineer), Jim Billings, and Tak Nakae. Oscar Hillig, as SFBP Program Manager, directed these ETEC efforts. This staff expresses deep appreciation to Dr. Frederick H. Morse for his leadership and guidance in shaping the manual to its final form and for the patience and encouragement he provided throughout this task.

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PREFACE

This Active Solar Heating Systems Design Manual for large commercial-scale service hot water and space heating solar energy systems represents two years of cooperative effort by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the Solar Energy Industries Association (SEIA), the American Consulting Engineers Council (ACEC), academia and Department of Energy (DOE) contractors. The challenge of creating a single design manual to satisfy the specific needs of solar designers for a variety of locations, applications and system types called on the talent and experience of specialists in many different areas.

It is Industry's responsibility to design, build and maintain state-of-the-art solar energy systems that satisfy a wide variety of markets and requirements. The Department of Energy has assumed the role of supporting Industry in the development of the technology base for advancement of solar energy systems that would accelerate their acceptance in the marketplace. During preparation of this manual, great effort was spent to distill information from sources with widely varied experiences and to translate it into a usable format that represents this collective knowledge base.

This manual is more than design information in another form. It is a design process which together with the companion Installation, Operation and Maintenance Manual represents a comprehensive coverage of the major elements that will significantly enhance the success of solar applications in buildings.

The Active Solar Heating Systems Design Manual was developed to give solar designers an effective means to use the collective knowledge of government and industry to better select options, from among the many now available, for improving the quality and energy efficiency of solar systems they design and build.

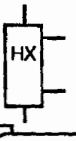
Legend for Design Manual Figures

Liquid System

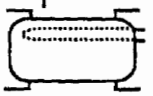
Major Component

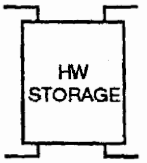

Collector Array


Pump

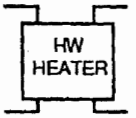


Heat Exchanger

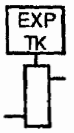

Solar Storage Tank with In-Tank Heat Exchanger



Hot Water Storage Tank



Water Heater



Expansion Tank/Air Separator



Expansion Tank

Piping and Fittings


Piping


Air Vent Valve


Check Valve


Backflow Preventer


Relief Valve (pressure or pressure and temperature)


Valve (open) Manually Operated


Valve (closed) Manually Operated


Control Valve (closed), Remotely Operated



Tempering Valve


3-Way Valve, Remotely Operated

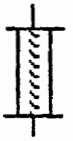

Pressure Regulating Valve


Pipe Cap

Air System

Major Component


Fan


Heat Exchanger, Liquid/Air


Pebble Bed, Thermal Storage



Furnace

Ducting and Fittings


Ducting


Control Damper, Remotely Operated


Damper, Manually Operated


Backdraft Damper

Legend for Design Manual Figures (continued)

Controls and Instrumentation



Differential Temperature Controller



Control Relay Coil



Time Delay Relay Coil



Valve Control Relay Coil



Damper Control Relay Coil



Motor Control Relay Coil



Heater Control Relay Coil



Temperature Gauge



Pressure Gauge



Pressure/Temperature Port
(P/T Plug or "Pete's Plug)



Flowmeter



Thermostat Switch
(normally closed, open on
temperature rise/fall)



Thermostat Switch
(normally open, closes on
temperature rise/fall)



Delay ON Relay (normally
closed; timing starts after
coil is energized and contact
opens at end of period)



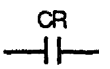
Delay OFF Relay (normally
closed; opens when energized
timing starts after coil is
de-energized and contact
closes at end of period)



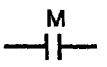
Flow Switch (normally open,
closes when required flow is
established)



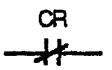
Double Acting Thermostat
Switch



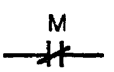
Control Relay Contact
(normally open; closes
when energized)



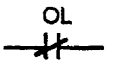
Motor Control Relay Contact
(normally open; closes
when energized)



Control Relay Contact
(normally closed; opens
when energized)



Motor Control Relay Contact
(normally closed; opens
when energized)



Overload Contact
(normally closed)



Pilot Light, Light ON
signifies output

Abbreviations and Acronyms for Design Manual

°C	Degree Celsius
°F	Degree Fahrenheit
I-P	Inch-Pound
SI	Systeme International
Btu	British Thermal Unit
hp	Horsepower
k	Kilo
M	Mega
J	Joule
W	Watt
h	Hour
s	Second
yr	Year
ft	Foot
in.	Inch
mm	Millimeter
m	Meter
mph	Miles Per Hour
Pa	Pascal
g	Gram
lb	Pound
psig	Pounds Per Square Inch Gauge
psi	Pound Per Square Inch
WG	Water Gauge
cfm	Cubic Feet Per Minute
gal	Gallon
gpm	Gallons Per Minute
L	Liter
Dia	Diameter
ppm	Parts Per Million
TDS	Total Dissolved Solids
% RH	Percent Relative Humidity
N/S or N-S	North/South
E/W or E-W	East/West
A/E	Architect/Engineer

U	Overall Heat Transfer Coefficient
UA	Overall Heat Transfer Coefficient (for specific area or device)
R	Thermal Resistance Rating (for thermal insulation)
UV	Ultra Violet
Vac	Voltage-Alternating Current
elev	Elevation
horiz	Horizontal
FC	Fail Close (close on loss of power)
FO	Fail Open (open on loss of power)
ETC	Evacuated Tube Collector
HX	Heat Exchanger
Max	Maximum
Min	Minimum
NC	Normally Closed
NO	Normally Open
DP	Double Pole
ST	Single Throw
DT	Double Throw
DHW	Domestic Hot Water
SHW	Service Hot Water
IPH	Industrial Process Heat
TC	Cold Temperature Sensor
TH	Hot Temperature Sensor
RTD	Resistance Temperature Detector
T Stat	Thermostat
DAS	Data Acquisition System
PRV	Pressure Relief Valve
NPSH	Net Pump Suction Head
P & ID	Piping and Instrumentation Diagram
SDD	System Design Description
SH	Space Heat
EPDM	Ethylene Propylene Diene Monomer
PVC	Polyvinyl Chloride

Abbreviations and Acronyms for Design Manual
(continued)

Organizations

ACEC	American Consulting Engineers' Council
ACI	American Concrete Institute
ANSI	American National Standards Institute, Inc.
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
AWS	American Welding Society
BOCAI	Building Officials and Code Administrators International
DOE	U.S. Department of Energy
ETEC	Energy Technology Engineering Center
IAPMO	International Association of Plumbing and Mechanical Officials
MSS	Manufacturers Standardization Society of the Valve and Fittings Industry
NBS	U.S. Bureau of Standards
NWS	National Weather Service
SEIA	Solar Energy Industries Association
SFBP	Solar In Federal Buildings Program
SMACNA	Sheet Metal and Air-Conditioning Contractors' National Association
SRCC	Solar Rating and Certification Corporation
TVA	Tennessee Valley Authority

EXECUTIVE SUMMARY

PURPOSE

This manual was prepared to provide architects/engineers (A/Es) of large active solar heating systems with the best available design information for large commercial-scale solar service water and space heating systems. It incorporates experience from the solar industry and from government-sponsored programs that have demonstrated and advanced the technology of active solar heating systems.

The manual is not a "stand-alone" document. The manual draws on information from both industry and government sources. It requires the use of referenced documents to address basic engineering and design practices. Addition or removal of information to adapt the manual to the individual needs of the architect/engineer is left for the user to do.

The manual is to be used by the A/Es of active solar heating systems from concept development through final design. Solar insolation calculations and system configurations are included for experienced A/Es of conventional heating systems who may not have a working knowledge of solar energy systems. The manual may also be used by a prospective owner to follow the progress of solar energy system design, from concept through final design. After the system is built, the manual's design package will provide a record of how and why certain design decisions were made, for reference during future repair or modification.

Finally, the manual provides information for preparation of system installation, operation and maintenance procedures. The companion volume to this design manual, Installation, Operation and Maintenance (IOM) Manual, should be used during preparation of the IOM procedures for the as-built solar energy system.

SCOPE

The manual is for use in designing commercial and industrial solar energy systems for service water heating and space heating. The systems described in this manual have been demonstrated to be dependable and efficient to operate. The systems are limited to those using flat plate or evacuated tube collectors, liquid or air cooled, and requiring solar storage of at least 1000 gal (3,800 L) of water or equivalent or a collector field of at least 700 ft^2 (65 m^2). The systems' highest operating temperature is that temperature recommended by the collector manufacturer.

The systems may also be considered for future use in seasonal storage projects when this concept has been proven for use. The high temperature range of these systems will be suitable for solar space cooling applications when the cost-effectiveness of this application has been improved. The stored solar energy of these systems can be used in existing heat pump systems. The integration of these solar energy systems with heat pump systems is not covered in this manual. All of these systems will add to the overall energy efficiency of a building that has used passive solar design techniques to reduce the base energy level needed for space and water heating.

SYSTEM CONFIGURATION

The manual presents optimized liquid collector system configurations for three freeze protection modes and an optimized air collector system configuration. The drainback design using water in the solar collector loop is suitable for heating service water at any site where the collectors can be mounted high enough above the drainback tank to ensure positive, complete draining. When drainback is not possible, a design using antifreeze in the solar collector loop (typically, 50/50 propylene glycol/water) can be used. Finally, for mild climates with minimum freeze potential, the simple recirculation design is recommended. Space heating projects that require a large percentage of fresh air for ventilation are served by the air collector system design.

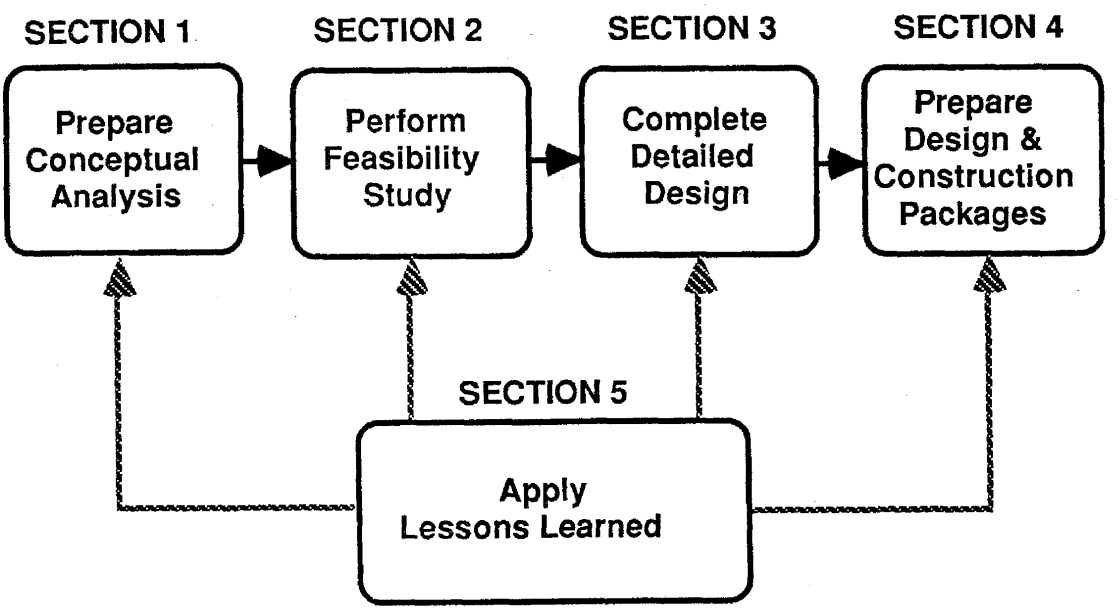
The systems to be designed by following this manual are most effective when used for low temperature heating of water or air; i.e., heating service water for large volume residential use, for commercial buildings, or for industrial processes that can use water up to 180°F (82°C). Preheating of fresh air for space heating a large building is also an efficient use of solar energy.

These systems are also most effective for loads that use the collected solar energy steadily during the day as it is collected so that little solar heat has to be stored for later use, minimizing or eliminating the need for storage.

DESIGN PROCESS

The manual consists of four interrelated sections that encompass the design process; i.e., Conceptual Analysis, Feasibility Study, Detailed Design, and Design and Construction Packages, and a fifth section, Lessons Learned, that lists common problems and solutions for solar energy system designs.

A\Es may use all sections in designing a project or may select only those specific sections needed, depending on their experience, and size and complexity of the proposed solar energy system.



Conceptual Analysis — This is a simple analysis to determine whether a full feasibility study is warranted. This analysis involves simple evaluations based on rules of thumb, charts, and typical performance results from existing systems. This analysis allows for the determination of the type of solar energy system to be used, a rough estimate of the load, and where the collectors could be placed; size of collector field and system cost are estimated. The results are summarized in a conceptual analysis summary.

If this study shows reasonable cost-effectiveness, the design process proceeds to the feasibility study.

Feasibility Study — This study estimates the cost-effectiveness of the proposed project. The first subsection presents procedures for determining the site data needed to design the system: energy conservation measures, sizing and timing of the heating loads to be satisfied, site and building characteristics, interface with existing heating systems, and selection of system configuration.

The second subsection presents procedures for sizing the collector field, estimating the system cost, and determining system cost-effectiveness. The results of this section are summarized in a solar energy system design description.

If this study shows that the solar energy system will be cost-effective, the design process proceeds to detailed system design. At this point, a contractual commitment for the design effort may be made.

Detailed Design — The first step in detailed design is to verify the design requirements and collector field sizing from the feasibility study. A system schematic (or piping/instrumentation drawing) is prepared to establish the optimum system configuration. Collector and storage subsystems design can then proceed in parallel with the electrical, instrumentation, and control design. Design review at 40% of the task completion confirms that the system configuration is still optimum or directs an iteration to improve the fit with the project's goals. A final design review at 90 to100% of task completion confirms that the design details are correct and complete. A final check of collector performance calculations is made to account for any design changes that were made, and a firm final cost estimate is prepared.

Output from the detailed design includes system performance calculations; economic evaluation; piping, structural, mechanical, thermal, and other design analyses; subsystem drawings; and component requirements.

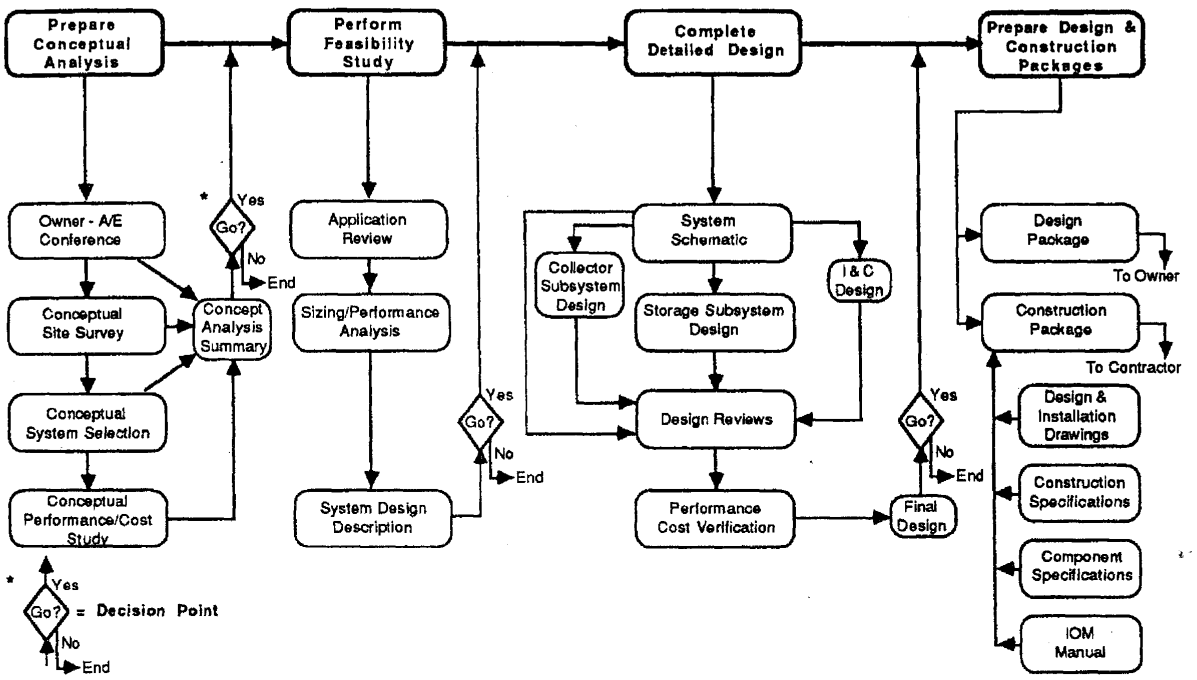
Design and Construction Packages — The design analyses, design and installation drawings, cost estimate, economic evaluation, and the solar energy system design description generated in Section 3 are compiled into a design package. The construction package includes all design and installation drawings, component specifications, and construction specifications. It is ready for construction bids when bidding procedures are added.

Lessons Learned — Problems commonly found in solar energy system design, potential effects of these problems, and ways to avoid them are presented. Problems found in construction and operation, caused by design mistakes, are described and solutions explained.

This section provides a quick reference by specific component for design problems commonly found that must be avoided; these lessons have been incorporated in the manual's design procedures. Review of this section can prevent the inadvertent inclusion of a design procedure that has been shown by accumulated field experience to be dysfunctional.

The sketch that follows illustrates the flow of work in the design process, as it is presented in the manual, with the major work packages and decision points identified.

SOLAR SYSTEM DESIGN PROCESS



An example of the design of a solar energy service water heating system following this design process is included as "Example System Design" and follows Section 5 of this manual.

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CONCEPTUAL ANALYSIS

SECTION 1

CONCEPTUAL ANALYSIS

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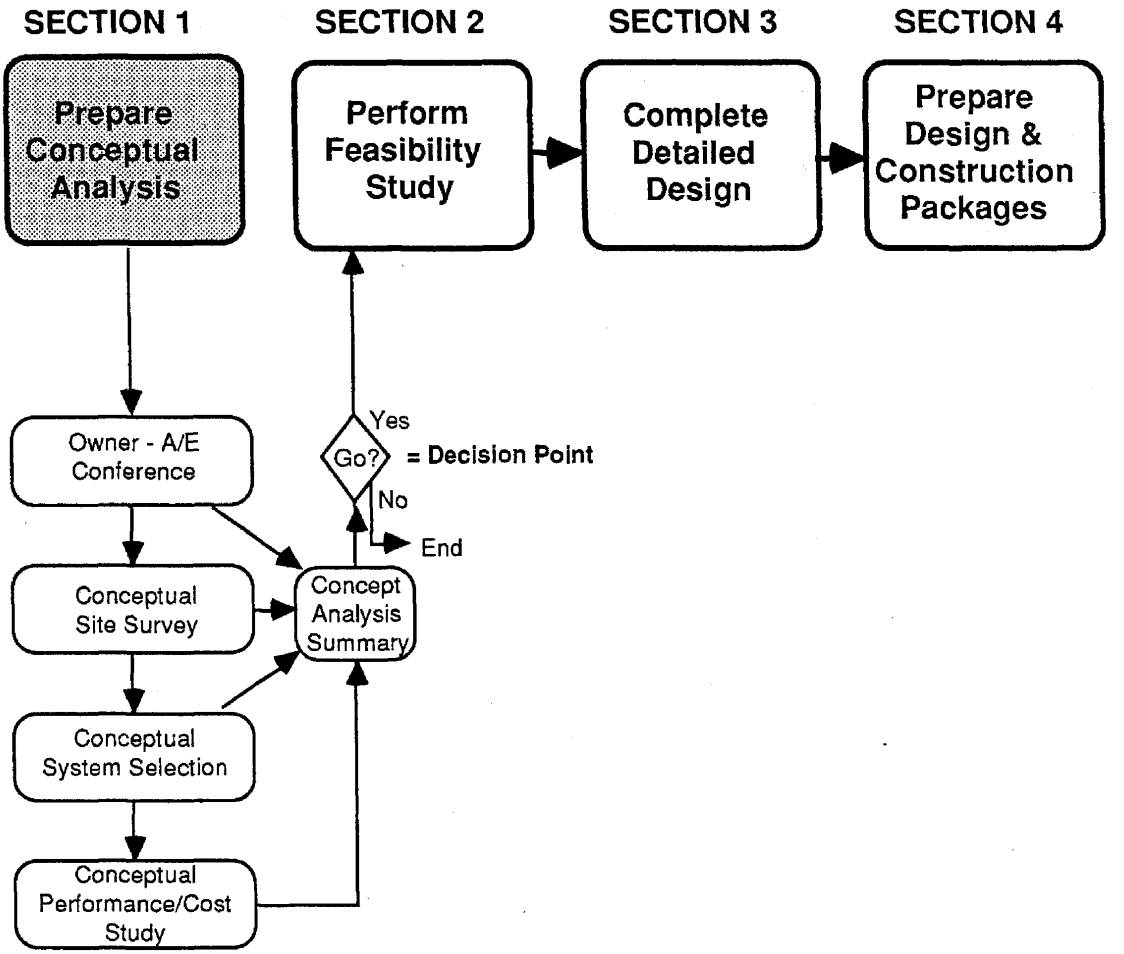
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1.1 OVERVIEW



The design process begins with a conference between architect/engineer (A/E) and prospective owner to draft purpose/size/load of a proposed system. The A/E surveys the site, records physical data needed for system design, selects the system that is best suited for the proposed load, and makes a simple, quick estimate of proposed system's performance, cost, and cost-effectiveness. A/E then summarizes and incorporates findings in a conceptual analysis summary and, if cost-effectiveness is reasonable, begins a feasibility study.

An example of the design of a solar energy service water heating system following this design process is included as "Example System Design" and follows Section 5 of this design manual.

1.2 OWNER / ARCHITECT/ENGINEER CONFERENCE

This conference determines the goals the owner has for the prospective solar energy system, an important but often overlooked procedure for establishing a sound and feasible design.

The A/E and owner should have some knowledge about the fraction of the total annual load that should be carried by the solar energy system. Although collector and storage subsystems could be sized large enough to fulfill total heating requirements throughout the year, such solar energy systems would not be cost-effective in most climates for most load profiles. Economical solar energy system designs dictate use of smaller solar energy systems in conjunction with auxiliary heaters capable of fulfilling total heating demands when solar collection is not possible and when stored solar heat is inadequate for user applications. At the conceptual analysis stage for solar space heating purposes, the fraction of annual load carried by solar generally is assumed to be in the range of 40 to 60%, and between 60 and 80% for solar water heating. The lower part of the range can be used for colder climates with less sun in winter times (such as northern regions of the country) and the higher part of the range for predominantly sunny climates.

Within these ranges of solar fraction, the solar water heating system would provide almost 100% of the total load during the sunniest months, and the solar space heating system would provide 80 to 90% of the total load during early fall and late spring.

In addition, the owner's goals for promotion of renewable energy/conservation of fossil fuel, overall cost benefits, and ownership of a solar energy system should be addressed. Checklist 1-1 should be used to summarize the owner/A/E conference.

1.3 CONCEPTUAL SITE SURVEY

During the conceptual site survey, the loads where solar heating can be most cost-effective are identified, hot water and/or space heating loads are estimated, the physical constraints of the site are noted, and locations for the collectors and storage tank(s) are identified.

1.3.1 Identifying the Load

In surveying a commercial or industrial site for possible installation of an active solar heating system, the A/E should look for applications where solar can be most efficient, such as:

- Low-temperature service water heating
- Constant-use daytime service water heating
- Ventilation makeup air preheating.

The A/E should also determine in this survey whether other sources of heat, such as waste heat recovery, are available at the site and whether other conservation measures that would significantly reduce the total building heating load also are available.

1.3.2 Preliminary Load Estimate

For retrofitting in an existing building, the existing records of hot water and/or space heating fuel usage or hot water consumption are excellent sources of thermal data and should be used to estimate the load(s).

If existing data on actual energy use are not available, an estimate should be made based on "typical" use data, i.e., gallons of hot water per day per person in office buildings or dormitories. These data are provided in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbooks: The 1987 Heating, Ventilating and Air-Conditiong (HVAC) Systems and Applications Volume, Chapter 57, for service water heating and the 1985 Fundamentals Volume, Chapter 25, for space heating. Space heating and service water heating loads may also be estimated by use of the graphical calculation techniques reported in the Tennessee Valley Authority (TVA) Energy Design Guidelines Series as the "Energy Nomographs" 1-1 derived from ASHRAE Handbook data noted above. The average use figures from ASHRAE or TVA references should be used for estimation of loads and should be reduced by one-third (33.3%) for solar energy system design. Experience acquired during design, installation, and monitoring of large Solar in Federal Buildings Program (SFBP) projects has shown that the ASHRAE "average" load was consistently higher than the actual load measured.

For a new building, the A/E should provide design load data.

Hot Water Load

Data for Checklist 1-2 should be determined as closely as possible. If historical hot water consumption data are available, the equation in Worksheet 1–1 can be used to calculate total thermal load. Supply cold water temperatures can be obtained from Table 1-1 or similar data. If fuel use data are available, the method in Worksheet 1–2 can be used to convert these data into thermal load.

Space Heating Load

Data for Checklist 1-3 should be completed as thoroughly as possible. Historical space heating fuel data can be converted to thermal load using conversion factors and conversion efficiencies in Worksheet 1–2.

1.3.3 Physical Constraints

The type of building, its location, occupancy, and type of water heating and space heating system impact the design and integration of solar energy systems. In retrofitting solar energy systems in existing buildings, site visits and surveys should be made to identify and record those items listed in Checklist 1-4 that apply to the type of solar energy system being considered. For buildings that are being designed, the building A/E should provide the checklist data.

A suitable location for the proposed system should be selected at the conceptual design stage. Calculation methods for the conceptual array, storage, and mechanical room sizes are provided in Section 1.5.1. In addition to installation requirements, space for future maintenance and repairs must be available. The existing or to-be-constructed building and

Table 1-1. Source and Monthly Temperature (°F) at the Source for Cold Water Supply in 14 Cities
[°C = 5/9(°F – 32)]

	Source*	J	F	M	A	M	J	J	A	S	O	N	D
Albuquerque	W	62	62	62	62	62	62	62	62	62	62	62	62
Boston	Re	32	36	39	52	58	71	74	67	60	56	48	45
Chicago	L	32	32	34	42	51	57	65	67	62	57	45	35
Denver	Ri	39	40	43	49	55	60	63	64	63	56	45	37
Fort Worth	L	46	49	57	70	75	81	79	83	81	72	56	46
Los Angeles	Ri,W	50	50	54	63	68	73	74	76	75	69	61	55
Las Vegas	W	73	73	73	73	73	73	73	73	73	73	73	73
Miami	W	75	75	75	75	75	75	75	75	75	75	75	75
Nashville	Ri	46	46	53	63	66	69	71	75	75	71	58	53
New York	Re	36	35	36	39	47	54	58	60	61	57	48	45
Phoenix	Ri,Re,W	48	48	50	52	57	59	63	75	79	69	59	54
Salt Lake City	W,C	35	37	38	41	43	47	53	52	48	43	38	37
Seattle	Ri	39	37	43	45	48	57	60	68	66	57	48	43
Washington	Ri	42	42	52	56	63	67	67	78	79	68	55	46

*Note that water temperature at point of use may be quite different from this source temperature depending on the municipal distribution system characteristics.

Abbreviations: C — Creek; L — Lake; Re — Reservoir; Ri — River; W — Well

Source data from Handbook of Air Conditioning System Design, pp. 5-41 through 5-46; McGraw Hill Book Company, New York (1965).