Systems Analysis Techniques for Annual Cycle Thermal Energy Storage Solar Systems

Frank Baylin
Sanford Sillman

Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Operated for the U.S. Department of Energy under Contract No. EG-77-C-01-4042
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.50

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.
SYSTEMS ANALYSIS TECHNIQUES FOR
ANNUAL CYCLE THERMAL ENERGY
STORAGE SOLAR SYSTEMS

FRANK BAYLIN
SANFORD SILLMAN

JULY 1980

PREPARED UNDER TASK No. 5525.00

Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042
THIS PAGE
WAS INTENTIONALLY
LEFT BLANK
FOREWORD

This document was prepared to fulfill part of the United States obligation on an agreement reached with the International Energy Agency/Annex VII—Central Solar Heating Plants with Seasonal Storage. SERI has the responsibility to inform the United States coordinator at Argonne National Laboratories about U.S. activities in modeling of combined annual cycle thermal energy storage/community solar heating systems. This activity is a component of a coordinated effort at the Solar Energy Research Institute to examine all aspects of energy storage technologies having applications in solar power systems.

The authors wish to express appreciation to a number of associates who contributed both information and critical reviews of this document. Richard Tabors of the M.I.T. Energy Laboratory provided invaluable assistance to S. Sillman in the original thesis research upon which Sec. 6.0 of this work is based. Alan Michaels, C. J. Swet, and Charles Wyman critically reviewed this work.

Michael Holtz, Chief
Building Systems Development Branch

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

Michael Davis, Manager
Buildings Division
THIS PAGE
WAS INTENTIONALLY
LEFT BLANK
SUMMARY

Community-scale annual cycle thermal energy storage (ACTES) solar systems are promising options for building heat and cooling. In this document we examine general aspects of systems analysis techniques for ACTES solar systems, we present details of two simulation tools developed at SERI, and we briefly outline related research and development programs in the United States.

A variety of approaches are feasible in modeling ACTES solar systems. The key parameter in such efforts, average collector efficiency, is first examined. Several approaches for simple and effective modeling are presented next. In addition, we examine methods for modeling building loads for structures based on both conventional and passive architectural designs.

Two simulation models for sizing solar heating systems with annual storage are presented next. One is a daily model based on daily maximum and daily total insolation. The second is a bimonthly model which uses a utilization formula to calculate long-term solar collection efficiency. Both models are simple and accurate. Validation is presented by comparison with the results of a study of seasonal storage systems based on SOLANSIM, an hour-by-hour simulation. These models are presently being used to examine the economic trade-off between collector field area and storage capacity.

Finally, we briefly examine programs in the U.S. Department of Energy directed toward developing either other system components such as improved tanks and solar ponds or design tools for ACTES solar systems. Substantial efforts are underway in the United States.
THIS PAGE
WAS INTENTIONALLY
LEFT BLANK
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>Collector Efficiency Functions</td>
<td>3</td>
</tr>
<tr>
<td>3.0</td>
<td>Annual Storage Modeling Strategies</td>
<td>7</td>
</tr>
<tr>
<td>4.0</td>
<td>Methods for Modeling Building Loads</td>
<td>11</td>
</tr>
<tr>
<td>5.0</td>
<td>Additional Design Parameters</td>
<td>13</td>
</tr>
<tr>
<td>6.0</td>
<td>Details of Two Simple Design Codes</td>
<td>15</td>
</tr>
<tr>
<td>6.1</td>
<td>System Configuration</td>
<td>15</td>
</tr>
<tr>
<td>6.2</td>
<td>The Daily Model</td>
<td>16</td>
</tr>
<tr>
<td>6.3</td>
<td>The Bimonthly Model</td>
<td>17</td>
</tr>
<tr>
<td>6.4</td>
<td>Validation</td>
<td>19</td>
</tr>
<tr>
<td>6.5</td>
<td>Conclusion</td>
<td>23</td>
</tr>
<tr>
<td>7.0</td>
<td>The DOE Program</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>31</td>
</tr>
</tbody>
</table>
THIS PAGE WAS INTENTIONALLY LEFT BLANK
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Average Operational Collector Efficiency Versus 57-&lt;T_A&gt; Divided by Total Insolation</td>
<td>4</td>
</tr>
<tr>
<td>2-2</td>
<td>Schematic Representation of Collector Efficiency</td>
<td>5</td>
</tr>
<tr>
<td>3-1</td>
<td>Use of a Simple Daily Model to Calculate Daily Collector Gain</td>
<td>7</td>
</tr>
<tr>
<td>3-2</td>
<td>Use of Utilization Function to Calculate Average Efficiency with Averaged Data</td>
<td>8</td>
</tr>
<tr>
<td>3-3</td>
<td>Storage Volume Per Unit versus Winter Net Load Per Unit: Single-Unit Buildings</td>
<td>10</td>
</tr>
<tr>
<td>5-1</td>
<td>Designs for Two-Tank Systems</td>
<td>14</td>
</tr>
<tr>
<td>7-1</td>
<td>Organization Chart: Conservation and Solar Energy, DOE</td>
<td>26</td>
</tr>
</tbody>
</table>

LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-1</td>
<td>Discrepancy between Calculated Winter Minimum Temperatures</td>
<td>20</td>
</tr>
<tr>
<td>6-2a</td>
<td>Discrepancy between Monthly Efficiencies: Daily Model</td>
<td>21</td>
</tr>
<tr>
<td>6-2b</td>
<td>Discrepancy between Monthly Efficiencies: Bimonthly Model</td>
<td>22</td>
</tr>
<tr>
<td>7-1</td>
<td>Projects in System Analysis of Annual Cycle Thermal Energy Storage/Solar Systems</td>
<td>27</td>
</tr>
<tr>
<td>7-2</td>
<td>Projects in Developing TES Components for ACTES Solar Systems</td>
<td>28</td>
</tr>
</tbody>
</table>
SECTION 1.0

INTRODUCTION

Solar energy systems based on annual cycle operation of a large thermal energy storage (TES) can be modelled in a relatively simple fashion because storage and distribution system temperatures vary slowly over time. The key problem in such an effort is characterizing performance of the solar collectors which have a dynamic response driven by rather complex insolation patterns.

Most solar models are arranged in terms of interacting components; solutions are derived in an interactive fashion. Components include storage, collectors, distribution systems, heat exchangers, and controls. Feedback between components which alters performance of each apparently necessitates simulation in steps, the length of which are determined by the most dynamic system component. The most accurate solutions would then be those using simulations with the shortest time steps and longest computing time. Below, we describe simulation methods which are far simpler and which need only consider those slowly varying parameters, such as operational temperature and total daily or bi-monthly insolation.

An understanding of collector efficiency is central in such an analysis. Insolation and collector efficiency determine the quantity of energy collected. This parameter, along with the building load profile, is a first order variable in determining sizes of the collector field, the distribution system, and the storage capacity. Second order system parameters which must be modelled correctly but which have less impact on overall design accuracy include storage and distribution system losses. Similarly, control strategies are determined once the sizes and types of major components are determined and effect the fine tuning of these sizes.

In this brief report, we first discuss collector efficiency functions. Second, we describe methods for modelling annual cycle TES (ACTES) solar systems. Third, we present a brief outline of methods for investigating building loads based on both conventional and passive architectural design. Fourth, we examine other aspects of system modelling such as validation and thermal versus economic optimization. Fifth, we present the details of two simple design codes for modelling ACTES solar systems. Sixth, we outline ongoing and completed DOE programs aimed at encouraging and developing such systems.
The complexity involved in determining collector efficiency depends upon which type of system is being considered. Below, we consider three systems to illustrate problems which are encountered.

The efficiency of a photovoltaic system is relatively easily modelled. Photovoltaic efficiency, while dependent on nonsystemic factors such as quality and age of the cells, may be regarded as a first order constant with actual efficiency varying only slightly between a clear and a cloudy day. The main problem in modelling a photovoltaic (PV) system is in matching the insolation and storage to load, on a daily or an hourly basis.

A second, more complicated case is for collector systems where long-term efficiency is a linear function of average insolation, ambient temperature, and operating temperature;

$$\text{efficiency } \alpha \left[ 1 - K \frac{T_0 - T_a}{I} \right].$$

Here, $T_a$ is the ambient temperature and $T_0$ is the operating temperature which depends on storage temperature and other heat transfer characteristics of the collector. Although this is clearly the case for instantaneous collector efficiency as a function of instantaneous insolation, ambient temperature, and operating temperature, it is only a partially accurate representation of actual system operation. As seen in Fig. 2-1, average collector efficiency is not an accurate linear function of 57 minus average ambient temperature divided by total yearly insolation (Points on this graph are for ten United States cities [1]).

One case where such modelling works well is for solar ponds [2], which are both storage and collection devices. Efficiency varies linearly with operating temperature. Operating temperature varies slowly and therefore total collected energy is a simple function of monthly or annual cumulative insolation. The critical parameter required is the effective U-value which determines the rate of energy loss.

In most solar collectors, instantaneous efficiency is a linear function of $(T_0 - T_a)/I$ until insolation drops below or until operating temperature increases above a critical level. The normal operational situation is curve AEF rather than curve AB of Fig. 2-2. If time-averaged insolation and temperature were used, one would incorrectly derive efficiency D, midway between points A and B, as the time average efficiency. Efficiency C, the actual average efficiency, is near midway on the curve representing the typical daily operational range.

The time averaged data are valid only for periods of time when collectors are operational. In order to greatly simplify the modeling of annual cycle TES
Figure 2-1. Average Operational Collector Efficiency versus
\[ \frac{57 - \langle T_A \rangle}{\text{Total Insolation}} \times 10^{-2} \]

(Tilt = Latitude)
solar systems and to take advantage of the very slow variation in operating and storage temperatures, a long-term insolation algorithm can be used.

It should be noted that, for daily storage solar systems, a second important problem in modelling is storage operation. The state of charge of storage, i.e. either full or empty, determines whether or not the load can be supplied and whether or not more energy can be collected or must be dumped. Consequently, accurate system modelling requires accurate simulation of the storage-load interaction as well as a determination of collector efficiency. For annual cycle TES systems, this problem is not a consideration. Full and empty storage occurs as a once-a-year phenomenon and is easy to model. Collector efficiency in this case is the one key parameter.

![Figure 2-2. Schematic Representation of Collector Efficiency](image-url)
SECTION 3.0

ANNUAL STORAGE MODELING STRATEGIES

Five general approaches can be used to model annual cycle TES solar systems.

- The first is the brute force method where the steps taken in an iterative simulation are small enough so that use of time-averaged insolation and temperature provides a reasonably accurate solution. A variety of design tools exist [3]. The most thoroughly developed is the University of Wisconsin TRNSYS simulation [4]; it is a flexible design tool with over 25 subroutines for collectors, storage, heat pumps, etc. A wide range of systems configurations can be designed. Fifteen-minute steps are recommended; hour-long steps often are used with sufficient accuracy.

- A simplified daily radiation model has been developed [5] which can be used in an effective and simple annual cycle model. Input is daily total insolation and daily maximum insolation. A sinusoidal or modified sinusoidal curve is derived based on these data (see Fig. 3-1). If we assume that collector operating temperature remains constant throughout the day (which is valid for a seasonal system), daily collector gain may be simply calculated. The accuracy of this method is comparable to that of an hour-by-hour calculation [5]. This simplified daily radiation algorithm is subsequently used in a daily model which yields comparable results to the SOLANSIM (University of Toronto hourly annual cycle storage model) simulation and requires dramatically reduced computer time (see Section 6.0).

![Figure 3-1. Use of a Simple Daily Model to Calculate Daily Collector Gain](image-url)
This daily model is much simpler than TRNSYS; input necessary for an annual run is reduced from 11,680 pieces of weather data for an hourly model to 1,460 and it can be used on a mini computer and possibly on a programmable pocket calculator such as a TI-59. It is useful for modelling seasonal systems which have relatively small storages whose temperatures may vary substantially in a week's period so that bimonthly or monthly models may not be sufficiently accurate. It can also be used for daily storage systems. The utilization formula outlined in the following paragraphs is not adequate for use with such a daily model. The primary disadvantage of this code is the need for an additional piece of data—the daily maximum insolation. In many cases the daily model may be unnecessary; often a monthly or bimonthly model is sufficiently accurate.

• Calculation of collector efficiency by use of a nonlinear utilization function [6] is probably the most effective for seasonal storage design (see Fig. 3-2). This function is generated statistically from climatic data. Long-term utilization was found to be constant irrespective of location, although dependent on climatic parameters. It can be effectively used to estimate average collector efficiency over a sufficiently long period (weeks or longer) when operating temperature remains fairly constant. This method has been used as input to the daily SERI model and has been validated against the SOLANSIM code [1]; it has also been validated by the University of Wisconsin. The major advantages of the utilization function are simplicity and availability. Unlike the preceding models, the calculations in this design method may be conveniently performed by hand rather than by computer. It should be noted that the daily model described above is in essence a "daily utilization function"; it uses operational inputs (temperature, insolation) and applies an indirect formula to calculate collected energy.

Figure 3-2. Use of Utilization Function to Calculate Average Efficiency with Averaged Data
The utilization function allows use of a simple monthly or bimonthly design. Use of the bimonthly model may more accurately determine performance because substantial changes can occur within a week or two week period in late summer or very early fall, which would result in substantial dumping of excess heat. A monthly model may not be as sensitive as required to such effects.

- P. J. Lunde has developed a model for annual storage systems [7,8]. Monthly data are tabulated as follows. The range of insolation values is divided into a number of discrete intervals. For each interval, the total hours during which insolation was at that level, the total insolation for these hours, and the average ambient temperature for these hours are listed. To calculate monthly performance, (1) collector operating temperature is estimated, (2) minimum or critical insolation is calculated, and (3) insolation collected is summed by calculating collector efficiency and heat collected at all levels about critical.

This method is accurate and can also be easily used by designers without access to a computer. However, it may only be used in locations for which monthly insolation data have been tabulated as described above. The utilization method does not require new data and is, therefore, easier to use.

- A method analogous to f-chart was developed at SERI [1,9]. This method is potentially an effective design tool for determining average collector efficiency, storage volume, and collector area. However, it is not a flexible design for detailed system analysis studies. Once a number of optimal systems are more clearly defined, it may be refined, validated more carefully, and employed as a simple, quick design tool as f-chart is presently used (see Figs. 2-1 and 3-3).
Figure 3-3. Storage Volume per Unit versus Winter Net Load per Unit: Single Unit Buildings.

Winter net load is equal to load plus storage and transmission losses minus collector gain for the months of November through February.

The diagonal line is the same as the diagonal lines in the 10- and 200-unit graphs.
SECTION 4.0
METHODS FOR MODELING BUILDING LOADS

The standard procedure for calculating building loads in the United States is the degree-day method. This is based on a steady state heat loss equation for the building shell:

\[ \text{Load} = U_a \left( T_b - T_a \right) \]  

(4-1)

where \( U_a \) is the overall building heat transfer coefficient, \( T_a \) the ambient temperature, and \( T_b \) a base temperature which is equal to the room temperature \((21^\circ C)\) less the gain due to heat from sunlight, human bodies and appliances. \( T_b \) is typically chosen as \( 18^\circ C \).

At the time this method became standardized, houses were typically poorly insulated, and passive and miscellaneous heat gains were relatively minor. For well-insulated houses, these gains become more significant and require accurate modelling.

A rough estimate of building heat loads may be obtained with a modified degree-day method using a base temperature less than \( 18^\circ C \) [10]. For very well insulated houses, the base temperature for calculating heat loads may be \( 10^\circ C \) or less [11]. When miscellaneous and especially passive heat gains play a major role in heating the building, the degree-day method is no longer valid. Among the factors which must be accounted for in properly estimating passive solar gain are:

- variations in passive gain with time, both from day to night, from clear to cloudy days, and from season to season;
- variations in passive gain from room to room in the building and from heat transfer within the house;
- extent of thermal mass in the building; and
- possibility of overheating during sunny days.

SERI is currently investigating a number of sophisticated models for passive building heat loads: DEROB, SUNCAT, and BLAST. All these are hourly simulations which attempt to model, with varying degrees of complexity, the heat transfer within the building. Presently, these models require sophisticated software for operation and await more thorough validation. In order to make these codes more generally applicable to designers, current work includes model validation using actual building load data, and development of a simplified and easier-to-use version of SUNCAT for use on a microcomputer [12,13].

An alternative to these models is the Solar Load Ratio (SLR) method, a formula which calculates the percentage of building load met by passive gain calculated from certain building parameters. Building load exclusive of passive gain is first estimated using the degree-day method. This load, as well as the glazing area, monthly insolation, and other parameters, is used to
calculate passive heat supplied, using a formula derived from correlations made with a more sophisticated model. In its present form, the SLR method is limited in applicability to certain types of small buildings with large thermal mass. Building design with the SLR formula can be augmented by using TEANET, a program designed for a programmable calculator which estimates daily building performance. TEANET can be used to explore building sensitivity to overheating, while SLR is used to estimate the Solar Savings Fraction [12,13].

Design tools for passive buildings, in short, are less advanced than design tools for active solar systems. Therefore, use of any design tool for obtaining building load estimates must be supplemented by sound architectural and engineering judgment.
SECTION 5.0
ADDITIONAL DESIGN PARAMETERS

Application of the models presented in Section 4.0 necessitates a consideration of some additional, important design parameters. The sizing method used by most researchers [14,15] involves choosing the smallest system which provides 100% space and domestic hot water heating and which avoids dumping heat during the summer. Collector size is minimized at the expense of increased storage capacity. The assumption is that collectors are more expensive than storage. The trade-off between collector field area and storage capacity is being investigated at SERI in order to provide an economic, as well as a thermal, optimization. McGarity has also investigated this problem [16]. It should be noted that such methods should include a treatment of performance during "worst-case" year where total insolation may fall as much as 20% below normal; different design strategies can be adapted for handle this case. Also, in cases where the decision has been made to use an aquifer, storage capacity can be increased at close-to-zero cost and collector area should obviously be minimized.

Models must be validated by actual performance data. Perhaps the largest unknowns to be studied are the behavior of thermal distribution systems and of certain types of annual storages. Simple tools to model the behavior of entire systems are available; correctly modeling the components is the challenge. Presently, the limit on the accuracy of most annual cycle codes is the measurement of solar insolation. Accurate measurement and calculation of solar insolation on a tilted surface is critical in choosing optimal collector tilt [17].

To illustrate the versatility of available design tools, we present a simple design method for the "two tank" system developed by Cha, Conner, and Mueller [15]. In this system, a solar collector operates with two storage tanks, one sized for daily storage and the other for seasonal storage. Heat is drawn preferentially from the daily storage tank, and the collector is operated to charge whichever tank is at the lower temperature. The technical advantage of this system is that low-temperature solar heat may be collected and utilized on a daily basis during the early winter months when the fully charged seasonal storage tank is too hot to permit efficient solar collection.

Our design procedure is a combination of two methods, the monthly utilization method for seasonal storage and f-chart for the daily storage system. Simulation is performed in 15-day intervals, using monthly average data. For each period, two separate cases are analyzed.

Case 1: The collector operates with the seasonal storage tank only. Daily storage is ignored. In this case, system performance is assessed using the utilization method, as though it were a one-tank system. Heat deliverable to load and end-of-period storage temperature is calculated.

Case 2: The collector operates with the daily storage tank only. In this case, the performance of the collector-plus-daily-storage system
is assessed with f-chart. The f-chart calculation supplies the percentage of the building load that can be met by the solar system with daily storage. The remainder of the building load is supplied from the seasonal storage tank so long as heat is available. Based on storage losses and heat supplied to load, the end-of-period temperature of the seasonal storage tank is calculated.

The two modes of operation then are compared on the basis of the final seasonal storage tank temperature. The case with the higher end-of-period storage temperature is assumed to represent the best mode of operation both in terms of amount of heat supplied to the load and in terms of amount of heat stored for the future. The system is then assumed to operate in the more favorable mode for the entire 15-day period. The heat supplied to load and the end-of-period storage temperatures are chosen from the calculation performed for that case.

Results of this design procedure (see Fig. 5-1) compare favorably with the original designs, based on hourly simulations [15]. A 5% error in predicting system performance and/or an error of up to 8% in system sizing are found. This discrepancy is caused by the difficulty in estimating the fraction of the load which can be supplied from storage. This fraction varies with daily weather. The accuracy of these results should illustrate both the usefulness and the limitations of monthly design tools.

The two-tank system was also simulated, using the daily radiation model with results virtually identical to the hourly simulation [5].

![Figure 5-1. Designs for two-tank systems](image)

Comparison of monthly simulation results (discrete points) with designs presented by Mueller. [15]

**System Specifications:**

<table>
<thead>
<tr>
<th>System</th>
<th>Small Tank Size</th>
<th>Large Tank Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.25 m²/m²</td>
<td>5 m²/m²</td>
</tr>
<tr>
<td>B</td>
<td>0.25 m²/m²</td>
<td>1 m²/m²</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1 m²/m²</td>
</tr>
</tbody>
</table>
SECTION 6.0
DETAILS OF TWO SIMPLE DESIGN CODES

Two simple computer models that can be used for sizing components of annual storage systems are presented here. One model uses a day-by-day simulation; the other calculates performance at 15-day (bimonthly) intervals. Both take advantage of the operating temperature of annual storage systems that varies slowly over long periods of time. Validation of the simulations is presented by comparison with results from the SOLANSIM hourly model developed at the University of Toronto [14].

6.1 SYSTEM CONFIGURATION

Both models start with a system configuration of three components: collector, storage, and load. Solar heat collection is determined by the collector algorithms, described below. Collected energy heats the storage tank according to storage size and heat capacity. Storage loss is calculated, based on storage U-value and ground temperature. Heat is removed from storage to meet the building load, and the resulting change in storage temperature is calculated again. Heat losses in transfer from collector to storage and from storage to load may be either included in the model directly or accounted for indirectly with the storage U-value and collector heat exchange factor (Pr in the collector equation, given below). The daily model is run daily and the bimonthly model is run for 15-day periods, each with their own collector algorithm.

The models assume that both space heat and hot water will be provided from storage. Building heat and hot water loads are a necessary input. The simulation allows building load to be provided when the storage temperature remains above a specified minimum. When storage temperature drops below the hot water delivery temperature, the solar heating system provides energy to preheat hot water based on a heat exchanger effectiveness formula. The fraction of hot water heat supplied from storage is determined by the equation:

\[ f_{HW} = \frac{TS-TC}{TH-TC} \]  \hspace{1cm} (6-1)

where TS is the effective storage temperature (modified by heat transmission effectiveness) and TH and TC are the hot and cold water temperatures.

6.2 THE DAILY MODEL

The daily model estimates the daily insolation as a simple sine curve. Necessary inputs are QTOT, the total daily insolation, and QMAX, the maximum of the hour-by-hour insolation for the day. Daily weather input is required for this model; if unavailable, it is better to use the bimonthly model.
Daily insolation is modelled as a sine curve such that the maximum insolation rate equals $Q_{\text{MAX}}$ and daily total insolation equals $Q_{\text{TOT}}$. The form of the daily insolation is taken as

$$Q(t) = Q_{\text{MAX}} \cos wt$$  \hspace{1cm} (6-1)

where $t$ is the time in hours, with noon being zero. From the stipulation that total daily insolation equals $Q_{\text{TOT}}$, it may be found that

$$w = 2 \frac{Q_{\text{MAX}}}{Q_{\text{TOT}}}$$  \hspace{1cm} (6-2)

On clear days, the sinusoidal function provides an accurate description of daily insolation. The authors contend that, on cloudy and partly cloudy days, this function provides an approximation of the varying insolation pattern of sufficient accuracy [5]. The accuracy of this model is examined in greater detail by Sillman [5].

Instantaneous solar heat collection is found by the collector equation [18]:

$$Q_{\text{COL}}(t) = F_r \left( \alpha \right) Q(t) - F_r U_1 (T_0 - T_A)$$  \hspace{1cm} (6-3)

where $F_r$ is the collector heat exchange factor; $(\alpha \tau)$ is the transmission absorption product, $U_1$ is the collector heat loss factor, $Q$ is the incident insolation, and $T_0$ and $T_A$ are the collector operating and ambient temperatures.

Using the sinusoidal formula for daily insolation, the daily total heat collection equation becomes:

$$Q_c = F_r \left( \alpha \tau \right) \int_{t_1}^{t_2} \left[ Q_{\text{MAX}} \cos wt - \frac{U_1}{(\alpha \tau)} (T_0 - T_A) \right] dt$$  \hspace{1cm} (6-4)

where $t_1$ and $t_2$ are the collector turn-on and turn-off times.

Operating and ambient temperatures are both assumed to be constant during the day. The collector is assumed to operate so long as heat collection is positive. The turn-on and turn-off times are equivalent then, given by the equation:

$$-t_1 = t_2 = t_x = \frac{1}{w} \left[ \arccos \frac{1}{Q_{\text{MAX}}} \frac{U_1}{(\alpha \tau)} (T_0 - T_A) \right]$$  \hspace{1cm} (6-5)

where $T_A$ is the average ambient temperature during daylight.
Upon integration, the total daily heat collection becomes:

\[ Q_c = F_r (\alpha T) Q_{TOT} \sin \omega t_x - 2 t_x F_r U_1 (T_0 - T_A) \] (6-6)

The daily model uses equations 6-2, 6-5, and 6-6 to find daily heat collection. Operating temperature is assumed to be storage temperature, and ambient temperature as daytime average temperature. After daily heat collection is found; daily change in storage temperature is calculated as described above in Section 6.1.

6.3 THE BIMONTHLY MODEL

The bimonthly collector algorithm uses the utilization method, developed by Liu and Jordon [18] and modified by Klein [6], which will be described here.

Instantaneous collector efficiency is given by the equation

\[ \text{eff} = F_r (\alpha T) - F_r U_1 \frac{(T_0 - T_A)}{Q(t)} \] (6-7)

This may be expressed in a different form as

\[ \text{eff} = F_r (\alpha T) (1 - X_C) \] (6-8)

where \( X_C \) is the critical radiation level, equal to

\[ X_C = \frac{U_1 (T_0 - T_A)}{(\alpha T) Q(t)} \]

As noted above, the long-term collector efficiency is a nonlinear function that cannot be calculated by using the instantaneous efficiency equations. The average long-term efficiency over a period of time for which \( T_0 \) and \( T_A \) remain constant, and for which the expected insolation remains uniform, will depend only on the day-to-day and hour-to-hour variations in insolation.

In the utilization, method, long-term efficiency is expressed as

\[ \text{eff} = F_r (\alpha T) \cdot \phi (X_C) \] (6-9)

where \( X_C \) is the critical level for noontime of an average day in the period and \( \phi(X_C) \) is the utilization function, derived by statistical aggregation of
weather data. Klein [6] gives the utilization function mathematically as:

$$\phi (X_C) = \exp \left[ \left( A + B \frac{RNS}{RS} \right) \cdot \left( X_C + C X_C^2 \right) \right]$$  \hspace{1cm} (6-10)

where

$$A = 2.943 - 9.271 K_t + 4.031 K_t^2$$
$$B = -4.345 + 8.853 K_t - 3.602 K_t^2$$
$$C = 0.170 - 0.306 K_t + 2.936 K_t^2$$

RNS and RS are the ratios of average insolation on a tilted surface to that on a horizontal surface, for noontime and for all day long, respectively. $K_t$ is the ratio of average daily horizontal insolation to the daily extraterrestrial insolation. The ratio RNS/RS acts as a parameter reflecting the effects of both collector tilt, latitudinal location, and changing insolation pattern with time of year.

In the model, collector efficiency is found via the utilization method for a 15-day interval. Collector operating temperature is assumed to be identically equal to the storage temperature, although an operating temperature adjustment to reflect a gain in collector efficiency as a result of storage tank stratification or other factors may be used. Correct determination of collector efficiency requires use of the average operating temperature for the period. To accomplish this, the model performs an iteration, initially calculating collector efficiency based on the operating temperature at the start of the period; calculating the change in storage temperature during the period due to collected energy, storage losses, and load; and returning to calculated collector efficiency based on the derived average storage temperature. The iteration is repeated until a self-consistent collector efficiency value is obtained.

For the seasonal storage systems studied, the maximum change in storage temperature was 12°C per month, or 7°C per half month. For these systems, no significant difference was found between a simulation based on 15-day intervals and one that used monthly intervals. For "intermediate" sized systems, midway between daily storage and full seasonal storage, the storage temperature can drop by 20-25°C in a month. For systems of this size, there were significant differences between the bimonthly and monthly simulations. For this reason a bimonthly interval was selected. The bimonthly interval provides other advantages when 15-day weather data are available instead of monthly averages: the yearly minimum temperature is found when it occurs in the middle of a month, and the amount of heat dumped in summer and fall is found more accurately. However, the bimonthly model may be used with monthly weather data, taking the daytime average temperature as $T_A$.  

18
6.4 VALIDATION

Validation was performed by a comparison with the results of the SOLANSIM hour-by-hour simulation developed at the University of Toronto [14]. Simulations were performed using SOLANSIM for a 50-house district with seasonal storage at 10 locations in the United States, with both standard flat-plate collectors and evacuated-tube collectors [1]. The insolation equivalent simulations were performed by using the daily and bimonthly models.

Providing proper insolation data is a major problem. The SOLANSIM runs all used Typical Meteorological Year weather data for hour-by-hour horizontal insolation. Tilted surface insolation was obtained using the anisotropic model developed by John Hay [17]. The average monthly insolation given by the Typical Meteorological Year data is up to 18% smaller than monthly insolation figures given in Klein, Duffie, and Beckman [19] and elsewhere. In addition, use of the anisotropic model for tilted insolation yields a different noontime insolation value and different solar ratios than do the isotropic model formulas suggested by Klein in his presentation of the utilization method [6].

The bimonthly model was run with tilted insolation values taken from the Typical Meteorological Year data with the anisotropic model. The parameter $X_{Tn}$ was calculated using the average daytime ambient temperature (for the time period 8:00 a.m. to 4:00 p.m.) and used the daily average maximum hourly insolation for the period in question for $Q_I$. The maximum hourly insolation was used for $Q_I$, rather than the average of noontime insolation, to correct for days which may be cloudy at noon and sunny at other times.

Tables 6-1 and 6-2 compare the results of the two models with that of SOLANSIM. Table 6-1 (a and b) gives the discrepancy between the two runs and SOLANSIM in the calculation of the minimum winter storage temperature.* Table 6-2 shows the discrepancy in calculation of monthly collector efficiency for some of the cities.

Error in calculation of the winter minimum temperature was always less than $3^\circ C$ and usually within $1.5^\circ C$. In general, monthly efficiencies were found correctly by the daily and bimonthly models to within one percentage point. However, there were several months for which the calculated monthly efficiency was off by three or four percentage points.

Viewed as a variance from the typical operating efficiency of 20%, the occasional three-percentage-point error in efficiency is significant. The models, nonetheless, correctly calculate the total yearly solar heat collection to within 3%. The models are successful because the occasions in which monthly efficiency is calculated inaccurately are isolated, rather than systematic, and because they typically occur during months of low insolation and collector

*For purpose of comparison, the winter minimum temperatures from the daily model, bimonthly model, and SOLANSIM were taken from temperatures at the end of the 15-day periods used in the bimonthly model. The minimum storage temperature found by SOLANSIM between the 15-day periods never differed by more than $1^\circ C$ from the end-of-period minimum and rarely differed by that much.
Table 6-1. DISCREPANCY BETWEEN CALCULATED WINTER MINIMUM TEMPERATURESa

<table>
<thead>
<tr>
<th>City</th>
<th>(a) Daily Model</th>
<th>(b) Bimonthly Model</th>
<th>(c) Bimonthly Model with Klein's Insolation Data and Tilting Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FPC  ETC</td>
<td>FPC    ETC</td>
<td>FPC  ETC</td>
</tr>
<tr>
<td>Albuquerque, N. Mex.</td>
<td>-0.9 -0.1</td>
<td>-1.9 -0.2</td>
<td>-0.7 +3.7</td>
</tr>
<tr>
<td>Bismark, N. Dak.</td>
<td>-0.2 +1.2</td>
<td>+0.6 +1.3</td>
<td>+1.6 +8.0</td>
</tr>
<tr>
<td>Boston, Mass.</td>
<td>-0.7 +1.5</td>
<td>-0.7 -0.5</td>
<td>-2.9 +1.4</td>
</tr>
<tr>
<td>Caribou, Maine</td>
<td>+0.4 +1.8</td>
<td>+2.8 +1.9</td>
<td>+2.1 +6.6</td>
</tr>
<tr>
<td>Dodge City, Kans.</td>
<td>-0.7 -0.1</td>
<td>-1.7 +0.2</td>
<td>-3.9 +0.1</td>
</tr>
<tr>
<td>Great Falls, Mont.</td>
<td>+0.2 +1.1</td>
<td>+0.1 +1.2</td>
<td>+3.0 +8.2</td>
</tr>
<tr>
<td>Madison, Wis.</td>
<td>+0.1 +1.6</td>
<td>+1.1 +1.3</td>
<td>-2.9 +2.6</td>
</tr>
<tr>
<td>Medford, Oreg.</td>
<td>-0.3 +1.0</td>
<td>+1.6 +1.3</td>
<td>+3.5 +3.1</td>
</tr>
<tr>
<td>Phoenix, Ariz.</td>
<td>-3.2 -0.4</td>
<td>-2.6 -0.4</td>
<td>-1.6 +1.4</td>
</tr>
<tr>
<td>Santa Maria, Calif.</td>
<td>-0.9 +1.5</td>
<td>+0.3 +1.0</td>
<td>+3.2 +8.6</td>
</tr>
</tbody>
</table>

aThe given in the Table is the difference in degrees Centigrade of TMIN(model) - TMIN(solansim) for each city, collector type (FPC = flat-plate collector, ETC = evacuated-tube collector), and model type.
Table 6-2a. DISCREPANCY BETWEEN MONTHLY EFFICIENCIES: DAILY MODEL\(^a\)

<table>
<thead>
<tr>
<th>Flat-Plate Collector</th>
<th>Ap</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, N. Mex.</td>
<td>-0.001</td>
<td>+0.021</td>
<td>+0.008</td>
<td>+0.008</td>
<td>-0.001</td>
<td>0</td>
<td>-0.010</td>
<td>-0.008</td>
<td>-0.023</td>
<td>-0.034</td>
<td>-0.014</td>
<td>-0.021</td>
</tr>
<tr>
<td>Boston, Mass.</td>
<td>+0.025</td>
<td>+0.015</td>
<td>+0.015</td>
<td>+0.002</td>
<td>+0.008</td>
<td>-0.004</td>
<td>-0.002</td>
<td>-0.013</td>
<td>-0.026</td>
<td>-0.001</td>
<td>-0.030</td>
<td></td>
</tr>
<tr>
<td>Dodge City, Kans.</td>
<td>+0.005</td>
<td>+0.008</td>
<td>+0.007</td>
<td>+0.004</td>
<td>+0.001</td>
<td>-0.001</td>
<td>-0.014</td>
<td>-0.021</td>
<td>-0.018</td>
<td>-0.006</td>
<td>-0.008</td>
<td>-0.013</td>
</tr>
<tr>
<td>Great Falls, Mont.</td>
<td>+0.024</td>
<td>+0.011</td>
<td>+0.017</td>
<td>+0.004</td>
<td>+0.005</td>
<td>-0.006</td>
<td>-0.014</td>
<td>-0.011</td>
<td>-0.007</td>
<td>-0.031</td>
<td>-0.001</td>
<td>-0.005</td>
</tr>
<tr>
<td>Madison, Wis.</td>
<td>+0.001</td>
<td>+0.012</td>
<td>+0.013</td>
<td>-0.009</td>
<td>-0.007</td>
<td>-0.002</td>
<td>-0.004</td>
<td>-0.010</td>
<td>-0.010</td>
<td>-0.016</td>
<td>+0.004</td>
<td>+0.006</td>
</tr>
<tr>
<td>Phoenix, Ariz.</td>
<td>-0.001</td>
<td>-0.002</td>
<td>+0.003</td>
<td>0</td>
<td>-0.005</td>
<td>-0.019</td>
<td>-0.021</td>
<td>-0.011</td>
<td>-0.024</td>
<td>-0.034</td>
<td>-0.032</td>
<td>+0.019</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evacuated Tube Collector</th>
<th>Ap</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, N. Mex.</td>
<td>+0.002</td>
<td>+0.018</td>
<td>+0.005</td>
<td>+0.008</td>
<td>+0.007</td>
<td>+0.005</td>
<td>-0.001</td>
<td>+0.006</td>
<td>-0.004</td>
<td>-0.015</td>
<td>-0.001</td>
<td>-0.013</td>
</tr>
<tr>
<td>Dodge City, Kans.</td>
<td>+0.005</td>
<td>+0.007</td>
<td>+0.001</td>
<td>+0.004</td>
<td>+0.002</td>
<td>+0.004</td>
<td>+0.003</td>
<td>-0.003</td>
<td>+0.007</td>
<td>+0.007</td>
<td>-0.003</td>
<td>-0.007</td>
</tr>
<tr>
<td>Great Falls, Mont.</td>
<td>+0.020</td>
<td>+0.011</td>
<td>+0.015</td>
<td>+0.008</td>
<td>+0.010</td>
<td>+0.006</td>
<td>+0.001</td>
<td>+0.003</td>
<td>+0.005</td>
<td>+0.005</td>
<td>+0.004</td>
<td>+0.005</td>
</tr>
<tr>
<td>Madison, Wis.</td>
<td>+0.013</td>
<td>+0.012</td>
<td>+0.014</td>
<td>+0.004</td>
<td>+0.008</td>
<td>+0.011</td>
<td>+0.011</td>
<td>+0.001</td>
<td>+0.009</td>
<td>-0.002</td>
<td>+0.006</td>
<td>+0.008</td>
</tr>
</tbody>
</table>

\(^a\)The table gives the difference in degrees Centigrade between efficiencies predicted by the model and those predicted by SOLANSIM.
Table 6-2b. DISCREPANCY BETWEEN MONTHLY EFFICIENCIES: BIMONTHLY MODEL

<table>
<thead>
<tr>
<th></th>
<th>Ap</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flat-Plate Collector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albuquerque, N. Mex.</td>
<td>-0.007</td>
<td>-0.002</td>
<td>+0.001</td>
<td>-0.001</td>
<td>-0.005</td>
<td>+0.009</td>
<td>+0.019</td>
<td>-0.002</td>
<td>-0.012</td>
<td>-0.025</td>
<td>+0.011</td>
<td>+0.003</td>
</tr>
<tr>
<td>Boston, Mass.</td>
<td>-0.007</td>
<td>-0.014</td>
<td>-0.021</td>
<td>+0.002</td>
<td>-0.011</td>
<td>+0.022</td>
<td>+0.011</td>
<td>+0.031</td>
<td>-0.021</td>
<td>-0.012</td>
<td>-0.048</td>
<td>-0.020</td>
</tr>
<tr>
<td>Dodge City, Kans.</td>
<td>-0.007</td>
<td>-0.009</td>
<td>-0.006</td>
<td>0.00</td>
<td>-0.003</td>
<td>-0.002</td>
<td>-0.018</td>
<td>-0.037</td>
<td>-0.025</td>
<td>-0.021</td>
<td>-0.030</td>
<td>-0.009</td>
</tr>
<tr>
<td>Madison, Wis.</td>
<td>+0.019</td>
<td>-0.010</td>
<td>+0.018</td>
<td>-0.018</td>
<td>+0.020</td>
<td>-0.024</td>
<td>-0.014</td>
<td>+0.003</td>
<td>-0.011</td>
<td>-0.002</td>
<td>-0.005</td>
<td>-0.001</td>
</tr>
<tr>
<td>Phoenix, Ariz.</td>
<td>-0.012</td>
<td>-0.005</td>
<td>-0.005</td>
<td>-0.006</td>
<td>-0.036</td>
<td>-0.018</td>
<td>-0.037</td>
<td>-0.004</td>
<td>-0.010</td>
<td>-0.019</td>
<td>-0.011</td>
<td>+0.012</td>
</tr>
<tr>
<td>Santa Maria, Calif.</td>
<td>-0.004</td>
<td>+0.003</td>
<td>+0.008</td>
<td>+0.003</td>
<td>+0.015</td>
<td>-0.001</td>
<td>-0.007</td>
<td>-0.009</td>
<td>-0.002</td>
<td>-0.020</td>
<td>-0.030</td>
<td>-0.006</td>
</tr>
</tbody>
</table>

|                |      |      |      |      |      |      |      |      |      |      |      |       |
| **Evacuated Tube Collector** |      |      |      |      |      |      |      |      |      |      |      |       |
| Albuquerque, N. Mex. | +0.003 | +0.005 | +0.006 | +0.007 | +0.008 | +0.003 | -0.004 | +0.003 | -0.002 | -0.002 | -0.001 | +0.003 |
| Dodge City, Kans.   | +0.003 | +0.005 | +0.003 | +0.002 | +0.003 | 0.00  | -0.013 | -0.004 | -0.005 | -0.004 | +0.003 |       |
| Madison, Wis.       | +0.011 | +0.009 | +0.014 | 0.00  | -0.005 | +0.012 | -0.004 | -0.015 | -0.001 | -0.011 | +0.009 | +0.009 |
| Santa Maria, Calif. | +0.006 | +0.007 | +0.020 | +0.005 | +0.007 | 0.00  | +0.006 | -0.001 | +0.002 | +0.002 | +0.001 | +0.001 |

*The table gives the difference in degree Centigrade between efficiencies predicted by the model and those predicted by SOLANSIM.*
utilization. For a seasonal storage system, these errors are not an appreciable fraction (less than 3%) of the yearly collection. Collector efficiency calculations were more accurate for evacuated-tube collectors than for flat-plate collectors because collector utilization was much higher for the former.

When the bimonthly model was run using Klein's isotropic tilting formula [6], results differed significantly. Isotropic tilting causes a smaller noontime tilted insolation and, consequently, a smaller calculated efficiency value. This difference amounted to four percentage points, compared to efficiency calculations based on anisotropic tilting. Calculated winter minimum temperature dropped by 5-8°C, equivalent to more than a weeks' worth of winter heat.

When the bimonthly model was run using both Klein's isotropic tilting [6] and the insolation data reported by Klein, Duffie, and Beckman [19], compensating errors resulted in a more accurate simulation. Minimum temperature discrepancy is given for these runs in Table 6-1, column c. Although most of the results in Table 6-1, column c appear accurate enough to be useful, there are major inaccuracies for some runs. This suggests that the accuracy of the insolation data and tilting algorithm is of greater importance than the relative accuracy of the simulation models.

6.5 CONCLUSION

For annual storage and for intermediate storage systems, the two simulations presented here are accurate tools for system design. Simulation inaccuracies are dwarfed by inaccuracies in weather data, variation of weather from year to year, and difficulty of proper estimation of heat exchange losses.

The bimonthly model is accurate for systems with storage temperature changes of no more than 12°C per 15-day interval. The daily model remains accurate whenever storage temperature changes no more than a few degrees per day. With an iteration, the daily model also can be used to size systems with short-term storage. The daily simulation is advantageous over the bimonthly model when day-to-day variations in storage temperature become important.

The value of the two models presented here lies in their use for designing systems. Unlike many of the hour-by-hour computer models, these simulations can be learned easily and run quickly without consuming much computer time.

Due to the ease of performing multiple simulation runs, these models also may be useful to researchers in assessing the various trade-offs in system sizing.
SECTION 7.0

DOE PROGRAMS

Relevant programs in the U.S. Department of Energy fall under the jurisdiction of the Assistant Secretary for Conservation and Solar Energy (see Fig. 7-1). Innovative research on all types of energy storage technologies is managed by the Office of Advanced Conservation Technologies (STOR). Solar technologies for building heating and cooling are being developed primarily in the Office for Solar Applications for Buildings (OSAB) although other elements of the overall solar program are involved in development and testing of components. For example, heliostat RD&D is managed by the Office of Solar Power Applications. The Office of Buildings and Community Systems directs activities in development of nonsolar technologies for building heating and cooling.

Below in Table 7-1, we list completed and ongoing projects directed solely toward system analysis of annual cycle thermal energy storage/solar systems. This list is assembled from two more thorough surveys [20,21].* We regret any omissions.

These projects are directed specifically for system analysis or management of such for annual storage systems. Below in Table 7-2, we list numerous other projects underway in development of TES components and, to a certain extent, in system analysis.

*Details of each project are available upon request.
Figure 7-1. Organization Chart — Conservation and Solar Energy (May 1980)
Table 7-1. PROJECTS IN SYSTEM ANALYSIS OF ANNUAL CYCLE THERMAL ENERGY STORAGE/SOLAR SYSTEMS

<table>
<thead>
<tr>
<th>Research Organization</th>
<th>Title</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific N.W. Laboratory</td>
<td>Seasonal TES Program (J. Minor)</td>
<td>Formulate and manage research in seasonal TES. Manage aquifer demonstration program for STOR. Coordinate development of codes such as AQUASTOR and CCC at Berkeley.</td>
</tr>
<tr>
<td>Univ. of California at Berkeley</td>
<td>Aquifer Modelling (Chin Fu Tsang)</td>
<td>Develop and validate CCC code which models physical characteristics of aquifers.</td>
</tr>
<tr>
<td>Argonne National Laboratory</td>
<td>Technical and Economic Analysis of TES Systems (J. Asbury)</td>
<td>Conduct analysis of selected TES systems. In particular, analysis of costs of annual storage tanks are completed.</td>
</tr>
<tr>
<td>Argonne National Laboratory</td>
<td>TES for Solar Program (A. Michaels)</td>
<td>Investigate TES for solar energy systems. In particular, model thermal stratification effects, and support research and analysis of annual cycle systems.</td>
</tr>
<tr>
<td>G. E. Tempo</td>
<td>Aquifer storage of cogenerated heat (C. Meyer)</td>
<td>Conduct general system analyses. Have developed simple model of heat distribution system.</td>
</tr>
<tr>
<td>University of Arizona</td>
<td>Seasonal storage system (C. Brent Cliff)</td>
<td>Model floating concentrator seasonal storage system.</td>
</tr>
</tbody>
</table>
### Table 7-2. PROJECTS IN DEVELOPING TES COMPONENTS FOR ACTES SOLAR SYSTEMS

<table>
<thead>
<tr>
<th>Project Title</th>
<th>Principal Investigator</th>
<th>Funding Source</th>
</tr>
</thead>
</table>
| Annual collection & storage of solar energy for heating of buildings | J. T. Beard  
Univ. of Virginia  
Dept. of Mech. Eng.  
Charlottesville, VA 22901 | OSAB |
| Soil heat transfer properties | Wynn Walker  
Colorado State University  
Solar Energy App. Lab  
Engineering Research Center  
Fort Collins, CO 80523 | OSAB |
| Solar space heat using annual storage Provident House and Alymer House | F. C. Hooper  
University of Toronto  
Mechanical Eng. Dept.  
Toronto, Ontario  
Canada M5S1A4 | OSAB |
| Viscosity stabilized solar ponds | Lloyd H. Shaffer  
Center for Environment & Man  
275 Windsor St.  
Hartford, CT 06120 | OSAB |
| Thermal performance of a hybrid solar residence | John Hull  
Ames Design Collaborative  
208 5th Street  
Ames, Iowa 50010 | OSAB |
| Salt gradient solar pond | Carl E. Nielson  
Ohio State University  
Research Foundation  
Department of Physics  
Ohio State University  
Columbus, OH 43210 | OSAB |
| Evaluation of Miamisburg solar pond | L. J. Wittenberg  
Monsanto Research Corp.  
Mound Facility  
Miamisburg, OH 45342 | OSAB |
| Salt gradient solar pond | H. Bryant  
University of New Mexico  
Dept. of Physics & Astronomy  
Albuquerque, NM 87131 | OSAB |
| Heat greenhouse with a solar pond | T. H. Short  
Ohio Agricultural Station  
Wooster, OH 44691 | USDA |
Table 7-2. PROJECTS IN DEVELOPING COMPONENTS FOR ACTES SOLAR SYSTEMS
(continued)

<table>
<thead>
<tr>
<th>Project Title</th>
<th>Principal Investigator</th>
<th>Funding Source</th>
</tr>
</thead>
</table>
| Saturated borax solar pond                      | T. L. Ochs
Energy Systems Center
Desert Research Institute
University of Nevada System
Boulder City, NV 89005                           | Private         |
| Long-duration earth storage of solar energy     | S. W. Yuan
A. M. Bloom
Civil, Mechanical & Env.
Engineering Department
George Washington University
Washington, D.C. 20052                           | STOR            |
| Twin Cities District Heating TES Study         | General Electric Company                                    | STOR            |
| Feasibility study for aquifer coolness storage at JFK airport | Henry Hibschmann
Desert Reclamation Inc.
6 Crabapple Lane
Plainfield, NJ 07060                             | STOR            |
|                                                 | M. E. Singer
New York State ERDA
Albany, NY 12223                                   | STOR            |
| Aquifer storage of cogenerated heat for district heating | Charles Meyer
G. E. Tempo
816 State Street
P.O. Box QQ
Santa Barbara, CA 93102                          | STOR            |
| TES in underground aquifer                      | C. F. Tsang
Lawrence Berkeley Labs
One Cyclotron Road
Berkeley, CA 95720                                | STOR            |
| Cold water storage in aquifers                  | D. L. Reddell
R. Davison
Texas A & M Research Foundation
FE Box H
College Station, TX 77843                         | STOR            |
| Aquifer hot water storage                       | J. C. Warman
F. J. Molz
Water Resources Research Institute
Auburn University
Auburn, AL 36830                                  | STOR            |
Table 7-2. PROJECTS IN DEVELOPING COMPONENTS FOR ACTES SOLAR SYSTEMS (concluded)

<table>
<thead>
<tr>
<th>Project Title</th>
<th>Principal Investigator</th>
<th>Funding Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of low temperature TES for TVA</td>
<td>A. M. Manaker</td>
<td>STOR</td>
</tr>
<tr>
<td></td>
<td>Energy Storage Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tennessee Valley Authority</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1360 Commerce Union Bank Bldg.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chattanooga, TN 37401</td>
<td></td>
</tr>
<tr>
<td>Environmental impact of aquifers</td>
<td>Elly K. Triegel</td>
<td>STOR</td>
</tr>
<tr>
<td></td>
<td>Oakridge Nat'l Labs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Impact Section</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P.O. Box X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oak Ridge, TN 37830</td>
<td></td>
</tr>
</tbody>
</table>

REFERENCES


4. TRNSYS: A Transient Simulation Program. Solar Energy Laboratory of the University of Wisconsin.


Additional Reading

Community-scale annual cycle thermal energy storage (ACTES) solar systems are promising options for building heat and cooling. A variety of approaches are feasible in modeling ACTES solar systems. The key parameter in such efforts, average collector efficiency, is first examined, followed by several approaches for simple and effective modeling. Methods are also examined for modeling building loads for structures based on both conventional and passive architectural designs. Two simulation models for sizing solar heating systems with annual storage are presented next. Validation is presented by comparison with the results of a study of seasonal storage systems based on SOLANSIM, an hour-by-hour simulation. These models are presently being used to examine the economic trade-off between collector field area and storage capacity. Finally, programs in the U.S. Department of Energy directed toward developing either other system components such as improved tanks and solar ponds or design tools for ACTES solar systems are examined.