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ANALYSIS OF COMMUNITY SOLAR SYSTEMS FOR COMBINED SPACE AND DOMESTIC HOT WATER HEATING USING ANNUAL CYCLE THERMAL ENERGY STORAGE

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ABSTRACT

A simplified design procedure is examined for estimating the storage capacity and collector area for annual-cycle-storage, community solar heating systems in which 100% of the annual space heating energy demand is provided from the solar source for the typical meteorological year. Hourly computer simulations of the performance of these systems were carried out for 10 cities in the United States for 3 different building types and 4 community sizes. These permitted the use of design values for evaluation of a more simplified system sizing method.

Results of this study show a strong correlation between annual collector efficiency and two major, location-specific, annual weather parameters: the mean air temperature during daylight hours and the total global insolation on the collector surface. Storage capacity correlates well with the net winter load, which is a measure of the seasonal variation in the total load, a correlation which appears to be independent of collector type.

INTRODUCTION

Most designs of solar heating systems utilizing low-temperature storage for space heating and domestic hot water are based on a "short term" storage capacity that can meet loads for no more than a few days during periods of insufficient collectible insolation. The economically optimal ratio of thermal storage capacity to collector area for such designs is typically between 200 and 400 KJ/m^{2}°C (i.e., for water, 1.25 to 2.5 gal/ft^{2}) [1].

Solar heating systems with annually cycled storages having storage capacity-to-collector area ratios typically 50 times greater than comparable "short term" systems have recently gained considerable acceptance as an important design alternative. For certain building types and climates these may offer the least cost per unit energy delivered over the life cycle of the system. The simplified f-Chart design procedure for "short term" systems is not applicable to "long term" systems, which are characterized by a slowly varying annual storage temperature. Thus there is a need for simplified design procedures for determining optimal configurations for such systems.

This paper examines parameters that have been found to be useful for annual storage system design. To provide the necessary data base, hourly simulations of these systems were performed. Three building types and four community sizes for each of ten locations in the United States were examined [2].

For each case, two collectors (a flat plate and an evacuated tube), set at two collector tilts, one equal to latitude and one to latitude plus 10 degrees, were examined.

The weather input data consisted of hourly air temperatures and insolation values taken from the typical meteorological year (TMY) data base for the site [3]. Global radiation incident on the inclined collector surface was calculated using Hay's anisotropic model for the sky diffuse component [4].

The criteria for the final system design for each case were (1) to provide 100% of the annual community space heating load and at least 85% of the annual community domestic hot water load from the solar source, and (2) to ensure a tank temperature cycle that rose close to the maximum permitted (design maximum) temperature of 80° C (176° F) and fell close to the lowest useful (design minimum) temperature of 32° C (90° F) over the year. This provided a stable basis for comparisons between sites and between systems.

DESIGN CONSIDERATIONS

In sizing the collector and storage for a given load, location, and collector type, two factors should be considered:

- the maximum and minimum storage temperatures reached over the annual cycle of the heat storage reservoir, and
- the total amount of uncollectible insolation over a full annual cycle of operation.

To be economically competitive, annual storage solar heating systems designed to provide 100% of a space heating load must maximize the utilization of both the collector and the storage subsystems.

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The collector is underutilized if the storage tank temperature is equal to its maximum design temperature when there is further collectible insolation available. That is, collectible insolation cannot always be delivered either to storage or to load and some must be wasted. The storage is underutilized if the storage temperature never reaches the maximum design storage temperature or never falls to the minimum design temperature over one year of operation.

Ideally, the designer should size the storage and collector so that all collectible insolation is either stored or used directly in meeting a coincident load, and so that the storage temperature reaches both design limits at least once during the year of operation. A system which never reaches the minimum storage temperature has in effect been sized to meet a larger heat load than it is servicing. The performance of a system which exactly achieves the maximum and minimum design storage temperatures, with no uncollectible insolation, is said to be unconstrained; other systems are storage-constrained or collector-constrained.

The approach to system design and to the sizing of subsystems should be consistent with the objective of minimizing the capital investment required to meet a given load. The solar acquisition cost, or initial investment cost, is considered to be a function of the costs of three independent parameters: storage and distribution system, collector field, and storage insulation. That is,

$$C(M_T,A_C,V_I) = K_0M_T + (K_1M_T)^{2/3} + K_2A_C + K_3V_I + K_4 \quad (1)$$

where K_0,K_1,K_2,K_3,K_4 are constants for a given optimization. This cost evaluation follows the example of Hollands and Orgill [5].

For relatively large systems, very high storage efficiencies can be achieved with relatively small investments in storage insulation (see Table 1), while providing 100% of the space heating load from the solar source. Typically, storage insulation costs represent no more than 5% of the total solar acquisition cost. Since our estimates of the total solar cost may be in error by at least this amount, it is reasonable for large systems to lump storage insulation costs into the constant term K_4 of eq. 1.

Table 1. **INSULATION COST AS A PERCENTAGE OF TOTAL COST FOR LARGE ANNUAL STORAGE SYSTEMS**

Site: Boston, Massachusetts
Weather Data: Typical Meteorological year (TMY)
Loads: 0.2 - 9.0 MJ x 10^7

Case	Total Cost ($\$x10^{-6}$)	Insulation Cost (%)	Storage Efficiency
1	0.71	3.8	92.2
2	1.43	3.4	94.0
3	1.97	2.7	95.6
4	2.47	2.9	95.9
5	3.81	2.4	96.9
6	4.84	2.7	97.1
7	5.19	2.8	97.0
8	9.11	2.2	98.0
9	11.52	2.5	98.2
10	23.76	2.6	98.7

Hooper and Cook [6] have shown that the solar acquisition cost for annual storage solar space heating systems is effectively minimized when collector and storage subsystems are sized to achieve unconstrained performance; that is, unconstrained sizing corresponds closely to cost-optimal sizing. Storages and collector arrays are thus sized approximately optimally over a considerable range of collector and storage cost assumptions. Furthermore, it was concluded that annually cycled solar systems appear to be most economic in providing large fractions of large space heating loads.

These results suggest that we should seek design methodologies that would allow sizing of large annual storage solar heating systems meeting 100% of the average annual space heating requirements with unconstrained operation. This requires a knowledge of the design and site-specific factors for unconstrained sizing derived from previous computer simulation experiments. The initial storage sizing requires specification of the total annual load and of the mean and limit storage temperatures. The initial collector sizing requires a knowledge of the total annual heating load to be met, the total annual storage heat loss, the overall annual collector efficiency, and the total annual insolation falling on the tilted plane of the collector. Further refinements and generalizations of this design method should follow when more detailed statistical analysis of the results of these simulation experiments become available.

INITIAL SIZING

Storage

For annual storage solar heating systems providing 100% of the space heating load and none of the domestic hot water (DHW) load and operations in northerly locations, it has been observed from previous simulations that the optimal storage mass is approximately related to the total load by the ratio:

$$K \equiv \frac{M_T C_p (T_T - T_{TMIN})}{\text{Annual Heating Load}} \cong 0.3 \quad (2)$$

where M_T = mass of storage media,

C_p = specific heat of the storage media,

T_T = mean annual storage temperature, and

T_{TMIN} = minimum design storage temperature.

However, the optimal storage sizing is also sensitive to other parameters that are functions of site specific conditions and design requirements. For example, storage sizing should also depend on the distribution of the total load over a year of operation and on the extent to which collectible insolation can meet immediate heating requirements.

Collector

The collector area required is given explicitly by

$$A = Q_T / (I_T \cdot CE) \tag{3}$$

where Q_T = total load to be met by solar including storage loss,

I_T = total insolation per unit collector surface for one year, and

CE = annual collector efficiency.

Thus, an accurate estimate of the collector requirements depends on a determination of the annual collector efficiency. This depends, among other factors, on the climate and the collector characteristics. Initial simulations were required to determine this parameter.

COMPUTER SIMULATION

Operation

The simulation uses an hourly time step beginning on April 1 for a one-year period. The space heating season for all cases was defined as the period from September 15 to May 15. Outside of this period, the space heating load is assumed to be zero.

For each time step, the program operates in the following stepwise manner. The storage heat loss is calculated first, using the tank temperature at the start of the hour. The resultant new tank temperature is then used in calculating the collector heat gain for the hour. Based on this new temperature, the domestic hot water load supplied by solar energy is determined. The space heating load supplied by solar energy is then calculated and the corresponding tank temperature is checked to ensure that it is less than or equal to the maximum design temperature. Any excess energy is rejected before the beginning of the next hour.

Weather Input

Inputs to the simulation include hourly values for air temperature and for total insolation on the inclined collector surface. The parameters necessary to provide the input data are air temperature, total irradiance on a horizontal surface, normal incidence direct irradiance, and a daily snow indicator for determining albedo. These are taken from the typical meteorological year (TMY) weather data base [3]. Hay's anisotropic model [4] was used to calculate the diffuse component of the total insolation on the tilted surface.

Heating Loads

The computer simulation does not treat the space heating and domestic hot water systems as separate. The cold water supply to the domestic hot water system is preheated with heat drawn from the thermal storage tank by means of a heat exchanger, assuming a fixed temperature drop. Supply water temperature to the DHW system varies between locations, usually depending upon the local average temperature of shallow groundwater. The DHW delivery temperature is fixed for all cases at 49°C (120°F). The DHW load, expressed in gallons per day per building unit, is a constant which, of course, differs for building types. The hourly DHW load varies throughout the day in a fixed manner.

A constant heat load factor is used to determine the hourly space heat demand during the heating season. The design (effective) thermostat setting depends on the assumed internal heat generation for each building type.

Collectors

Slope-intercept data chosen for a typical flat plate and for an evacuated tube collector were used for efficiency calculations. The slope and intercept values used for the flat-plat collector were 6.104 $W/m^2 {}^\circ C$ and 0.711, respectively; for the evacuated tube they were 1.170 and 0.447. These efficiencies were reduced by a constant factor to account for collector performance deterioration due to dirt accumulation, selective surface aging, and other factors. The collector inlet temperature was assumed to be 1.1°C less than the mean tank temperature to allow for temperature stratification in the tank. For the case when the collector was out of operation in the previous hour, the control strategy was that the collector would be brought into operation for the following hour if the collector characteristic curve showed an efficiency greater than zero at an inlet temperature taken as 7.1°C above the mean tank temperature. When the collector was already in operation, it would be withdrawn from operation over the next hour if the curve indicated an efficiency less than zero at an inlet temperature taken as 4.1°C above the mean tank temperature.

Storage

The storage tank is assumed to be well mixed and unstratified. A below-ground storage tank with top flush with the surface of the ground was assumed. The shape of the tank was taken as cylindrical, with vertical axis and with radius equal to depth. The insulation along the tank wall and floor is specified for all tank sizes to have a maximum 22-cm (R50) thickness of polyurethane insulation and is so distributed that the heat loss is equal for all points on the tank surface. The lid insulation thickness is specified as 33 cm (R60) of fiberglass.

An effective thermal resistance for each of the tank sizes was calculated based on a more detailed finite-difference transient soil heat transfer model. The model assumes a horizontal isothermal boundary in the soil at a depth 10% greater than that of the tank floor and a vertical isothermal boundary in the soil at a distance from the tank wall equal to 1.1 times the tank radius. The Equivalent Thermal Resistance (ETR) values used in the tank heat loss calculations for this study are shown in Fig. 1 as a function of tank radius.

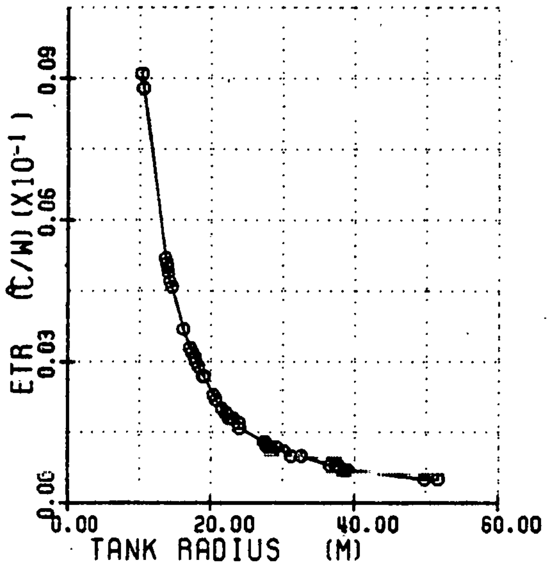

Fig. 1. The Equivalent Thermal Resistance (ETR) to Heat Flow from the Thermal Storage as a Function of the Tank Size for Tanks with Depth Equal to Radius. Soil Conductivity Taken as 1.73 W/m^2°C.

The maximum temperature that the storage water is permitted to attain at the end of any hour is 79.4°C (175°F). When the storage temperature exceeds this maximum, solar energy must either be used to service the heat load or be dumped.

SIMULATION RESULTS

The design objective requires that collector and storage be sized to permit unconstrained system performance. In this way all the cases simulated were operationally equivalent, at least to the extent that unconstrained sizing is achieved. Within the time limitations on the project it was not possible to meet this objective precisely, resulting in some systems having to reject small amounts of collectible insolation and in some systems not being able to utilize fully their storage capacities. This variation from the objective was kept to a minimum so that a valid general correlation could be determined for future system design purposes. Differences in sizings from location to location may be largely attributable to differences in site-specific, weather-related parameters and to design requirements, such as collector characteristics, rather than to inconsistencies in overall system operations.

Figure 2 shows the variation in K (initial storage sizing criteria defined in eq. 2) with the percentage DHW

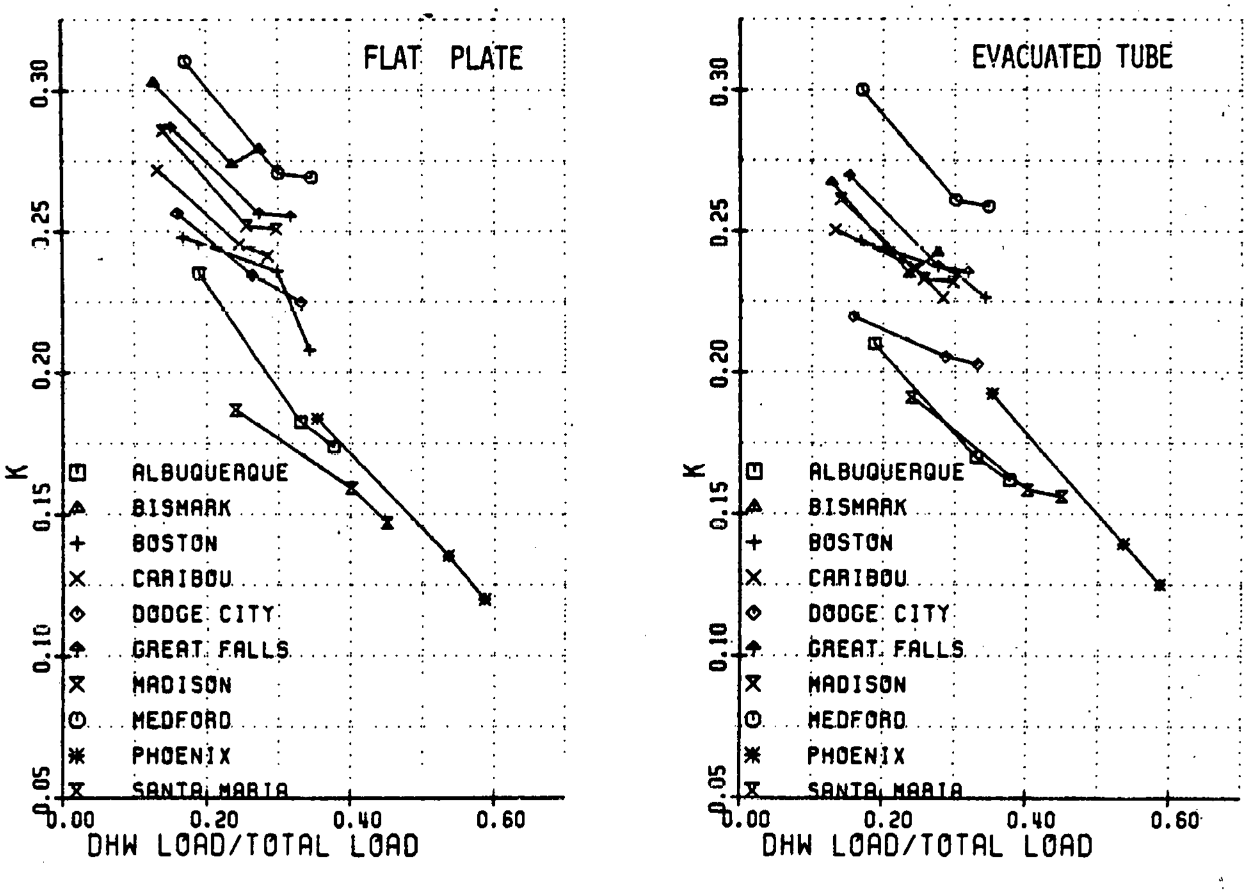

Fig. 2. Initial Storage Sizing Criteria vs. % DHW Load

load for the different locations. Although the general trend at any location shows a decreased need for storage as the domestic hot water load fraction increases, this in itself is not sufficient for design purposes. Similar results were presented by Baylin et al. [2] where storage volume was expressed as a function of total winter load. The difference in K values between locations shows the need for relating storage size to some other factor able to account for the variation in load and insolation throughout the year.

Results presented by Baylin et al. [2] show a good correlation between storage size and net winter load, net winter load being the integrated monthly difference between the heat load and collector gain for the winter period defined as the months of November, December, January, and February. Figures 3 and 4 show this relationship, identifying three points for each location. The points for each location represent the three different building types, always sequenced from left to right as the 200-unit apartment building, the 10-unit condominium, and the single-family residence. The storage to net winter load ratio appears to be generally independent of location and collector characteristics.

The annual collector efficiency required for sizing collector area is shown in Figs. 5 and 6 as nearly linear relationships with the site-specific weather parameters of average annual daylight air temperature (TA) and total annual incident insolation per unit collector area (I). Annual collector efficiencies are found to be essentially constant for a particular location regardless of the building type or system size. However, the relationship between the efficiency, the air temperature, and the insolation is some function of the specific collector characteristics, and different correlations would apply for collectors with characteristics substantially different from those of the chosen collectors.

CONCLUSIONS

A general correlation has been shown between the annual collector efficiency, a simple function of the annual incident insolation on the collectors, and the average ambient air temperature during the daylight hours. This has been done for only two solar collector characteristic performances, but a simple extension of the work to include the range of slopes and intercepts usually encountered in commercial collectors will yield an empirical correlation which should be of direct use in the preliminary or approximate design of large annual storage systems operating in the unconstrained (optimal) manner.

A useful general correlation has also been shown between the storage size and the net winter heat load that appears to be independent of the collector characteristics assumed for the classes of systems studied.

Examination of the performance curves shows the effect of the local climate upon annual storage system performance. As would be expected, the annual average collector efficiencies are lower in colder and cloudier regions, although the sensitivity to these factors is dependent upon the collector selected.

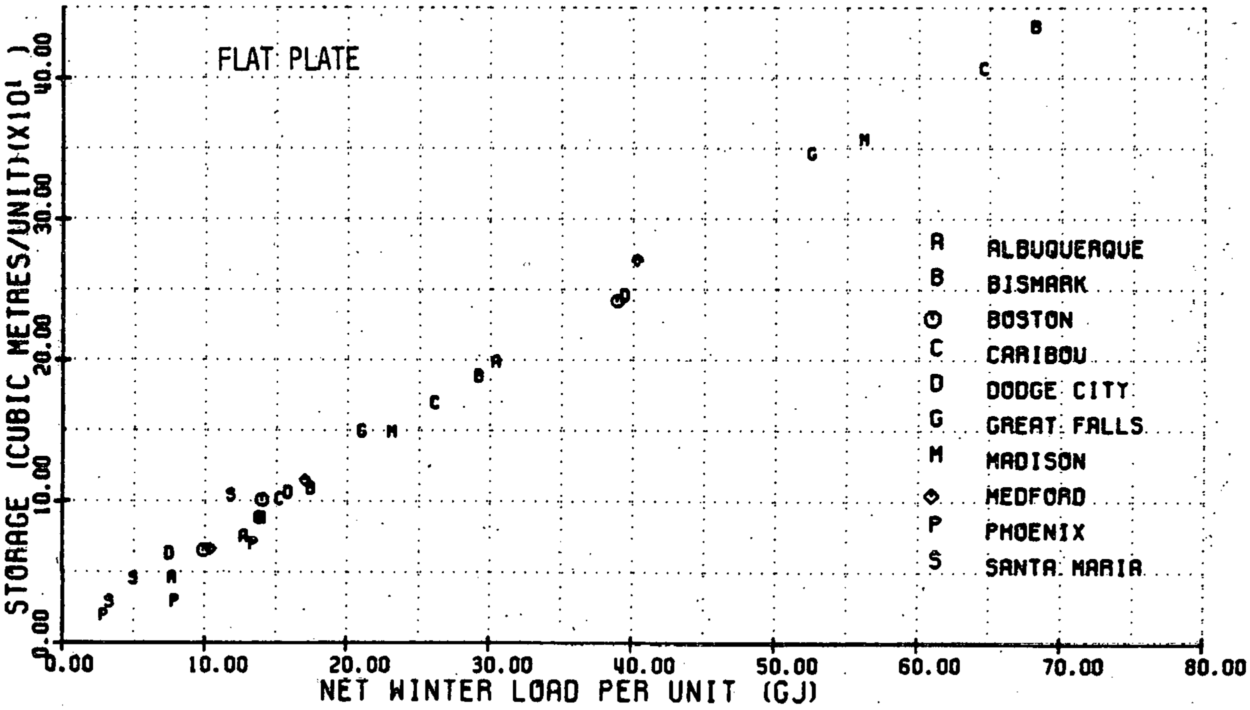

Fig. 3. Storage Size vs. Net Winter Load Correlation for Systems With Flat-Plate Collectors

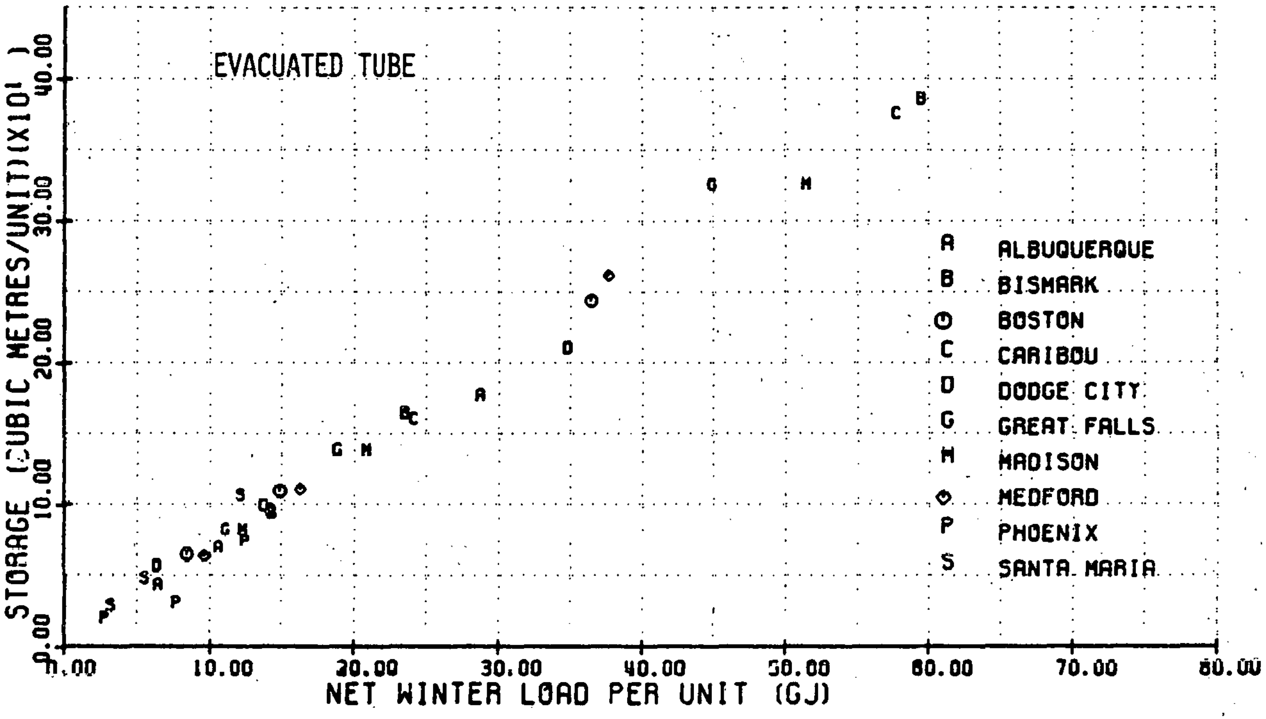

Fig. 4. Storage Size vs. Net Winter Load Correlation for Systems With Evacuated-Tube Collectors.

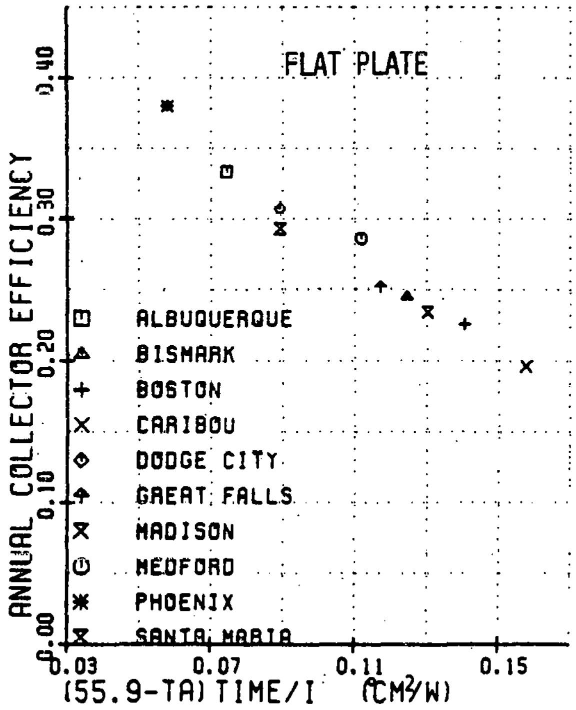

Fig. 6. The Annual Average Collector Efficiency as a Function of the Annual Incident Insolation and the Average Ambient Air Temperature During Daylight Hours for Evacuated-Tube Collectors.

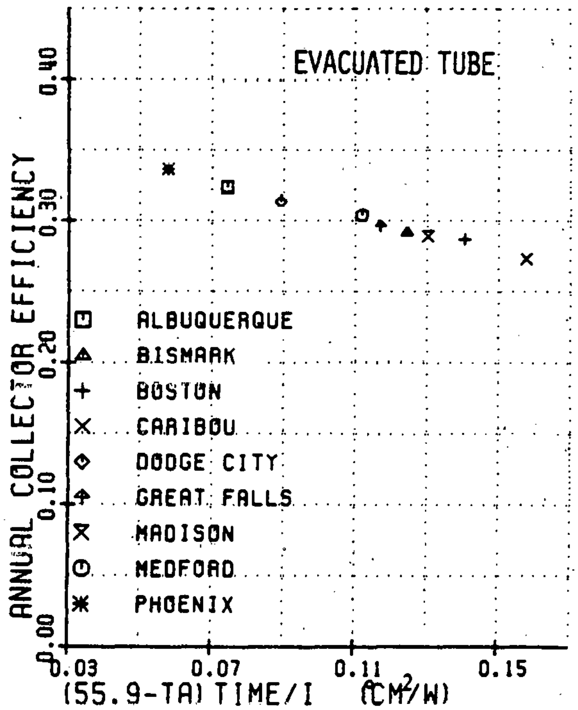

Fig. 5. The Annual Average Collector Efficiency as a Function of the Annual Incident Insolation and the Average Ambient Air Temperature During Daylight Hours for Flat-Plate Collectors.

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