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ANNUAL-CYCLE THERMAL ENERGY STORAGE FOR A COMMUNITY SOLAR SYSTEM:
DETAILS OF A SENSITIVITY ANALYSIS

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FOREWORD

This document is part of a coordinated effort at the Solar Energy Research Institute (SERI) to examine all aspects of energy storage technologies having applications in solar systems. Storage systems are perceived as being critically important to many solar energy applications.

This research examines applications of annual-cycle thermal energy storages (ACTES) to solar space heating and domestic hot water systems. This effort is the forerunner of a more thorough analysis of the value of ACTES technologies (such as large constructed tanks, aquifers, in-ground pits, and solar ponds) to solar energy systems. The data in this report are designed to aid the planning efforts of the Chemical and Thermal Energy Storage program in the Office of Advanced Conservation Technologies at the U. S. Department of Energy.

The authors wish to express appreciation to a number of associates who contributed both information and critical reviews of this document. Frank Hooper and his associates at the University of Toronto developed the code upon which this work is based. C. J. Swet, a private consultant, and Michael Holtz and Charles Wyman of SERI all reviewed the completed document and provided valuable advice.

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SUMMARY

This report presents results and conclusions of a simulation and sensitivity analysis of community-sized, annual-cycle thermal-energy-storage (ACTES) solar energy systems. The analysis which is based on an hourly simulation is used to (1) size systems in 10 locations, (2) identify critical design parameters, and (3) provide a basic conceptual approach for future studies and designs. This research is a forerunner to an economic analysis of this particular system (based on large constructed tanks) and a general analysis of the value of ACTES technologies for solar applications.

Systems were sized for 10 locations in the United States. Three different building types (single family residences, multifamily residences, and apartment buildings) and four different community sizes (50-, 200-, 400-, and 1,000-unit sizes) were modeled. All designs used each of two collector types (flat plate and evacuated tube) at each of two different tilt angles. In all, 440 systems were sized.

Two linear relationships were derived which simplify system sizing. The average ambient temperature is used to determine average yearly collector efficiency. This parameter combined with estimates of space/DHW loads, storage/distribution losses, and total yearly insolation per square meter allows estimation of collector area. Storage size can be estimated from the winter net load which is based on space and DHW loads, storage and distribution losses, and collector solar heat gain for the winter months.

These algorithms, which would be applicable to other types of annual storages such as aquifers, can be further refined as results from the operation of ACTES solar systems become available. Calculations also can be refined with more detailed knowledge of a particular community design.

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INTRODUCTION

Most active solar systems are optimized to provide approximately 50-70% of the space heating load; a full-sized backup power source may be required to supplement the solar system. The capital cost of the solar system and the auxiliary supply must be more than offset by fuel savings so that this option may be economical. If electric heat is used as a backup, the most common form in present solar homes, auxiliary heat is occasionally required at peaks in the electric utility demand profile. In such cases, the real cost that the utility must pay for this backup power is likely to be greater than the market price.

Solar systems designed to supply 100% of space-heating loads using diurnal thermal storage are poor economic choices; the extra storage capacity and storage volume required to supply heating for those rare but extended periods of cloud cover would be underutilized at most times. Annual cycle thermal energy storage (ACTES) systems are an alterative method of utilizing solar energy to provide 100% of space-heating loads.

An ACTES system employs a very large storage—typically enough to supply a month or more of space heat—and stores heat collected during the summer and fall to help supply the winter peak load. Such a system increases, rather than reduces, collector utilization while extending the proportion of heat provided to 100%. Because the cost of large-scale storage to store a given amount of energy can be substantially less than the cost of collectors to supply the same amount of energy, incorporating an ACTES into building designs may allow economical use of 100% solar energy systems by permitting use of excess summer insolation to meet winter heating loads. Penetration of solar energy technologies into certain sectors of the buildings' heating and cooling markets may well be radically hastened by use of such long-term energy storages [1].

The need for seasonal storage is depicted in Figure 1-1, which shows month-to-month variation in load and insolation for both a northern city (Madison, Wisc.) and a southern city (Phoenix, Ariz.). The load shows a very sharp winter peak when insolation drops off. The load profile shows less of a peak for an apartment complex (HUB 200, 2 hundred unit buildings) than for single family houses (SUB 50, 50 single-unit buildings) because the hot water load makes up a greater proportion of the total load for an apartment complex. Both load and insolation vary less throughout the year in Phoenix than in Madison, but even in Phoenix the discrepancy between load and insolation is large enough that ACTES systems may be feasible for large-enough communities.

Figures 1-2a and 1-2b outline the simulated operation of a seasonal storage system for the two cities (Madison and Phoenix) and building types (single family and apartment). The top graphs show monthly load and collector gain (collector gain is defined as the energy collected per month as measured at the collector output). The difference between the two (shaded area) indicates the amount of heat to be provided by storage during the winter. The bottom graphs show the storage temperature and the collector efficiency. Storage temperature follows a similar pattern for both cities, rising to the mid-70s°C by early autumn and then dropping through the winter as heat is drawn to satisfy the winter load. The collector efficiency drops sharply in the winter months. This effect is much more severe for Madison, where efficiency drops below 10%, than for

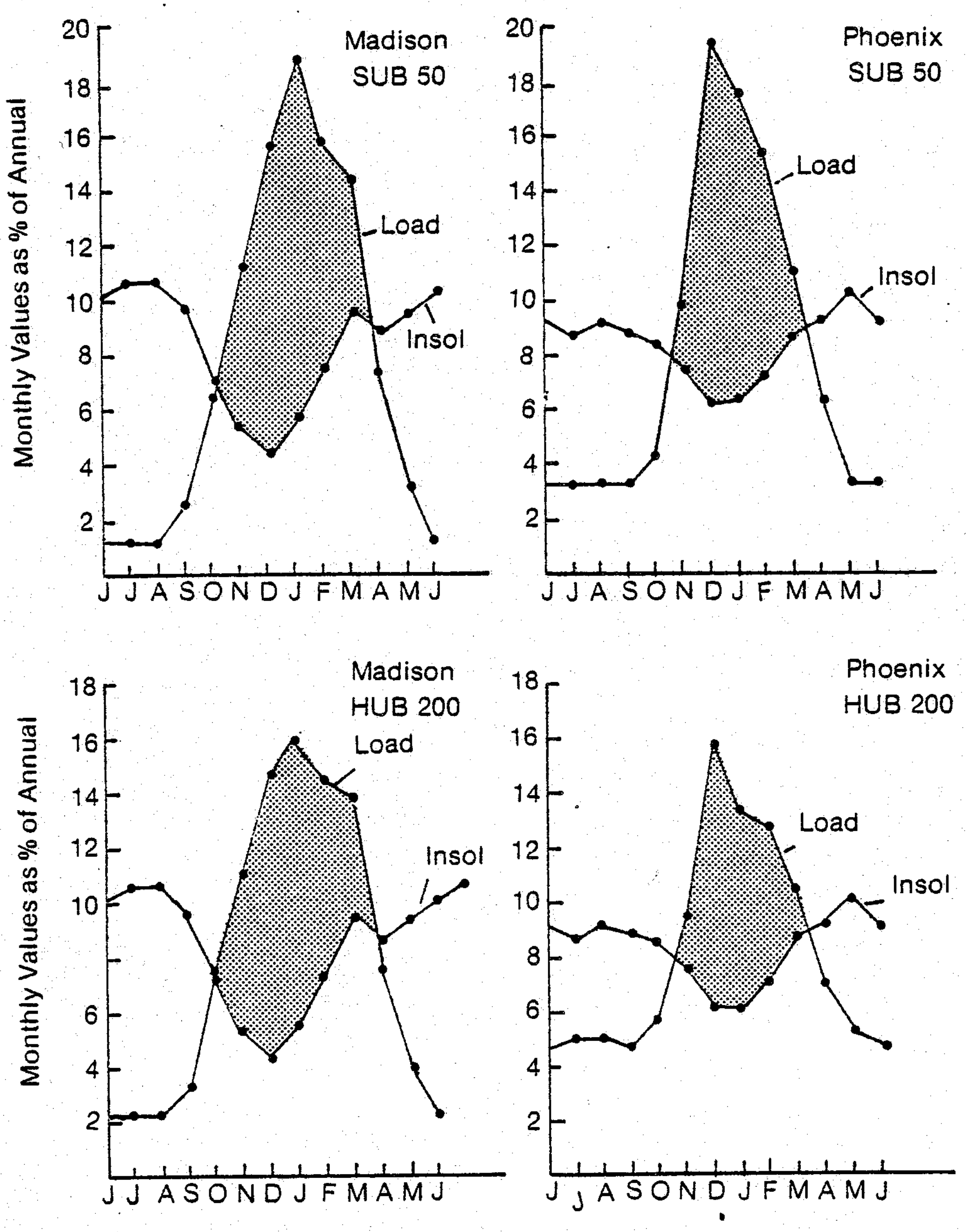
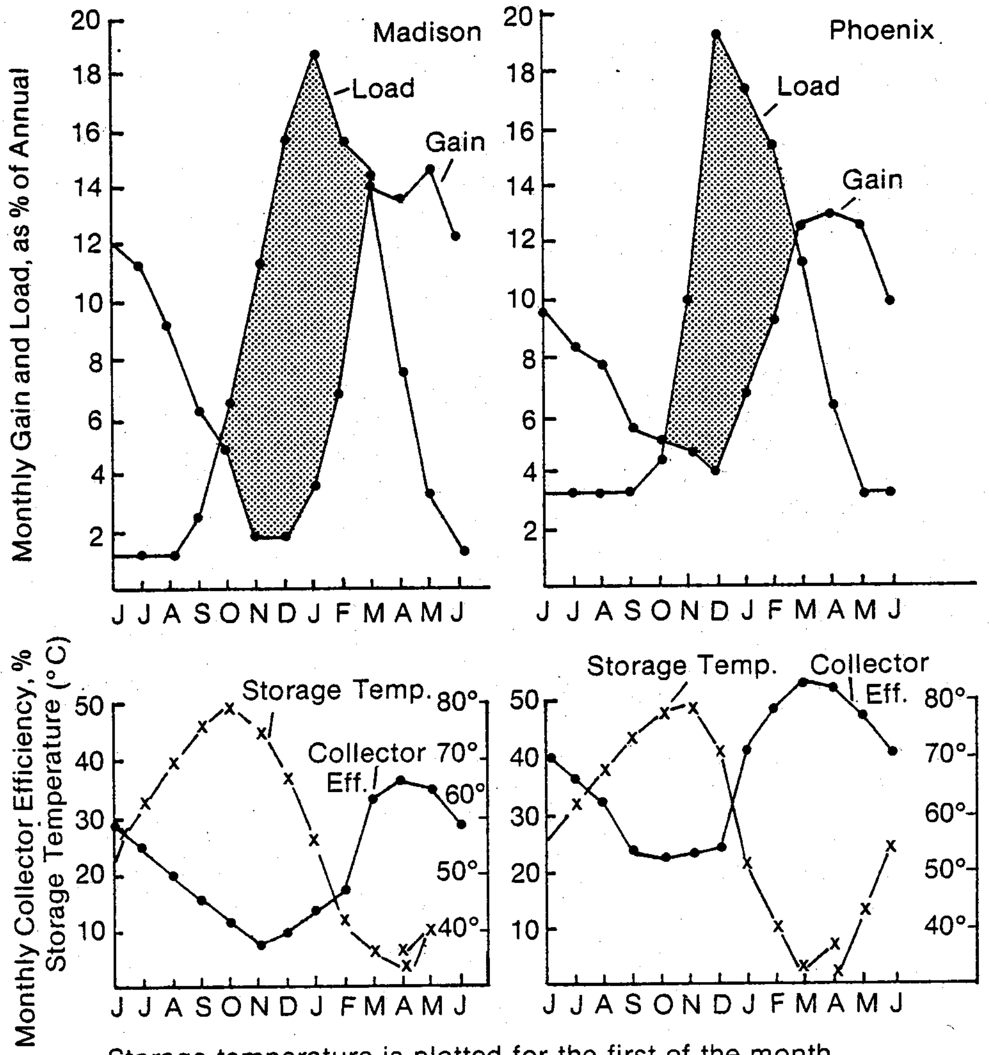
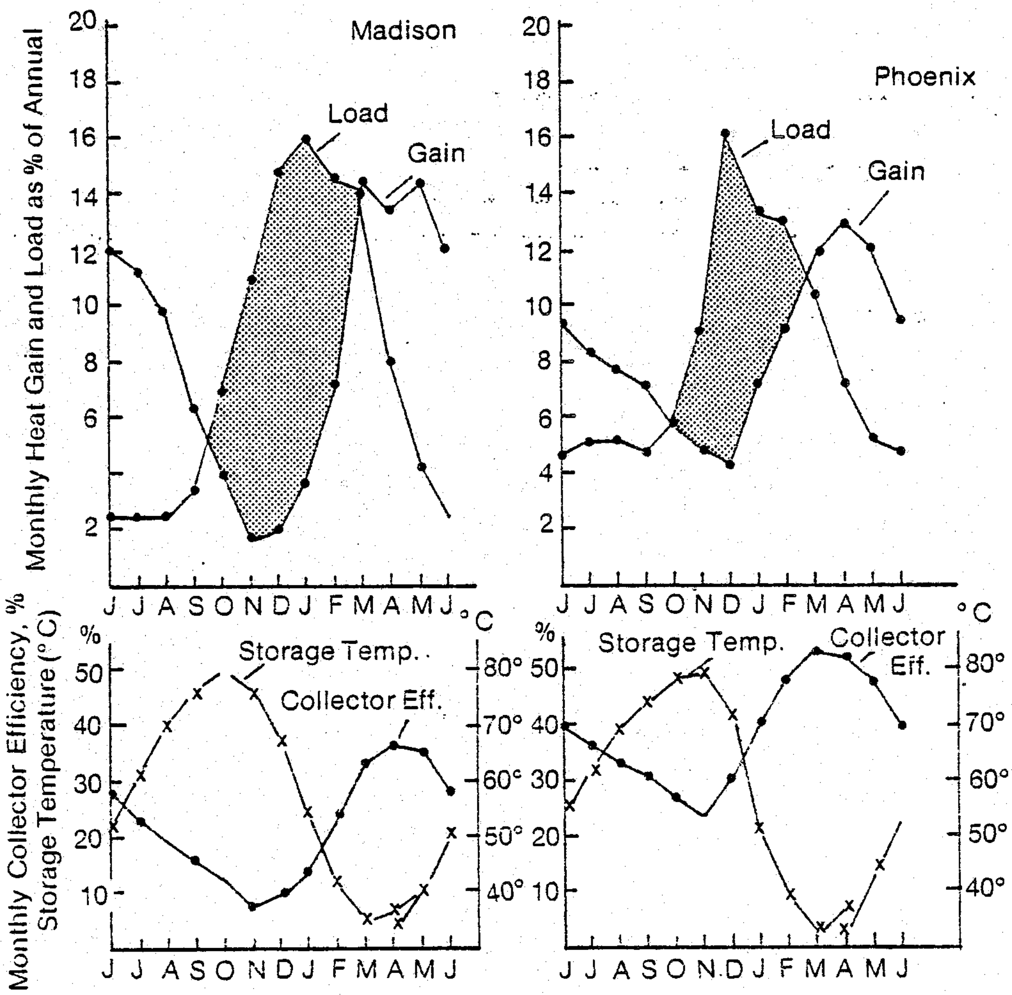


Figure 1-1. Month-by-Month Insolation and Heat Loads (Including Hot Water) [expressed as a % of annual load and insolation]



Storage temperature is plotted for the first of the month.

Figure 1-2a. Month-by-Month Collector Gain, Heat Load, Efficiency, and Temperature Flat Plate, Tilt = Latitude, SUB 50.



Storage temperature is plotted for the first of the month.

Figure 1-2b. Month-by-Month Collector Gain, Heat Load, Efficiency, and Temperature Flat Plate Collector, Tilt = Latitude, HUB 200.

Phoenix where efficiency remains above 20%. The low winter collector efficiency is another important reason for investigating seasonal storage, especially in northern cities.

A wide variety of devices for storing thermal energy are presently available or are under development [2]. A general classification of such technologies is presented in Figure 1-3. Because of economics of scale in both cost and efficiency, it may be advantageous to build common, district storage systems to serve 50 or more housing units. Aquifers, large constructed tanks, and earth beds are potentially feasible and attractive near-term technologies. Aquifer storages which may allow low-cost storage of thermal energy are actively being developed in a program managed by Battelle Pacific Northwest Laboratories for the Office of Advanced Conservation Technologies in the U.S. Department of Energy (DOE). However, aquifer storages may not be feasible in certain locations. Large constructed tanks for use in ACTES have already been built at two locations in Canada by a team from the University of Toronto [3,4] and at one location in Sweden [5], and they are being designed in Canada [3,4], Sweden [5,6], and France [7]. Problems may be encountered with underground constructed tanks if the water table is high or if a high flow velocity is required for a solar system.

1.1 SCOPE OF STUDY

An analysis based on an hourly simulation of an ACTES solar system is used to (1) size systems in 10 locations, (2) identify critical design parameters, and (3) provide a basic conceptual approach for future studies and designs.

The computer code was developed at the University of Toronto by Hooper and his associates [8]. The storage is a large, cylindrical, constructed water tank. Three different building types (single-family residences, multifamily residences, and apartment buildings), and four different community sizes (50-, 200-, 400- and 1,000-unit sizes) were modelled in 10 geographic locations. In addition, systems having two collector types (flat plate and evacuated tube) at two different tilt angles were designed. Soil conductivity was varied for one of the configurations. An optimization method (see Section 2.0 for details) was used with this code to size the storage and the collector field for all 440 configurations as well as to provide a daily record of parameters, such as collector-efficiency storage-tank temperature and building load.

This particular computer code was used because it was the only one available in North America, it has been validated already in one demonstration project, Provident House [3], and it has been used to design a second larger facility, the Alymer community [4]. By using SERI support services and the University of Toronto code, an extensive and thorough study could be performed quickly. This work has suggested a number of avenues for further research.

1.2 ADVANTAGES AND DISADVANTAGES OF ACTES

Annual-cycle thermal energy storage (ACTES) systems are designed with sufficiently large capacities so that daily, and even weekly, variations in insolation have little effect on system performance. This operational characteristic and the ability to collect the summer heat for use in winter heating loads and the winter coolness for use in summer

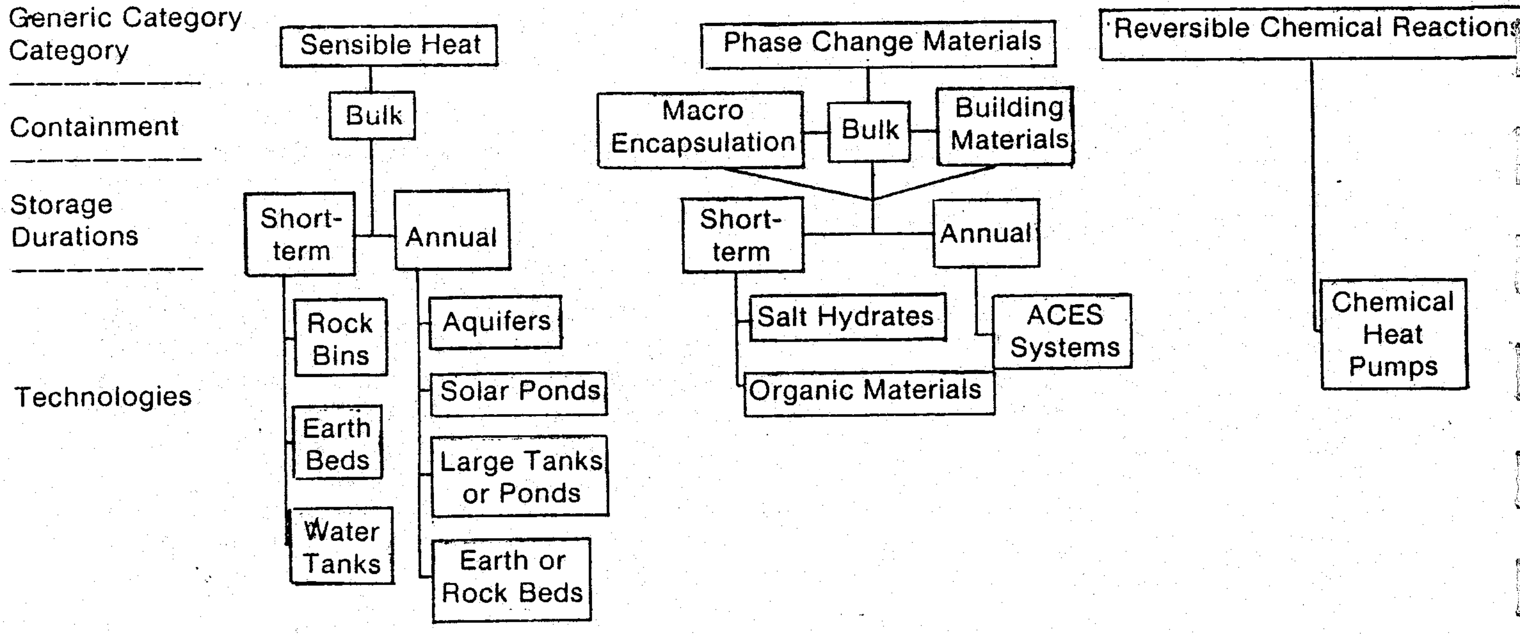


Figure 1-3. General Classification of Thermal Energy Storage Technologies.

cooling loads allow for the design of solar systems that meet 100% of all loads. The advantages and disadvantages, listed below, accrue from both the ACTES concept and the incorporation of district solar heating.

1.2.1 Advantages

- The collector area can be reduced because collector utilization is markedly improved. Use of well-designed homes or buildings may further reduce requirements for solar collectors.
- Overall collection efficiency improves because collector stagnation in summer is all but eliminated.
- As the storage size increases, the unit cost of storage decreases.
- As the storage size increases, the unit heat losses decrease and storage efficiency increases because the surface area-to-volume ratio of the container decreases proportionately to the increase of the radius.
- Statistical averaging of demand in a community increases system reliability.
- Shared loads can decrease overall energy requirements. In fact, some well-designed single-family passive-designed residences or large commercial buildings are actually, on occasion, energy sources. For communities in which none of the buildings are energy sources, shared loads may only decrease overall power requirements.
- Unit costs for energy-moving equipment may be less expensive on a large scale.
- Operation and maintenance is an expense shared by community residents.
- A community system may have the financing and tax advantages of a utility.

1.2.2 Disadvantages

- An energy distribution system with all the incumbent thermal losses and water freezing problems is required.
- Energy losses from storage are larger over a longer period of time.
- Large capital outlays are required for the storage component because ACTES systems are larger per unit of load than those for diurnal systems.
- Management and operation of ACTES community systems must be an ongoing effort by trained personnel.

1.3 FACTORS IN ACTES PERFORMANCE AND ECONOMICS

A number of important factors and design trade-offs can be identified in ACTES solar systems which will affect performance and economics. These include insolation profile and building load, collector storage trade-off, stratification and heat losses, passive design, collector design, and ownership options. The results of this research quantify these observations along with others.

1.3.1 Stratification and Heat Loss

For a given volume, the more closely a storage tank approaches a spherical shape, the lower the heat losses are, if other factors such as tank insulation and soil conditions are held constant. Thus, a cylindrical tank with radius, r, equal height, h, (minimize the surface area to volume ratio, $2/h + 1/r$, given that volume is constant, and $h = r$ results) is optimal. However, in general the smaller the diameter to height ratio of a cylindrical tank, the more the fluid will be thermally stratified. With these considerations in mind and with the use of stratification enhancers such as tank baffles [9], an optimum design point will be found in trading off height and diameter.

A recent Canadian study [10], which shows annual storage to be presently uneconomical, uses the worst possible tank shape—a very flat cylinder. In designing a system, a stratified, high-efficiency storage should be used. Generally, the larger the thermal utility, the lower the unit cost of storing energy.

1.3.2 Transmission Loss

Transmission loss in larger community systems is an important design consideration. These losses, as well as storage losses, determine the overall thermal efficiency of storage and directly affect the size of collector fields. An inefficient system is not likely to be economical. The type of collector, operating temperatures, soil temperatures and moisture content, distribution system configuration, and type and quantity of insulation determine the transmission losses. Such factors are more important in larger, more dispersed communities that require additional piping and controls.

1.3.3 Soil Conductivity

The drier the soil surrounding the storage and distribution system, the lower the heat losses will be, if other factors are held constant. Soil moisture content varies from location to location. A factor in locating an ACTES system is, therefore, the soil characteristics. In those cases (e.g., in many parts of Florida) where the water table is shallow and interferes with either the storage tank or the distribution system, difficulties will be encountered.

1.3.4 Reflectors and Other Methods for Enhancing Collector Performance

In some climates, winter snow cover will increase solar gain especially when collectors are steeply inclined. Designs in new construction may increase system performance and lower costs by incorporating some form of reflectors.

1.3.5 Insolation Profile and Building Load

The ACTES system derives its economic advantages from collecting energy during the summer, when both insolation and collector efficiency are higher, for use in winter. As a consequence, collector utilization improves and the collector area can be reduced. It may be argued that the larger the variation between summer and winter insolation (i.e., the more northerly one builds the solar systems), the better the economics. However, a latitude beyond which ACTES solar systems are uneconomical may be approached because the total annual insolation is too low and the increase in winter load more than offsets the advantages of summer energy collection. Figure 1-4 demonstrates the dramatic difference in insolation quantity and profile between Kenya which has no heating load and Sweden. These conclusions depend on system size. A higher load will require larger storage to have lower associated unit-storage cost.

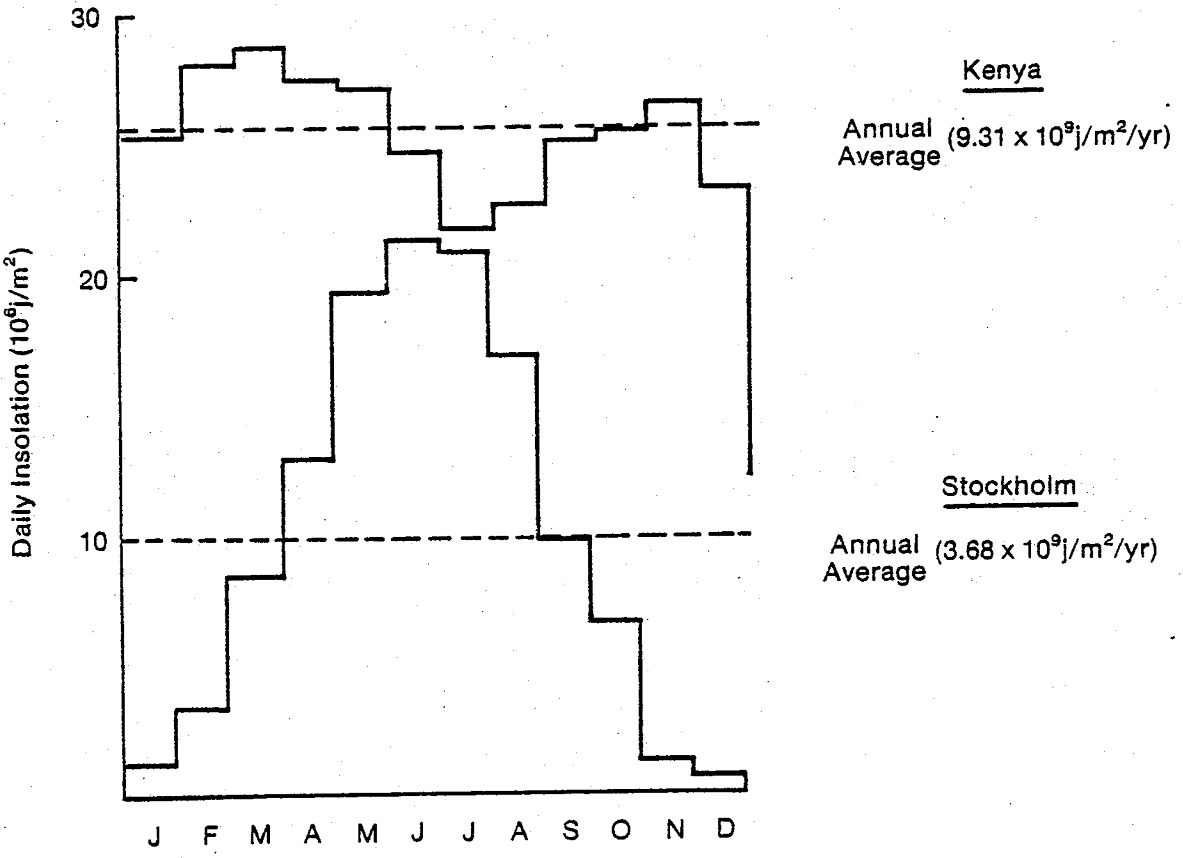


Figure 1-4. Average Daily Horizontal Insolation by Month for Stockholm and Kenya.

The seasonal variation in heat load may also affect the desirability and the sizing of ACTES systems. As shown in Figure 1-2, buildings in which domestic hot water load is larger and space heat load is smaller have a flatter seasonal load profile and, therefore, require a smaller ACTES system.

1.3.6 Passive Designs

A community of passive solar homes may have a much lower load which is displaced in time by the built-in thermal storage. In order to be economical, such a community probably will be required to be larger in order to reach an economic storage-tank size. In addition, load requirements will be displaced in time and, consequently, will affect the results of any simulation. Therefore, use of a heat load factor which, combined with hourly weather data, is used to calculate an hourly heating load would not be applicable for passive design analyses.

As mentioned above, passive designs result in a flatter seasonal load profile. As a result, the ACTES systems needed to provide 100% solar heating may be proportionately smaller and, consequently, economically advantageous.

1.3.7 Collector Storage Trade-off

When designing an ACTES system to meet a specified load or load percentage, a trade-off exists between collector and storage size—increasing storage size to a certain point allows use of a smaller collector field. The exact trade-off between collector and storage is determined by the relative cost of each component. One uniform sizing algorithm was used for all systems presented here (see Section 2.2).

1.3.8 Collector Design

Flat-plate collectors (FPC) are designed for a medium-range temperature operation. Therefore, use of such collectors would produce only moderate winter energy collection and necessitate use of either larger or more-efficient storages. However, FPC can be rotated or tilted at various angles that optimize performance at different times of the year.

Evacuated-tube collectors (ETC) have higher efficiency at lower ambient temperatures. Therefore, fewer collectors are needed to provide a given amount of heat. Collectors could be placed on or near the actual storage site, allowing the facility to be utility managed and owned. The present disadvantage of ETC is higher initial cost, although in some applications ETC have lower life-cycle delivered energy costs than FPC.

1.3.9 Ownership Options

These systems can be owned by builders, community groups, utilities, or others. Operation and maintenance will be effected best by trained personnel. Larger systems may have to be managed by groups with more technical expertise.

Solar collectors can be placed on individual dwellings or located at a central solar plant. Difficulties may arise in some instances. For example, if solar collectors are situated on individual buildings and owned by residents but the energy derived from the collectors is owned and managed at the central storage and control location by a utility, then residents may be legally able to disconnect their collectors from the main feed lines (by either turning a valve or planting a tree in front of their homes). Such an individual action would place a burden on other members of the solar community.

SECTION 2.0

RESEARCH METHODS

This study is based on a code developed at the University of Toronto [3,4]. A brief description of methods used in the computer program is provided in Appendix A. Section 2.0 describes the input and output, the independent and dependent variables, and the procedure used in sizing the components of the ACTES solar system. In addition, preliminary designs are presented for the various configurations. These plans are used in more detail in the economic analysis in the second volume of this study.

2.1 VARIABLES

Variables are grouped into two categories. Unconstrained variables are major elements of the sensitivity analysis. Constrained variables are preselected.

2.1.1 Unconstrained Variables

The following parameters were varied: community size and housing type, geographic location, collector type, collector tilt angle, soil conductivity, design ambient temperature, and insulation thickness.

2.1.1.1 Community Size and Housing Type

Several community sizes and housing types are examined. Single-family detached homes, 10-unit condominiums, and 200-unit apartment complexes provide a range of building types and are judged to be representative of current U.S. housing trends. Community sizes are varied from 50 to 200, 400, and 1,000 units. Thus, a total of 11 configurations (3 x 4 minus the excluded 50-unit apartment complex) are considered.

The choice of building configuration is based on those used in the recent OTA report on solar energy [11]. Single-family residences of 2,000 ft^2 and 10-unit 3-bedroom condominiums with a 1,300 ft^2 total area were modelled. The 200-unit apartment complex was 10 stories consisting of 160 one-bedroom units of 850 ft^2 and 40 two-bedroom units of 950 ft^2.

2.1.1.2 Geographic Location

Weather tapes having complete data from 10 U.S. cities were used. An insolation map of the United States is shown in Figure 2-1. The locations of the 10 cities are shown in Figure 2-2. Total yearly insolation and latitude can be used to characterize the geographic locations of the ACTES solar systems. These two variables, not linearly related to latitude as shown in Figure 2-3, and combinations of these variables are used in the sensitivity analysis in Section 3.0. Table 2-1 lists the total yearly insolation on a surface whose tilt equals the latitude, the average ambient temperature, and the total degree centigrade days by city.

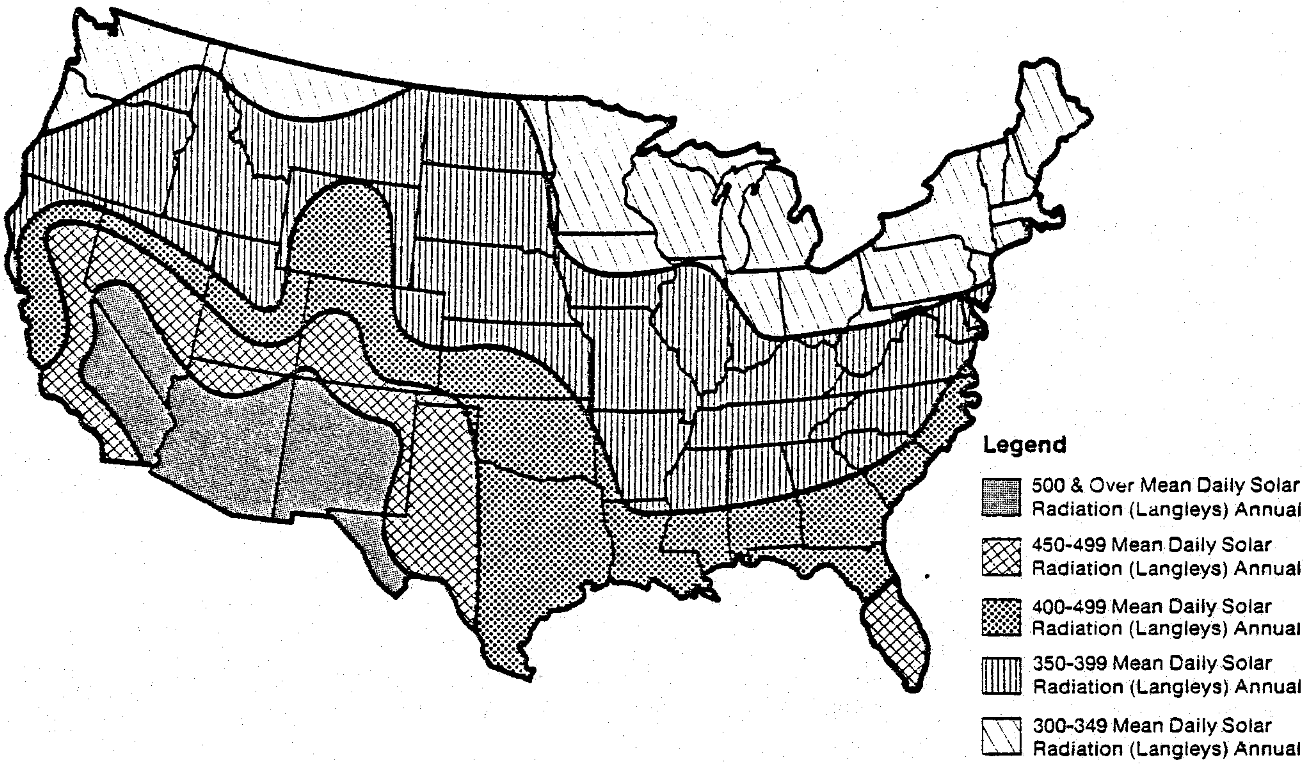


Figure 2-1. Insolation Map of the United States.

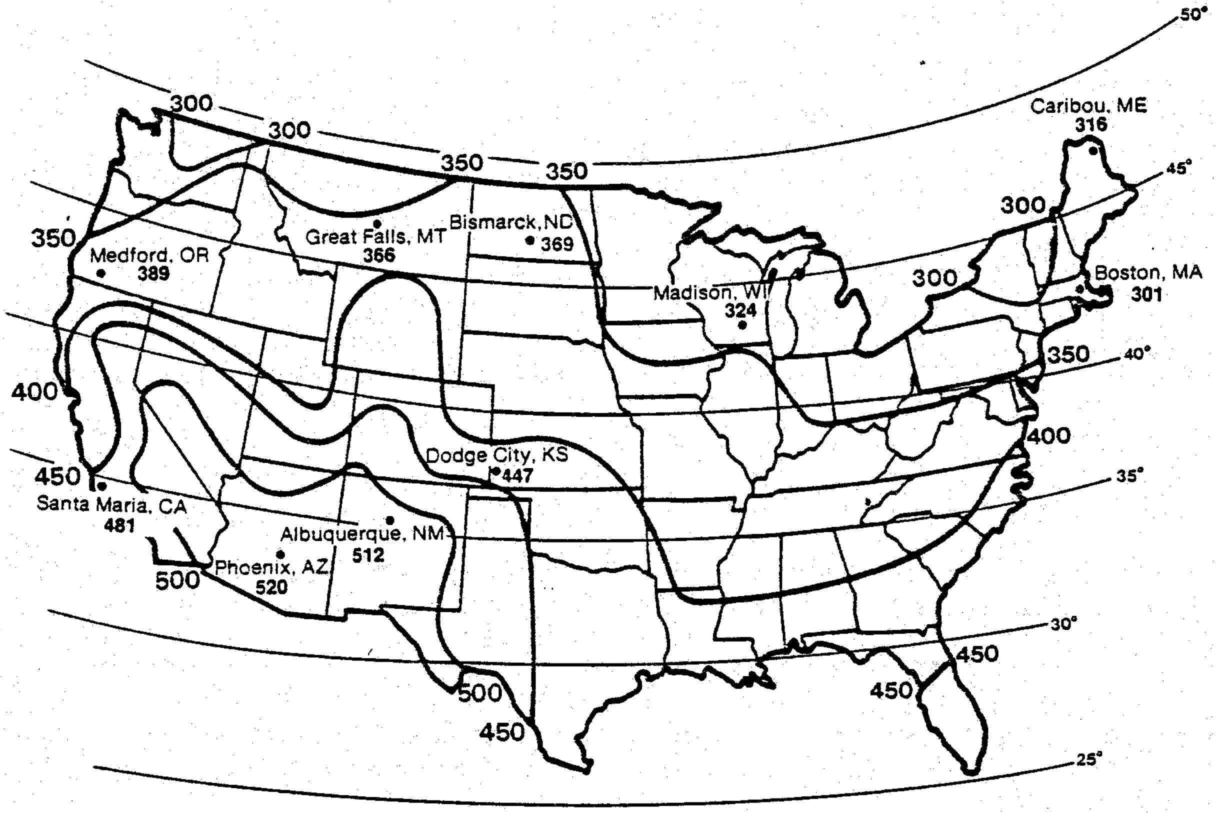


Figure 2-2. Location of Cities in Study.

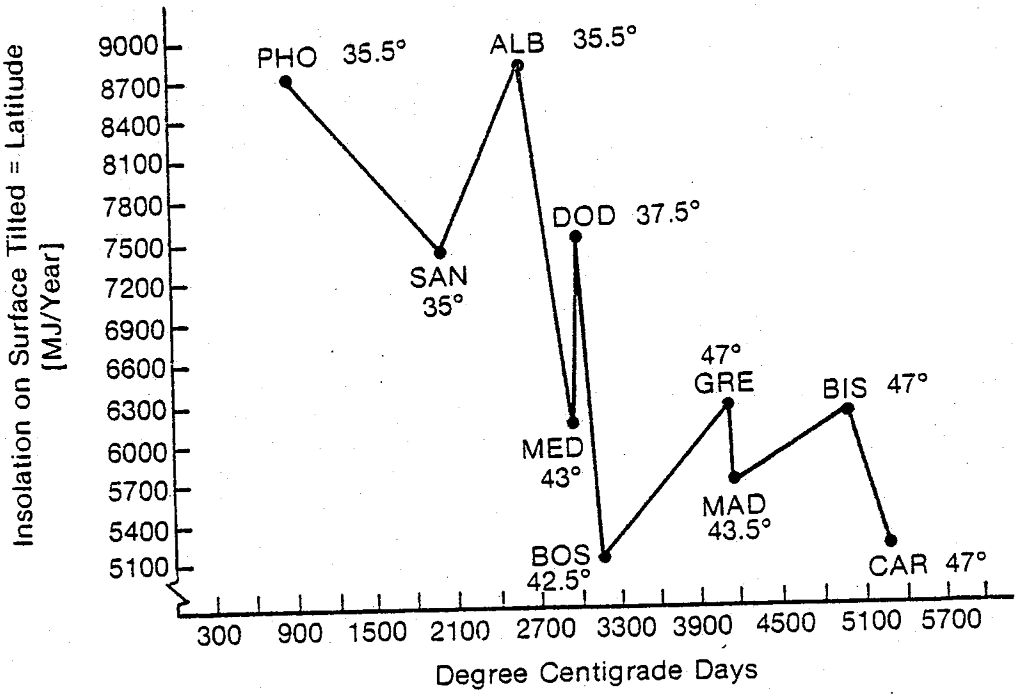


Figure 2-3. **Relationship between Insolation, Latitude, and Degree Days for Cities in Study**

Table 2-1. TOTAL INSOLATION AND DEGREE DAYS BY CITY

City	Total Insolation on Tilted Surface = Lat (Mj/m^2/year)	Total Degree Centigrade Days	Average Ambient Temperature (°C)
Caribou	5239	5313	4.2
Bismark	6205	4995	5.6
Madison	5698	4191	8.0
Great Falls	6262	4158	7.8
Boston	5138	3256	10.5
Dodge City	7503	3044	12.3
Medford	6085	2991	11.4
Albuquerque	8754	2587	13.3
Santa Maria	7401	2032	13.2
Phoenix	8719	897	22.1

2.1.1.3 Collector Type

Two collector types are examined in this study, evacuated tube collectors (ETC) and a medium-performance flat-plate collector (FPC). Efficiency curves used for these collectors are shown in Figure 2-4.

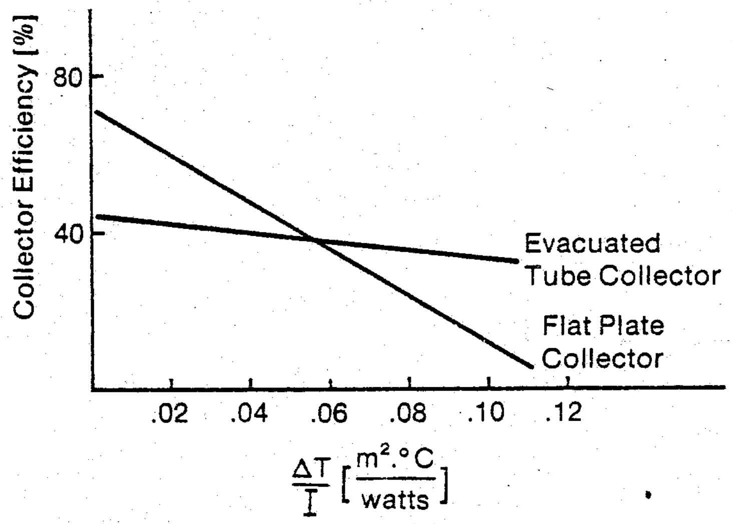


Figure 2-4. Collector Performance Curves.

2.1.1.4 Collector Tilt

Two collector tilt angles were chosen: tilt equal to latitude and tilt equal to latitude plus 10 degrees. The choice of angles was based on a personal communication with F. C. Hooper. No procedure was devised to determine an optimum tilt angle for annual storage. Such a procedure would be based upon the relative magnitudes of energy gains and losses and building loads over an entire season. In total, four configurations of collectors were used for this study.

2.1.1.5 Soil Conductivity

Substantial variation in soil conductivity strongly affects the thermal efficiency of ACTES. Soil conductivities and thermal capacities were varied in one configuration to represent a range of conditions ranging from very dry to very damp soils. The following were used as baseline values judged to be representative of soil conditions in North America:

- soil thermal conductivity—1.7307 W/m°C,
- soil density—1762.0 kg/m^3, and
- soil thermal capacity—1.0 kJ/kg °C.

2.1.1.6 Design Ambient Temperature

The design ambient temperature is a design device developed by ASHRAE [12] used to ensure that the space heating system is adequate to maintain comfort levels for all but the most extreme weather conditions. A value was chosen for each of the 10 locations so that the outside ambient temperature would remain above the design ambient temperature for 99% of the time during a normal winter [12]. Use of this value allowed the storage capacity and collector field area to be chosen more accurately for the initial computer run.

2.1.1.7 Insulation Thickness

The storage tank insulation is distributed by the University of Toronto code to minimize tank heat losses. This distribution counteracts the tendancy of the upper portions of the partially stratified tank to have greater heat losses. The total amount of wall and floor insulation was limited to a maximum thickness of approximately 9 in. (0.22 m). The limit was required because layers of greater thickness on the tank interior would not be stable structurally and could possibly creap at the elevated tank temperatures.

The lid insulation thickness was chosen as a uniform 13 in. (0.333 m) for all sites. This value was chosen with respect to physical and structural considerations.

2.1.2 Constrained Variables

A variety of parameters were chosen which have either a fixed value or a value that changed somewhat across the unconstrained variables. These include transmission losses, heat load factor, domestic hot water (DHW) delivery temperature, maximum design tank top temperatures, inlet temperature to the DHW System, and thermostat setting.

2.1.2.1 Transmission Loss

The University of Toronto simulation was designed to model an ACTES system that would provide heating and domestic hot water for only one building. Losses resulting from transmission of thermal energy among the storage facility, the load, and the collectors was, therefore, considered to be negligible. In order to estimate conservatively the effect of transmission losses in piping, the single-unit, multifamily, and apartment complexes were assumed to have losses of 10%, 5%, and 0% respectively added to the community heat-load factor (see below). The ACTES was assumed either to be integral to or adjacent to the apartment complex. The single-family community has substantially more piping than the multifamily grouping.

2.1.2.2 Heat Load Factor

The heat load factor was used to determine building energy load. When coupled with the hourly weather data, this factor provided a calculated hourly building load. The heat load factor for a single-family residence of 2,000 ft^2 feet was chosen to be 500 Btu/degree hour, based on a recent SAI study [13] and a personal communication with Steve Hogg of SERI. The value for the multifamily condominium based on the OTA study [11] was 202 Btu/degree hour per unit (this is an average since the units on the end of the building with more exposed surface area will have higher heat losses than the middle units). The heat load factor for the apartment complex was 25,748 Btu/degree hour, or 130 Btu/degree hour per unit [11].

2.1.2.3 Domestic Hot Water (DHW) Delivery Temperature

The DHW delivery temperature was chosen to be 120°F—lower than the normal 140°F but still in a perfectly functional range. This temperature was selected for two reasons. First, this lower temperature allows attainment of a more nearly 100% solar system. Other designs (for example, one has one ACTES tank and multiple DHW tanks which would be charged first [14]) would easily permit attainment of 100% solar systems. Second, the lower temperature maintains the philosophy of this study—use of renewable energy sources and conservation of energy.

2.1.2.4 Maximum Design Tank Top Temperature

The maximum-design tank-top temperature was chosen to be 175°F (79.4°C). This temperature is well within present limits of plastic liners for storage tanks, and it places less stress on tank insulation and on piping than higher temperatures would. It is also the maximum design temperature of the Lyngby home in Denmark, an ACTES design that is currently operating [15].

2.1.2.5 Inlet Temperature to DHW System

The water main temperature was taken to be the average temperature of shallow groundwater [16]. It is, therefore, location dependent.

2.1.2.6 Thermostat Setting

The effective thermostat setting is the temperature requirement that is actually experienced by the space heating system. The temperature is always a few degrees lower than the actual thermostat setting. In this study, 68°F (20°C) was chosen as the actual thermostat setting and 65°F (18.3°C) was used as the design thermostat readings.

2.2 SIZING PROCEDURE

Once all the input parameters were chosen, the ACTES systems were thermally optimized, viz. minimum storage volume and collector areas which adequately supplied the load were chosen. However, as noted above, the trade-off between collector field area and storage size was not examined in detail. The sizing method used in this study selected the smallest systems that provided 100% space heating and that avoided dumping collected heat during the summer. No cost considerations were included except in the "fine tuning" of systems during which the decision was typically to increase either collector or storage size. In such cases, storage size was always chosen as the least-cost alternative for the following reasons.

This method represents a natural sizing optimum because a larger storage tank would not provide any extra useable storage capacity. It is also consistent with standard assumptions about sizing annual storage systems by others [4,17]. System sizing trade off, in preliminary results from research underway at SERI, plots as an inflection point between two roughly linear regions in the performance isoquants (Figure 2-5). Hypothetical cost curves along the isoquant are shown in Figure 2-6. Depending on the relative cost of collector and storage, the economic optimum may occur with daily (2-6 days), intermediate (4-7 weeks), or seasonal storage (3-4 months) [16].

Before actually running the simulation, a rough size estimate was made. A short computer program based on a correlation developed by James Cook at the University of Toronto was used.

Next, using these estimates, a simulation was performed and results of the run were examined to determine whether the proposed configuration provided 100% solar space heating. Next, the tank temperature distribution was examined to determine (1) whether the maximum design tank temperature (79.4°C) had been reached; i.e., was the storage tank utilized efficiently or was the tank too large; and (2) whether the minimum design tank temperature had been reached (28°C); i.e., was the collector field too large. New estimates for collector area and storage size were made based on this information, and the simulation was rerun.

The work was arranged by site. All 44 cases for each site were completed before sizing of the next site began.

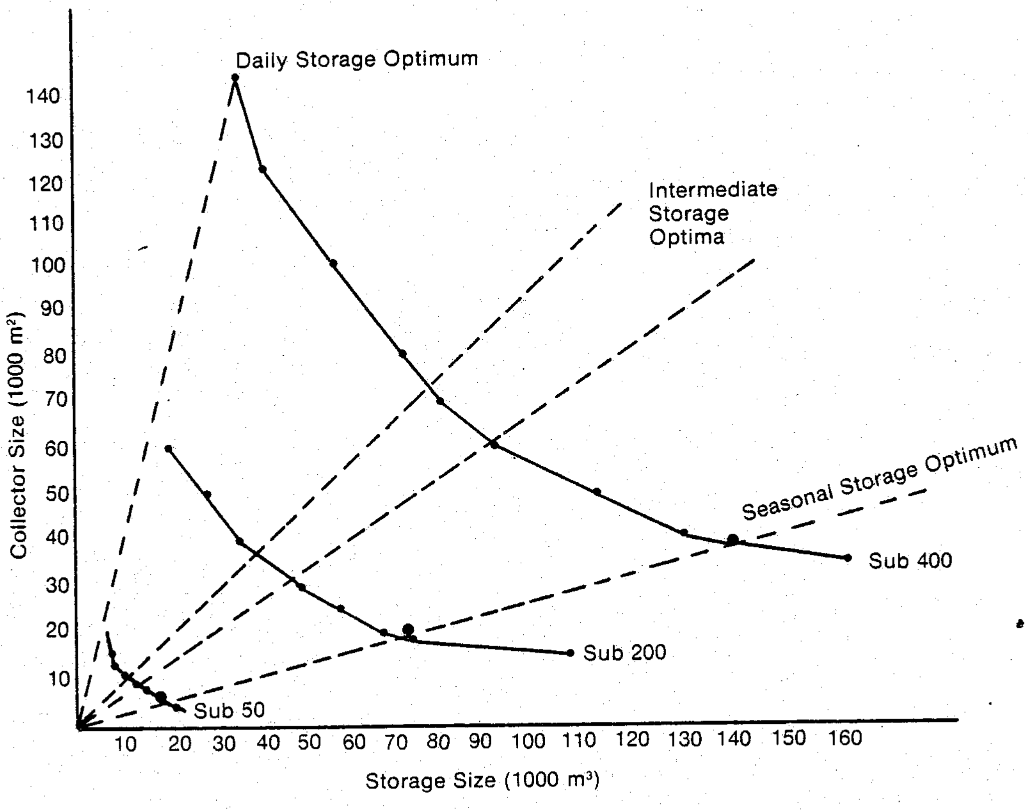


Figure 2-5. Performance Isoquants for Annual Storage Systems in Madison, Wisconsin

Systems presented are designed to supply 100% of space heat requirements and 80% of hot water.

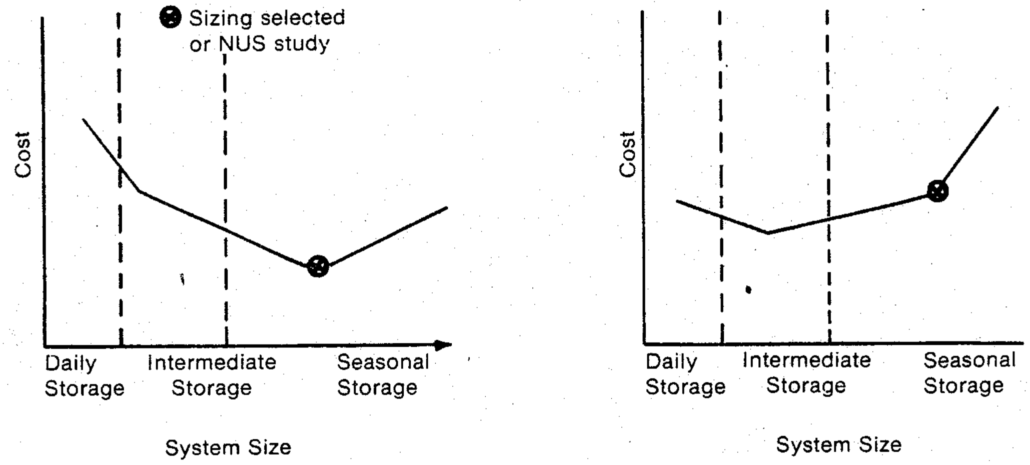


Figure 2-6. Hypothetical Plots of Costs versus System Size for Isoquants in Figure 2-5 for Two Different Collector and Storage Costs.

SECTION 3.0

RESULTS

An analysis of the baseline designs for ACTES solar systems generated from the University of Toronto computer code are presented in this section. The data serve three purposes. First, sizes of storage and collector components are presented for 44 community designs in 10 geographic locations. Second, these results form the basis for a sensitivity analysis that is used to identify the critical design parameters in such an ACTES solar system.* Third, the results enable us to present general guidelines for sizing ACTES systems in any location.

3.1 PROCEDURE

Results are organized as follows. Critical factors in sizing collector field area and storage tank volume are analyzed in Section 3.2. The sensitivity of design parameters to community size are investigated in Section 3.3. These considerations are used in a comparison of annual versus daily cycle storage/solar energy systems (Section 3.4). All figures for Section 3.0 are placed at the end of the section, pages 27-46, for better readability of text.

Table 3-1 lists the design variables in this study. All explanatory graphs are presented either in the text or in Appendix B. Table 3-2 lists those relationships which were graphed. A number of proxies were used for location including total yearly insolation, yearly building load, and total degree days. In all the graphs, the following abbreviations are used:

- SUB: Single-unit building; single residence;
- TUB: 10-unit building; multifamily residence; and
- HUB: 200-unit building; apartment complex.

3.2 ANALYSIS OF SYSTEM SIZING

In this section, patterns and regularities are examined in the simulated system sizes which point toward general system sizing algorithms. System sizing will be approached in two stages: collector area is sized to meet the yearly load, and storage is sized to meet the extra winter heat requirement. The course of this analysis as well as the final outcome are both presented to help the reader understand design complexity as well as the conclusions.

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*Even if second-order analysis would result in the resizing of some components, the consistency from design to design in this analysis allows us to have confidence in searching for system-to-system variations. Similarly, although the size of collector fields and storage tanks can, within limits, be traded-for one another, the choice of the relative sizes was reasonable and consistent across all systems.

Table 3-1. DESIGN VARIABLES UNDER CONSIDERATION

Independent Variables:	Total insolation
	Yearly degree days
	Total building or community load
	Community size
	Community type[a]
	Collector type
	Collector inclination angle
	DHW load
Dependent Variables:	Collector area
	Solar energy collected
	Storage volume, radius and mass
	Solar energy stored
	Storage energy loss
	Average overall collector efficiency[b]
	Average operational collector efficiency[c]
	Min/max tank temperature
	DHW performance

[a] HUB, TUB, or SUB.

[b] Total load plus storage and distribution losses divided by total insolation.

[c] Collected energy divided by total insolation.

Table 3-2. GRAPHIC REPRESENTATIONS

Versus community size:

Variable	Number of Graphs	Units
Collector area	10	m^2
Solar energy collected	10	Mj/yr
Storage volume	10	m^3
Storage tank radius	10	m
Storage volume per collector area	10	m^3/m^2
Solar energy stored per solar energy collected	10	—
Solar energy stored	10	Mj/yr
Storage loss per solar energy stored	10	—

Versus location (total insolation, load, degree days, or other):

Variable	Units
Collector area/unit	m^2
Storage volume/unit	m^3
Average operational collector efficiency	%
Average overall collector efficiency	%

3.2.1 Collector Sizing

The key to collector sizing is the estimation of collector efficiency. The nonlinearity in the plots of collector area versus annual load per unit divided by the yearly insolation per square meter (Figures 3-1, 3-2, and 3-3) results from variations in average collector efficiency with climate. In colder climates, the insolation per square meter tends to decrease while the load per unit tends to increase (Figure 2-3). In these colder climates, average collector efficiencies of evacuated-tube collectors (ETC) are higher than those of flat-plate collectors (FPC) (Figure 2-4). The curves for FPCs, therefore, are above those for ETCs. In warmer climates, average efficiencies of FPCs are greater than those for ETCs. The relationships in Figures 3-1, 3-2, and 3-3 do not show this functional crossover.

Collector operating efficiency depends directly upon two factors: the intensity of insolation and the thermal difference between collector operating temperature and outdoor ambient temperature. Indirectly, the efficiency may depend upon a variety of climatic parameters. Efficiency was found to be virtually constant among all building types for a given location. Since the average collector operating temperature varied little among locations, the key parameters are ambient temperature and insolation. Figures 3-4 and 3-5 present the variation in annual operating efficiency, defined as the heat collected divided by the incident insolation, versus insolation and ambient temperature for all 10 locations. The range for each point in the efficiency graphs indicates the variation of efficiency at a particular location across the simulated community sizes.

Figures 3-4 and 3-5 show that, while efficiency generally does increase with insolation and ambient temperature, the patterns were highly irregular. An index was sought that reflected the effect of both insolation and ambient temperature. Such an index was determined by the familiar equation for collector efficiency:

$$\begin{aligned}\text{collector efficiency} &= \text{heat gain} - \text{heat loss}\\ &= F_r(\tau\alpha) - F_r U_l \frac{T_o - T_a}{I}\end{aligned}$$

where

T_o = collector outlet temperature,
T_a = collector inlet temperature, and
I = insolation per square meter.

The parameter

$$\frac{T_o - T_a}{I}$$

was used as an index against which to plot collector efficiency, with T_o equal to 57°C (the average annual storage temperature is close to 57° for all simulations). Plots of efficiency versus this index are shown in Figures 3-6 and 3-7 which indicate a consistent, nearly linear relationship, accurate enough to be used in system sizing.

A system-sizing algorithm would make use of the relationship:

$$\text{collector efficiency} = \frac{\text{load}}{\text{incident insolation}} .$$

The yearly heat load, including storage losses as part of the load, is estimated. Collection efficiency is from Figure 3-6 or 3-7. Collector area may be found by the formula:

$$\text{collector area} = \frac{\text{load}}{\text{efficiency x insolation/m}^2}$$

where load equals total yearly space plus DHW load plus storage and distribution losses.

One further problem should be noted in the sizing algorithm just outlined. The overall collector efficiency—equal to the building load plus the storage loss divided by the incident insolation—is not exactly the same as the operating efficiency (collector gain divided by insolation) used earlier. There are two differences between the former (overall efficiency) and the latter (operating efficiency). First, if heat is dumped in summer, this heat is not counted in the overall efficiency but is counted in the operating efficiency. This has a very small effect. Second, collector gain is greater than the heat load because most systems have been oversized to provide a margin of safety. In the simulation, storage temperature is initially set at 34°C and often ends at 37°C or 38°C. The extra heat collected to raise the tank temperature from 34°C to 37°C is credited to the collector in the operating efficiency calculation but not in the overall efficiency.

The operating efficiency has been used in order to be consistent with results from the overall simulation. Use of the overall efficiency introduces inaccuracy because the degree of oversizing was different for different locations. Figures 3-8 and 3-9 represent overall efficiency versus the index. Again, the pattern is linear but less consistent than patterns in the previous graphs.

For system sizing, we recommend using the operational efficiency graphs (Figures 3-6 and 3-7) and then oversizing the collector by 10%. This oversizing provides a margin of safety against both inaccuracy in the sizing algorithm and severe weather conditions. Needless to say, the efficiency curves are accurate only for those collectors that perform similarly.

3.2.2 Storage Sizing

As described in Section 2.2, storage in these systems is sized so the maximum design temperature is attained in the summer and fall and the design minimum is reached late in the winter. The storage tank must be sized so that the approximately 40°C drop in temperature releases enough heat to meet the surplus load in winter. This "winter net load" which must be provided from storage is equal to the shaded area (the difference between winter load and winter heat gain) seen in Figure 1-2.

In Figures 3-10, 3-11, and 3-12, storage tank volume is plotted versus the winter net load plus storage losses, the net load encompassing the months November through February. Points on these graphs follow a linear pattern, with all three community types (SUB, TUB, and HUB) plotting onto the same line. There is only one minor irregularity: systems with collector tilt at LATITUDE + 10 use a slightly larger storage volume than the linear relation would predict.

Figures 3-10, 3-11, and 3-12 can be used to size storage volume. Load for the four winter months, including storage losses, can be estimated. Collector gain for these months also must be estimated. This is not an easy task. Table 3-3 presents winter efficiencies for both EPCs and ETCs in all 10 cities. Winter gains may be found by multiplying winter efficiency by collector area (based on the sizing algorithm in Section 3.2.1) and by winter insolation. The difference between load and gain determines the winter net load from which the storage system may be sized.

Table 3-3. WINTER COLLECTOR EFFICIENCIES
(November through February)

City	FPC	ETC
ALB	.27	.32
BIS	.13	.24
BOS	.165	.25
CAR	.13	.23
DOD	.24	.29
GRE	.14	.25
MAD	.155	.25
MED	.17	.24
PHO	.35	.34
STM	.29	.29

Because winter collector efficiency is hard to estimate, it is desirable to explore other storage-sizing algorithms. Figures 3-13, 3-14, and 3-15 depict storage size versus total annual load for both flat-plate collectors and evacuated tube collectors. While there is a pattern of increasing storage size per load, the pattern is not consistent enough to be useful in design. This is especially true because the SUB, TUB, and HUB plots do not lie along the same line (the line drawn through the points in the SUB plot was reproduced in the TUB and HUB plots for comparison). This is due to the fact that winter, not annual, load determines the need for storage, and the proportion of winter-to-annual loads is different for the three community types. Other irregularities can be noted. Evacuated-tube collectors take smaller storage sizes than flat-plate collectors. Cities with low winter insolation (such as Medford, Oreg.) require larger storage volumes.

Graphs of storage versus winter load in Figures 3-16, 3-17, and 3-18 may be more suitable for rough designs. However, these would oversize the storage system when evacuated tube collectors are used or systems are designed for warm climates, because significant winter heat collection is neglected (compared to net winter load graphs).

3.3 SENSITIVITY OF DESIGN PARAMETERS TO COMMUNITY SIZE

Design variables were plotted against community size with building type and solar collector type as parameters. In all these graphs, collector tilt was equal to latitude. Ten graphs, one for each location, were plotted for each design variable (see Table 3-2). All graphs are shown in Appendix B.

3.3.1 Collector Area versus Community Size

Required collector area increases linearly with community size and with building load. Single-unit residences that have the largest unit loads require larger collector areas. In cities with severe climates, substantially less area is required for evacuated-tube than flat-plate collectors. Graphs of the slope of the collector area versus community size give the collector area required per unit. These figures are tabulated in Table 3-4.

Table 3-4. UNIT COLLECTOR AREA REQUIREMENTS

	SUB		TUB		HUB	
City	FPC (m^2)	ETC (m^2)	FPC (m^2)	ETC (m^2)	FPC (m^2)	ETC (m^2)
Caribou	158.5	111.5	74.1	52.0	43.2	30.3
Bismark	99.0	83.8	46.3	39.2	27.0	22.8
Madison	97.5	78.6	46.3	37.3	26.9	21.7
Great Falls	80.0	69.4	38.4	33.2	22.2	19.2
Boston	88.0	69.5	46.6	34.5	25.0	19.8
Dodge City	42.6	42.3	21.1	20.6	12.8	12.2
Medford	53.9	51.3	26.5	25.2	15.2	14.5
Albuquerque	29.4	29.5	14.5	14.8	8.4	8.7
Santa Maria	27.7	21.1	14.1	13.8	8.0	7.9
Phoenix	11.3	13.1	6.8	7.9	11.3	4.3

As expected, there are substantial differences in the unit collector area needed for various climates, different building types, and FPCs versus ETCs.

3.3.2 Solar Energy Collected versus Community Size

The collected solar energy is a linear function of community size. There is little difference between energy collected by different types of collectors because collector areas have been adjusted to match loads. A more detailed discussion of the collection of solar energy follows in Section 3.4.

3.3.3 Storage Volume versus Community Size

Storage volume is almost a linear function of community size. Use of ETCs allows a substantial reduction in storage volume, especially in more northern locations.

In general, ETCs allows maintenance of a higher storage temperature and, hence, relatively smaller storage tanks. In order to better understand the magnitute of the storage tanks under study, see Table 3-5 which lists tank volume and radius for the 1,000-unit complexes.

The largest tank considered is for a community of 1,000 single residences in Caribou, Maine. This tank has a volume of 434,410 m^3 and a radius of 51.8 m. By comparison, the tank for a community of five 200-unit apartment buildings has less than one-fourth of the volume, 10,786 m^3, and a radius of 31.8 m. In colder climates, ETCs offer a substantial savings in storage volume. In Caribou, the tank volume for the community of 1,000 single units is reduced by 66,500 m^3, or approximately 15%.

Table 3-5. STORAGE TANK VOLUMES FOR 1,000-UNIT COMPLEXES
(Collector Tilt = Latitude)

	HUB (10^4 m^3)		TUB (10^4 m^3)		SUB (10^4 m^3)	
City	ETC	FPC	ETC	FPC	ETC	FPC
Caribou	8.970	10.786	16.327	16.529	37.089	43.741
Bismark	9.575	10.986	16.630	18.444	38.702	43.439
Madison	7.861	8.486	13.505	14.594	32.957	35.577
Great Falls	7.861	8.466	13.505	14.715	32.960	35.578
Boston	5.946	6.551	9.585	10.885	24.390	26.517
Dodge City	5.757	5.758	9.333	10.394	21.212	24.242
Medford	6.400	6.632	11.096	11.510	26.204	27.111
Albuquerque	3.931	4.338	6.601	7.156	16.932	18.746
Santa Maria	2.596	2.586	4.545	4.434	10.303	10.101
Phoenix	1.613	1.612	2.721	2.469	6.349	6.249

3.3.4 Storage Volume/Collector Area versus Community Size

As community size increases, the ratio of storage volume to collector area increases in most cases, although the increase is more rapid at the smaller community sizes. In the more northern locations, the ratio is smallest for FPCs because larger areas are needed to deliver energy at the lower operating efficiencies. In all cases in warmer climates, the storage volume to collector area ratio is largest for SUB. This was true in almost all the colder locations except where the ETC efficiency was low enough to warrant use of large collector areas. For example, in Caribou both the HUB (ETC) and TUB (ETC) have higher ratios than SUB (FPC). The range of storage-volume-to-collector-area ratio is about 2 to 7 m^3/m^2.

3.3.5 Solar Energy Stored versus Community Size

Stored solar energy is practically a linear function of community size. As expected, more energy is stored per year in the colder climates because buildings have higher loads. Also as expected, more energy is stored when using FPCs because ETCs are more efficient when ambient temperatures are low. This effect is less pronounced in warmer climates.

3.3.6 Storage Loss/Energy Stored versus Community Size

Storage loss per energy stored (one minus the storage efficiency) decreases as the community size and, in turn, the storage volume increases. This is simply an expression of the fact that losses decrease as surface area to volume of storage decreases. The three community types, each having distinctly different storage sizes, are grouped in order on all 10 graphs. Efficiency of storage increases as one goes from colder to warmer climates. The highest yearly efficiency is over 96% in Phoenix for 10 HUBs using FPCs. The lowest, approximately 84%, is for TUB-40 in Medford.

3.4 ANNUAL VERSUS DIURNAL (DAILY) STORAGE

A fundamental question in these considerations is how do ACTES solar systems compare to conventional solar systems based on diurnal storages? Although a more thorough answer is presently under study which examines the economics of collector-storage trade-offs, we can draw some preliminary conclusions here. To this end, we compare the ACTES solar systems designed in this study with conventional solar systems for similar building types (SUB) in all 10 locations. Conventional systems are sized by the F-chart method, assuming 75 liters of storage per square meter of each solar collector.

The percentage of solar heat that could be delivered by conventional systems with the same collector field area as the one designed for the seasonal storage systems was calculated. Figure 3-19 presents these solar percentages for the 10 locations, graphed versus the ratio of winter-to-annual insolation. Three observations were apparent.

- Without annual storage, about 65% of the heat load is provided by solar energy. Therefore, the annual storage adds 30% additional energy and reduces or eliminates the need for backup equipment.
- Annual storage provides the greatest advantage in cities with poor winter insolation. Medford, Oreg., which receives a very small percentage of its annual insolation in winter, is the city where annual storage is by far the most advantageous. Annual storage tended to be less useful in warmer climates (Phoenix, Albuquerque). Although the difference between these cities and cities in colder climates (Boston and Madison) does not appear to be very striking from this technical analysis, the difference in delivered energy costs is more pronounced (see forthcoming report on economic analysis).
- ETCs improve performance of an ACTES solar system as compared with FPCs because ETCs operate well over the relatively large temperature differences in seasonal storages. An ACTES system can collect and store heat at 60-70° C, but conventional systems operate on the average at lower temperatures. Consequently, ETCs are more advantageous for ACTES solar systems. A counterbalancing trend occurs in cities with severe or cloudy winters. In such places, effective collection of winter insolation requires use of ETCs. Consequently, in Medford which has a cold, cloudy winter, use of a diurnal storage system is less effective with FPCs than with ETCs.

The F-chart also was used to size daily storage systems that match the performance—96% solar—of the ACTES solar systems designed here. It was found that double to triple the collector area is required compared with the corresponding ACTES solar system (Figure 3-20).

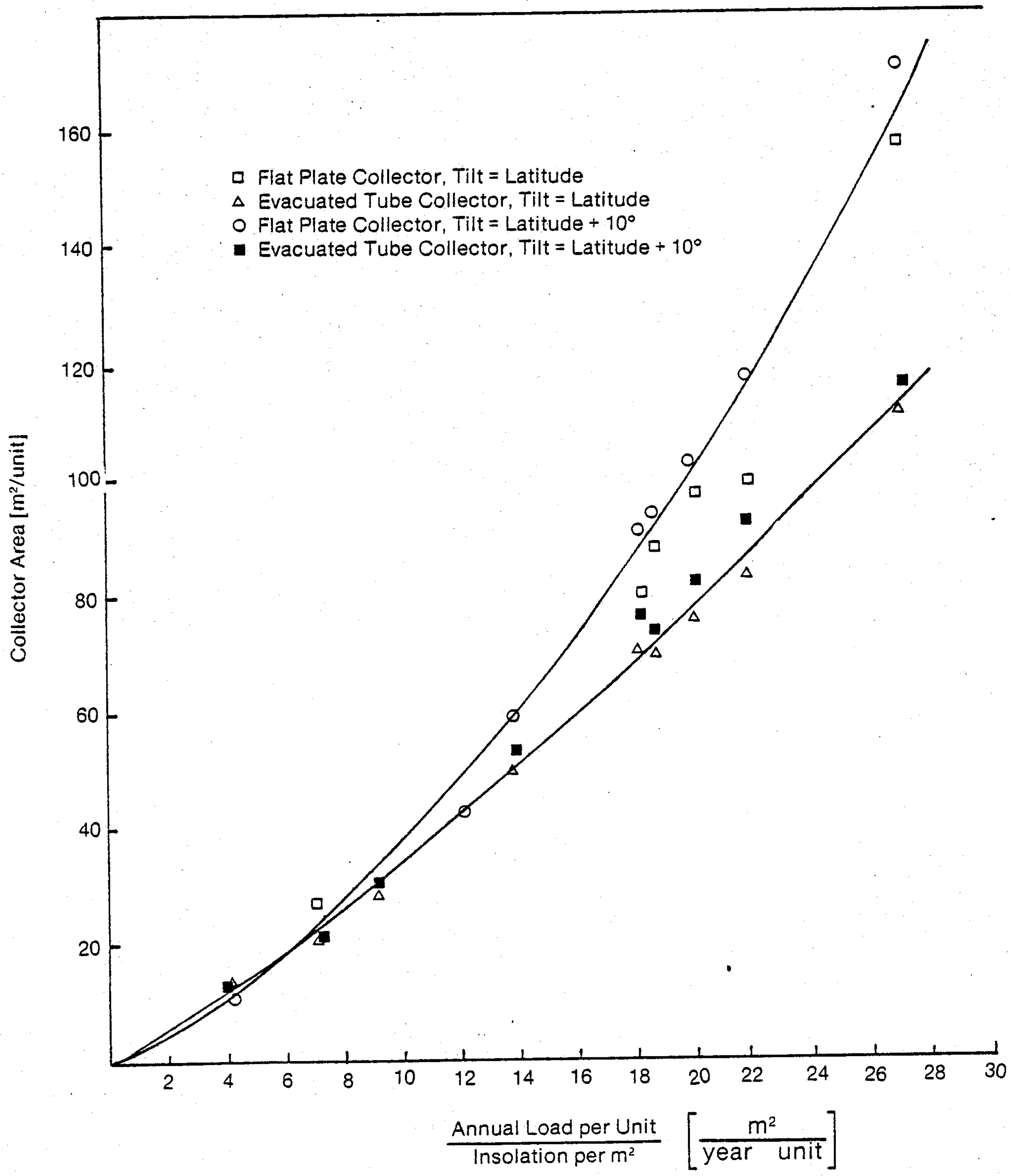


Figure 3-1. Collector Area per Unit versus Annual Load per Unit Divided by Insolation per Square Meter for Single-Unit Buildings

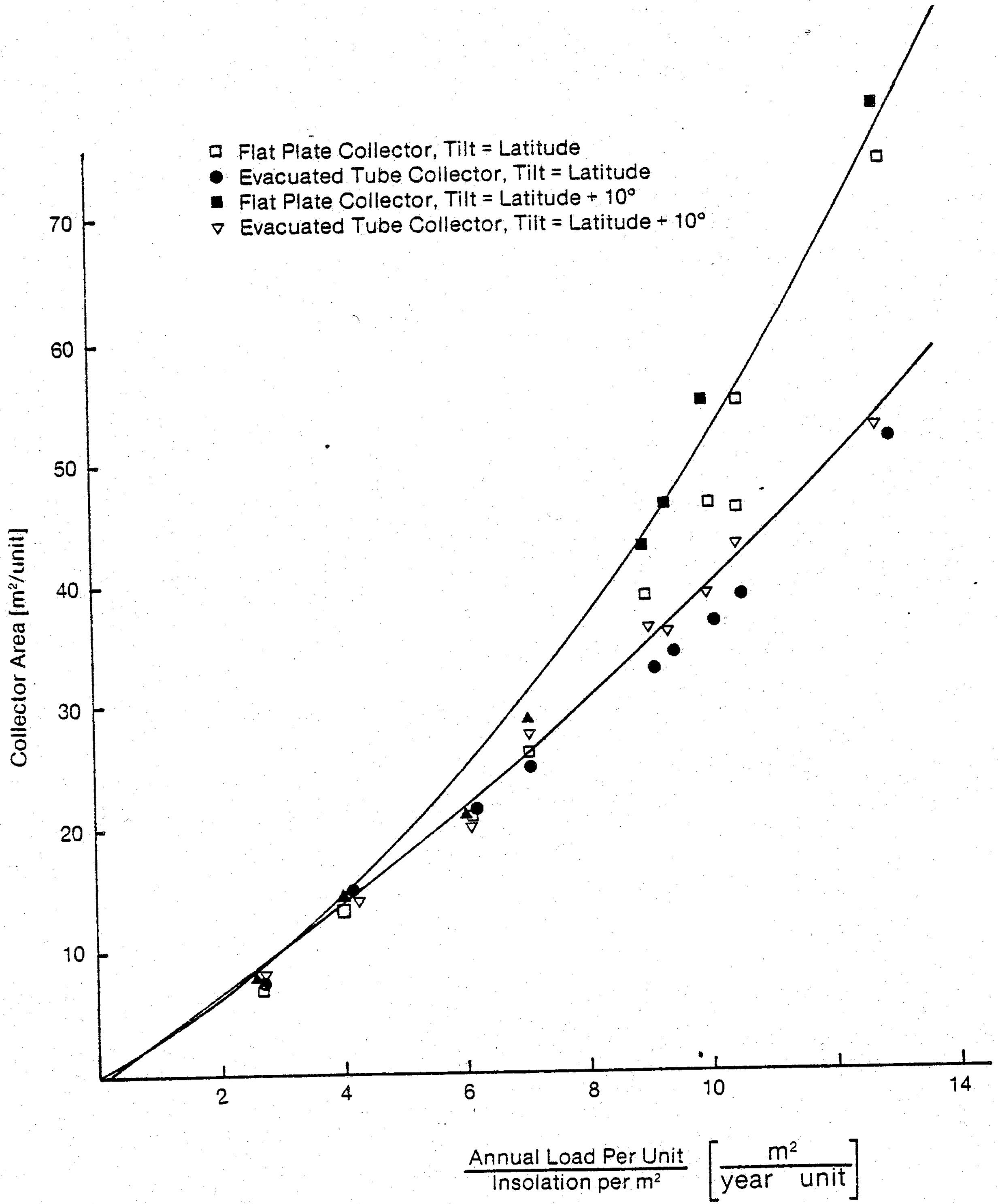


Figure 3-2. Collector area per Unit versus Annual Load per Unit Divided by Insolation per Square Meter for 10-Unit Buildings

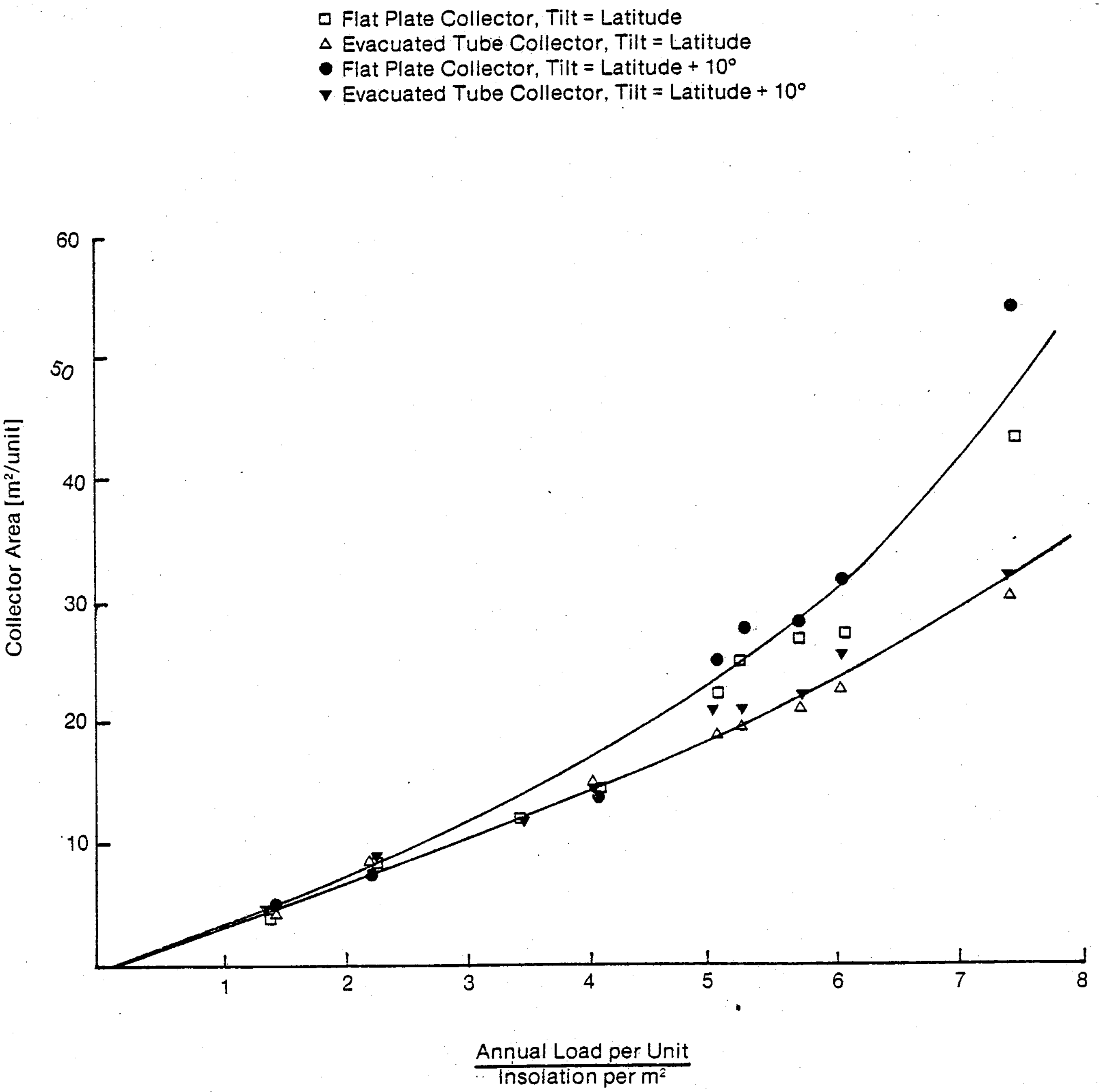


Figure 3-3. Collector Area per Unit versus Annual Load per Unit Divided by Insolation per Square Meter for 200-Unit Buildings

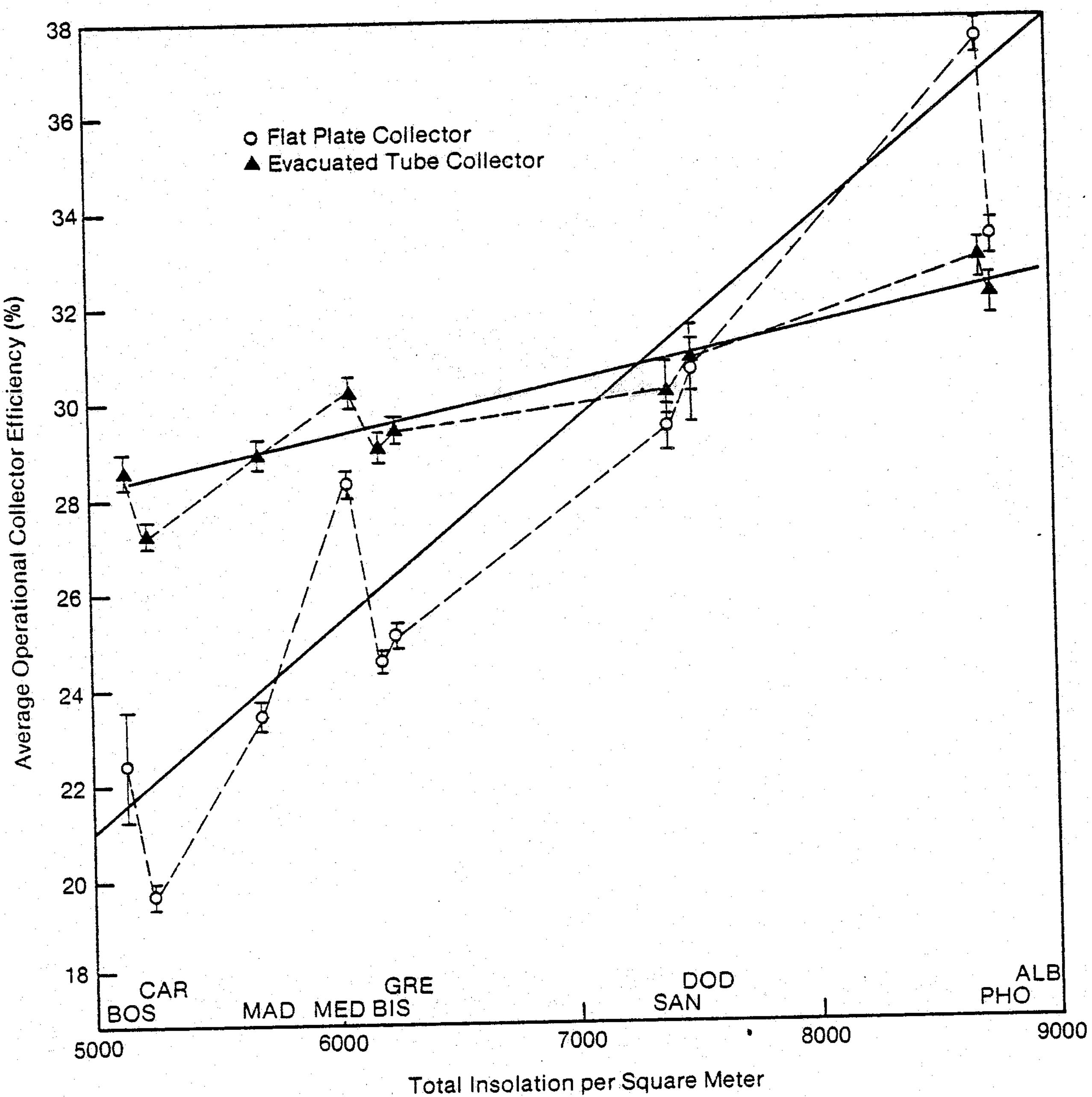


Figure 3-4. Average Operational Collector Efficiency versus Total Insolation per Square Meter (Tilt = Latitude)

Error bars represent the standard deviation

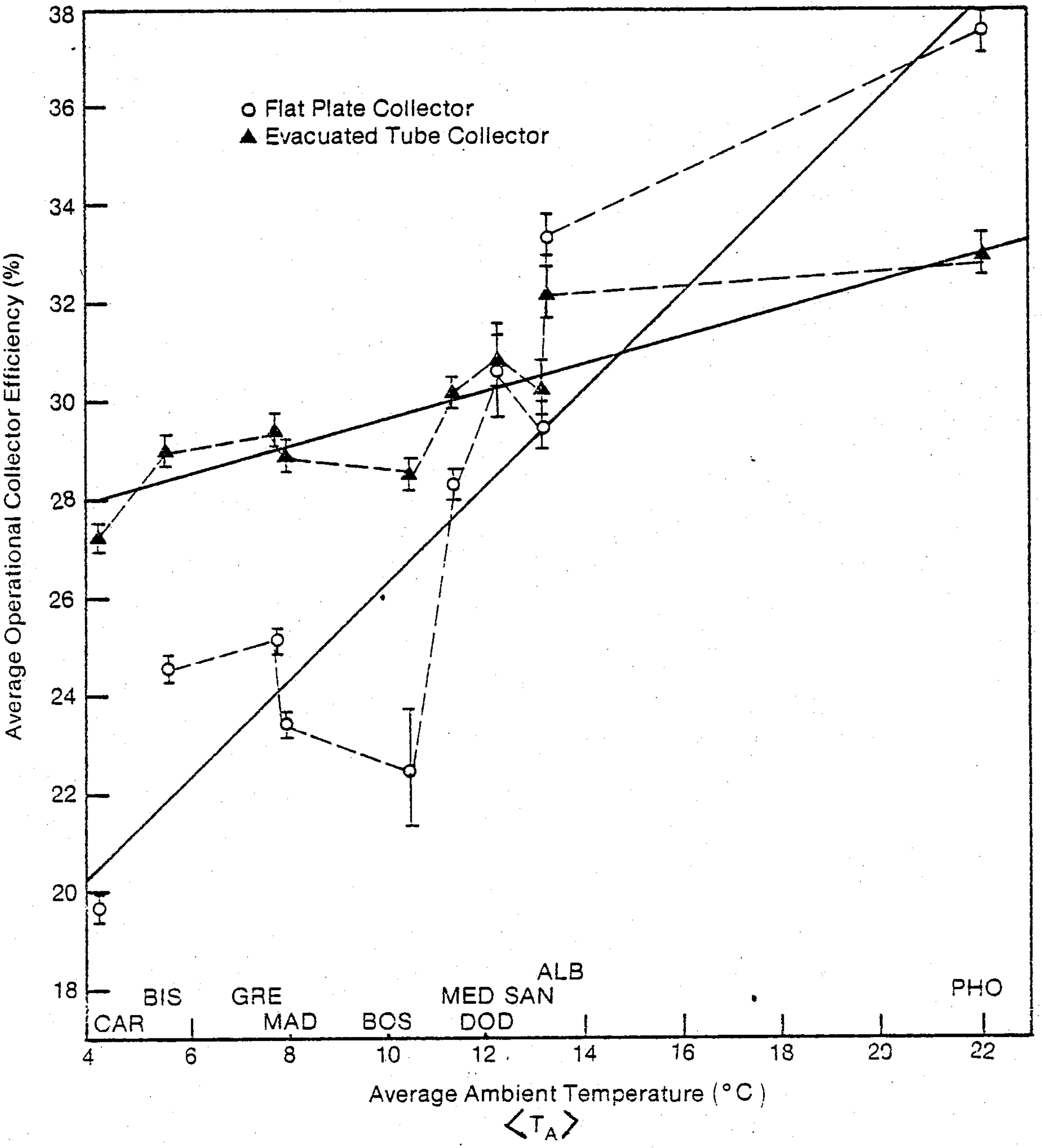


Figure 3-5. Average Operational Collector Efficiency versus Yearly Average Ambient Temperature (Tilt = Latitude)

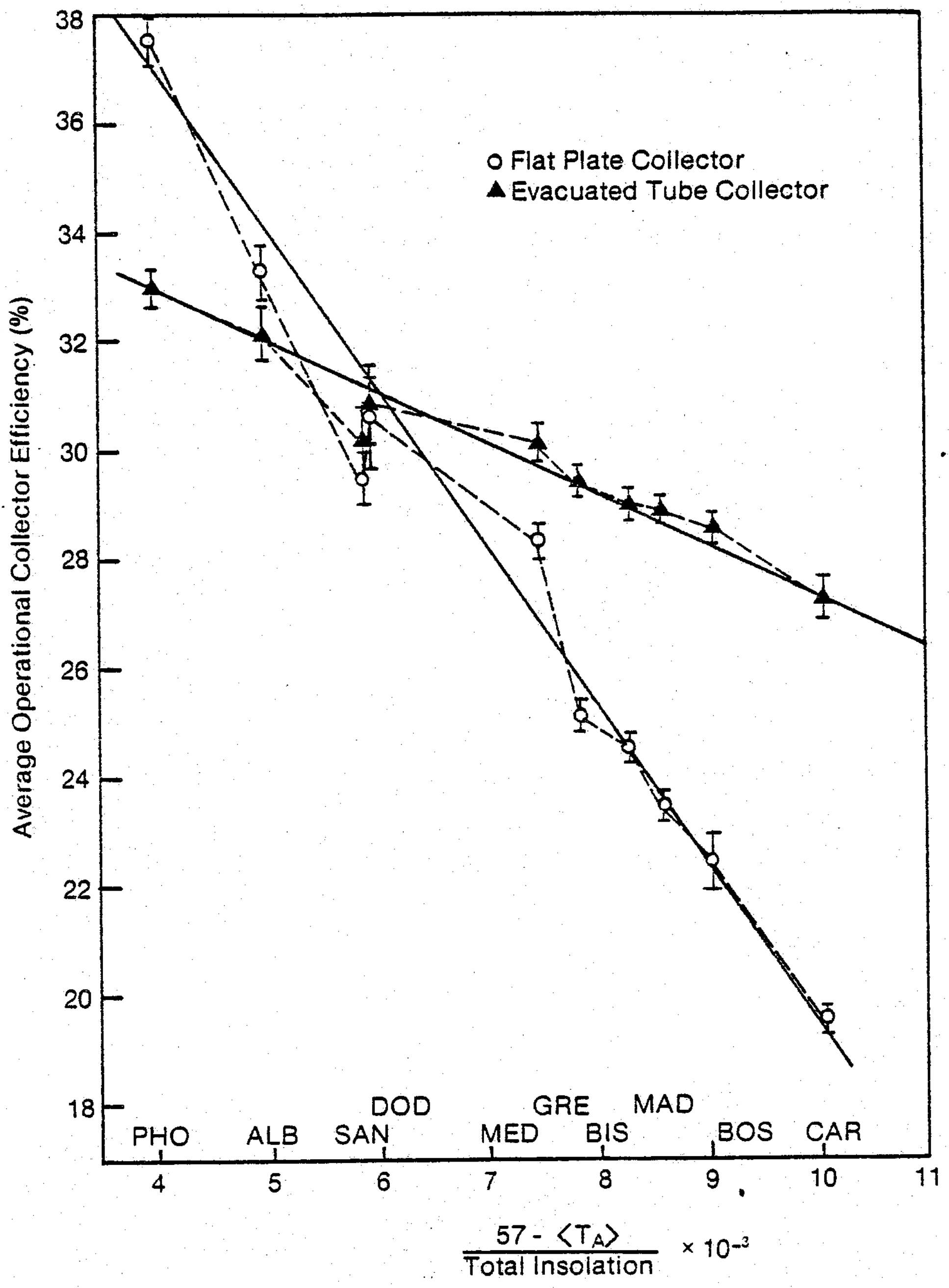


Figure 3-6. Average Operational Collector Efficiency versus $\frac{57 - \langle T_A \rangle}{\text{Total Insolation}}$ (Tilt = Latitude)

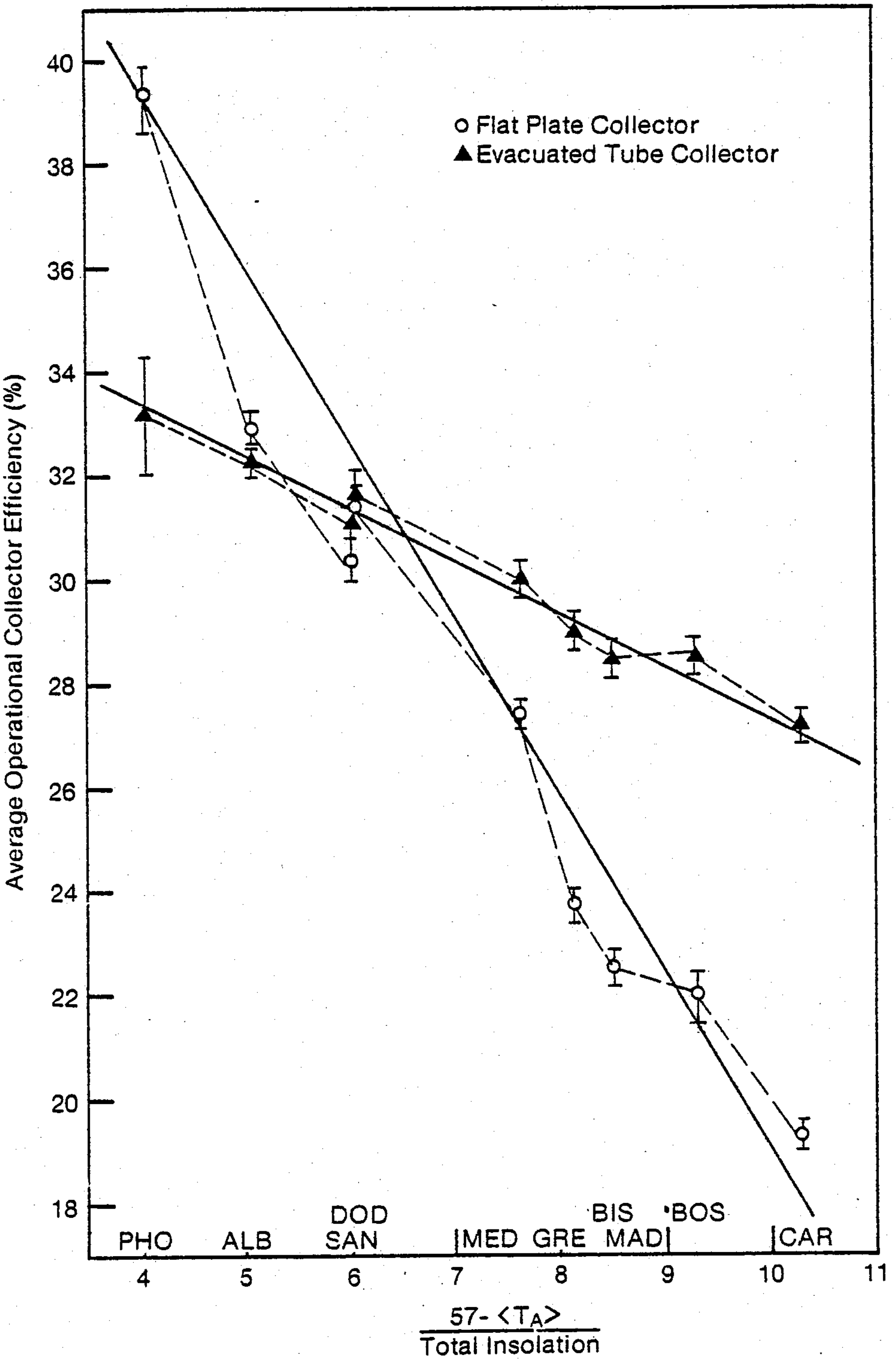


Figure 3-7. Average Operational Collector Efficiency versus $\frac{57-\langle T_A \rangle}{\text{Total Insolation}}$ (Tilt = Latitude + 10)

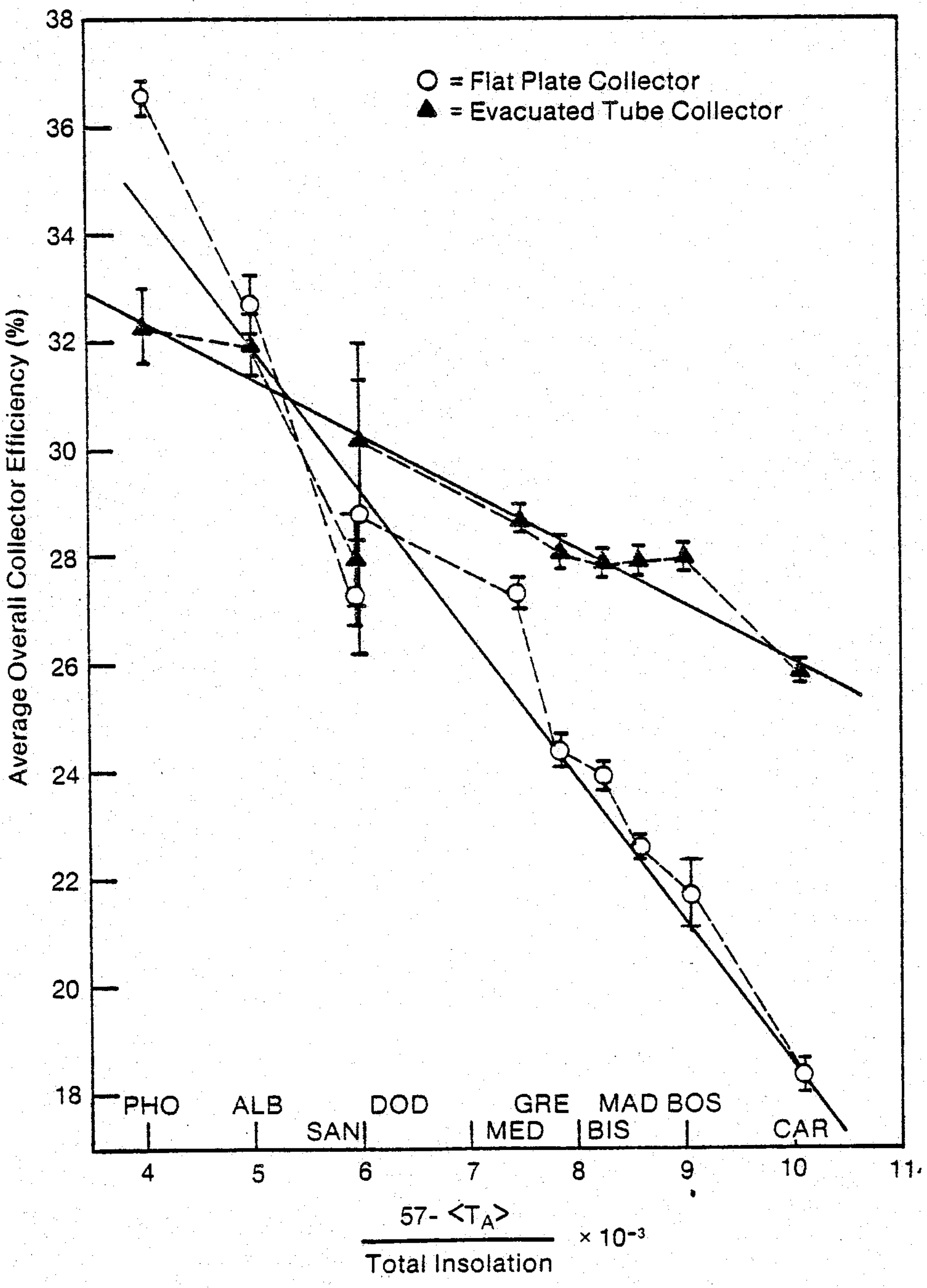


Figure 3-8. Average Overall Collector Efficiency versus $\frac{57-\langle T_A \rangle}{\text{Total Insolation}}$ (Tilt = Latitude)

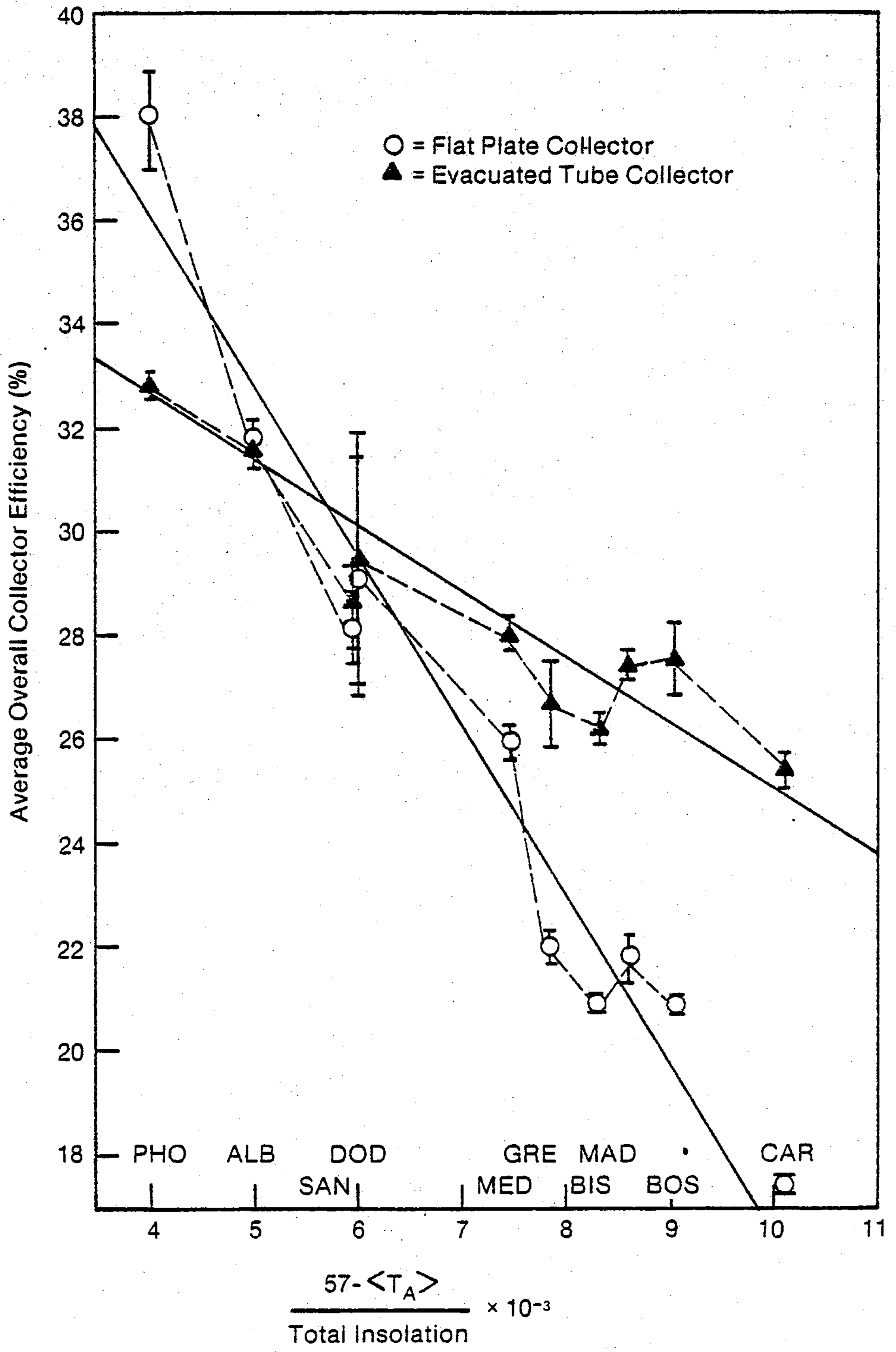


Figure 3-9. Average Overall Collector Efficiency versus $\frac{57-\langle T_A \rangle}{\text{Total Isolation}}$ (Tilt = Latitude + 10)

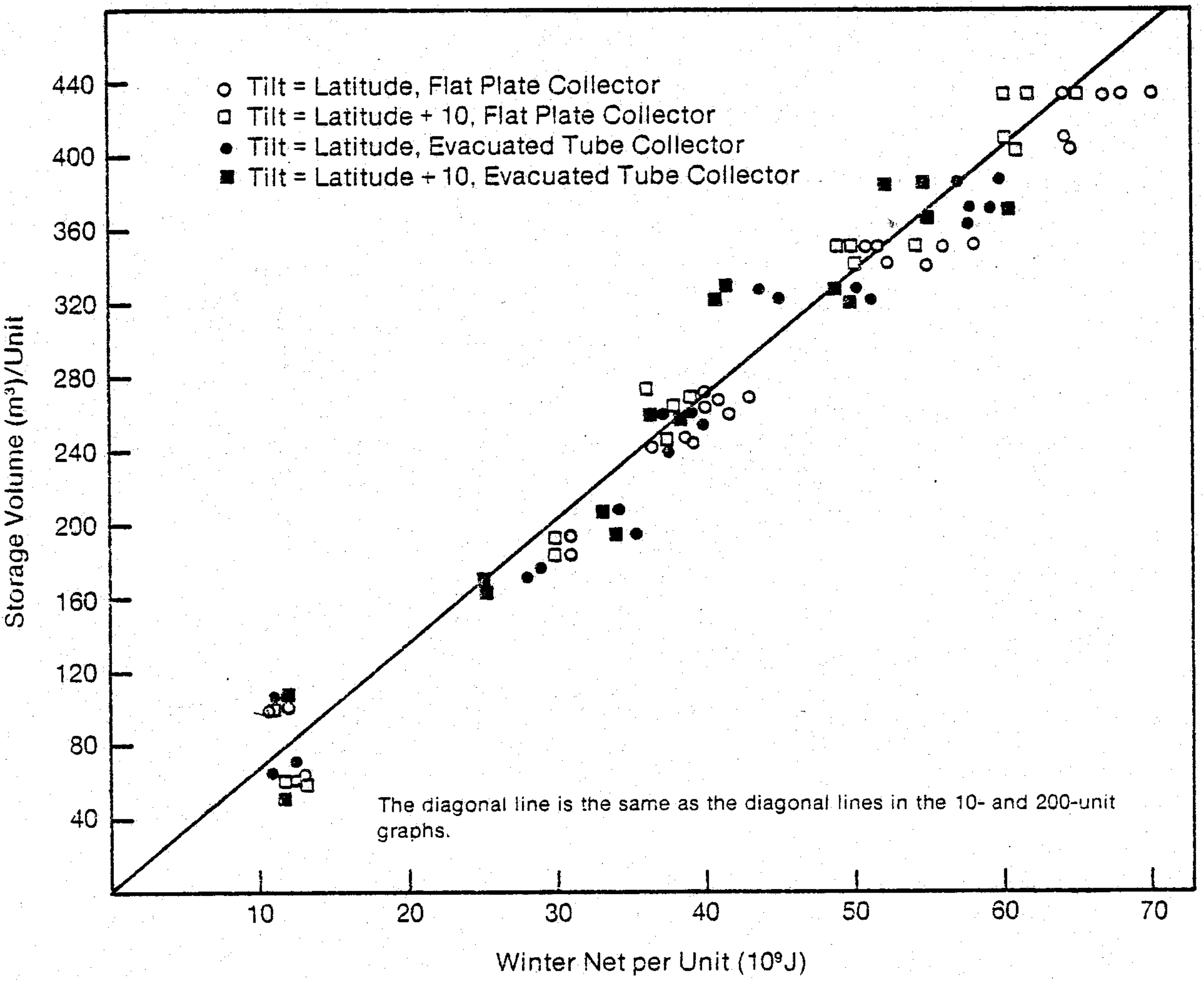


Figure 3-10. Storage Volume per Unit versus Winter Net Load per Unit: Single Unit Buildings.

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

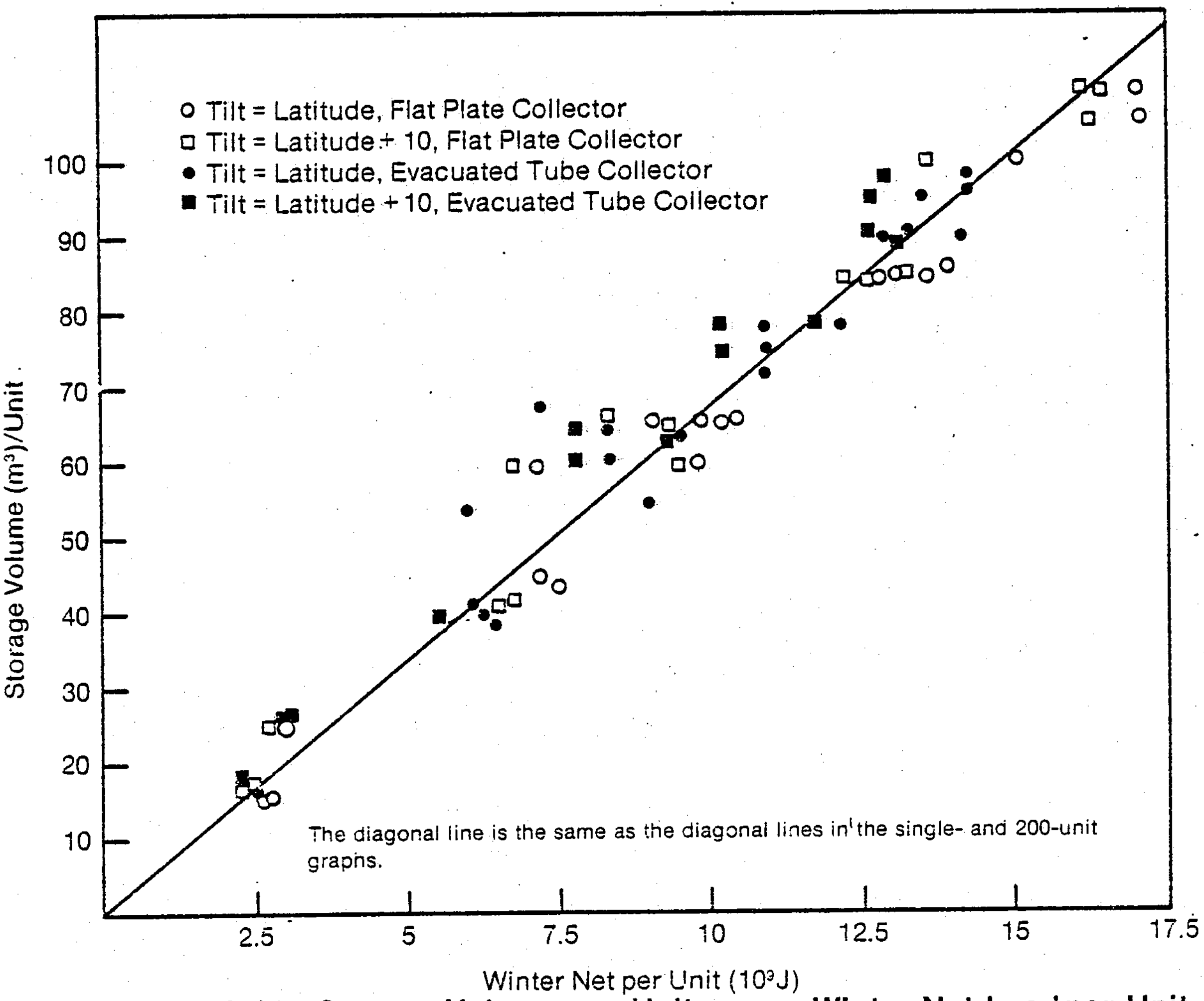
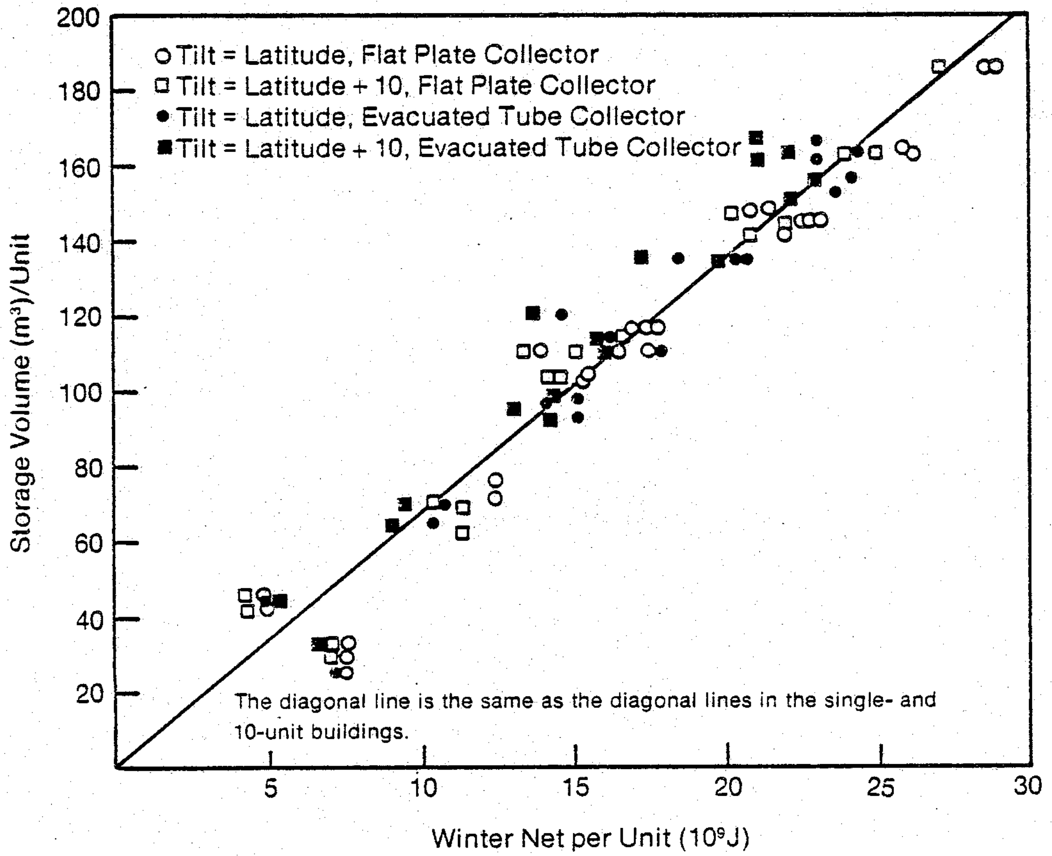


Figure 3-11. Storage Volume per Unit versus Winter Net Load per Unit 10-Unit Buildings.

Winter net load equals building load plus storage and transmission losses minus collector gain, for the months November through February.



The diagonal line is the same as the diagonal lines in the single- and 10-unit buildings.

Figure 3-12. Storage Volume per Unit versus Winter Net Load per Unit: 200-Unit Buildings.

Winter net load equals building load plus storage and transmission losses minus collector gain, for the months November through February.

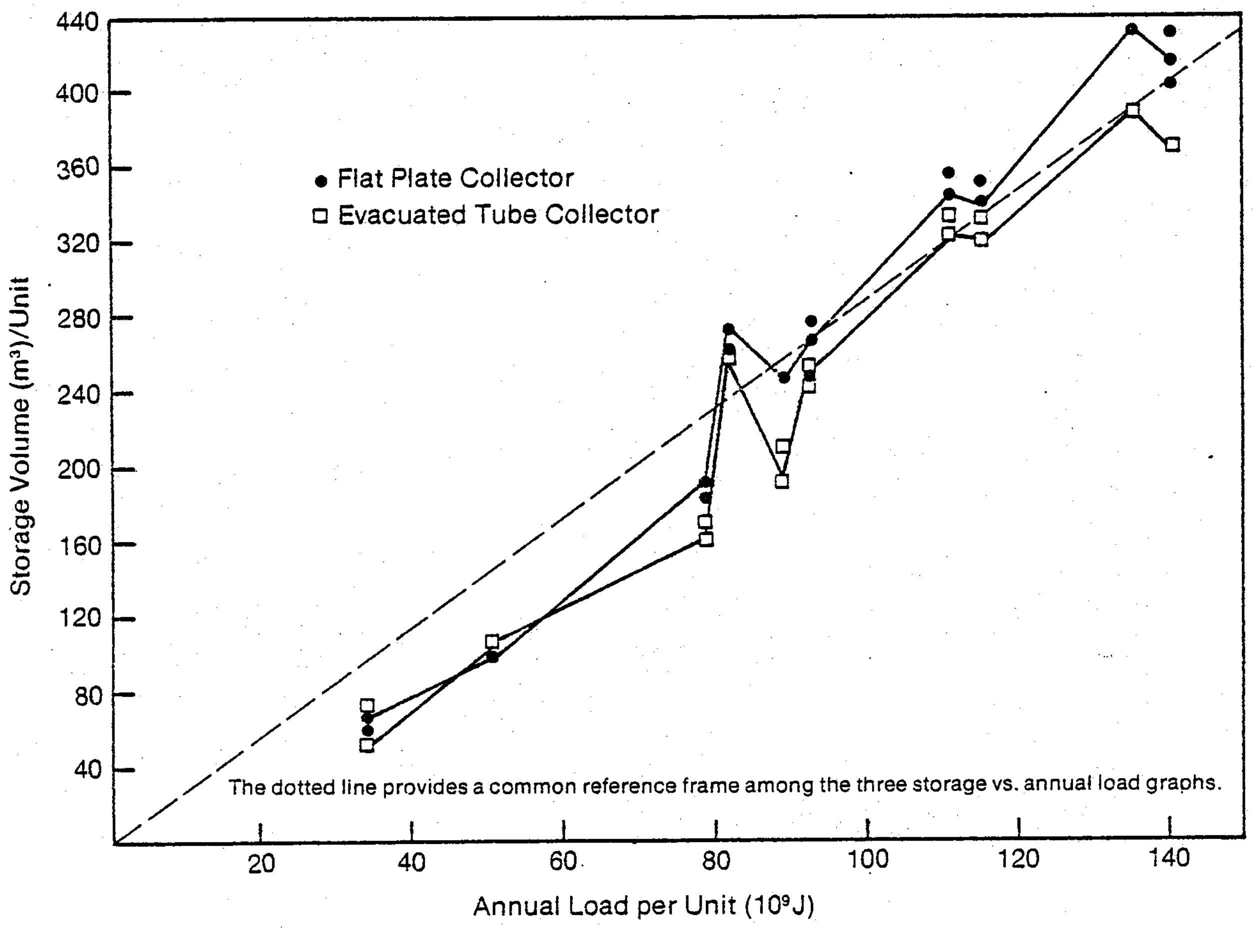
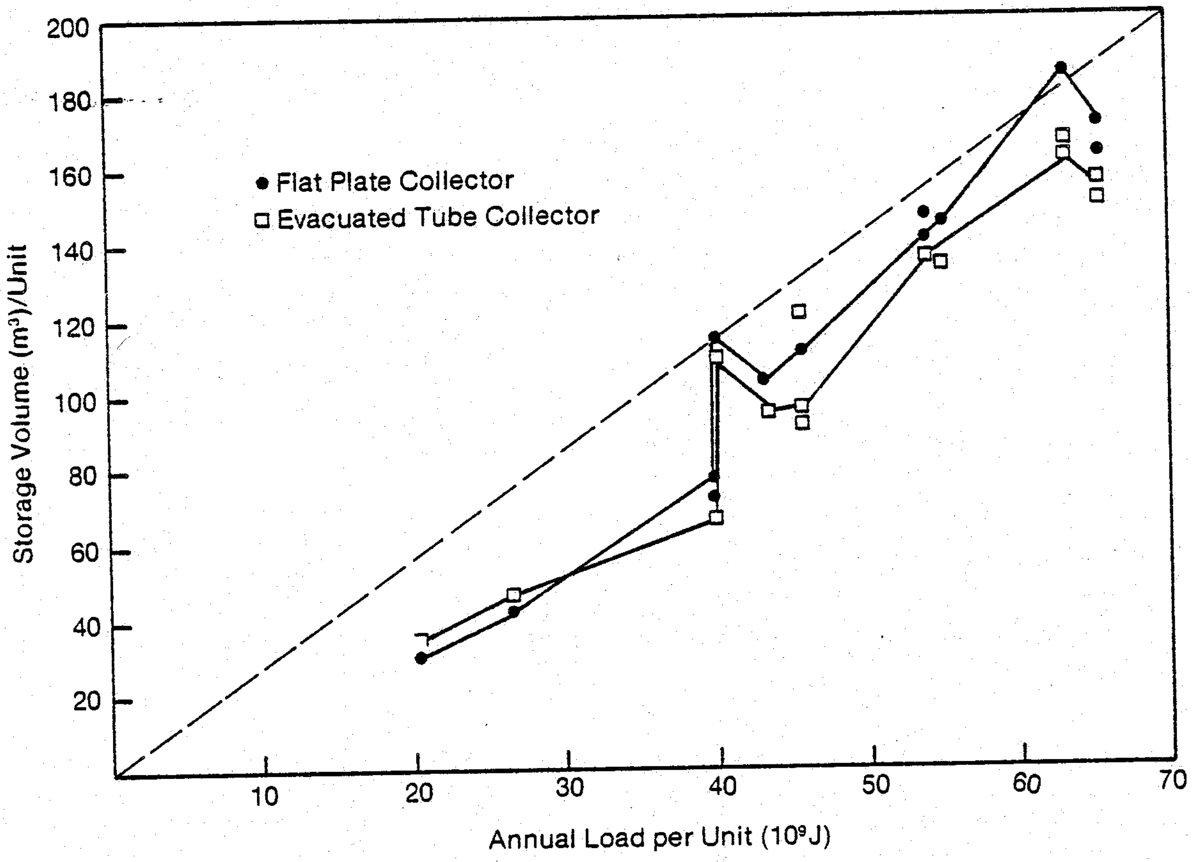


Figure 3-13. Storage Volume per Unit versus Annual Load per Unit: Single-Unit Buildings (Space and Water Heat).



Note: The dotted line provides a common reference frame among the three storage vs. annual load graphs.

Figure 3-14. Storage Volume per Unit versus Annual Load per Unit: 10-Unit Buildings (Space and Water Heat).

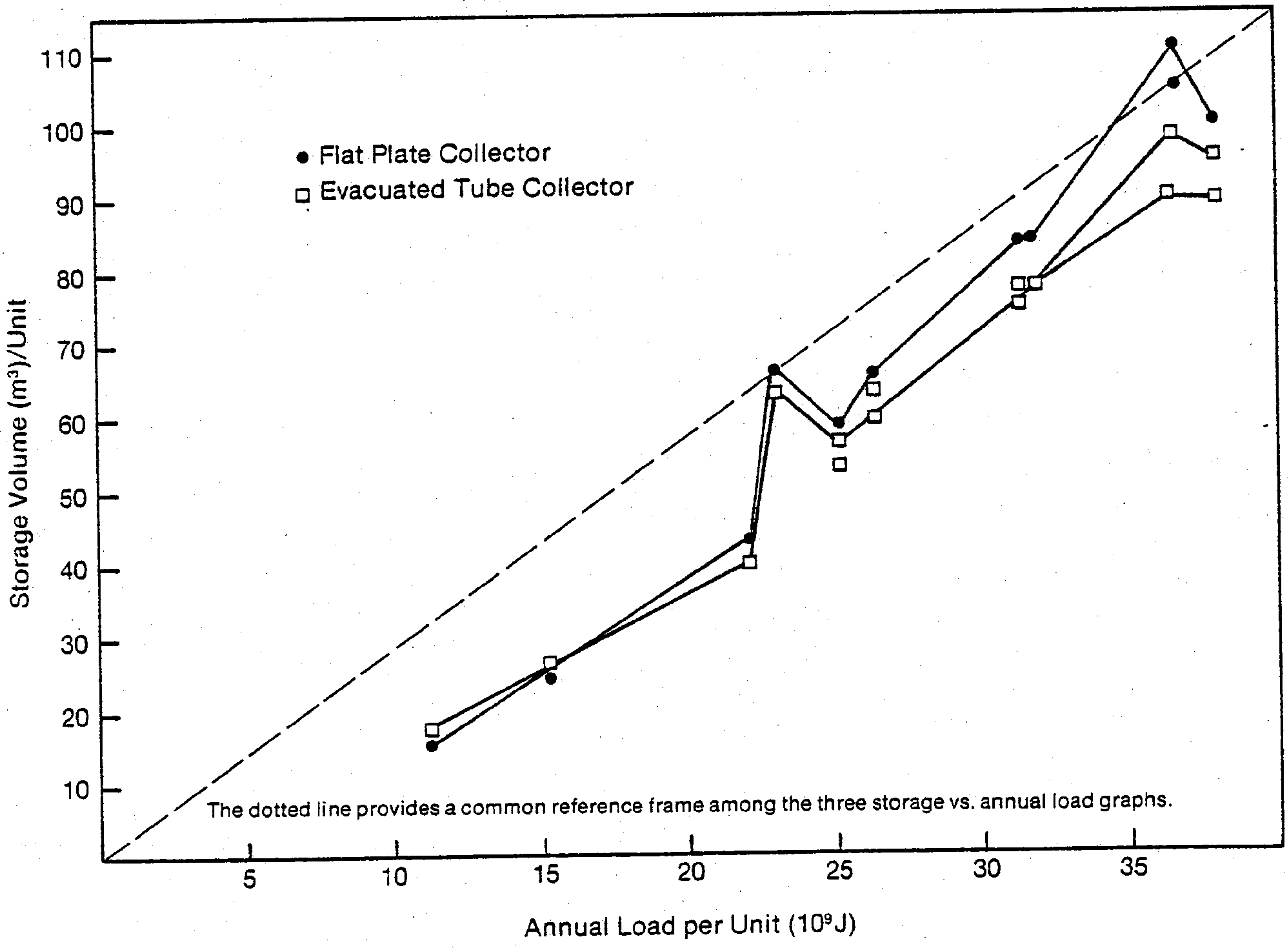


Figure 3-15. Storage Volume per Unit versus Annual Load per Unit: 200-Unit Buildings (Space and Water Heat).

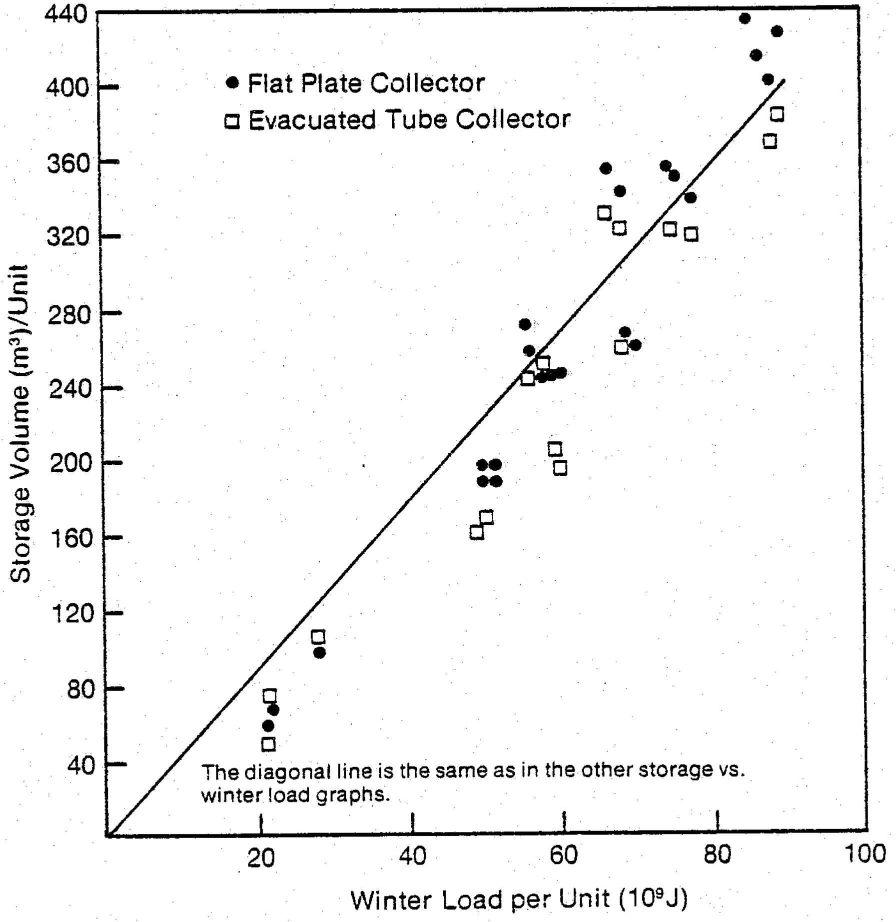


Figure 3-16. Storage Volume per Unit versus Winter Building Load Plus Storage Losses per Unit: Single Unit Buildings.

Winter load includes space and water heat, November through February

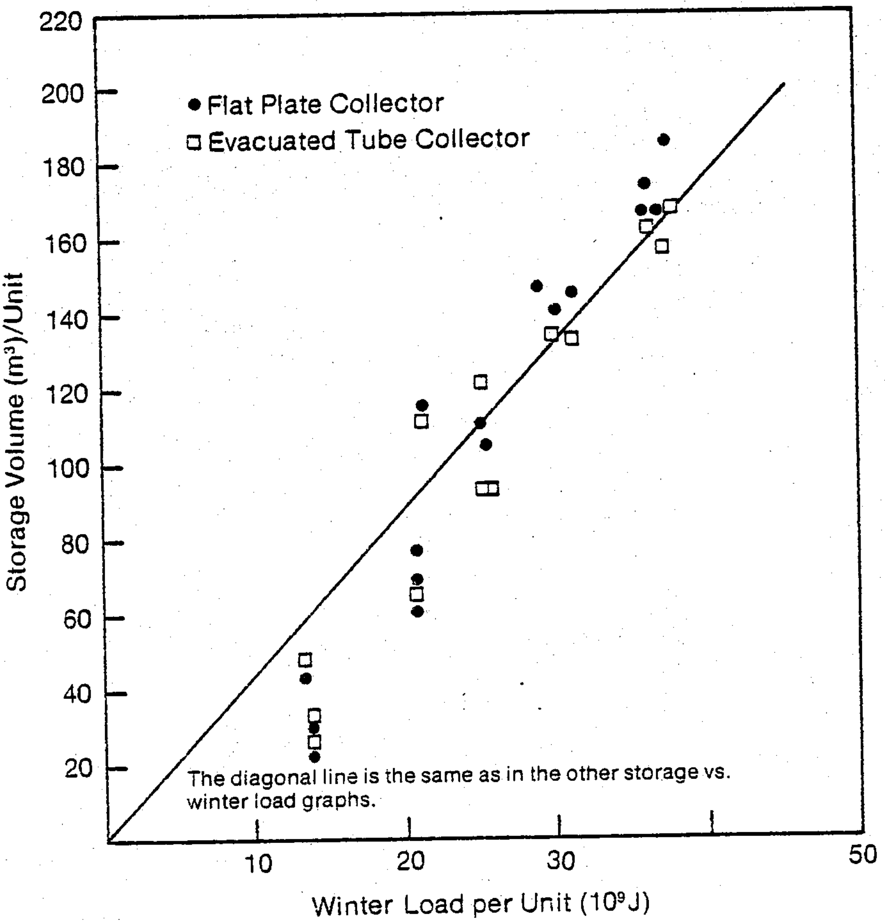


Figure 3-17. Storage Volume per Unit versus Winter Building Load Plus Storage Losses per Unit: 10-Unit Buildings.

Winter load includes space and water heating load for November through February

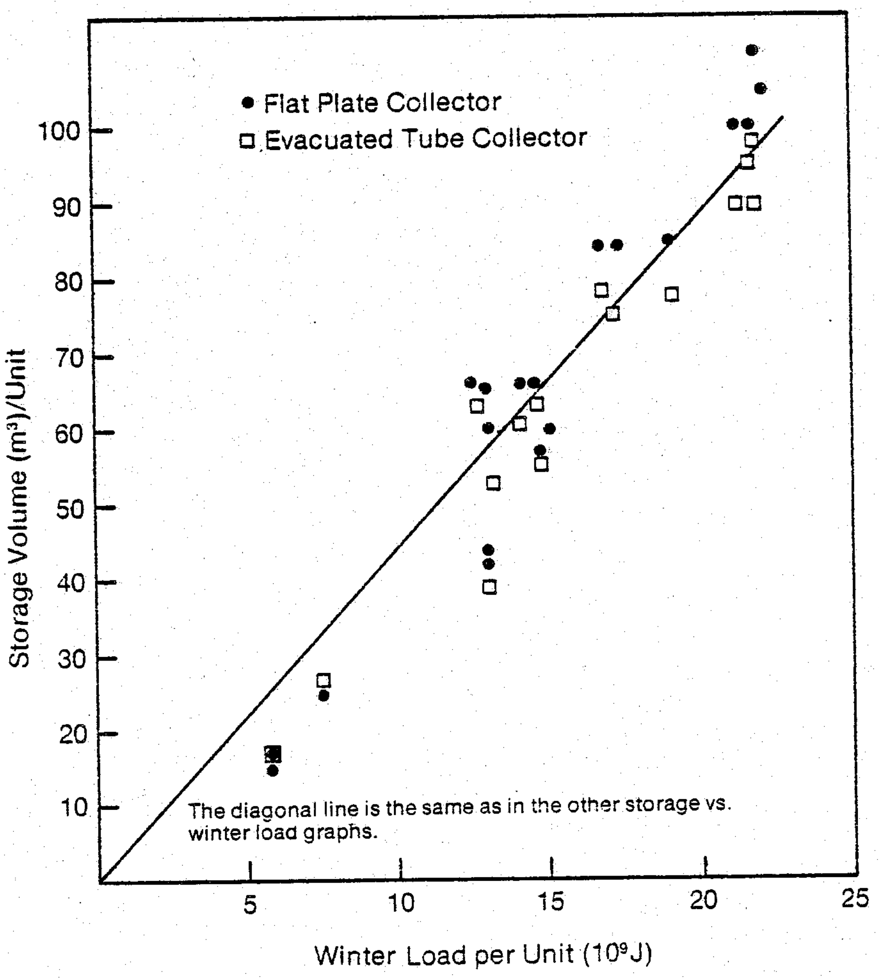


Figure 3-18. Storage Volume per Unit versus Winter Building Load Plus Storage Losses per Unit: 200-Unit Buildings.

Winter load includes space and water heating loads for November through February

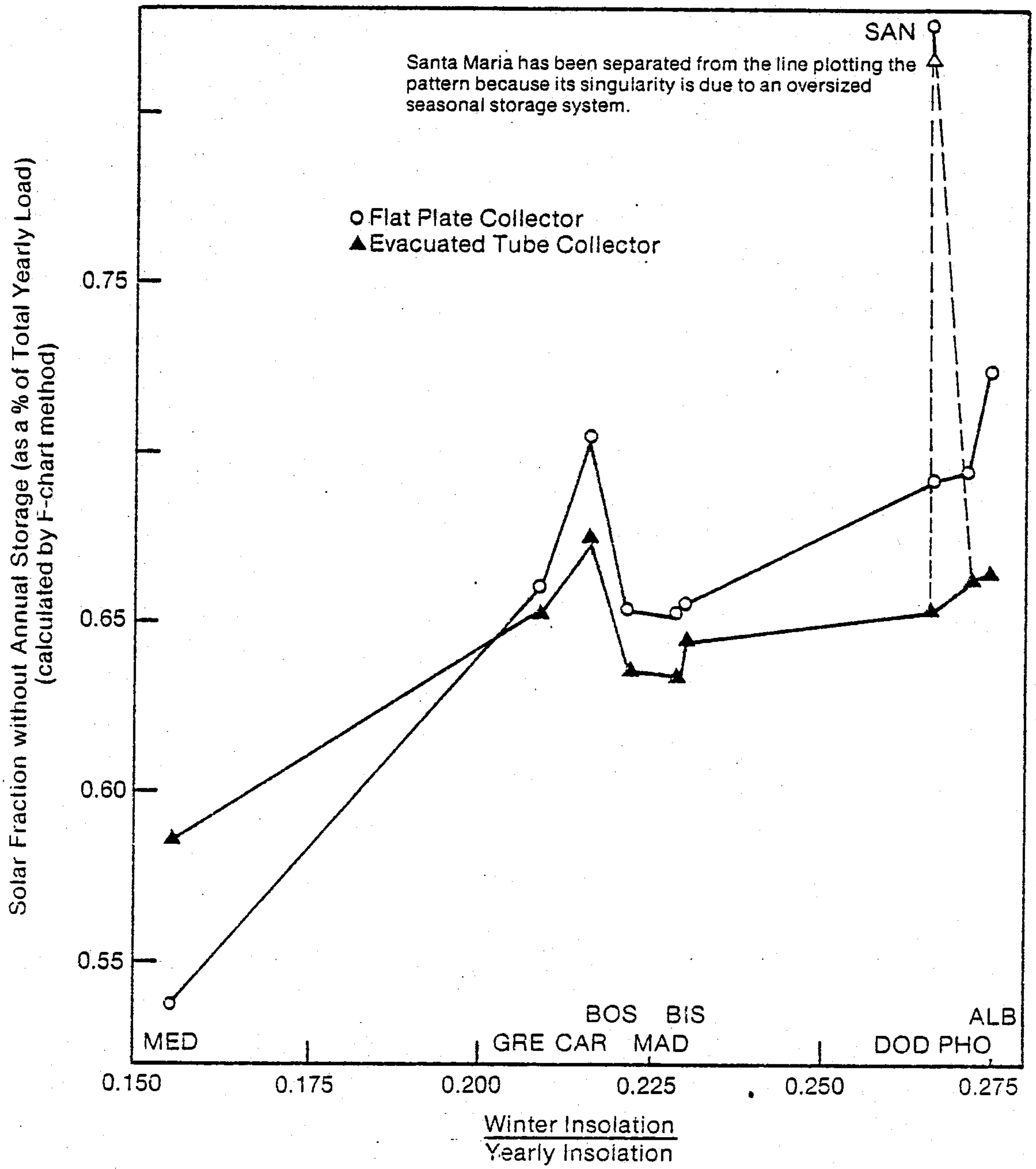


Figure 3-19. **Solar Yield without Annual Storage versus Winter Insolation to Annual Insolation Ratio.**

Single Unit Building, 50 Units, Tilt = Latitude
Winter insolation is for months of November through February.

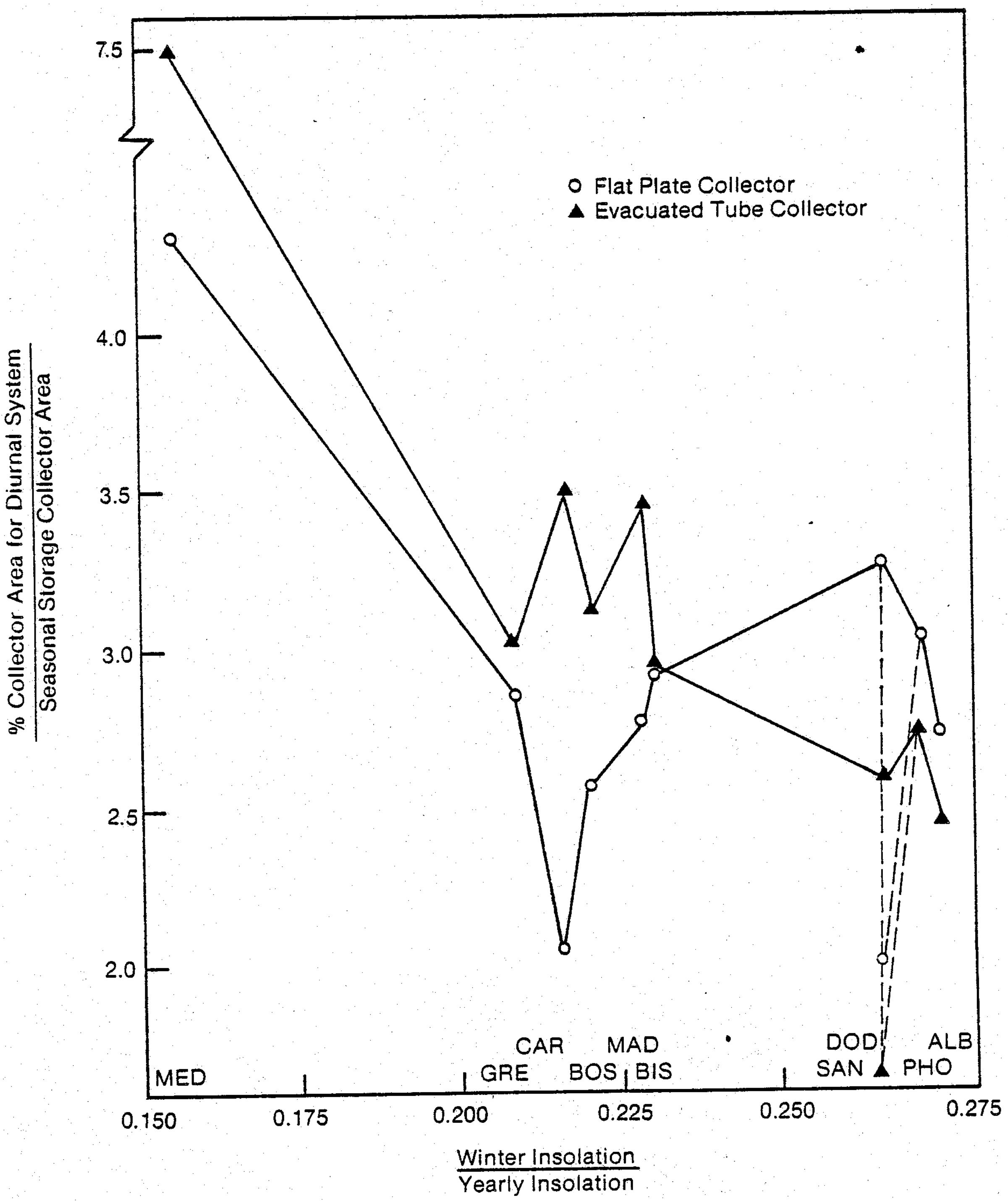


Figure 3-20. Collector Size for a Diurnal Solar System (96% Solar Fraction) vs. Winter Insolation to Annual Insolation Ratio.

Single Unit Building, 50 Units, Tilt = Latitude

A 96% solar system was sized by F-chart method. Collector size is expressed as a ratio to collector size of the seasonal storage systems.

SECTION 4.0

CONCLUSION

Collector field area and storage volume have been sized for 440 community designs in 10 geographic locations. Analysis of the data has allowed identification of those parameters that have first-order effects on component sizing. Storage size is determined by the difference between "winter net" and collected energy. Collector area then is sized to fully charge storage.

Two linear relationships were derived which allow system sizing. The average ambient temperature is used to determine average yearly collector efficiency. This parameter combined with estimates of space/DHW loads, storage/distribution losses, and total yearly insolation per square meter allows estimation of collector area. Storage size can be estimated from the winter net load which is based on space and DHW loads, storage/distribution losses, and collected solar heat for the winter months.

The algorithms, which would be applicable to other types of annual storages such as aquifers, can be further refined as results from the operation of ACTES solar systems become available. Calculations also can be refined with more detailed knowledge of a particular community design.

These results provide information to allow DOE program managers to identify the critical design parameters for ACTES solar systems and to more carefully target future activities. In addition, these data will be of use to other researchers in examining the feasibility of such systems.

In order to more accurately judge the relative merits of ACTES solar systems in different climates, a more detailed systems study and economic analysis is underway. Preliminary results indicate that as the DHW-to-space-heating-load ratio decreases and as community size decreases, system economics become less favorable. Modifications to the design presented here, such as incorporating a two-tank (annual storage for space heating; daily storage for DHW) storage system or using multiple tanks for annual storage of both heat and cold [14], may be economically promising technologies. In addition, the trade-off between storage and collectors [16] is being studied.

Results from both the technical and economic analyses are being used as inputs to a more general analysis of the value of ACTES technologies in solar systems. Aquifers, large constructed tanks or pits, and solar ponds are being compared.

SERI

SECTION 5.0

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APPENDIX A

SIMULATION PROGRAM DESCRIPTION

This program simulates the performance of an ACTES space heating and domestic hot water system for a single building using hourly time increments. The major components in the system are: the liquid-type solar collectors with an optional reflector arranged in a drain-down type of configuration; right-circular cylindrical constructed tank with optimally distributed insulation for the storage of solar heat water; double-walled heat exchanger to provide domestic hot water; and water-to-air heat exchanger to provide space heating.

The crux of this program is its calculation of storage heat loss. This is performed by a lumped parameter effective-thermal-resistance (ETR) model. This model assumes that the thermal properties of soil are time, space, and temperature independent.

The tank insulation distribution subroutine is an integral part of the ETR calculation. An insulation distribution is assumed such that tank-conductive heat loss for a given total volume of insulation is minimized.

The domestic hot water (DHW) heat exchanger operates with a user-specified temperature drop across the heat exchanger. For this study, a value of 4.5°F (2.5°C) was used. At this time, there is no DHW heat-exchanger simulation model in the program. The load distribution of DHW is a function of time of day.

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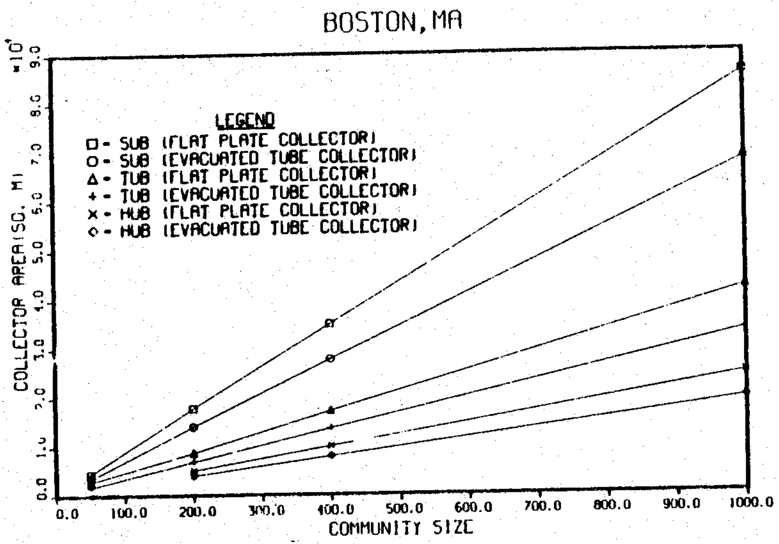
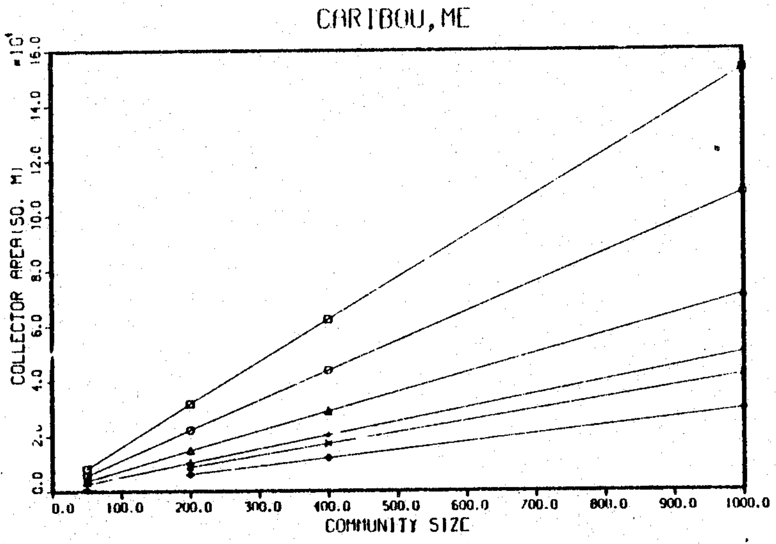
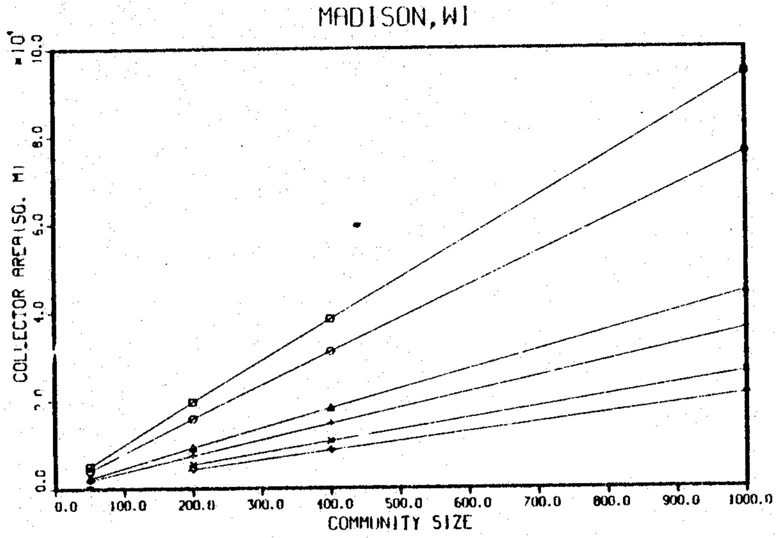
APPENDIX B

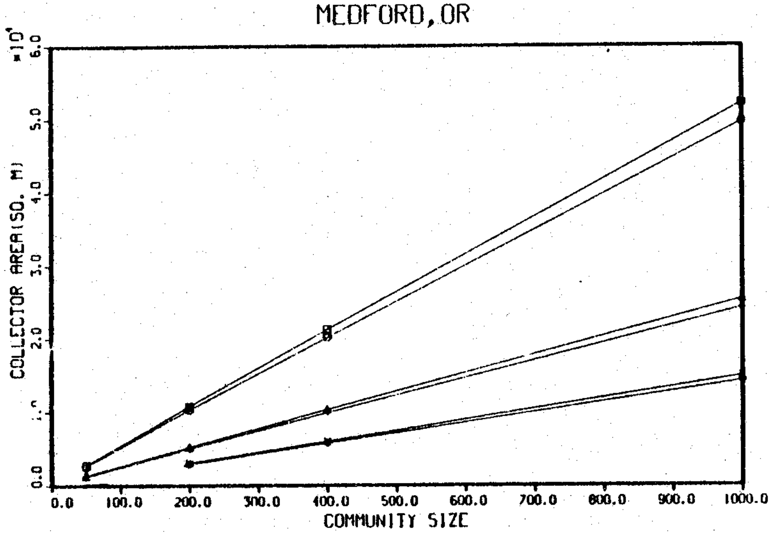
GRAPHS OF VARIABLES VERSUS COMMUNITY SIZE

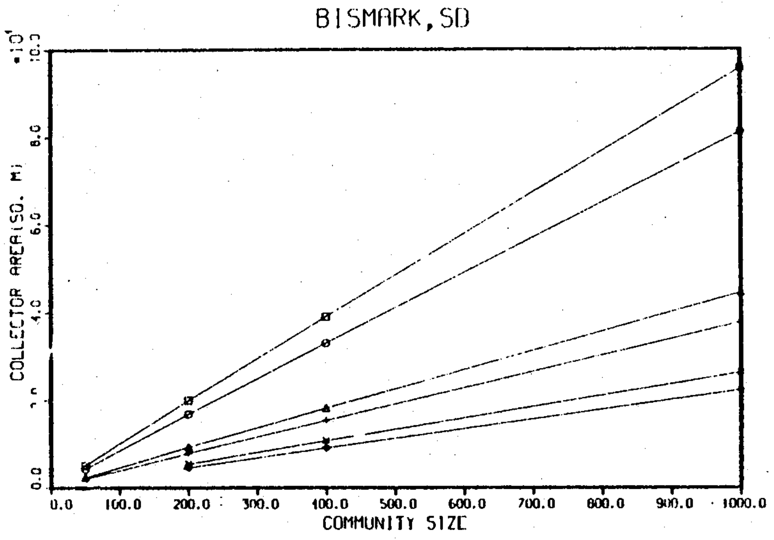
The important design variables plotted against community size with building type and solar collector type as parameters are presented below (also see Section 3.3). (In all graphs that follow collector tiltwas equal to latitude.) Collector area, solar energy collected, storage volume, the ratio of storage volume to collector area, solar energy stored, and the ratio of storage loss for energy stored are plotted. The data presented here should allow first order design of an ACTES solar system in many communities with climates similar to those chosen for this study.

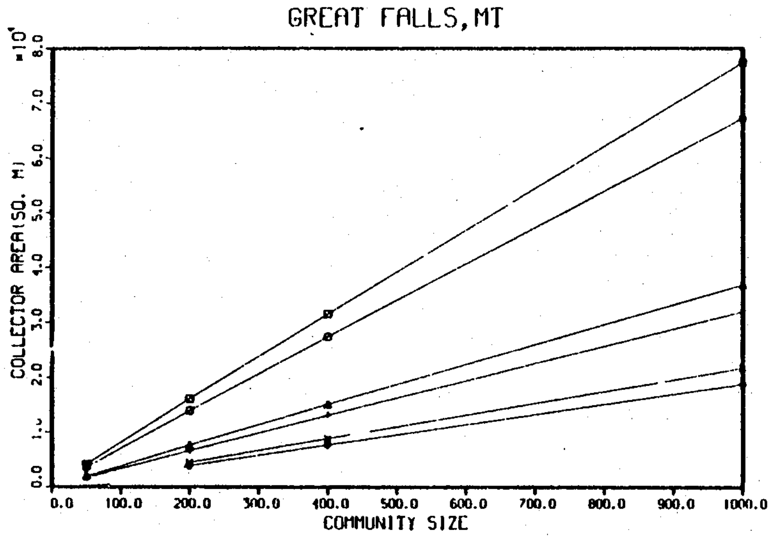

BOSTON, MA
LEGEND
□ - SUB (FLAT PLATE COLLECTOR)
○ - SUB (EVACUATED TUBE COLLECTOR)
△ - TUB (FLAT PLATE COLLECTOR)
+ - TUB (EVACUATED TUBE COLLECTOR)
× - HUB (FLAT PLATE COLLECTOR)
◇ - HUB (EVACUATED TUBE COLLECTOR)
COLLECTOR AREA (SQ. M)
*10⁴
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

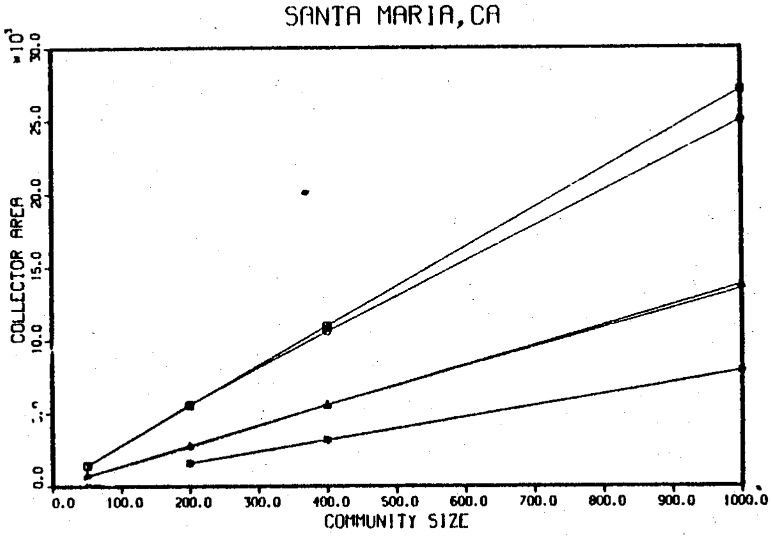

CARIBOU, ME
COLLECTOR AREA (SQ. M)
*10⁴
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

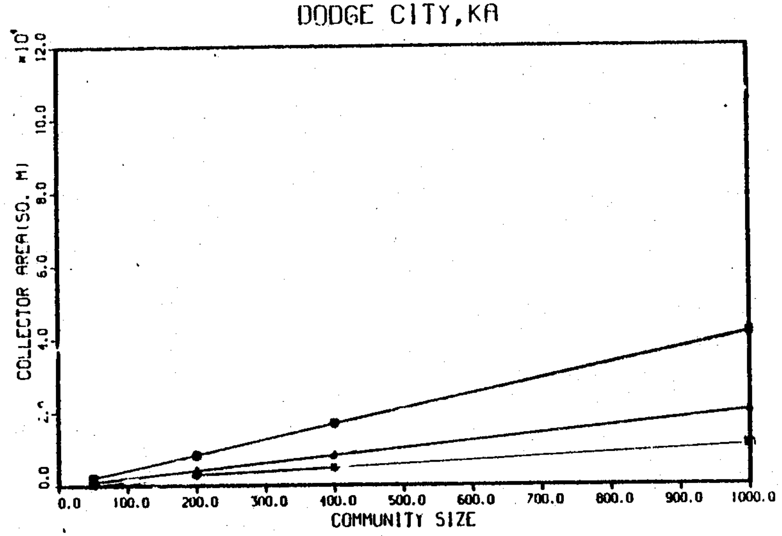

MADISON, WI
COLLECTOR AREA (SQ. M)
*10⁴
0.0
2.0
4.0
6.0
8.0
10.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

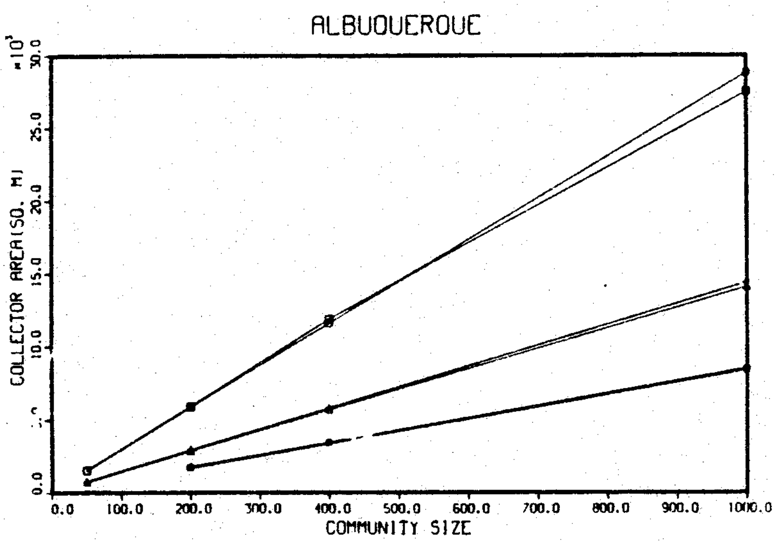

MEDFORD, OR
COLLECTOR AREA (SQ. M)
*10⁴
0.0
1.0
2.0
3.0
4.0
5.0
6.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

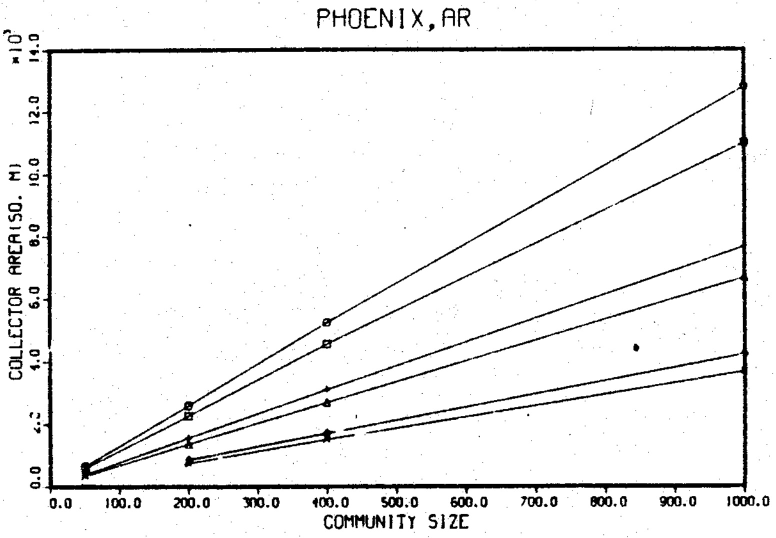

BISMARK, SD
×10¹
COLLECTOR AREA(SQ. MI)
0.0
2.0
4.0
6.0
8.0
10.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

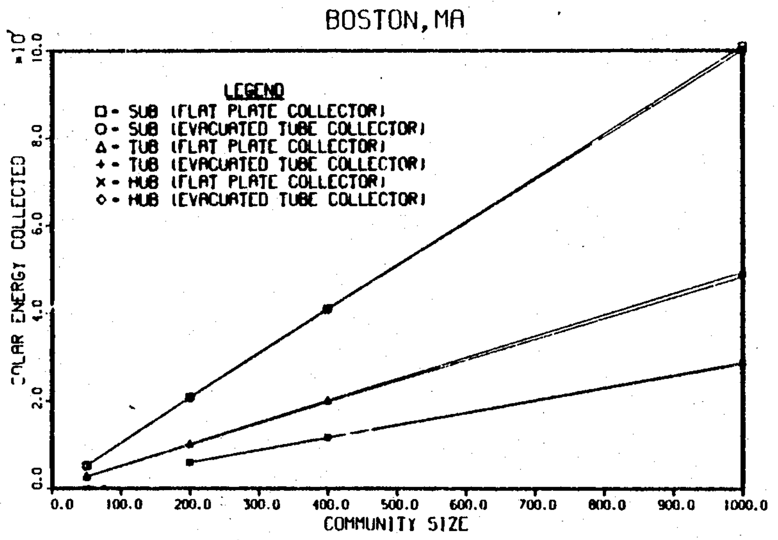

GREAT FALLS, MT
×10¹
COLLECTOR AREA(SQ. MI)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

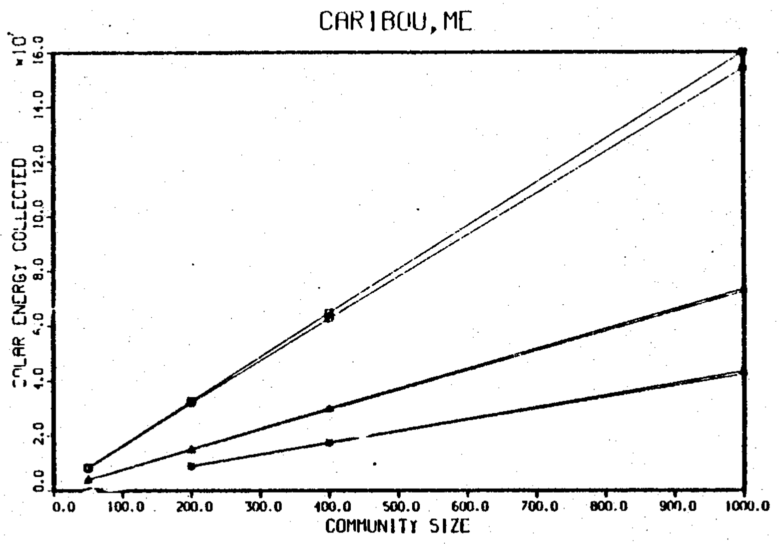

SANTA MARIA, CA
×10³
COLLECTOR AREA
0.0
5.0
10.0
15.0
20.0
25.0
30.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

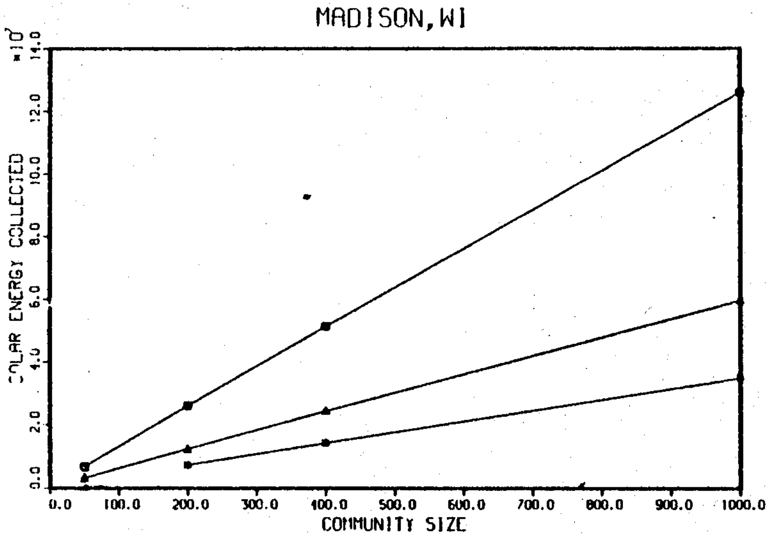

DODGE CITY, KA
×10¹
COLLECTOR AREA(SQ. MI)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

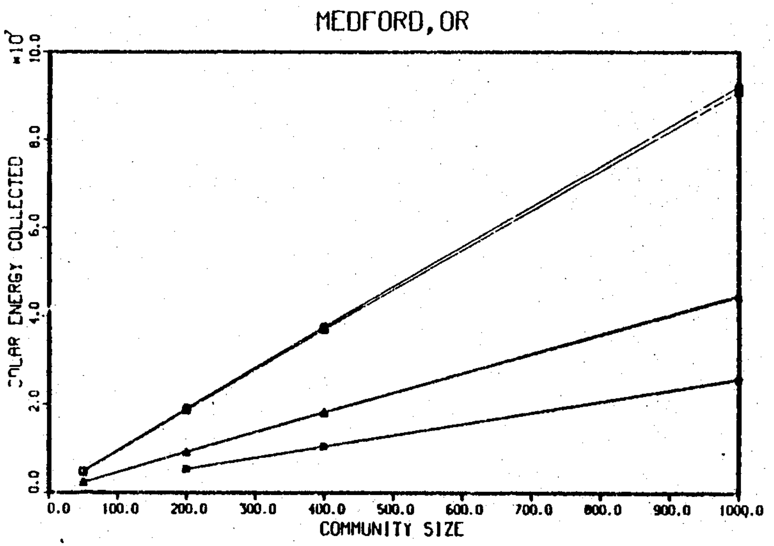

ALBUQUERQUE
COLLECTOR AREA(SQ. M)
x10^3
0.0
5.0
10.0
15.0
20.0
25.0
30.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

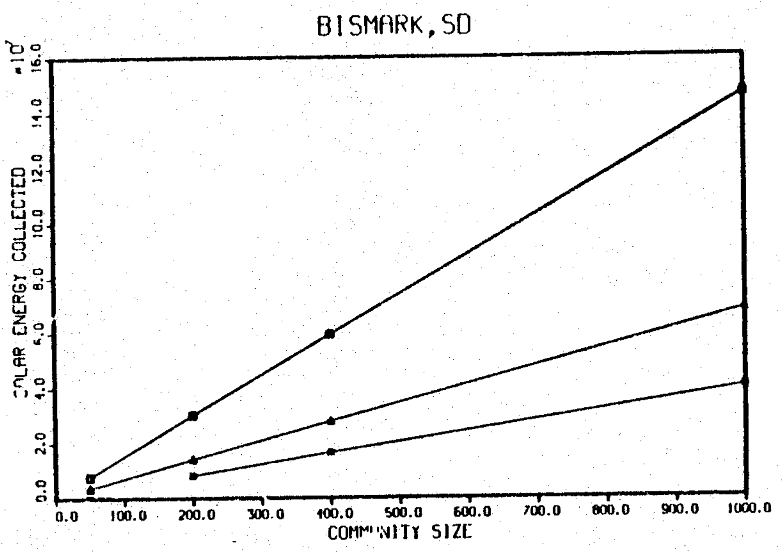

PHOENIX,AR
COLLECTOR AREA(SQ. M)
x10^3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

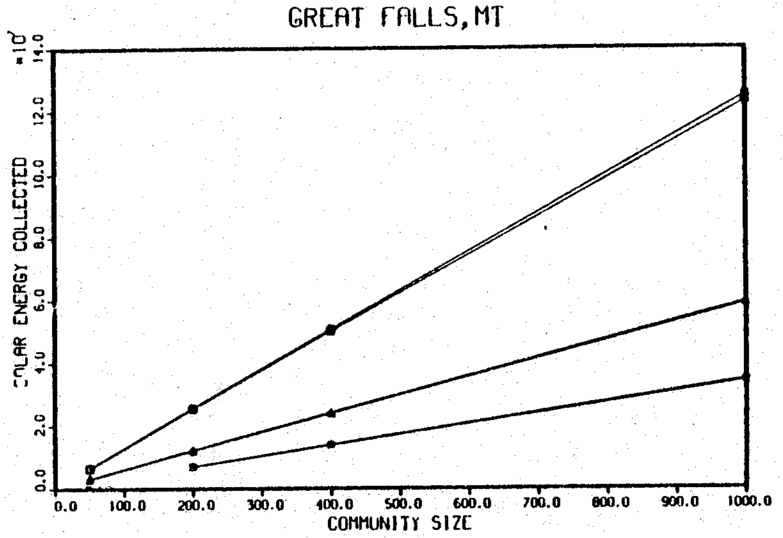

BOSTON, MA
LEGEND
□ - SUB (FLAT PLATE COLLECTOR)
○ - SUB (EVACUATED TUBE COLLECTOR)
△ - TUB (FLAT PLATE COLLECTOR)
+ - TUB (EVACUATED TUBE COLLECTOR)
× - HUB (FLAT PLATE COLLECTOR)
◇ - HUB (EVACUATED TUBE COLLECTOR)
SOLAR ENERGY COLLECTED
×10⁷
0.0
2.0
4.0
6.0
8.0
10.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0


CARIBOU, ME
SOLAR ENERGY COLLECTED
×10⁷
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0


MADISON, WI
SOLAR ENERGY COLLECTED
×10⁷
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0


MEDFORD, OR
SOLAR ENERGY COLLECTED
×10⁷
0.0
2.0
4.0
6.0
8.0
10.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0


BISMARK, SD
*10^7
SOLAR ENERGY COLLECTED
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


GREAT FALLS, MT
*10^7
SOLAR ENERGY COLLECTED
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
0.0
100.0
200.0
300.0
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500.0
600.0
700.0
800.0
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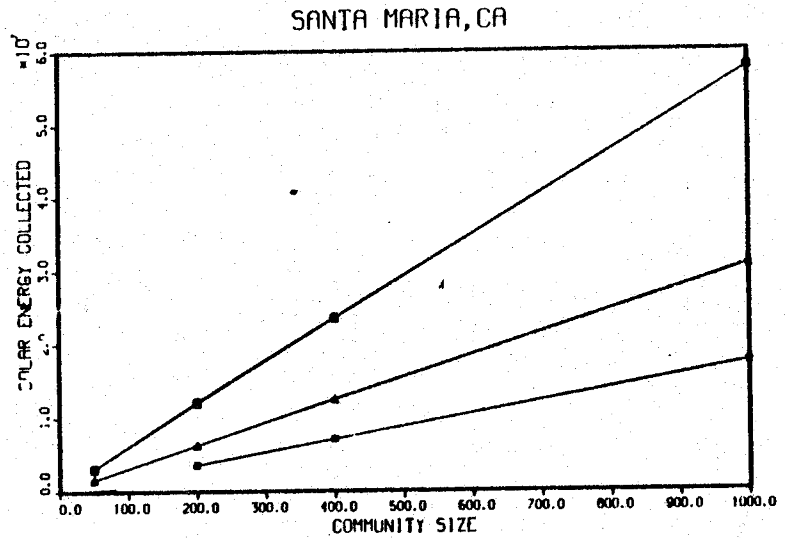
1000.0
COMMUNITY SIZE


SANTA MARIA, CA
*10^7
SOLAR ENERGY COLLECTED
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
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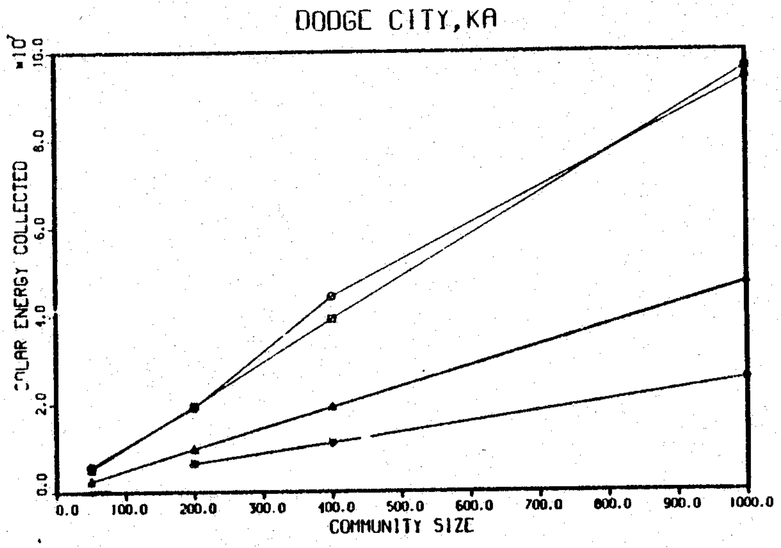
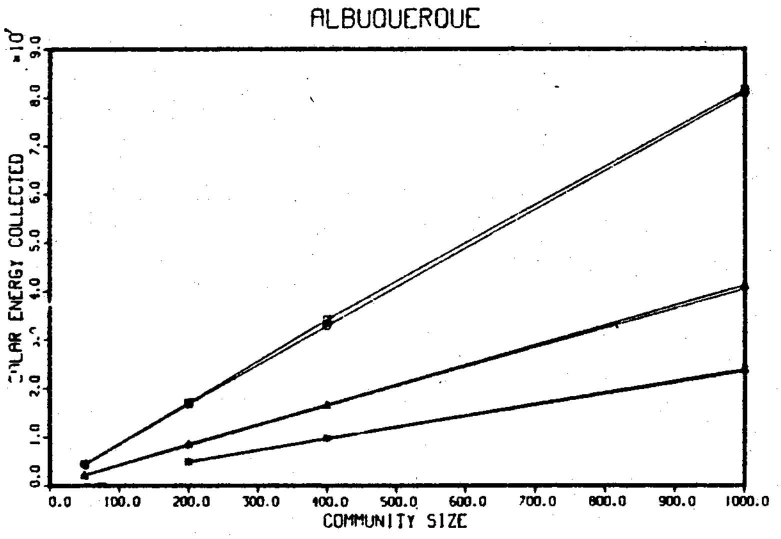
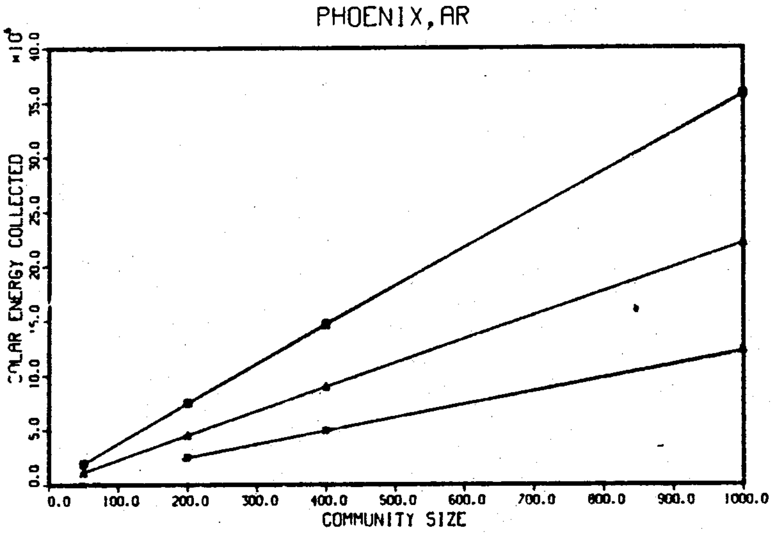
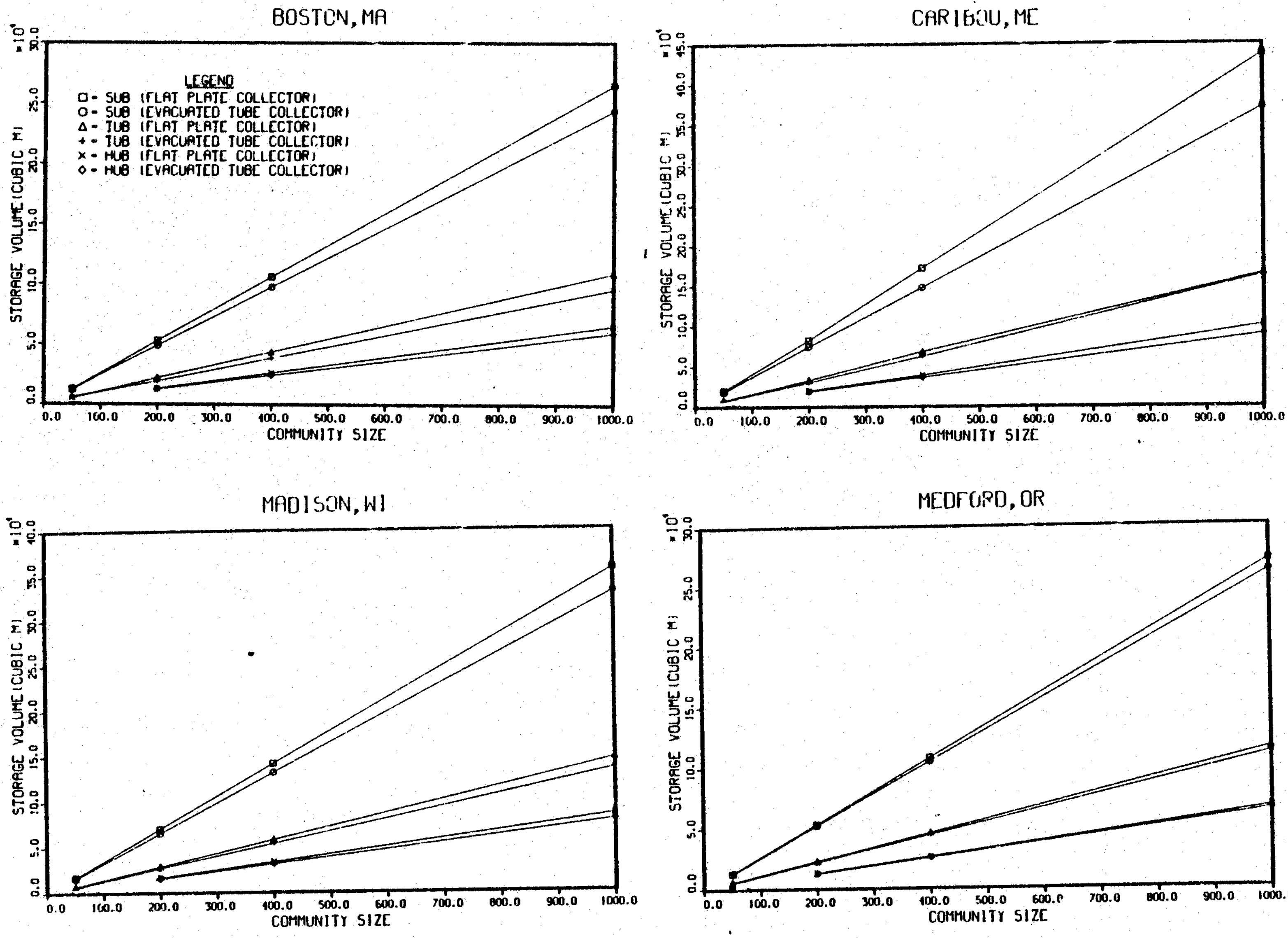
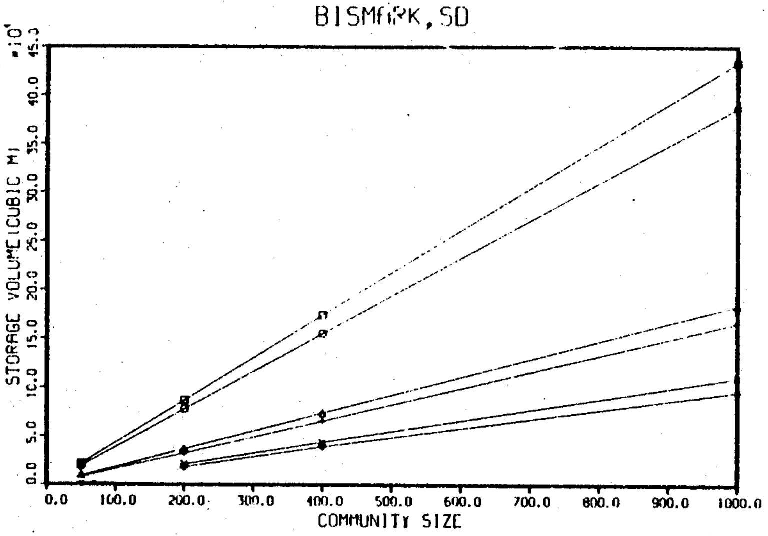
900.0
1000.0
COMMUNITY SIZE

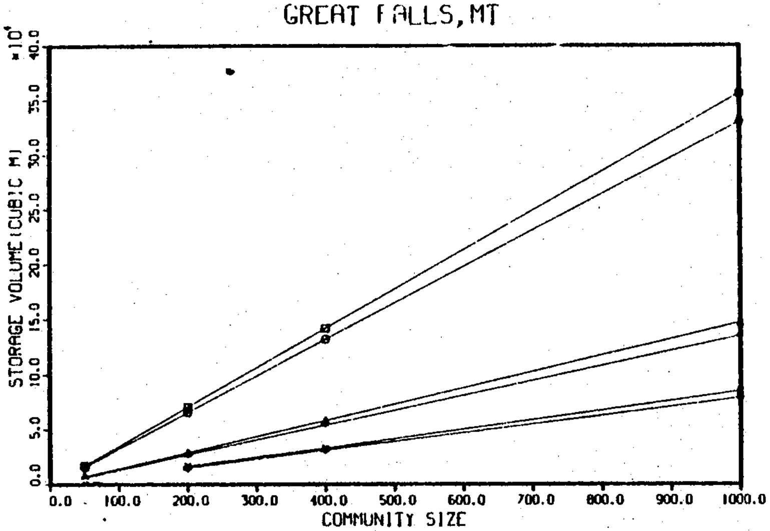

DODGE CITY, KA
*10^7
SOLAR ENERGY COLLECTED
0.0
2.0
4.0
6.0
8.0
10.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


ALBUQUERQUE
SOLAR ENERGY COLLECTED
×10^7
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


PHOENIX, AR
SOLAR ENERGY COLLECTED
×10
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


BOSTON, MA
LEGEND
□ - SUB (FLAT PLATE COLLECTOR)
○ - SUB (EVACUATED TUBE COLLECTOR)
△ - TUB (FLAT PLATE COLLECTOR)
+ - TUB (EVACUATED TUBE COLLECTOR)
× - HUB (FLAT PLATE COLLECTOR)
◇ - HUB (EVACUATED TUBE COLLECTOR)
STORAGE VOLUME (CUBIC M)
×10⁴
0.0
5.0
10.0
15.0
20.0
25.0
30.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
CARIBOU, ME
STORAGE VOLUME (CUBIC M)
×10⁴
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
COMMUNITY SIZE
MADISON, WI
STORAGE VOLUME (CUBIC M)
×10⁴
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
COMMUNITY SIZE
MEDFORD, OR
STORAGE VOLUME (CUBIC M)
×10⁴
0.0
5.0
10.0
15.0
20.0
25.0
30.0
COMMUNITY SIZE


BISMARK, SD
STORAGE VOLUME (CUBIC M)
$\times 10^4$
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


GREAT FALLS, MT
STORAGE VOLUME (CUBIC M)
$\times 10^4$
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
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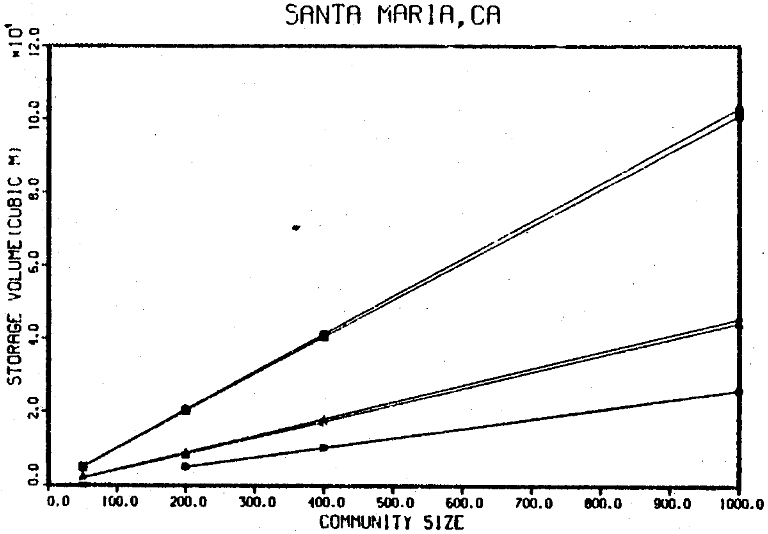
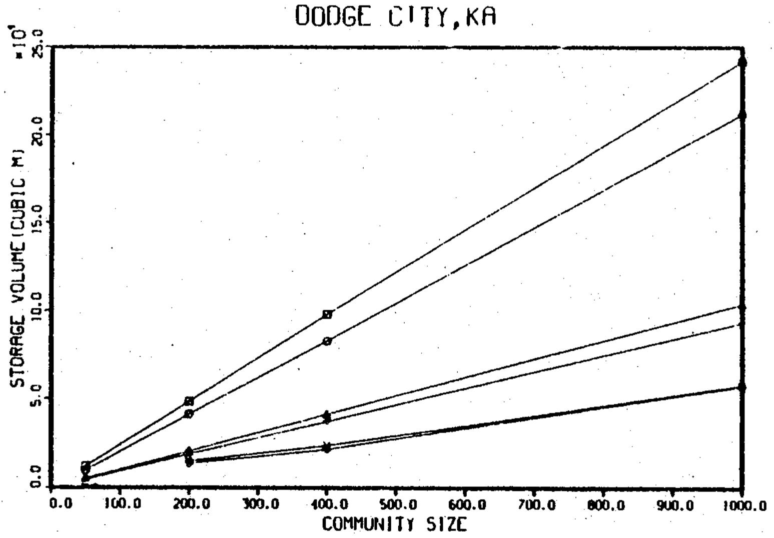
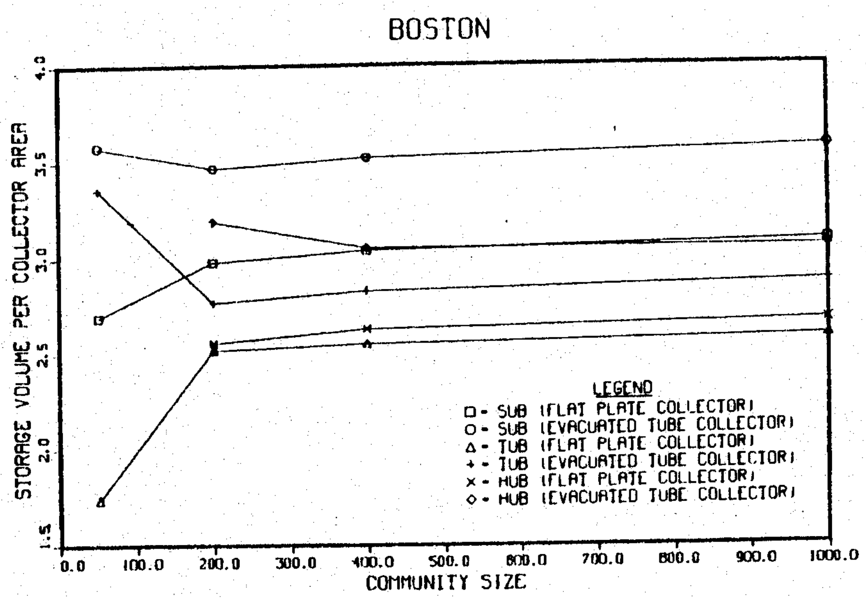
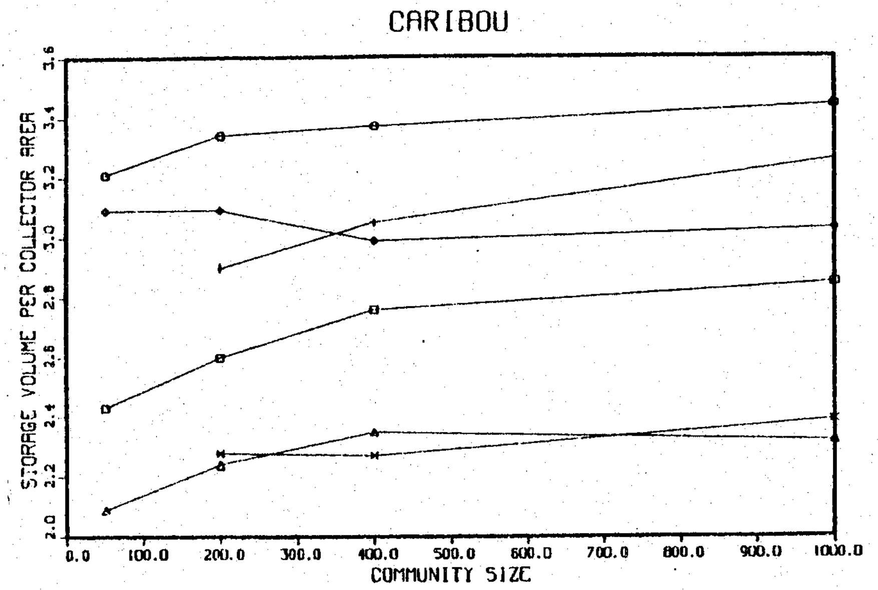
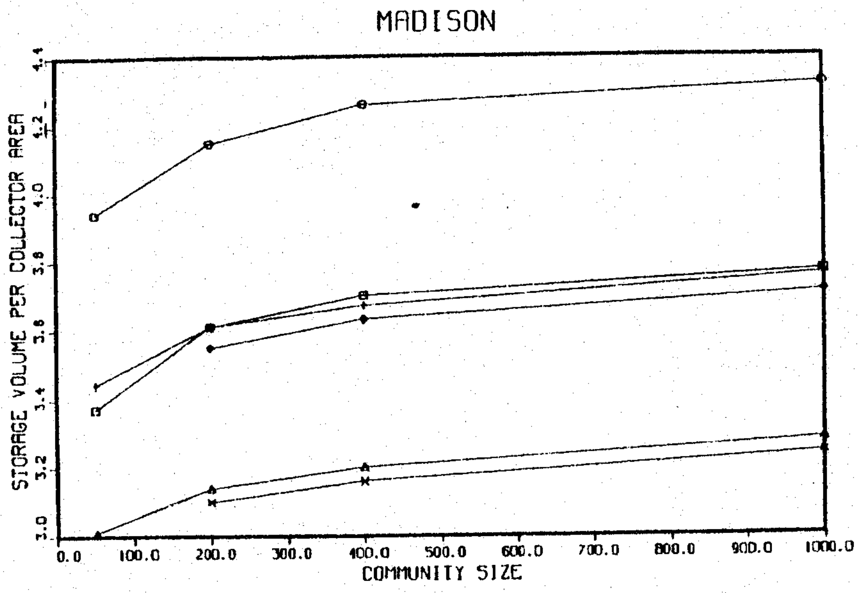
800.0
900.0
1000.0
COMMUNITY SIZE

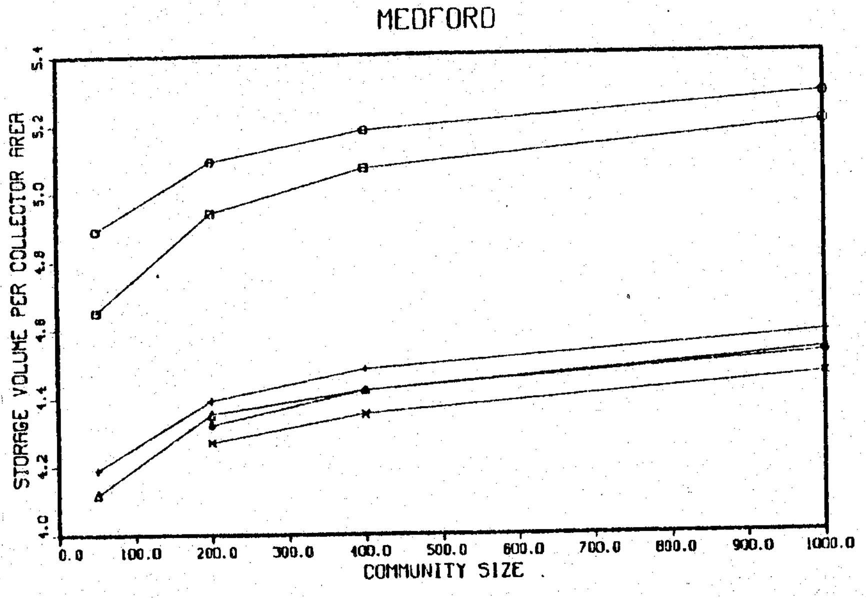

SANTA MARIA, CA
STORAGE VOLUME (CUBIC M)
$\times 10^4$
0.0
2.0
4.0
6.0
8.0
10.0
12.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

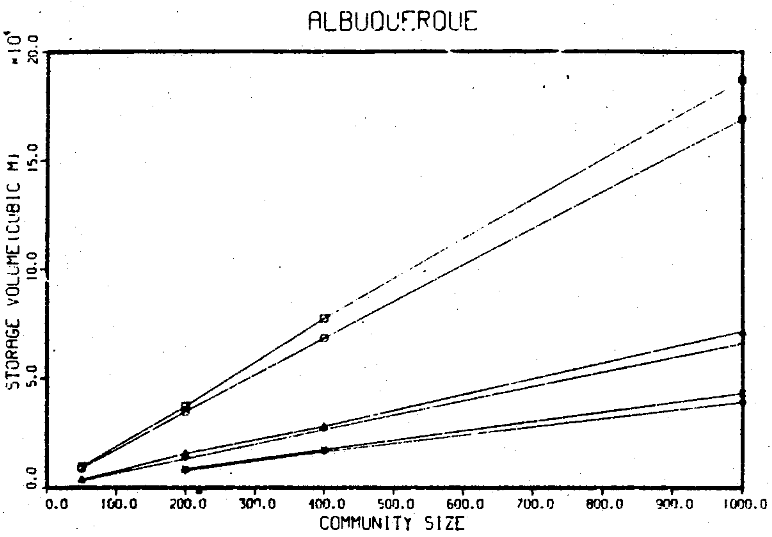

DODGE CITY, KA
STORAGE VOLUME (CUBIC M)
$\times 10^4$
0.0
5.0
10.0
15.0
20.0
25.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

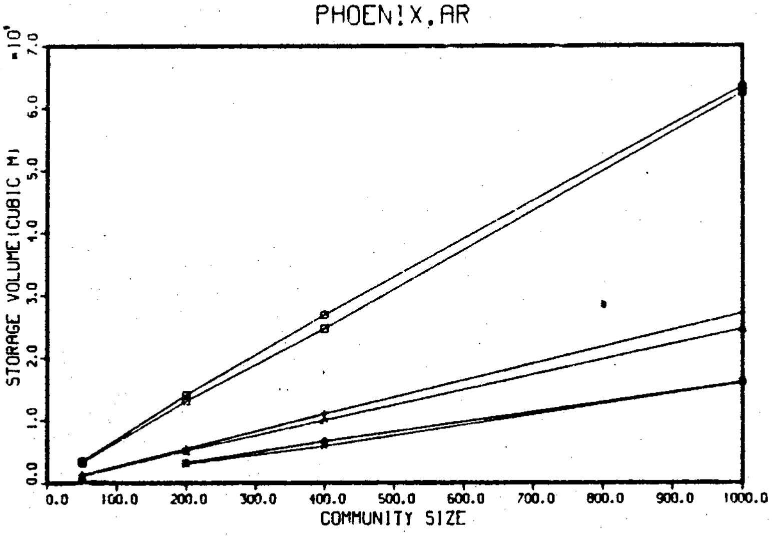

BOSTON
STORAGE VOLUME PER COLLECTOR AREA
1.5
2.0
2.5
3.0
3.5
4.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE
LEGEND
□ - SUB (FLAT PLATE COLLECTOR)
○ - SUB (EVACUATED TUBE COLLECTOR)
△ - TUB (FLAT PLATE COLLECTOR)
+ - TUB (EVACUATED TUBE COLLECTOR)
× - HUB (FLAT PLATE COLLECTOR)
◇ - HUB (EVACUATED TUBE COLLECTOR)

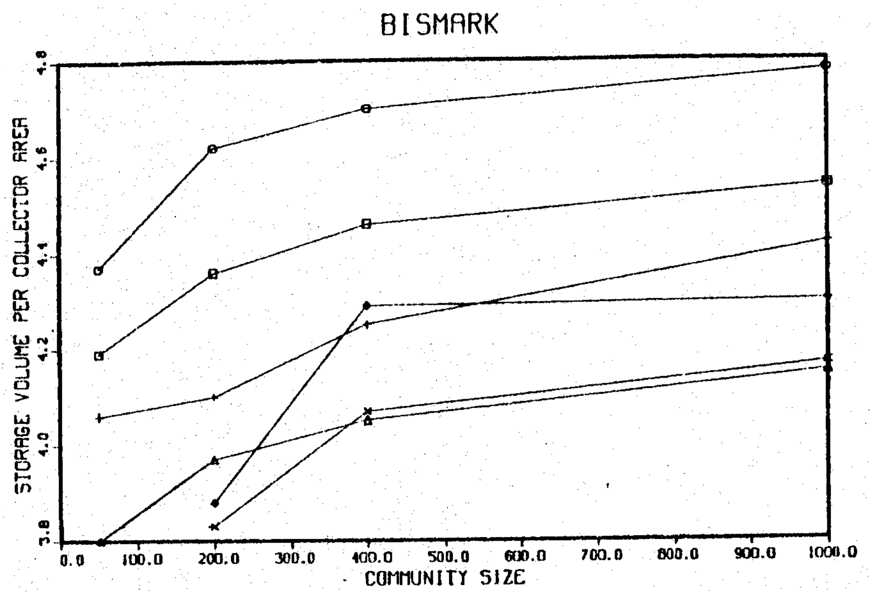

CARIBOU
STORAGE VOLUME PER COLLECTOR AREA
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

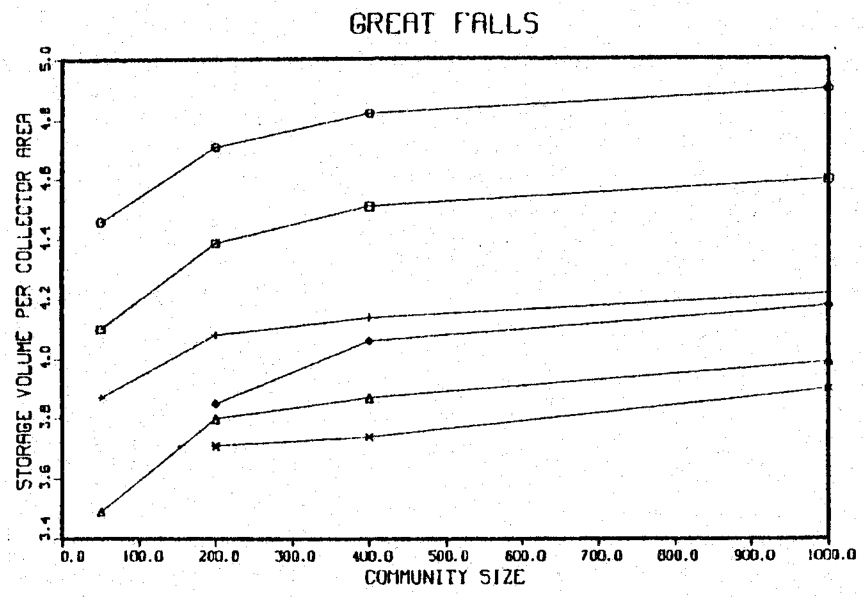

MADISON
STORAGE VOLUME PER COLLECTOR AREA
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

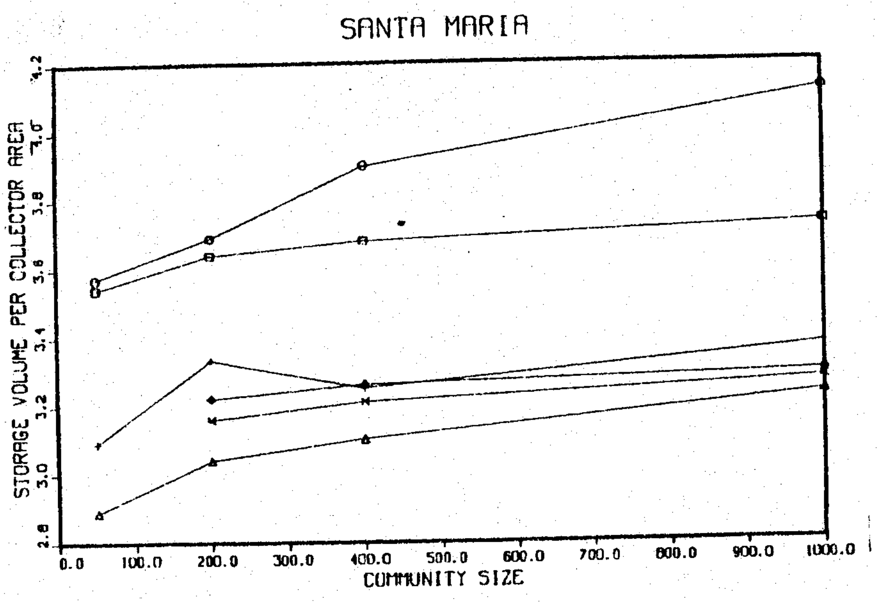

MEDFORD
STORAGE VOLUME PER COLLECTOR AREA
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

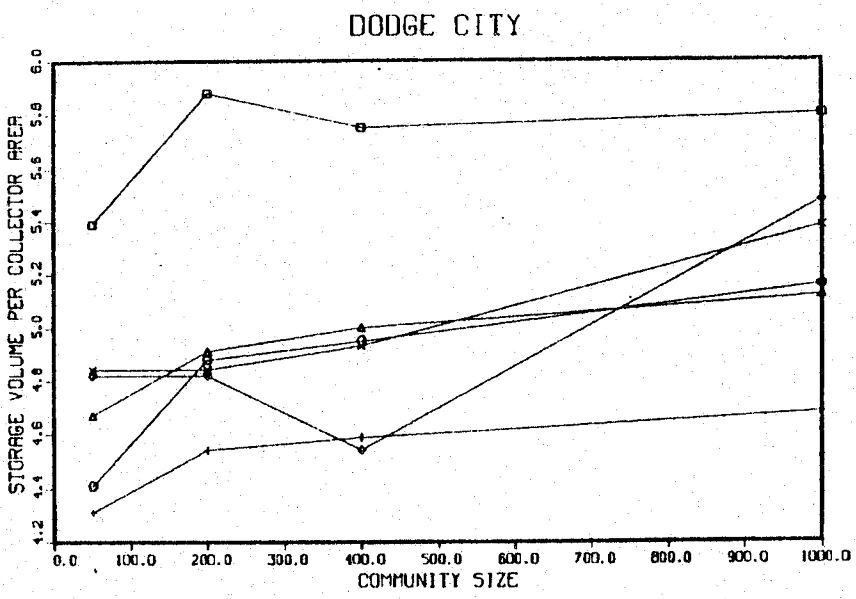

ALBUQUERQUE
STORAGE VOLUME(CUBIC M)
*10^4
0.0
5.0
10.0
15.0
20.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

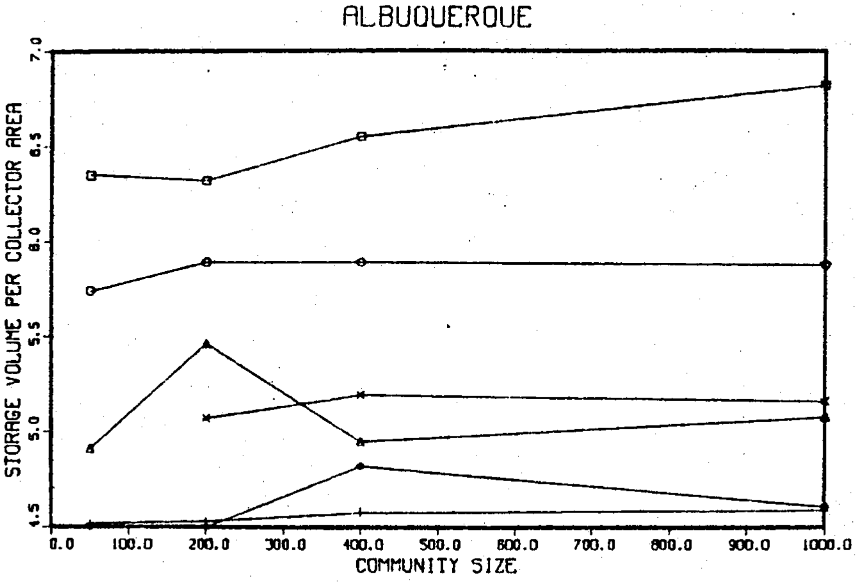

PHOENIX,AR
STORAGE VOLUME(CUBIC M)
*10^4
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

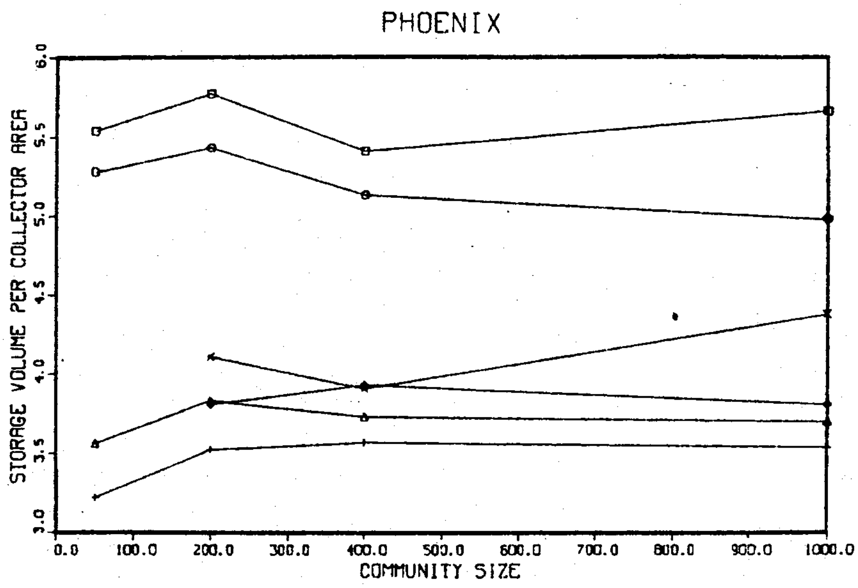

BISMARK
STORAGE VOLUME PER COLLECTOR AREA
3.8
4.0
4.2
4.4
4.6
4.8
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

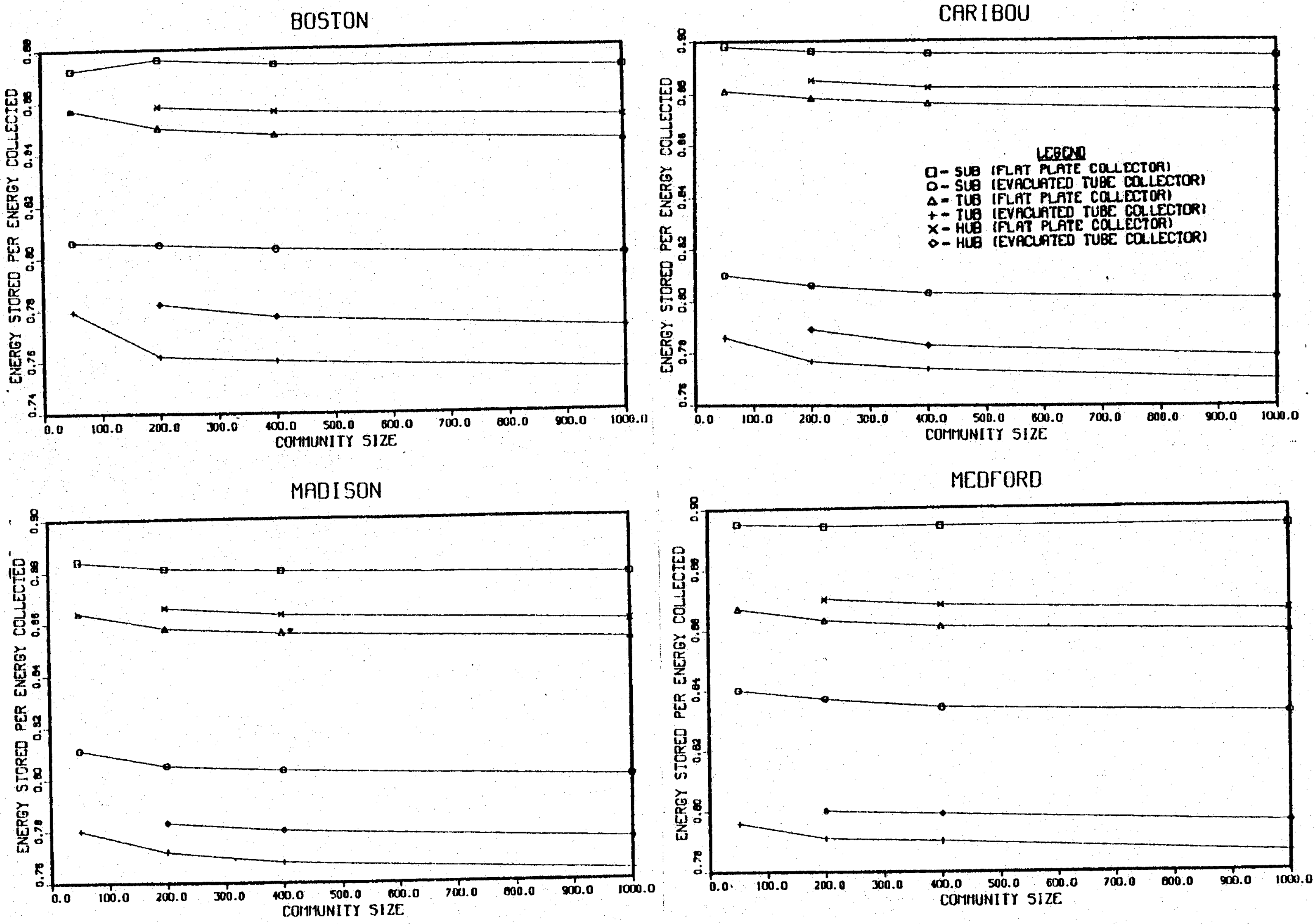

GREAT FALLS
STORAGE VOLUME PER COLLECTOR AREA
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

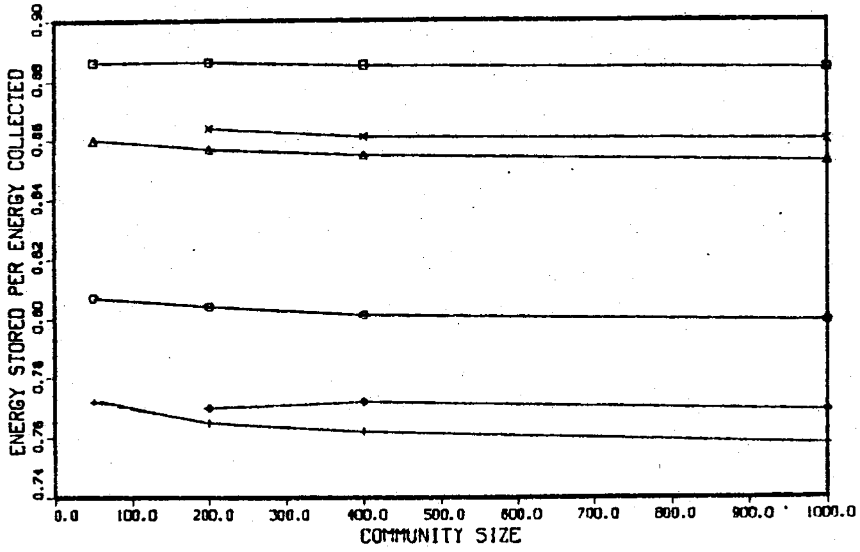

SANTA MARIA
STORAGE VOLUME PER COLLECTOR AREA
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


DODGE CITY
STORAGE VOLUME PER COLLECTOR AREA
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

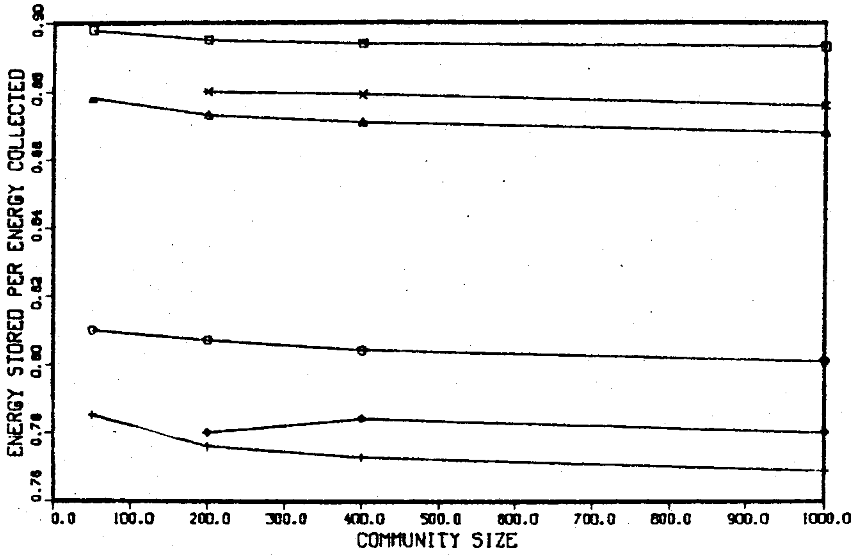

ALBUQUERQUE
STORAGE VOLUME PER COLLECTOR AREA
4.5
5.0
5.5
6.0
6.5
7.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


PHOENIX
STORAGE VOLUME PER COLLECTOR AREA
3.0
3.5
4.0
4.5
5.0
5.5
6.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

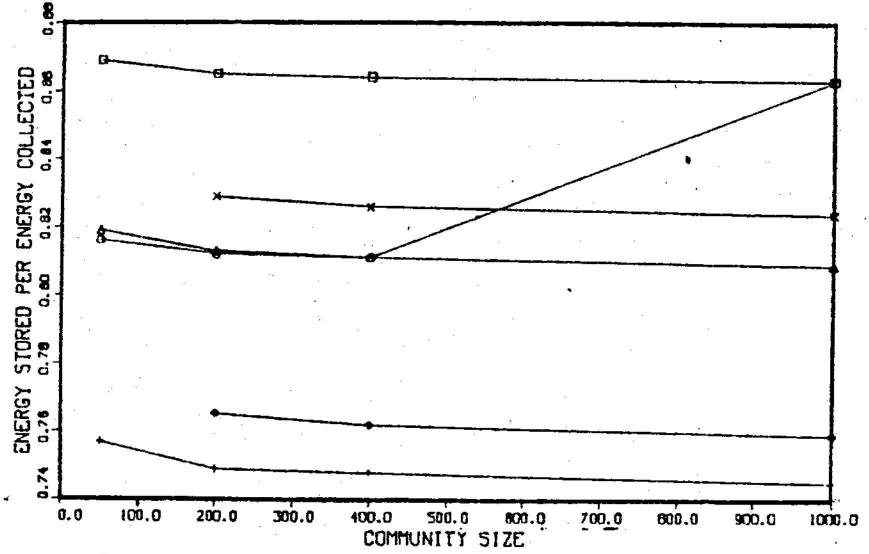

BOSTON
CARIBOU
MADISON
MEDFORD
ENERGY STORED PER ENERGY COLLECTED
COMMUNITY SIZE
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
LEGEND
□ - SUB (FLAT PLATE COLLECTOR)
○ - SUB (EVACUATED TUBE COLLECTOR)
△ - TUB (FLAT PLATE COLLECTOR)
+ - TUB (EVACUATED TUBE COLLECTOR)
× - HUB (FLAT PLATE COLLECTOR)
◇ - HUB (EVACUATED TUBE COLLECTOR)



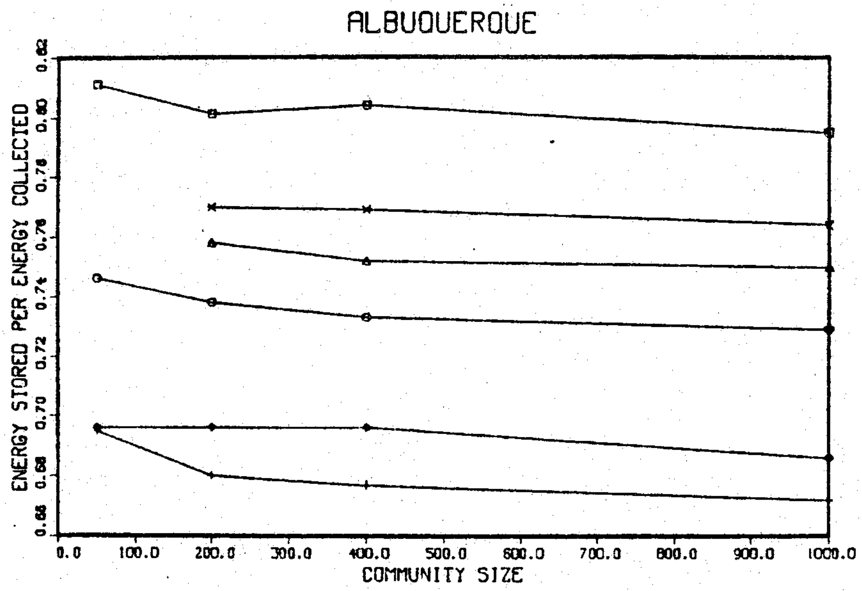
GREAT FALLS

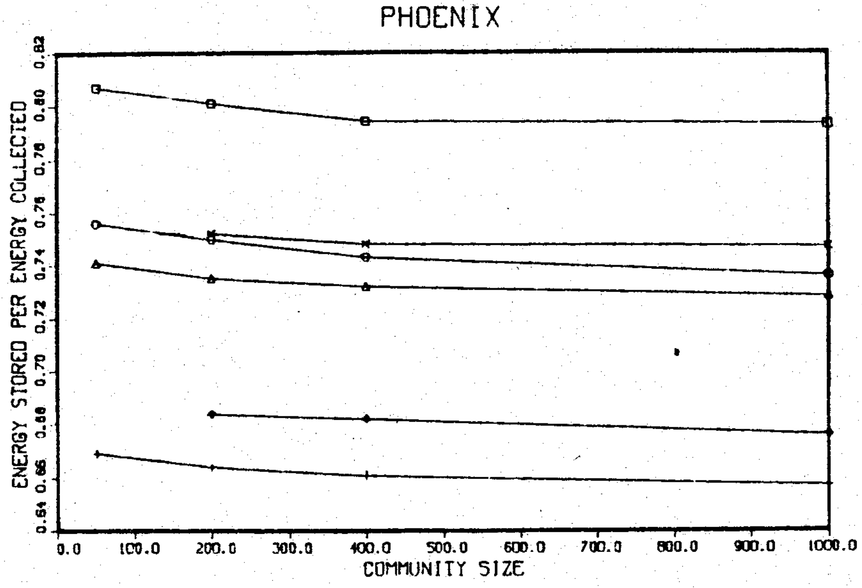


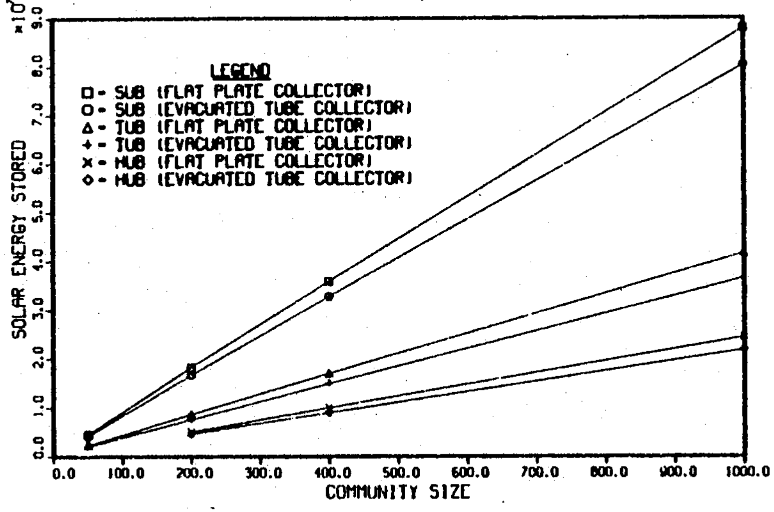
BISMARK



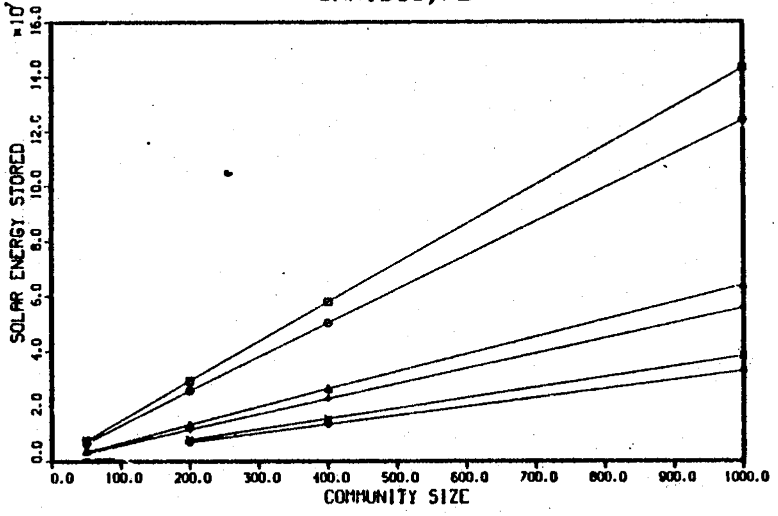
SANTA MARIA


ALBUQUERQUE
ENERGY STORED PER ENERGY COLLECTED
0.66
0.68
0.70
0.72
0.74
0.76
0.78
0.80
0.82
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

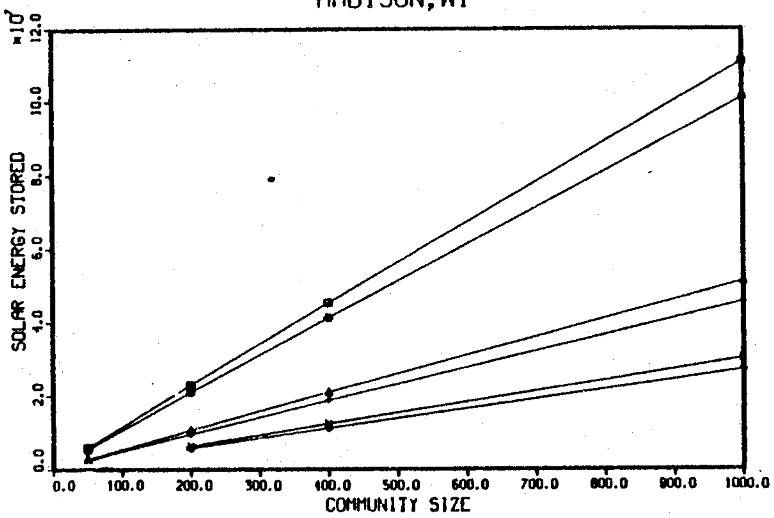

PHOENIX
ENERGY STORED PER ENERGY COLLECTED
0.64
0.66
0.68
0.70
0.72
0.74
0.76
0.78
0.80
0.82
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE



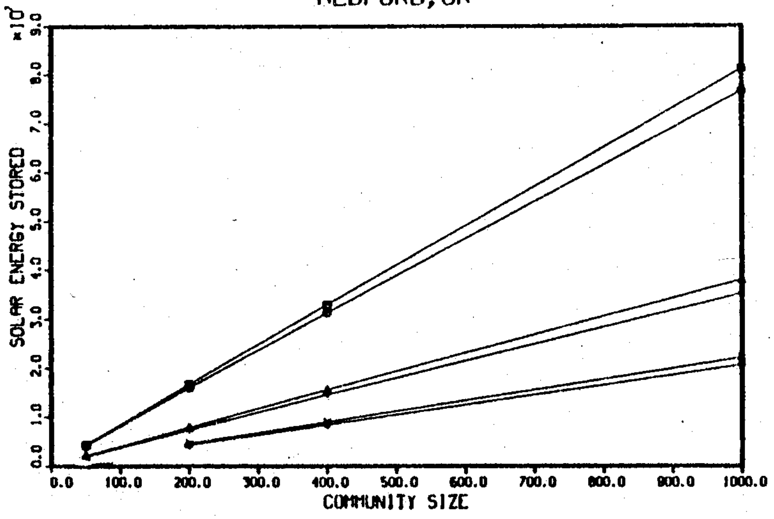
BOSTON, MA



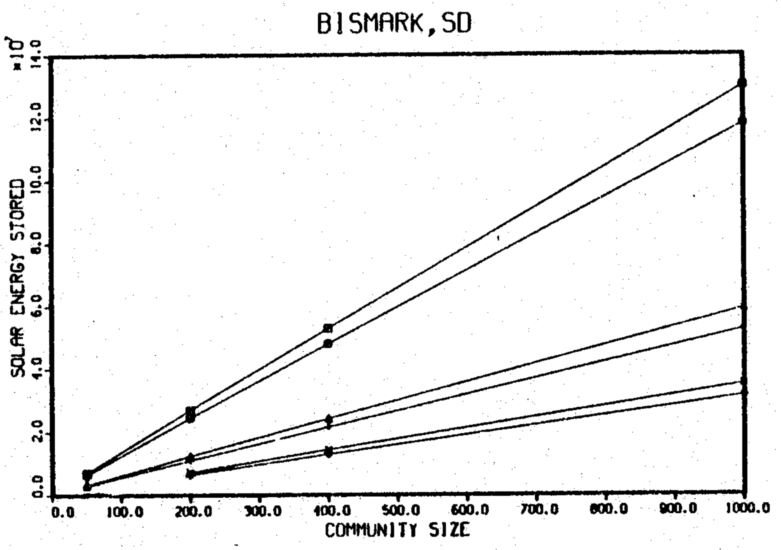
CARIBOU, ME

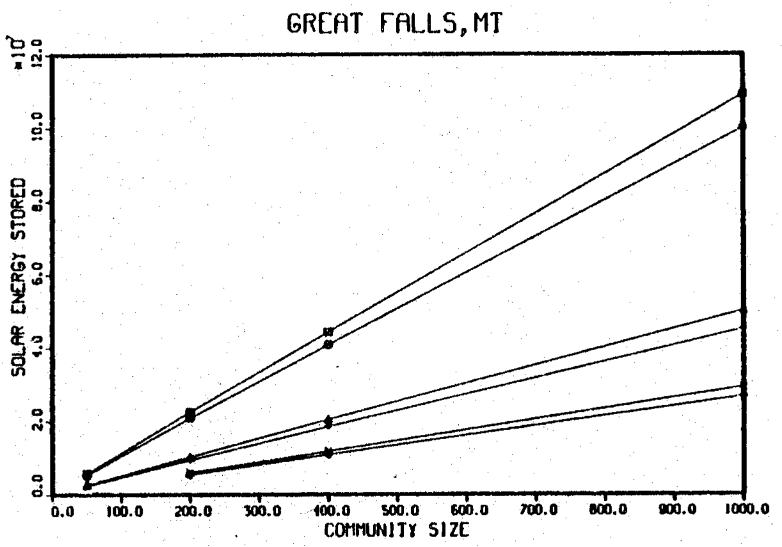


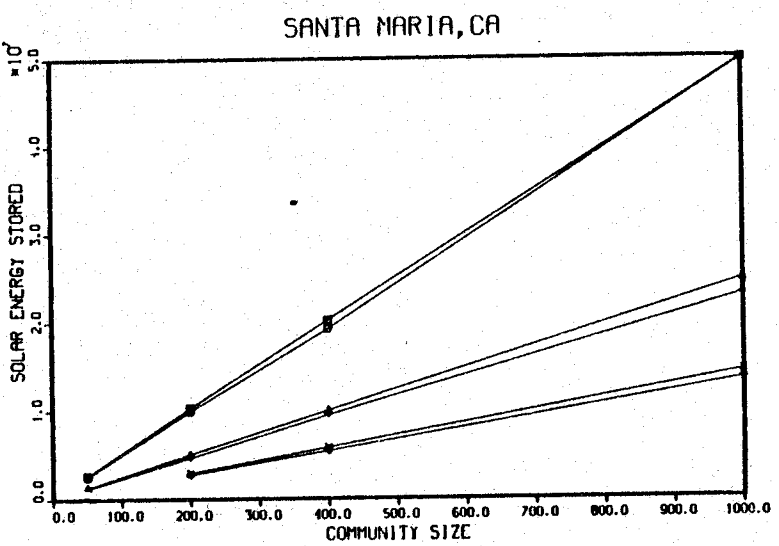
MADISON, WI

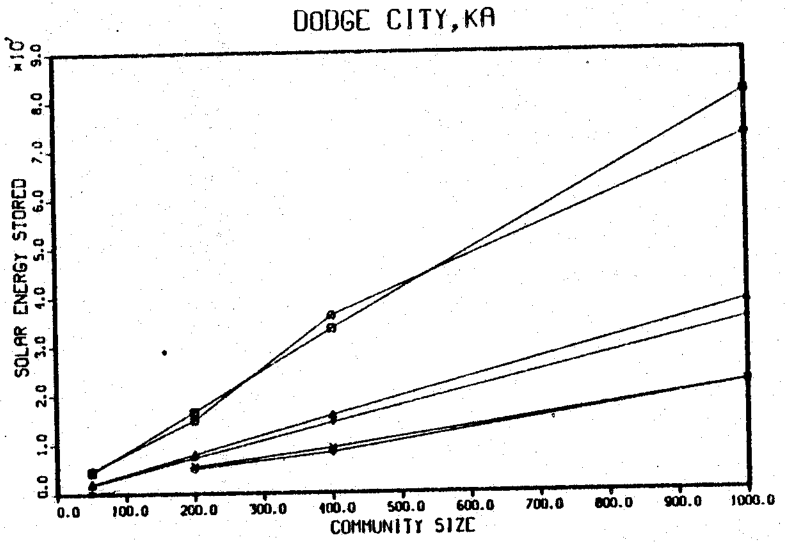


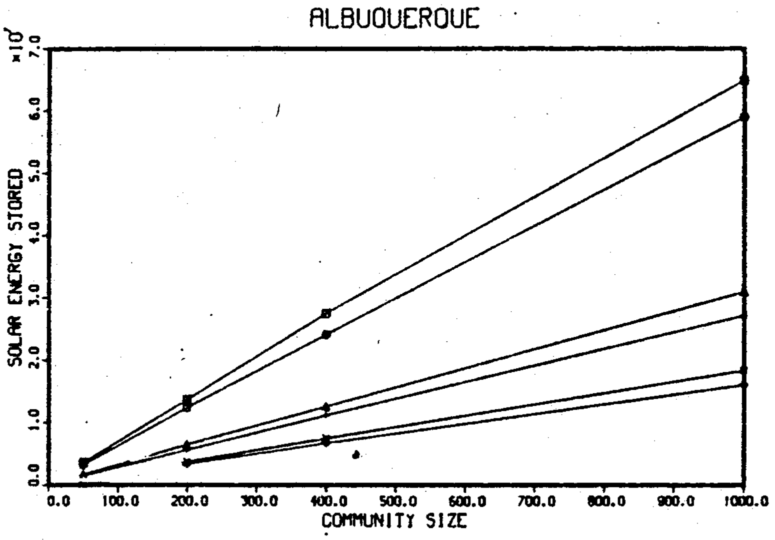
MEDFORD, OR

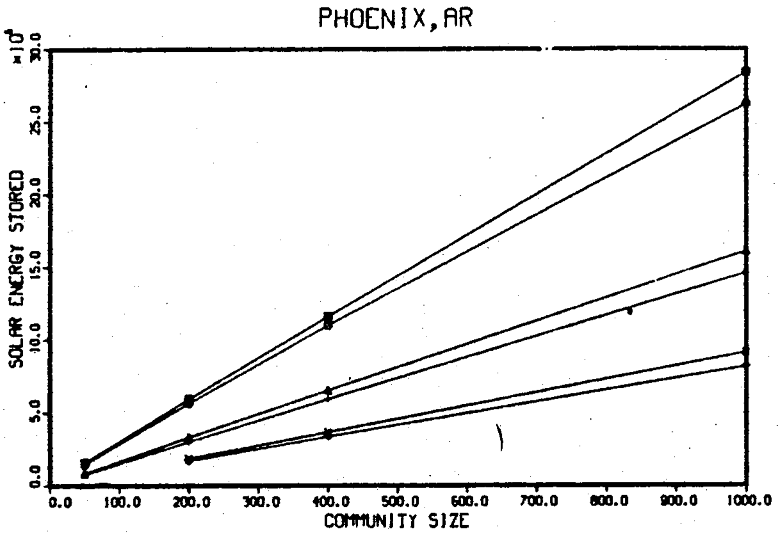

BISMARK, SD
×10⁷
SOLAR ENERGY STORED
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

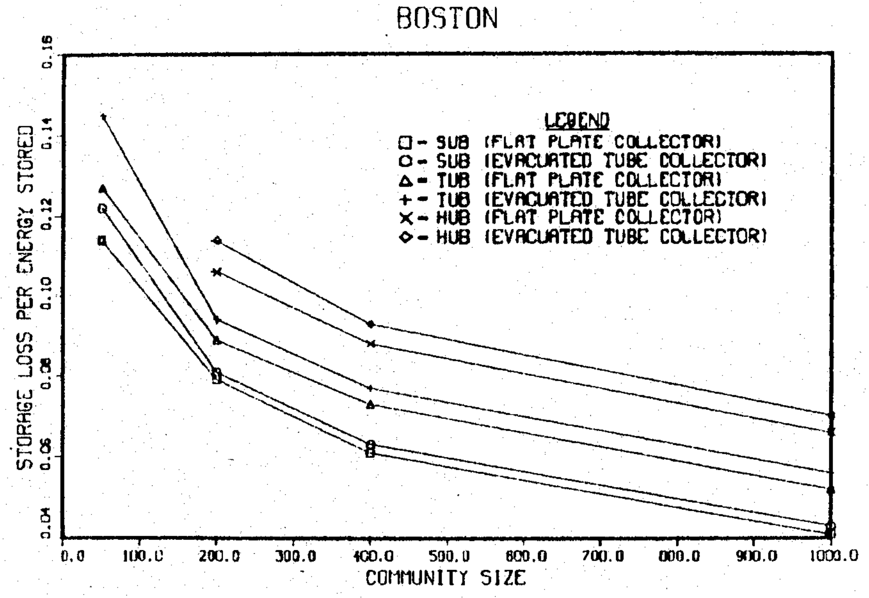

GREAT FALLS, MT
×10⁷
SOLAR ENERGY STORED
0.0
2.0
4.0
6.0
8.0
10.0
12.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0


SANTA MARIA, CA
×10⁷
SOLAR ENERGY STORED
0.0
1.0
2.0
3.0
4.0
5.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

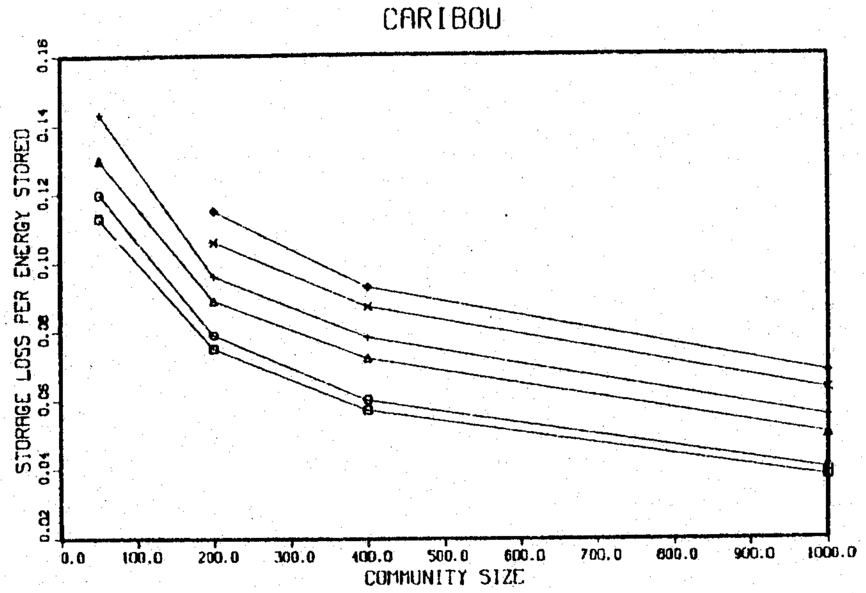

DODGE CITY, KA
×10⁷
SOLAR ENERGY STORED
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0


ALBUQUERQUE
×10
SOLAR ENERGY STORED
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0

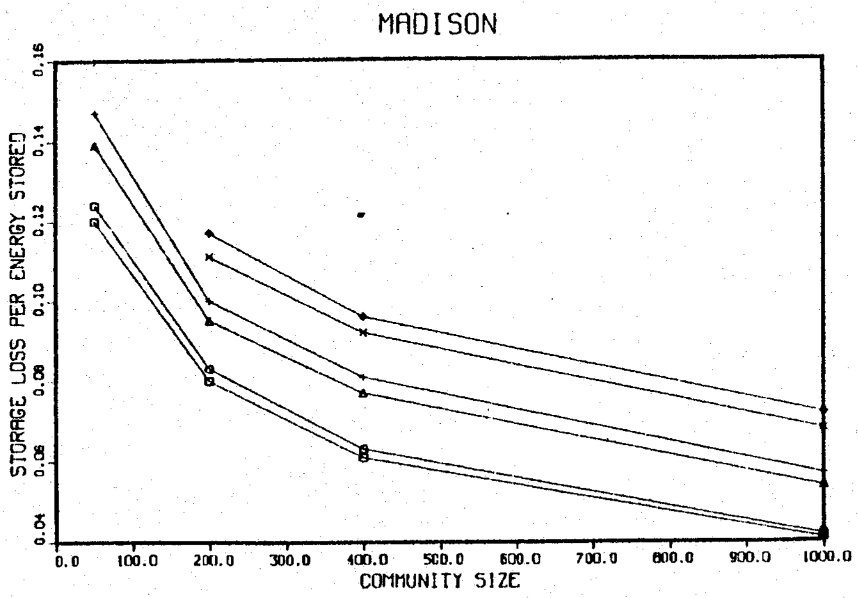

PHOENIX,AR
×10
SOLAR ENERGY STORED
0.0
5.0
10.0
15.0
20.0
25.0
30.0
COMMUNITY SIZE
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0



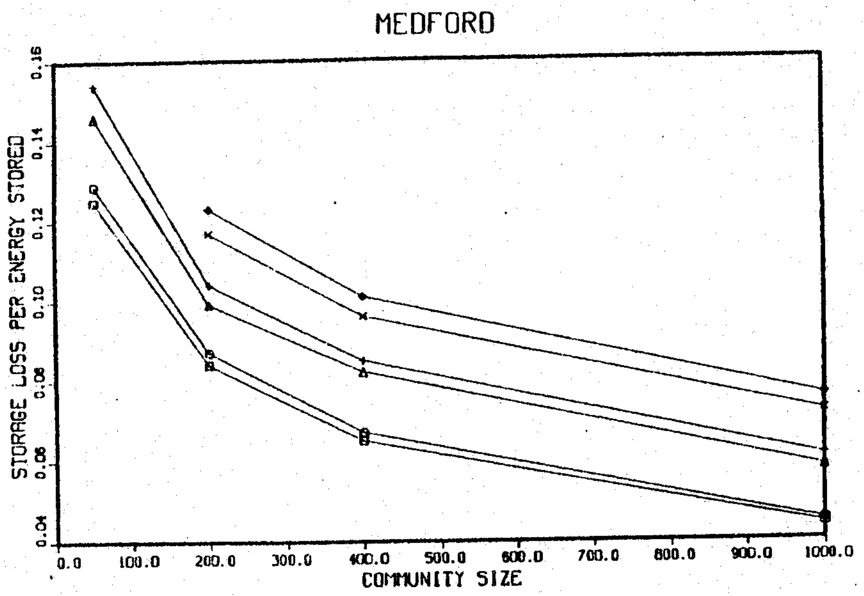
BOSTON



CARIBOU

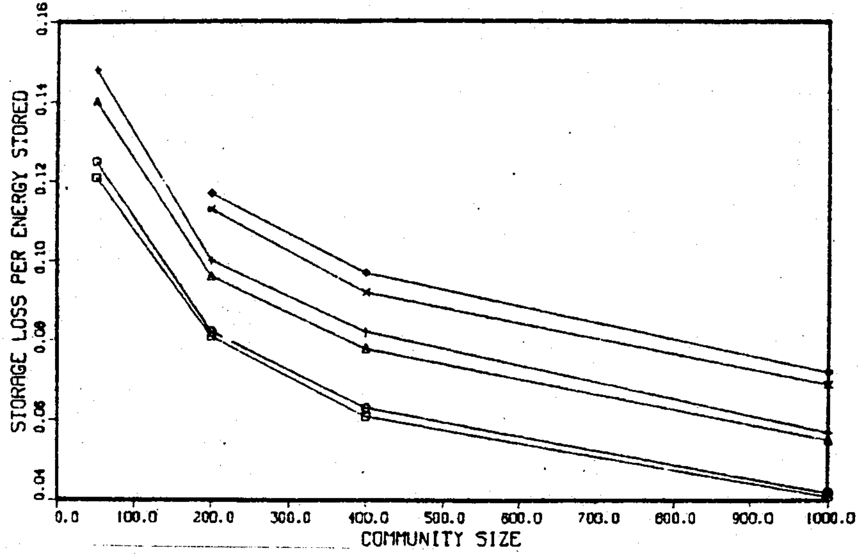


MADISON

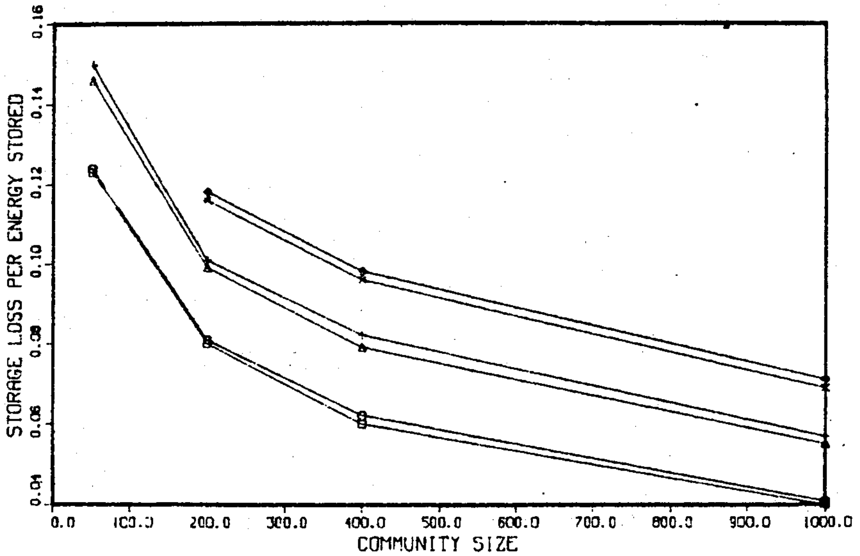


MEDFORD

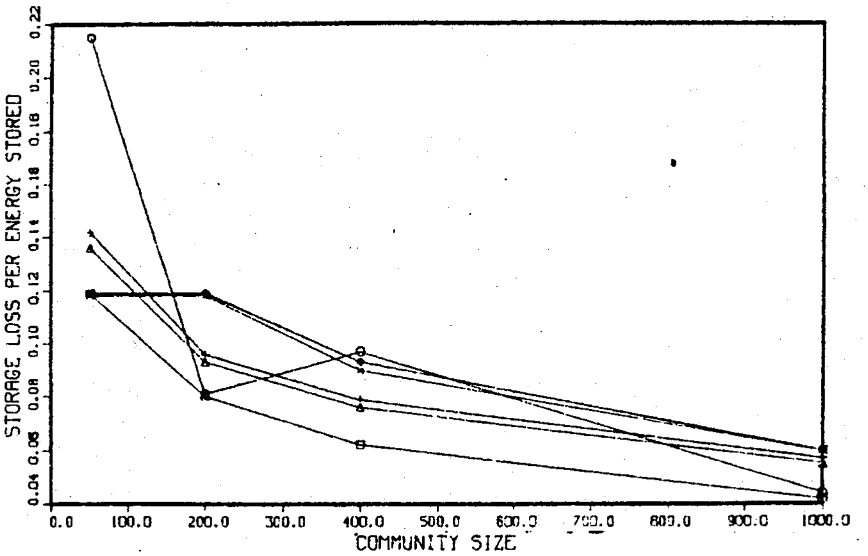
GREAT FALLS

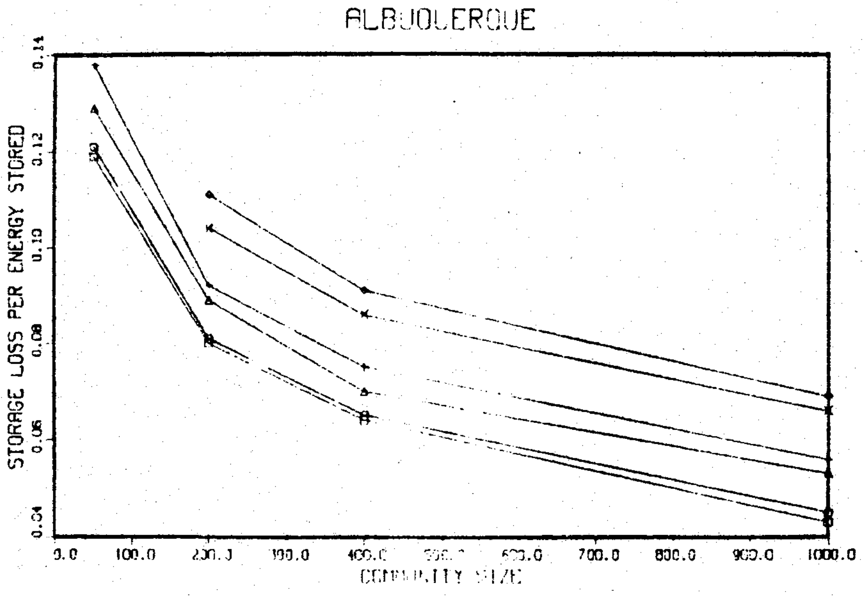


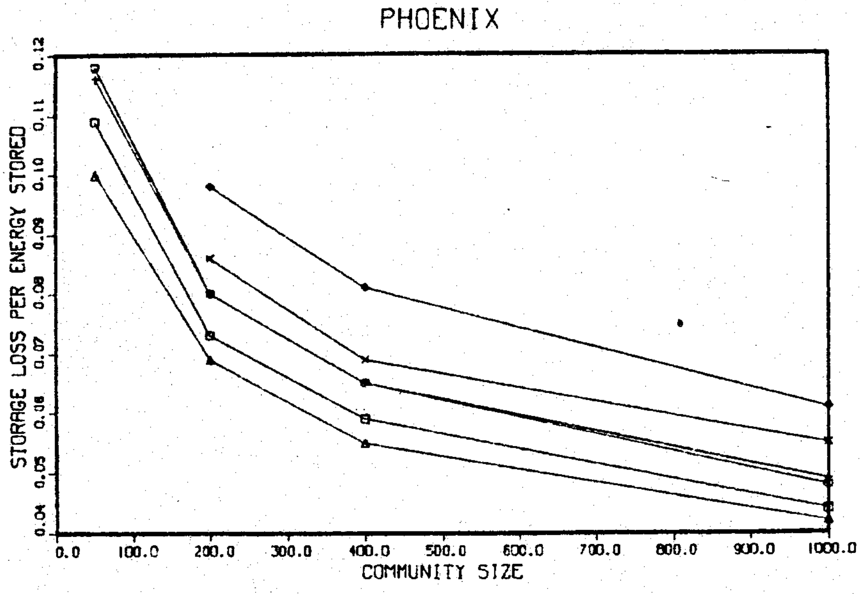
BISMARK



DODGE CITY




ALBUQUERQUE
STORAGE LOSS PER ENERGY STORED
0.04
0.06
0.08
0.10
0.12
0.14
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE


PHOENIX
STORAGE LOSS PER ENERGY STORED
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
COMMUNITY SIZE

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4. Title and Subtitle

Annual-Cycle Thermal Energy Storage for a Community
Solar System: Details of a Sensitivity Analysis

5. Publication Date
July 1980

6.

7. Author(s)
Frank Baylin, Rosemary Monte, Sanford Sillman

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Solar Energy Research Institute
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Golden, Colorado 80401

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(C)

(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report presents results and conclusions of a simulation and sensitivity analysis of community-sized, annual-cycle thermal-energy-storage (ACTES) solar energy systems. The analysis which is based on an hourly simulation is used to (1) size systems in 10 locations, (2) identify critical design parameters, and (3) provide a basic conceptual approach for future studies and designs. This research is a forerunner to an economic analysis of this particular system (based on large constructed tanks) and a general analysis of the value of ACTES technologies for solar applications. A total of 440 systems were sized for 10 locations in the United States. Three different building types and four different community sizes were modeled. All designs used each of two collector types at each of two different tilt angles.

Two linear relationships were derived which simplify system sizing. The average ambient temperature is used to determine average yearly collector efficiency. This parameter combined with estimates of space/DHW loads, storage/distribution losses, and total yearly insolation per square meter allows estimation of collector area. Storage size can be estimated from the winter net load which is based on space and DHW loads, storage and distribution losses, and collector solar heat gain for the winter months.

17. Document Analysis

a. Descriptors: Simulation ; Energy Storage ; Annual Energy Storage ; Design ; Feasibility Studies ; Comparative Evaluation ; Seasonal Variation ; Efficiency ; Energy Efficiency ; Thermal Efficiency ; Load Management ; Solar Energy ;Solar Heating Systems ; Solar Cooling Systems ; Heating ; Air Conditioning ; Heating Systems ; Cooling Systems ; Annual Cycle Energy System ; Mathematical Models ; Statistical Models ; Residential Buildings ; Houses ; Apartment Buildings ; Geographical Variations ; Solar Collectors ; Flat Plate Collectors ; Evacuated Tube Collectors ; Tanks ; Size ; Solar Space Heating ; Hot-Water Systems ; Sensitivity Anal

b. Identifiers/Open-Ended Terms
Identifiers: Annual-Cycle Thermal Energy Storage (ACTES)

c. UC Categories

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