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Systems Analysis Techniques for Annual Cycle Thermal Energy Storage Solar Systems

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SERI

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A Division of Midwest Research Institute

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SYSTEMS ANALYSIS TECHNIQUES FOR ANNUAL CYCLE THERMAL ENERGY STORAGE SOLAR SYSTEMS

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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.

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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.

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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 interative 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 bimonthly 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.

SECTION 2.0

COLLECTOR EFFICIENCY FUNCTIONS

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;

$$\text{i.e., efficiency } \alpha \left[1 - K \left(\frac{T_o - T_a}{I}\right)\right] .$$

Here, T_a is the ambient temperature and T_o 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 functon of $(T_o - T_a)/I$ 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

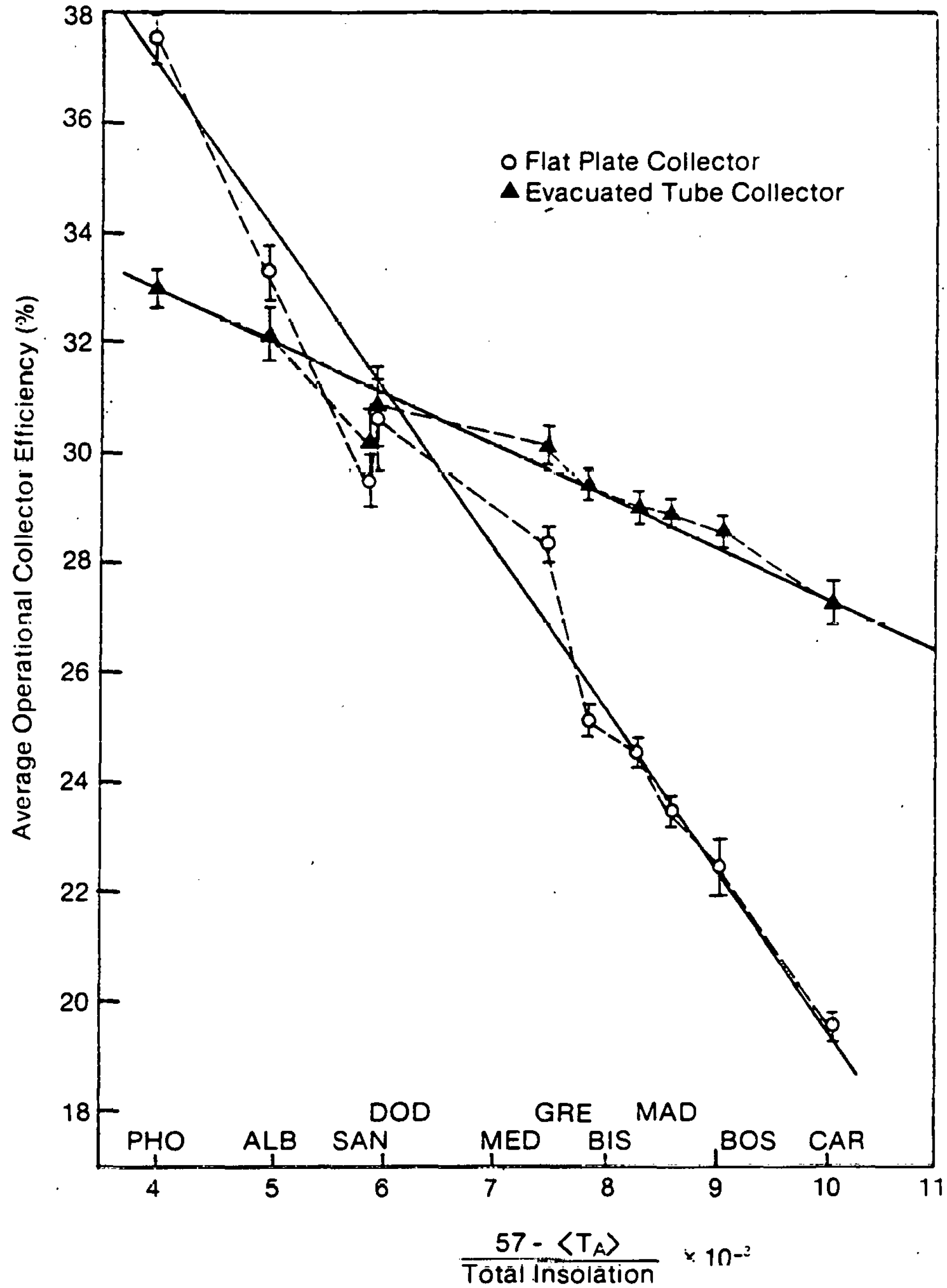


Figure 2-1. Average Operational Collector Efficiency versus $\frac{57 - \langle T_A \rangle}{\text{Total Insolation}}$ (Tilt = Latitude)

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.

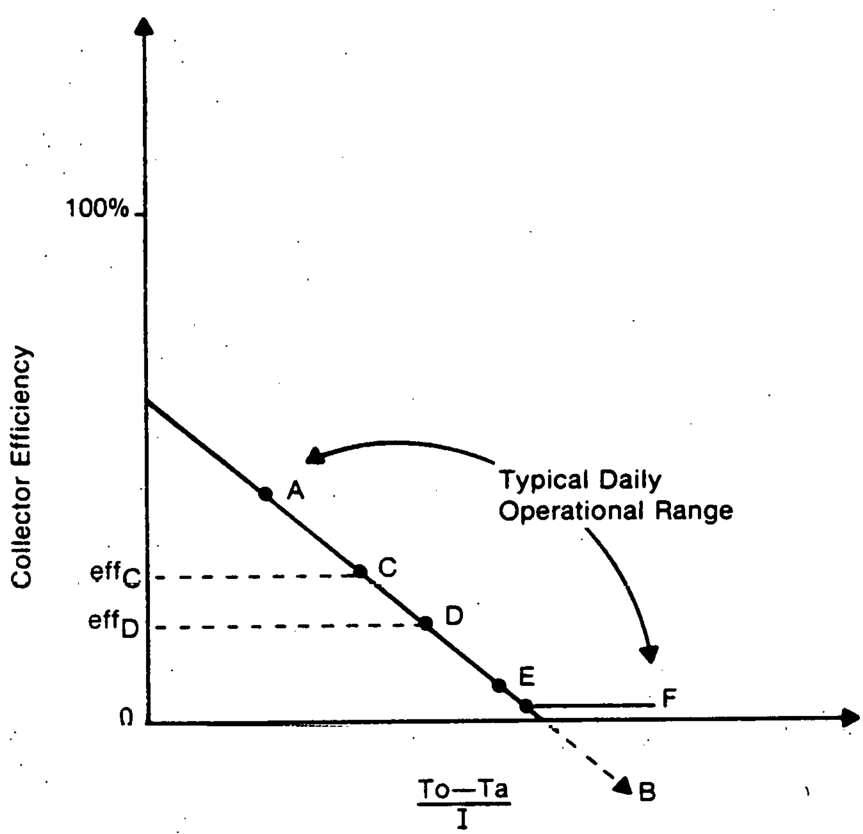


Figure 2-2. Schematic Representation of Collector Efficiency

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).

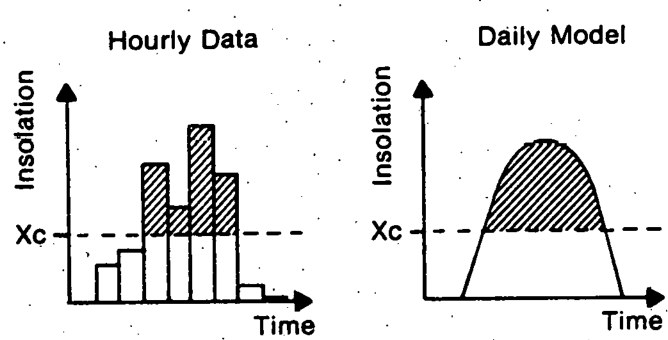


Figure 3-1. Use of a Simple Daily Model to Calculate Daily Collector Gain

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.

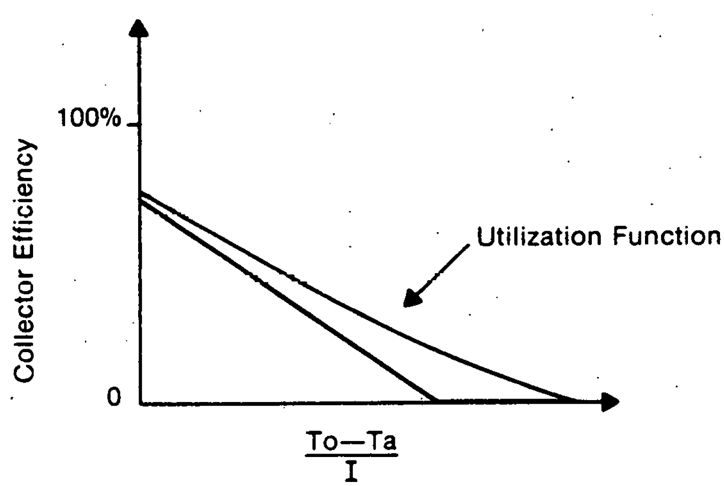


Figure 3-2. Use of Utilization Function to Calculate Average Efficiency with Averaged Data

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).

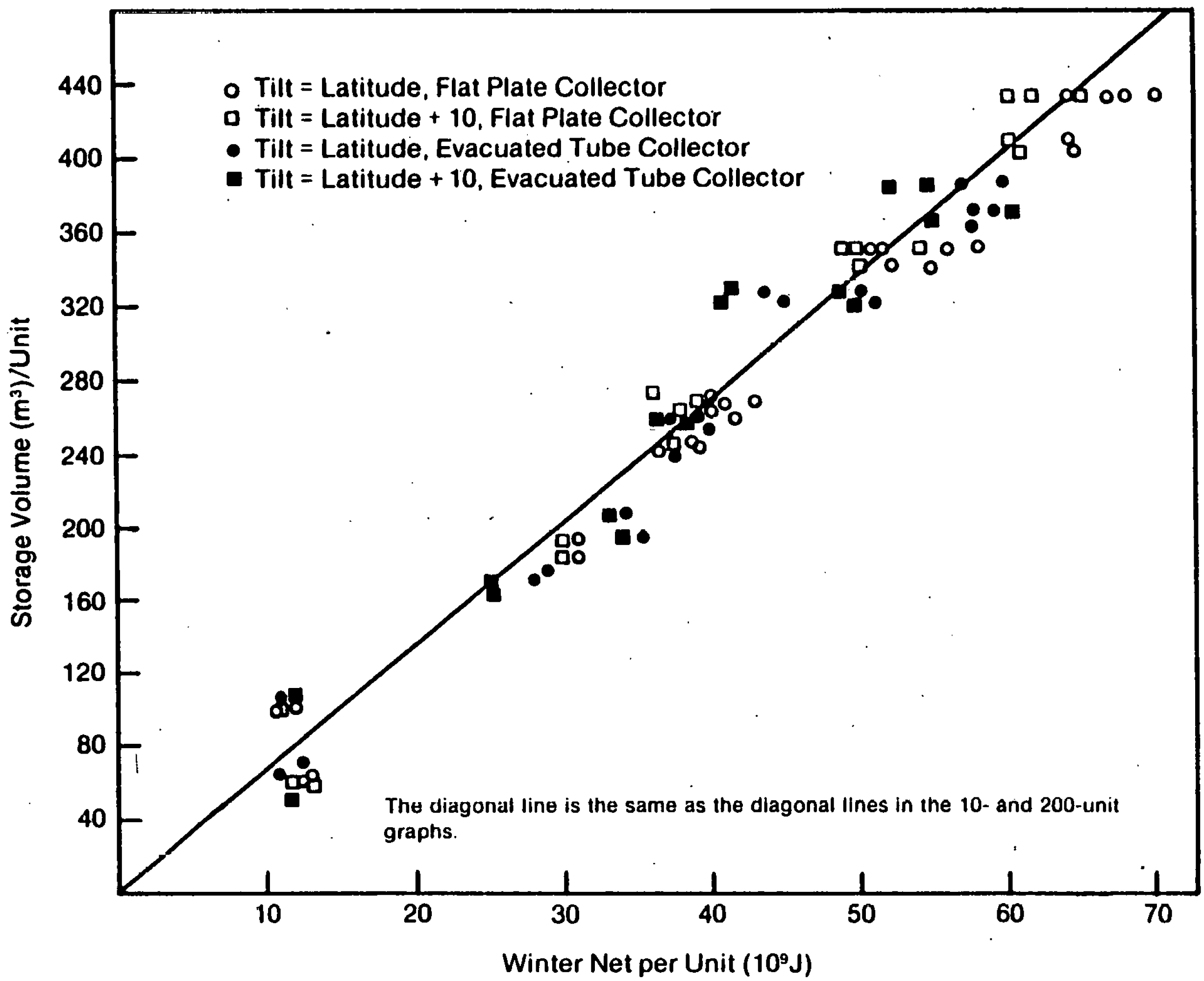


Figure 3-3. Storage Volume per Unit versus Winter Net Load per Unit: Single Unit Buildings.

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

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:

$$\text{Load} = U_a \, [T_b - T_a] \tag{4-1}$$

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°C) less the gain due to heat from sunlight, human bodies and appliances. T_b is typically chosen as 18°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°C [10]. For very well insulated houses, the base temperature for calculating heat loads may be 10°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 stretegies 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 sytems and of certain types of annual storages. Simple tools to model the behavior of entire systems are available; correctly modelling 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 proceduce (see Fig. 5-1) compare favorably with the orginal 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 limiations 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].

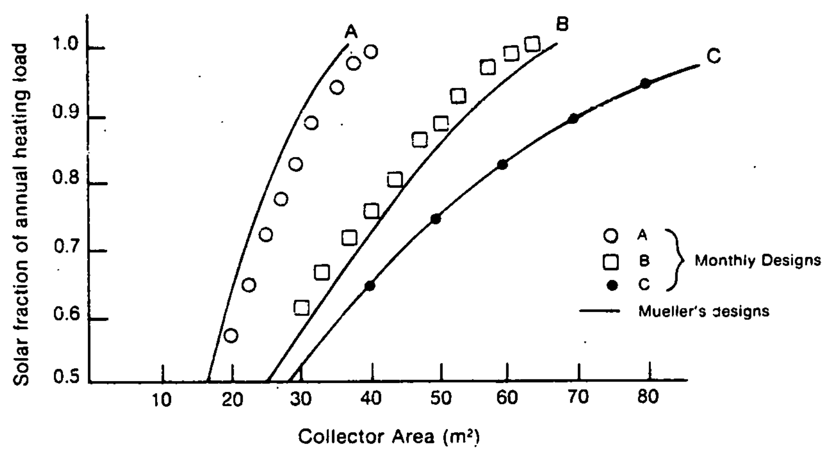


Figure 5-1. Designs for two-tank systems

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

System Specifications:		Small Tank Size Collector Area	Large Tank Size Collector Area
	A	0.25 m³/m²	5 m³/m²
	B	0.25 m³/m²	1 m³/m²
	C	0	1 m³/m²

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 (F_r 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:

$$f_{HW} = \frac{TS-TC}{TH-TC} \qquad (6-1)$$

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 QMAX and daily total insolation equals QTOT. The form of the daily insolation is taken as

$$Q(t) = QMAX \cos wt \tag{6-1}$$

where t is the time in hours, with noon being zero. From the stipulation that total daily insolation equals QTOT, it may be found that

$$w = 2 \frac{QMAX}{QTOT} \tag{6-2}$$

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]:

$$Q_{COL}(t) = F_r\ (\alpha\tau)\ Q(t) - F_r U_1\ (T_O - T_A) \tag{6-3}$$

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_O and T_A are the collector operating and ambient temperatures.

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

$$Qc = Fr\ (\alpha\tau) \int_{t_1}^{t_2} \left[QMAX \cos wt - \frac{U_1}{(\alpha\tau)} (T_O - T_A) \right] dt \tag{6-4}$$

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:

$$-t_1 = t_2 = t_x = \frac{1}{w} \left[\arccos \frac{1}{QMAX} \frac{U_1}{(\alpha\tau)} (T_O - \overline{T}_A) \right] \tag{6-5}$$

where $\overline{T}_A$ is the average ambient temperature during daylight.

Upon integration, the total daily heat collection becomes:

$$Qc = Fr\ (\alpha\tau)\ QTOT\ \sin wt_x - 2\ t_x\ FrU_1\ (T_O-T_A) \tag{6-6}$$

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

$$eff = F_r\ (\alpha\tau) - F_r\ U_1 \frac{(T_O-T_A)}{Q(t)}\ . \tag{6-7}$$

This may be expressed in a different form as

$$eff = F_r\ (\alpha\tau)\ (1 - X_C) \tag{6-8}$$

where X_C is the critical radiation level, equal to

$$X_C = \frac{U_1}{(\alpha\tau)} \frac{(T_O-T_A)}{Q(t)}\ .$$

As noted above, the long-term collector efficiency is a nonlinear function that cannot be calculated by using the instanteous efficiency equations. The average long-term efficiency over a period of time for which T_O 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

$$eff = F_r\ (\alpha\tau) \cdot \Phi\ (X_C) \tag{6-9}$$

where $\bar{X}_c$ 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:

$$\Phi\,(X_C) = \exp\left[\left(A + B\,\frac{R_{NS}}{R_S}\right) \cdot \left(X_C + C\,X_C^2\right)\right] \qquad (6\text{-}10)$$

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.

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 XC_n 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°C and usually within 1.5°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°C from the end-of-period minimum and rarely differed by that much.

Table 6-1. DISCREPANCY BETWEEN CALCULATED WINTER MINIMUM TEMPERATURES[a]

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

[a]T 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]

	Ap	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	March
Flat-Plate Collector												
Albuquerque, N. Mex.	-0.001	+0.021	+0.008	+0.008	-0.001	0	-0.010	-0.008	-0.023	-0.034	-0.014	-0.021
Boston, Mass.	+0.025	+0.015	+0.015	+0.002	+0.002	+0.008	-0.004	-0.002	-0.013	-0.026	-0.001	-0.030
Dodge City, Kans.	+0.005	+0.008	+0.007	+0.004	+0.001	-0.001	-0.014	-0.021	-0.018	-0.006	-0.008	-0.013
Great Falls, Mont.	+0.024	+0.011	+0.017	+0.004	+0.005	-0.006	-0.014	-0.011	-0.007	-0.031	-0.001	-0.005
Madison, Wis.	+0.029	+0.012	+0.013	-0.009	-0.007	-0.002	-0.004	-0.010	-0.010	-0.016	+0.004	+0.006
Phoenix, Ariz.	-0.001	-0.002	+0.003	0	-0.005	-0.019	-0.021	-0.011	-0.024	-0.034	-0.032	+0.019
Evacuated Tube Collector												
Albuquerque, N. Mex.	+0.002	+0.018	+0.005	+0.008	+0.007	+0.005	-0.001	+0.006	-0.004	-0.015	-0.001	-0.013
Dodge City, Kans.	+0.005	+0.007	+0.001	+0.004	+0.002	+0.004	+0.003	-0.003	+0.007	+0.007	-0.003	-0.007
Great Falls, Mont.	+0.020	+0.011	+0.015	+0.008	+0.010	+0.006	+0.001	+0.003	+0.005	+0.005	+0.004	+0.005
Madison, Wis.	+0.013	+0.012	+0.014	+0.004	+0.008	+0.011	+0.011	+0.001	+0.009	-0.002	+0.006	+0.008

[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[a]

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

[a]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.

SERI

SECTION 7.0

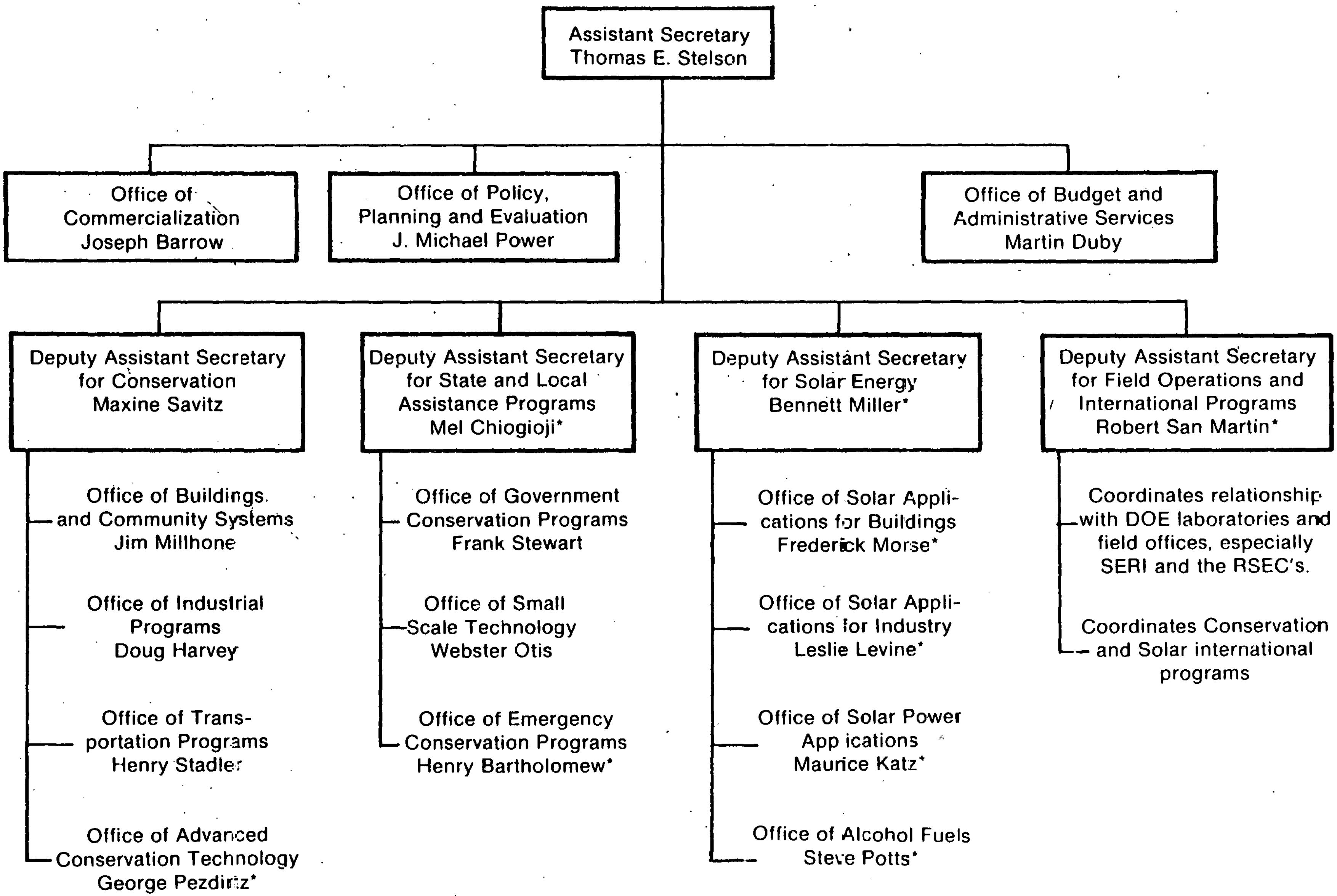
DOE PROGRAMS

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.



*Acting.

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

Research Organization	Title	Project Description
Pacific N.W. Laboratory	Seasonal TES Program (J. Minor)	Formulate and manage research in seasonal TES. Manage aquifer demonstration program for STOR. Coordinate development of codes such as AQUASTOR and CCC at Berkeley.
Univ. of California at Berkeley	Aquifer Modelling (Chin Fu Tsang)	Develop and validate CCC code which models physical characteristics of aquifers.
SERI	Solar Pond Research (J. Jayadev)	Develop technical and economic analysis tools for solar ponds. Develop SOLPOND code.
Argonne National Laboratory	Technical and Economic Analysis of TES Systems (J. Asbury)	Conduct analysis of selected TES systems. In particular, analysis of costs of annual storage tanks are completed.
Argonne National Laboratory	TES for Solar Program (A. Michaels)	Investigate TES for solar energy systems. In particular, model thermal stratification effects, and support research and analysis of annual cycle systems.
G. E. Tempo	Aquifer storage of cogenerated heat (C. Meyer)	Conduct general system analyses. Have developed simple model of heat distribution system.
University of Arizona	Seasonal storage system (C. Brent Cliff)	Model floating concentrator seasonal storage system.

Table 7-2. PROJECTS IN DEVELOPING TES COMPONENTS FOR ACTES SOLAR SYSTEMS

Project Title	Principal Investigator	Funding Source
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	Canadian govt.; 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)

Project Title	Principal Investigator	Funding Source
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 Berkely 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)

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

REFERENCES

1. F. Baylin; R. Monte; S. Sillman. Annual Cycle Thermal Energy Storage for a Community Solar System--Details of a Sensitivity Analysis. Golden, CO: Solar Energy Research Institute; SERI/TR355-575; June 1980.

2. J. S. Jayadev; M. Edesess. Solar Ponds. Golden, CO: Solar Energy Research Institute; SERI/TP-641-587; March 1980.

3. Systems Analysis Branch, Solar Energy Research Institute. Analysis Methods for Solar Heating and Cooling Applications: Passive and Active Systems. Golden, CO: Solar Energy Research Institute; SERI/SP-35-232R; January 1980.

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

5. S. Sillman. Investigation of a Simple Daily Solar Radiation Model Suitable for Use in the Design of Solar Heating Systems. Golden, CO: Solar Energy Research Institute; forthcoming.

6. S. A. Klein. "Calculation of Flat-Plate Collector Utilizability." Solar Energy. Vol 21 (No 5): pp 393-402; 1978.

7. P. J. Lunde. "Prediction of Average Collector Efficiency from Climatic Data." Solar Energy. Vol 19 (No 6): pp 685-689; 1977.

8. P. J. Lunde. "Prediction of the Performance of Solar Heating Systems Utilizing Annual Storage." Solar Energy. Vol 22: pp 69-75; 1978.

9. F. Baylin; R. Monte; S. Sillman; F. C. Hooper; J. D. McCLenahan. Economic Analysis of Community Solar Heating Systems Using Annual Cycle Thermal Energy Storage. Golden, CO: Solar Energy Research Institute; forthcoming.

10. ASHRAE Handbook of Fundamentals: Systems. Chapter 43. Menasha, WI; 1976.

11. W. A. Shurcliffe. Superinsulated Houses and Double Envelope House. Cambridge, MA; March 1980.

12. R. Judkoff. "Beyond Mass and Glass: An Overview of User-Oriented Passive Design Tools." Proceedings of the Third National Passive Solar Heating Conference. San Jose, CA; January 1979.

13. R. Judkoff. "Passive System Design and Sizing Methods." Solar Federal Buildings Program Workbook. Chapter 9. Golden, CO: Solar Energy Research Institute; May 1980.

14. F. C. Hooper; et al. Solar Space Heating Systems Using Annual Heat Storage Progress Report. Washington, D.C.: U.S. Department of Energy; COO-2939-6, October 1978.

15. B. K. Cha; D. W. Conner; R. O. Mueller. "A 'Two-Tank' Seasonal Storage Concept for Solar Space Heating of Buildings." Proceedings of Second Miami International Conference on Alternative Energy Sources. Miami, FL; December 10-13, 1979.

16. A. E. McGarity. "Optimum Collector-Storage Combinations Involving Annual Cycle Storage." Proceedings of Solar Energy Storage Options. San Antonio, TX; March 19-20, 1979; pp. 165-173.

17. J. E. Hay. "Calculation of Monthly Mean Solar Radiation for Horizontal and Inclined Surfaces." Solar Energy. Vol 23: pp. 301-307; 1979.

18. B. Liu; R. Jordan. "The Long-Term Average Performance of Flat-Plate Solar Energy Collectors." Solar Energy. Vol. 7: p. 53; 1963.

19. S. Klein; W. Duffie; R. Beckman. Solar Heating Design. Wiley and Sons.

20. F. Baylin. Low Temperature Thermal Energy Storage: A State-of-the-Art Survey. Golden, CO: Solar Energy Research Institute; SERI/RR-54-164; July 1979.

21. F. Baylin; M. Merino. Survey of Sensible and Latent Heat Thermal Energy Storage Projects. Golden, CO: Solar Energy Research Institute; SERI/RR-355 456; forthcoming.

Additional Reading

C. J. Swet; F. Baylin. Central Unresolved Issues in Thermal Energy Storage for Building, Heating, and Cooling. Golden, CO: Solar Energy Research Institute; SERI/RR-355-455; June 1980.

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16. Abstract (Limit: 200 words)

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.

17. Document Analysis

a. Descriptors: Storage; Energy Storage ; Annual Energy Storage ; Systems Analysis ; Simulation ; Energy Models ; Statistical Models ; Load Management ; Design ; Feasibility Studies ; Comparative Evaluation ; Efficiency ; Energy Efficiency ; Thermal Efficiency ; Solar Collectors ; Solar Energy ; Solar Heating Systems ; Heating ; Solar Cooling Systems ; Air Conditioning ; Annual Cycle Energy System ; Research Programs ; Experiment Planning ; Demonstration Programs ; Seasonal Variation.

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