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ECONOMIC ANALYSIS OF COMMUNITY SOLAR HEATING SYSTEMS THAT USE ANNUAL CYCLE THERMAL ENERGY STORAGE

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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 with applications in solar energy systems. Storage subsystems are considered critical to many solar energy applications.

This research examines the economics of applications of annual cycle thermal energy storage (ACTES) to solar space heating and domestic hot water systems. This effort is based on an earlier sensitivity analysis of such systems [1] and is a forerunner of two more thorough studies: an analysis of trade-offs between storage volume and collector field area; and a general study of the value of ACTES solar 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 their appreciation to numerous associates who contributed both information and critical reviews of this document, particularly Michael Davis, Michael Holtz, and Charles Wyman of SERI.

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SUMMARY

The economics of community-scale solar systems that incorporate a centralized annual cycle thermal energy storage (ACTES) coupled to a distribution system are examined in this document. Systems were sized for three housing configurations: single-unit dwellings, 10-unit, and 200-unit apartment complexes in 50-, 200-, 400-, and 1000-unit communities in 10 geographic locations in the United States. Thermal energy is stored in large, constructed, underground tanks. Costs were assigned to each component of every system to allow calculation of total costs. Results are presented as normalized system costs per unit of heat delivered per building unit.

These methods allow (1) identification of the relative importance of each system component in the overall cost, and (2) identification of the key variables that determine the optimum sizing of a district solar heating system. In more northerly locations, collectors are a larger component of cost. In southern locations, distribution networks are a larger proportion of total cost. Larger, more compact buildings are, in general, less expensive to heat. For the two smaller-scale building configurations, a broad minima in total costs compared with system size is often observed.

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SECTION 1.0

INTRODUCTION

Community-scale solar energy systems that incorporate a centralized annual cycle thermal energy storage (ACTES) coupled to a distribution system may offer an attractive alternative to more conventional forms of heating or to solar systems based on diurnal storage. The economics on which such a decision should be based depend on component costs, system design, building densities, and climate, etc. We have attempted in this report to analyze the feasibility of this option by designing and sizing ACTES solar systems and by estimating system costs. Conclusions reached are necessarily limited by the sensitivity of the problem to basic assumptions about capital costs, interest rates, fuel costs, inflation rates, and details of system design.

The economic analysis is based on a sensitivity analysis of a community-scale ACTES solar system [1,2,3,4]. In this analysis, three housing configurations—single-unit dwellings (SUB), 10-unit condominiums (TUB), and 200-unit apartment complexes (HUB) in 50-, 200-, 400-, and 1000-unit sizes—were modeled in 10 geographic locations in the United States on the basis of previously developed methods [1]. Two collector types were used for each configuration: flat plate and evacuated tube—oriented at tilt angles equal to latitude or equal to latitude plus ten degrees. Collector field areas and required storage volumes were obtained for all 44 configurations at each of the 10 locations, and general sizing algorithms were derived.

We subsequently have designed distribution systems for each of the SUB, TUB, and HUB configurations and have determined costs for 220 systems that have collectors oriented at tilt equal to latitude. This analysis has allowed us to identify the critical cost components of such systems, determine both economies and diseconomies of scale, and draw some preliminary conclusions about the economic feasibility of such systems.

A number of technical options for seasonal storage of thermal energy are available, including large tanks constructed above or below grade, aquifers, and solar ponds. This study considers only large constructed tanks although the results derived can be generalized to include other storage options.

Design of large community thermal utilities is complex. The general features of such thermal distribution systems are examined in Sec. 2.0. The decision to examine three specific designs for each community size is discussed. Trade-offs in system design are presented in Sec. 3.0. Details of cost assumptions are provided in Sec. 4.0. An economic analysis is outlined in Sec. 5.0. All costs are expressed in normalized form for two reasons. First, this allows more direct cross-comparisons. Second, these costs are variable with site and time, and the risk of actual dollar values being misinterpreted is too great. Conclusions are presented in Sec. 6.0.

SERI

SECTION 2.0

GENERAL ASPECTS OF THERMAL DISTRIBUTION SYSTEMS

Most conventional residential district heating systems in current use in the United States supply steam to the heating load at above 100 psi (690 mpa) or hot water above 100° C. Annual storage solar heating systems using flat-plate collectors that appear most economical are low-temperature systems in which the stored water reaches a maximum temperature well below 100° C. Operation at these lower temperatures results in higher collector efficiencies and permits the use of less expensive materials such as plastic pipes and foamed insulation. However, it requires larger fluid flows and, consequently, larger pipes and pumps and larger heat transfer surface areas in the heating units. The economic optimum trade-off dictates operational temperatures of about 35° C minimum and 80° C maximum in most locations.

There are many ways of arranging thermal storage for district heating. For instance, each building can have its own storage tank, or all may share a single tank, or some combination of these can be used. For the purpose of this study, each community design (i.e., 50 single-family residences, SUB 50) shares a single, buried, hot water storage tank.

Special requirements are imposed on a system that combines distributed heat sources and heat loads with a central storage. Figure 4-1 shows the essential elements for the control and operation of such a system.

Basically, there is a two-pipe distribution and collector system in which one main carries water at a temperature ΔT_c higher than in the other parallel main. Generally ΔT_c would be on the order of 10° to 25° C. During normal operation, a corresponding temperature difference will occur in the thermal storage tank, maintained by the density stratification effect. The absolute temperature level of stored water will vary over the year, from a maximum of about 75° C in October to a minimum of about 40° C in March.

Each building served by the system will normally have both a solar collector bank, on the roof or elsewhere, and a heating system that uses locally thermostatically controlled fan-coil units or similar warm water heaters. A control valve on the return water from the heating units will hold the discharge temperature ΔT_c below the warm main temperature. Room temperature control will be achieved by control of the air flow through the heater coils. The flow through the collectors is initiated whenever the collector outlet temperature exceeds the warm main temperature by some predetermined amount ΔT_e of about 5° C. The temperature difference ΔT_c is subsequently maintained by a thermostatically controlled valve. The collector pump remains in service until ΔT_e goes negative as the insolation available falls below the threshold value corresponding to the outlet temperature $T_1 + \Delta T_c$.

Flow in the mains can be in either direction. In sunny summer weather, flow would be from the cold main to the warm main, as heat would accumulate in the storage. On a winter evening, flow would be in the other direction. During intermediate days in the year, some houses could, at a given time, have a net heat demand while others provide a net heat supply.

The pumping arrangements to maintain the necessary flows can be made in several ways. Figure 4-1 presents one alternative. The type of arrangement to be selected depends entirely on the building loads and building heat sources.

In practice, because of thermal capacitance in the piping, and practical control function considerations, the actual controls and pumping arrangements would be somewhat more complex. The arrangements for draindown of the collectors to prevent freezing, for instance, are not shown nor are the domestic hot water subsystems. These extra devices could add to the total system cost, although we expect our conservative assumptions will compensate for these extra costs.

SECTION 3.0

TRADE-OFFS IN SYSTEM DESIGN

Three different community types were examined in this study. Single-family residences, 10-unit condominiums, and 200-unit apartment buildings were chosen to represent the range of heating load characteristics encountered in community systems. Ten different locations in the United States were studied to reflect a wide variety of climates. Community sizes ranged from 10 to 1000 living units. Each system was designed to provide 100% of the space heating load and approximately 85% of the service hot water load from the solar source in a typical meteorological year.

The complete analysis of the economic trade-offs is quite complex. However, the sensitivity of system performance is readily expressed by three principal system variables—storage capacity, collector area, and insulation thickness. Especially in the larger-sized thermal storages, very high storage efficiencies are possible with very modest capital outlays for thermal insulation. For such systems, the total solar acquisition cost is relatively insensitive to marginal changes in the insulation thickness, and the major design choice is of the particular combination of collector area and storage volume.

Using an hourly simulation, it was possible to define the range of technically satisfactory collector area and thermal storage capacity sets that would meet the design load requirements. Figure 3-1 shows a typical example of such a set for a community of 200 single family residences in Madison. The plot points represent combinations of collector area and storage capacity that provide 100% of the space heating load in a typical year and that fully utilize the heat stored during the summer season.

For collectors with defined orientation and characteristics, an infinite number of combinations of collector area and storage size can satisfy the design criteria. The optimum configuration will be the combination at which the marginal costs of adding storage are equal to the marginal savings owing to reduction in collector area for a given performance. Previous analysis [1] has shown that systems in which the storage temperature cycles annually, normally reaching the design maximum of about 80° C and the minimum of about 35° C only once per year, inherently offer the best economics for northern locations [3]. The collector use factor is then unity, and the available capacity of the storage is fully utilized in the typical year. This type of system is said to be operating unconstrainedly [5]. For this study, all systems were designed for this mode of operation. Figure 3-1 shows the location of this unconstrained design point for the Madison community.

In warm climates where the service hot water load is a large percentage of the total load, the optimum point may favor a lower storage volume relative to collector area than that for unconstrained operation because higher temperatures are required for this domestic hot water load. The smaller the ratio of storage capacity to collector area for a given performance, the higher the mean annual storage temperature and, consequently, the higher the solar fraction of the heat delivered to domestic hot water (DHW). For the points on Fig. 3-1, the solar fraction for DHW ranged from 84.5% to 97.6% at storage capacities of 122.5×10^6 kg to 7.5×10^6 kg, respectively. Thus, for a given space heating performance, a reduction in collector area and cost must be great enough to offset not only the consequently increased cost of storage but also the increased cost of auxiliary DHW heating energy.

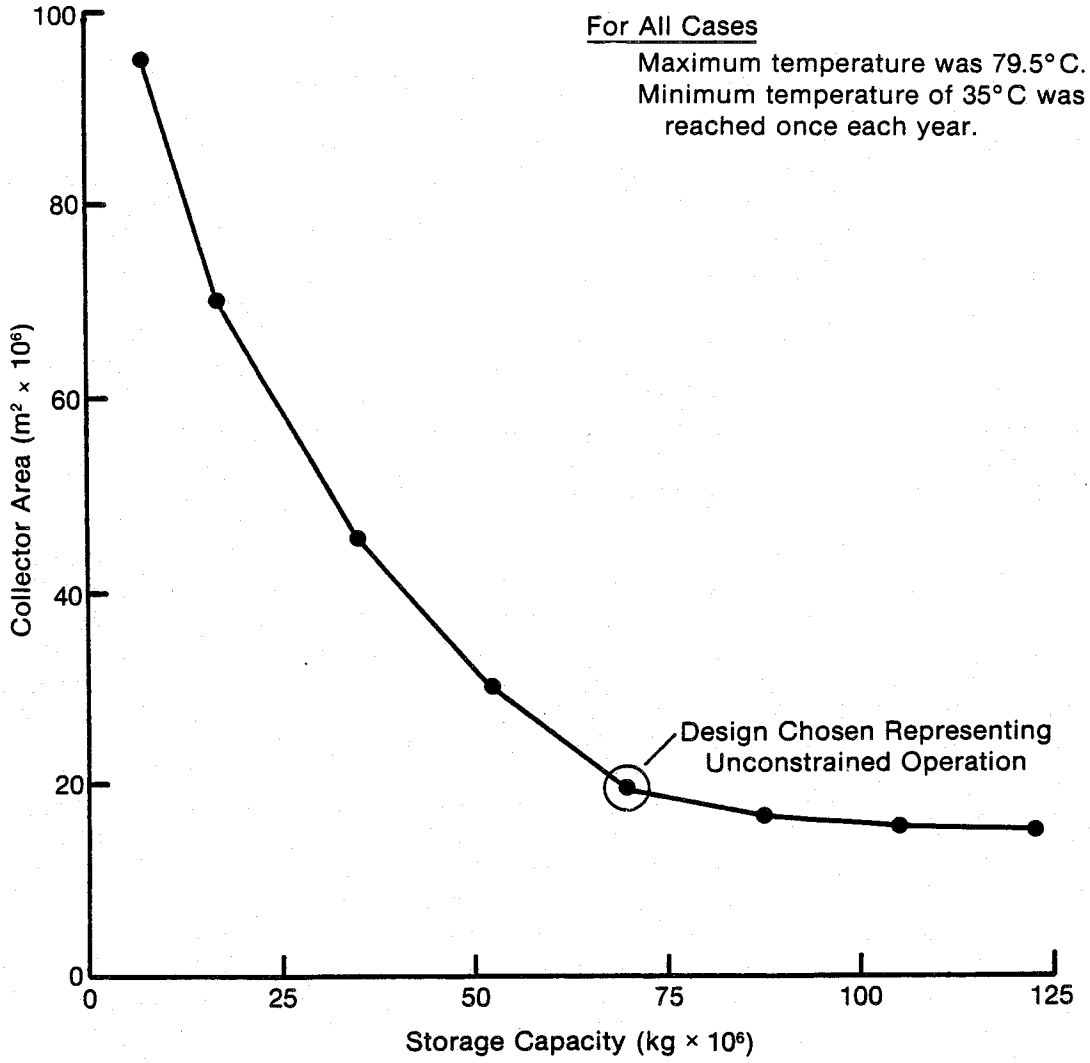

Figure 3-1. Designs for 100% Solar Space Heating for a Community of 200 Single-Family Residences in Madison.

In addition to these major variables, a considerable number of other factors must be considered and design choices made. To retain a comparable basis among the different installations, similar design concepts were compared. Certain minor design features might otherwise have been selected differently. For instance, in southern areas in which no freezing problem is encountered, the cost of freeze protection measures can be avoided.

The selection of a particular flat-plate solar collector to serve all applications is another arbitrary choice. In the colder climates, more of the operating hours are experienced when the collectors are functioning in a higher range of values of $\Delta T/I$ (I is the instantaneous insolation) than they do for more southern locations. Generally for the northern zones the economic optimum choice would favor a collector of higher performance but greater expense. This trade-off between the first cost and the annual value of the collected energy is typical of the necessary design decisions (see in Fig. 3-2). If collector A is twice as costly on an installed unit area basis than collector B, its performance at the warm site being only about 10% better than that of collector B would not justify its selection, while at the cold site it would double the collected energy per unit area as compared to B and be well justified.

All the classic trade-off decisions in the distribution systems are involved also, such as pipe size compared with pump capital and operating power costs. The case for pipe insulation thickness versus total annual costs is shown in Fig. 3-3. Here again, there would be small variations from site to site in the optimum thickness. These variations were suppressed to have systems fully comparable in other respects.

Other factors that influence the final design choice include site-to-site variations in the cost and availability of electric power and of auxiliary fossil fuel, in labor efficiency and cost, in building materials costs, in soil conditions, in land costs, in the ratio of direct to diffuse radiation, and in wind velocities. Design decisions, optimal for all the sites examined, are not possible to make. The degree to which this affects the conclusions reached is unknown but probably is not so great as to invalidate the basic site-to-site trends that constituted the objective of the study.

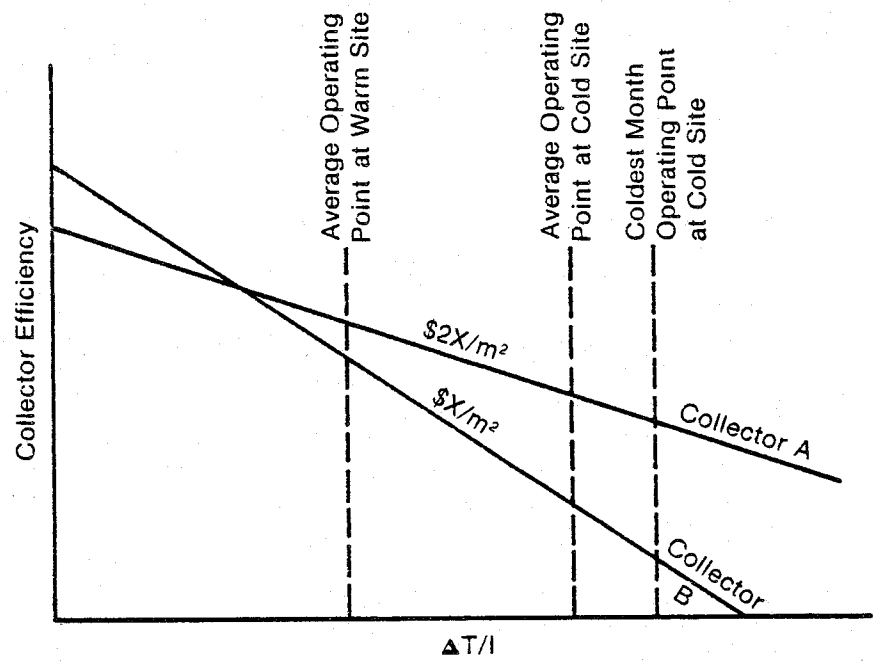

Figure 3-2. Collector Field Area vs. Storage Volume.

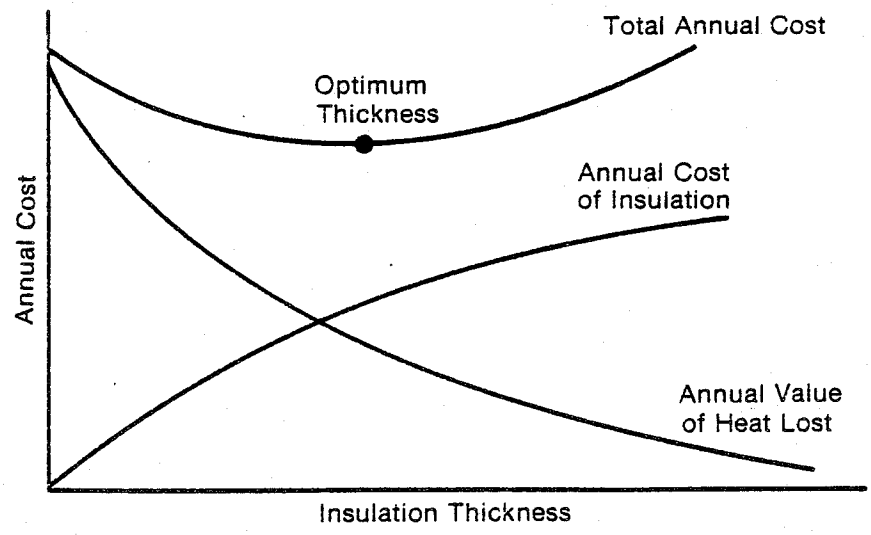

Figure 3-3. Insulation Thickness vs. Annual System Cost.

SECTION 4.0

METHODS

4.1 COMPONENT SIZING

Collector and storage sizing for 10 cities and 11 system sizes have been described earlier [1,2,3]. Methods for sizing the piping and distribution system are presented here.

Piping is separated into three components: the collector loop, the secondary loop, and the primary loop. The collector loop includes all piping, pumps, and controls within each building, the traditional "auxiliary costs" of a solar heating system. The secondary loop links each group of 50 living units, and the primary loop links the secondary loops with storage (see Fig. 4-1). The primary and secondary loops taken together form the distribution network. Not all building configurations have all the loops present; e.g., 50-unit systems have no primary loop; 100-unit buildings have no secondary loop. It was assumed that piping and distribution would be the same for evacuated-tube collectors as for flat-plate collectors.

Pipe diameters for the collector loop were chosen to handle a mass flow rate of 101.9 kg/h for each m^2 collector area. Fluid velocity in the pipes was set at 1.5 m/s (5 ft/s). Flow rates for the primary and secondary loops were taken as the sum of the flow rates in the piping feeding into the loop.

Collector loop length for SUBs was taken to be 22.8 m (75 ft) with 7.9 m (26 ft) vertical heads [6]. For TUBs and HUBs, the collector loop length was taken at 45.7 m (150 ft) and 121.9 m (400 ft) with heads of 7.9 m (26 ft) and 30.5 m (100 ft), respectively. Secondary and primary loop piping lengths were selected based on an assumed building configuration. Secondary loop length was 887 m (2910 ft) for single-unit buildings and 594 m (1950 ft) for 10-unit buildings. Primary loop lengths are given in Table 4-1.

Table 4-1. PRIMARY LOOP LENGTHS

System Type		Length (m)	Length (ft)
SUB	200	823.0	2700
SUB	400	1646.0	5400
SUB	1000	4115.0	13500
TUB	200	5486.0	1800
TUB	400	1097.0	3600
TUB	1000	2743.0	9000
HUB	400	548.6	1800
HUB	1000	1097.0	3600

Head loss in the primary and secondary loops was calculated by friction head losses per linear foot of pipe. Secondary loop head losses were from 39.6 m (130 ft) to 63.4 m (208 ft). Primary loop head losses were from 61.0 m (200 ft) to 274 m (900 ft), depending

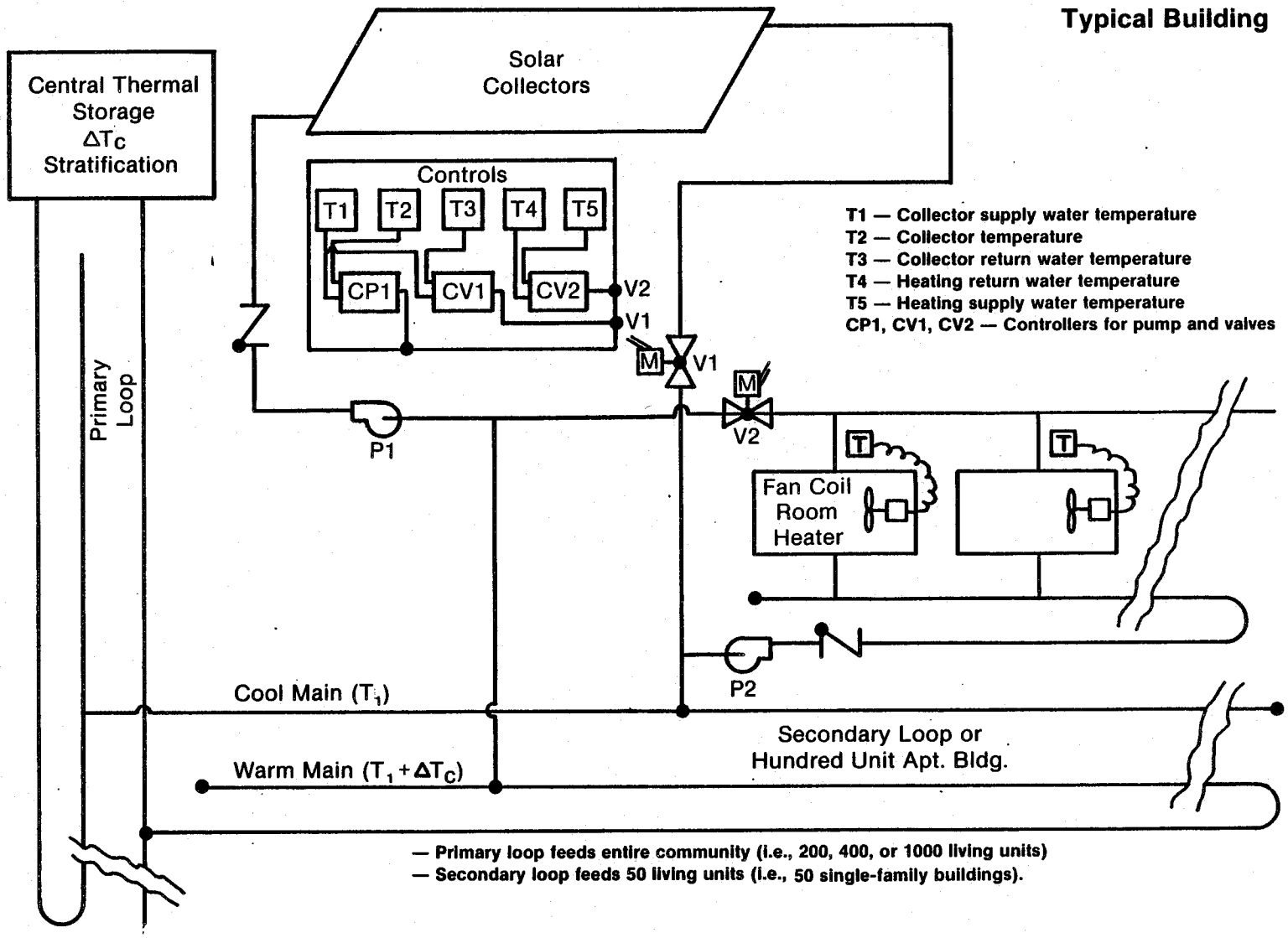

Figure 4-1. General Schematic of Distribution System.

on the system size and location. Note that, for the design assumption used here, primary and secondary loop head losses are greater in warm locations where the heating load is less because systems in these locations have smaller pipe diameters with the same linear flow rate.

Separate pumps and controls were assumed for the loops. Pumps ranging in power from 1.1 kW to 300 kW and in cost from $1,000 to $17,000 were selected from a catalog of the Bell and Gosset Company. Most of the primary loops required several pumps to meet the required flow rate and head loss. Because the costs of pumps and controls were small compared with the cost of piping, pumps were not selected with precision.

The current report includes four systems—TUB 10 and SUB 1, 10, and 25—that were not sized in a previous SERI report [1]. These systems were added to this report to more closely examine the economies of scale for larger systems and to compare individual single- and 10-unit building heating systems with the district heating systems.

Sizing of the SUB 1, 10, and 25 and TUB 10 systems was based on SUB and TUB 50 systems, with the smaller system sized in direct proportion to the number of units. This is justified for two reasons. First, the variation in collector and storage sizing relative to load among 50-unit through 1000-unit systems was always less than 5% and typically less than 3%. Such a deviation in collector and storage size can safely be ignored. Second, it was judged that, for small systems, the decrease in distribution losses would compensate for the proportional increase in storage loss that is the cause of increased efficiency in larger systems. Consequently, the efficiency of smaller systems may be justifiably assumed to equal that of 50-unit systems. Practically, this sizing is of sufficient accuracy for 10- and 25-unit systems. Dimensions of the SUB 1 system are of questionable accuracy but are included here as a rough comparison.

Lengths of distribution systems for the SUB 10 and SUB 25 systems were assumed to be equal to 20% and 50% of the SUB 50 length, respectively. Other details of the sizing of the distribution system for SUB 10 and SUB 25 were identical to the sizing of larger systems.

4.2 COMPONENT COSTING

Selection of costs for system components presented a major problem because the cost of the three major components (collector, storage, and distribution piping) are subject to major variations. The following section presents a summary of cost estimates for system components and gives the costs chosen for the economic analysis in this study.

It must be emphasized that costs estimated for system components, and estimates for total system costs, vary by a factor of two or more [6,7]. Part of this variation is caused by possible differences in local requirements and conditions; for example, a need for separate support structure for the solar collectors, or differences in the size and sophistication of the distribution and control system, and possibly soil type [7]. The variation in costs may also be due to the fragmentation of the solar heating market, in which market competition has not yet eliminated inferior systems.

We have selected component costs for this analysis to be near average market costs. We have tended to select costs from the lower end of the cost range, especially when the cost range reflects difficulties of the individual site. The rationale is that district solar systems are expected to be built first in particularly favorable sites and with advanced

architectural design. We have avoided spectacularly low cost assumptions, although in some cases such low costs may be reasonable and worth investigating. All costs are in 1979 dollars and include contractor overhead and profit. Selected costs are not considered a definitive statement but, rather, were chosen as sample costs for this economic analysis.

4.2.1 Collector Costs

Collector costs are subject to two uncertainties. First, costs for currently available solar collectors vary over a wide range. Second, mass production, an increasingly defined market place, and other forces may substantially decrease collector prices in the future [7].

A variety of sources report the cost of manufactured flat-plate collectors to be \$110-\$170/m^2, uninstalled [6,7,8,9]. The authors have confirmed this cost range in discussions with several manufacturers. It is possible, however, to find cost estimates both much higher and much lower than this range. A recent conference on site-built solar collectors included price estimates of \$40-\$85/m^2 of collector area installed, for a collector of reasonable performance [10].

Prices for evacuated-tube collectors vary from \$150-\$300/m^2, depending largely on collector performance [6,9]. Although there have been claims that evacuated-tube collectors could be mass produced at much lower costs, no such claims have been substantiated.

Installation of an assembled collector, such as one that is mounted directly onto a slanted roof, can cost as little as \$15-\$30/m^2 if installation is simple. More difficult conditions may push the installation cost up to \$80/m^2 or higher. Systems that require a separate support structure for the collectors are particularly expensive.

Our study uses collector plus installation costs of \$140/m^2 for flat-plate collectors and \$200/m^2 for evacuated-tube collectors. Assumed collector performance was low: the parameters Fr(at) and FrU_1 were set, respectively, at 0.661 and 6.104 W/m^2 °C for flat-plate collectors and 0.397 and 1.17 W/m^2 °C for evacuated-tube collectors.

4.2.2 Storage Tank Costs

The most comprehensive study of the cost of large storage tanks was performed by the Office of Technology Assessment [6] (see Fig. 4-2). Although there is a considerable range in the reported costs, especially for small storage tanks, the costs may be fitted fairly well to a linear plot on the logarithmic graph. This plot corresponds to the equation:

$$\text{Cost } (\$/m^3) = 300 \times \text{Volume } (m^3)^{-0.27} \ .$$

With adjustment for inflation, the constant term becomes 385 in 1979 dollars.

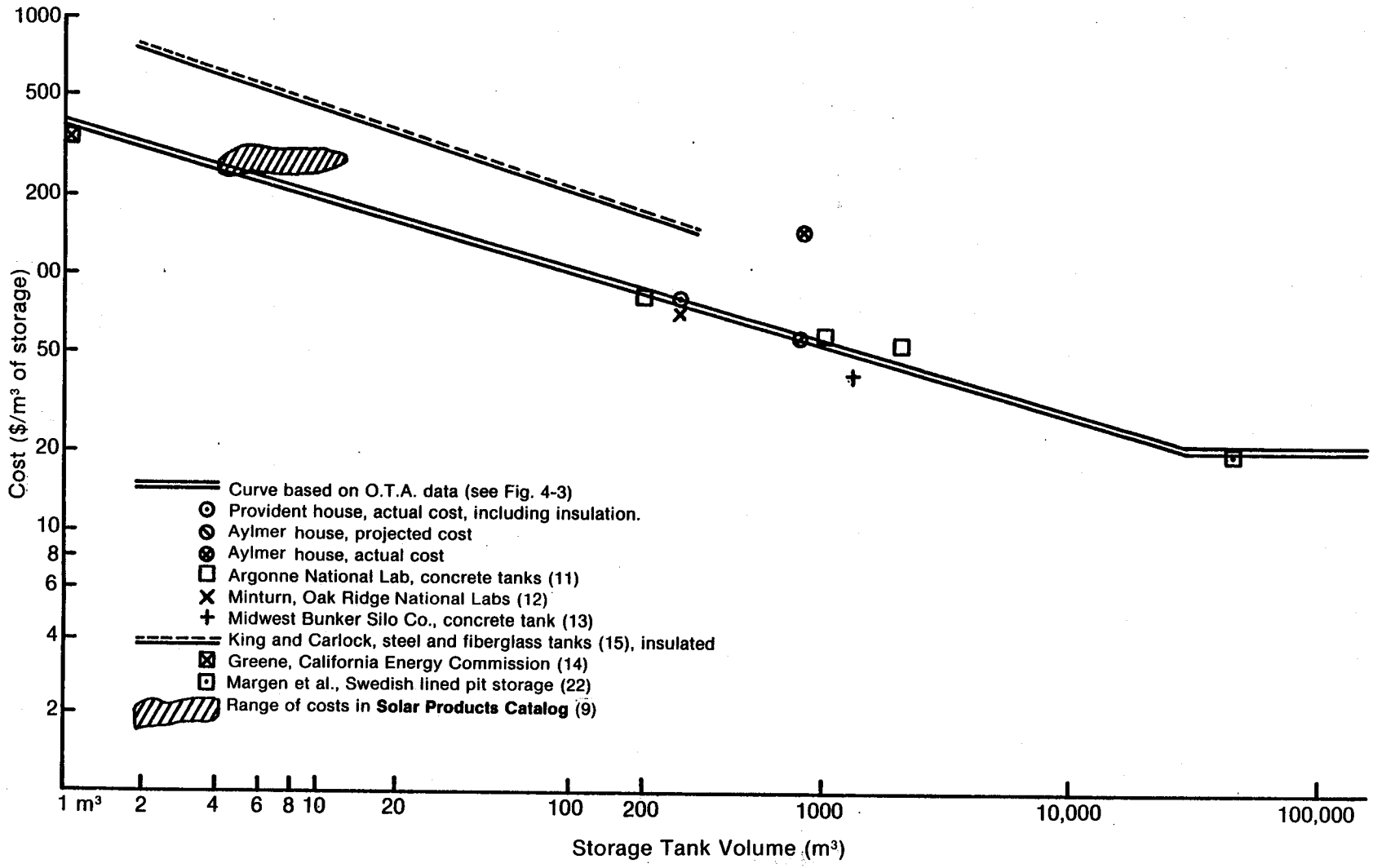

Figure 4-2. Comparison of Estimates of Storage Tank Costs (all costs in 1979 $).

Figure 4-3 gives other estimates of storage costs in comparison to the previous equation. The Office of Technology Assessment (OTA) costs for large tanks are apparently consistent with costs reported by more recent studies [11] and with the estimates of researchers and manufacturers [12,13].* These costs, however, assume favorable soil conditions. When soil conditions are poor, particularly when groundwater is near the surface, the actual storage costs for large tanks may be two to three times as much as is shown in Fig. 4-3. An illustration of this was the Aylmer house storage tank, which cost more than twice as much as orginally projected.

King, Carlock, and Shingleton report costs for small and intermediate size storage tanks that are nearly double the costs of the OTA report [15]. Possible reasons for this discrepancy are the inclusion of the cost of insulation and the use of more expensive materials in the King and Carlock study. The OTA report also shows a greater variation in the cost of small tanks than in the cost of large ones.

King, Carlock, and Shingleton estimate the cost of insulation for storage tanks to be in the range of $\$10$-$\$20/m^2$ of tank surface for R-10 to approximately $\$100/m^2$ for R-30 [15]. Because the surface area-to-volume ratio decreases for large tanks, the cost of insulation becomes progressively smaller per unit volume for larger storage tanks. For a 10,000-m^3 tank, the cost of insulating to the R-11 level of $\$10/m^2$ adds only $\$0.30/m^3$ volume.

In addition, studies have suggested [6,16,17] that the insulating effect of the surrounding earth makes storage insulation unnecessary for 500-m^3 tanks or larger. There are, however, limitations to the use of the earth as an insulator: initial storage losses remain high until the surrounding earth is heated and poor soil conditions (notably, running groundwater) could negate the insulating value of earth.

Since we are assuming favorable soil conditions for our study and since the cost of insulation is negligible for large tank sizes, we will ignore insulation costs for tanks of 1000 m^3 or larger. For smaller tanks, we assume insulation at a cost of $\$40/m^2$ surface area. For the tank cost itself, we use the curve drawn from the OTA data (adjusted for inflation).

In locations where land is available and inexpensive and soil conditions are suitable, it may make economic sense to use a solar pond for storage. Edesess et al. [18] report that for a 700-m^2 surface area salt solar pond, including the equivalent of 1000-m^3 storage volume, the total cost is approximately $\$30/m^2$ of surface area, or $\$21/m^3$ of storage. Although such a pond would replace collectors as well as storage, the cost of land may make such a system impractical in an urban or suburban location. However, a saltless solar pond, consisting merely of a lined pond that is 30 m in diameter and 10 m deep, covered with insulation, would provide 700 m^3 of storage at a cost of under $\$4/m^3$. Although of uncertain effectiveness as solar collectors, saltless ponds seem very likely to provide cheap, large-scale storage of solar heat where suitable land is available.

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*The Midwest Bunker Silo Corporation has frequently been sited as a manufacturer of large storage tanks at a very low cost. A company spokesman claims that although they do sell a 1600-m^3 tank for $\$25/m^3$, the tank is for agricultural uses. When such tanks are sold for commercial purposes, a 30% surcharge is added. In addition, this cost does not reflect contractor overhead and profit, which would add another 25%. The total cost of $\$40/m^3$ is comparable to other estimates presented here.

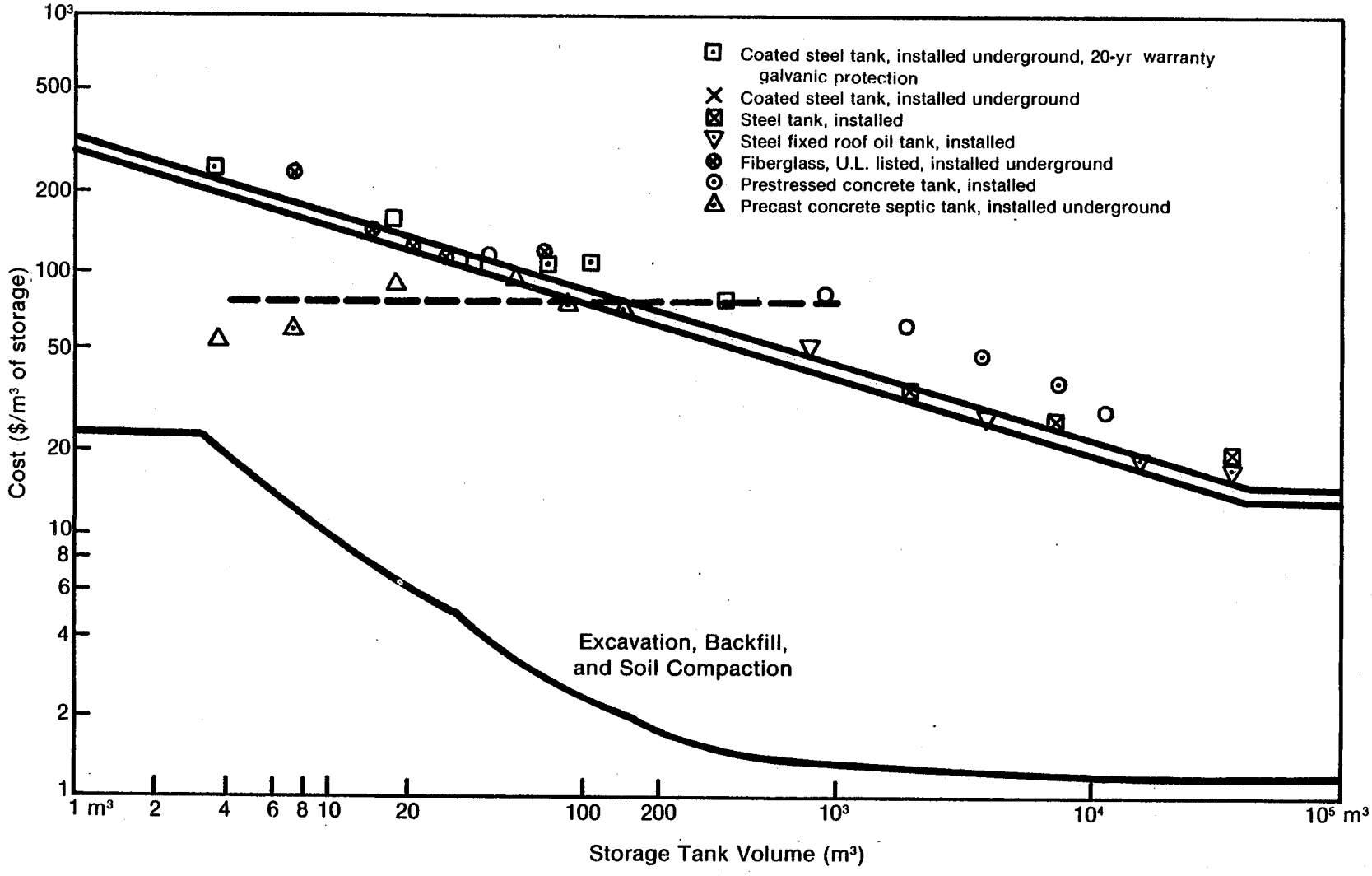

Figure 4-3. Cost of Uninsulated Buried Storage Tanks (in 1976 $), reported by Ref. 6.
The double line represents the curve the authors fitted to the plot, following the equation $C = 300\ V_S^{-0.27}$, with $C_{Min} = 17\ \$/m^3$.

4.2.3 Piping and Distribution System Costs

The distribution cost is the most difficult to estimate because costs vary widely with location and soil type. In our costing estimate, we make no attempt to deal with local variations; average values are selected as estimated prices.

Piping costs were taken from Means' Building Construction Cost Data [19]. For the collector loop, schedule 40 galvanized black steel piping was used. Cost for a 2-in. diameter pipe was $26 per linear meter, including installation, plus $16 per linear meter for 2 in. of fiberglass insulation.

Costing for the distribution loops (primary and secondary loops) was more complicated. The assumed cost was taken from Means' estimate for corrugated steel outdoor piping, the only outdoor piping included. Means' Cost Data also provides the cost of piping insulation for pipes up to 61 cm (24 in.) in diameter. Insulation costs for larger pipes were estimated from Means' cost for small pipes. Table 4-2 presents the costs used for this study.

Table 4.2. ASSUMED PIPING AND INSULATION COSTS FOR THE DISTRIBUTION SYSTEM

Pipe Diameter (in.)	Costs ($/Linear meter)		
	Piping (m)	Insulation (2" polyurethane)	Excavation
8	16.40	49.20	9.80
12	24.90	65.60	9.80
24	52.50	105.00	16.40
36	105.00	131.20	29.50
48	134.50	164.10	108.30
60	203.40	190.90	118.10
72	301.90	213.30	137.80

Similar piping costs have been reported for low-temperature district heating systems using smooth steel outdoor piping instead of corrugated steel [20]. There have been several district heating systems that use piping costs which are higher by a factor of three or more [21], but these have been systems equipped to use pressurized water above the boiling point.

The total cost of the distribution loops was taken as the sum of calculated piping cost and the cost of pumps. A 10% extra charge was added to the piping cost to account for controls, elbows, and other special pipe fittings and miscellaneous expenses.

Total costs for the collector loop came to $2,500 for a single-unit building, $4,000 for a 10-unit building, and $10,000 for a 200-unit building. These costs compare with the lowest costs of auxiliary equipment reported by King and Carlock in their survey of solar installations [7]. Reasons for differences in cost include sophistication of control equipment and length of piping assumed.

For the primary and secondary loops, the cost of pumps was insignificant compared to the cost of piping. Secondary loop costs ranged among the different cities from $100,000 to $200,000 for a loop of 50 houses. Primary loop costs ranged from $100,000 to $3 million, depending on location and system size. Locational variation was caused by the difference in pipe diameters among the 10 cities.

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SECTION 5.0

RESULTS

Results of an economic analysis based on the costs cited in Sec. 4.0 are presented here. The goals of this presentation are to illustrate the relative importance of each system component in the overall cost and to identify the key variables that determine the optimum sizing of a district solar heating system. It should be noted that our conclusions show general trends only; they are not meant to provide hard costs. In particular, the differences among the 10 cities described here are based solely on climatic variations; the local cost variations, which can be equally significant, are ignored.

Figure 5-1 shows the normalized total system cost per unit of heat delivered based on storage, collector, and piping costs cited in Sec. 4.0. Costs were normalized with respect to a TUB 1000 system with flat-plate collectors (note that all of Figs. 5-1 to 5-11 are normalized on the same basis). Cities in Fig. 5-1 are listed in order of increasing insolation. Collector cost, the largest component of total cost, decreases with increasing insolation as a result of increased collector efficiency. Storage and distribution costs, each of roughly equal magnitude, remain constant per unit heat delivered for all the northern cities. Storage costs are relatively smaller and distribution costs are relatively higher in warmer cities than in cooler ones. In Phoenix, which has a relatively small heat load, distribution costs are the major component.

Evacuated-tube collector systems were found to be more expensive than flat-plate collector systems in all cities except Caribou, Maine. In Caribou and in Boston, costs for flat-plate and evacuated-tube systems were virtually equal.

The cost breakdown by components, as presented in Fig. 5-1, varies somewhat for the two other building configurations. For single-unit buildings, auxiliary costs per unit of heat delivered are approximately three times as great as in TUBs. For HUBs, distribution costs are negligible. In addition, the storage component increases for smaller systems.

Figures 5-2 through 5-11 show the cost variation among each building configuration and system size for the 10 cities. Examination of these charts will identify the key parameters that determine system optimization.

Auxiliary costs (the collector loop) remain constant for each building type, regardless of system size. The auxiliary cost is only a significant part of the total cost for single-unit buildings. The cost of the collectors remains a constant fraction of system output. Collector overall efficiency does improve with increasing system size, but this typically amounts to only a 3% reduction in collector cost for 1000-unit systems as compared to 50-unit systems [1]. Consequently, economic optimization is most sensitive to variations in storage and distribution (primary and secondary loop) costs.

Storage cost per unit volume, as explained in Sec. 4.2.2, was assumed to decrease and level off at $\$22/m^3$ for tanks larger than 40,000 m^3. The distribution cost, on the other hand, varies somewhat irregularly. Distribution costs are, of course, zero for the single-building systems. Increasing system size always increases the distribution cost per unit of heat delivered.

Although the distribution cost appears to level off for 200-unit systems, the cost increases again from 400 to 1,000 units. For larger district heating systems, increasing distribution losses eventually reduce system efficiency to the point at which the system economics suffer. Aside from assuming 10%, 5%, and 0% overall distribution losses for the SUB, TUB, and HUB systems, respectively, this variation in distribution losses was ignored in this work and in the earlier paper [1].

Results for the 10 cities show that costs drop consistently as system size increases, owing to economies of scale in storage. The economic optimum for all cities and building types occurred when storage reached 40,000 m^3, the size at which we assumed there would be no more economies of scale in storage costs. The optimum system sizing, therefore, depends almost entirely on the economies of scale in storage. The conclusions in this report are valid for constructed tanks and are subject to change because storage prices may vary from region to region. We also stress that new technologies such as saltless solar ponds, lake storage, or aquifers may lower storage costs dramatically.

Perhaps the most interesting comparison is between a single-building system and the larger district heating system. For single-unit buildings, it is clear that individual annual energy storage is inferior to district storage systems. For 10-unit buildings, the case is less clear. For most cities, the analysis demonstrates that district heating systems are less expensive than individual systems. For Phoenix and Santa Maria, however, individual systems appear cheaper. In these cities, heat loads are low and subsequently the distribution system is a proportionately greater factor in the total cost, and the savings are more significant from elimination of the distribution system. These results suggest that individual systems for 10-unit buildings, which incorporate greater conservation, also may have an advantage over district heating systems in colder cities.

The variations among building types in these results are not surprising. For larger, individual building units, the system cost per unit heat delivered decreases, providing an additional savings to that already realized because the building load is reduced. Figures 5-2 to 5-11 indicate the reasons that larger unit buildings result in reduced costs. For 100-unit buildings, the savings over 10-unit buildings stem mainly from reduction in the distribution system cost. For 10-unit buildings as opposed to SUBs, savings result because auxiliary costs are decreased; furthermore, system efficiency is increased because for larger buildings, in which the hot water load is a greater proportion of the annual load, the demand for heat is more level throughout the year than for single-unit buildings.

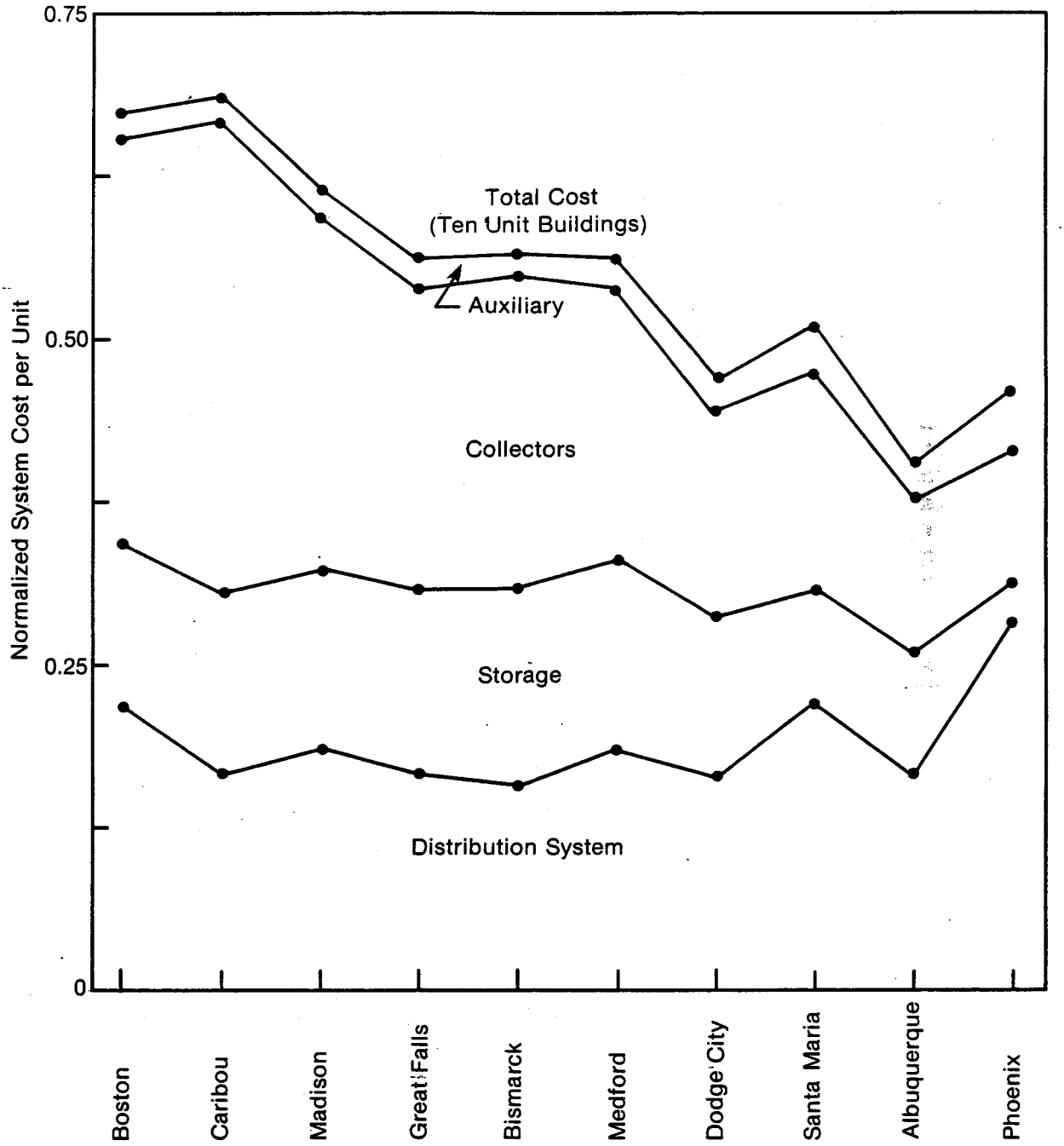

Figure 5-1. Total System Cost per Unit Heat Delivery for Ten Cities. TUB-1000 Sized Systems, with Flat-Plate Collectors.
Total cost is broken down into 4 components: distribution system, storage, collector, and auxiliary solar equipment ("collector loop").

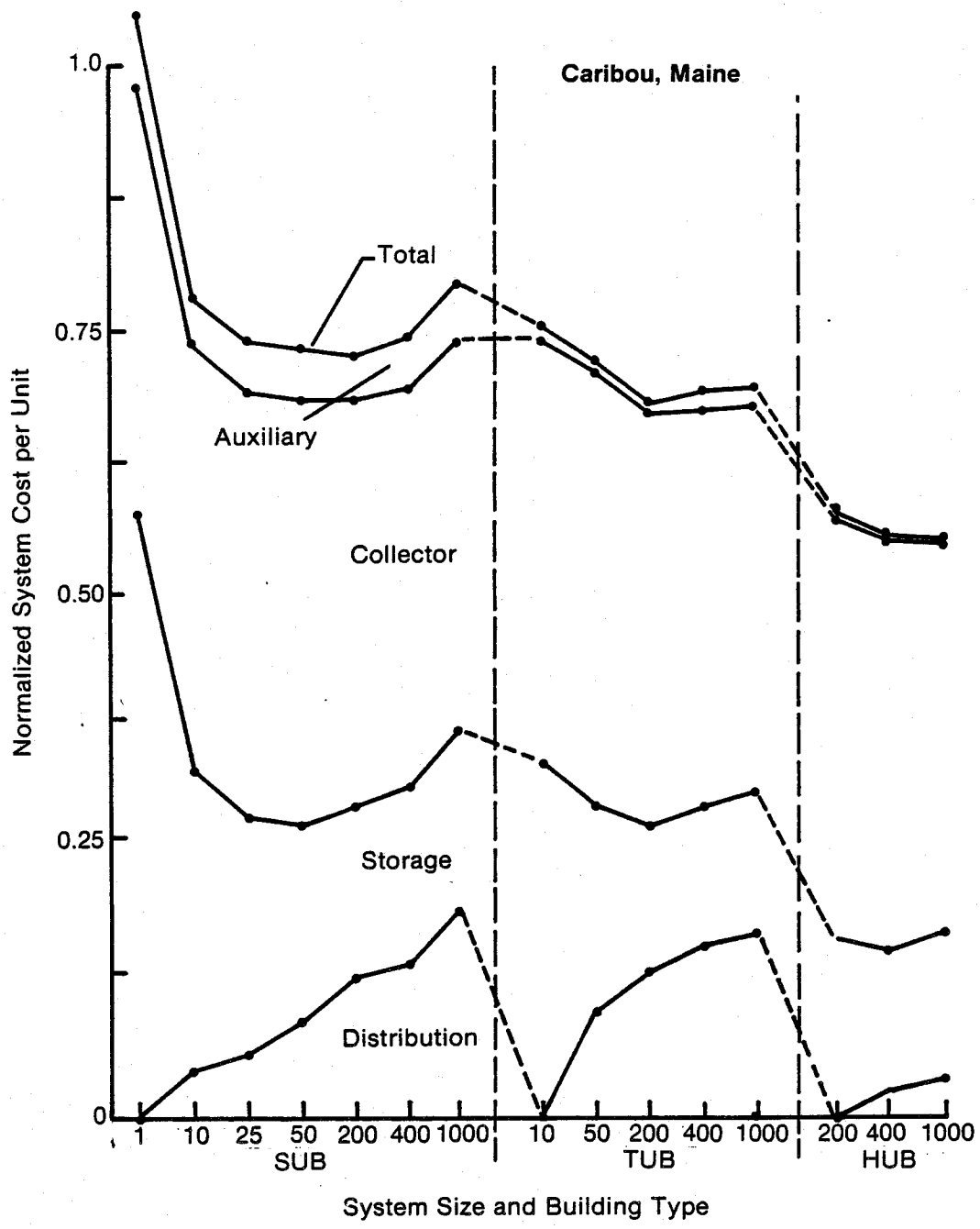

Figure 5-2. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

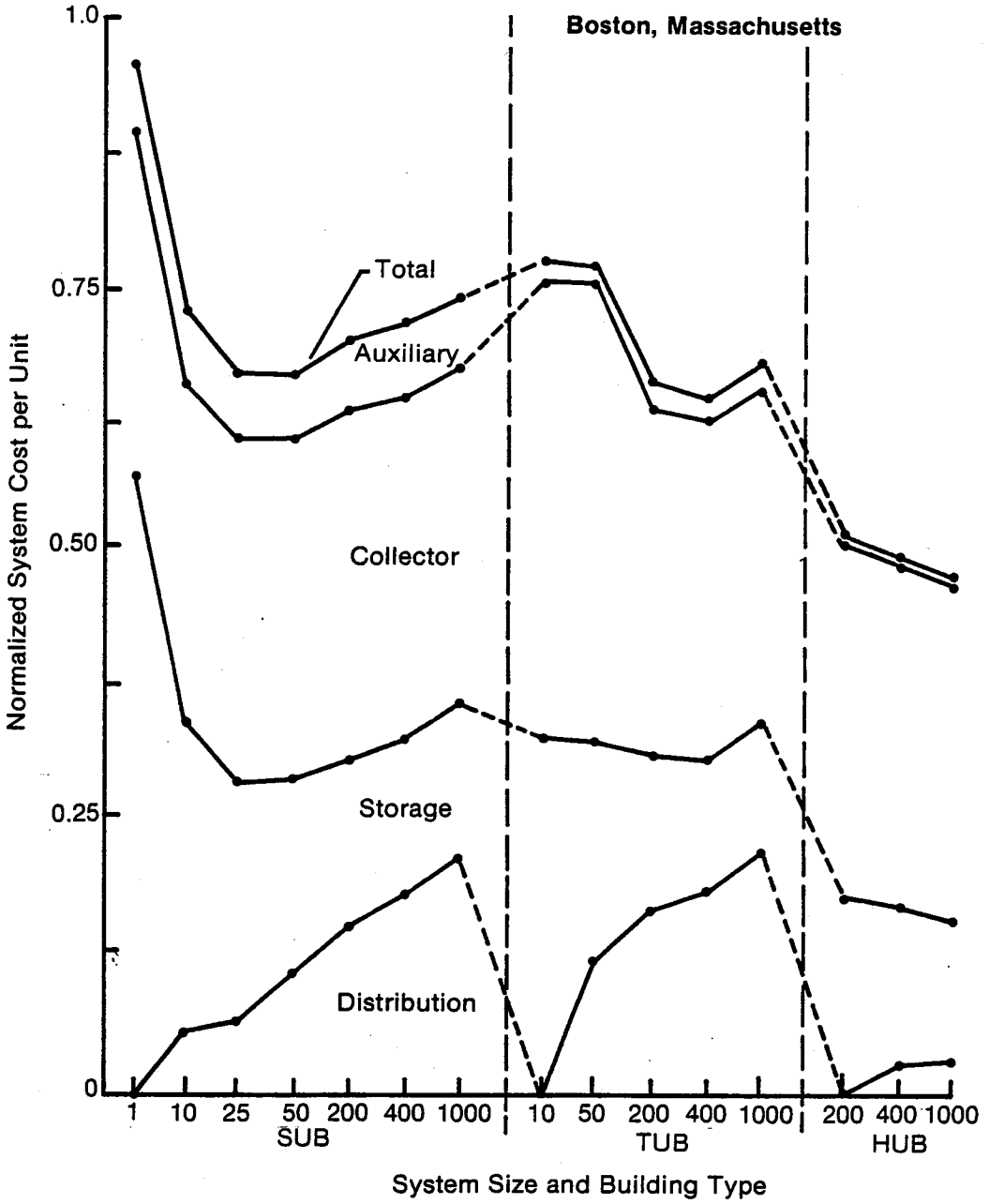

Figure 5-3. Cost per Unit Heat Delivered for Different Building Configurations.

Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

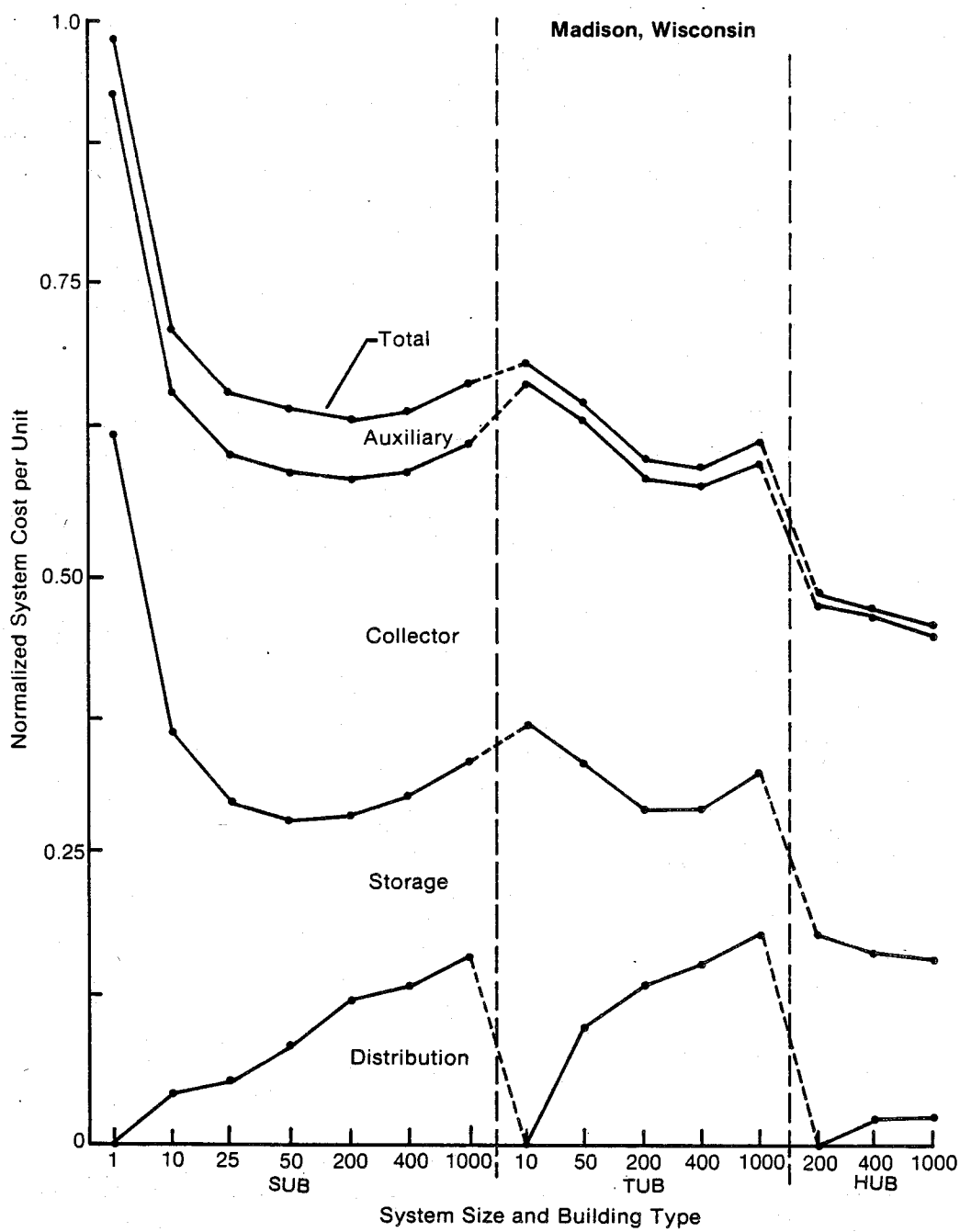

Figure 5-4. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

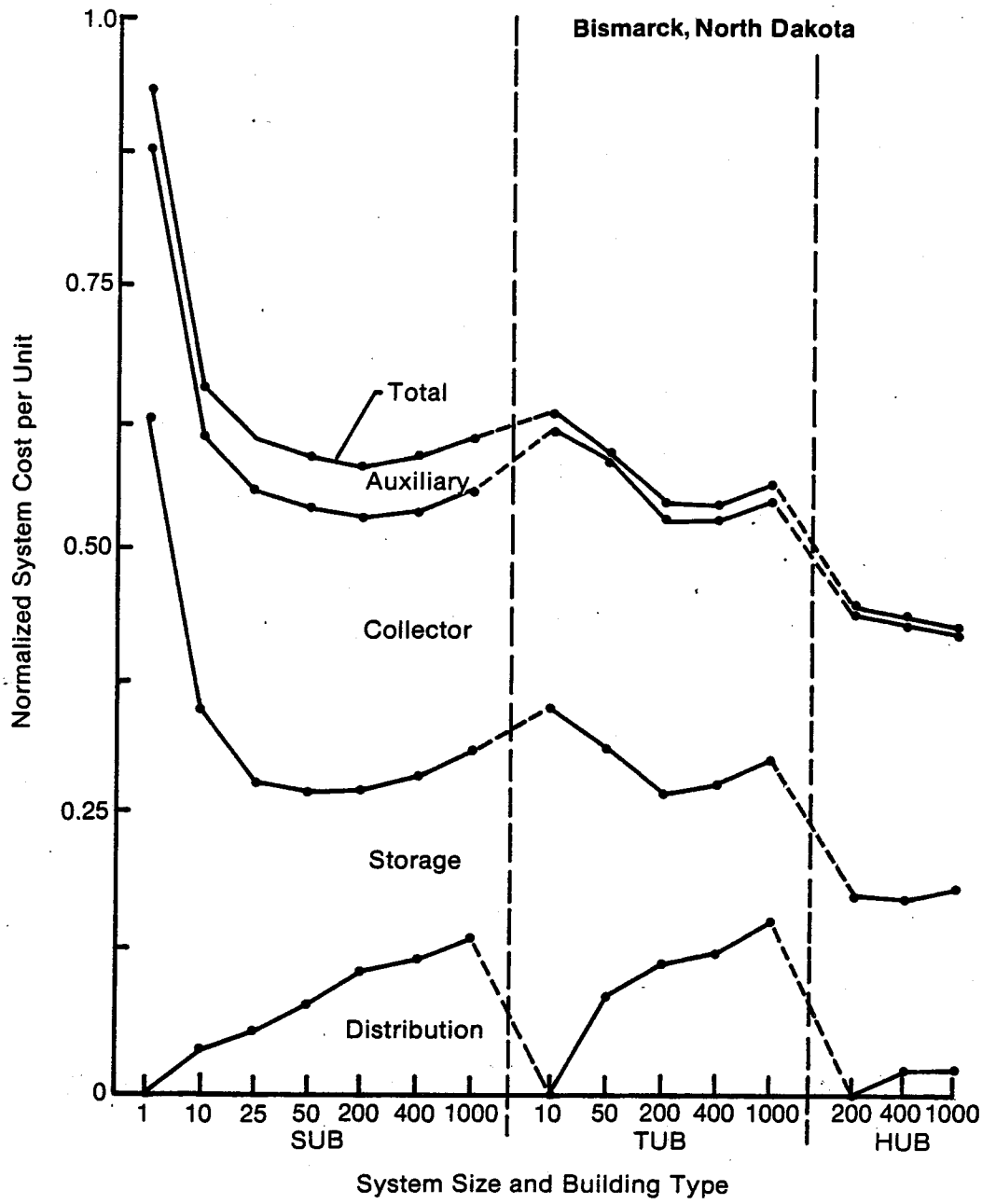

Figure 5-5. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

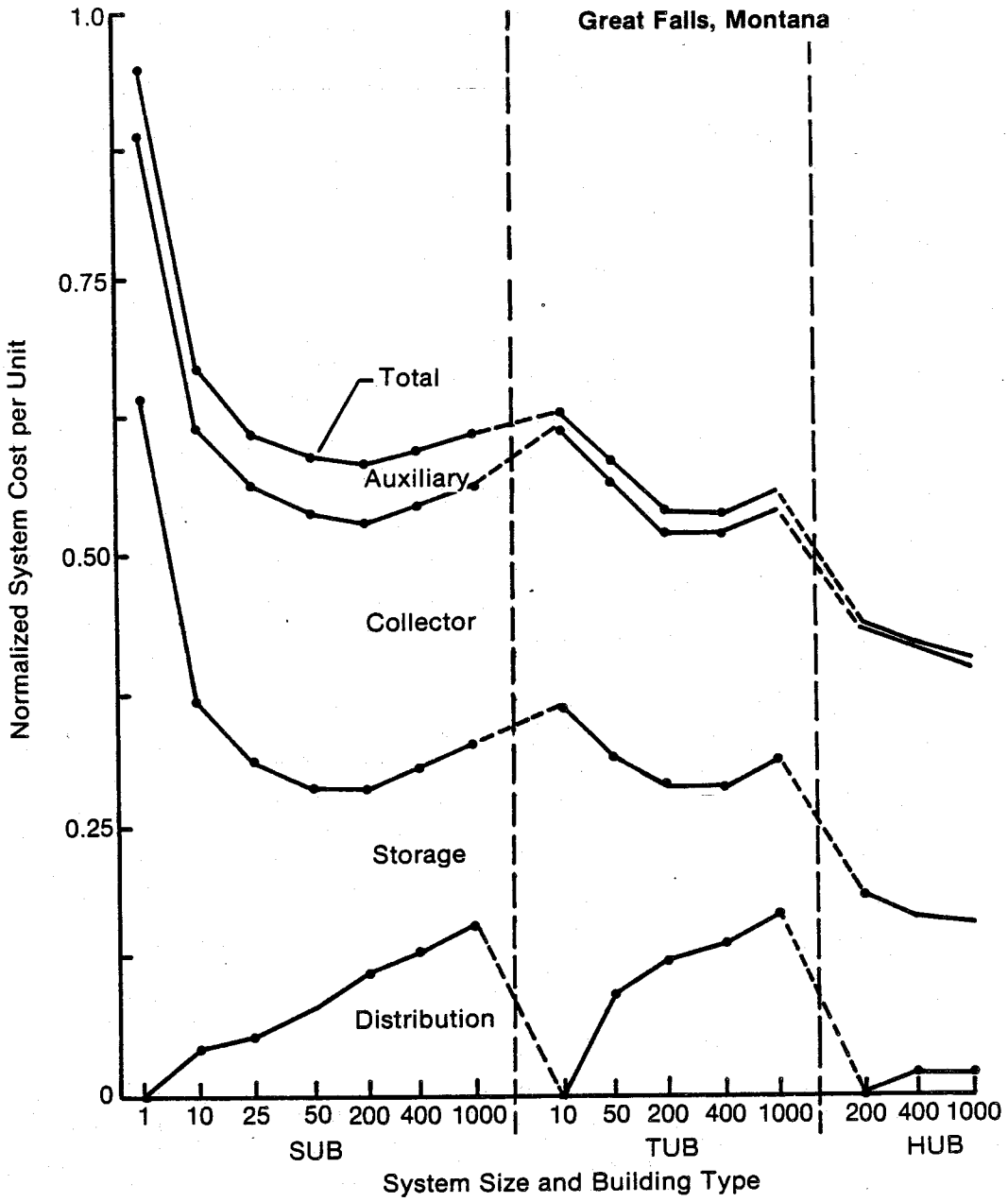

Figure 5-6. Cost per Unit Heat Delivered for Different Building Configurations.

Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

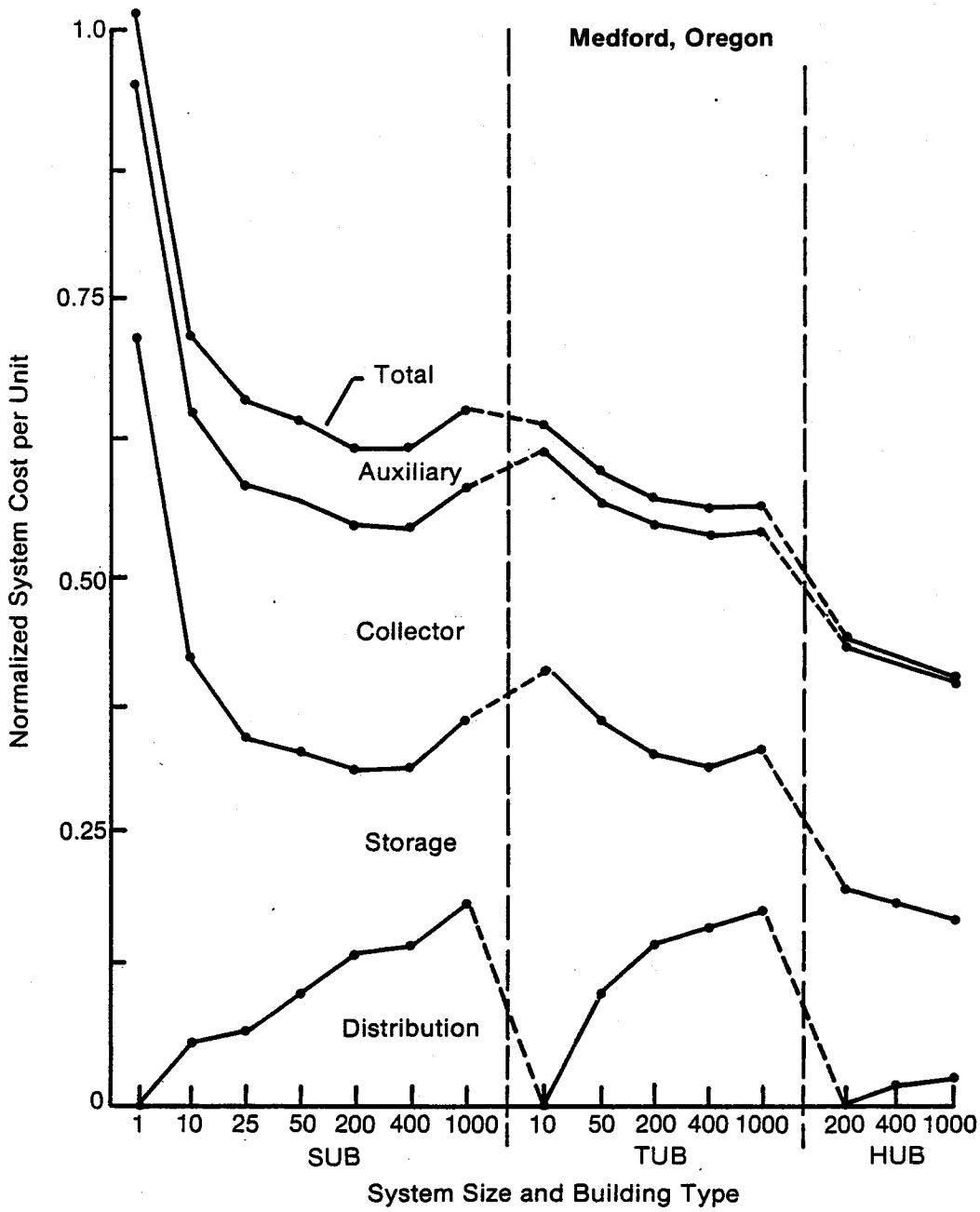

Figure 5-7. Cost per Unit Heat Delivered for Different Building Configurations.

Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

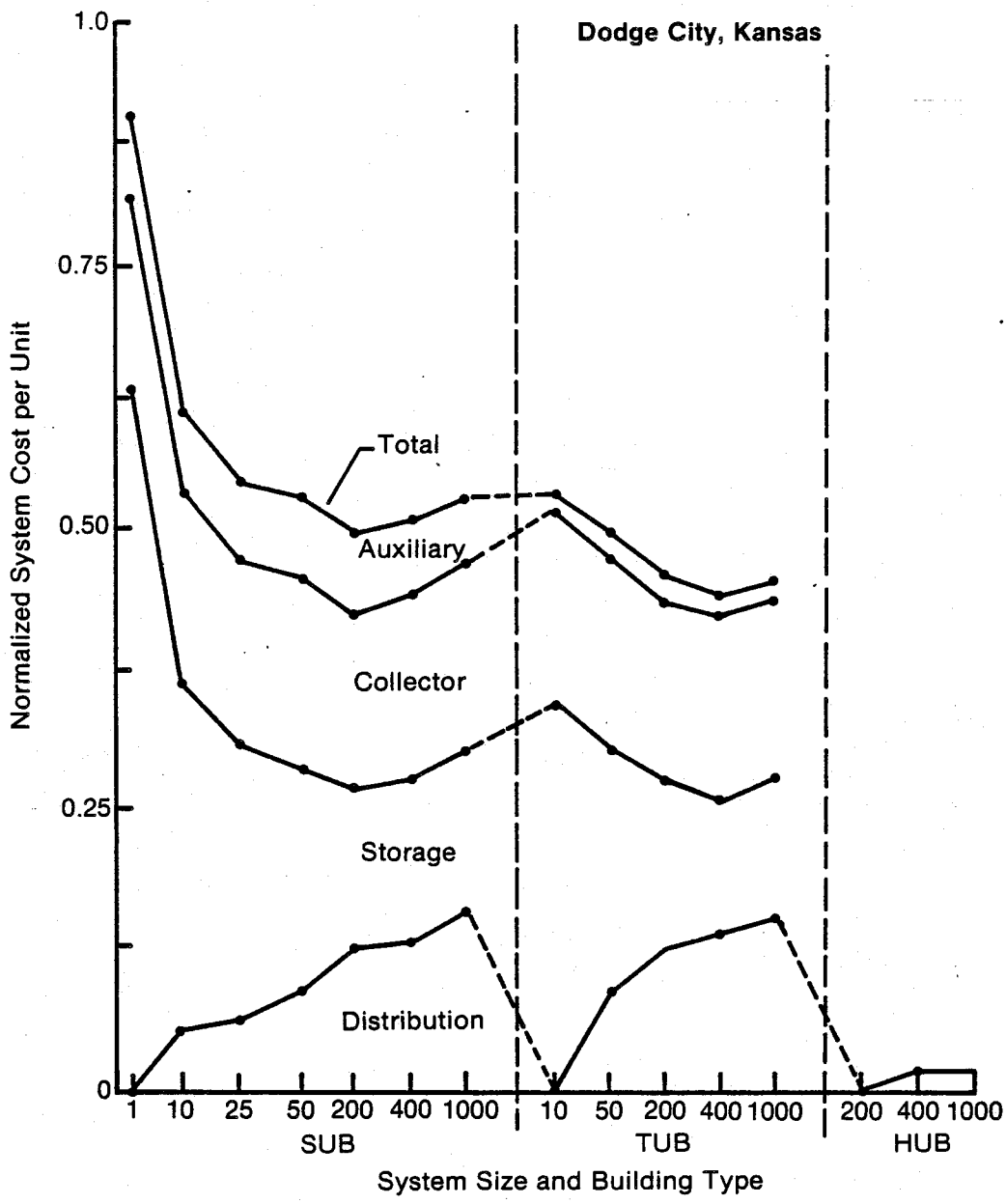

Figure 5-8. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

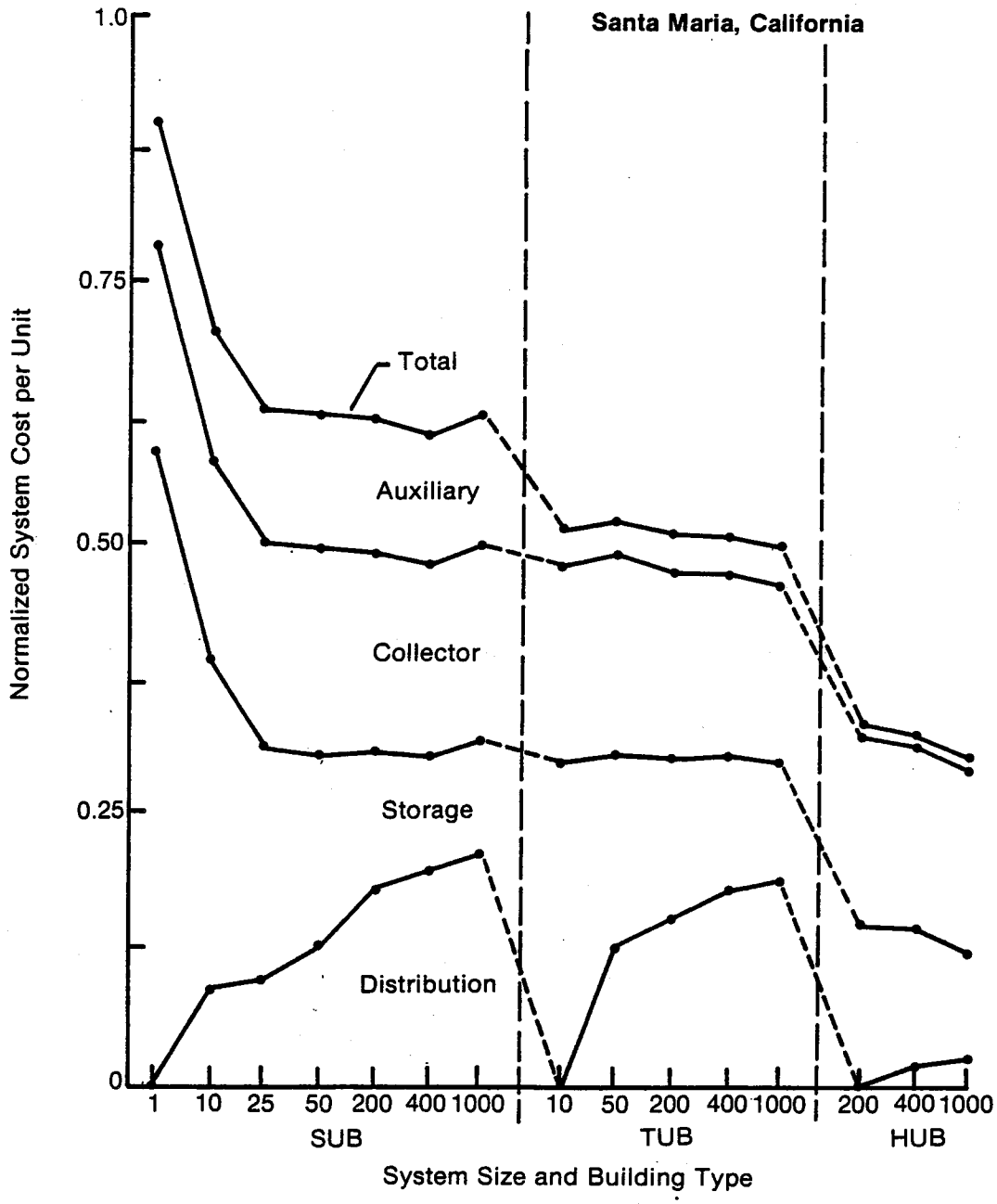

Figure 5-9. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

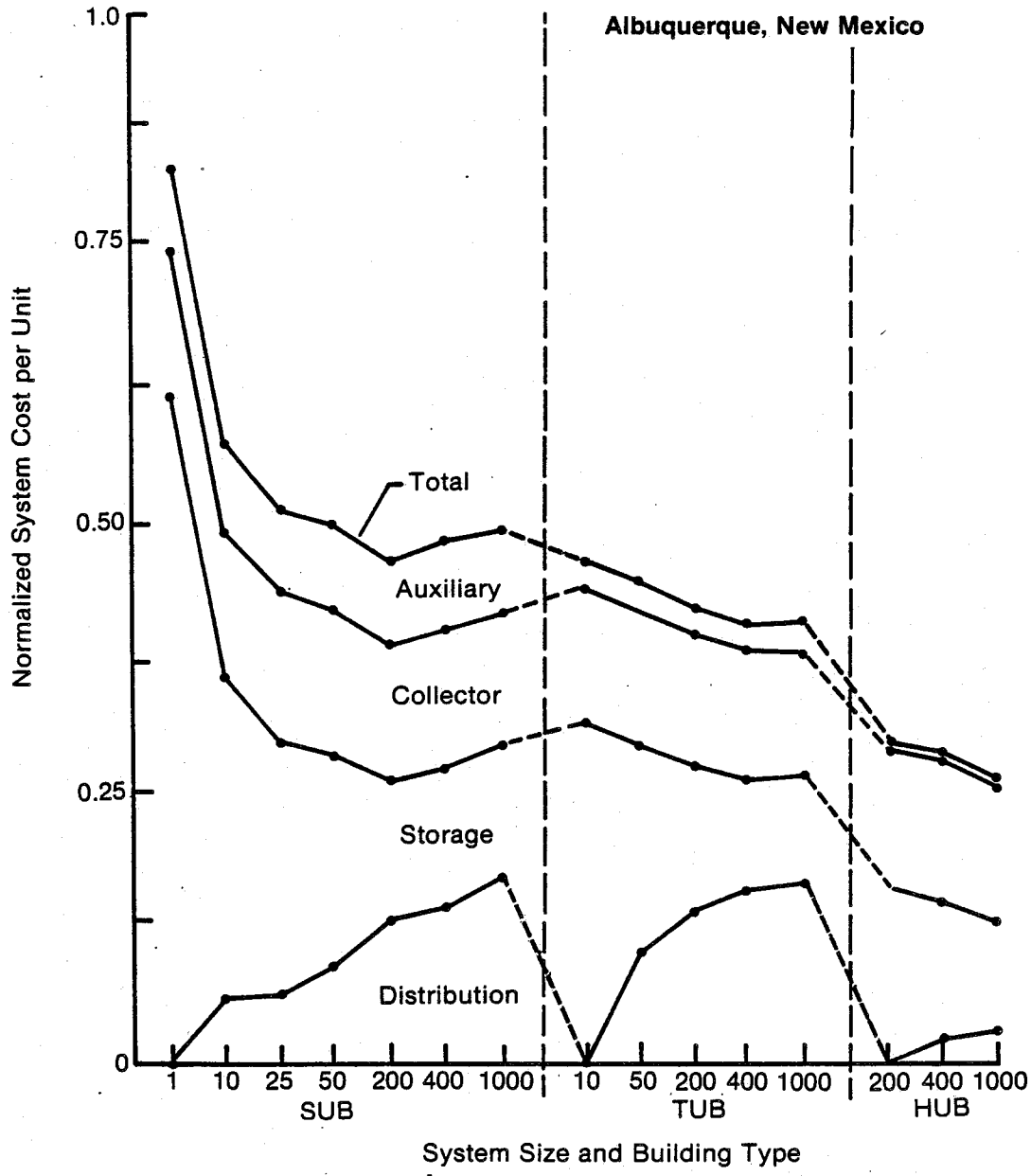

Figure 5-10. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

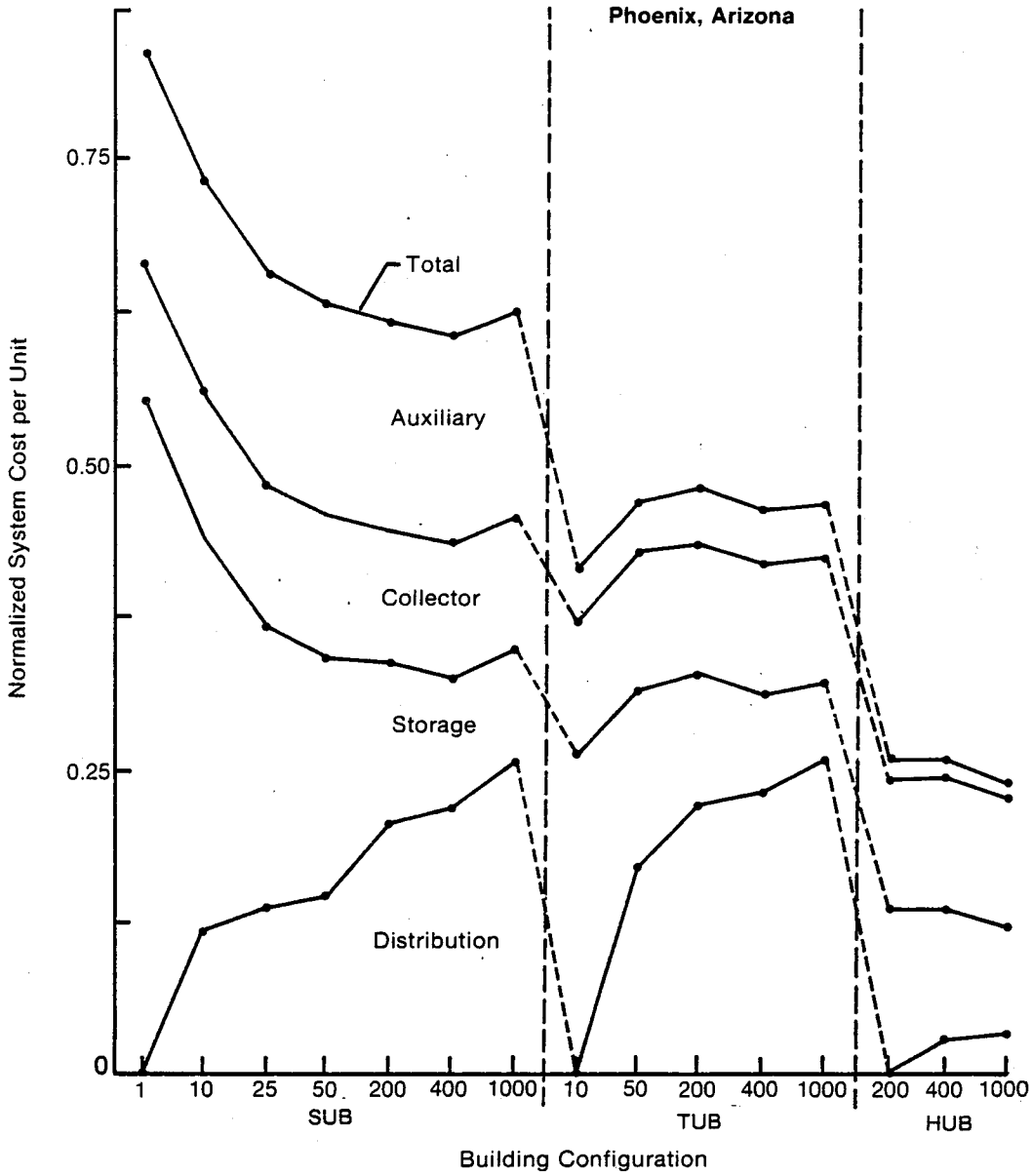

Figure 5-11. Cost per Unit Heat Delivered for Different Building Configurations.
Costs are divided into (1) distribution system (primary and secondary loops), (2) storage, (3) collectors, and (4) auxiliary (collection loop).

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SECTION 6.0

CONCLUSIONS

The goals of this analysis, as stated in Sec. 5.0, are to identify the relative importance of each system component in the overall cost and to identify the key variables that determine the optimum sizing of a district solar heating system. Interpretation of the results of the study provides a partial answer to these queries: the constraint on the conclusions is uncertainty in component costs. All costs are expressed in normalized form for this reason.

The most uncertain component of cost is the distribution system. Costs assumed here are substantially lower than those for steam or pressurized water distribution systems. They may possibly be reduced by use of low-cost plastic piping components. Also, costs of excavation vary from region to region. Costs are lower for new construction compared to retrofit construction. Finally, use of some innovative distribution systems may substantially lower costs. For example, an inexpensive distribution network may be constructed by laying pipes in basements and connecting through basement walls.

Solar energy is cheaper in climates with higher insolation levels. However, annual cycle thermal energy storage (ACTES) may be more valuable in northern climates with lower insolation. Figure 5-1 demonstrates that the collectors are a substantially larger component of cost in northern cities. The extra expense for an ACTES is also a smaller proportion of collector costs. Once an investment is made for solar collectors in Boston and Albuquerque, then the additional investment in an ACTES is more profitable in Boston. The relative cost of the distribution system also increases as one proceeds southward. In Phoenix, a large distribution system may be prohibitively expensive and unnecessary. In cities with substantial winter insolation, well-designed buildings may render ACTES solar systems uneconomical. (A publication on the value of ACTES in different climates for conventional homes and homes incorporating energy-conserving and passive features, The Trade-Off Between Collector Area and Building Conservation in Annual Storage Solar Heating Systems by Sanford Sillman, is presently underway at SERI and will be published shortly.)

The community type has important effects on the system cost per unit heat delivered. Larger, more compact buildings are, in general, less expensive to heat (see Figs. 5-2 to 5-11). This drop-off in unit cost from SUBs to TUBs to HUBs is more pronounced in Phoenix than in Caribou, for example, because the distribution and auxiliary system costs that are reduced by the same proportion are a higher percentage of the total in Phoenix than in Caribou. In addition, a relatively flat optimum in total costs is apparent in all cases for SUBs and in most cases for TUBs. Total cost is only slowly decreasing with system size in HUBs because as system size increases the distribution system costs rise while unit storage costs fall. All other cost components remain relatively constant. In HUBs the storage cost reduction dominates the distribution network cost increase. An interesting situation would occur if substantial reductions were realized in collector or storage costs; the distribution costs would then rise relatively faster. The optimum in the SUB costs would be sharper and 10- to 20-unit developments might be the most economical.

The results suggest that efforts should concentrate on lowering collector costs and increasing collector efficiencies in northern latitudes while they should emphasize lowering distribution system costs in more southern locations. Certainly, the highest payoff

would be from designing inexpensive ACTES solar systems in locations with higher heating loads. Systems may be very attractive that combine low-cost collectors with heat pumps to collect energy inexpensively on a large scale during the summer for use with an ACTES. The conclusions in this study are useful even though hard costs are not available; the trends in cost and the conclusions are still valid. We expect that the effect of changes in costs will not radically affect the validity of our conclusions.

SECTION 7.0

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16. Abstract (Limit: 200 words)

This report examines the economics of community-scale solar systems that incorporate a centralized annual cycle thermal energy storage (ACTES) coupled to a distribution system. Systems were sized for three housing configurations: single-unit dwellings, 10-unit, and 200-unit apartment complexes in 50-, 200-, 400-, and 1000-unit communities in 10 geographic locations in the United States. Thermal energy is stored in large, constructed, underground tanks. Costs were assigned to each component of every system in order to allow calculation of total costs. Results are presented as normalized system costs per unit of heat delivered per building unit. These methods allow (1) identification of the relative importance of each system component in the overall cost, and (2) identification of the key variables that determine the optimum sizing of a district solar heating system. In more northerly locations, collectors are a larger component of cost. In southern locations, distribution networks are a larger proportion of total cost. Larger, more compact buildings are, in general, less expensive to heat. For the two smaller-scale building configurations, a broad minima in total costs versus system size is often observed.

17. Document Analysis

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