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COMMERCIAL APPLICATIONS OF SOLAR TOTAL ENERGY SYSTEMS

Final Report, Volume 2, Technical

By
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B. L. McFarland
S. J. Nalbandian
W. W. Willcox
E. P. French
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July 1978

Work Performed Under Contract No. EY-76-C-03-1210

Rockwell International
Atomics International Division
Canoga Park, California

U.S. Department of Energy

Solar Energy

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FINAL REPORT

VOLUME 2 – TECHNICAL

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FOREWORD

This is the final report for the Commercial Applications of Solar Total Energy Systems (STES) Program, developed under the Department of Energy (DOE) Contract EY-76-C-03-1210 [formerly, Energy Research and Development Administration (ERDA) Contract E(04-03)-1210]. The work was performed by Atomics International (AI), Division of Rockwell International Corporation, during the period from May 10, 1976 through June 1978. The technical effort was completed June 1, 1977; however, the final report was delayed due to requested changes to the preliminary report and the required authorization to revise the report during the period of ERDA transition to DOE.

The work is reported in four volumes as follows:

Volume 1 — Summary

Volume 2 — Technical

Volume 3 — Conceptual Designs and Market Analyses

Volume 4 — Appendices

The study was performed in the Advanced Programs Department of AI, under S. J. Nalbandian, Project Manager with support primarily from the following Rockwell personnel:

M. G. Boobar (AI)
B. L. McFarland (AI)
W. W. Willcox (AI)
E. P. French (Space Division)
K. E. Smith (Space Division)

In addition two subcontractors provided support relating to building configurations, energy demand, building codes and conventional total energy systems. They were the Envirodyne Energy Services and The Energy Group, a subsidiary of Welton-Becket Associates.

The DOE (Washington D.C.) Program Manager was Mr. J. E. Rannels. Technical direction for the study was provided by Dr. R. W. Harrigan, Technical Monitor, of Sandia Laboratories, Albuquerque, New Mexico.

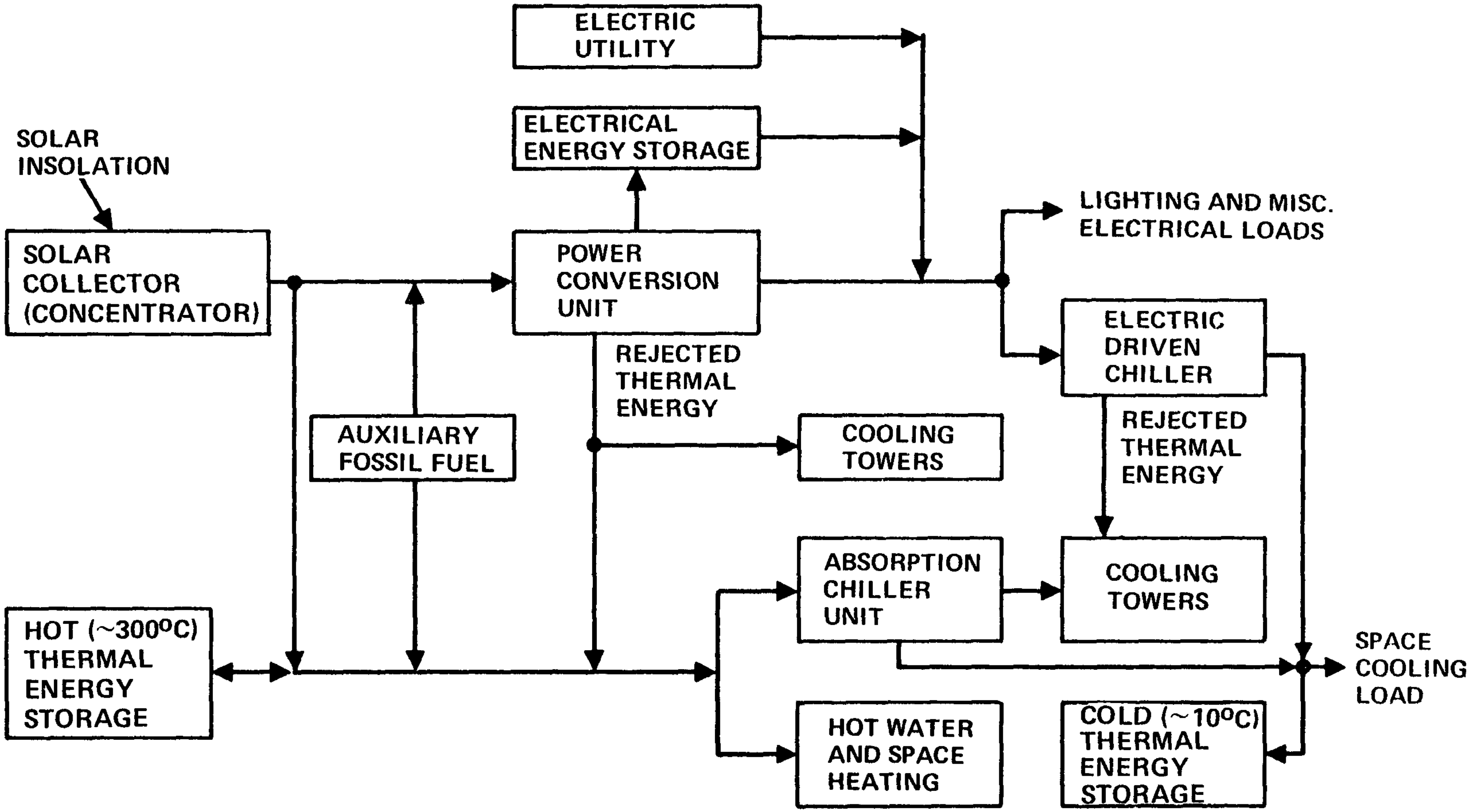

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Figure 1. Solar Thermal STES Concept Block Diagram

1.0 INTRODUCTION AND SUMMARY

The overall objective of this program was to assess the feasibility of using solar energy to provide a significant fraction of the energy needs of commercial buildings that have energy demands greater than 200 kWe. The 200-kWe limit was arbitrarily established to provide applications which reasonably could be expected to economically justify an onsite power generation system. Specific program objectives are presented in Section 1.2, Volume 1.

A solar total energy system (STES) is one that provides a combination of electrical and thermal power to the user to supplement or replace conventional energy sources. Figures 1 and 2 show the generic concepts considered for this program.

As indicated in Figure 1, a solar thermal STES utilizes a concentrating solar collector to produce a high-temperature fluid which supplies energy to a power conversion system (PCS) and/or hot thermal energy storage for later use to power the PCS. The electrical energy produced by the PCS is used to supply the user's electrical demand loads (lighting, vapor compression chillers, etc.) and/or an electrical energy storage system. Rejected thermal energy from the PCS can be cascaded to supply the user's thermal demand loads and/or absorption chiller refrigeration units with all excess energy exhausted to the atmosphere primarily through a cooling tower.

Figure 2 shows schematically how a photovoltaic STES can consist of (1) direct conversion of the solar energy to electricity by photovoltaic arrays, which may or may not involve concentrators, and (2) collection of low grade thermal energy either from the cooling of concentrating photovoltaic arrays or by separate flat plate solar collectors which supply the user's thermal demand loads.

Figures 1 and 2 show energy storage in several places to indicate the numerous options possible in configuring the systems and which need to be evaluated to determine the most economical configuration for a given application. This evaluation can be expensive for conceptual design studies if a detailed computer program such as SOLSYS,[(1)*] PVSOLSYS,[(2)] or modified TRNSYS[(3)] is used. Thus, an

*Numbers in superscript parenthesis refer to references.

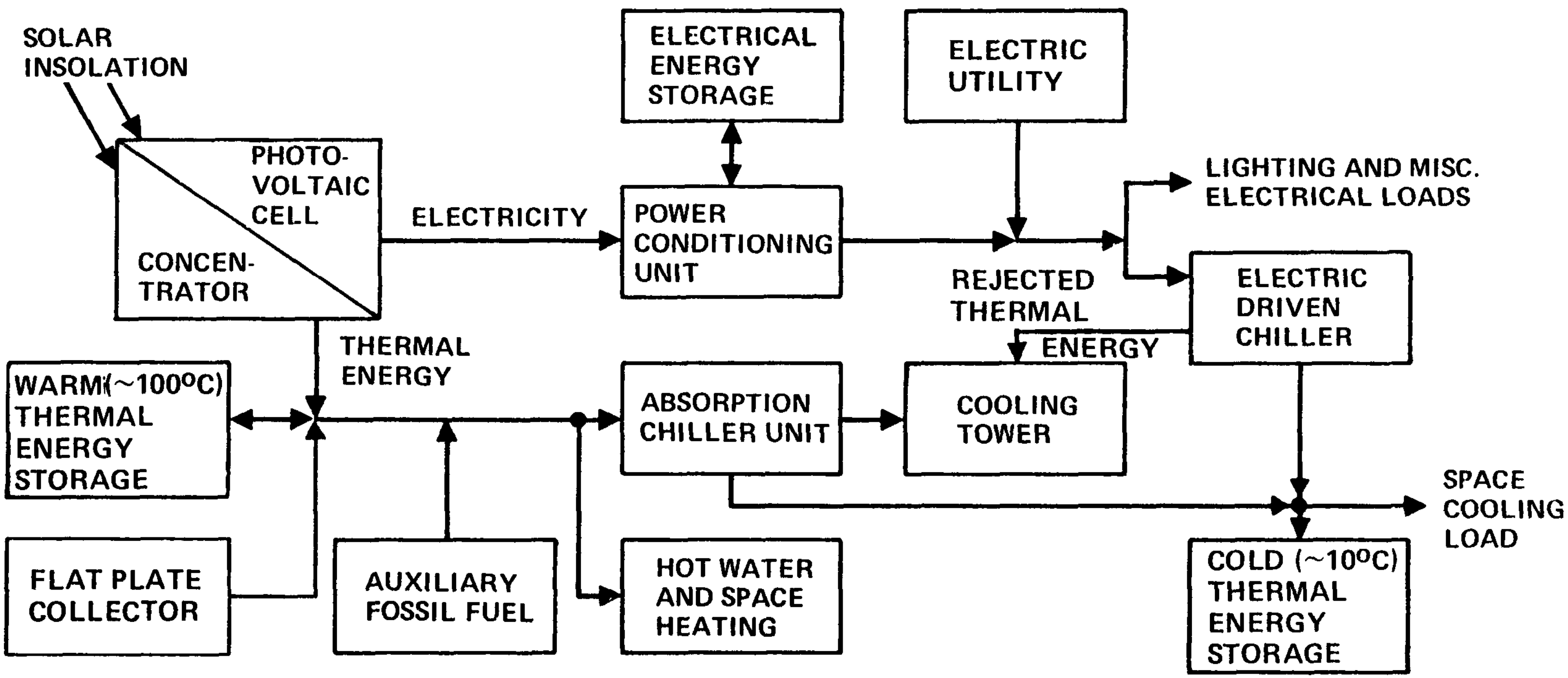

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Figure 2. Photovoltaic STES Concept Block Diagram

alternate method of developing the economical optimum STES configuration was felt to be needed to assess applicability of various STES concepts and building configurations at different site locations within the continuous United States.[4,5]

The STESEP Computer Code (see Section 5.0) was developed for a quick evaluation method for tradeoffs related to (1) cascading of thermal power conversion systems, (2) determination of optimum collector sizes and operating conditions (make or buy decisions for auxiliary energy), and (3) comparison of solar total energy concepts in various parts of the country and in various types of commercial buildings to assess their future economic potential for various economic scenarios.

The individual STES component-subsystem models are of necessity simplified and are used together with a deterministic model (see Section 4.2) of the solar-environmental site condition to enable screening calculations to be made inexpensively. The results from these screening calculations defined the economics of the system and were used directly for conceptual trend studies as discussed in Sections 2.0 and 3.0 of Volume 3.

Concurrently, data on commercial buildings (e.g., categories, energy demand, demographic population, etc.) were developed and used to define six model building configurations (see Section 4.6) which could be used as representative commercial buildings within six various regions (12 specific sites) of the United States. The six configurations included four building types (a low rise office building, a large retail store, a medium-size shopping center and a large shopping center) typifying current building designs. The remaining two configurations used the large shopping center model except that the energy demand was changed to reflect future building designs. One assumed retrofitting the existing large shopping center model with an energy conservation program while the other assumed a new construction of a shopping center designed to meet expected future energy conservation codes.

This volume of the final report discusses the approach employed to develop: (1) STES concept configurations and component data, (2) commercial buildings application data, and (3) computer simulation programs for evaluating various STES concept-commercial buildings applications.

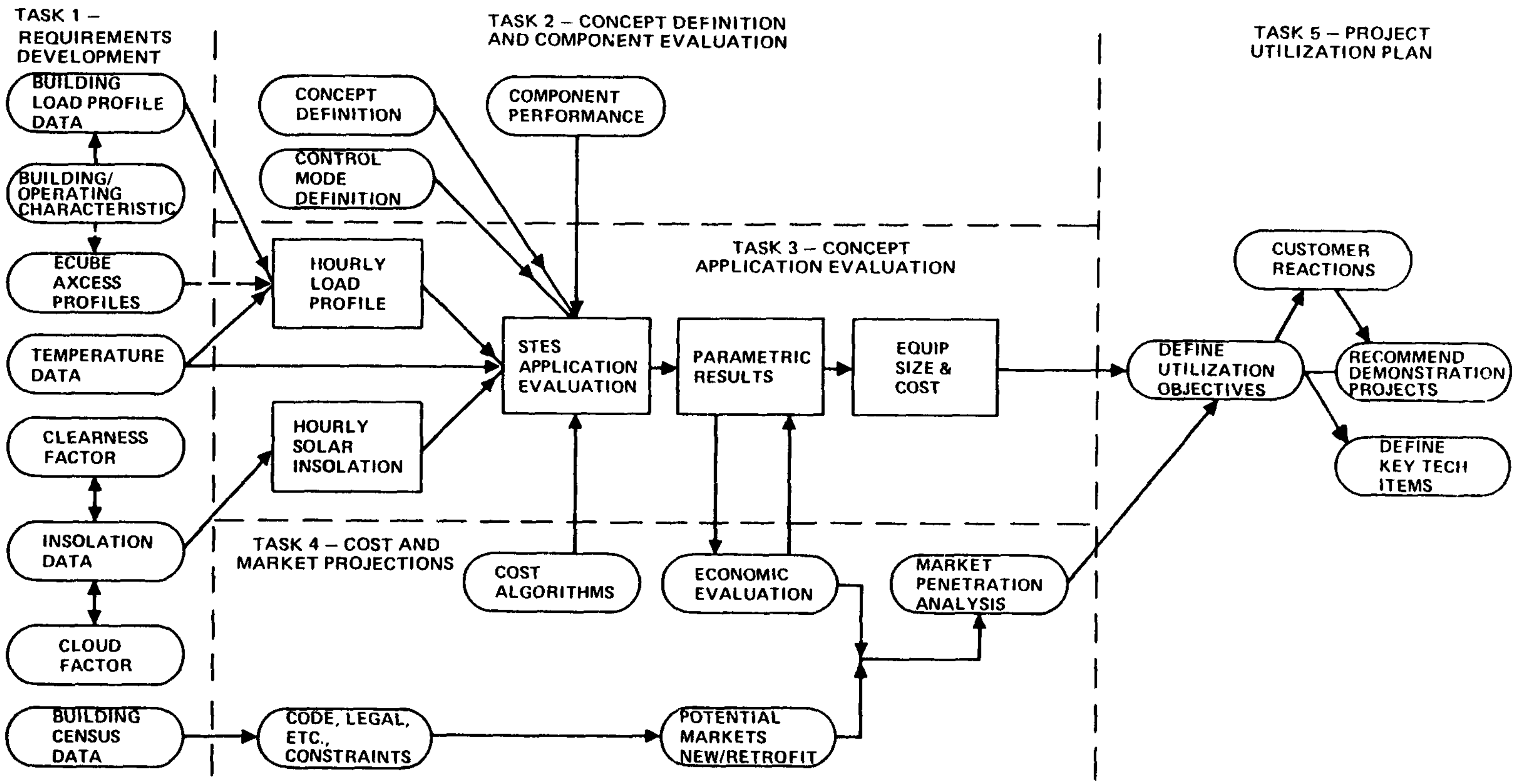

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Figure 3. STES Program Logic

2.0 PROGRAM APPROACH AND CONCEPTS SELECTION

2.1 PROGRAM APPROACH SUMMARY

To accomplish the objectives set forth in Section 1.2, Volume 1, the study effort was separated into five major technical task areas. The interrelation of these tasks are shown in Figure 3. The primary efforts for these tasks are discussed in the following paragraphs.

Task 1 – Requirements Development. Commercial building types, operating characteristics and configurations were evaluated and energy demand data were developed. Isolation and climatic data were evaluated for selection of candidate representative sites. An insolation evaluation methodology was developed and used to define the insolation at each representative site. The Task 1 effort was primarily performed by Rockwell Space Division personnel with support from the subcontractors.

Task 2 – Concept Definition and Component Evaluation. Various STES concepts were evaluated and an organic Rankine cycle STES and a photovoltaic STES concept were defined as preferred configurations. Component and subsystem performance characteristics were evaluated and components state-of-the-art were assessed. Three modes of operation were assumed for the solar thermal STES (organic Rankine cycle). One was essentially an on-site stand alone concept utilizing auxiliary fossil fuel to supplement the solar energy with no electric utility interface. The second mode provided the total thermal energy requirements at the site from the cascaded energy from the organic Rankine cycle power conversion system with supplemental electrical energy purchased from the electric utility to meet any additional electrical energy demands of the site application. The third mode considered operation of the organic Rankine cycle power conversion system operation whenever adequate solar insolation was available regardless of the site application demand requirements and stored any excess electric energy in battery systems. This latter mode was the only operating mode assumed for the photovoltaic STES.

Task 3 – Concept Application Evaluation. The building energy demand profile data and site environment and insolation data from Task 1 and the STES concepts component data and control mode data from Task 2 resulted in a large number of

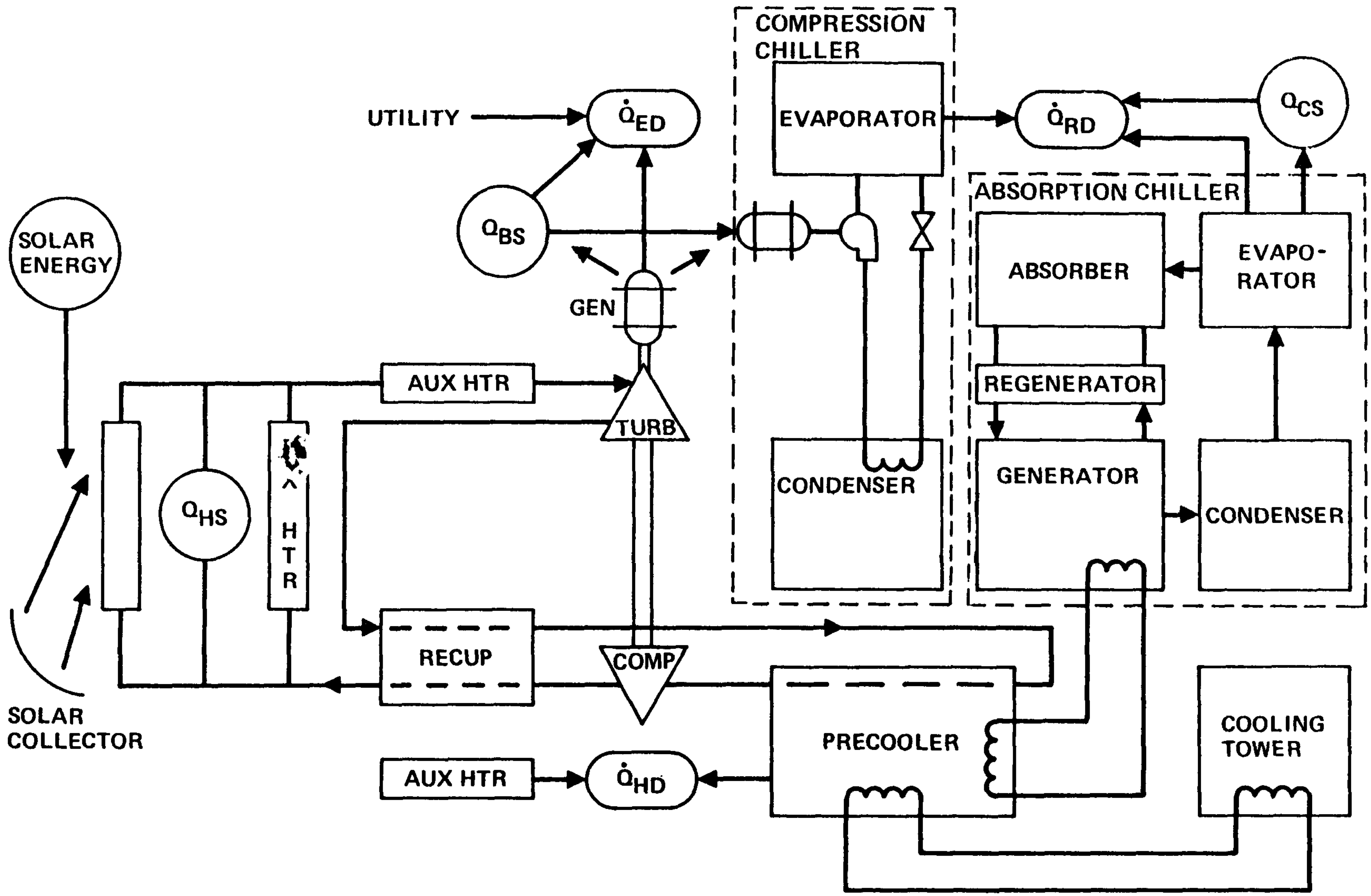

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Figure 4. Diagram of Solar Thermal STES Concept
(Brayton Cycle Power Conversion System)

variables which required development of a computer simulation code for concept evaluation purposes. The computer code provided a means for parametric evaluation of performance and economic parameters (from Task 4) for the various concept and building applications. As a result, preferred STES configurations including equipment sizing and costs could be defined inexpensively at the various sites.

Task 4 — Cost and Market Projections. A costing methodology and algorithms for various components were developed for use with the Task 3 computer simulation code. In addition, cost of electricity at the various representative sites were obtained and the effects of the demand rates were assessed. Economic evaluation of the STES concepts at the various sites provided data on the amount of energy produced by the STES in comparison with that provided by the utility for each configuration at the different sites. These data, in conjunction with the Task 1 building census data, were then utilized to develop potential market applications and penetration rates estimates discussed in Section 4.0, Volume 3.

Task 5 — Project Utilization Plan. The preceding tasks provided necessary data to enable identification of preferred STES utilization for commercial building applications, definition of key technology development issues and recommended demonstration objectives. These are discussed in Section 5.0, Volume 3.

2.2 STES CONCEPTS

The generic concepts for solar thermal and photovoltaic STES shown in Figures 1 and 2 were used to define a Brayton cycle STES concept, a Rankine cycle STES concept and a photovoltaic STES concept. Figures 4, 5, and 6 define these systems and the components or other elements which comprise each system.* Table 1 compares these STES concepts for application to the commercial sector on a qualitative basis.

The low pressure Brayton cycle concept was considered to be one of the more suitable STES concepts for commercial building applications because of several inherent advantages shown in Table 1. In particular, the low pressure (<15 psig) open cycle air, Brayton cycle and the photovoltaic cycle are the only concepts considered that may not require a licensed operator and the attendant operating costs. Consequently, the absorber designs applicable for the Brayton Cycle

*See list of symbols, page 167.

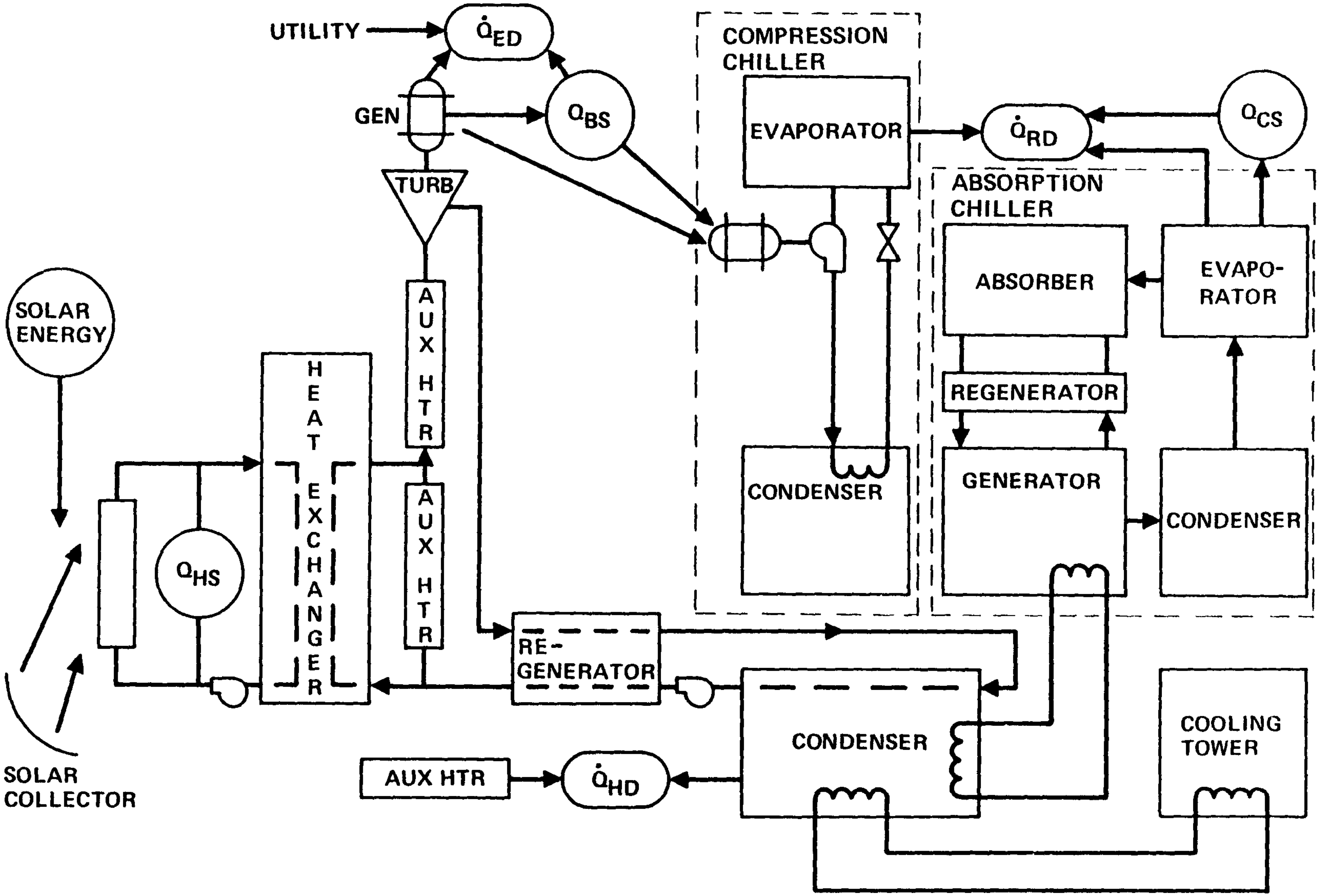

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Figure 5. Diagram of Solar Thermal STES Concept
(Rankine Cycle Power Conversion System)

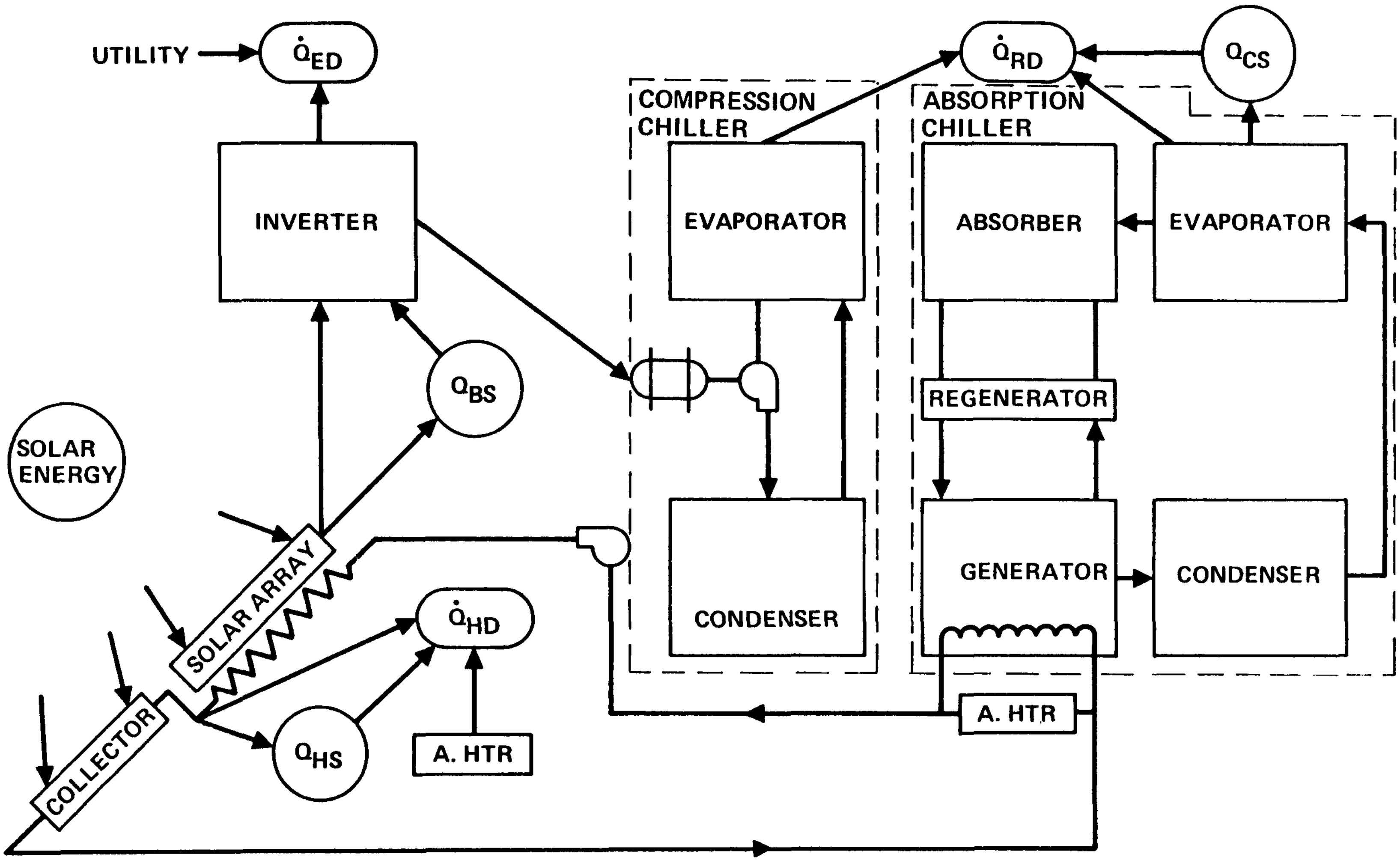

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Figure 6. Diagram of Photovoltaic STES Concept

TABLE 1

COMPARISON OF STES CONCEPTS

Power Conversion System Concept	Advantages	Disadvantages
Organic Rankine	1. Distributed Collector Can be Used 2. Can be Cascaded for Thermal Load	1. Requires Licensed Operator or Automatic Safety Controls 2. Fire Hazard 3. Low Performance
Steam Rankine	1. High Performance Potential when superheated steam is used	1. Requires Licensed Operator or Automatic Safety Controls 2. Requires Point Focus Receiver (higher temperature) 3. Fire Hazard Because of Second Fluid for Storage 4. Large Performance Loss to Cascade
Brayton Cycle (High Pressure)	1. High Performance Potential 2. Can be Cascaded for Thermal Load	1. Requires Licensed Operator 2. Requires Point Focus Receiver (higher temperature) 3. Current Concepts of Thermal Storage Not Feasible for STES 4. Fluid Leakage Problems
Brayton Cycle (Low Pressure)	1. High Performance Potential 2. Can be Cascaded for Thermal Load 3. No Operator Required 4. Thermal Storage Feasible for STES	1. Requires Advanced Central Receiver Concept 2. Probably Requires Fossile Fuel Topping Cycle to Produce Needed Turbine Inlet Temperatures
Photovoltaic	1. High Performance Potential 2. Simple Control Systems 3. No Operator Required	1. High Cost of Array 2. Cascading Inefficient

were reviewed to determine if they would be suitable for operating at pressure below 15 psig (usual code limit) at the temperatures required by the cycle (700 to 900^{0}C); and it was concluded that none of current designs would be suitable for application to a commercial STES. The principal problem area is the large internal surface heat transfer area required to transfer the energy to the low pressure gas without an excessive pressure loss. Radiation losses from this surface must be minimized through use of a cavity type receiver with an effective concentration ratio above 500:1 so that gas (air) temperatures in the 700^{0}C to 900^{0}C range can be maintained.

Receivers of this type are now (1978) under development by JPL under the Dispersed Power Systems Program so that future studies may be able to compare Rankine and Brayton cycle systems. For this study, which was performed in the 1976-1977 time frame, the Brayton cycle collector was not sufficiently developed to include the system in comparisons of STES for commercial building application. However, solar collector technology suitable for the Rankine cycle STES was considered under development[6-15] and some test data are available. Consequently, only the Rankine cycle was included in this study for the solar thermal STES concept.

STES Control Modes

The performance of the STES is dependent on the control logic used to operate the system. In addition, the type of energy storage also depends on this control logic. Three generic methods of control of the STES were considered. These determine how the power conversion system (PCS) is operated and are as follows:

1) Thermal Control — When the power conversion system (PCS) is sized and operated to provide the building heating, ventilating, and air conditioning (HVAC) and process heating demand load (using reject heat), the system is controlled by the thermal load. In this mode, the PCS always operates to provide enough reject thermal energy for the heating and cooling (thermal) loads. Electricity purchased from the utility is used to meet any unsatisfied building electrical load.

2) Electrical Control — The PCS is operated to provide the entire electrical load for the building. Auxiliary fossil-fired boilers are

TABLE 2

CONTROL MODES FOR STES CONCEPTS

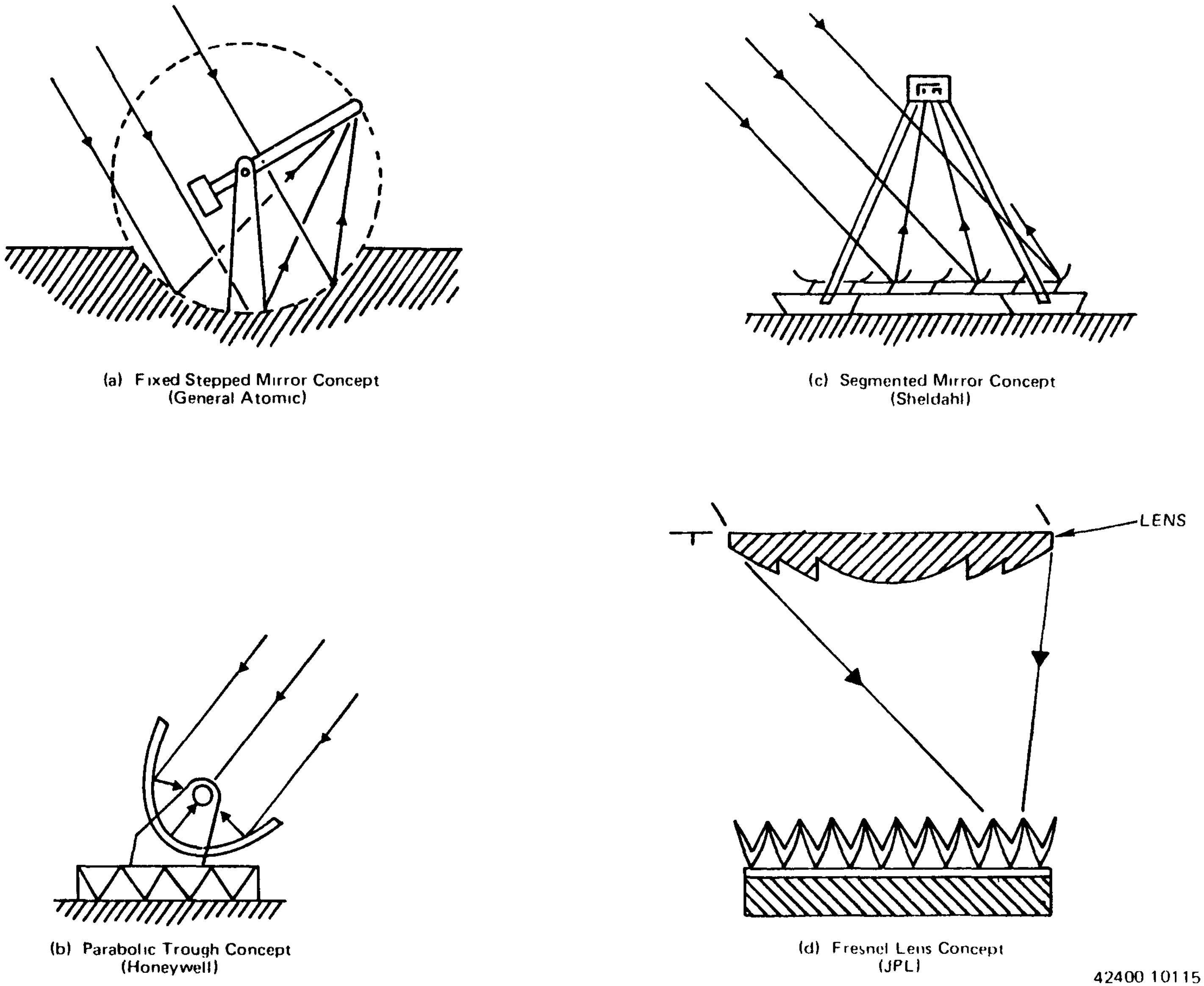
Mode	Description
Electrical Control	Power Conversion System (PCS) Supplies Total Electrical Load (Stand alone concept) Hot thermal (300°C) storage required No utility electricity used Cold storage optional* (10°C) Auxiliary fuel used Type of chiller optional* Not used for photovoltaic STES
Thermal Control	PCS Supplies Total Thermal Load Hot thermal storage required Cold thermal storage optional* Utility electricity used Auxiliary fuel used Type of chiller optional* Not used for photovoltaic STES
Solar Control	PCS Accommodates Available Solar Insolation Applicable for photovoltaic and STES solar thermal For photovoltaic system warm (100°C) thermal storage optional* No hot thermal storage needed Cold thermal storage optional* Battery storage required (no utility buy back) No peak shaving storage considered Type of chiller optional*

*Determined by cost tradeoff

used in conjunction with the solar collector to provide sufficient energy to the PCS to make the system stand alone with no electricity purchased from the utility.

3) Solar Control — The PCS is sized and operated to utilize the solar energy collected by the system. Utility electricity is used to meet any unsatisfied building electrical or cooling load while fossil fuel is burned to meet any unsatisfied building heating requirements.

Solar thermal systems (Rankine cycle PCS) was considered operable in any one of the three control modes (i.e., electrical, thermal, solar) and used either hot thermal storage or battery storage for energy storage in conjunction with cold storage for refrigeration needs. The photovoltaic STES (nonconcentrator system) was operated in the solar control mode only since the flat plate collectors used for meeting the building thermal loads decouple the electrical and thermal requirements. Table 2 summarizes the main features of each of these control modes.



(a) Fixed Stepped Mirror Concept (General Atomic)

(b) Parabolic Trough Concept (Honeywell)

(c) Segmented Mirror Concept (Sheldahl)

(d) Fresnel Lens Concept (JPL)

Figure 7. Distributive Collector Concepts

3.0 COMPONENT CHARACTERIZATION

To evaluate the STES concepts, solar thermal and photovoltaic, the component and subsystems shown in Figures 5 and 6 have been characterized in terms of their performance and cost parameters

The following discussion describes the derivation of the major components models selected for use in evaluating the various STES concepts.

The models derived to characterize these components were of necessity simplistic, so that the computer code using these models could be operated inexpensively and with a minimum of input information about the system or specific components in the system.

3.1 SOLAR ENERGY COLLECTORS

A STES that produces electricity from a heat engine must achieve temperatures beyond the range of flat-plate collectors and will require a tracking, concentrating collector to efficiently heat the working fluid to the necessary temperature range of 230 to 400°C for Rankine cycles STES or 700 to 900°C for Brayton cycle STES. Unfortunately, collector designs suitable for use with the Brayton cycle[16-18] are in a conceptual design period and were not considered to be in hardware development stage suitable for use in commercial buildings for the present study. The combination of a gaseous coolant and extremely high turbine temperature requirements were primary considerations resulting in deletion of Brayton cycle solar collectors from the study program. Collectors suitable for use with the Rankine cycle STES are being developed for both distributed and central receiver configurations. While the configurations discussed below cannot yet be considered "state-of-the-art," the hardware development programs currently in progress should ensure their commercial availability.

3.1.1 Distributed Collectors

Four basic concepts of distributed concentrating collectors being developed for liquid coolants are shown in Figure 7.[6-15] For these collectors, the optical and thermal losses determine their operating efficiencies and are somewhat

TABLE 3

SOLAR CONCENTRATING COLLECTORS

Concept Source	Reference	Concentration Ratio (A_c/A_a)	Optical Efficiency, η_{oc}(%)	Receiver** Emissivity $\left(\frac{\varepsilon_c A_r}{A_a}\right)$	Receiver Convective Loss Coefficient (U)	
					W/m^2-h-^oC	Btu/ft^2-h-^oF
Segmented Mirror						
Sheldahl-Planar	6, 7	30	64(67)*	1.5	8.5	1.5
Sheldahl-V†	6, 7	30	(71)	0.37	8.2	1.44
Itek	6, 8	46	(75)	1.2	1.4	0.24
Parabolic						
Honeywell (NSC)§	6, 9	31	63	1.8	5	0.89
Honeywell (SC)§	6, 9	31	60	0.39	5	0.89
Sandia (NSC)§	10, 11	42	(65)	2	14.1	2.5
Sandia (SC)§	10, 11	42	(64)	0.3	14.1	2.5
JPL†	12	16.8	65	1.0	0.6	0.1
Fresnel Lens						
McDonnell Douglas	13, 14	(40)	(63)	(1)	(5.6)	(1)
Fixed Mirror	6, 15	41	65	(0.3)	(5.6)	(1)

*Numbers in parentheses are estimated values.
†Evaluated from transient data — solid absorber.
§NSC = nonselective coating, SC = selective coating.
**Value used in Equation 1 and which contains area correction term to account for different radiating areas, A_r, and illuminated areas, A_a, on the receiver.

different for each concept. For the evaluation of the :S concepts, the losses can be represented by:*

$$q_{use} = \eta_{oc} I A_c - U A_a (\bar{T} - T_a) - \sigma \varepsilon_c A_a (\bar{T}^4 - T_a^4) \qquad \ldots(1)$$

Data from References 6 through 15 have been used for preliminary evaluation of the loss coefficients for these collectors. These are listed in Table 3 and were used for the collector analyses effort.

Figure 8 provides additional mid-day distributive collector performance data.[11] The solid line represents the performance characteristics selected for representing distributive collector performance in the 1985 time frame as discussed in Section 5.0.

Using the deterministic insolation model discussed in Section 4.2 in conjunction with Equation 1 allows one or two axis tracking collectors to be simulated accurately as well as nontracking distributed collectors based on the solar zenith angle, Θ_z, shown in Figure 9.

The direct normal insolation predicted by this model is used directly in Equation 1 for two-axis tracking systems, while for one-axis east-west oriented tracking systems, the incident insolation is given by:

$$I = I_{DN} (1 - \sin^2 h \cos^2 \delta)^{1/2} \qquad \ldots(2a)$$

and for a N-S orientation:

$$I - I_{DN} \cos\delta \qquad \ldots(2b)$$

For nontracking nonconcentrating collectors, the incident insolation is given by:

$$I = \frac{I_{DN} + 0.384\ I_c}{1.33} [\cos \delta \cos(\phi - T) \cos h + \sin(\phi - T) \sin\delta] \qquad \ldots(3)$$

*See list of symbols on page 167.

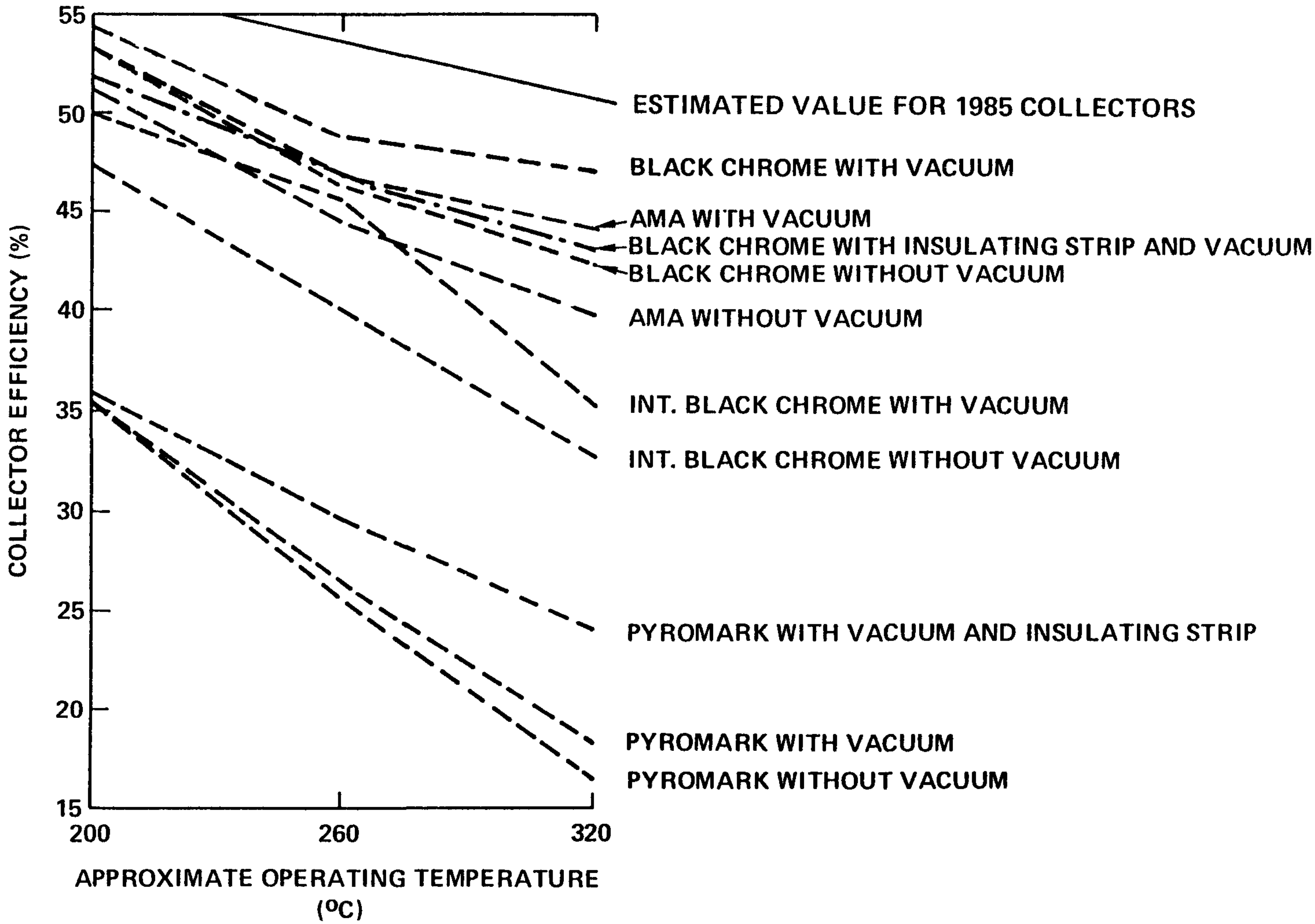


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Figure 8. Distributed Collector Performance Comparison with Sandia Test Data

- APPLIES ANALYTICAL EXPRESSIONS FOR PREDICTABLE EFFECTS
  - SUN POSITION (ZENITH ANGLE θ_Z) AS FUNCTION OF LATITUDE, TIME OF DAY, AND SEASON
  - TRANSMISSION THROUGH THE STANDARD ATMOSPHERE AS FUNCTION OF SEASON:

$$A \cdot \exp(-B/\cos\theta_Z)$$

- DERIVES AVERAGE LOCAL CORRECTIONS BASED ON MEASURED DIRECT AND HORIZONTAL RADIATION
  - RADIATION IS OBSCURED BY CLOUDS FOR (1 - CF) FRACTION OF THE TIME
  - WHEN NOT CLOUDED, LOCAL ATMOSPHERIC EFFECTS ATTENUATE RADIATION BY THE CLEARNESS FACTOR, CN

$$I_{DN} = CN \cdot A \cdot \exp(-B/\cos\theta_Z)$$

  - TOTAL HORIZONTAL RADIATION I_H (DIRECT AND DIFFUSE) ESTIMATED BY LINEAR FORMULA,

$$I_{DN} = \alpha'(I_H/I_H^o) + \beta'$$

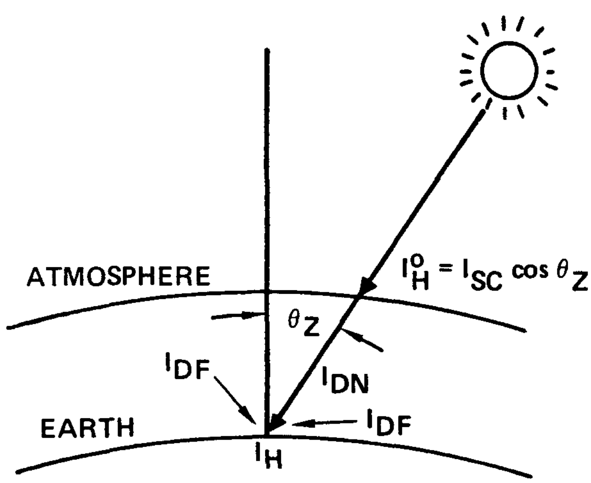

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Figure 9. Deterministic Insolation Model

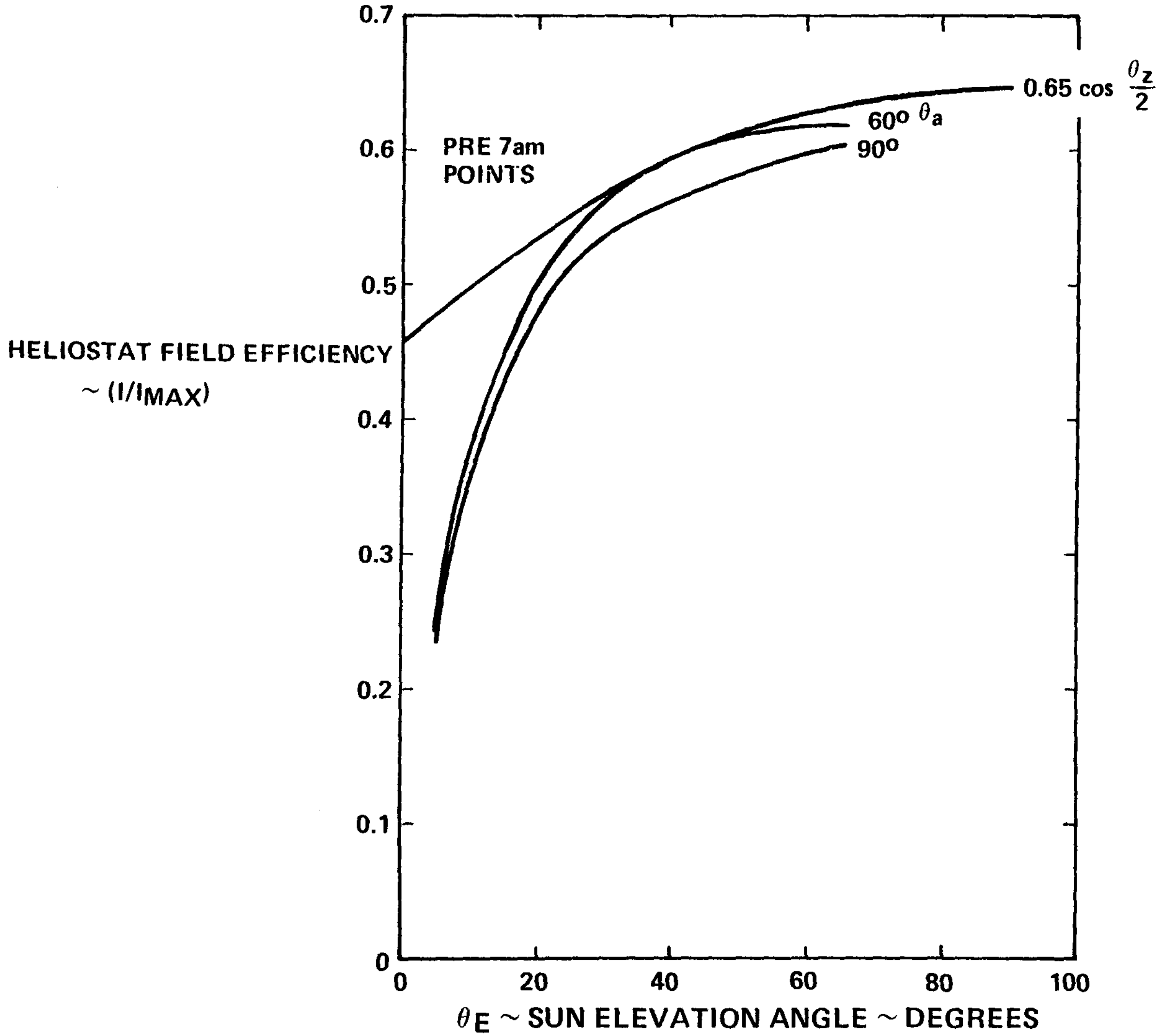

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Figure 10. Comparison of Sandia and Cosine Law Results for Barstow 10 MWe Pilot Plant

The total horizontal insolation is:

$$I_h = \frac{I_{DN} + 0.384\ I_c}{1.33} \cos \theta_z \qquad \ldots(4)$$

where

$$\theta_z = \cos \delta \cos \phi \cos h + \sin \phi \sin \delta\ . \qquad \ldots(5)$$

3.1.2 Central Receivers

Equation 1 also accurately represents the behavior of central receivers if the incident insolation on the absorber is known. The multiple reflection paths from the mirror field precludes the use of simple expressions[19-21] to accurately represent the incident insolation such as those described above. In this program, the direct horizontal insolation has been used in conjunction with cosine of half of the solar angle in Equation 1 to approximate the behavior of the central receiver.

$$I = I_{DN} \cos 0.5\theta_z = I_{DN} \sqrt{0.5(1 + \cos \theta_z)}\ . \qquad \ldots(6)$$

Performance test data for central receivers were not available at the time of the study. However, the 5-MWt facility at Sandia should soon be testing several of the central receiver concepts under development.

Predictions of the heliostat efficiency of the 10-MWe plant to be installed at Barstow, California[22] are shown in Figure 10, along with Equation 6 to indicate that this simple expression gives reasonable predictions for the field cosine losses for 5 h either side of solar noon. Since the sun will not normally be acquired at azimuth angles below 20 deg, this inaccuracy will not normally affect the results for this study.

Estimates for the optical efficiency of small central receivers vary from 0.65[22] to 0.72.[23] Probable concentrations ratios will vary from 250 to 1000. Convective losses[21] will be 2 to 4 times that of distributed systems and the receiver surface emissivity will be above 0.9. These values were used in Equation 1 for this study.

3.1.3 Coolant Pressure and Thermal Losses

Both the distributed and central receiver solar collector systems must be actively cooled. The high temperatures needed for efficient power conversion system operation ∿300°C (∿600°F) severely limits the type of coolant that can be used. Based on the results of the extensive study reported in Reference 19, Caloria HT-43 was selected to provide coolant performance data. Equation 1 is used to predict the energy absorbed by the coolant, and a coolant velocity necessary to limit the wall-to-coolant temperature difference to a specified value (DTW) is computed using the turbulent Nusselt equation with bulk properties of the fluid.

$$N_{Nu} = 0.023\, N_{Pr}^{1/3}\, N_{Re}^{0.8} \qquad \ldots(7)$$

The hydraulic power to produce 20 velocity heads for the coolant flow with a 70% efficient pump was used as the pumping loss for distributed collectors. For central receivers, an additional head is required equal to the tower height.

For distributed collector systems, a thermal energy loss equal to 5% of the collected energy is assumed to account for the piping loss between the collectors and power conversion system.

3.1.4 Photovoltaic Array Performance

Photovoltaic cells convert solar energy directly into electricity but must be connected in arrays to produce easily usable power. One hundred to several hundred cells will normally be connected in series to produce voltage levels compatible with commercial equipment. Consequently, estimating array performance is a complicated process; but, for this study, array efficiency was assumed to represent performance characteristics of the array. An array packing factor of 0.95 was assumed and the photovoltaic array performance was corrected for cell temperature excursions by the equation:

$$\text{array efficiency} = [1 - \beta(T_{cell} - T_{ref})]\, \eta_{oc} \qquad \ldots(8)$$

Figure 11 depicts the effect of temperature on cell efficiency for both silicon and gallium arsenide photovoltaic devices. For purposes of this study gallium arsenide cells were not considered since their application would require a concentrator and tracking to cost effectively utilize the high temperature advantages and expected higher cost of these devices. A nontracking flat plate silicon cell array was assumed based upon the intensive government sponsored activities devoted to developing low cost silicon arrays (e.g. $0.50 per peak watt by early 1980's).

The performance of the photovoltaic array is based on an input cell efficiency at 28°C (15% conversion efficiency was assumed). Equation 1 is used to compute the passively cooled cell temperature each hour based on the ambient air temperature and the input loss coefficient. The cell performance was corrected for temperature effects by the linear coefficient.

Since many of the commercial buildings considered for STES application have all electric power systems, the photovoltaic STES concept is considered a likely candidate for retrofit conversion to solar power. However, the use of electricity for space and process heating is generally both uneconomical and wasteful of energy. For these cases the building heating system is assumed to be

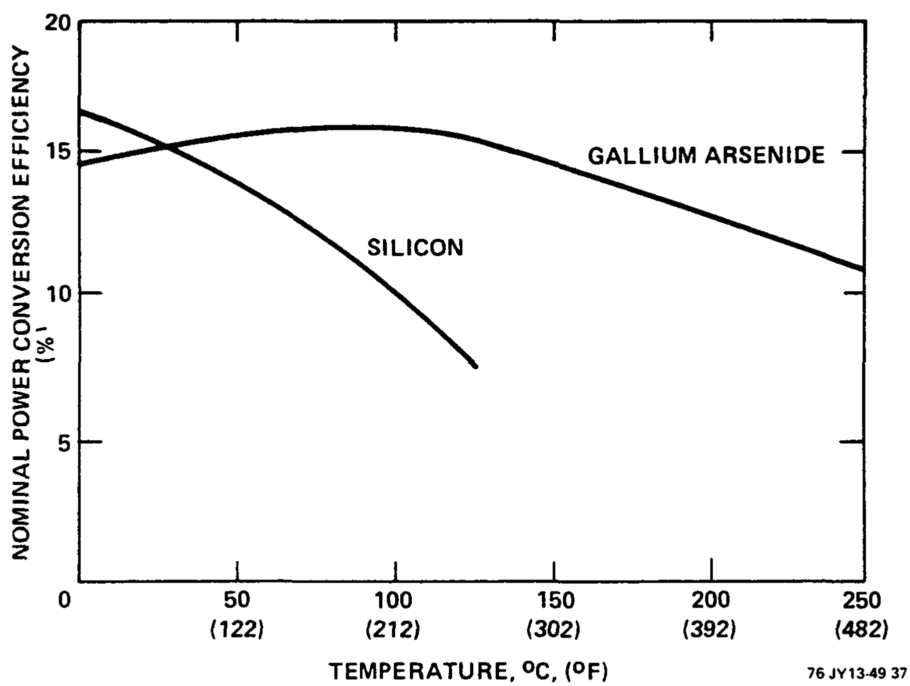

Figure 11. Solar Photovoltaic Devices Performance

converted to use a thermal source of energy. This also enables direct comparison to be made of photovoltaic and solar thermal total energy systems since the base or original operating cost for the building is the same for either system. Flat plate solar collectors can also be used in conjunction with the solar arrays for providing the thermal needs.

3.2 ENERGY STORAGE SUBSYSTEMS

Energy storage is necessary for STES concepts to:

1) Prevent interruption of power due to intermittent cloud cover (smooth out the solar profile).

2) Extend the usable period of operation of the system to nonsunlight periods.

The amount of storage capability will depend upon the application and type of backup or auxiliary energy available. Both the thermal and battery storage systems were considered in evaluating the STES concepts.

The thermal energy can be stored in the collector fluid or in a secondary material (and/or fluid). For STESEP it has been assumed that the additional system complexity required to use a secondary fluid for the storage subsystem would not be cost effective, and only systems using the collector fluid as the transfer medium were considered.

Three types of thermal storage systems suitable for single fluid use have been considered. They are: (1) the double (multiple) tank system of in-line storage, (2) the neat fluid thermocline system of off-line storage, and (3) the dual media thermocline (hot rocks and oil) system of the off-line storage.

For systems requiring a large amount of thermal storage (such as the 100-MWe system described in Reference 19, the cost of the fluid eliminates thermocline and multiple tank storage in favor of dual media storage. However, when only a small amount of energy storage is possible (see Section 5.2), the oil cost does not influence the selection, and efficiency becomes the governing criterion. Double (multiple) tank storage was selected for the STESEP Computer Program on this basis.

3.2.1 Multiple Tank Thermal Storage

Because of the large operational temperature range of the collector fluid, expansion tanks are required to accommodate the volume changes of the fluid. The double tank storage concept uses separate tanks and pumps for the hot and cold legs of the system with a ullage volume equivalent to one of the tanks.

During system operation, the hot leg pump is controlled by PCS demand and the cold leg pump by the collector outlet temperature so that one of the tanks is filling while the other tank is emptying. Thus, both the PCS and collector thermal condition are matched and a separate expansion tank eliminated. The two tanks are designed for complete mixing (i.e., thermal capacitor operation) and, therefore, have only small temperature changes as they fill and empty out of phase with each other. The inert cover gas system can be coupled to minimize makeup gas requirements and trace heaters can even be used to maintain tank temperatures during long outage periods or to preheat the tanks during startup.

The primary loss from this type of storage is that occurring through the insulation and tank supports. This is a function of the tank geometry and duration of storage at temperature, so that an average thermal efficiency can be estimated from an overall energy balance as follows:

Flat Head Tanks:*

$$\eta_{st} = 1 - \frac{(q/A)_{ins}\, t}{\rho c_p (T_{co} - T_{ci})} \frac{2}{D} (2 + D/L) \qquad \ldots(9)$$

Spherical Head Tanks:

$$\eta_{st} = 1 - \frac{(q/A)_{ins}\, t}{\rho c_p (T_{co} - T_{ci})} \frac{12}{D} \frac{1 + L/D}{2 + 3\, L/D} \qquad \ldots(10)$$

Normally, spherical tanks (L/D = 0) will be preferred for double tank storage systems even with low system pressure to minimize thermal losses and aid complete mixing in the tanks.

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*See list of symbols on page 167.

For cold and warm thermal energy storage, a separation bladder in the tank enables the same results to be obtained with a single tank (and pump) so that Equations 9 and 10 apply equally well for hot and cold thermal systems when appropriate thermal conditions are used.

3.2.2 Hot Oil Thermal Stability

An important aspect of the cost of organic Rankine cycle concepts is the thermal stability of the oil used as the heat transfer fluid. Consequently, the thermal stability data developed at Rocketdyne[24,25] has been incorporated into the analysis effort of this study. An Arrhenious-type equation is used to relate the decomposition of the oil to the peak system temperature and was used with the Rocketdyne estimate[24] of the average storage temperature. Decomposition data for both Therminol 66 and Caloria HT-43 were obtained (and are in reasonable agreement with the data reported in Reference 26) and used to compare the storage system costs for the two fluids. Caloria HT-43 was found to be less expensive and, therefore, was the fluid used for this study effort.

The decomposition rate equation used for Caloria HT-43 in the presence of solids is as follows:

$$dr = 1.53 \times 10^6 \exp (21,000/T_{co}) \qquad \ldots(11)$$

where

dr = wt %/hr and T_{co} is in ^oK.

The experimental decomposition rates were found to be only slightly different without the presence of solids for Caloria HT-43 so the same decomposition rate can be used for either. This decomposition rate is divided by the stay time factor of 6.4 from Reference 24 to obtain the predicted loss rate for the system. Replacement costs are then considered as recurring costs in the analysis

3.2.3 Battery Storage System

A survey of the literature on battery storage systems was made, but did not turn up specific information on either system efficiency or costs. Table 4 from Reference 27 indicates the type of information found during the survey. Cycle life data and performance data in the literature are not relatable to either charge/discharge ratio or to the depth of discharge. Consequently, a

TABLE 4

CHARACTERISTICS OF STORAGE BATTERIES

Batteries			Performance							
			Current (April 1976)				Projected			
Systems	Electrolytes	Temperature ($^{\circ}F$)	Wh/kg	W/kg (peak)	Life (No. of Cycles)	Cost ($/kWh)	Wh/kg	W/kg	Cycle Life	Cost ($/kWh)
Near Term (1-2 years)										
Lead/Acid (SOA)	Aqueous H_2SO_4	Ambient	22	50	1000	80	22	50	>1750	45
Intermediate Term (3-5 years										
Lead/Acid (Advanced)	Aqueous H_2SO_4	Ambient	-	-	-	-	50	50	>1500	50
Zn/Cl_2	Aqueous $ZnCl_2$	Ambient	<66	<60	<100	>2000	130	100	>1000	50
Long Term (5 years)										
Li/MS	LiCl-KCl eutectic	400-450	100	120	<250	>2000	150	150	>1000	40
Na/S	β-alumina	300-350	90	100	<200	>2000	170	120	>1000	40
$Na/SbCl_4$	β-alumina + $NaAlCl_4$	200	-	-	5000*	>2000	110	70	>1000	40
Redox	Aqueous Ti/Fe chloride	Ambient	22	-	50	-	55	50	>1000	30

*2-Wh laboratory cell.

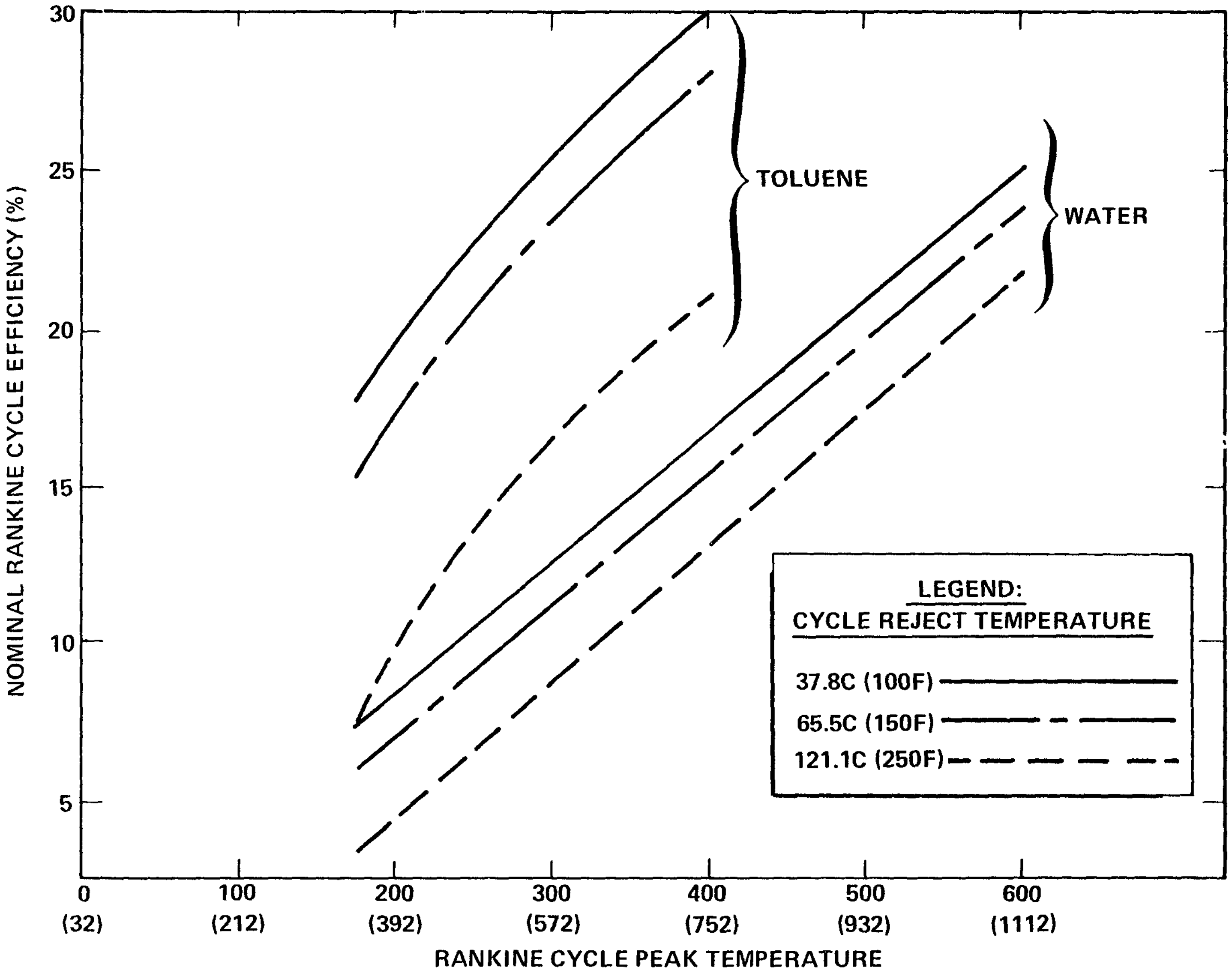

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Figure 12. Heat Reject Temperature Effects on Rankine Cycle

fixed (0.85) battery efficiency factor was assumed which is independent of the charge-discharge rate and depth of discharge. This yields an overall in/out energy efficiency for the battery storage system of 0.722 (i.e.0.85^2). The dc-to-a inverter efficiency is assumed to be 0.95. Based on an optimistic estimated life of 7 years, a recurring cost of 20% of the battery cost has been assumed to include both battery replacement and maintenance of the battery system.

3.3 RANKINE CYCLE POWER CONVERSION SYSTEMS

The Carnot efficiency of a thermal power conversion system is defined by the upper and lower cycle temperature limits and represents the maximum efficiency attainable for those limits. Practical systems such as the Rankine cycle system will operate at a fraction of this efficiency so that the efficiency of a Rankine cycle power conversion system can be represented by*

$$\eta_{PCS} = R_c \left(\frac{T_t - T_{cnd}}{T_t}\right) \qquad \ldots(12)$$

where R_c will be about 0.5[28] for an organic Rankine cycle. Without reheat, a steam Rankine cycle will give somewhat lower performance as indicated in Figure 12. Consequently, this study has assumed the use of an organic Rankine cycle PCS in the STES.

The condensed working fluid will be heated by turbine exhaust gases in organic Rankine systems in a recuperator, which normally will be 90 to 95% effective. The recuperator model assumed to determine the working fluid temperature at the inlet to the main heat exchanger is derived from an energy balance for a fixed effectiveness recuperator. It can be expressed as:

$$T_{ei} = T_t - 1.1\, R_c(T_t - T_{cnd}) \qquad \ldots(13)$$

This assumes equal vapor and liquid specific heat with a 90% recuperator effectiveness and given a reasonable estimate of the conditions for operation of the interconnecting heat exchanger (IHX) between the collector fluid and the turbine working fluid.

*See List of Symbols, p 167.

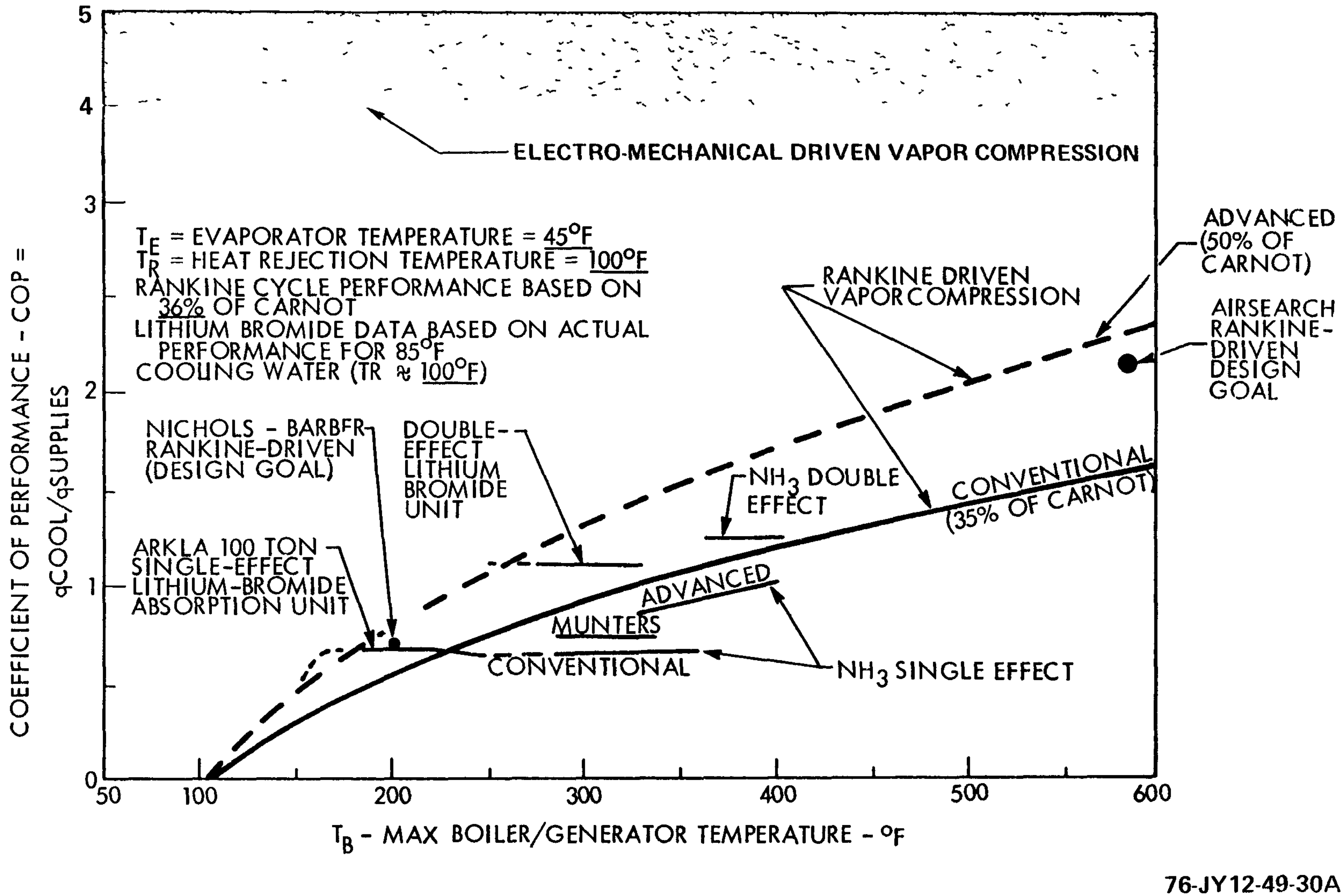

Figure 13. Air Conditioning (Cooling) Performance Comparisons

3.4 HEATING, VENTILATING AND AIR CONDITIONING (HVAC) SYSTEMS

Reject energy from the Rankine cycle PCS can be cascaded to an absorption chiller system to provide cooling for the building. A simplified model of the absorption system was assumed as a fixed fraction of the Carnot refrigeration cycle efficiency in the same manner as used for the PCS. A nominal 35 percent ratio was used in the analyzer giving the absorption cycle efficiencies shown in Figure 13 and represented by the equation:

$$COP = 0.35 \frac{T_{cs}}{T_{ct}} \frac{T_{ct} - T_a - \Delta T_{cnd}}{T_a + \Delta T_{cnd} - T_{cs}} \qquad \ldots(14)$$

Figure 13 also shows the range of Coefficient of Performance (COP) normally produced by commercial vapor compression chillers. A COP of 4.5 was assumed in this study for vapor compression chillers.

Because of efficiency problems with lithium bromide-water absorption systems, a PCS condenser temperature of greater than 105^{o}C (220^{o}F) is required to include the absorption refrigeration system in the analysis. The cold thermal energy storage system discussed in Section 3.2 is automatically included in the analysis when absorption refrigeration systems are analyzed to provide maximum utilization of the energy.

When the Rankine cycle PCS is operated at condenser temperatures below 105^{o}C (220^{o}F), the reject PCS energy is exhausted through the dry cooling tower discussed in Section 3.5 and an electrically driven vapor compression refrigeration system is used to meet the refrigeration demand load of the building.

The building heating system was assumed to use the PCS reject energy at the condenser temperature with 100% efficiency. Fossil fuel was assumed to be used during periods when the building heating and process heat (hot water) demand exceeds the energy available from the PCS. The fossil fuel was assumed to be utilized with a 75% thermal efficiency.

3.5 HEAT EXCHANGERS

Heat exchangers for Rankine cycle STES application are state-of-the art, as are control techniques for the exchangers.

The main heat exchanger serves as high-pressure boiler for the turbine working fluid (which can either be a saturated or superheated vapor) using collector fluid as the energy source. An additional complication is the provision for firing the boiler with fossil fuels, which should not increase the cost significantly over conventional boilers.

The cooling tower requirement will probably be met with an air-cooled heat exchanger, either as a direct condenser for the turbine vapor or as an indirect heat dump using a liquid coolant. Both techniques are in use, with selection made based on the relative location of the turbine and cooling tower.

To model the cooling tower, an air flow rate was assumed that gave an effectiveness of 0.7 for direct condensation of the excess turbine exhaust, which was not required for the building load.

For simplicity in simulation of the main heat exchanger operation, the effective mean temperature difference (MTD) for the heat exchanger was specified and the overall heat transfer coefficient (U) was based on the calculated heat transfer coefficient for the collectors. Using equal thermal capacity streams for both the turbine and collector fluids allows a simple estimate to be made for the area required for the heat exchanger since:

$$q_{use} = U \cdot A_x \cdot MTD \qquad \ldots(15)$$

For supercritical systems, the "pinchpoint" does not present any problems and the solar collector inlet (T_{ci}) and outlet (T_{co}) temperatures are directly calculated.

3.6 COMPONENT CHARACTERISTICS CONCLUSIONS

Components suitable for use in experimental solar total energy systems exist, but only in a limited size range and small quantities. Neither collectors nor arrays suitable for commercial application exist at this time (1976), but could be available for utilization in the 1985 to 1990 time frame without requiring any technology breakthrough. Performance of the experimental designs being tested at Sandia Laboratories, Albuquerque, New Mexico, and elsewhere is probably adequate if costs for the components and subsystems can be reduced to the projected levels, and system lifetimes will meet the assumed durations of 20 to 30 years.

Present concepts of storage systems have unsatisfactory efficiencies and costs, and hence will probably be one of the prime factors in limiting the size of solar total energy systems relative to the building demand loads in the commercial sector since much of the excess solar energy (above the building demand) is lost while in storage for systems in the 200-kWe to 10-MWe power size range.

Power conversion systems for STES are currently limited to organic Rankine cycle systems when line focus distributed collectors are used while steam Rankine cycles are available when point focus or central receiver STES are used.

HVAC systems of conventional designs and heat exchangers are components available in a wide range of capacities and quantities although the efficiency of the components needs improvement for STES application.

TABLE 5

PRELIMINARY SITE SELECTION

Potential Sites (SHAC)*	2-Source Minimum	Assumed Site Represented by	Preliminary Site Selection
Boston/Blue Hill, Mass.	Yes		Blue Hill, Mass.
Washington, D.C.	Yes		Washington, D.C.
Madison, Wis.	Yes		Madison, Wis.
Nashville, Tenn.	Yes		Nashville, Tenn.
Dallas/Ft. Worth, Tx.	Yes		Ft. Worth, Tx.
Omaha, Neb.	Yes		Omaha, Neb.
Pheonix, Ariz.	Yes		Pheonix, Ariz.
Miami, Fla.	Yes		Miami, Fla.
Seattle, Wash.	Yes		Seattle, Wash.
Charleston, South Carolina	No	Nashville	
Bismarck, North Dakota	No	Madison	
Los Angeles, Calif.	Yes		Los Angeles, Ca.
New York City, N.Y.	Yes	Boston	
Denver, Colo.	No	Albuquerque	
Albuquerque, N.M.	Yes		Albuquerque, N.M.
Las Vegas, Nev.	No	Albuquerque	
Salt Lake City, Utah	No	Albuquerque	
Chicago, Ill.	No	Madison	
Atlanta, Ga.	No	Nashville	
Santa Maria, Calif.	No	Los Angeles	
Wilmington, Delaware	No	Washington, D.C.	
Mobile, Alabama	No	Nashville	

*SHAC - Solar Heating and Cooling Studies[29-32]

4.0 COMMERCIAL APPLICATION REQUIREMENTS DEFINITION

Definition of the commercial application requirements was a major objective of this study in order to develop suitable STES concepts and estimates for potential market penetration. To accomplish this objective, data were obtained through published literature, surveys, in-house studies, and subcontractors' (The Energy Group and Envirodyne Engineers) files. The primary requirement areas investigated include potential site characteristics, building types and configurations, census data, building operational characteristics and energy demands, effect of energy conservation, safety, and other constraints (i.e., building codes and standards). The results of these studies were used in selection of representative sites and building models to enable evaluation of the STES for commercial applications. This section describes the development of the requirements data selected for use in this study.

4.1 SITE SELECTION

A reasonable number of sites within the continental United States needed to be identified which would be representative of climatic and environmental conditions one would normally encounter in commercial building applications. An important criterion for selection of these sites was also the availability of the type of data needed to perform the STES evaluation. A number of studies had been performed previously regarding solar heating and cooling (SHAC) applications which included commercial as well as residential applications. Four of these studies were used as basic source documents for characterizing potential sites. The four studies were performed by General Electric Company, Westinghouse Electric Corporation, TRW Systems Group, and InterTechnology Corporation.[29-32]

It was assumed that the application of STES criteria would be more constraining than that for SHAC applications only; however, it should not result in idenfifying entirely new classes of sites that needed to be considered. The four referenced sources list a total of 22 potential sites as shown in the first column of Table 5. At least two of the four sources selected the 12 cities indicated in Table 5 by a "yes in the second column. By correlating these data, 11 preliminary sites, as indicated in the fourth column of Table 5, were selected. The remaining 11 sites were assumed to be representative of the selected sites shown in the third column of the table. In reviewing the source data, little if any correlation in the approach taken to determine regional characteristics was noted. However, there was a fair correlation in the selection of cities for representing a cross section of the U.S. climatology.

For the final site selection, it was decided to reestablish regions which appear to represent the potential differences between STES and SHAC application from a technical standpoint. The factors used for selection criteria included:

1) Primary region boundaries were defined along equal insolation regimes (i.e., annual total horizontal insolation lines). This was based on the assumption that regions of significantly different solar intensity may influence the solar energy availability for STES.

2) The primary regions were further subdivided on the basis of significantly different humidity conditions and the amount of space heating that would be required.

The result was the identification of the six regions shown in Figure 14.

Each of the six regions have climatological features approximately characterized as shown in Table 6. The data sources for the sites are shown in Table 7. After comparing the 11 preliminary site locations from Table 5 with the climatic regions shown in Figure 14, it was decided to add another location in a high-humidity region. Lake Charles, Louisiana, was chosen which gave the final 12 sites listed in Table 8. The major characteristics for these sites are also provided in the table.

TABLE 6

CLIMATIC REGIONS

Region	Location	General Description	Climate Descriptors (Langleys)	Demography
1	Gulf and South Atlantic	High Cooling High Humidity Low Heating Good Insolation	>400	Medium Population High Growth
2	Mid-Belt	Medium Cooling High Humidity Medium Heating Fair Insolation	>350	Medium Population Low Growth
3	Southwest and South Central	High Cooling Low Heating Low Humidity Excellent Insolation	>450	Low Population High Growth
4	Northeast and Great Lakes	No Cooling High Heating High, Short Humidity Poor Insolation	<350	High Population Fair Growth
5	Northwest and North Central	No Cooling High Heating Low Humidity, Fair Insolation	>350	Low Population Low Growth
6	Northwest Coast	No Cooling Medium Heating Poor Insolation	<350	Low Population Low Growth

TABLE 7

DATA SOURCES FOR CLIMATE AND INSOLATION SUMMARY DATA

Site	ASHRAE Design Conditions	Degree Days	Percent Sunshine	Dry Bulb Temperatures	Average Daily Incident Radiation
Lake Charles, La.	4*	2	1(New Orleans)	1(New Orleans)	5
Miami, Fla.	4	2	1	1	5
Nashville, Tenn.	4	2	1	1	5
Washington, D.C.	4	2	1	1	6
Albuquerque, N.M.	4	2	1	3	5
Ft. Worth, Texas	4	2	1		5
Los Angeles, Ca.	4	2	1	3	5
Phoenix, Ariz.	4	2	1	3	5
Blue Hill, Mass.	4(Boston)	2	1(Boston)	1(Boston)	5
Madison, Wis.	4	2	1	1(Green Bay + 1.2°F)	5
Omaha, Neb.	4	2	1(Lincoln)	1(Lincoln + 0.5°F)	5
Seattle, Wash.	4	2	1	1	5

*Data Source Legend References:

1. "Climatic Atlas of the United States," U.S. Department of Commerce (June 1968)
2. Climatography of the U.S., No.81 (by State), U.S. Department of Commerce (August 1973)
3. Local Climatological Data, U.S. Department of Commerce (1972)
4. ASHRAE Handbook of Fundamentals, ASHRAE (1972)
5. ERDA Report No. ERC-R-76005, "Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Contract E(11-1)-2590 Arizona State U., Spectrolab, Inc.
6. Eldon C. Boes, et al, "Distribution of Direct and Total Solar Radiation Availabilities for the U.S.A," Sandia Laboratories Energy Report, SAND 76-0411 (1976)

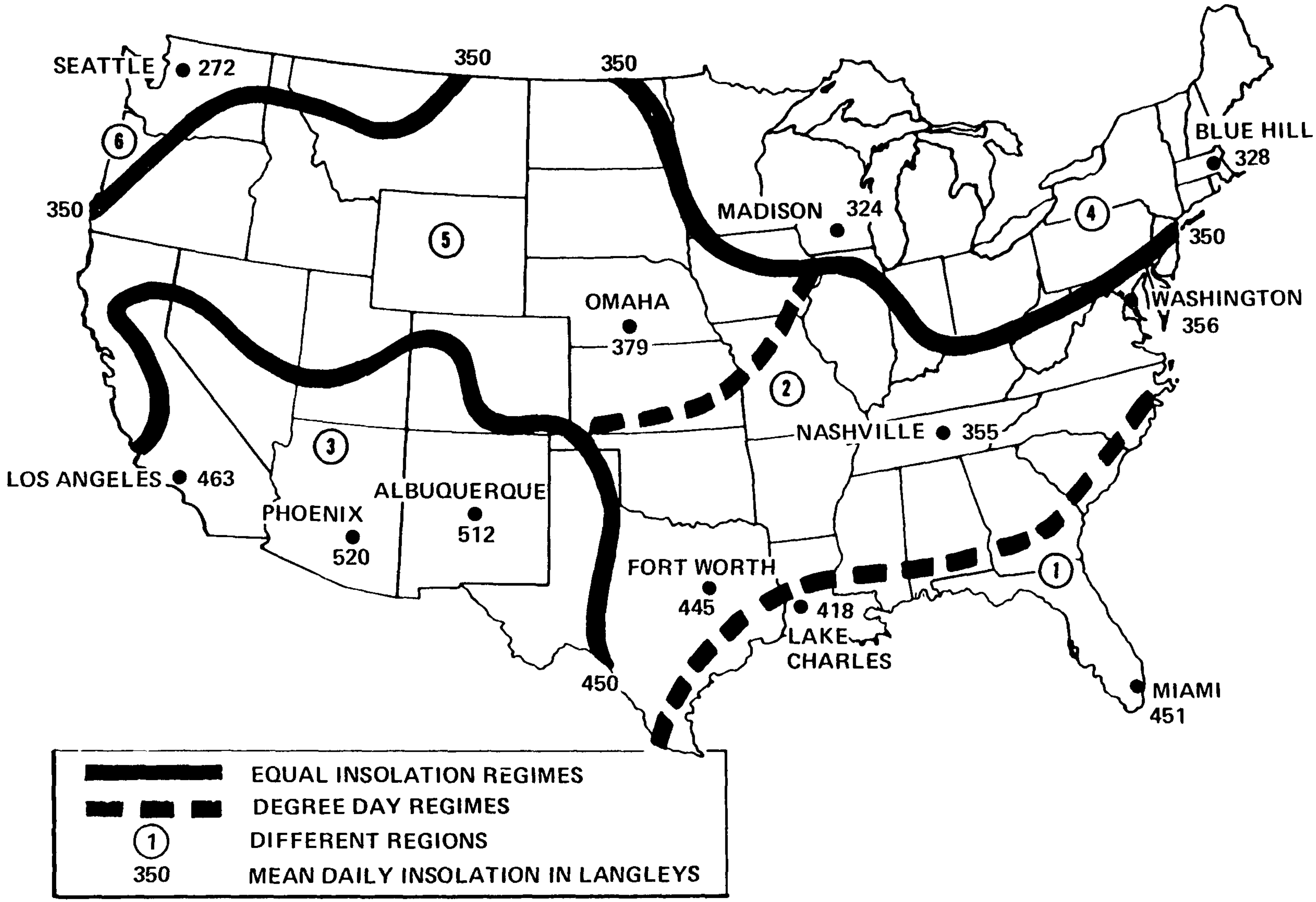

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Figure 14. Candidate STES Study Regions and Sites
(Six Regions, Twelve Sites)

TABLE 8

CHARACTERISTICS OF CANDIDATE STES SITES

REGION	LOCATION	TOTAL INSOLATION (Btu/ft^2-DAY)			HEATING DEGREE DAY (HDD)*		COOLING DEGREE DAY (CDD)*		DESIGN WINTER TEMPERATURE (DRY BULB) (97-1/2 %) (°F)	DESIGN SUMMER TEMPERATURE (2-1/2 %) (°F)	WET BULB TEMPERATURE (°F)	HUMIDITY RATIO (W) lb H_2O / lb DRY AIR	ANNUAL MEAN TEMPERATURE (°F)
		YEAR AVG.	DEC.	JUNE	DEC.	YEAR AVG.	JUNE	YEAR AVG.					
1	LAKE CHARLES, LA.	1542	923	2181	338	1498	471	2739	33	91	60	0.019	68.3
1	MIAMI, FLA.	1664	1166	1963	56	206	480	4038	47	90	65	0.019	70.3
2	NASHVILLE, TENN.	1310	553	2033	763	3696	348	1694	16	95	50	0.018	59.4
2	WASHINGTON, D.C.	1314	612	1822	856	4211	288	1415	19	92	55	0.017	57.3
3	ALBUQUERQUE, N. M.	1889	1018	2679	893	4292	291	1316	17	94	20	0.007	56.8
3	FT. WORTH, TEXAS	1642	904	2402	530	2382	468	2587	24	100	40	0.016	65.5
3	LOS ANGELES, CA.	1708	899	2199	218	1245	115	1145	44	90	36	0.011	64.8
3	PHOENIX, ARIZ.	1919	1037	2727	388	1552	588	3508	34	106	27	0.012	70.3
4	BLUE HILL MASS.	1210	498	1882	1094	6335	69	457	10	88	50	0.015	48.3
4	MADISON, WIS.	1196	424	1897	1336	7730	96	460	-5	88	53	0.015	44.9
5	OMAHA, NEB.	1399	627	2014	1147	6049	236	1173	-1	94	53	0.018	51.5
6	SEATTLE, WASH.	1003	218	1701	710	4695	23	200	32	79	47	0.011	52.6

*BASE TEMPERATURE = 65°F

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4.2 SITE INSOLATION CHARACTERIZATION

Performance predictions for solar energy systems require a mathematical model of the energy incident on the collectors. It is possible to model the long-term behavior of a solar energy system using actual hourly insolation data recorded for the location in question (site) as an input to a transient simulation program like TRYSYS.[3] Such an approach probably gives the best estimate of the performance of a specified solar system. However, it can be expensive if many sites require evaluation, since the simulation must extend over a long period of time to have meaningful predictive value.

A second difficulty with the use of hourly insolation data is its limited availability. Complete hourly data for both total horizontal* and direct normal† radiation at 33 sites over a 2-year period has been prepared on tape by the Aerospace Corporation[33] and 26 sites by Sandia.[34] The two sets overlap to a large extent, giving a total of 41 sites for which detailed hourly data are available. While these sites are fairly well distributed geographically, they do not cover all regions of possible interest. For example, Southern California is represented by seven sites, but there are none for the San Francisco bay area (Northern California).

Data on total horizontal radiation exists for many other sites. However, it is often incomplete and covers variable periods of time. Moreover, hourly values of direct normal radiation must be estimated analytically from the total horizontal values.

In summary, detailed hourly data were available for only a limited number of selected sites, and even for those, application of the data would be a costly process requiring large computer facilities. It was judged inappropriate to the requirements of this study where the primary objectives were concept evaluation and system definition.

At the other extreme, solar energy input to a system can be estimated from average values obtained by numerical integration of the hourly data referred to

*Sum of direct (beam) and diffuse radiation falling on a horizontal surface.
†Direct (beam) radiation falling on a surface normal to the sun's direction.

above. Both the Sandia Laboratories and Aerospace Corporation tape data have been processed to yield daily averages of total horizontal and direct normal radiation on a monthly basis.[34,35] More extensive tables are available for average daily values of total horizontal radiation in Reference 36 (80 sites) and Reference 37 (117 sites). The Climatic Atlas[37] also contains maps from which insolation can be estimated for any site in the United States.

In order to evaluate the useful energy input from average daily values, the latter must be modified by factors which account for the effect of collector aperture orientation and thermal efficiency. These factors can be estimated well enough to carry out preliminary screening. They depend, however, on site location, the time of year, and the detailed systems configuration in a complicated way. Any attempt to define optimum configurations or to assess the influence of component parameters requires a more detailed approach.

The method selected is eclectic, incoporating the features of several methods already in use. It attempts to make maximum use of predictable factors, introducing random factors associated with local weather in the simplest way possible. This approach lends itself to a formulation using simple mathematical expressions suitable for use by hand calculators and small computers. This methods is described in detail in Appendix A, Volume 4. The following summarizes its application in this study.

4.2.1 Deterministic Insolation Model

4.2.1.1 Extraterrestrial Solar Radiation

Solar radiation reaching the top of the earth's atmosphere may be predicted quite accurately. Its intensity is a near constant, I_c, modified only by a small correction, R, which takes into account the effect of seasonal variations in the earth-sun distance. According to Reference 38, this distance correction is approximately:

$$R = 1.0 + 0.033 \cos (360 n'/365) \qquad \ldots(16)$$

where n' is the day of the year. Monthly values of R are also given in Table 9.

TABLE 9

SEASONALLY VARYING SOLAR RADIATION PARAMETERS

Date	R	δ (degree)	A/I_c	B
January 21	1.031	-20.0	0.909	0.142
February 21	1.021	-10.8	0.897	0.144
March 21	1.006	0.0	0.876	0.156
April 21	0.989	+11.6	0.839	0.180
May 21	0.975	+20.0	0.815	0.196
June 21	0.968	+23.45	0.804	0.205
July 21	0.969	+20.6	0.801	0.207
August 21	0.979	+12.3	0.818	0.201
September 21	0.999	0.0	0.850	0.177
October 21	1.011	-10.5	0.881	0.160
November 21	1.026	-19.8	0.902	0.149
December 21	1.033	-23.45	0.911	0.142

The angle of incidence on a horizontal surface (the zenith angle Θ_z) depends upon the geographic location (latitude ϕ), the solar declination δ, and the local solar time, as measured by the hour angle h.

$$\cos \Theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos h \qquad \ldots(17)$$

The solar declination is a function of the day of the year and is given approximately by:

$$\delta = 23.45 \sin [284 + n'(360/365)] \qquad \ldots(18)$$

The declination is also given in Table 9.

4.2.1.2 Estimation of Direct (Beam) Radiation During Noncloudy Times

On noncloudy days, most of the extraterrestrial radiation penetrates the atmosphere with small change in direction. A portion of the initial radiation is absorbed by molecular atmospheric constituents; another fraction is scattered out of the beam direction by molecules, droplets, and suspended solid particles. The attenuation, which depends upon the concentration of absorbers and scatterers in the atmosphere, can be considered to have a local component and a general component which exhibits systematic seasonal variations.

The ASHRAE Handbook of Fundamentals[39] presents a semitheoretical expression for direct normal radiation, I_{DN}, which follows this approach. It is expressed in terms of an apparent extraterrestrial irradiation A and an extinction coefficient B based on air mass.

$$I_{DN} = CN \cdot A \cdot \exp\left(-B/\cos \phi_z\right) \qquad \text{...(19)}$$

where I_{DN} is the irradiation on a surface normal to the beam. The term A includes both the effects of upper atmosphere absorption and of variable earth-sun distance. Table 9 gives monthly values of A and B based upon empirical data from Reference 39. These values have been used in the numerical results reported here. The factor CN is a "clearness number" which characterizes the average local transmittance of the atmosphere. It may exhibit seasonal variations.

4.2.1.3 Estimation of Diffuse Radiation

A certain amount of the radiation scattered by atmospheric constituents and cloud surfaces reaches ground level from directions other than that of the direct beam. The amount of this diffuse radiation received is a complicated function of the state of the atmosphere, the sun's position, ground reflectance, and surface orientation. The diffuse component is estimated by means of two simplifying assumptions: (1) that the diffuse radiation is independent of the orientation of the receiving surface and (2) that the direct normal radiation is linearly related to the "percent possible," the fraction of total (direct plus diffuse) radiation falling on a horizontal surface at ground level compared with the extraterrestrial value. These assumptions result in the following relationship between direct and diffuse radiation intensities:

$$I_{DN} = \alpha' \frac{I_{DN} \cdot \cos \theta_z + I_{DF}}{I_c \cdot R \cdot \cos \theta_z} + \beta' \qquad \text{...(20)}$$

The coefficents α' and β' are empirically determined by linear regression analysis of simultaneous measurements of both total and direct components. Although they are found to depend to some extend on site location and time of day, they are treated as constants in the present application.

4.2.1.4 Effect of Cloud Cover

Solar radiation exhibits periods of reduced intensity associated with the obscuration of sunlight by clouds. The effects range from long-term overcasts, which may last for days, to broken cloud cover, which may block the sun for only a fraction of an hour. The net effect of cloud cover is to reduce the average radiation measured at a given site below the unclouded values. Cloud effects are dependent on local atmospheric characteristics and vary seasonally. In the present method, the effect of cloud cover is approximated very simply. On the average, for each hour of the day, the proportion of unclouded time is assumed to be a constant, CF. During the remaining fraction (1-CF), solar radiation is considered to be nil. The evaluation methodology using CN and CF and data on sunfall outage is discussed in Section 5.1.2.

4.2.2 Climate and Insolation Summary

For each of the twelve selected sites, data summary sheets were prepared for use in the STES evaluation effort. Tables 10 through 21 contain the climate and insolation data used for each of the representative sites as input to the STESEP computer code (see Section 5.0) for obtaining the results discussed in Section 2, Volume 3.

CLIMATE AND INSOLATION SUMMARY

TABLE 10

SITE NAME ALBUQUERQUE N M LATITUDE 35 05° LONGITUDE 106 62°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2%

DRY BULB TEMP 8 3 °C, 94 °F;

WIND SPEED LOW

SUMMER – 2 1/2%

DRY BULB TEMP 34 4 °C, 94 °F,

WET BULB TEMP 18 3 °C, 65 °F

DESIGN RELATIVE HUMIDITY 20 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	513	389	331	156	32	0	0	0	4	121	342	496
	°F	924	700	595	282	58	0	0	0	7	218	615	893
COOLING	°C	0	0	0	3	37	162	236	200	89	4	0	0
	°F	0	0	0	6	67	291	425	360	160	7	0	0

PERCENT POSSIBLE SUNSHINE·

70	72	72	76	79	84	76	75	81	80	79	70

AVERAGE AMBIENT TEMPERATURE RANGE·

MAX D B	°C	8 0	1' 2	14 9	20 6	25 7	31 4	32 9	31 1	27 9	21 5	13 4	9 1
	°F	46 4	52 2	58 8	69 1	78 3	88 6	91 2	88 0	82 3	70 7	56 1	48 3
MIN D B	°C	-4 7	-2 5	0 4	5 7	11 1	16 2	18 8	17 9	14 2	7 4	-0 5	-3 6
	°F	23 5	27 5	32 7	42 2	51 5	61 1	65 8	64 3	57 6	45 3	31 1	25 6

AVERAGE DAILY INCIDENT RADIATION.

HORIZ	kWh/m2	3 58	4 50	6 00	7 30	8 29	8 63	7 39	7 23	5 87	6 23	3 80	3 48
	Btu/ft2	1136	1427	1903	2116	2630	2738	2343	2292	1861	1658	1205	1105
DIRECT	kWh/m2	6 77	7 11	8 48	9 10	10 00	10 40	8 43	8 90	7 37	8 19	6 90	7 23
	Btu/ft2	2149	2254	2591	2887	3172	3299	2691	2824	2337	2599	2189	2292

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 96	0 87	0 99	0 92	1 17	1 17	1 03	1 10	0 93	1 05	0 97	1 14
CLOUD FACTOR	0 84	0 85	0 85	0 87	0 89	0 92	0 87	0 866	0 90	0 89	0 89	0 84

CLIMATE AND INSOLATION SUMMARY

TABLE 11.

SITE NAME BLUE HILL , MASS. LATITUDE 42.22° LONGITUDE 71.02°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -12.2 °C, 10 °F;

WIND SPEED HIGH

SUMMER – 2 1/2%

DRY BULB TEMP 31.1 °C, 88 °F;

WET BULB TEMP 23.3 °C, 74 °F

DESIGN RELATIVE HUMIDITY 50 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	668	583	513	312	151	30	3	8	62	203	378	608
	°F	1203	1050	924	561	271	54	6	14	111	366	681	1094
COOLING	°C	0	0	0	0	6	38	108	83	18	0	0	0
	°F	0	0	0	0	10	69	195	150	33	0	0	0

PERCENT POSSIBLE SUNSHINE:

47	56	57	56	59	62	64	63	61	58	48	48

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	2.8	2.8	7.2	13.3	20.	24.4	27.8	26.7	22.8	17.2	11.1	4.4
	°F	37	37	45	56	68	76	82	80	73	63	52	40
MIN D.B.	°C	-5	-5	-.6	4.4	10	15	18.3	17.2	13.9	8.3	3.3	-2.8
	°F	23	23	31	40	50	59	65	63	57	47	38	27

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	1.87	2.68	4.03	5.07	6.00	6.33	5.71	5.23	4.17	3.35	1.71	1.90
	Btu/ft2	593	850	1278	1608	1903	2008	1811	1659	1323	1063	542	603
DIRECT	kWh/m2	4.06	4.64	5.94	6.33	7.03	7.10	6.42	6.42	5.60	5.48	3.42	4.26
	Btu/ft2	1288	1472	1884	2008	2230	2252	2036	2036	1776	1738	1085	1351

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.74	0.61	0.75	0.82	0.91	0.92	0.79	0.81	0.81	0.92	0.62	1.05
CLOUD FACTOR	0.69	0.75	0.76	0.75	0.77	0.79	0.80	0.79	0.78	0.76	0.70	0.69

CLIMATE AND INSOLATION SUMMARY

TABLE 12

SITE NAME FT WORTH TEXAS LATITUDE 32 83° LONGITUDE 97 05°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2%

DRY BULB TEMP -4 4 °C, 24 °F,

WIND SPEED HIGH

SUMMER – 2 1/2%

DRY BULB TEMP 37 8 °C, 100 °F,

WET BULB TEMP 25 6 °C, 78 °F

DESIGN RELATIVE HUMIDITY 40 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	348	253	186	49	0	0	0	0	0	33	159	294
	°F	626	456	335	88	0	0	0	0	0	60	287	530
COOLING	°C	0	0	14	52	131	260	341	343	212	78	6	0
	°F	0	0	25	94	236	468	614	617	381	141	11	0

PERCENT POSSIBLE SUNSHINE:

56	57	65	66	67	75	78	78	74	70	63	53

AVERAGE AMBIENT TEMPERATURE RANGE

MAX D B	°C	13 3	15 6	19 4	24 4	28 3	33 3	35 6	35 6	31 7	26 1	18 9	14 4
	°F	56	60	67	76	83	92	96	96	89	79	66	58
MIN D.B	°C	1 7	3 9	6 7	12 2	17 2	21 7	23 9	23 9	20	13 3	6 7	2 8
	°F	35	39	44	54	63	71	75	75	68	56	44	37

AVERAGE DAILY INCIDENT RADIATION

HORIZ	kWh/m2	3 06	3 86	5 19	5 20	6 81	6 81	7 42	7 10	5 27	4 39	2 94	2 61
	Btu/ft2	971	1224	1646	1649	2160	2160	2354	2252	1672	1393	933	828
DIRECT	kWh/m2	5 10	5 61	6 71	5 67	7 55	7 58	8 65	8 74	6 47	6 42	4 61	4 55
	Btu/ft2	1618	1779	2128	1799	2395	2404	2744	2772	2052	2052	1462	1443

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 78	0 75	0 81	0 66	0 97	0 87	1 0	1 02	0 79	0 81	0 66	0 71
CLOUD FACTOR	0 75	0 76	0 81	0 81	0 82	0 87	0 88	0 88	0 86	0 84	0 79	0 76

CLIMATE AND INSOLATION SUMMARY

TABLE 13

SITE NAME LAKE CHARLES LA LATITUDE 30 12° LONGITUDE 93 22°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2%

DRY BULB TEMP 0 6 °C, 33 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 33 9 °C, 93 °F;

WET BULB TEMP 26 1 °C, 79 °F

DESIGN RELATIVE HUMIDITY 60 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	231	170	111	14	0	0	0	0	0	20	98	188
	°F	415	306	200	26	0	0	0	0	0	36	177	338
COOLING	°C	12	16	30	79	176	262	299	296	223	106	18	4
	°F	21	29	54	143	316	471	539	533	402	191	33	7

PERCENT POSSIBLE SUNSHINE:

49	50	57	63	66	64	58	60	64	70	60	46

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D B	°C	17 8	19 4	21 7	25 6	28 9	32 2	32 8	32 8	30 6	26 7	21 1	18 3
	°F	64	67	71	78	84	90	91	91	87	80	70	65
MIN D.B.	°C	7 2	8 9	11 1	14 4	17 8	21 7	22.8	22 8	20 6	16 1	10	7 8
	°F	45	48	52	58	64	71	73	73	69	61	50	46

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	2 42	3 68	4 55	5 20	6 48	5 87	6 23	5 68	5 00	4 48	3 06	2 52
	Btu/ft2	766	1167	1443	1649	2055	1862	1976	1802	1586	1421	971	799
DIRECT	kWh/m2	3 35	4 89	4 54	5 53	7 29	6 43	7 10	6 68	5 83	5 94	4 35	3 87
	Btu/ft2	1063	1551	1729	1754	2312	2040	2252	2119	1849	1884	1380	1228

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 48	0 70	0 68	0 67	0 90	0 77	0 96	0 85	0 77	0 76	0 64	0 69
CLOUD FACTOR	0 70	0 71	0 76	0 79	0 81	0 80	0 76	0 78	0 80	0 84	0 78	0 68

CLIMATE AND INSOLATION SUMMARY

TABLE 14

SITE NAME LOS ANGELES CA LATITUDE 34 05° LONGITUDE 118 23°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2,

DRY BULB TEMP 6 7 °C 44 °F,

WIND SPEED VERY LOW

SUMMER – 2 1/2%

DRY BULB TEMP 32 2 °C, 90 °F,

WET BULB TEMP 21 1 °C, 79 °F

DESIGN RELATIVE HUMIDITY 36 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	149	115	106	69	33	14	0	0	3	19	63	121
	°F	268	207	190	124	60	25	0	0	5	35	113	218
COOLING	°C	6	8	6	14	28	64	143	157	131	78	24	0
	°F	10	14	10	25	51	115	258	282	236	140	44	0

PERCENT POSSIBLE SUNSHINE

70	69	70	67	68	69	80	81	80	76	79	72

AVERAGE AMBIENT TEMPERATURE RANGE

MAX D B	°C	18 3	18 9	20 3	21 4	22 9	25 1	28 5	28 5	28 0	25 2	22 9	19 7
	°F	65 0	66 0	68 6	70 6	73 3	77 1	83 3	83 3	82 4	77 3	73 3	67 5
MIN D B	°C	8 1	9 0	10 1	11 7	13 3	14 9	17 0	17 2	16 3	14 1	11 2	9 3
	°F	46 6	48 2	50 2	53 0	56 0	58 9	62 6	62 9	61 4	57 4	52 1	48 8

AVERAGE DAILY INCIDENT RADIATION

HORIZ	kWh/m^2	2 94	3 32	5 23	6 57	6 23	6 27	8 13	7 49	5 87	4 19	3 27	3 03
	Btu/ft^2	931	1054	1658	2083	1975	1988	2579	2353	1861	1330	1036	962
DIRECT	kWh/m^2	5 32	4 86	7 32	8 00	7 03	6 73	9 32	8 84	7 50	6 23	5 63	5 16
	Btu/ft^2	1688	1541	2323	2538	2231	2136	2957	2804	2379	1975	1787	1637

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 64	0 49	0 79	0 99	0 82	0 81	1 15	1 07	0 92	0 73	0 70	0 83
CLOUD FACTOR	0 84	0 83	0 84	0 82	0 83	0 83	0 89	0 90	0 89	0 87	0 89	0 85

CLIMATE AND INSOLATION SUMMARY

TABLE 15

SITE NAME MADISON WIS LATITUDE 43 13° LONGITUDE 89 33°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2%

DRY BULB TEMP -20 6 °C, -5 °F,

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 31 1 °C, 88 °F,

WET BULB TEMP 23 9 °C, 75 °F

DESIGN RELATIVE HUMIDITY 53 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	830	696	599	328	165	40	8	22	96	263	505	742
	°F	1494	1252	1079	591	297	72	14	39	173	474	909	1336
COOLING	°C	0	0	0	0	10	53	96	86	8	3	0	0
	°F	0	0	0	0	18	96	172	154	14	6	0	0

PERCENT POSSIBLE SUNSHINE

44	49	52	53	58	64	70	66	60	56	41	38

AVERAGE AMBIENT TEMPERATURE RANGE

MAX D B	°C	-3 3	-2 2	2 8	11 7	18 9	24 4	28 3	27 2	22 2	16 1	5 6	-1 1
	°F	26	28	37	53	66	76	83	81	72	61	42	30
MIN D B	°C	-12 2	-12 2	-6 1	1 7	7 2	13 9	15 6	15	10 6	4 4	-2 2	-8 9
	°F	10	10	21	35	45	57	60	59	41	40	28	16

AVERAGE DAILY INCIDENT RADIATION

HORIZ	kWh/m2	1 77	2 46	3 68	5 47	6 03	7 13	6 71	6 16	4 50	3 26	1 80	1 56
	Btu/ft2	563	780	1167	1734	1912	2260	2127	1953	1427	1033	571	495
DIRECT	kWh/m2	3 52	4 18	5 10	6 90	7 29	8 67	8 19	7 97	6 30	5 26	3 43	3 35
	Btu/ft2	1116	1325	1617	2187	2311	2448	2596	2526	1997	1667	1087	1062

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 78	0 62	0 72	1 00	0 94	1 09	0 98	1 04	0 96	0 94	0 86	1 00
CLOUD FACTOR	0 66	0 70	0 72	0 73	0 76	0 80	0 84	0 81	0 78	0 75	0 64	0 62

CLIMATE AND INSOLATION SUMMARY

TABLE 16

SITE NAME MIAMI, FLA LATITUDE 25.80° LONGITUDE 80.27°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 8.3 °C, 47 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 32.2 °C, 90 °F;

WET BULB TEMP 26.1 °C, 79 °F

DESIGN RELATIVE HUMIDITY 65 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	29	37	9	0	0	0	0	0	0	0	7	31
	°F	53	67	17	0	0	0	0	0	0	0	13	56
COOLING	°C	67	81	118	167	224	267	298	308	278	221	127	88
	°F	121	145	212	300	403	480	536	555	501	397	229	159

PERCENT POSSIBLE SUNSHINE:

66	72	73	73	68	62	65	67	62	62	65	65

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	24.4	25.	26.7	28.3	29.4	31.1	31.7	32.2	31.1	29.4	26.7	25
	°F	76	77	80	83	85	88	89	90	88	85	80	77
MIN D.B.	°C	14.4	15.	16.1	18.9	21.1	23.3	23.9	23.9	23.9	21.7	18.3	15
	°F	58	59	61	66	70	74	75	75	75	71	65	59

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	3.81	4.79	5.90	6.67	6.68	5.97	6.42	5.71	4.80	4.90	3.80	3.65
	Btu/ft2	1205	1518	1870	2114	2118	1892	2035	1810	1522	1553	1205	1157
DIRECT	kWh/m2	5.52	6.50	7.32	7.47	7.55	6.63	7.19	6.10	5.27	6.48	5.20	5.58
	Btu/ft2	1750	2061	2320	2368	2393	2102	2279	1934	1671	2054	1648	1769

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.69	0.70	0.80	0.89	0.93	0.83	0.92	0.76	0.68	0.86	0.71	0.76
CLOUD FACTOR	0.81	0.85	0.85	0.85	0.83	0.79	0.81	0.82	0.79	0.79	0.81	0.81

CLIMATE AND INSOLATION SUMMARY

TABLE 17

SITE NAME NASHVILLE, TENN LATITUDE 36 12° LONGITUDE 86 68°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -8.9 °C, 16 °F;

WIND SPEED LOW

SUMMER – 2 1/2%

DRY BULB TEMP 35 °C, 95 °F;

WET BULB TEMP 25.6 °C, 78 °F

DESIGN RELATIVE HUMIDITY 50 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	460	373	291	98	25	0	0	0	6	100	277	424
	°F	828	672	524	176	45	0	0	0	10	180	498	763
COOLING	°C	0	0	11	16	85	193	252	233	122	29	0	0
	°F	0	0	19	29	153	348	453	419	220	53	0	0

PERCENT POSSIBLE SUNSHINE:

42	47	54	60	65	69	69	68	69	65	55	42

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	9 4	10.6	15	21 7	26.7	31 1	32.8	32.2	29 4	23 3	15	10
	°F	49	51	59	71	80	88	91	90	85	74	59	50
MIN D.B.	°C	-0.6	0.6	3.9	8 9	13.9	18.9	21.1	20.0	16.1	9 4	3.3	0
	°F	31	33	39	48	57	66	70	68	61	49	38	32

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m²	1.97	2.89	3 71	5.07	6 13	5.77	5.90	5 61	4.37	3 87	1.94	1.84
	Btu/ft²	625	917	1177	1608	1944	1830	1871	1779	1386	1228	615	584
DIRECT	kWh/m²	3.26	4.04	4 48	5 63	6 68	5 90	6 19	6.23	5 03	5.39	2 90	3 06
	Btu/ft²	1034	1281	1421	1786	2119	1871	1963	1976	1596	1710	920	971

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0 56	0 61	0 56	0 71	0 84	0 69	0 76	0 79	0 65	0 80	0 40	0 64
CLOUD FACTOR	0 65	0 69	0 74	0 78	0 81	0 83	0 83	0 83	0 83	0 81	0 74	0 65

CLIMATE AND INSOLATION SUMMARY

TABLE 18

SITE NAME OMAHA, NEB LATITUDE 41 37° LONGITUDE 96 02°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -18 3 °C, -1 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 34 4 °C, 94 °F;

WET BULB TEMP 25 6 °C, 78 °F

DESIGN RELATIVE HUMIDITY 53 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	730	576	481	217	82	11	0	3	39	167	417	637
	°F	1314	1036	865	391	148	20	0	6	71	301	750	1147
COOLING	°C	0	0	0	6	48	131	210	186	61	11	0	0
	°F	0	0	0	10	86	236	378	334	110	19	0	0

PERCENT POSSIBLE SUNSHINE:

57	59	60	60	63	69	76	71	67	66	59	55

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D B	°C	1 7	3 9	9 4	17 8	23 9	29 4	33 9	32 2	27 8	21 1	11 1	5
	°F	35	39	49	64	75	85	93	90	82	70	52	41
MIN D.B	°C	-8 3	-6 7	-1 7	5	11 1	17 2	20 6	19 4	13 9	7 2	-0 6	-5
	°F	17	20	29	41	52	63	69	67	57	45	31	23

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	2 45	2 89	4 19	5 33	5 84	6 90	6 84	5 94	4 67	3 84	2 40	2 10
	Btu/ft2	777	916	1328	1690	1851	2187	2168	1883	1480	1217	761	666
DIRECT	kWh/m2	5 58	4 68	5 90	6 60	6 55	7 8[illegible]	7 90	7 32	6 10	6 29	4 77	4 81
	Btu/ft2	1769	14[illegible]1	1870	2092	2076	2482	2504	2320	1934	1994	1512	1525

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 94	0 64	0 75	0 84	0 81	0 97	0 93	0 90	0 88	0 99	0 89	1 02
CLOUD FACTOR	0 76	0 77	0 78	0 78	0 79	0 83	0 87	0 84	0 82	0 81	0 77	0 74

CLIMATE AND INSOLATION SUMMARY

TABLE 19

SITE NAME PHOENIX ARIZ LATITUDE 33 43° LONGITUDE 112 02°

ASHRAE DESIGN CONDITION

WINTER - 97 1 2%

DRY BULB TEMP 1 1 °C, 34 °F,

WIND SPEED VERY LOW

SUMMER – 2 1/2%

DRY BULB TEMP 41 1 °C, 106 °F,

WET BULB TEMP 24 4 °C, 76 °F

DESIGN RELATIVE HUMIDITY 27 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	238	162	103	33	0	0	0	0	0	9	101	216
	°F	428	292	185	60	0	0	0	0	0	17	182	388
COOLING	°C	0	8	12	78	197	327	451	415	313	133	14	0
	°F	0	14	21	141	355	588	812	747	564	240	26	0

PERCENT POSSIBLE SUNSHINE.

76	79	83	88	93	94	84	84	89	88	84	77

AVERAGE AMBIENT TEMPERATURE RANGE·

MAX D B	°C	17 8	20	23 9	28 9	33 9	38 9	40 6	38 9	36 7	30 6	23 3	18 9
	°F	64	68	75	84	93	102	105	102	98	87	74	66
MIN D B	°C	1 7	3 9	6 1	10	13 9	18 9	23 9	22 8	19 4	12 8	5 6	2 8
	°F	35	39	43	50	57	66	75	73	67	55	42	37

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	3 61	4 50	5 97	7 23	8 00	8 10	7 74	6 87	5 93	5 13	3 74	3 42
	Btu/ft2	1145	1427	1894	2293	2538	2569	2455	2179	1881	1627	1186	1085
DIRECT	kWh/m2	6 42	6 86	8 16	8 97	9 65	9 67	9 19	8 26	7 43	7 81	6 39	6 65
	Btu/ft2	2036	2176	2588	2845	3061	3067	2915	2620	2357	2477	2027	2109

EFFECTIVE ATMOSPHERE FACTORS.

CLEARNESS NO	0 83	0 76	0 85	0 92	0 96	0 96	1 02	0 91	0 84	0 89	0 82	0 92
CLOUD FACTOR	0 87	0 89	0 91	0 94	0 96	0 97	0 92	0 92	0 94	0 94	0 92	0 88

CLIMATE AND INSOLATION SUMMARY

TABLE 20

SITE NAME SEATTLE WASH LATITUDE 47 45° LONGITUDE 122 30°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2%

DRY BULB TEMP 0 °C, 32 °F,

WIND SPEED LOW

SUMMER – 2 1/2%

DRY BULB TEMP 26 1 °C, 79 °F,

WET BULB TEMP 18 3 °C, 65 °F

DESIGN RELATIVE HUMIDITY 47 %

DEGREE DAYS

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	410	319	329	238	143	69	31	32	68	184	297	372
	°F	738	574	592	429	258	124	56	57	123	332	534	670
COOLING	°C	0	0	0	0	0	12	50	38	10	0	0	0
	°F	0	0	0	0	0	22	90	69	18	0	0	0

PERCENT POSSIBLE SUNSHINE

27	34	42	48	53	48	62	56	53	36	28	24

AVERAGE AMBIENT TEMPERATURE RANGE

MAX D B	°C	6 7	8 3	10 6	14 4	18 9	21 1	24 4	23 9	22 8	15 6	10 0	7 8
	°F	44	47	51	58	66	70	76	75	73	60	50	46
MIN D B	°C	0 6	1 7	2 2	5 0	7 2	10 0	12 2	12 2	8 3	6 7	3 3	2 2
	°F	33	35	36	41	45	50	54	54	47	44	38	36

AVERAGE DAILY INCIDENT RADIATION

HORIZ	kWh/m2	1 19	1 96	3 10	4 20	5 94	6 00	6 19	5 13	4 03	2 19	1 10	0 84
	Btu/ft2	379	623	982	1332	1883	1903	1965	1627	1279	696	349	266
DIRECT	kWh/m2	2 68	3 46	4 52	5 10	7 00	6 97	7 45	6 45	5 70	3 48	2 20	1 90
	Btu/ft2	849	1099	1433	1618	2220	2210	2364	2046	1808	1105	698	604

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 93	0 76	0 75	0 74	1 02	1 08	0 98	0 95	1 03	0 91	0 78	0 87
CLOUD FACTOR	0 52	0 58	0 65	0 69	0 73	0 69	0 79	0 75	0 73	0 60	0 53	0 49

CLIMATE AND INSOLATION SUMMARY

TABLE 21

SITE NAME WASHINGTON, D C LATITUDE 38 89° LONGITUDE 77 03°

ASHRAE DESIGN CONDITION

WINTER – 97 1/2%

DRY BULB TEMP -7 2 °C, 19 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 33 3 °C, 92 °F;

WET BULB TEMP 25 0 °C, 77 °F

DESIGN RELATIVE HUMIDITY 55 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	506	431	343	147	40	0	0	0	8	106	283	476
	°F	911	776	617	265	72	0	0	0	14	190	510	856
COOLING	°C	0		4	5	62	148	216	191	101	21	0	0
	°F	0	0	8	9	111	267	388	344	181	37	0	0

PERCENT POSSIBLE SUNSHINE:

46	53	56	57	61	64	64	62	62	61	54	47

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B	°C	6 7	7 8	12 2	18 9	24 4	28 3	30 6	29 4	26 1	20	13 9	7 8
	°F	44	46	54	66	76	83	87	85	79	68	57	46
MIN D.B.	°C	-1 1	-1 7	2 2	7 8	13 3	18 3	20 6	20	16 1	10	3 9	-0 6
	°F	30	29	36	46	56	65	69	68	61	50	39	31

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	2 20	2 90	4 20	5 20	5 70	6 40	5 90	5 40	4 60	3 50	2 30	2 00
	Btu/ft2	699	919	1331	1648	1807	2029	1870	1712	1458	1110	729	634
DIRECT	kWh/m2	3 80	4 10	5 00	5 70	5 60	6 40	5 50	5 50	5 20	4 70	3 60	3 60
	Btu/ft2	1205	1300	1585	1807	1775	2029	1744	1744	1648	1490	1141	1141

EFFECTIVE ATMOSPHERE FACTORS

CLEARNESS NO	0 78	0 62	0 74	0 81	0 79	0 90	0 82	0 83	0 85	0 80	0 73	0 85
CLOUD FACTOR	0 68	0 73	0 75	0 76	0 78	0 80	0 80	0 79	0 79	0 78	0 73	0 69

4.3 COMMERCIAL BUILDING CENSUS

Estimates of the number and distribution (i.e., by size and geographic region) of candidate STES applications within the commercial sector were required to be defined. For purposes of this investigation, these applications have been defined as facilities which require at least 200 kWe. The candidate applications have been categorized as:

1) The retail sector, as represented by shopping centers or integrated shopping complexes having more than 1860 m^2 (20,000 ft^2) of gross leasable area (GLA). It was assumed that the energy requirements for the lower size buildings is about 108 W/m^2 (10 W/ft^2) as discussed in Section 4.4.
2) Office buildings (including banks, federal, states, local, and privately owned) which are less than 10 stories high. It was assumed that high rise buildings would not have adequate available land area for the required solar collector field area.
3) Other, including hotels and motels below 3 stories, warehouses, nursing homes, dormitories, etc. (Schools, libraries, auditoriums, religious institutions, etc., were relegated to the institutional and recreational sectors).

4.3.1 Shopping Centers and Retail Establishments

Information relative to shopping centers and retail establishment census data was compiled and evaluated in order to develop potential market estimates. The total number of commercial shopping centers (including nearly every type of retail establishment) was about 18,500 in 1975.[40] These centers are categorized by size (i.e., GLA) and range from under 1860 m^2 (20,000 ft^2) to over 92,900 m^2 (1,000,000 ft^2) and are generally classified as:[41]

Super Regional — Consists of 69,700 m^2 (750,000 ft^2) and over of GLA area and three or more major department stores.

Regional Center — Consists of 50 to 100 stores, including at least one major department store; 35 or more acres land area; dependent upon population of about 150,000 people; and has usually over 27,880 m^2 (300,000 ft^2) in GLA.

Community Center — Consists of 20 to 40 stores, including one junior department store; 20 to 25 acres of land area; 5,000 families needed for support; usually has 9,290 to 27,800 m^2 (100,000 to 300,000 ft^2) in GLA.

Neighborhood Center — Consists of 10 to 15 stores including food, drug, sundry, and personal service stores; 5 to 10 acres of land area; needs at least 1,000 families for support; and usually has under 9,290 m^2 (100,000 ft^2) in GLA.

In order to estimate the distribution of the 18,500 centers by size within the six regions selected in Section 4.1, samplings of the data were performed to establish possible trends.

Figure 15 presents the variation in total GLA as a function of city population. The amount of GLA appears to lie within a two-to-one range for a given city population. Also it can be seen that the total GLA increases nearly directly with increasing city populations. This correlates with the data on category classification on the basis of population of people.

The distribution of centers by size (GLA) is given in Figure 16. Over two-thirds of the 18,500 centers have a GLA in excess of 4,647 m^2 (50,000 ft^2) and represent the major market potential for STES sized to provide more than 200 kWe minimum in future energy conserving building designs. The variance within the several size categories, the cities, states, and/or regions, sampled was relatively small.

Table 22 shows the distribution of these establishments by number, size, and total GLA for the various states and the District of Columbia. Also given in this table are the urban population percentages for the state. These values are based upon the 1975 census data[42] for the distribution of urban and rural population for each state and were used in developing the total GLA on a state-by-state basis. Figures 17 and 18 show the average shopping center size for urban and rural areas sampled respectively. Based upon these data, the average (weighted arithmetic) sized shopping center in the United States has about 14,777 m^2

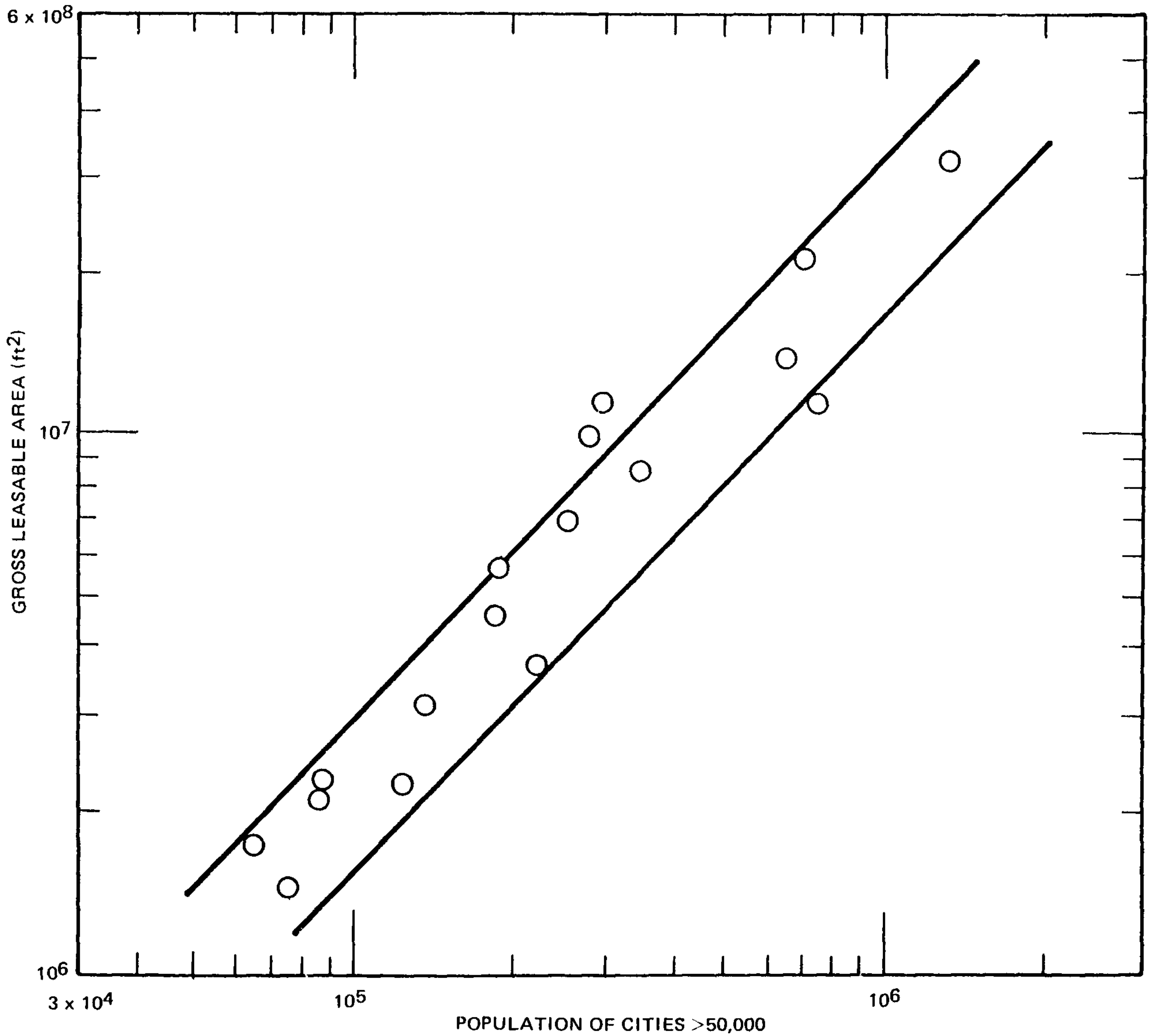


Figure 15. Variation in Shopping Center Size as a Function of City Population

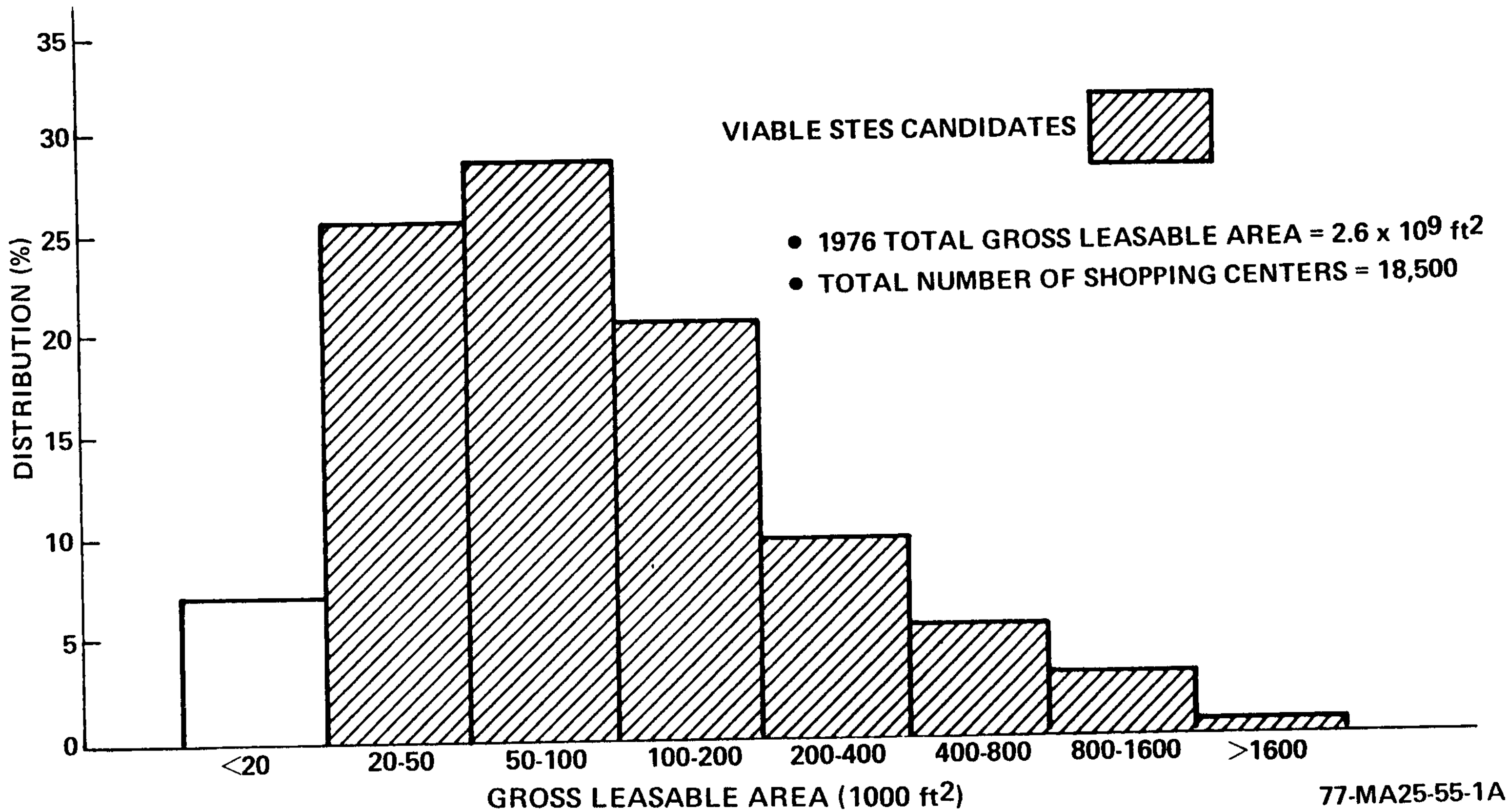


Figure 16. Shopping Centers — Distribution by Size

TABLE 22

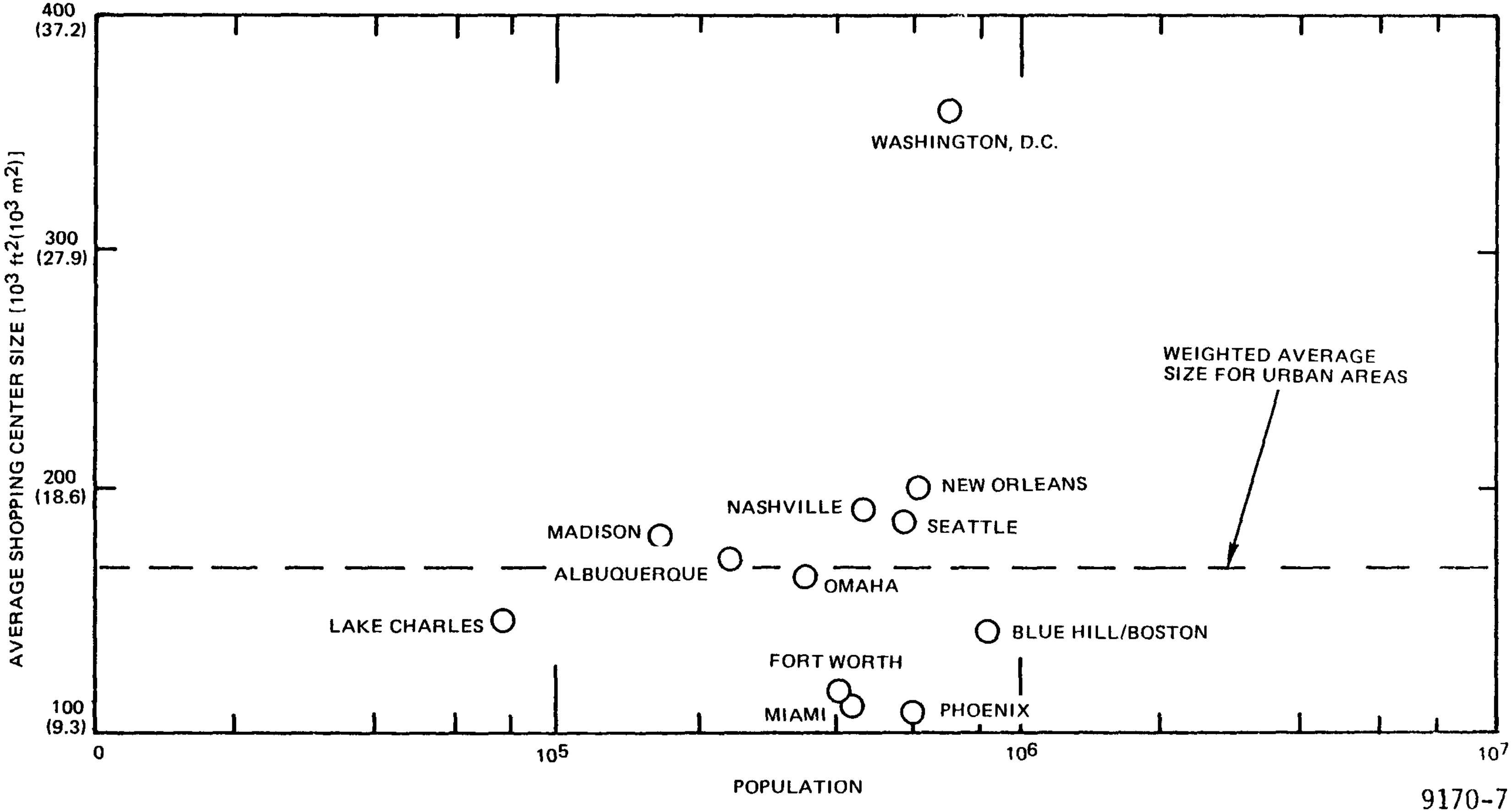
SHOPPING CENTER/RETAIL ESTABLISHMENT
– STATE BY STATE DISTRIBUTION
(Sheet 1 of 2)

State	Urban Population Percentage	Number of Establishments	Average [$10^3 m^2$ (10^3 ft^2)]		Total Gross Leasable Area $10^6 m^2$ (10^6 ft^2)	
Alabama	58	329	12.4	(134)	4.1	(44)
Arizona	79.6	443	13.6	(146)	6.0	(65)
Arkansas	50	226	12.0	(129)	2.7	(29)
California	90.9	2234	14.2	(153)	31.7	(341)
Colorado	78.5	319	13.5	(145)	4.3	(46)
Connecticut	77.4	391	13.5	(145)	5.3	(57)
Delaware	72.2	74	13.2	(142)	0.9	(10)
District of Columbia	100	13	14.7	(158)	0.2	(2)
Florida	80.5	1015	13.7	(147)	13.8	(149)
Georgia	60.3	608	12.5	(135)	7.6	(82)
Indiana	64.9	446	12.8	(138)	5.7	(61)
Illinois	93.0	676	13.7	(148)	9.3	(100)
Idaho	54.1	62	12.5	(135)	0.7	(8)
Iowa	57.2	142	12.4	(133)	1.8	(19)
Kansas	66.1	267	12.8	(138)	3.4	(37)
Kentucky	52.3	272	12.1	(130)	3.2	(35)
Louisiana	66.1	408	12.8	(138)	5.2	(56)
Maine	50.8	110	12.0	(129)	1.3	(14)
Maryland	76.6	415	13.4	(144)	5.6	(60)
Massachusetts	84.6	541	13.8	(149)	7.5	(81)
Michigan	73.8	463	13.3	(143)	6.1	(66)
Minnesota	66.4	252	12.9	(139)	3.2	(35)
Mississippi	44.5	223	11.7	(126)	2.6	(28)
Missouri	70.1	458	13.1	(141)	5.9	(64)
Montana	53.4	64	12.2	(131)	0.7	(8)

TABLE 22

SHOPPING CENTER/RETAIL ESTABLISHMENT
— STATE BY STATE DISTRIBUTION
(Sheet 2 of 2)

State	Urban Population Percentage	Number of Establishments	Average $[10^3 m^2 (10^3 ft^2)]$		Total Gross Leasable Area $[10^6 m^2 (10^6 ft^2)]$	
Nebraska	61.5	101	12.6	(136)	1.3	(14)
Nevada	80.9	81	13.7	(147)	1.1	(12)
New Hampshire	56.4	87	12.4	(133)	1.1	(12)
New Jersey	88.9	463	14.1	(152)	6.5	(70)
New Mexico	69.8	143	13.0	(140)	1.8	(20)
New York	85.6	917	13.9	(150)	12.7	(137)
North Carolina	45.0	483	11.7	(126)	5.7	(61)
North Dakota	44.3	29	11.7	(126)	0.4	(4)
Ohio	75.3	757	13.4	(144)	10.1	(109)
Oklahoma	68.0	318	12.9	(139)	4.1	(44)
Oregon	67.1	203	12.9	(139)	2.6	(28)
Pennsylvania	71.5	791	13.1	(141)	10.4	(112)
Rhode Island	87.1	102	14.0	(151)	1.4	(15)
South Carolina	47.6	251	11.9	(128)	3.0	(32)
South Dakota	44.6	19	11.7	(126)	0.2	(2)
Tennessee	58.7	396	12.4	(134)	4.9	(53)
Texas	79.7	1552	13.6	(146)	21.1	(227)
Utah	80.4	70	13.7	(147)	0.9	(10)
Vermont	32.2	52	11.0	(119)	0.6	(6)
Virginia	63.1	466	12.7	(137)	5.9	(64)
Washington	72.6	303	13.2	(142)	4.0	(43)
West Virginia	39.0	80	16.1	(173)	0.9	(10)
Wisconsin	65.9	285	12.8	(138)	3.6	(39)
Wyoming	60.5	26	12.5	(135)	0.4	(4)



9170-7

Figure 17. Shopping Centers — Average Size Urban Areas

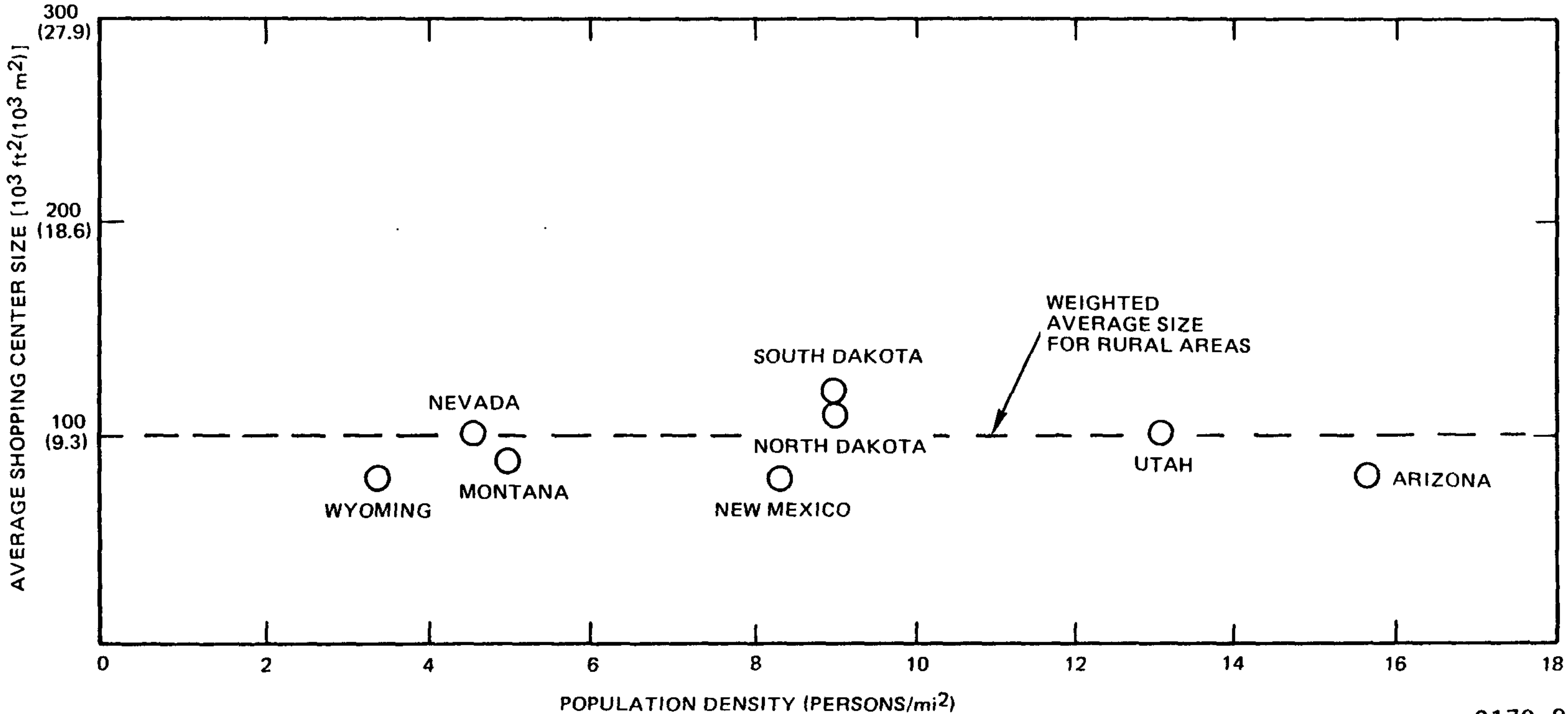


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Figure 18. Shopping Centers — Average Size Rural Areas

(159,000 ft^2 of GLA for urban areas and about 9,290 m^2 (100,000 ft^2) for rural areas. Distribution of shopping center and retail establishment GLA in each of the six STES climatic regions (Refer to Figure 14) are shown in Table 23.

TABLE 23
REGIONAL DISTRIBUTION OF SHOPPING CENTERS AND RETAIL ESTABLISHMENTS (GLA)

Region	GLA ($10^6 m^2$)	GLA (10^6 ft^2)
1	27.5	296
2	72.9	785
3	41.3	444
4	65.7	707
5	30.0	323
6	5.9	63
Total Continental U.S.	243.3	2,618

This information on the shopping centers/retail establishments was employed to further develop STES market potential and penetration rate estimates on a region-by-region, site-by-site basis for the STES applications as discussed in Section 4.0, Volume 3.

4.3.2 Office Buildings

The 1976 edition of the "Downtown and Suburban Office Building Experience Exchange Report"[43] and the data presented in Reference 44 indicate that in 1975, the distribution of commercial office buildings in the United States was as shown in Table 24.

The referenced data also showed that the downtown and suburban office buildings under 10 stories on the average represent about 13.3% of the total commercial office area. Assuming 50% of this sample represents facilities which require an energy demand of more than 200 kWe, then the candidate office building population is less than 27.9 x $10^6 m^2$ (300 x 10^6 ft^2). It was also assumed that the regional distribution of office buildings normally followed the demographic patterns

TABLE 24

CHARACTERISTICS OF COMMERCIAL OFFICE BUILDINGS

Item	Downtown[43]		Suburban[43]		Total Sample Inventory[44]
Stories	<5	5-10	<5	5-10	
No. of Buildings ($\times 10^3$)	22*	55*	30*	29*	366
Area [$10^6 m^2$ (ft^2)]	3.2(35)*	29(311)*	8.5(92)*	13.4*145)*	406(4382)
Average Building Size [$10^3 m^2$ (ft^2)]	3.0(32)	10.8(117)	5.8(63)	9.4(102)	—
% All Buildings	6.1	15.1	8.2	8.0	—
% Total Area	0.8	7.1	2.1	3.3	—

*Indicates quantity calculated from combined data in References 43 and 44

established for the shopping centers and retail establishments. This information was used in developing the potential market and penetration estimates discussed in Section 4.0, Volume 3.

4.3.3 Other Buildings

Data on "other" building categories found within the commercial sector are reported in Reference 44. These typically include the types of facilities shown in Table 25.

TABLE 25

CHARACTERISTICS OF OTHER COMMERCIAL BUILDINGS

Item	Number of Buildings	GLA [$10^6 m^2$ (ft^2)]	Average Size [$10^3 m^2$ (ft^2)]
Health Related	48,000	165 (1787)	3.4 (37)
Warehouses	248,000	299 (3324)	1.2 (13)
Hotels and Motels (<3 Stories)	30,000	57 (619)	1.9 (21)
Miscellaneous	37,000	98 (1061)	2.5 (27)
Totals	365,000	620 (6691)	—

The "applicable fraction" of these facilities (i.e., those STES installations which require $\gtrsim$200 kWe) was estimated to be on the order of 25% of the gross leasable area. Regional distributions were also assumed to be the same as those developed for the shopping centers and retail establishments. This information was used in developing the potential market and penetration estimates discussed in Section 4.0, Volume 3.

4.4 COMMERCIAL BUILDING ENERGY USAGE

In order to develop a meaningful correlation between building energy usage and building construction, site and building internal system parameters, a comprehensive survey was made of several sources of building energy usage. Utility companies represented the primary source surveyed and requests for information regarding energy usage were sent to about 19 utilities located throughout the United States. The other sources of building data included; various developers, operators, architectural and engineering firms, the Edison Electric Institute, and the Group to Advance Total Energy, Incorporated (GATE), who are representatives from gas companies.[45] The scope of the requested information included, but was not limited to: building relative construction type, seasonal peak load profile on a daily basis, building square footage, energy cost data, and energy demand trends with regard to conservation criteria. The types of buildings of interest were: shopping centers, offices, hotels/motels, and large retail stores. In addition to these specific items, any other available data concerning energy use of commercial buildings was requested. Details of the data received are included in Appendix B, Volume 4, for information only. This information was used to help define necessary building energy profiles that could be considered representative of the various commercial building categories. The intent was to develop typical model building configurations which could be used as representative application models for STES performance evaluation discussed in Section 2.0, Volume 3.

4.4.1 Actual Metered Energy Demand Data

Very few of the building data sets received were of sufficient detail to enable filling out the summary forms shown in Table 26. Most of the information received either lacked sufficient building data or hourly usage profiles to be of use in developing a usage prediction correlation. Also, the sample size of complete data available was inadequate to develop a meaningful correlation. Subsequently, alternate methods of simulating energy consumption of buildings as functions of building parameters and site climatology must be utilized.

One exception to the above was provided through the Southern California Edison Company and the Broadway-Hale Store, San Bernardino, California.

TABLE 26

SAMPLE COMMERCIAL BUILDINGS SUMMARY
(Sheet 1 of 2)

I. BUILDING DESCRIPTION

TYPE: OBH OFFICE HIGH RISE   CODE: ______

LOCATION: CITY OF COMMERCE   ORIENTATION/EXPOSURE: ~N

TOTAL FLOOR AREA: 4 WALLS EXPOSED

10.86 km^2 (117.5 k ft^2)   NO. OF FLOORS 10

OCCUPANCY TYPE: ______   PERSONS/m^2: ~0.1

ITEM	CONSTRUCTION TYPE	AREA		U-VALUES	
		m^2	ft^2	kj/m^2-hr-C^o	Btu/ft^2-hr-^{o}F
ROOF	STEEL CONCRETE		~11.8 k		0.10
WALLS	STEEL CONCRETE		~52 k		0.3
GLAZING*	~10% OF WALL AREA		~5.2 k		1.13

*SHADING COEFFICIENT ______ PERCENT OF TOTAL WALL AREA: ______%

NORMAL OPERATING:

HOURS: 7:30 am   DAYS: 5:30 pm (M-F)

HOURS: 9:00 am   DAYS: 1:00 pm (SAT)

HOURS: –   DAYS: – (SUN)

MONTH/SEASONAL VARIATIONS:

CLOSED HOLIDAYS

II. LOAD DATA

DAY 19   MONTH FEBRUARY   YEAR 1969

ELECTRICAL	PEAK	TIME	AVERAGE
LIGHTING	283 kW	1100	3378 kWh
AIR CONDITIONING	228 kW	1530	4046 kWh
OTHER	144 kW	1100	1763 kWh
THERMAL			
HEATING	1069 Mj/h	1700	2249 Mj
COOLING	302 Mj/h	1500	4802 Mj
HOT WATER	36 Mj/h	1700	136 Mj

77-J20-9-58

TABLE 26

SAMPLE COMMERCIAL BUILDINGS SUMMARY
(Sheet 2 of 2)

III LOAD PROFILE DATA

AVERAGE PEAK HOURLY ELECTRICAL AND HOT WATER LOADS (kWe) FOR 1969

HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
ELECTRICAL LOAD	178	174	177	190	207	238	274	365	436	433	441	443	444	460	456	441	368	335	291	257	241	221	217	209
HOT WATER LOAD	0	1	1	0	1	0	1	3	3	3	2	3	4	4	3	4	8	4	2	0	4	0	0	1

AVERAGE DAILY PEAK ELECTRICAL USAGE (kWh) 7552

STANDARD DEVIATION 728 03

AVERAGE DAILY HOT WATER USAGE (kWh) 50

STANDARD DEVIATION 8

MONTHLY USAGE (MWh) FOR 1969

MONTH	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
ELECTRICAL	185 4	184 5	210 4	181 1	193 8	189 7	230 1	239 2	228 8	248 2	219 6	222 3
HEATING	63 1	78 8	50 9	4 4	2 0	0 9	0	0	0	0	0	27 8
COOLING	26 2	22 8	17 6	50 2	46 1	47 1	106 9	120 6	90 7	46 0	46 0	37 3
HOT WATER	1 3	1 1	1 3	1 2	1 2	1 0	1 0	1 0	1 1	1 2	1 1	1 2

INTEGRATED YEARLY USAGE (MWh)

ELECTRICAL 2438 45

HEATING 227 94

COOLING 673 38

HOT WATER 13 79

IV EQUIPMENT DATA

TOTAL CONNECTED ELEC SERVICE 1905 kW

VAPOR COMPRESSOR RATING 2 X 160 TONS ? COP

LIGHTING AVERAGE 3 W/ft^2 INCANDESCENT PERCENTAGE UNKNOWN %

MISC ELECTRICAL 3 67 W/ft^2

AIR CONDITIONING ELECTRICAL 3 19 W/ft^2

SPACE HEATING TYPE/CAPACITY ELECTRICAL RATING 2 16 (643) MBtu/h (kW)

WATER HEATING TYPE/CAPACITY ELECTRICAL RATING 153 585 (45) Btu/h (kW)

UTILITY BASIC SERVICE 1969 DOLLARS

ELECTRICITY 45042 84 $/YEAR RATE 1 35 ¢/kWh

NATURAL GAS NA $/YEAR RATE NA ¢/kWh

FUEL OIL NA $/YEAR RATE NA $/10^6 Btu

77-J20-9-59

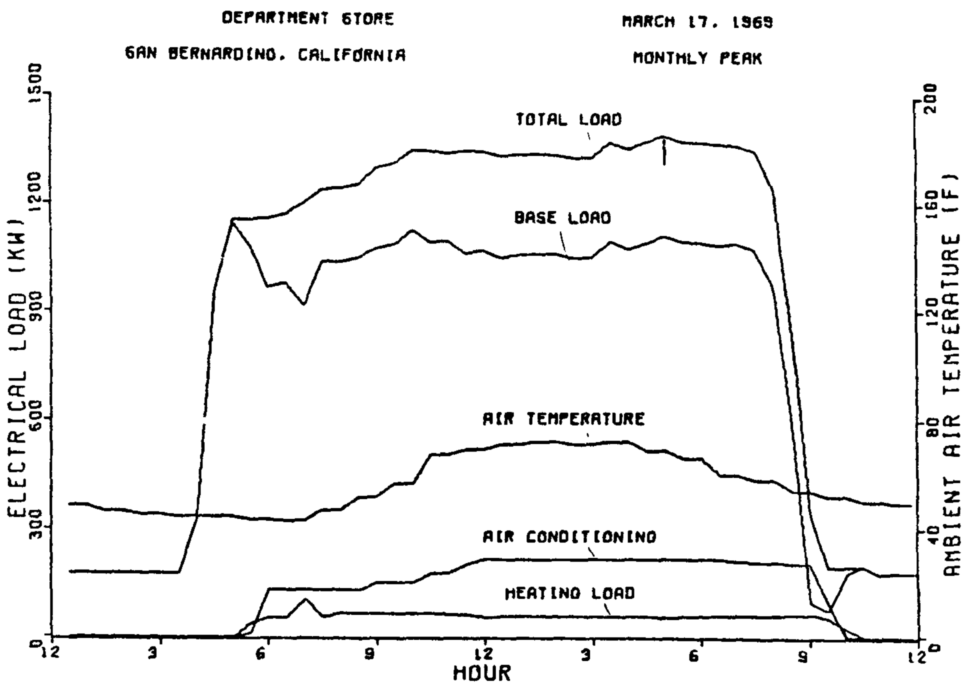

Figure 19. Metered Energy Data — March 1969

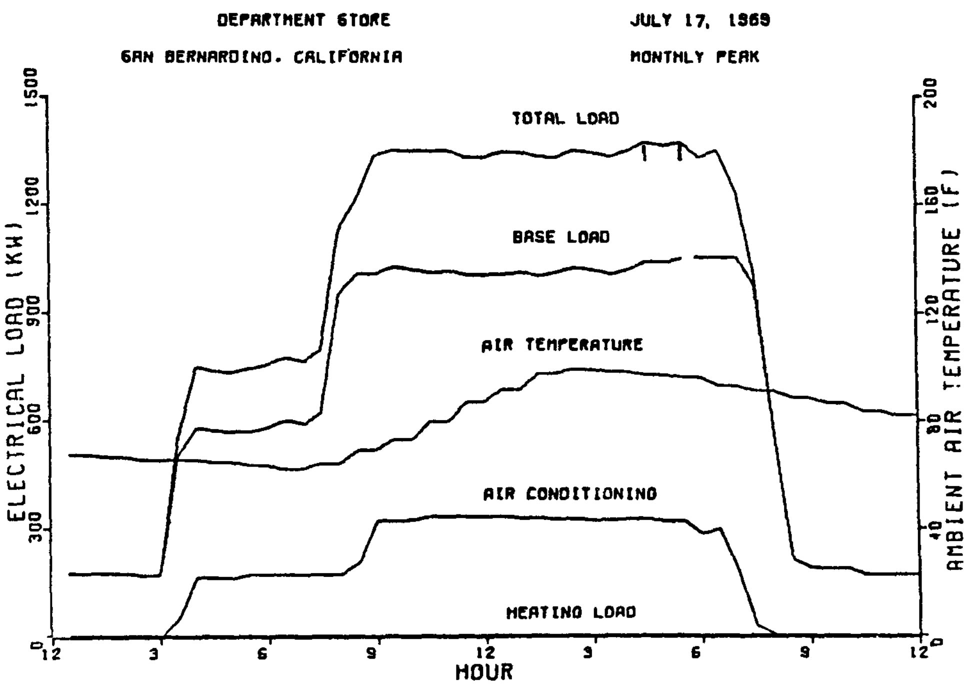

Figure 20. Metered Energy Data — July 1969

Figures 19 and 20 show hourly load profiles and ambient air temperatures for this three story building which consists of about 13,475 m^2 (145,000 ft^2) of total floor area. The total peak load is not significantly different for spring and summer days shown even though the air conditioning demand increases during the summer. Also, the Engineering Supervision Company was in the process of metering a number of buildings in Los Angeles, California, under an ERDA contract to determine peak load leveling needs. Figure 21 provides measured load profiles for these buildings for one day in December 1976.

For purposes of this study, it was decided that an alternate systematic method for defining commercial building energy demands was required. Thus computer simulation methods were investigated and the "real" metered data were used for verification purposes where appropriate.

4.4.2 Simulation of Building Energy Demands

It appears that during times of low energy costs, peak demand and initial installation cost were about the only items of common interest to the architect/engineer, utility, developer, and subsequent owner. Consequently, time-related demands (load profiles) were of little other than academic interest. Simulation programs primarily were developed to study control strategies and to optimize first cost of various equipment schemes. Only recently, with rising interest in energy conservation, have load simulation programs come into general use and, even now, these are not normally used in design of building. In designing solar total energy systems, computerized simulation techniques are essential since the load to match the solar energy available.

Appendix C, Volume 4, provides additional information on available energy demand simulation programs and, in particular, the Alternate Choice Comparison for Energy Systems Selection (AXCESS)[46] program developed by the Edison Electric Institute (EEI) used in this study. The Energy Group (TEG), a subsidiary of Welton-Becket Associates, developed simulated energy demand profiles for selected buildings under subcontract to Atomics International. The simulation was conducted using the AXCESS program on actual buildings defined directly from architectural drawings. From about 80 candidate buildings, six were selected for evaluation and determination of building type effects. The buildings selected are described in Table 27. The simulation provided a comparison of energy demand

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NATIONAL ENERGY PEAK LEVELING PROGRAM
DAILY DEMAND FOR ALL COMPLEXES

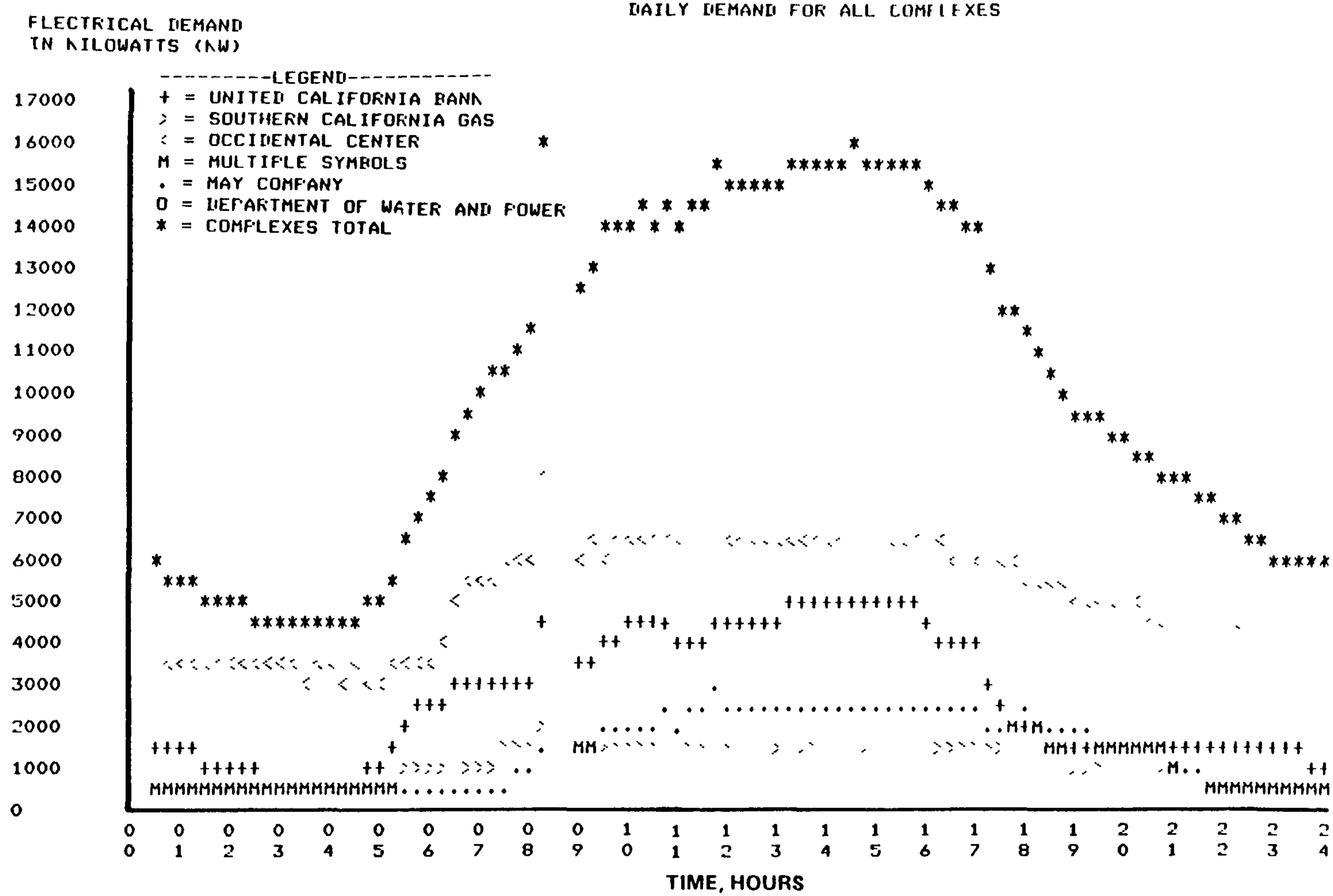

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Figure 21. National Energy Peak Leveling Program — Daily Demand for All Complexes

TABLE 27

TYPICAL COMMERCIAL BUILDING TYPES

OFFICE BUILDING	LOW RISE	HIGH RISE
FLOOR AREA:	25,000 SQ FT (2323 m^2)	248,000 SQ FT (23,048 m^2)
COMPLETION DATE:	1964	1970
LOCATION:	LOS ANGELES, CALIFORNIA	LOS ANGELES, CALIFORNIA
DESCRIPTION:	THREE STORIES PLUS BASEMENT; PRECAST CONCRETE AND SOLAR BRONZE GLASS EXTERIOR; PRECAST CONCRETE FRAME	FIFTEEN STORIES; EXPOSED AGGREGATE CONCRETE AND SOLAR BRONZE GLASS EXTERIOR; REINFORCED CONCRETE FRAME
INTERNAL SYSTEMS:	6 SIMULATED	5 SIMULATED
RETAIL STORE	**SMALL**	**LARGE**
FLOOR AREA:	55,000 SQ FT (5111 m^2)	260,000 SQ FT (24,163 m^2)
COMPLETION DATE:	1967	1972
LOCATION:	NEWPORT BEACH, CALIFORNIA	CERRITOS, CALIFORNIA
DESCRIPTION:	TWO-LEVEL STORE ON OPEN WALL IN MAJOR SHOPPING CENTER; SPLIT BLOCK, TERRA COTTA TILE, AND WHITE CONCRETE FACADE.	TWO-LEVEL ABOVE GRADE AND ONE BELOW ON ENCLOSED MALL IN MAJOR SHOPPING CENTER; HEAVILY TEXTURED STUCCO AND YELLOW TONE GLAZED, CERAMIC VENEER TILE FACADE, SLOPING WALLS.
INTERNAL SYSTEMS:	3 SIMULATED	2 SIMULATED
SHOPPING CENTER	**SMALL**	**LARGE**
FLOOR AREA:	224,000 SQ FT (20,876 m^2)	775,000 SQ FT (72,026 m^2)
COMPLETION DATE:	1977	1962
LOCATION:	NEWPORT BEACH, CALIFORNIA	TORRANCE, CALIFORNIA
DESCRIPTION:	OPEN, STAGGERED MALL; SINGLE LEVEL SHOPS, TWO-LEVEL DEPARTMENT STORE; TILE AND CONCRETE FACADES.	OPEN MALL, 50 SHOPS IN SINGLE-LEVEL BUILDINGS, A FOUR-LEVEL AND A TWO-LEVEL DEPARTMENT STORE; NATURAL STONE AND CONCRETE FACADE.
INTERNAL SYSTEMS:	4 SIMULATED	4 SIMULATED

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by building type, size, and internal system design. Eleven primary (i.e., energy generation/conversion) and sixteen terminal (i.e., distribution, ducting) heating, ventilating, and air conditioning (HVAC) internal systems that could be installed in these six example buildings were evaluated. By eliminating all of those systems that were felt to have insufficient application to warrant consideration, six primary and eight terminal systems were selected as being representative of typical internal systems that might be installed in the six example buildings. These systems were the ones used in determining the load profiles through computer simulation. Table 28 provides a summary of the primary terminal systems selected and arranged by applicable building type.

TABLE 28

BUILDING INTERNAL SYSTEMS (SIMULATED)
(Sheet 1 of 2)

Terminal	Primary
Low Rise Office Building (OBL)	
1. Dual Duct	1. Boiler and refrigeration
2. Multizone	2. Boiler and refrigeration
3. Single zone reheat	3. Furnace and refrigeration
4. Unitary heat pumps	4. Heat pump
5. Variable volume with reheat	5. Boiler and refrigeration
6. 4-pipe fan coil	6. Boiler and refrigeration
High Rise Office Building (OBH)	
1. Dual duct	1. Boiler and refrigeration
2. Variable volume with reheat	2. Boiler and refrigeration
3. Single zone reheat	3. Furnace and refrigeration
4. 4-pipe fan coil	4. Boiler and refrigeration
5. 4-pipe induction	5. Boiler and refrigeration

TABLE 28

BUILDING INTERNAL SYSTEMS (SIMULATED)
(Sheet 2 of 2)

Retail Store — Small (RSS)

Terminal	Primary
1. Unitary cooling with separate heating	1. Furnace and Unitary Cooling
2. Unitary heat pumps	2. Heat pump
3. Single zone reheat	3. Furnace and refrigeration

Retail Store — Large (RSL)

Terminal	Primary
1. Multizone	1. Boiler and refrigeration
2. Single zone reheat	2. Furnace and refrigeration

Shopping Center — Small (SCS)

Terminal	Primary
1. Unitary heat pumps	1. Heat pump
2. Unitary cooling units with separate heating	2. Furnace and Unitary Cooling
3. Single zone reheat	3. Furnace and refrigeration
4. Multi zone	4. Boiler and refrigeration

Shopping Center — Large (SCL)

Terminal	Primary
1. Unitary cooling units with separate heating	1. Furnace and Unitary Cooling
2. Multizone	2. Boiler and refrigeration
3. Unitary heat pumps	3. Heat Pump
4. Single zone reheat	4. Furnace and refrigeration

Using the AXCESS computer program, energy demands analyses were conducted on these buildings to investigate the effects of the heating, ventilating, and air conditioning (HVAC) internal system variations. The number of HVAC systems simulated by the Energy Group for each building (shown in Table 28) are discussed below.

TABLE 29

BUILDING — HVAC SYSTEM ANALYSIS MATRIX

HVAC System	Low-Rise Office (OBL)	High-Rise Office OBH)	Small Retail Store (RSS)	Large Retail Store (SCS)	Small Shopping Center (SCS)	Large Shopping Center (SCL)
Dual Duct	X	X				
Multizone	X			X	X	X
Single-Zone Reheat	X	X	X	X	X	X
Variable Volume Reheat	X	X				
4-Pipe Induction		X				
4-Pipe Fan Coil	X	X				
Unitary Heat Pumps	X		X		X	X
Unitary Cooling with Separate Reheat			X		X	X

4.4.2.1 HVAC System Analyses Methodology and Results

For a given HVAC system, operating in a specific building, AXCESS will synthesize and categorize the energy usage on an hourly, monthly, and yearly basis and present the data in the form of periodic meter readings. The HVAC system types considered were Dual Duct, Multizone, Single Zone Reheat, Variable Volume with Reheat, 4-Pipe Induction, 4-Pipe Fan Coil, Unitary Heat Pumps, and Unitary Cooling with Separate Reheat. Table 29 summarizes which of the HVAC systems were considered for each building.

The dual duct systems utilized in the AXCESS codes consist of a central unit which supplies heated and cooled air, each at a constant temperature, to two separate ducts per space or building zone. Mixing boxes in each space, fed by the ducts, supply the proper air temperature by combining the properly dampered hot and cold flow from the ducts. A simplified schematic flow diagram of a typical dual duct system is shown in Figure 22.

A multizone system, as shown in Figure 23, heats and cools several separate zones, of varying load requirements from a single central heating/cooling unit. Each zone is served by a separate thermostat which controls the flow of hot or cold air to that zone from the central unit. Flow control and mixing are achieved in mixing units, one of which is located in each zone.

A single zone-reheat system is a modified single zone system capable of providing a high degree of temperature and humidity control. The single zone system provides heating and cooling to the entire building, or one area of the building which has uniform heat gain or loss considered as a "single zone" by means of a single thermostat. A typical zone system is shown in Figure 24.

Variable volume with reheat systems, as shown in Figure 25, provides heated or cooled air at a constant temperature to all zones through variable air volume boxes located in each zone. The boxes adjust the air quality to match the load requirements of each space. Reheating is supplied as necessary at each box exit.

The 4-pipe induction system consists of an air handling unit which supplies heated or cooled, high pressure primary air, to individual induction boxes located in each space. The boxes induce room air into the primary air and discharge the resultant mixture into the space through heating or cooling coils which fine

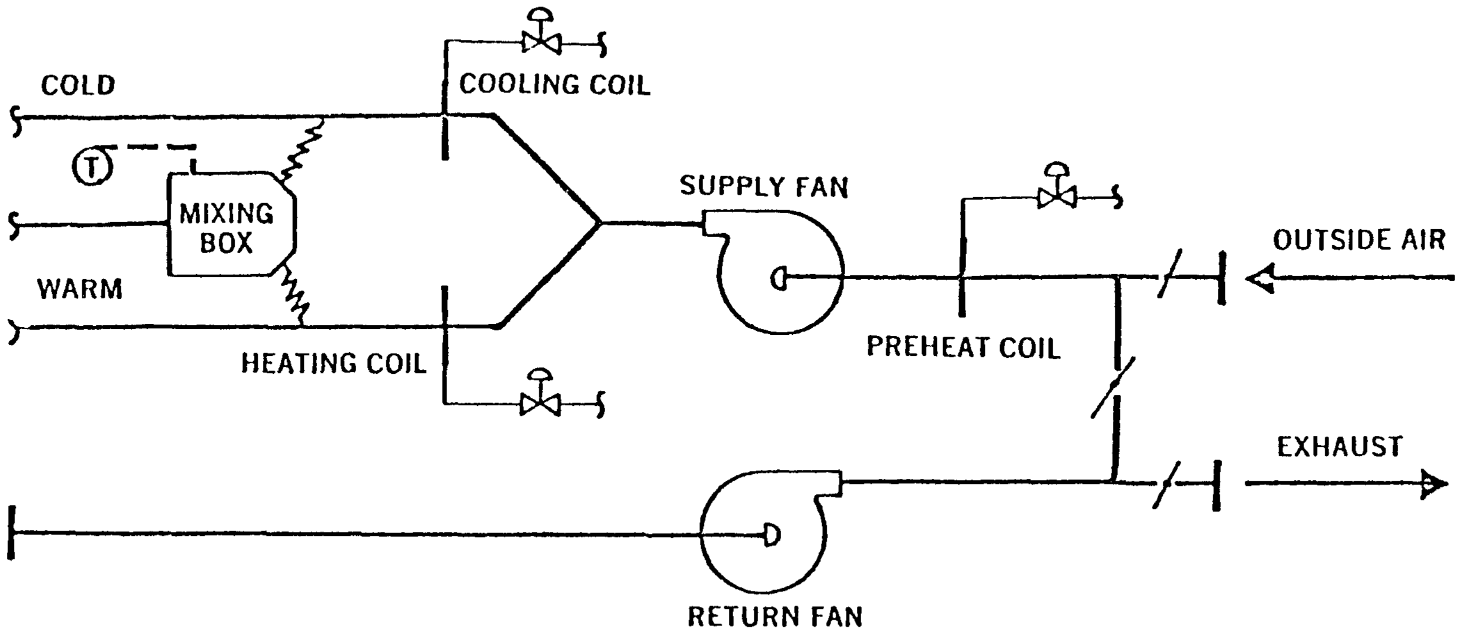

Figure 22. Dual Duct System

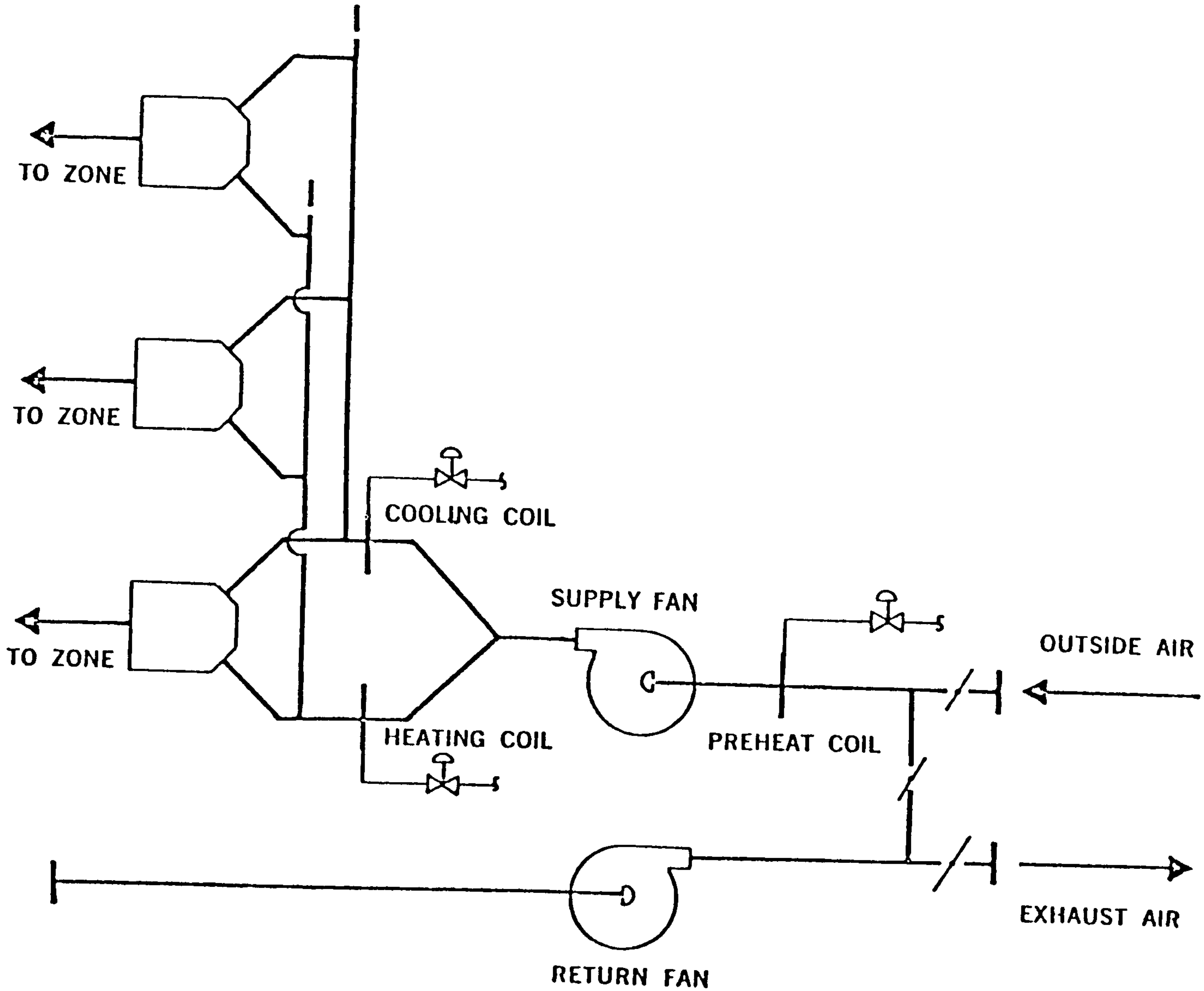

Figure 23. Multizone System

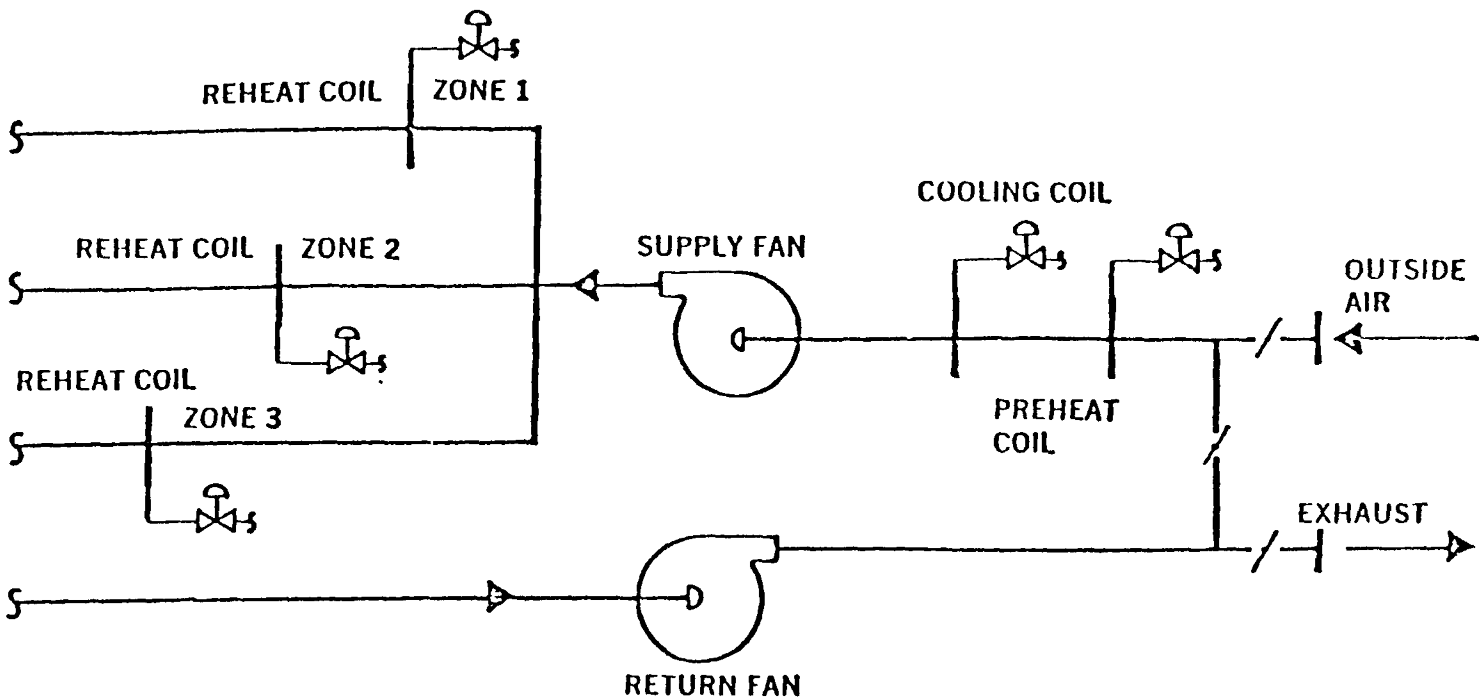

Figure 24. Single Zone Reheat System

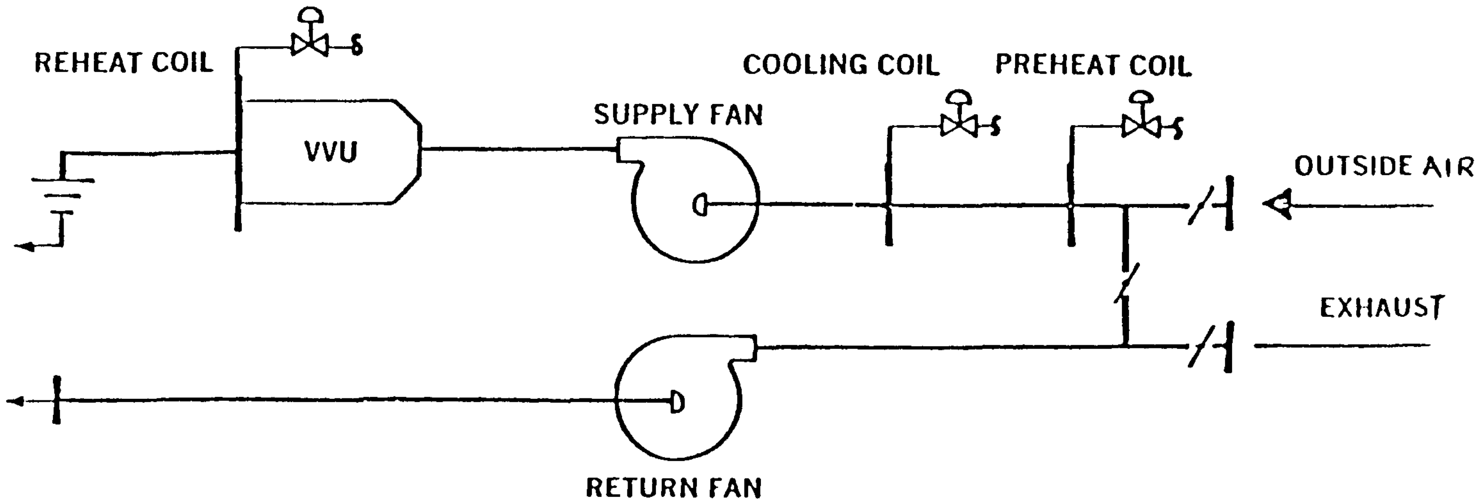

Figure 25. Variable Volume with Reheat System

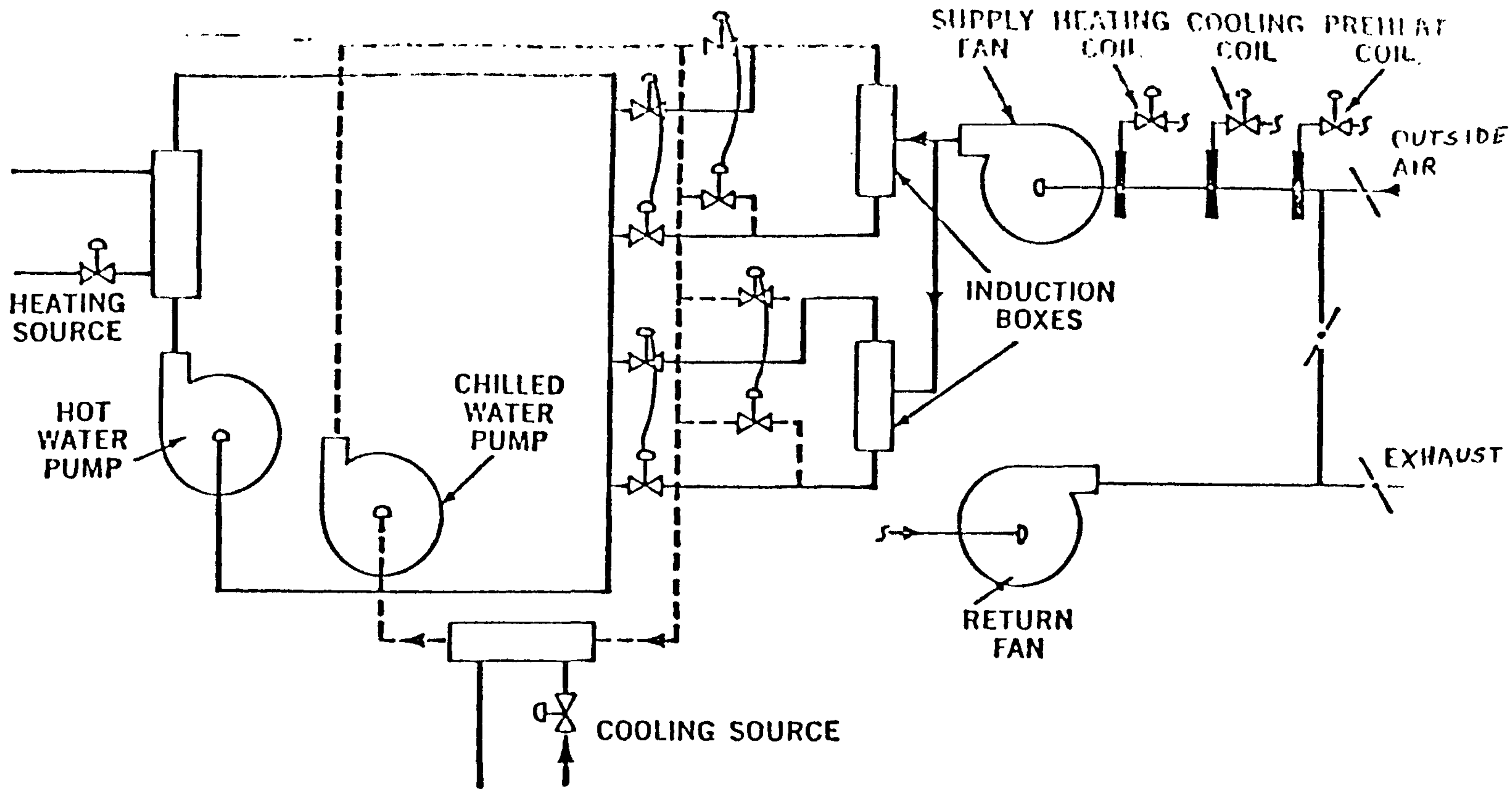

Figure 26. 4-Pipe Induction System

tune the mixture temperature. As shown in Figure 26, the heating and cooling coils are supplied by separate 4-pipe hot and chilled water sources

4-pipe fan coil is a combination four (4) pipe hot and chilled water supply, fan coil system. The fan coil system, as shown in Figure 27, consists of several units each with its own fan and heating and/or cooling coil.

Figure 28 shows the schematic of a unitary heat pump system. In this scheme, each zone or space is served by a single unit or if the space is small enough several spaces may be combined and served by one unit.

A unitary cooling with separate reheat is illustrated in Figure 29. It consists of one or more unitary air conditioning (cooling units) serving one or more zones with separate reheat prior to zone air discharge. Each heat coil is controlled by a separate thermostat.

While the output from the AXCESS code is comprehensive and complete, its format is too detailed to be directly compatible with the input requirements of the computer codes discussed in Section 5.0 effort which analyze candidate STES. Typical output of the AXCESS code includes the following categories of usage: total electricity, interior lights, total gas primary heating system, gas primary heating systems, auxiliary and terminal systems. The required energy usage input for the STES codes derived from this data and the methodology used is discussed in Appendix C, Volume 4.

Based on the data presented in Appendix C, Volume 4, the ratio of thermal (heating and cooling) to electric power usage for each system is shown in Table 30 for each of the six example buildings. The systems are listed in order of increasing energy consumption. Generally, as consumption increases the ratio of thermal to electrical power usage also increases.

The computed hourly usage data is summarized on a system-by-system basis in Figure 30 for the low-rise office building. These data were compared to the computed hourly energy profile of two systems for the large retail store model as shown in Figure 31 and good agreement on a qualitative basis was obtained.

The results from this analysis suggest that a criterion for selection of buildings for retrofit application of solar total energy systems is the energy consumption of the current HVAC systems installed in the building.

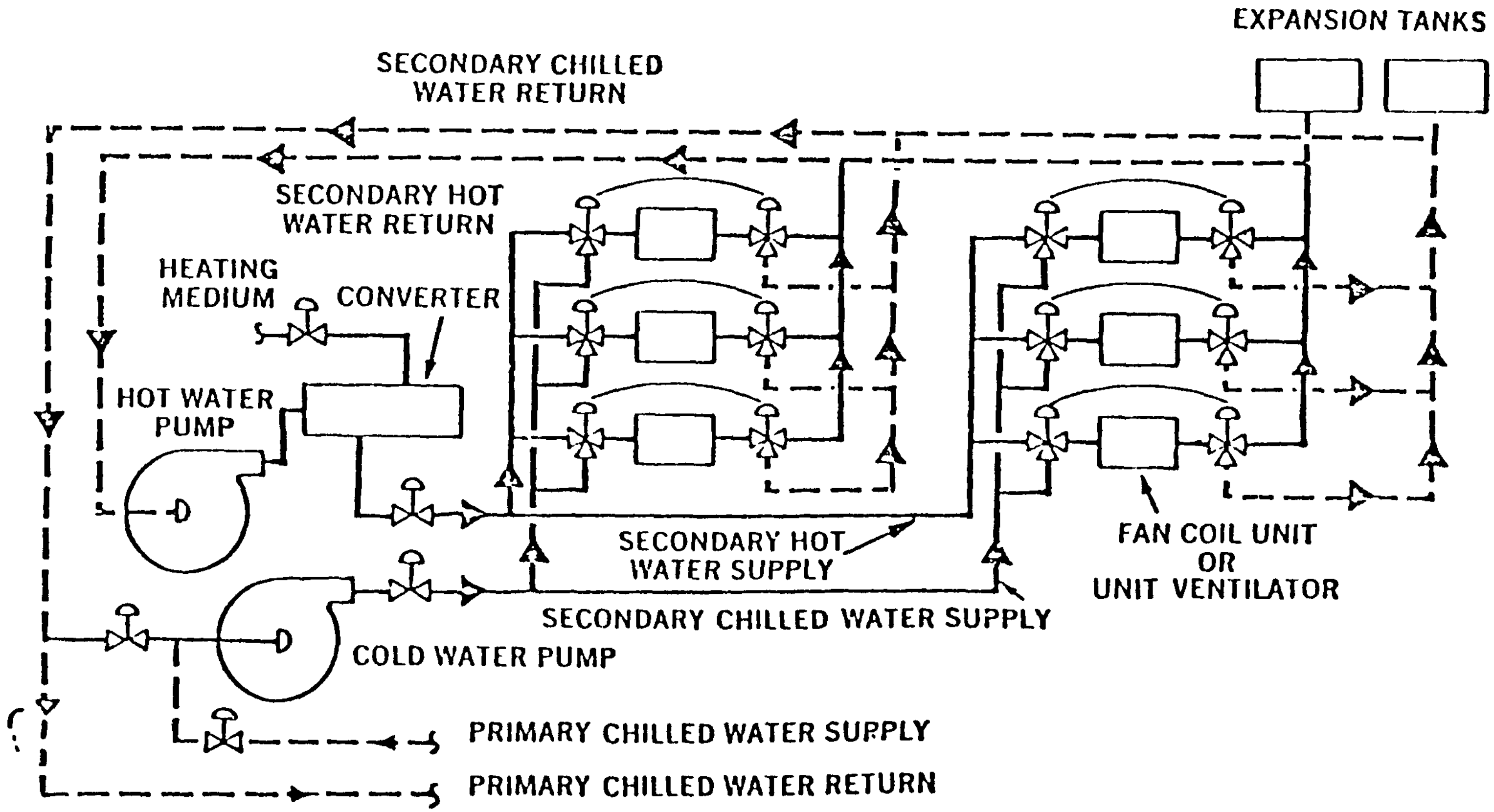

Figure 27. 4-Pipe Fan Coil System

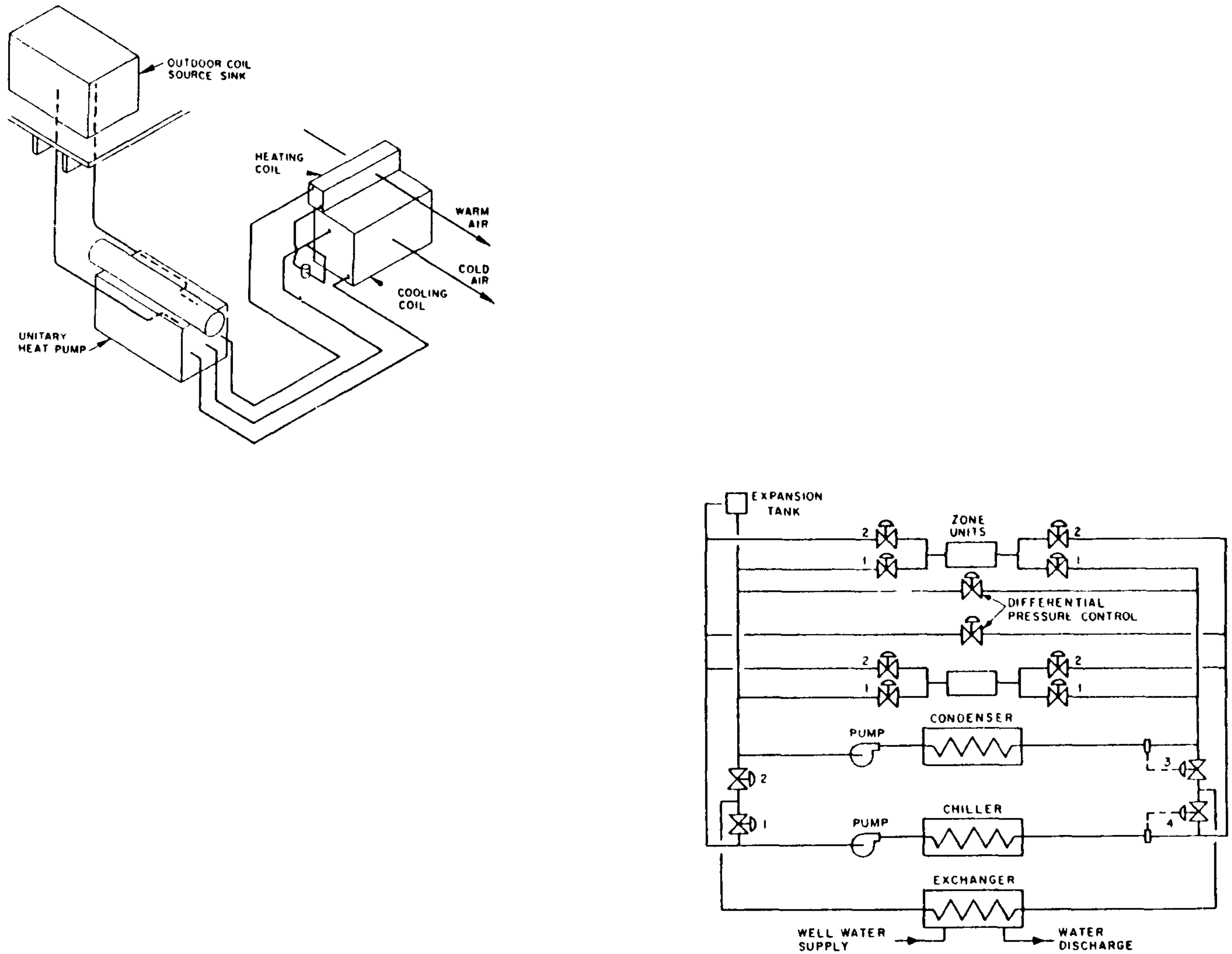

Figure 28. Unitary Heat Pump System

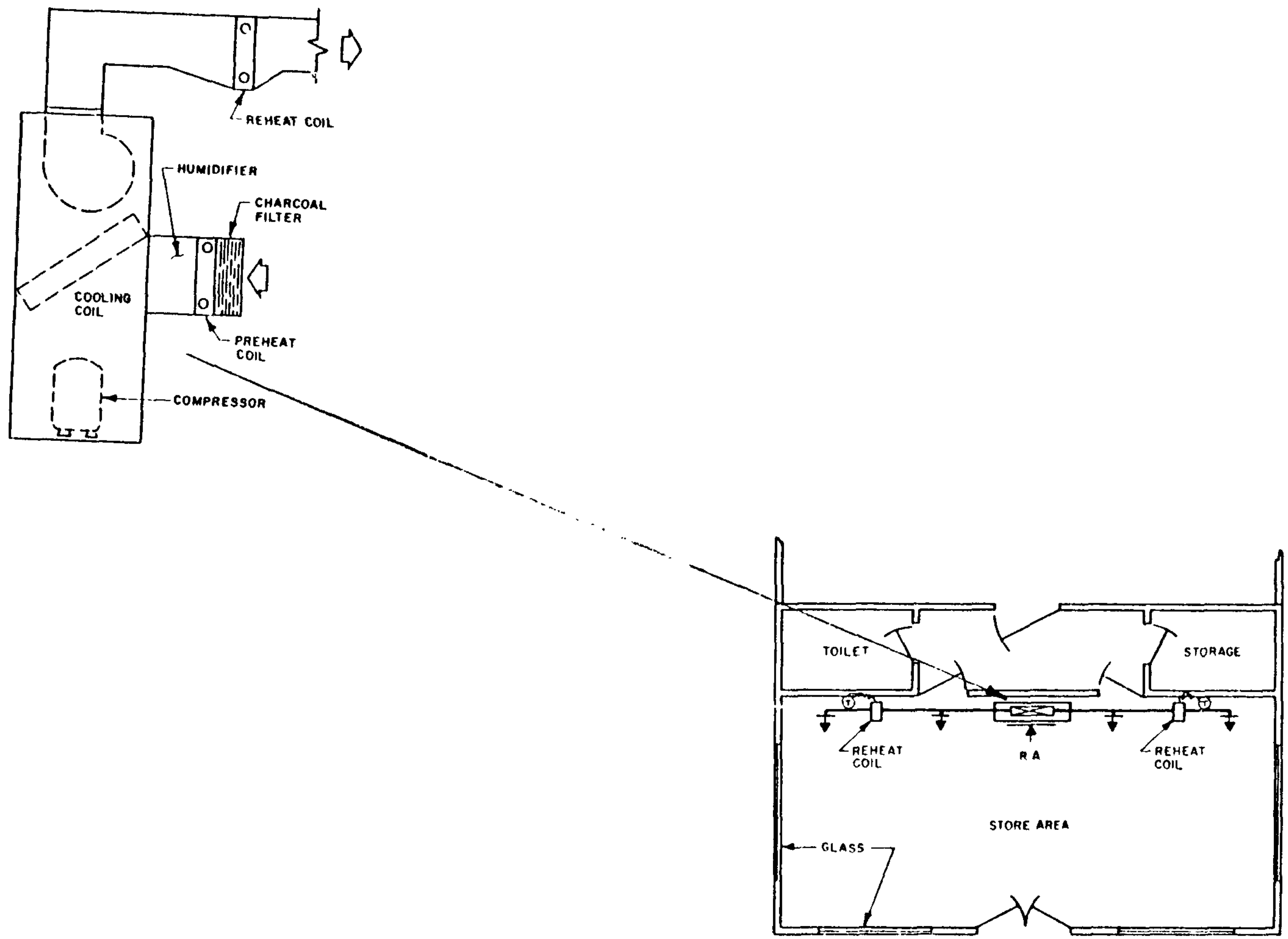

Figure 29. Unitary Cooling with Separate Heating System

TABLE 30

RATIO OF THERMAL TO ELECTRICAL ENERGY USAGE

HVAC System	Consumption Rating	Low-Rise Office	High-Rise Office	Small Retail Store	Large Retail Store	Small Shopping Center	Large Shopping Center
Unitary Cooling With Separate Reheat	1	NC*	NC	0.4	NC	0.4	0.3
4-Pipe Fan Coil	2	0.9	1.1	NC	NC	NC	NC
Unitary Heat Pumps	3	1.2	NC	0.4	NC	0.5	0.3
Variable Volume With Reheat	4	2.9	2.0	NC	NC	NC	NC
Multizone	5	4.0	NC	NC	0.7	1.8	1.8
Dual Duct	6	5.4	4.0	NC	NC	NC	NC
Single Zone Reheat	7	5.7	3.8	0.6	1.1	1.6	2.1
4-Pipe Induction	8	NC	3.9	NC	NC	NC	NC

* NC = System not considered in this building.

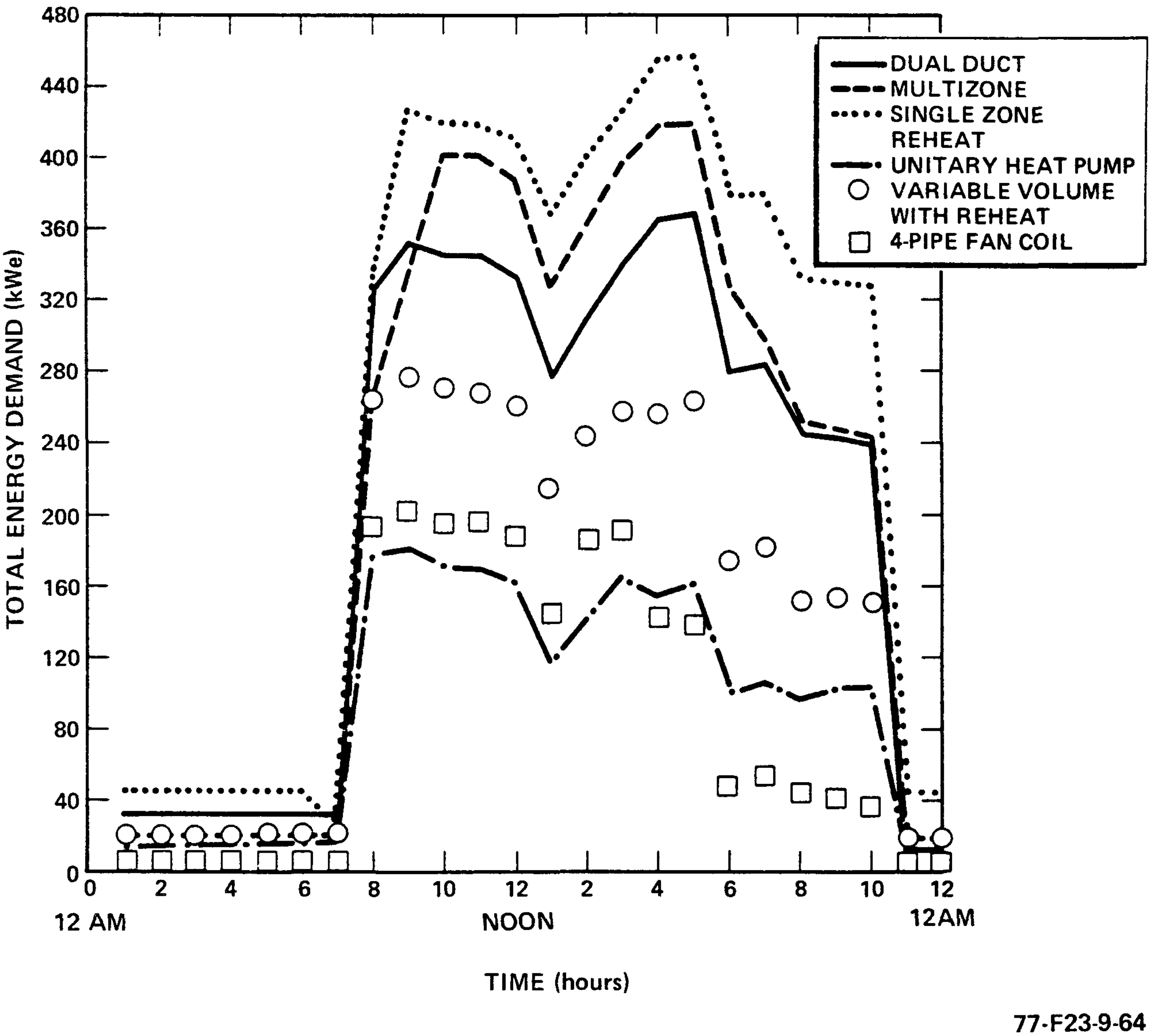

Figure 30. Simulated Total Energy Demand
(Low Rise Office Building)

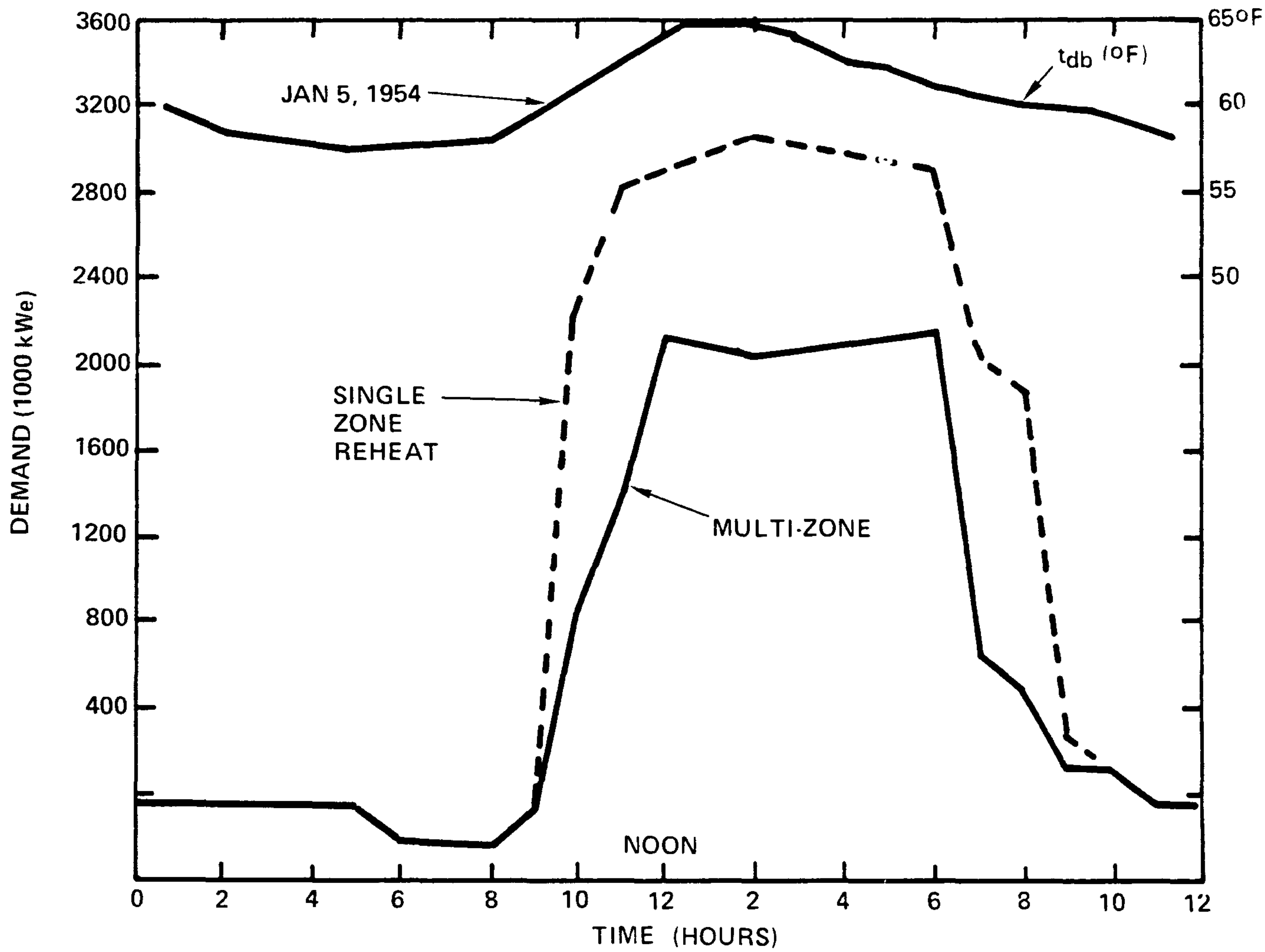

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Figure 31. Simulated Total Electrical Demand, Large Retail Store

There would normally be more of an economic incentive to retrofit an existing building with a high energy consumtpion HVAC system; whereas, new buildings are expected to be designed with energy conservation in mind to obtain minimum energy consumption. This would imply that the same land area available for collection of solar energy would result in providing a higher percentage of the existing building energy demand for the lower energy consumption design. Thus a greater cost savings should be realized.

From Table 30, it can be seen that the lower energy consumption HVAC designs will tend to reduce the thermal to electrical energy usage ratio for the building to about 1.1 or less from values as high as 5.7. The sensitivity of STES design to the energy usage and electrical to thermal ratio is discussed in Section 2.0, Volume 3.

4.4.3 Energy Conservation Effects

It is commonly accepted that properly applied energy conservation measures could save an average of 30% of the energy consumed in existing buildings. New buildings built to energy conserving standards would use about 50% of less of the energy consumed by their existing counterparts.[47] In a survey of owners of major retail store chains, it was found that all had implemented energy conservation programs. Some had started investigations of energy consumption as early as 1969 (see Section 4.4.1). Claims of reduced energy consumption as a result of these efforts range from 13% to 25%. Aside from making good economic sense, energy conservation is becoming the law-of-the-land. Many of the new laws are based on ASHRAE Standard 90-75 recommendations.[48]

Among the most important aspects of the standard are the establishment of maximum U-values and lighting. Typical of legislation implementing similar standards is Title 24 under the California State Administrative Code.[49] One of the most stringent and controversial provisions is the lighting standard which would restrict the integrated lighting load to an average of 21.5 W/m^2 (2 W/ft^2) for most buildings.

In considering suitable commercial applications for STES, it was essential to consider the effect of applied energy conservation. Some measures, such as double glazing, are expensive to apply and are seldom considered to be cost effective today for commercial buildings. However, when compared with the present cost of utilizing solar energy, even costly means of conservation may appear favorable. This being the case, it is unlikely that STES will be applied to buildings unless combined with reasonable programs to conserve energy. This is very evident in proposed federally-funded solar heating and cooling demonstration programs in which such measures are emphasized as criteria in project selection. From an electrical power standpoint, energy conservation will result in a larger minimum gross leasable area (GLA) buildings for cost effective STES application. AT 43 watts per square meter (4 W/ft^2) total kWe demand, the lower limit would be 467 m^2 (50,000 ft^2) for requiring a system power level of 200 kWe peak. From a thermal energy standpoint, however, energy conservation may be less significant in STES buildings since more heat may be rejected by the prime mover than is required for either heating or cooling. Thus, STES probably would be designed to provide partial electrical load with the balance obtained from an electrical utility. The net result is to emphasize the importance of a proper systems engineering effort applied to projected STES installations involving full cycle costing to consider the interaction of energy conservation methods, building demands and electrical/thermal balance.

It is a fairly simple matter to calculate the sensitivity of commercial building energy consumption to variation in ambient conditions. It can be shown theoretically that, assuming steady state conditions, regional effects are minimal except in buildings having large glass areas. This was verified by data (Appendix B, Volume 4) on consumption for similar stores having common operational procedures and occupancy (i.e., supermarkets) that indicated relative independence of climate. The same can be said for the differences in consumption as affected by energy conservation. The successive application of more stringent energy conservation measures can lead to significant reduction in consumption.

It is impossible, however, to generalize the effects of energy conservation for commercial buildings. Often buildings in the same location which appear to be similar have radically different consumption patterns. This is primarily because

1) It is difficult or impractical to determine or to control building operating conditions or occupancy levels.

TABLE 31

ENERGY CONSERVATION RESULTS FOR TWO SIMILAR OFFICE BUILDINGS

Location: Building Type: Area: Height: Year Built:	Charlottesville, Virginia Office 137,731 ft^2 6 floors 1965		Columbia, South Carolina Office 97,253 ft^2 6 floors 1952	
Item	Energy Conservation Program		Energy Conservation Program	
	Before (1973)	After (1974)	Before (1973)	After (1974)
Illumination				
At work stations. . . . (footcandles)	85	50	100	50
In work areas . . . . . (footcandles)	85	30	100	30
In nonwork areas. . . . (footcandles)	30	10	30	10
Lamps . . . . (number)	2,330	2,580	3,260	2,520
Thermostat Setting				
Summer. . . . . (^{o}F)	74	78	74	78
Winter. . . . . (^{o}F)	74	68	74	68
Building Occupancy				
Working . . . . (hours)	9	8.75	9	9
Custodial . . . . (hours)	+8	+6.5	+8	+4
Fan Operation				
Weekday . . . . (hours)	15	14	12	9
Weekend . . . . (hours)	0	0	0	0

Savings

	Charlottesville, Virginia	Columbia, South Carolina
kWh consumed in 1973	2,740,000 (19.8 kWh/ft^2)	1,077,400 (11.1 kWh/ft^2
kWh consumed in 1974	1,590,000 (11.5 kWh/ft^2)	911,900 (9.1 kWh/ft^2)
kWh saved	1,150,000 (8.3 kWh/ft^2)	165,500 (2.0 kWh/ft^2)
	1,150,000 kWh saved x 2.3¢/kWh = $26,400 for 1974	165,500 kWh saved x 2.2¢/kWh = $3,600 for 1974

2) There is an extreme difference in energy consumption between types of internal HVAC and lighting systems utilized.

Table 31, for example, is data taken from a Federal Energy Administration (FEA) study[50] of office buildings across the country. As can be seen from the summary of conditions, energy conservation measures were similar in each case. A variation of 15% to 42% savings in total energy consumption occurred in buildings which were not radically dissimilar in appearance and which were within somewhat similar climatic regions. Closer examination indicates the greater saving in the Charlottesville, Virginia, was due to a much higher demand load per unit area initially. The demand loads (on a square footage basis) for the two buildings following the conservation program were within 25% of each other with most of this difference attributed to the greater number of heating/cooling degree days in Charlottesville, Virginia.

These two buildings are typical of many commercial establishments today in that electricity is used to supply all building loads. Thus even after a conservation program, the building loads may be >100 W/m^2. It appears likely that heating loads will be accomplished with solar energy or fossil fuel rather than electricity in the future to save energy. Figure 32 presents data on the potential energy savings that may be expected in the future designs implementing energy conservation trends. The trend implies minimizing energy requirements for the internal HVAC system, which will also result in the type of HVAC system most compatible with a STES concept.

Figure 33 compares the average electrical energy demand for typical building types analyzed (see Appendix D, Volume 4) and the probable effect of energy conservation for retrofit, new construction and new standards (ASHRAE 90-75) that would result.

As another example, the Energy Management Service in Portland, Oregon, has implemented an energy conservation design into an existing building through modifications of lighting loads and other conservation methods. Figure 34 shows good correlation of the actual demand in 1975 with that estimated for an average year, except for the discrepancy about the month of July. This difference is probably due to different operational and climatic differences in 1975 from the average conditions assumed in the simulation case.

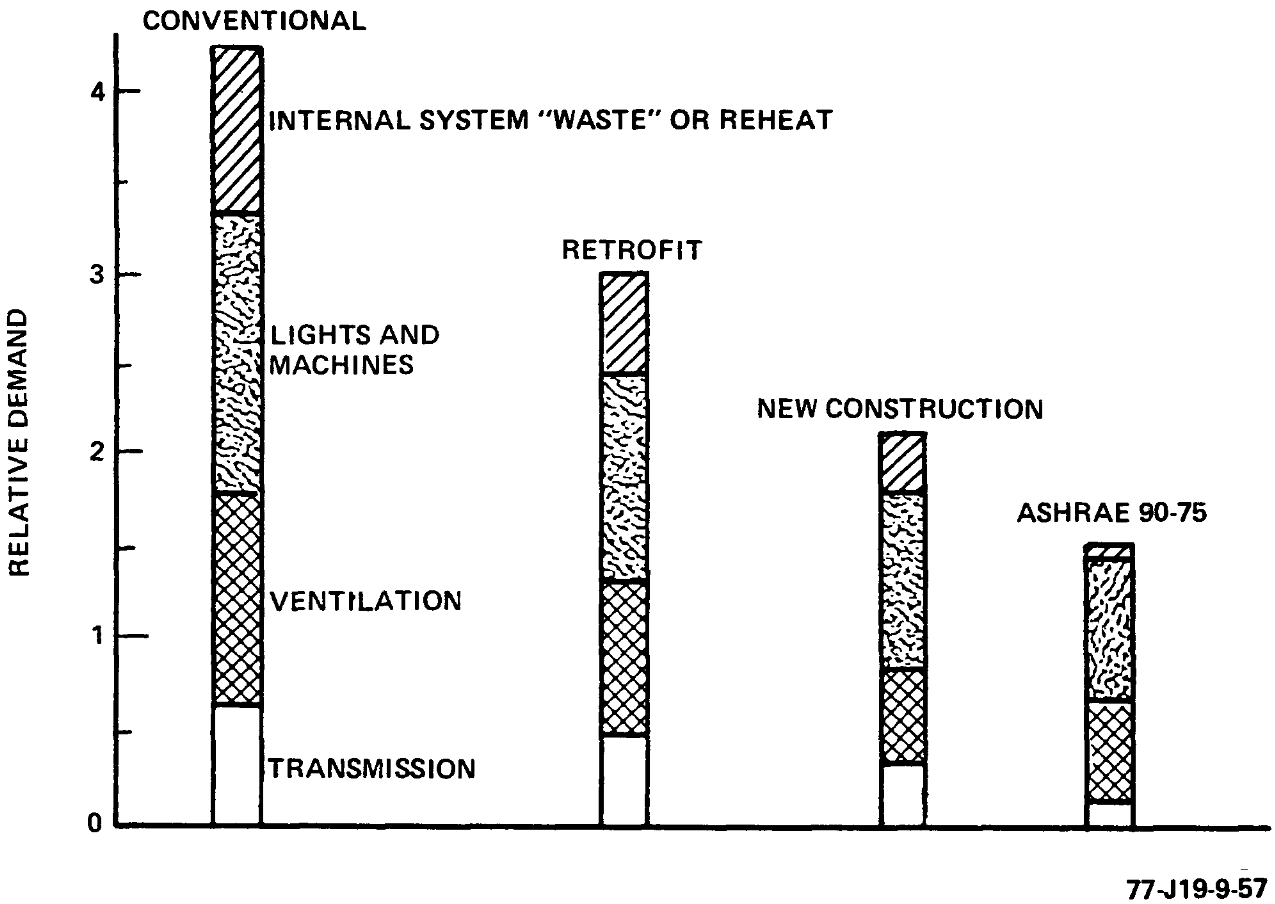

Figure 32. Energy Conservation Potential

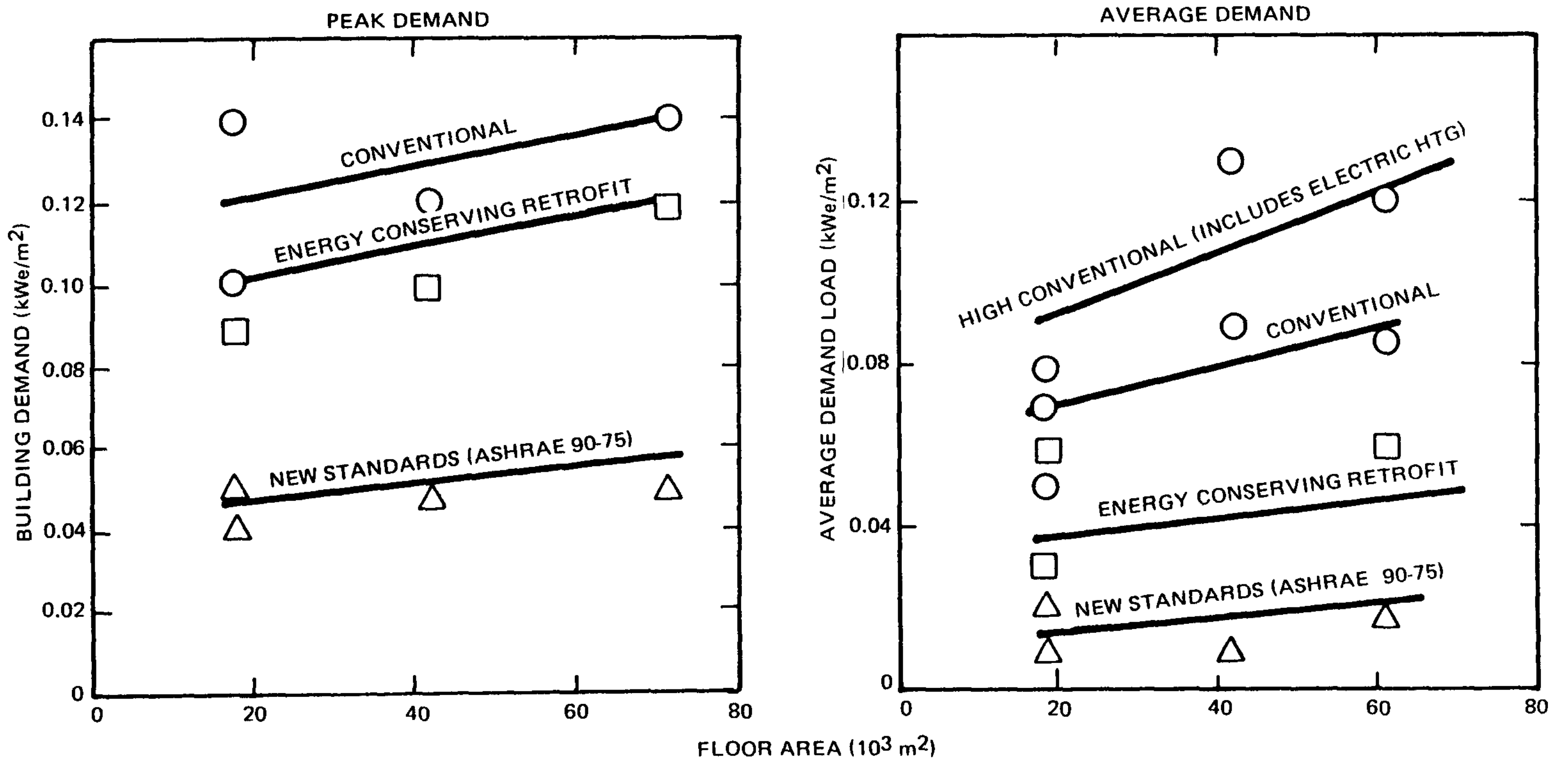

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Figure 33. Effect of Floor Area on Building Electrical Loads

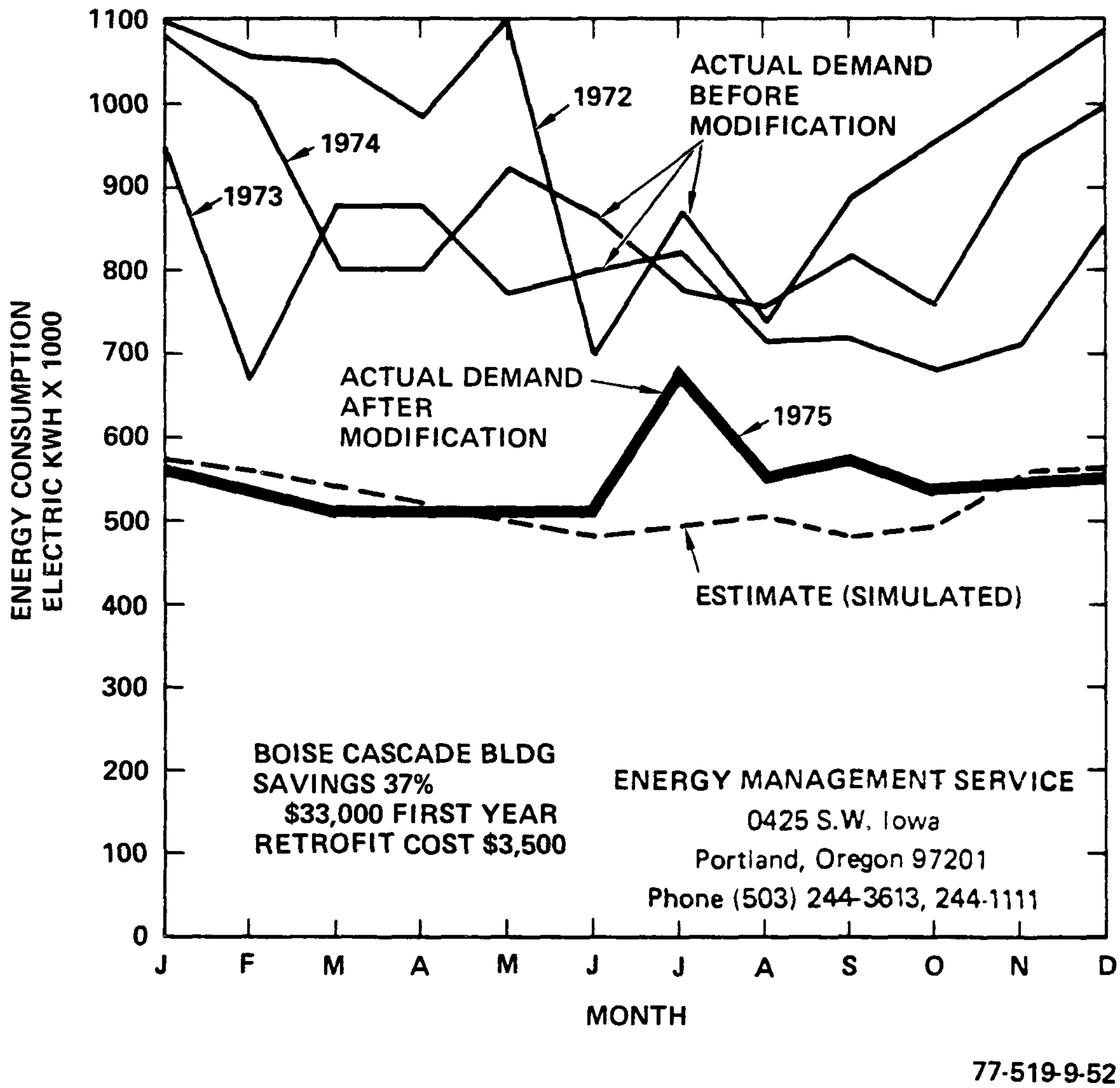

Figure 34. Energy Conservation Example

4.5 CODES AND STANDARDS

4.5.1 General

As with all building construction, local building codes and other restrictions will apply to STES. These are usually imposed by local ordinances or state laws which implement various codes and standards. Some cities such as Los Angeles, California; have implemented a Solar Building Code. With the help of Envirodyne Engineering Services, a survey of code restrictions was made by contacting building departments in 14 different cities. Information in the following areas was sought:

1) Restrictions on tower height

2) Pressure/temperature limitations in water/steam circuits.

   Licensed operator requirements.

3) Restrictions on the use of flammable, toxic fluid (toluene)

4) Parking and open space requirements

5) Requirements affecting pressurized storage

6) Restrictions affecting 100,000 to 500,000 gallon hot oil storage

4.5.2 Survey Results

Since none of the agencies had encountered an STES in their jurisdictions, replies were of necessity general in character. Definitive decisions would require a case-by-case evaluation based on specific site drawing submittals.

Requirements varied considerably, although there are some generalized results as follows:

1) Tower Restrictions: Height restrictions are largely a function of zoning, with airport proximity the major limiting factor. Structural requirements are usually prescribed. The Uniform Building Code requires that towers more than 75 ft above grade be constructed of iron, steel, or reinforced concrete and that towers having any cross-sectional area greater than 100 ft^2 shall have the supporting frame extended to the ground.

2) Pressure/Temperature Restrictions: Some jurisdictions (and/or unions) require licensed operators for systems with pressures exceeding 15 psig. Others do not require operators when the system is automatically controlled. Compliance with the ASME Boiler and Pressure Vessel Code is a common requirement.

3) Flammability, Toxicity Restrictions: This may be the most restrictive area in connection with STES. Toluene (candidate working fluid in the Organic Rankine Cycle STES) is an NFPA Class IB (flash point under 73°F, boiling point above 100°F) flammable liquid. However, where a liquid is artifically heated to a temperature above the flash point it falls into a lower category, in this case Class AI, which is the class with the most severe restrictions. In certain zones (i.e., Fire Zones 1 and 2: High Value Downtown Districts), storage of Class I liquids in aboveground tanks is prohibited. Where aboveground storage is permitted, drainage or diking must be provided as necessary to protect adjacent property. Furthermore, underground storage can be subject to restrictions on location with respect to tank size and proximity of nearby structures. In most jurisdictions, flammable liquids are subject to the fire codes and to approval by the fire department.

The toluene circuit of an STES would ordinarily fall under hazardous location Class I of the National Electrical Code (NFPA No. 70, ANSI CI). This class covers locations where flammable gases or vapors are or may be present in the air in sufficient quantities to produce explosive or ignitable mixtures. There are two divisions under this class: Division 1 where hazardous conditions exist during the course of normal operation, and Division 2 where hazardous conditions exist only under abnormal conditions. Since toluene in an STES is in a closed circuit, it would, on the face of it, be considered in the less restrictive Division 2. However, the authority having jurisdiction is given certain judgemental latitude in defining the appropriate Division. One aspect that could create a Division 1 situation is the possibility that loss of toluene might create a simultaneous failure of electrical equipment. While

Division 2 is somewhat less restrictive, electrical equipment in general must be of explosion proof construction approved for Class 1, Group D locations. There is a National Fire Code (NFPA No. 37) entitled: "Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines." It does not, however, offer any particular guidance for an STES.

4) Additional Space for Collectors: Structures built over parking areas seem to be the most promising spaces for additional collectors.

5) Pressurized Water/Steam Storage: This should not create any major impediment as long as containment devices are properly constructed. Vessels subjected to pressures above 15 psig (with minor exemptions relating to small sizes and low heat imputs) are governed by the construction and inspection procedures of the ASME Boiler and Pressure Vessel Codes, Section VIII, Pressure Vessels. Piping is governed by ANSI B31 Standard Code for Pressure Piping. System function determines the pressure/temperature/material requirements for piping. Steam piping will generally fall under the Power Piping section of the code. For temperatures below 750^{o}F, carbon steel is generally used.

6) Hot oil Storage (100 to 500,000 Gallons): While officials had not encountered this situation, they did not see any problems if the oil is nontoxic and noncombustible. Fuel oil, which is combustible, is subject to certain storage restrictions. The Uniform Mechanical Code (and NFPA No. 31), for example, limits indoor storage of fuel oil to a total of 50,000 gallons with an individual tank size limit of 25,000 gallons. Although the Code does not specify particular fuel oil storage temperature limits, it does prescribe that steam used for oil heating be no higher than 15 psig. This effectively limits the fuel oil temperature to a maximum of 250^{o}F.

The general conclusion that can be drawn from the Code investigation is that the most likely areas of concern are the flammability and toxicity restrictions relating to toluene and the hot oil storage. However, until specific plans are initiated to proceed with a demonstration program, no definite conclusions can be drawn on the basis of either the written codes or conversations with building officials.

Because of a lack of specific experience with the features of STES, they are not directly addressed by the codes. Toluene, for example, is covered by NFPA requirements when used as a solvent through ventilation and maximum air concentration stipulations. Storage of toluene is also covered in fire codes by virtue of its hazard classification. It is highly unlikely, however, that there are any code provisions directed toward use of high pressure and temperature toluene as the working substance in a closed cycle prime mover.

Until definite plans are submitted for specific sites and/or a backlog of operating experience is developed, there is considerable uncertainty in defining specific requirements. While some of the building officials indicated that they foresaw no particular problems, it is likely that a plan submittal could give rise to stringent restrictions on construction and operation or even a prohibition. Among the possible conditions that could be imposed are:

1) Installation in a separate structure at a distance from occupied areas.
2) Underground storage tanks.
3) Fire enclosures, automatic extinguishing systems and/or other protective devices.
4) Round-the-clock attendance by licensed personnel.

Hazardous substances (i.e., gasoline, natural gas) are currently used and stored in areas occupied by the public, albeit under well-defined conditions. However, knowledge gained through long experience has permitted development of relatively standardized safeguards; a situation which has not yet occurred with STES.

4.6 MODEL BUILDING SELECTIONS FOR STES CONCEPTS EVALUATION

From the preceding Sections 4.3 and 4.4., it was concluded that energy data (load profile) on actual buildings would be of little use in this study unless the type of internal system, building characteristics, and operational modes are also known. Furthermore, any pronounced similarity between the actual buildings and those finally selected as candidates for demonstration would be as likely as a model reference building where the required characteristics can be defined. Also, obtaining real load profile data on actual buildings was difficult since little measurements have been made in the past, except for cases where a specific problem may have necessitated such data as discussed in Section 4.4.1. It was therefore decided to develop model reference commercial buildings which could be used in evaluation of the STES.

From a requirements standpoint for this study, STES building models must provide configurations and energy demands which are reasonably representative of the potential U.S. market. Based on the background of the previous sections, four representative buildings were selected as candidate types for the commercial building applications as described in Table 32. For each of these buildings, a total of four HVAC systems were postulated as candidate systems. They included (1) a typical high energy consumption "conventional" system, defined by the AXCESS simulations provided in Appendix C, Volume 4; (2) a "reference" system determined by recalculating the average energy consumption profiles accordingly (see Appendix D, Volume 4); (3) an "energy conserving retrofit" version of the typical system selected again by using appropriately modified AXCESS simulation consumption profiles (see Appendix D, Volume 4); and (4) a HVAC system/building model which reflects proposed "new standards" (ASHRAE 90-75) of construction and energy consumption (see Appendix D, Volume 4).

4.6.1 Candidate Model Building Characteristics

For each of the postulated systems the following assumptions were taken to arrive at the sixteen candidate building configuration models.

1) Monthly energy consumption profiles can be assumed to have the same form as those derived by AXCESS simulation for similar building types.

TABLE 32

POTENTIAL MODEL COMMERCIAL BUILDINGS FOR STES APPLICATION EVALUATION

Building Type	Floor Area $[m^2(ft^2)]$	No. Stories	Construction	Glass Area (%)	HVAC Systems
Low Rise Office (OBL)	18,590 (200,000)	3	Medium	20	(1) Conventional - dual duct (2) Reference - variable air volume with reheat (3) Energy conserving retrofit - variable air volume with reheat (4) Energy conserving new standards - variable air volume with reheat
Large Retail Store (RSL)	18,590 (200,000)	3	Medium	0	(1) Conventional - multizone (2) Reference - multizone (3) Energy conserving retrofit multizone (4) Energy conserving new standards multizone
Medium Shopping Center (SCM)	41,820 (450,000)	2	Medium	0	(1) Conventional - multizone (2) Reference - unitary heat pumps (3) Energy conserving retrofit - unitary heat pumps (4) Energy conserving new standards - unitary heat pumps
Large Shopping Center (SCL)	69,700 (750,000)	2	Medium	0	(1) Conventional - multizone (2) Reference - multizone (3) Energy conserving retrofit - multizone (4) Energy conserving new standards - multizone

2) The high energy consumption, conventional system can be used as the basis of the profiles for the other three system configurations. The high energy consumption, conventional system was chosen to have an average consumption as close as possible to the average calculated consumption for the "reference" system.

3) The AXCESS simulated energy consumption profiles can be scaled to meet the size requirement of the model buildings with the postulated HVAC systems. (Uses the same energy per square foot as the appropriate building simulated by AXCESS).

4) Ventilation thermal loads, both sensible and latent, can be neglected as they contribute a maximum of 10% to total electrical load in most cases.

5) A standard construction can be assumed for the conventional, retrofit and reference buildings, regardless of building location.

6) Lighting loads for the "reference" building model were as follows.

Building	Lighting Load Assumption (W/m^2)	(watts/ft^2)
Large Shopping Center (SCL)	65	6
Medium Shopping Center (SCM)	54	5
Large Retail Store (RSL)	65	6
Low-Rise Office (OBL)	43	4

7) Ventilation requirements were taken as 12 cfm per occupant.

The detailed calculations used in determining the average energy usages for each postulated HVAC system in each model building are provided in Appendix D, Volume 4.

In order to verify these assumptions in predicting the consumption of the candidate building models, a comparison was made to other building model studies in the literature and by surveying actual loads data. Appendix D, Volume 4 provides more detail information on defining the energy consumption for the various model buildings. This investigation covered both regional effects and internal system load assumptions. The following generalized results were noted:

1) The use of a single type of construction for each commercial building type regardless of region, and the selection of the construction details is valid (see Appendix D, Volume 4).

2) The variation in the major load (cooling) in the prime applications (shopping centers and large retail stores) throughout the U.S. is within ±10% from region to region. In other words, regional effects are relatively insignificant.

3) Assumptions for occupancy and ventilation are valid with the possible exception of the office building where ventilation requirements should be increased from 12 to 25 cfm/per occupant.

4) Lighting loads should probably be reduced as follows for the reference building cases.

   SCL - from 86 to 65 W/m^2 (8 to 6 W/ft^2)
   SCM - from 75 to 54 W/m^2 (7 to 5 W/ft^2)
   RSL - from 86 to 65 W/m^2 (8 to 6 W/ft^2)
   OBL - from 86 to 43 W/m^2 (8 to 4 W/ft^2)

   These lighting values may still be on the high side of the current average, however, the range will vary greatly depending on the "degree" of the particular service the facility provides to the occupants.

A summary of building characteristics assumed for each of the candidate models is given in Tables 33 through 36. The resultant monthly energy usage breakdown for each of these building configurations is provided in Tables 37 through 40.

4.6.2 Model Building Configurations Selection

For purposes of evaluating STES performance at each of the twelve sites, sixteen building configurations were considered too extensive for defining STES application sensitivity criteria. It was decided that each of the four model buildings having a conventional HVAC System would be evaluated to define the influence on STES performance due to various types of buildings. In addition, the

TABLE 33

MODEL LOW RISE OFFICE BUILDING (OBL)

Building Type - OBL | No. Floors - 3

Floor Area - 18,590 m^2 (200,000 ft^2) | Roof Area - 6,227 m^2 (67,000 ft^2)

Wall Area - 3,346 m^2 (31,600 ft^2) | Glass Area - 734 m^2 (7,900 ft^2)

Length - 111.6 m (366 ft) | Height 11.0 m (36 ft)

Width - 55.8 m (183 ft)

Parameter	HVAC System			
	Reference	High (Conv.)	Energy Conservation Retrofit	Energy Conservation New Standards
U (Roof) (Btu/ft^2-h-°F)	0.15	0.15	0.15	0.05
ρ (Roof) (lb/ft^2)	35	35	35	37
U (Walls) (Btu/ft^2-h-°F)	0.16	0.16	0.16	0.08
ρ (Walls) (lb/ft^2)	70	70	70	72
U(Glass) (Btu/ft^2-h-°F)	1.13	1.13	1.13	0.65
Shading Coefficient	0.95	0.95	0.95	0.83
HVAC Type	VAV* w/Reheat	Dual Duct	VAV* w/Reheat	VAV* 10% Reheat
Chiller Coefficient of Performance	3.9	3.9	3.9	3.9
Normal Lighting (W/ft^2)	8	8		2
Other Electrical Load (W/ft^2)	2	2		1.5
HVAC Peak Power (W/ft^2)	3.33	4.92		1.8
Bldg Elec Peak Power (W/ft^2)	13.33	14.92		5.3
Total Peak Power Demand (MWe)	2.7	2.98		1.06
Avg "Open Hours" Load (MWe)	2.4	2.66		0.96
Hours Per Month Open	189	189	189	189
Avg Month "Open Hours" Energy (MWh)	454			181
Avg "Closed Hours" Load (MWe)	0.6			0.1
Hours Per Month Closed	507			
Avg Month "Closed" Energy (MWh)	304			51
Total Avg Month Energy (MWh)	524		401	160
(kWh/ft^2-mo)	2.62	5.61	2.0	0.8
Avg Number of People (110/ft^2)	1818	1818	1818	1818
Ventilation/Infiltration (cfm/person)	12	12	10	10
Total Ventilation (cfm)	21,816	21,816	18,180	18,180
Thermal Lag (h)(summer)	3	3	3	4

*Variable Air Volume

TABLE 34

MODEL LARGE RETAIL STORE (RSL)

Building Type - RSL

No. Floors - 3

Floor Area - 18,590 m^2 (200,000 ft^2)

Roof Area - 6,227 m^2 (67,000 ft^2)

Wall Area - 3,355 m^2 (36,100 ft^2)

Glass Area - insignificant

Length - 111.6 m (366 ft)

Height - 12.8 m (42 ft)

Width - 55.8 m (183 ft)

Parameter	HVAC System			
	Reference	High (Conv.)	Energy Conservation Retrofit	Energy Conservation New Standards
U (Roof) (Btu/ft^2-h-°F)	0.15		0.15	0.05
ρ (Roof) (lb/ft^2)	35		35	37
U (Walls) (Btu/ft^2-h-°F)	0.16		0.16	0.08
ρ (Walls) (lb/ft^2)	70		70	72
U (Glass) (Btu/ft^2-h-°F)	NA		NA	NA
Shading Coefficient	NA		NA	NA
HVAC Type	Multi-zone		Multi-zone	Multi-zone
Chiller Coefficient of Performance	3.9		3.9	3.9
Normal Lighting (W/ft^2)	8			2
Other Electrical Load (W/ft^2)	2			1
HVAC Peak Power (W/ft^2)	3.07			2
Bldg Electrical Peak Power (W/ft^2)	13.07			5
Total Peak Power Demand (MWe)	2.6			1
Avg "Open Hours" Load (MWe)	2.4			0.7
Hours Per Month Open	308		308	284
Avg Month "Open Hours" Energy (MWh)	739			199
Avg "Closed Hours" Load (MWe)	0.8			0.1
Hours Per Month Closed	388		388	412
Avg Month "Closed" Energy (MWh)	311			41
Total Avg Month Energy (MWh)	1050		804	240
(kWh/ft^2-mo)	5.25		4	1.2
Avg Number of People (110/ft^2)	2000		2000	2000
Ventilation/Infiltration (cfm/person)	12		10	10
Total Ventilation (cfm)	24,000		20,000	20,000
Thermal Lag (h)(summer)	4		4	5

TABLE 35

MODEL MEDIUM SIZE SHOPPING CENTER (SCM)

Building Type - SCM | No. Floors - 2

Floor Area - 41,820 m^2 (450,000 ft^2) | Roof Area - 20,910 m^2 (225,000 ft^2)

Wall Area - 5,232 m^2 (56,300 ft^2) | Glass Area - insignificant

Length - 204.2 m (670 ft) | Height - 8.5 m (28 ft)

Width - 102.1 m (335 ft)

Parameter	HVAC System			
	Reference	High (Conv.)	Energy Conservation Retrofit	Energy Conservation New Standards
U (Roof) (Btu/ft^2-h-°F)	0.15	0.15	0.15	0.05
ρ (Roof) (lb/ft^2)	35	35	35	37
U (Walls) (Btu/ft^2-h-°F)	0.16	0.16	0.16	0.08
ρ (Walls) (lb/ft^2)	70	70	70	72
U (Glass) (Btu/ft^2-h-°F)	NA	NA	NA	NA
Shading Coefficient	NA	NA	NA	NA
HVAC Type	Unitary (Roof & Wall)	Multi-zone	Unitary (Roof & Wall)	Unitary (Roof & Wall)
Chiller Coefficient of Performance	3.5	3.9	3.5	3.5
Normal Lighting (W/ft^2)	7	7		2
Other Electrical Load (W/ft^2)	1	1		1
HVAC Peak Power (W/ft^2)	2.74			2
Bldg Electrical Peak Power (W/ft^2)	10.74			5
Total Peak Power Demand (MWe)	4.8			2.25
Avg "Open Hours" Load (MWe)	4.5			1.57
Hours Per Month Open	308			284
Avg Month "Open Hours" Energy (MWh)	1386			446
Avg "Closed Hours" Load (MWe)	1.12			0.225
Hours Per Month Closed	388			412
Avg Month "Closed" Energy (MWh)	435			93
Total Avg Month Energy (MWh)	1820	3928	1382	539
(kWh/ft^2-mo)	4.04	8.72	3.07	1.19
Avg Number of People (110/ft^2)	4500	4500	4500	4500
Ventilation/Infiltration (cfm/person)	12	12	10	10
Total Ventilation (cfm)	54,000	54,000	45,000	45,000
Thermal Lag (h)(summer)	4	4	4	5

TABLE 36

MODEL LARGE SHOPPING CENTER (SCL)

Building Type - SCL

No. Floors - 2

Floor Area - 69,700 m^2 (750,000 ft^2)

Roof Area - 34,850 m^2 (375,000 ft^2)

Wall Area - 6,756 m^2 (72,700 ft^2)

Glass Area - insignificant

Length - 264.0 m (866 ft)

Height - 8.5 m (28 ft)

Width - 132.0 m (433 ft)

Parameter	HVAC System			
	Reference	High (Conv.)	Energy Conservation Retrofit	Energy Conservation New Standards
U (Roof) (Btu/ft^2-h-°F)	0.15	0.15	0.15	0.05
ρ (Roof) (lb/ft^2)	35	35	35	37
U (Walls) (Btu/ft^2-h-°F)	0.16	0.16	0.16	0.08
ρ (Walls) (lb/ft^2)	70	70	70	72
U (Glass)(Btu/ft^2-h-°F)	NA	NA	NA	NA
Shading Coefficient	NA	NA	NA	NA
HVAC Type	Multi zone	Multi zone	Multi zone	Multi zone with 10% Reheat
Chiller Coefficient of Performance	3.9	3.9	3.9	3.9
Normal Lighting (W/ft^2)	6			2
Other Electrical Load (W/ft^2)	4			1
HVAC Peak Power (W/ft^2)	3.07			1.53
Bldg Electrical Peak Power (W/ft^2)	13.07			4.53
Total Peak Power Demand (MWe)	9.8			3.4
Avg "Open Hours" Load (MWe)	9			3.1
Hours Per Month Open	308			284
Avg Month "Open Hours" Energy (MWh)	2772			880
Avg "Closed Hours" Load (MWe)	3			0.375
Hours Per Month Closed	388			412
Avg Month "Closed" Energy (MWh)	1156			155
Total Avg Month Energy (MWh)	3928	6045	3007	1035
(kWh/ft^2-mo)	5.23	8.05	4.0	1.38
Avg Number of People (110/ft^2)	7500	7500	7500	7500
Ventilation/Infiltration (cfm/person)	12	12	10	10
Total Ventilation (cfm)	90,000	90,000	75,000	75,000
Thermal Lag (h)(summer)	4	4	4	5

TABLE 37

MONTHLY ENERGY USAGE BREAKDOWN (MWh)
LOW RISE OFFICE BUILDING (OBL)

Mo	Elec.	Heat.	Cool.	Hot H_2O	Total	Elec.	Heat.	Cool.	Hot H_2O	Total
	Reference Model					High Consumption: Conventional Model				
J	124	221	192	16	553	205	528	478	24	1235
F	113	193	181	14	501	186	445	451	21	1104
M	124	178	203	16	521	205	474	512	24	1214
A	123	160	195	16	494	204	428	481	24	1136
M	120	139	213	15	487	199	402	519	22	1142
J	124	108	220	16	468	204	301	483	24	1011
J	130	101	235	16	482	212	255	475	24	966
A	121	106	235	15	477	199	255	470	22	946
S	124	100	224	16	464	204	213	419	24	860
O	125	147	212	16	500	205	373	482	24	1084
N	119	153	201	15	488	197	349	430	22	998
D	129	192	198	16	535	212	453	463	24	1153
	Energy Conserving: Retrofit Model					Energy Conserving: New Standards Model				
J	95	169	147	12	423	38	68	59	5	170
F	86	148	139	11	384	34	59	55	4	152
M	95	136	155	12	398	38	54	62	5	159
A	94	123	149	12	378	38	49	60	5	152
M	92	107	163	11	373	37	43	65	5	150
J	95	82	169	12	358	38	33	67	5	143
J	100	77	180	13	370	40	31	72	5	148
A	92	81	179	11	363	37	32	72	5	146
S	95	76	172	12	355	38	31	69	5	143
O	96	112	162	12	382	38	45	65	5	153
N	91	117	154	11	373	36	47	62	5	150
D	99	147	151	13	410	40	59	61	5	165

TABLE 38

MONTHLY ENERGY USAGE BREAKDOWN (MWh)
LARGE RETAIL STORE (RSL)

Mo	Elec.	Heat.	Cool.	Hot H_2O	Total	Elec.	Heat.	Cool.	Hot H_2O	Total
	Reference Model					High Consumption: Conventional Model				
J	659	168	223	2	1052	659	168	223	2	1052
F	595	153	228	2	970	595	153	228	2	970
M	659	185	274	2	1110	659	185	274	2	1110
A	639	146	326	2	1110	639	146	326	2	1110
M	657	151	340	2	1050	657	151	340	2	1150
J	639	128	353	2	1110	639	128	353	2	1110
J	661	83	393	2	1130	661	83	393	2	1130
A	657	77	398	2	1130	657	77	398	2	1130
S	639	103	365	2	1110	639	103	365	2	1110
O	659	143	346	2	1150	659	143	346	2	1150
N	637	177	251	2	1062	637	177	251	2	1162
D	661	187	180	2	1006	661	187	180	2	1006
	Energy Conserving: Retrofit Model					Energy Conserving: New Standards Model				
J	502	128	170	2	802	151	38	51	1	240
F	454	117	173	2	745	136	35	52	0	224
M	502	141	209	2	853	151	42	63	1	256
A	487	111	248	2	848	146	33	75	1	254
M	501	115	259	2	877	150	35	78	1	263
J	487	98	269	2	855	146	29	81	1	257
J	503	63	299	2	867	151	19	90	1	260
A	501	58	303	2	864	150	18	91	1	259
S	487	79	278	2	845	146	24	83	1	254
O	502	109	264	2	876	151	33	79	1	263
N	485	135	191	2	813	146	41	57	1	244
D	503	143	137	2	785	151	43	41	1	235

TABLE 39

MONTHLY ENERGY USAGE BREAKDOWN (MWh)
MEDIUM SHOPPING CENTER (SCM)

Mo	Elec.	Heat.	Cool.	Hot H_2O	Total	Elec.	Heat.	Cool.	Hot H_2O	Total
	Reference Model					High Consumption: Conventional Model				
J	1002	958	---	26	1987	1430	1936	887	37	4291
F	1187	673	---	31	1890	1290	1470	1284	33	4076
M	1441	601	---	38	2080	1425	1516	1523	37	4501
A	1183	676	---	31	1890	1384	1508	1180	36	4108
M	1432	567	---	37	2036	1424	1316	1644	36	4420
J	1297	487	---	34	1818	1384	987	1530	36	3937
J	1203	461	---	32	1696	1431	747	1452	38	3667
A	1191	474	---	31	1696	1424	717	1448	36	3624
S	1045	454	---	27	1527	1384	574	1317	36	3311
O	1412	490	---	37	1939	1430	1188	1554	37	4208
N	1183	482	---	31	1696	1378	988	1267	36	3669
D	1236	671	---	33	1939	1431	1485	1220	38	4173
	Energy Conserving: Retrofit Model					Energy Conserving: New Standards Model				
J	503	481	---	13	997	195	186	---	5	386
F	454	258	---	12	723	176	100	---	5	280
M	502	209	---	13	724	194	81	---	5	280
A	487	278	---	13	778	188	108	---	5	301
M	500	198	---	13	712	194	77	---	5	276
J	486	183	---	13	682	189	71	---	5	265
J	·503	193	---	13	710	195	75	---	5	275
A	501	199	---	13	713	194	77	---	5	276
S	487	211	---	13	711	189	82	---	5	276
O	503	175	---	13	691	195	68	---	5	268
N	485	197	---	13	695	188	76	---	5	269
D	503	273	---	13	790	195	106	---	5	306

TABLE 40

MONTHLY ENERGY USAGE BREAKDOWN (MWh)
LARGE SHOPPING CENTER (SCL)

Mo	Elec.	Heat.	Cool.	Hot H_2O	Total	Elec.	Heat.	Cool.	Hot H_2O	Total
	Reference Model					High Consumption: Conventional Model				
J	1402	1020	1028	49	3500	2174	1582	1594	76	5426
F	1273	908	1339	45	3630	1961	1399	2062	69	5591
M	1400	974	1537	49	3960	2167	1507	2380	76	6130
A	1359	943	1281	48	3630	2104	1460	1983	74	5621
M	1398	920	1594	48	3960	2165	1425	2469	75	6134
J	1374	897	1640	48	3960	2104	1374	2512	74	6064
J	1410	911	1720	50	4090	2175	1405	2653	77	6310
A	1408	860	1719	49	4090	2165	1380	2625	75	6245
S	1366	843	1634	48	3890	2104	1298	2517	74	5993
O	1422	963	1655	50	4090	2174	1472	2529	76	6251
N	1358	877	1418	47	3700	2095	1353	2188	73	5709
D	1445	1003	1361	50	3830	2175	1541	2091	77	5884
	Energy Conserving: Retrofit Model					Energy Conserving: New Standards Model				
J	1080	786	792	38	2696	373	271	273	13	930
F	974	659	1025	34	2778	336	240	353	12	958
M	1077	749	1183	38	3046	372	258	408	13	1051
A	1045	725	985	37	2793	361	250	340	13	964
M	1076	708	1227	37	3048	371	244	423	13	1052
J	1045	682	1248	37	3013	361	235	431	13	1040
J	1081	691	1318	38	3135	373	238	455	13	1082
A	1076	658	1304	37	3103	371	237	450	13	1071
S	1046	645	1251	37	2978	361	222	431	13	1027
O	1080	731	1257	38	3106	373	252	434	13	1072
N	1041	672	1087	36	2837	359	232	375	13	979
D	1073	766	1039	38	2924	370	264	359	13	1009

large shopping center, considered as a primary application area for commercial applications of STES, was evaluated for both the energy conservation retrofit and the energy conservation new standards configurations to help define possible effects due to conservation. The six model building configurations and their assumed energy requirements are summarized in Table 41.

TABLE 41

SELECTED MODEL BUILDING CONFIGURATIONS

Building		Floor Area [m^2(ft^2)]	HVAC System	Energy Demand (MWh/yr)		
				Electrical	Thermal	
Type	Computer File Name				Cooling	Heating
Large Shopping Center	SHOPCL	69,700 (750,000)	Conventional Multizone	25,565	27,604	17,195
Large Shopping Center	SCLECR	69,700 (750,000)	Energy Conserving Retrofit-Multizone	12,694	13,716	8,508
Large Shopping Center	SCLNS	69,700 (750,000)	Energy Conserving New Standards-Multizone	4,381	4,732	2,943
Medium Shopping Center	SHOPCM	41,820 (450,000)	Conventional Multizone	16,815	16,306	14,432
Large Retail Store	STOREL	18,590 (200,000)	Conventional Multizone	7,762	3,677	1,701
Low Rise Office	OBLCH	18,590 (200,000)	Conventional Dual Duct	2,432	5,663	4,476

4.7 CONCLUSIONS

There is a considerable variability in weather conditions in the United States which can be categorized into six climatic regions. The Gulf and South Atlantic regions are considered to be highest in apparent growth potential for commercial buildings.

A deterministic model for approximating the site environmental weather conditions was developed that allows a simple representation of the insolation available for tracking and non-tracking collectors to be made using data normally available in the Climatic Atlas.

The commercial market sector was evaluated for STES application through census data which indicated that shopping centers and large retail stores were the most likely markets for STES in the commercial sector. The census data also indicated that the size of urban shopping centers is relatively independent of the city population with an average size of 16,000 m^2 (150,000 ft^2). Rural shopping centers tend to be smaller with an average size of 9,000 m^2 (100,000 ft^2

The energy usage in commercial buildings varies widely depending on store hours and internal HVAC systems utilized more than on the external weather conditions. Most of the buildings considered in this study were "thermally heavy" and external thermal losses were not a major part of the building heating and cooling requirements. Computer simulation study results using the AXCESS substantiated this conclusion for six model building configurations that were assumed as representative of the commercial sector buildings.

Because of the sensitivity to internal HVAC and lighting systems, building energy demand will be strongly affected by conservation methods and standards so that prediction of building energy usage in the 1985-1990 time frame is difficult. New standards such as ASHRAE 90-75 could cause a reduction in average building energy usage by a factor of 3 to 4, if implemented. Consequently, any study of the 1980-2000 period must consider a wide range of energy usage rates in projecting market demand.

5.0 EVALUATION METHODOLOGY

Although the component characterizations described in Section 3.0 are relatively simple, combining them with an appropriate energy balance to produce a solar total energy system capable of meeting the building load profiles is a tedious task. This task is best accomplished through the use of a computer program. The building energy requirements can then be approximated by inclusion of electricity and fuel costs as well as environmental data for each site location and analyzed in conjunction with the available insolation. In this study, a computer program was developed to analyze Rankine cycle and photovoltaic STES while a program to analyze Brayton cycle STES was developed but not completed after it was concluded that predicting the thermal performance of the Brayton cycle collector was not within the scope of the study. Consequently, only the Rankine cycle and photovoltaic STES are discussed in the remaining report sections. A combined listing of the Rankine cycle and photovoltaic STES is given in Appendix E. This program designated STESEP is not intended to replace the larger more sophisticated programs (i.e., SOLSYS,[1] TRNSYS[3] but instead to provide reasonable estimates of component sizes for a more detailed evaluation by the larger and more detailed programs. Also, as discussed in Appendix F subroutines were developed for modifying TRNSYS and a validation of the computer program STESEP for the organic Rankine STES concept was made for one building condition at one site utilizing actual weather tape data. The result of the comparison was reasonable and justified the use of the computer program STESEP for evaluation of the various STES conceptual designs in the model buildings and site locations.

In the discussion that follows, the main sections of the computer programs are described to indicate the logic used in comparisons of the STES conceptual design for each building.

5.1 SOLAR TOTAL ENERGY SYSTEM EVALUATION PROGRAM (STESEP)

Two versions of a small computer program have been written in FORTRAN for use on the General Electric (Honeywell) 440 computer to evaluate the Rankine cycle and photovoltaic STES concepts. These programs evaluate building loads and collector (or solar array) behavior and size components necessary for the STES

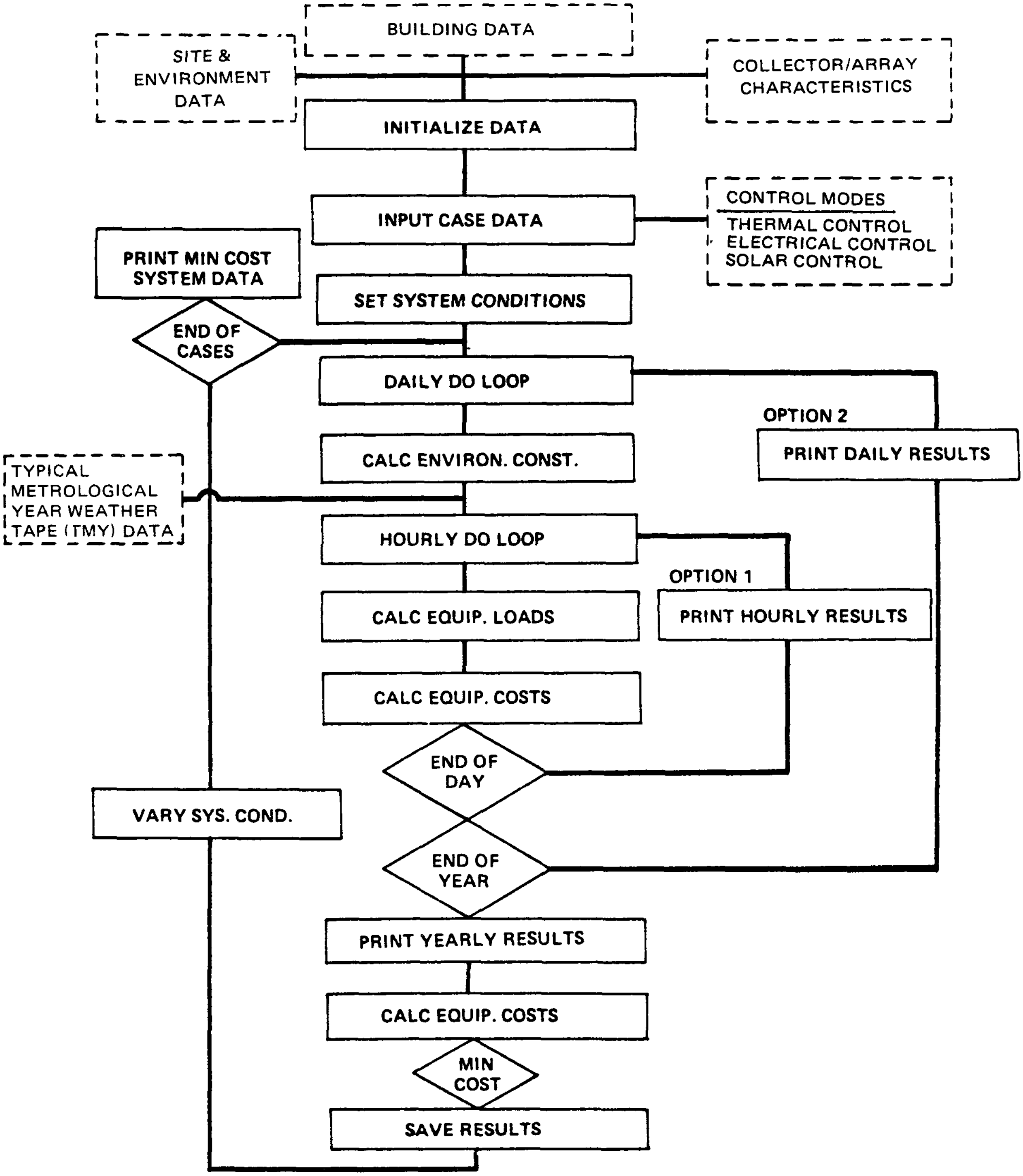

Figure 35. STESEP Logic Diagram

concept being evaluated. A program logic diagram for STESEP is shown in Figure 35. The program uses hourly energy balances to define the STES operation. Table 42 shows the input requirements for the program and lists the program output in general terms.

The site and environmental conditions are combined with the building load parameters, as discussed in the following text, to approximate the electrical, heating, and cooling loads for the building. The solar energy input is estimated, based on the analysis described in Section 4.2 and combined with the preselected control mode to determine the hourly energy transfer rates. After a complete year of operation has been analyzed, the maximum energy transfer rates are used to determine equipment sizes. The installed costs of the various equipment items and the system operation and maintenance costs are then computed employing the algorithms described in Section 5.1.3.

The annualized system resultant cost is then determined using the procedures described in the JPL/ERDA cost methodology.[(51)]

TABLE 42

STESEP INPUT/OUTPUT PARAMETERS

Input Parameters	Output Parameters
Building Data	Load Profiles (Monthly and Hourly
Environment (Site) Data	Component Sizes
Collector/Array Characteristics	Capital Investment
Operational Data	Annualized Cost

5.1.1 Building Load Characterization and Verification

Although most industrial and commercial facilities can be classified as "thermally heavy" (i.e., significant thermal energy generated within the building due to occupancy, lighting, and equipment) the variation in energy demands throughout the year as well as the variable solar energy availability must be considered in any application of STES. This is a function of both the building construction, shape and operational conditions, as well as, the local environmental conditions which can vary significantly in different parts of the country.

Direct calculation of the building energy demands is extremely difficult and beyond the scope of a small computer program like STESEP and in the absence of actual data should be accomplished with a more elaborate program such as AXCESS[46] or ECUBE[52].

As discussed in Sections 4.4 and 4.6, the energy demands of commercial buildings are primarily a function of the lighting and HVAC system of the building. Commercial buildings are normally "thermally heavy" so that environmental effects are less important than the internal operating parameters (e.g., hours of operation, illumination/unit area, etc.) in determining the building loads. Prediction of the type of HVAC system which should be selected for commercial buildings in the 1985 to 2000 time frame is also difficult so, consequently, six typical commercial building configurations were selected during the development of STESEP as discussed in Section 4.6. The electrical and thermal loads for these buildings were then used to define coefficients in the simplified load equations used by the STESEP computer program.

Since the building loads for commercial buildings are primarily a function of the way the building internal systems are operated, the yearly loads must also be available to allow adjustment of several program constants so that the electrical, heating, and cooling loads can be balanced. The STESEP program uses six constants to obtain the balance. These constants* are CEL, CVR, CVH, CHD, CHL, CRL and are used to obtain agreement between the STESEP predictions for hourly, monthly, and yearly loads with the values determined from a more exact source as discussed in Section 4.4.

The refrigeration and heating demand loads are related to the input hourly loads by the following equation:*

$T_a > T_{SP}$

$$\dot{Q}_{RD} = \dot{Q}_T \left[CEL \cdot EL(t) + CVR \cdot OL(t) + CHL \cdot CRL \cdot (T_a - T_{SP})\right] \quad \ldots(20a)$$

$$\dot{Q}_{HD} = \dot{Q}_T \left[CVH \cdot OL(t) - CEL \cdot EL(t) + CHD \cdot HL(t)\right] \quad \ldots(21a)$$

*See list of symbols, page 167.

For $T_a < T_{SP}$,

$$\dot{Q}_{HD} = \dot{Q}_T \left[CVH \cdot OL(t) - CEL \cdot EL(t) = CHL \cdot (T_{SP} - T_a) + CHD \cdot HL(t) \right] \quad \text{...(20b)}$$

$$\dot{Q}_{RD} = \dot{Q}_T \left[CEL \cdot EL(t) + CVR \cdot OL(t) \right] \quad \text{...(21b)}$$

'he electrical demand load is given by:

$$\dot{Q}_{ED} = \dot{Q}_T \cdot EL(t) \quad \text{... (22)}$$

The coefficients in these equations are empirical constants for the building and are adjusted by the user to match demand loads for the building which must be obtained from another source (e.g., metered data, AXCESS, etc.). Reference 53 gives the procedure for adjusting the coefficients to allow STESEP Code to produce the desired loads.

It should be noted that the building thermal capacitance does not appear in Equations 20 and 21 nor does a term representing the solar energy input. The thermal capacitance of the buildings is approximated by shifting the time of day when the maximum and minimum air temperatures occur (see Equation 23). This shifts the hourly variation of the building loads to approximate shift caused by wall and roof capacitance.

Energy input from the sun has been neglected since shadow effects from the collectors depend strongly on their placements around (and on) the building and these locations are usually not known during conceptual analyses.

Evaluation of the demand loads for commercial buildings is beyond the scope of the STESEP computer program. Another source of this data must be used which can be actual metered data for the building under consideration, output from a computer program such as AXCESS(46) or ECUBE(52) or even generalized energy requirements such as specified in Reference 52. In this study, simulations with the AXCESS program were used to define load profiles for six model buildings as

TABLE 43

BUILDING SURVEY: USAGE SIMULATION ACCURACY

Building File Name	Predicted Electrical Usage (MWh/yr)	Actual (MWh/yr)	Error (%)	Predicted Cooling Usage (MWh/hr)	Actual (MWh/yr)	Error (%)	Predicted Heating Usage (MWh/yr)	Actual (MWh/yr)	Error (%)
SHOPCL	25570	25565	+.02	27798	27604	+.70	17230	17195	+.20
SCLECR	12693	12694	-.00	13730	13716	-.10	8513	8508	+.06
SCLNS	4385	4381	+.09	4767	4732	+.74	2955	2943	+.41
OBLCH	2431	2432	-.04	5620	4663	-.76	4499	4476	+.51
STOREL	7761	7762	-.01	3656	3677	-.57	1695	1701	-.35
SHOPCM	16810	16815	-.03	16305	16306	-.01	14394	14432	-.26

discussed in Section 4.6. Table 43 compares the STESEP simulation with the AXCESS results for the model buildings showing the very good agreement obtained by this simple methodology.

As another verification of the method for approximating building loads, actual metered data for a department store (see Section 4.4.1) was approximated using Equations 20a thru 22 resulting in the curves shown in Figures 36 and 37. Figure 36 shows the predicted heating, cooling, and electrical loads for a San Bernardino department store. Figure 37 compares the hourly load prediction for June with the metered data for the maximum load day in June 1969. When the variability introduced by weather conditions and operational variations is considered, the agreement between prediction and metered data is very good both on a monthly basis and on an hourly basis.

5.1.1.1 Approximation of Reference Building HVAC Systems

In order to estimate the cost effectiveness of the STES as used in commercial buildings, a reference building load profile must be defined for each building that realistically considers actions the owner would probably take whether or not a STES was used. Since the model building types (see Section 4.6) considered in this study cover the complete range of energy conservation measures now contemplated, only methods of meeting the demand loads are of concern for definitions of the reference case. Most large commercial buildings today use all electric systems (see Section 4.4) that use strip heaters to provide the heating loads. Conversion of space heating and water heating loads to fossil fuel (oil - since gas hookups will probably be discouraged in the 1985 time period) would be more compatible with STES, as well as more economical over the complete range of cost parameters considered. Also, cascaded vapor compression chillers would probably be used for their economic advantages. The reference cost for the building energy, therefore, was based on the following:

1) Use of fossil fuel to supply space heating and process heat (hot water) to the building

2) Use of electric-driven vapor compression chiller

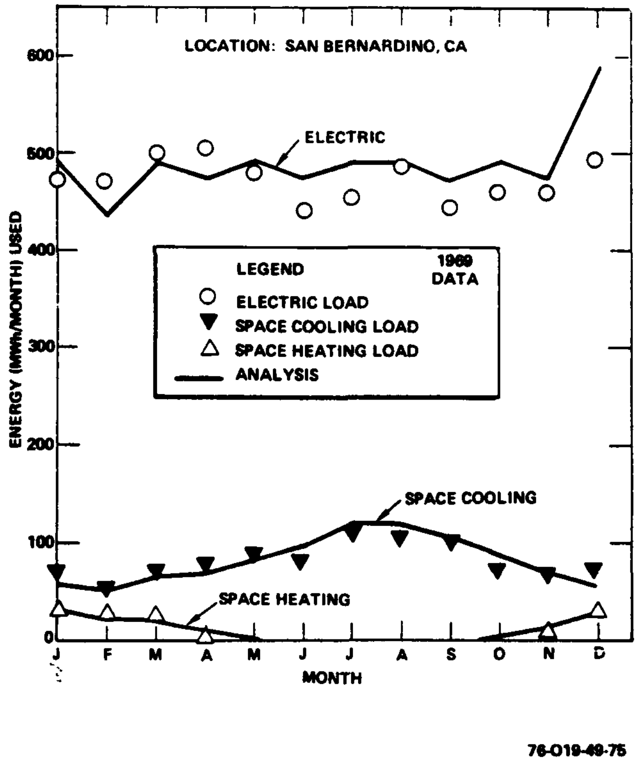

Figure 36. Comparison of Department Store Energy Data With Evaluation Program Predictions — Monthly Loads

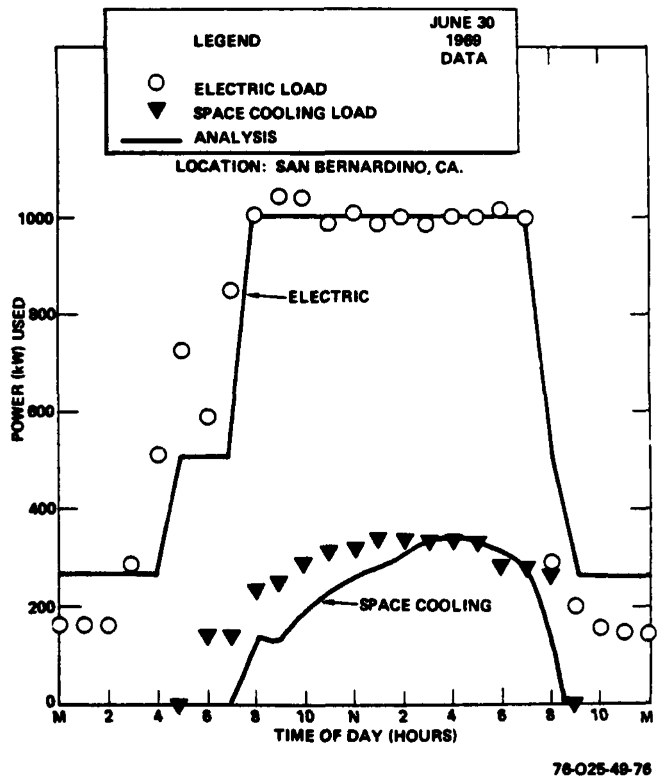

Figure 37. Comparison of Department Store Energy Data With Evaluation Program Predictions — Hourly Loads

5.1.2 Approximation of Environmental Data and Verification

The environmental data for twelve representative sites shown in Tables 10 thru 21 provides the input parameters necessary for the STESEP computer code.

5.1.2.1 Temperature Data

The monthly maximum and minimum temperatures from these tables for the site location were used in approximating the thermal requirements of the building in the STESEP Computer Program. A sinusoidal variation in the air temperature was assumed to occur as shown in the following equation. This gives very good agreement with heating and cooling degree day data.

$$T_a = T_{mn} - (T_{mx} - T_{mn})[1 + \cos(h + t_L)]/2. \qquad \ldots (23)$$

A lag (t_L) is introduced into the air temperature to compensate for building capacitance effects as discussed previously.

Table 44 shows the good agreement produced for heating degree days and cool ing degree days for the twelve sites by this method. The discrepancies correspond to an error of $<1^{o}$ in air temperature in Equation 23.

5.1.2.2 Approximation of Solar Insolation

The deterministic method of approximating solar insolation described in Section 4.2 allows the STESEP to evaluate flat plate, 1-axis and 2-axis tracking distributed collectors directly, but it cannot directly predict weather outages as described in References 54 to 56. Table 44 also compares the direct normal radiation used by STESEP with that of Reference 54 to verify the integration used by the code.

To estimate realistically the usable energy collected by the STES, the analysis approach used in Reference 54 has been adopted and was based on the percent possible sunshine (PP) data for the site.

The percent possible sunshine for a site can be related to the number of days with 50% of the possible sunfall as indicated in Figure 38. For the days that it is cloudy (<50% sunshine), it is assumed that the operator of the STES will not attempt to start up the system and hence the STES will not produce any usable output for these days. The remaining days (>50% sunshine) are assumed to be sunny and the STES will produce usable output.

TABLE 44

SITE SURVEY: CLIMATIC STIMULATION SURVEY

Site	STESEP Predicted HDD/yr*	Actual HDD/yr	Error (HDD)	STESEP Predicted CDD/yr†	Actual CDD/yr	Error (CDD)	Predicted Insolation§ (Btu/ft²-Day)	Actual Insolation (Btu/ft²-Day)	Error (%)
Lake Charles, LA	1211	1498	-288	2671	2739	-68	1764	1763	+0.06
Fort Worth, TX	2371	2382	-11	2766	2587	+179	2037	2053	-0.78
Blue Hill, MA	6051	6335	-284	636	457	+179	1750	1763	-0.74
Albuquerque, NM	4388	4292	+95	1437	1316	+121	2604	2615	-0.42
Washington, DC	4236	4211	+25	1285	1345	-60	1542	1551	-0.58
Seattle, WA	4720	4487	+233	279	199	+80	1496	1505	-0.60
Phoenix, AR	1869	1552	+317	3542	3508	+34	2508	2523	-0.59
Omaha, NB	5817	6049	-232	1346	1173	+173	1949	1964	-0.76
Miami, FL	186	206	-20	3958	4038	-80	2024	2029	-0.25
Madison, WI	7737	7729	+8	620	460	+160	1838	1828	+0.55
Los Angeles, CA	1441	1245	+197	1168	1185	-17	2156	2166	-0.46
Nashville, TN	3632	3696	-64	1807	1694	+113	1538	1554	-1.03

*HDD = Heating Degree Days
†CDD = Cooling Degree Days
§Direct Normal Insolation

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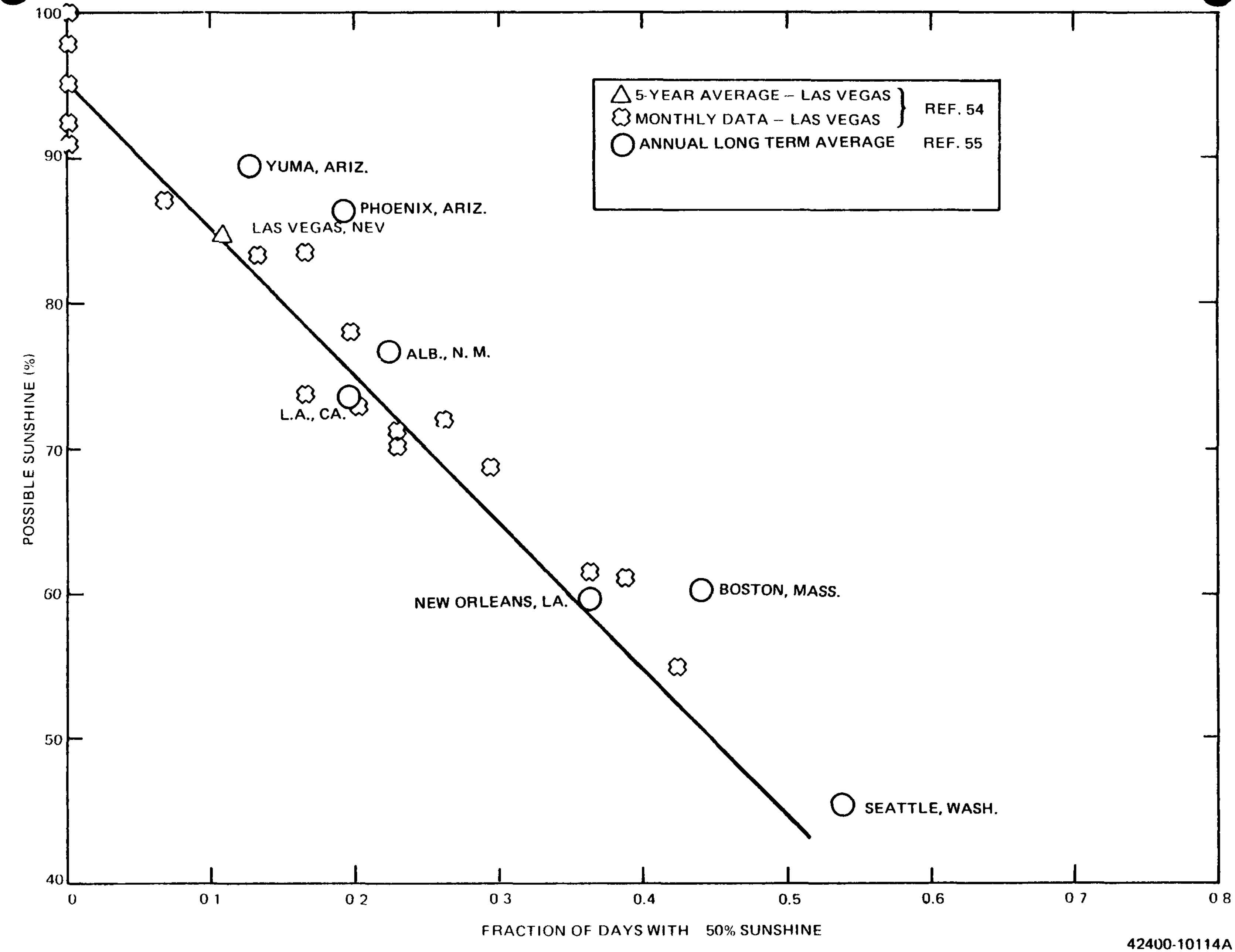

Figure 38. Sunfall Outage Correlation

This curve also represents well the National Oceanic and Atmospheric Administration (NOAA) data for fraction of cloudy days (greater than 0.8 sky cover) versus percent possible sunshine in Reference 54 which presents long-term averages for many locations throughout the U.S.A. The equation used in this program to represent the data is:

$$\text{Fraction Sunny Days (FSD)} = (5 + PP)/100 \qquad \ldots (24)$$

The collector performance was computed using the deterministic insolation equations from Section 3.1 for a clear sky based on the clearness number CN. The collector output was then corrected for the FSD in the month based on Equation 24. The collector performance obtained in this manner agreed to within a few percent with the analyses of Reference 13 which used a direct integration of the same weather-tape data. While this does not verify the method, the agreement does lend confidence to the predicted results.

The STESEP methodology allows a number of conceptual designs to be evaluated, at minimum expense, to determine the proper operating strategy, in addition to determining equipment sizes, costs, and energy output. Because of the weather outages, a significant amount of the design load for the building will have to be supplied by conventional means. The standby fossil fuel system can provide this load, or it can be obtained from the utility during off hours, stored, and used as needed during peak-load periods. The "make or buy" decision is dependent on the relative costs of fuel and electricity at the site, as well as on the STES design itself. The STESEP program analyzes both "making" and "buying" of this energy, to determine the most cost effective way to produce the energy for the desired site load profile.

5.1.3 Cost Algorithms

A number of algorithms, based on 1976 price estimates, have been developed for the capital costs of candidate capital equipment and items, redundancy effects, and operations and maintenance costs and are incorporated in the STESEP Computer Code. They are discussed in the following paragraphs.

5.1.3.1 Capital Equipment Costs

Algorithms for the installed costs for the several candidate capital equipment items considered were obtained from References 57 thru 63 and are presented in Table 45. Preliminary computations indicate that the collector, storage, and power conversion systems will approach 90% of the initial capital outlays.

The several power conversion system cost algorithms have been compared for a 1-MWe unit. The costs ranged from $365,000 to $375,000. (Costs for equivalent "conventional" fossile fuel-fired gas turbine and 900-rpm reciprocating engine installations, derived from Reference 57, were $357,000 and $500,000.)

5.1.3.1.1 Estimated Cost of Small Central Receivers and Towers

In order to compare the performance of small central receivers with distributive collectors for STES commercial applications, algorithms for cost of the receiver and tower are required. In Reference 60, it was suggested that $\$100/m^2$ should be used for the installed cost of distributed collectors and $\$65/m^2$ for the heliostats used in a central receiver system. The cost of the receiver/tower was not given.

Reference 21 gives estimates for three small systems designed at the University of Houston and refers to previous analyses of large systems (100-200 MWe). Reference 19 describes one of these large systems in detail and has been used in conjunction with References 21 and 23 as the basis for this cost estimate.

In Reference 64, the height requirement for the central receiver tower is discussed. It is shown that the tower height will be approximately proportional to the square root of the heliostat area.

The cost of the tower itself will be proportional to the height of the tower raised to a power greater than unity. If the cost is assumed proportional to the square of the height, then the tower cost will be proportional to the heliostat area. Since the absorber area is also proportional to the heliostat area for a given concentration ratio, the total costs of the tower/receiver/plumbing should be related directly to the heliostat area.

Figure 39 shows the unit costs ($\$/m^2$) presented in References 21 and 19 for six systems ranging in size from a heliostat area of 1,100 to 855,000 m^2. These

TABLE 45

COST ALGORITHMS FOR CAPITAL EQUIPMENT

Unit	Size Range	Algorithm	Reference
1. Collector:			
a) Distributive	—	$100/m^2	61
b) Heliostats		$65/m^2	61
2. Storage:			
a) Hot Storage	150 - 150,000 ft^3	Cost = \$352 (vol, ft^3)$^{0.515}$ + \$12 (vol, ft^3)	58,63
b) Cold Storage	150 - 150,000 ft^3	Cost = \$352 (vol, ft^3)$^{0.515}$	63
c) Battery	—	Cost = \$50 (size, kWh) + \$75 (system size, kW)	57
3. Packaged Steam Boilers	10^4 - 10^5 lb Steam/h-Unit	Cost/Unit = \$3690 (lb Steam/h Unit)$^{0.32}$	57
4. Refrigeration:			
a) Centrifugal Chillers (Electric)	250-2000 tons	Cost/Unit = \$4240 (tons/Unit)$^{0.61}$	57
b) Centrifugal Chillers (Engine)	500-2000 tons	Cost/Unit = \$2270 (tons/Unit)$^{0.745}$	57
c) Absorption Chillers (Steam)	250-1200 tons	Cost/Unit = \$2194 (tons/Unit)$^{0.7}$	57
5. Power Conversion Systems:			
a) Sunstrand Organic Rankine Cycle	100-1000 kW	Cost = \$3815 (kW/Unit)$^{0.66}$	59
b) Rankine Cycle — Steam	1-1000 kW	Cost = \$22,700 + \$350 (kW)	60
c) Rankine Cycle — Steam	1000-1,000,000 kW	Cost = \$2150 (kW)$^{0.825}$	60
6. Shell & Tube Heat Exchangers	20-2000 ft^2	Cost/Unit = \$300 (Area, ft^2)$^{0.56}$	62
7. Cooling Towers — Dry	—	Cost/Unit = \$40 (Area, ft^2)$^{0.6}$	63

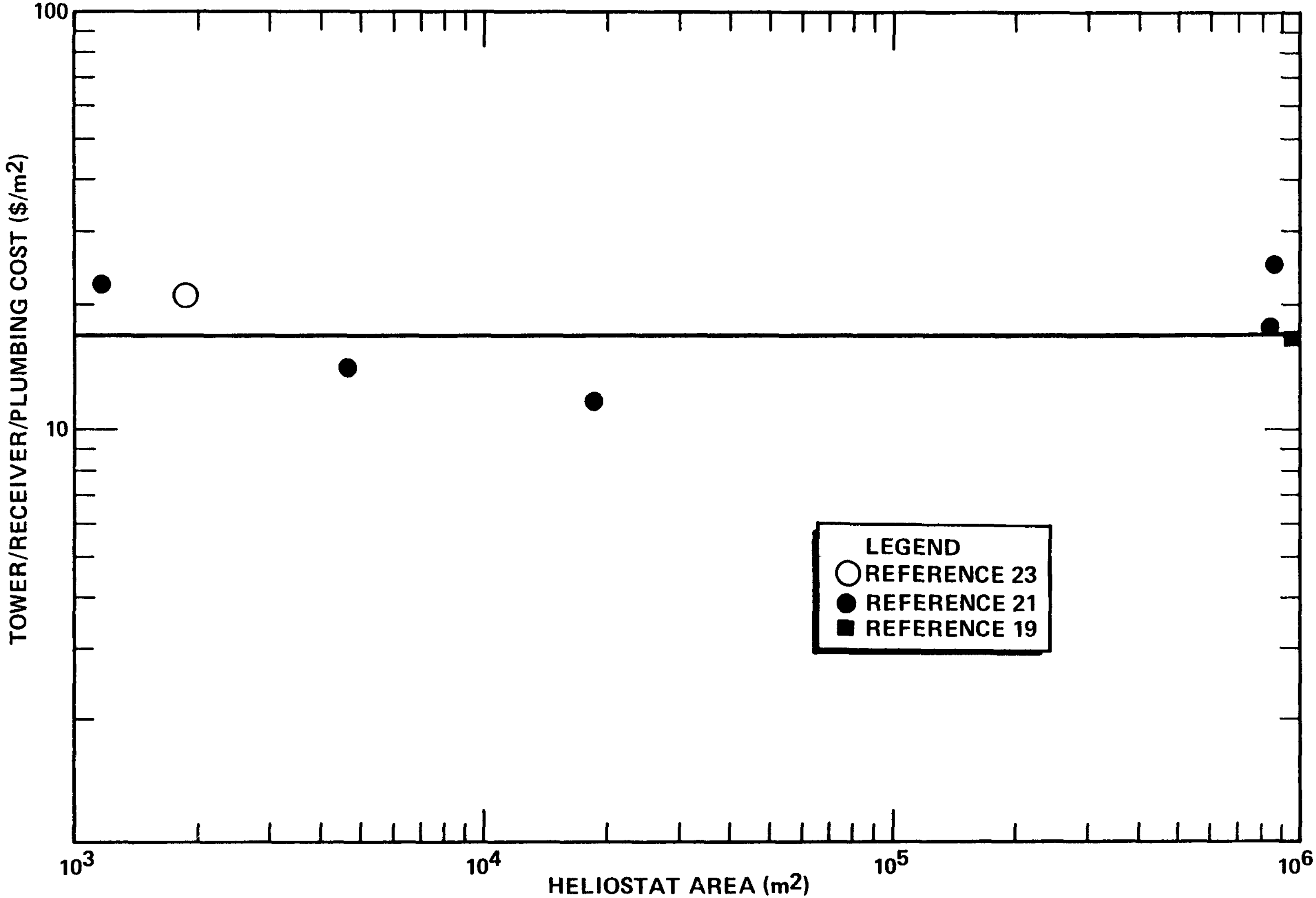

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Figure 39. Effect of System Size on Central Receiver Cost

COST ~(NO. UNITS) (SIZE)

OR

$$\frac{C_2}{C_1} \sim \frac{N_2}{N_1}\left(\frac{S_2}{S_1}\right)^n$$

WHERE:

	SIZE	N	
S =	100	1	N_1
S_2	100	2	N_2
	50	3	
	33	4	
	25	5	

AND n = 0.5; 0.6; 0.7

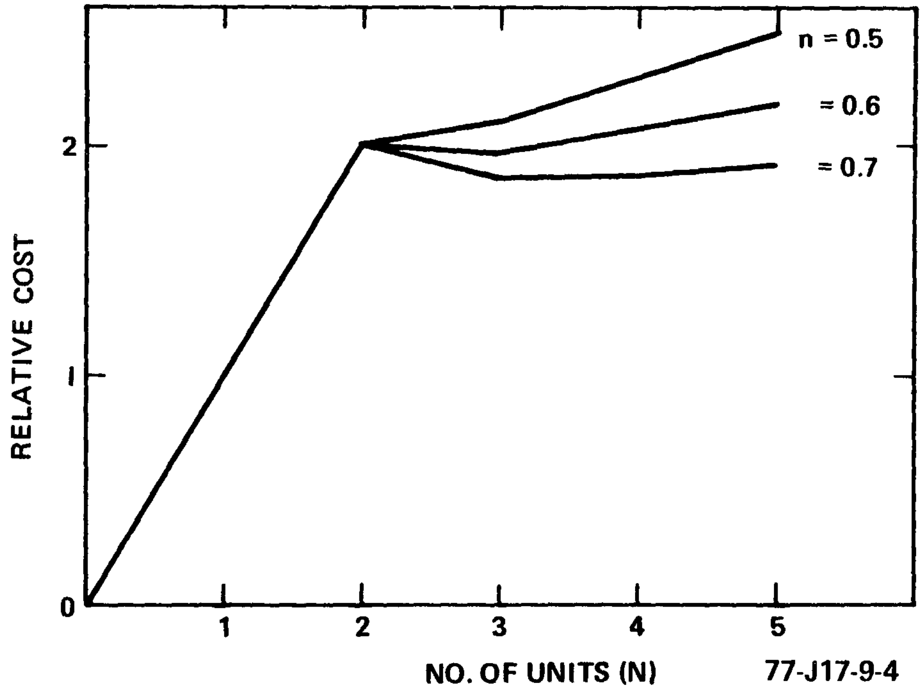


Figure 40. Effect of Redundancy on System Cost

data indicate that 17 $\$/m^2$ is a reasonable cost estimate over this range. The central receiver reference costs can, therefore, be related to the heliostat area by the algorithm:

$$\text{Central Receiver Cost} = (65 + 17)\ \$/m^2 = 82\ \$/m^2 \qquad \text{... (25)}$$

5.1.3.1.2 Effect of Redundancy of Subsystem Capital Costs

A scaling relationship was developed and the effect of selected subsystem redundancy on cost was assessed. Figure 40 shows the approximate effect of the number of units used to provide redundancy on the capital cost of a system when the unit costs are a power law function of the component size. That is,

$$\text{Unit Cost} \cong (\text{Unit Size})^n \qquad \text{...(26)}$$

The exponent, n, normally varies between 0.5 and 0.7.[57] To provide redundancy, one extra unit is assumed to be needed in the system so that the total cost is given by:

$$\text{Total Cost} \cong \left(\frac{\text{Design Capacity}}{\text{Unit Size}} + 1\right)\left(\text{Unit Size}\right)^n \qquad \text{...(27)}$$

As indicated in Figure 40 the cost of the redundant system is approximately double that of the nonredundant system independent of the number of components used with very little effect indicated for the power law exponent on the system cost.

5.1.3.2 Operations and Maintenance Costs

The operations and maintenance cost algorithms for both attended and "unattended" organic Rankine cycle plants were estimated based on the analyses of Reference 57. The data were developed by allocating supervision, operations, and maintenance labor as a function of plant size and operating hours in accordance with the guidelines suggested in Reference 57. Current quotations were used for labor rates (indirect, direct, and contract maintenance); materials and supply costs were estimated as a function of the number of kilowatt hours generated annually. Table 46 presents the allocations by category for attended

TABLE 46. OPERATIONS AND MAINTENANCE COSTS — FULLY ATTENDED RANKINE CYCLE

Installed Capacity (Nom.) (MWe)	Power Generated (kWh x 10^6/yr)	Materials & Supplies ($1000/yr)	Operators		Supervision ($1000/yr)	Maintenance		Cost ($/kWh)
			Number	Cost ($1000/yr)		Direct ($1000/yr)	Contract ($1000/yr)	
0.6	3	12	3	81	35	33	14	5.8
1.0	5	20	3	81	35	33	23	3.8
5.0	25	100	4	108	35	99	46	1.6
10.0	50	200	5	135	35	165	92	1.3
20.0	100	400	5	135	35	165	138	0.87
40.0	200	800	5	135	35	165	138	0.64

TABLE 47. OPERATIONS AND MAINTENANCE COSTS — "UNATTENDED" RANKINE CYCLE

Installed Capacity (Nom.) (MWe)	Power Generated (kWh x 10^6/yr)	Materials & Supplies ($1000/yr)	Operators		Supervision ($1000/yr)	Maintenance		Cost ($/kWh)
			Number	Cost ($1000/yr)		Direct ($1000/yr)	Contract ($1000/yr)	
0.6	3	12	0	0	35	66	14	4.2
1.0	5	20	0	0	35	66	23	2.9
5.0	25	100	0	0	35	99	46	1.1
10.0	50	200	0	0	70	165	92	1.1
20.0	100	400	0	0	105	165	138	0.81
40.0	200	800	0	0	105	165	138	0.60

Rankine cycle plants while Table 47 presents the allocation for unattended Rankine cycle plants. Figure 41 shows the effect of installed capacity on the operation and maintenance cost contribution to the cost of electricity from the plant. The operations and maintenance costs for attended Rankine cycle plants are well represented by the equation:

$$\text{Cost/year} = 132\ (\text{kWh/year})^{0.523} \qquad \dots (28)$$

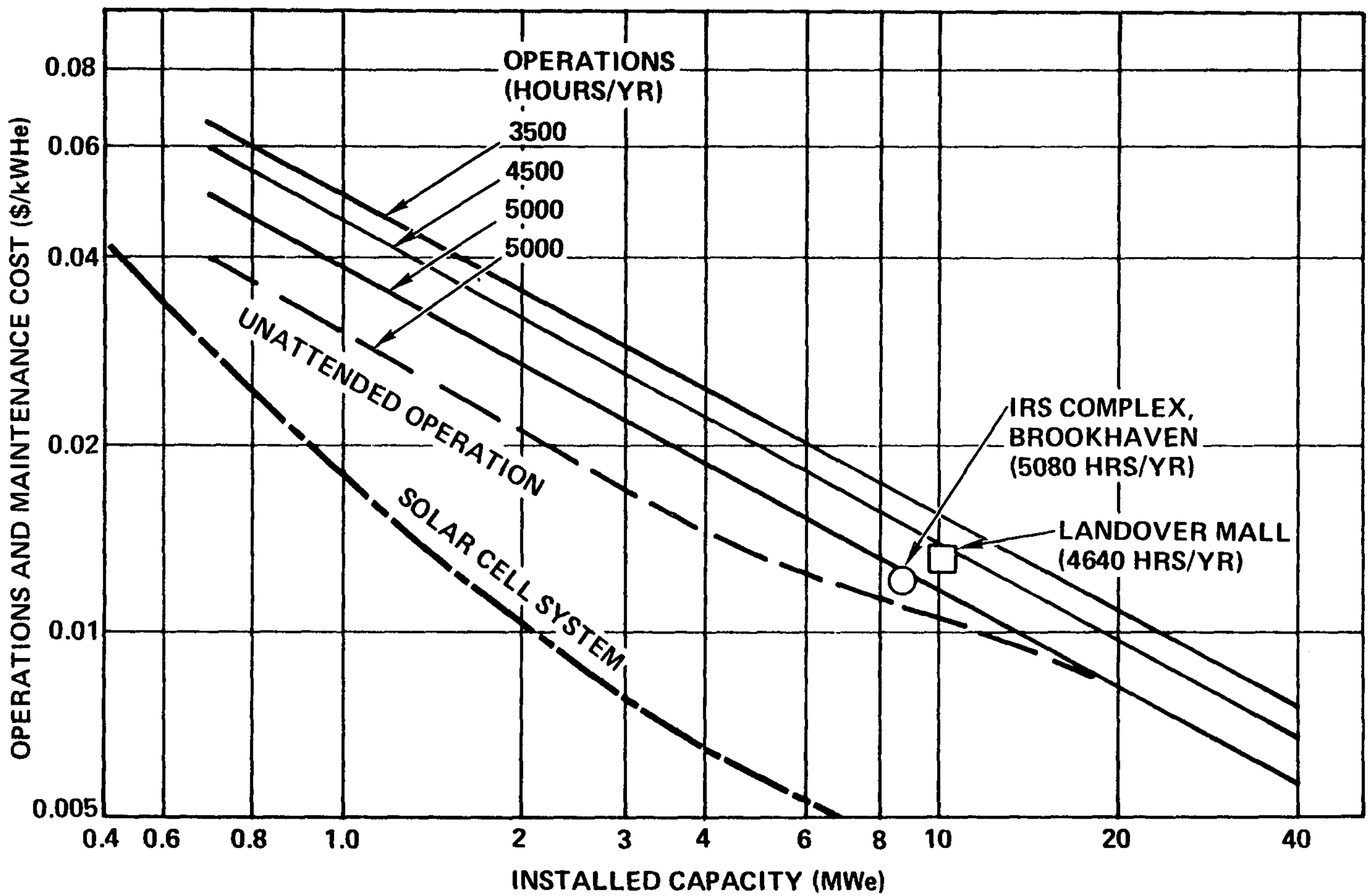
The operation and maintenance cost algorithm for a nontracking photovoltaic STES is also shown in Figure 41. The data were developed in a similar manner to the Rankine cycle plant costs by allocating supervision operations and maintenance labor as a function of plant size and operating hours as shown in Table 48. The algorithm used for photovoltaic STES is given by:

$$\text{Cost/year} = 80{,}000 + 2.68 \times 10^{-3}\ (\text{kWh/year}) \qquad \dots (29)$$

5.1.2.2 Approximation of Purchased Power Costs

The solution to potential load profile problems appears to lie in the combination of a peak-shaving system or a load-leveling system with the STES, so that purchased power in the late evening and early morning may be stored if desired for use during low insolation periods whether in the early evening or during cloudy days. The alternate approach is to generate the energy onsite with fossil fuel backup as part of the STES and reduce the peak purchased power as required. Either or both of these techniques can be used to produce load profiles that are acceptable to utilities; however, to evaluate the economic aspects requires definition of the cost of purchased electricity at specific sites fairly accurately. The Federal Power Commission (FPC)[65] publishes a rate summary for commercial users of electricity which can be used to define the constants in an empirical equation of the form:

$$\$/\text{kWh} = C_1\ (\text{kW/kWh})^{C_2} / \text{kW}^{C_3} \qquad \dots (30)$$



ALGORITHM: OPS AND MAINT COST ($/kWHe)	$\sim 0.044/(\text{MWe})^{0.523}$	$\pm 15\%$
(ATTENDED PLANT)	$\sim 132/(\text{kWHe/YR})^{0.523}$	

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Figure 41. Cost Algorithm (Operation and Maintenance)

TABLE 48. OPERATIONS AND MAINTENANCE COSTS — SOLAR PHOTOVOLTAIC SYSTEM

Installed Capacity (Nom.) (MWe)	Power Generated (kWh x 10^6/yr)	Materials & Supplies ($1000/yr)	Operators		Supervision ($1000/yr)	Maintenance		Cost ($/kWh)
			Number	Cost ($1000/yr)		Direct ($1000/yr)	Contract ($1000/yr)	
0.6	3	6	0	0	35	33	14	2.93
1.0	5	10	0	0	35	33	14	1.84
5.0	25	50	0	0	35	33	28	.58
10.0	50	100	0	0	35	50	40	.45
20.0	100	200	0	0	35	75	60	.37
40.0	200	400	0	0	35	100	80	.31

This type of equation acknowledges that current rate schedules have both a demand and energy charge and can, therefore, approximate the charges that will occur in the cost of purchased power as the load profile of the building changes. Figure 42 shows the variation in cost of electricity for the sites considered in this study.

5.1.3.4 System Annualized Costs

The figure of merit used by the STESEP Computer Program to evaluate the various STES concepts is the JPL/ERDA[51] "annualized cost." This is, in effect, a present value analysis of the total system life cycle costs. This concept considers the effects of both inflation (g) of capital costs (CI) and escalation in the cost of fuel and operating expenses (g_f).

Reference 51 gives the complete development of this method, which relates the annualized cost of the systems to the following relationship between capital investment (CI) and recurring cost (RCC): Appendix G discusses the cost sensitivities of these financial parameters in greater detail.

$$\overline{AC} = (\overline{FCR} \times CI_{pv} + CRF \times RCC_{pv})/(1 + g)^{p} \quad \ldots (31)$$

From the "annualized cost" of the building configuration without a solar total energy system, an incremental return on investment (ΔR.O.I.) can be computed as:

$$\Delta R.O.I. = (\overline{AC}_{o} - \overline{AC}_{stes})/CI_{stes} \quad \ldots (32)$$

In a like manner, the "breakeven" cost of electricity (B.E.C.E.) can be computed for each system as follows:

$$B.E.C.E. = \left(\frac{\$}{kWh}\right) \times \left[\frac{\overline{FCR}(CI_{stes} - CI_{o})_{pv} + CRF(OPM_{stes} - OPM_{o})_{pv}}{CRF(kWh_{o} - kWh_{STES})_{pv}}\right] \ldots (33)$$

All of these cost parameters are sensitive to the specific cost parameters (g, g_f, k, system life, etc.) but are useful for comparing systems for fixed

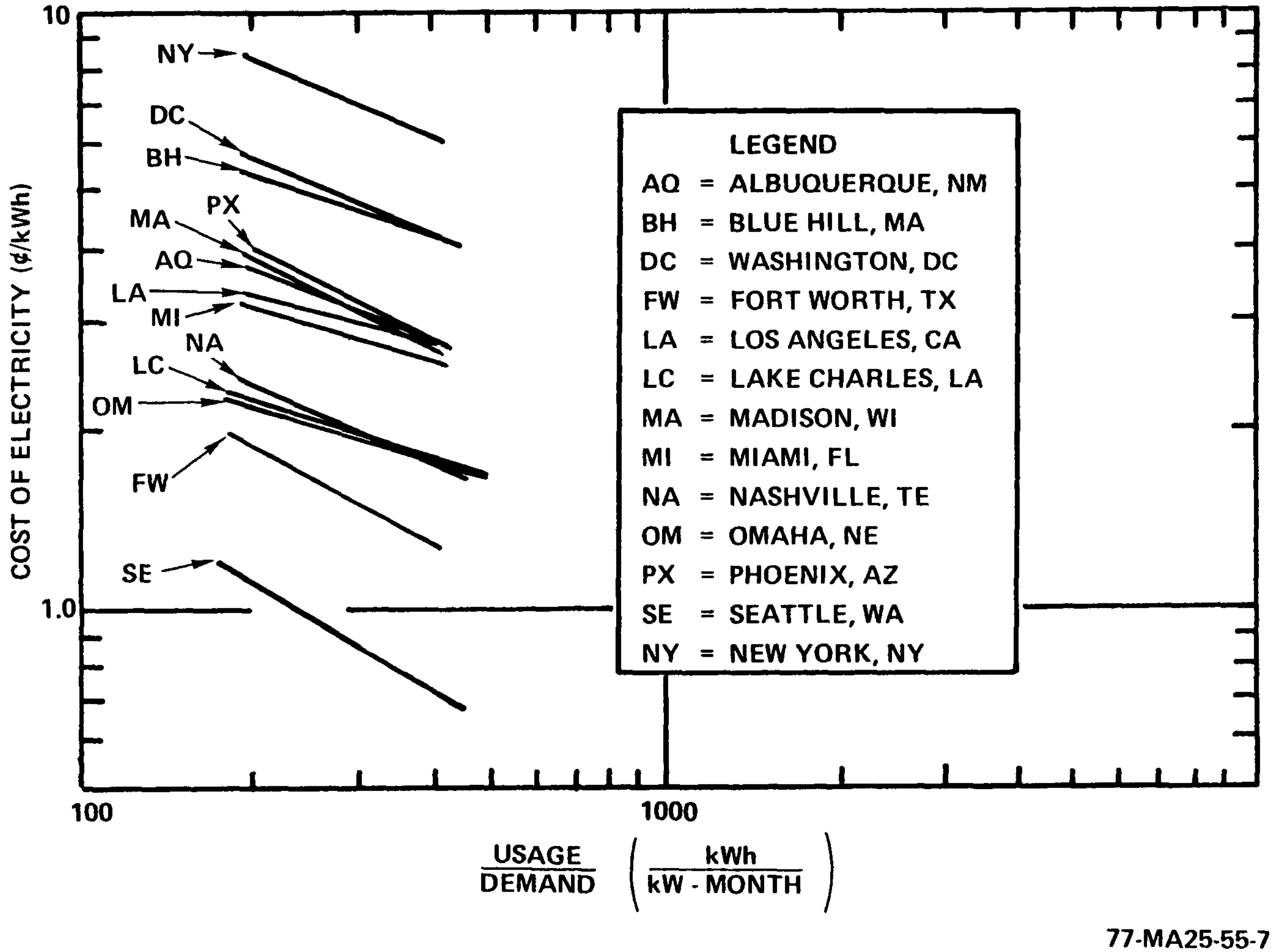

Figure 42. Present Cost of Electricity

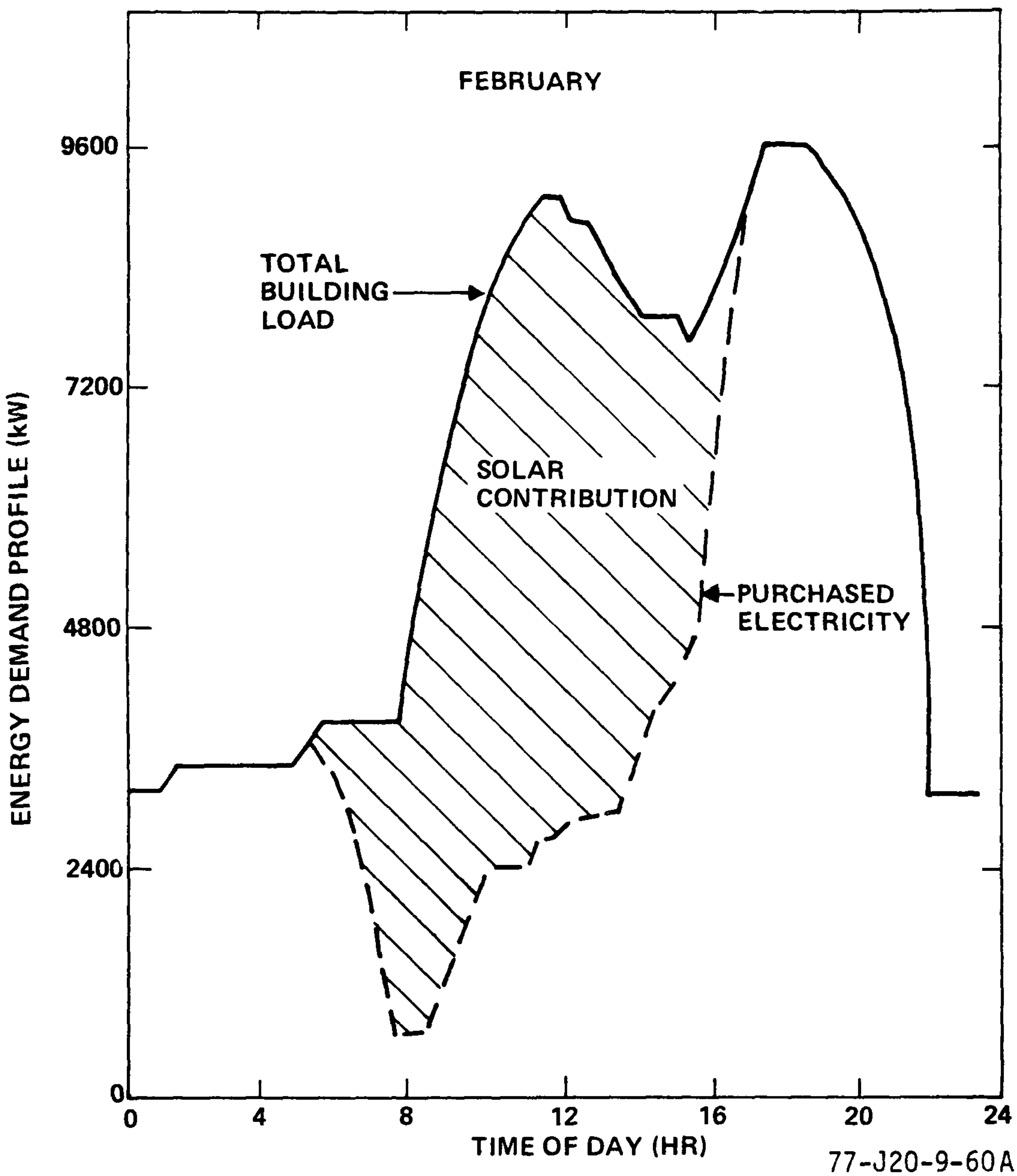

Figure 43. Typical Hourly Load Variation

economic parameters. Limit analysis can then be used to evaluate the effects of uncertainties in the cost parameters.

5.2 APPROXIMATION OF AUXILIARY ENERGY REQUIREMENTS

A maximum value could be specified for the electric energy purchased from the utility, which requires the STESEP program to size the PCS to produce all demands greater than this value with use of fossil fuel, where necessary, to meet these demand loads. A minimum can also be specified for the energy purchased from the utility which requires the STESEP program to size batteries and collectors to generate and store excess energy overnight for use during the following day. The STESEP program is, therefore, capable of evaluating a wide range of make or buy conditions for each STES design concept. This feature of the program was found to be necessary in order to maintain credibility for the conceptual STES designs, which tend to produce very poor load profiles from the utilities' point of view, as discussed in Reference 66. The weather outages discussed previously are the primary cause of this problem, since they prevent the peak demand load of the building from being reduced by the STES and require that the utility add additional power generation capability. This has been recognized as a problem by all investigators(54) and must be considered as part of the evaluation method.

STES sized to provide 40% or less solar contribution may not generate enough energy to cost effectively utilize either thermal or battery storage (as illustrated in Figure 43 for a photovoltaic STES concept) for an average winter day. Figure 43 shows that the peak purchased power for a day in February, for example, has not been reduced by the STES; although a 30% reduction in total energy has been accomplished.

Current utility contracts normally contain a ratchet clause that would use this peak demand value to set the price of all electricity purchased for a period of from one to twelve months. The quantity of storage required for a STES this size to reduce the peak value would be large and the alternate approach of onsite backup (fossil fuel) systems is much more cost effective. On site backup systems also protect the owner from the extended cloudy periods to be expected which would deplete any amount of storage and require the purchase of all power from the utility.

The utilities' attitudes toward solar energy systems in general has been positive but cautious. Many utilities are involved in solar energy programs of their own. For example, in California both Pacific Gas and Electric and Southern California Edison have active solar energy programs. Also, Southern California Gas Company has two solar-driven air conditioning projects. Alabama Power and light is a prime contributor on one of the DOE-sponsored solar heating and cooling demonstration projects. Among others actively involved are: Portland General Electric Company, Massachusetts Electric, Narraganset Electric, and Granite State Electric.

From discussions with personnel from these utilities, a primary concern of the utilities (as with most business), is the economic aspect. In addition, the utilities place high emphasis on reliability of service. Most of the federally funded solar energy programs refer to conventional utility supplies as "backup" systems to solar energy. Whenever the solar energy system cannot meet the demand, the utility is expected to supply the difference. Almost invariably the "backup" system must be capable of providing 100% of the demand when needed. While solar energy systems can, in some cases, assist in load leveling, it is more often that utilities must supply peak demands on their own.

Recognizing the possible erosion of their traditional market, some utilities are considering rate restructuring which could pose a problem for solar energy systems economically. An article in the January 1977 ASHRAE Journal cites Public Service Company of Colorado as an example. The utility has obtained permission to charge new residential customers on a demand/energy rate (DER) rather than on a declining block rate as at present. The DER would impose a charge based upon the 15-minute high demand encountered during the month. This is similar to commercial rates which, of course, bear serious implications for STES application to commercial buildings. As previously discussed, the cooperation of the utilities is essential to solar energy systems utilization success, at least in the STES case. Some incentive must, therefore, be offered which will attract utilities as solar energy advocates, most likely this must come from increased storage requirements for load leveling probably involving use of battery storage and the purchase of off-peak power or from onsite fossil fuel backup systems.

This is illustrated in Figure 44 which shows a typical load profile for a shipping center before and after installation of a STES producing 30% of the electrical load.

In this example, the installation of a Rankine cycle STES, providing about 30% of the building demand electrical load, did not reduce the peak demand of the building and, therefore, increased the unit price of its purchased electricity. Operation of the PCS with fossil energy to reduce the peak demand and improve the building load profile produced the most cost effective system considered.

5.3 LAND UTILIZATION CONSTRAINTS

Commercial buildings are normally located in relatively high-cost land areas ($10/m^2 to $50/m^2 or more) and consequently do not normally have a large parking area. Multi-tiered parking is common where land costs favor multistory buildings. Data from Reference 67 indicate that parking areas are usually less than the total building floor areas for shopping centers, while the parking area is considerably smaller for office buildings (particularly true for high-rise buildings).

Because of the land utilization factor and high land cost surrounding commercial buildings, the purchase of additional land for collector use only would add an incremental cost of $40/m^2 to $120/m^2 to the capital investment for the additional collectors. Since the reference cost for distributive collectors was assumed at $100/m^2 (see Section 5.1.3), the cost of land for these additional collectors could be considered as doubling the collector cost.

With all collector (and solar array) systems, the land utilization efficiency affects both the cost of connecting piping, etc., and the total amount of energy that can be captured on a fixed amount of land. Shadowing effects are important for all designs and must be considered in establishing the field construction for a specific application. The shadowing analyses from Reference 67 are considered to be sufficiently accurate for conceptual design sizing studies and have been used to establish the land utilization efficiencies used in the STESEP program to set the usable daily collection period for the collector and array systems (see Section 4.2)

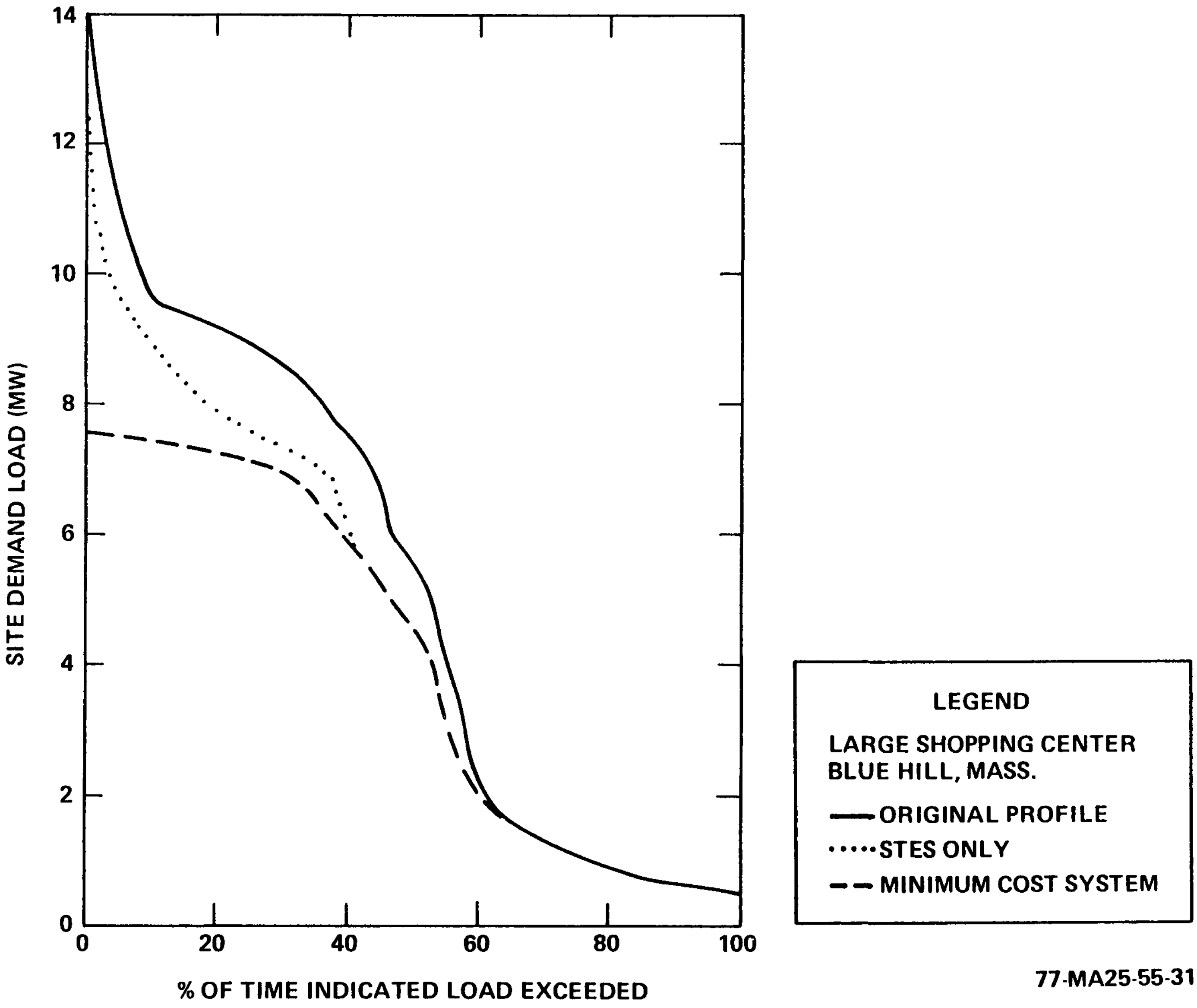

Figure 44. Typical Load Profiles for Commercial Buildings

Several assumptions were made in the analysis in Reference 67 which need to be repeated for clarity.

1) North-south (N-S) spacing should be made to prevent shadowing since this could reduce the winter output during the entire day.

$$\frac{Y}{L_c} = \frac{\text{N-S spacing}}{\text{collector length}} = \cos\phi + \frac{\sin\phi}{\tan(90-\delta_{max}-\phi)} \qquad \ldots(34)$$

2) The angle to prevent E-W shadowing is approximated by:

$$\cos\theta_z \geq \frac{W_c}{2X} = \frac{\text{collector width}}{\text{E-W spacing}} \qquad \ldots(35)$$

Based on this analysis, the STESEP computer program uses a default value for the east-west (E-W) spacing ratio of 0.4 which gives a 20 to 25% land utilization depending on the site latitude.

For tracking collectors, Figure 45 from Reference 13 shows the effect of collector spacing on performance for comparison with the simplistic analysis results from Reference 67. These studies indicate that collector area-to-land area ratios will probably be kept below 1/3 for distributed systems to prevent excessive shadowing losses. Reference 64 indicates the similar result for central receivers, since shadowing losses for both types of systems increase rapidly as the collector spacing is decreased. When area requirements for power conversion systems, energy storage, etc., are considered, an overall land utilization efficiency for STES using tracking collectors of 1/4 appears reasonable and should be used for estimating an upper limit for collector areas to be considered.

Nontracking flat plate collectors and photovoltaic arrays which are tilted at an angle equal to the latitude can more effectively utilize the available area, since shadowing effects are minimized although cosine losses are large. Equation 34 indicates that collector area-to-land area ratios of 0.6 can be obtained without shadowing losses at 34^{o} latitude. Land utilization for tracking arrays is illustrated in Figure 46 which is a picture of the array field from the direction of Polaris (perpendicular to the sun's rays). In the upper portion

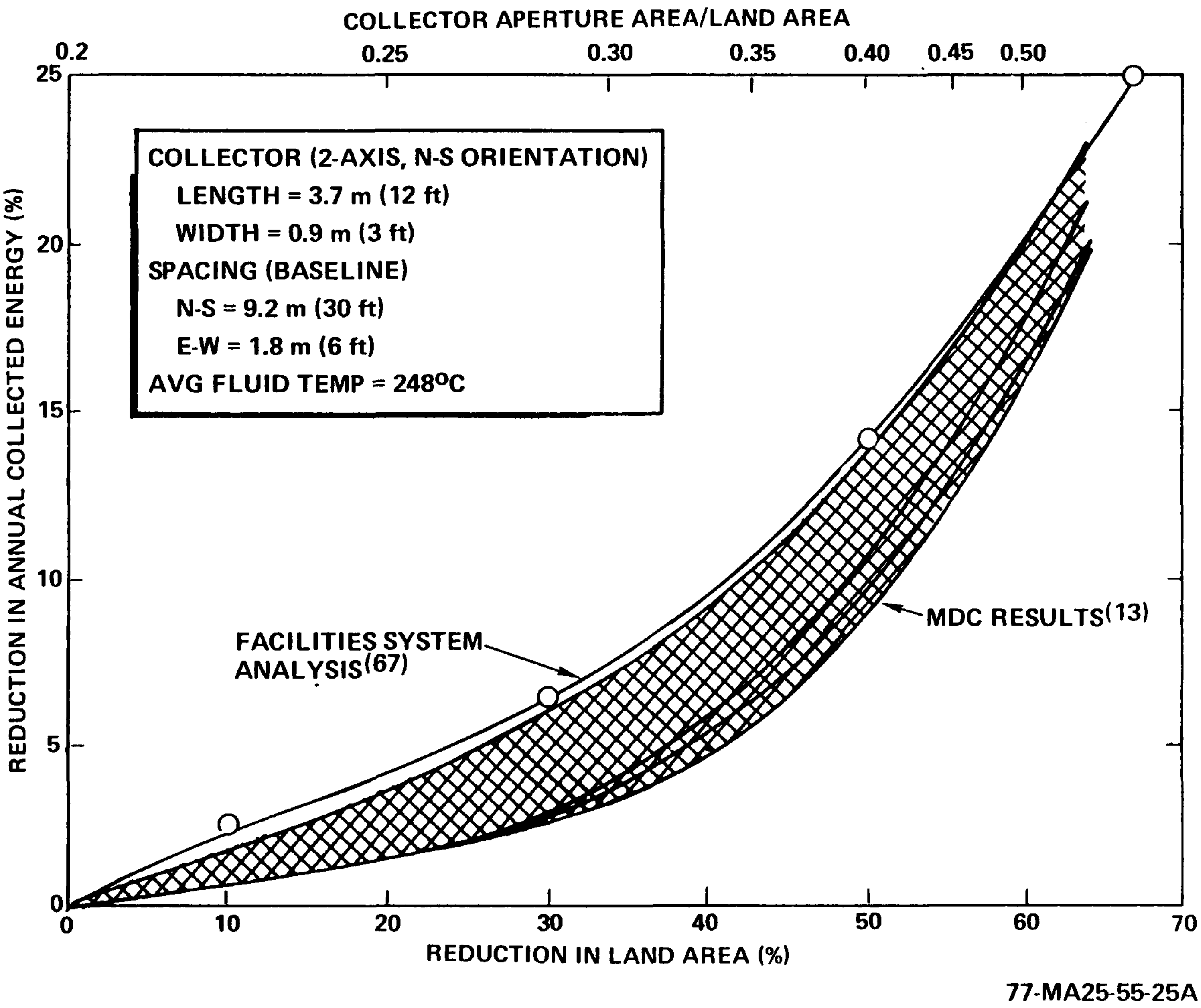

Figure 45. Effect of Collector Spacing

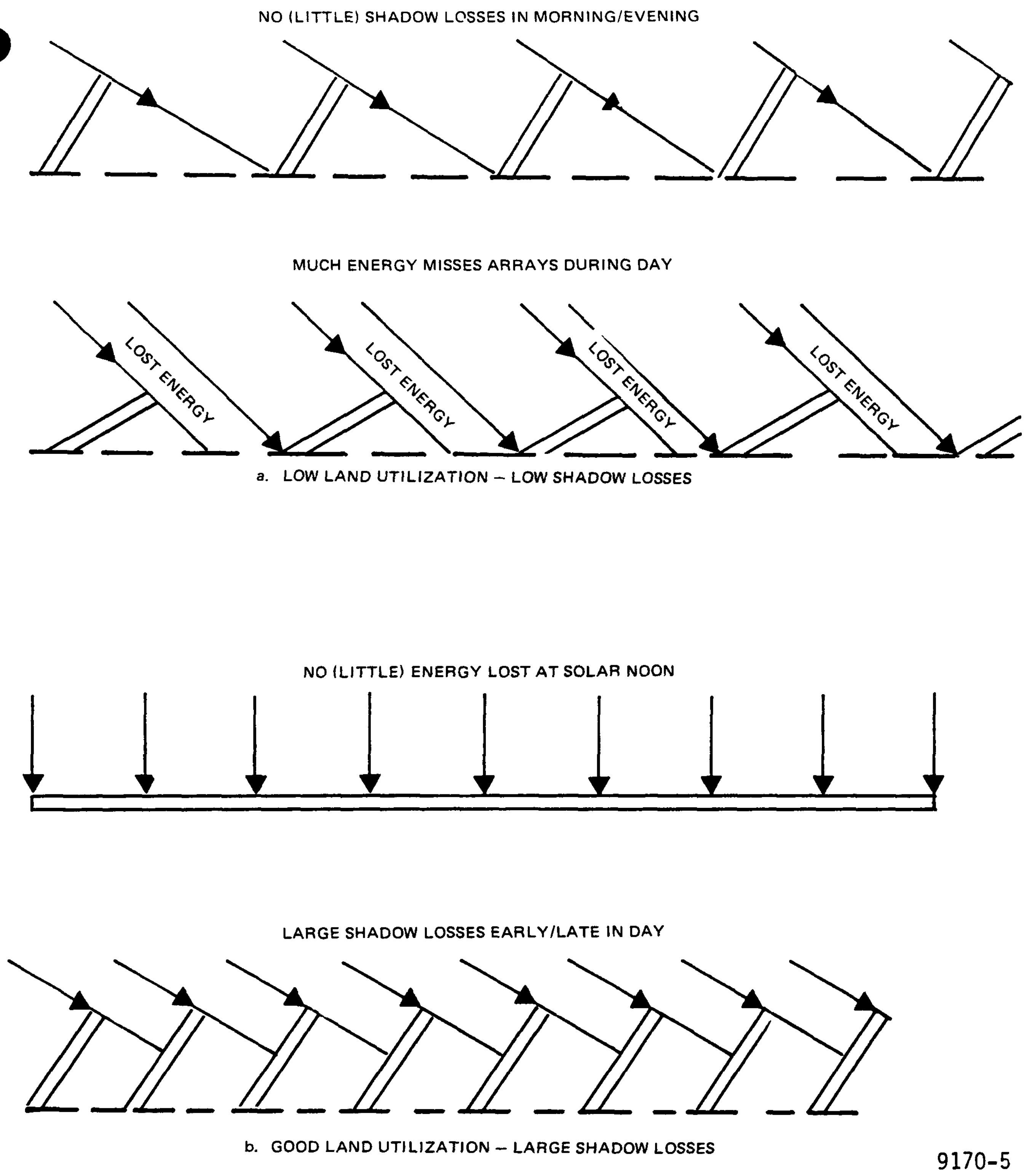

Figure 46. Effect of Spacing on Tracking Array Performance

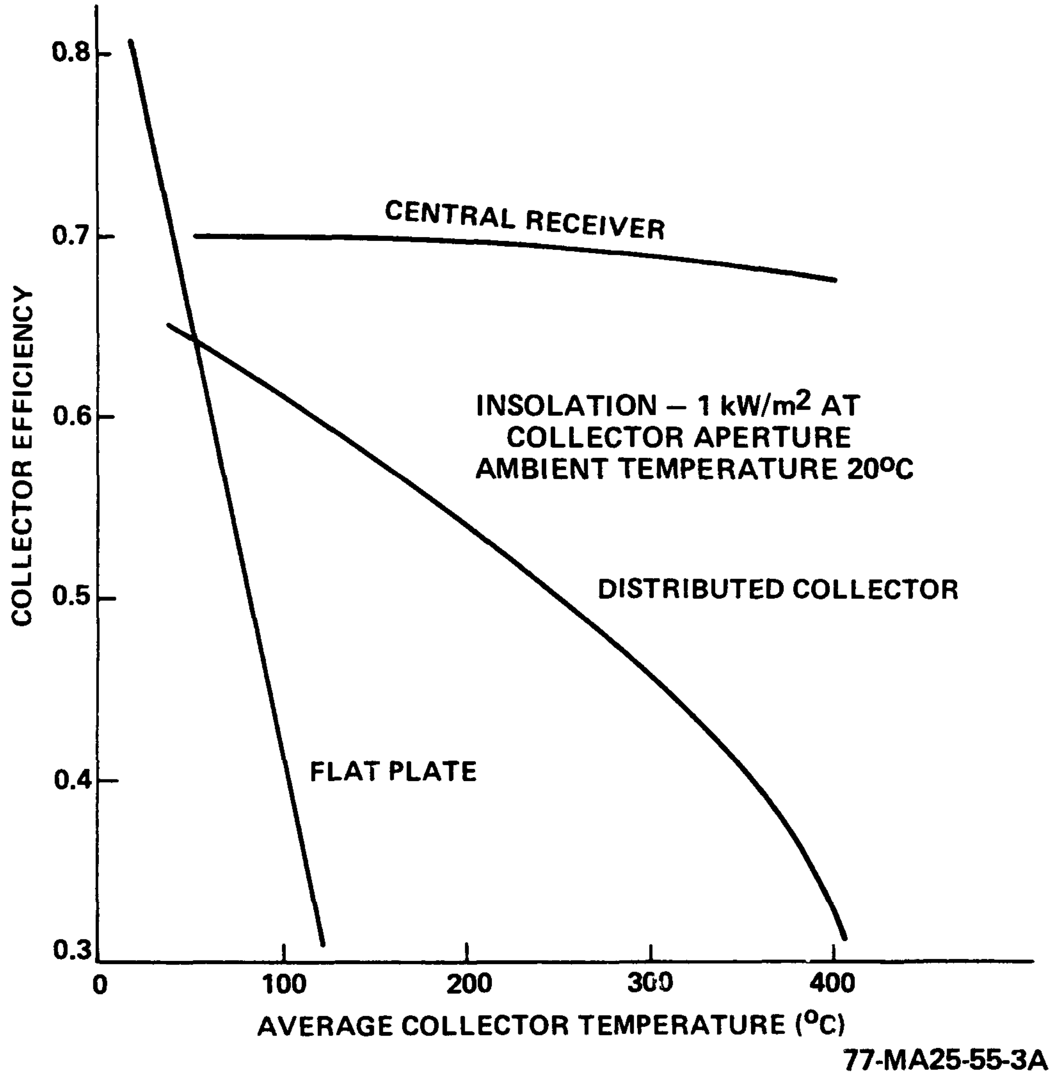

Figure 47. Collector Efficiencies Used in Analysis

of the figure, the tracking arrays are spaced to prevent shadow losses in the morning and evening. For this system much solar energy will not be intercepted by the arrays during mid-day and hence the power output on a fixed land area will be low although shadow losses are nil. In the lower portion of the figure, the opposite extreme is pictured where the tracking arrays are spaced to capture all of the noontime solar energy. The shadow losses in the morning and evening now become large and while the power output from a fixed land area is larger, the efficiency of the system has been decreased 20 to 30% from the widely spaced configuration.

A nontracking array tilted at the latitude would intercept all of this solar energy throughout the day and would capture about 20% less energy per unit area than the tracking array (cosine effects). The nontracking array with its better land utilization would therefore produce almost double the energy output from a fixed land area.

For this study, a total land area availability of four times the floor area of the building was assumed for a collector field limit. This limits the tracking collector/array areas to less than the floor area and non-tracking arrays tilted at the latitude to less than twice the floor area. As discussed in section 5.2, this upper limit on collector/array area restricts the total energy output from the STES to less than 50% of the buildings energy needs. This in turn prevents effective utilization of energy storage systems so that the most cost effective systems are those which do not require energy storage, and which therefore produce 20 to 30% of the energy requirements of the building. The exception to this is the photovoltaic STES where load leveling usage of the battery storage system provides an additional cost benefit and use of the entire land area for the system seems to be cost effective.

5.4 SUMMARY OF COLLECTOR CHARACTERISTICS SELECTED

The various solar thermal collectors considered included the distributed concentrator configuration, distributed flat plate configuration and central receiver configurations. Figure 47 illustrates the noon-day efficiency characteristics selected to represent 1985 state of the art collectors for use in the analysis of the STES configurations for commercial buildings as discussed in Section 2.0, Volume 3. As discussed earlier (Section 3.0) efficiency estimates for point focus distributive collectors were not available for use in the study consequently only a line focus collector was used in the study. However, it was assumed to be used as a two axis tracker to maximize the power output of the system.

5.5 CONCLUSIONS

For evaluation of STES concepts in commercial building, a small computer code, STESEP, was developed and used. Considerations such as relations between weather conditions, building loads, STES configurations, and STES operating (control) modes for assessing the economic feasibility of the various concepts can be evaluated using this code.

Effects of changes in the energy usage to demand rate will have an important impact on the acceptability of STES in commercial buildings and must not be allowed to put the burden for backup spinning reserves on the utility. Instead, the STES needs onsite backup capability to maintain existing load profiles for the buildings.

Land utilization will always be a problem with solar systems and will favor use of non-tracking photovoltaic systems if their cost goals ($0.50 per peak watt) are met. In addition, the small amount of usable land around commercial buildings will limit the STES capability to provide the buildings' energy needs to below 50% and will make efficient usage of energy storage systems difficult.

Costs of solar system components require further definition since the cost estimates for collectors, arrays, etc., are based on analytical estimates rather than actual production cost data which can only be obtained after production lines have been established.

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LIST OF SYMBOLS

A, B, C, D	Equation constants
a_1, a_2	
A_a	Absorber area that is illuminated
A_c	Collector area
A_r	Absorber area that radiates
A	Heat exchanger area
C, C_p	Specific heat
CEL	Coefficient of heat generation from electrical lighting
CF	Cloud factor
CHD	Coefficient of process heat
CHL	Coefficient of heat loss
CN	Cloud number
CRL	Coefficient for humidity effects
CVH	Coefficient of heating ventilation
CVR	Coefficient of cooling ventilation
COP	Coefficient of performance
D	Diameter
dr	Decomposition rate of oil
E-W	East-West
EL(t)	Fraction of maximum electrical as a function of time
F_o	Eigenfunction of matrix temperature
g_c	Gravitational constant
h	Solar hour angle
HL(t	Fraction of maximum process heat as a function of time
H_{DN}	Daily total direct normal insolation
H_n	Daily total horizontal insolation
I_c	Solar constant
I_1, I_2, I_3	Insolation integrals
I	Direct insolation
I_{DN}	Direct normal insolation
I_h	Total horizontal insolation
J	Mechanical equivalent of heat
k	Thermal conductivity
L	Length
L_c	Collector (heliostat) length
MTD	Mean temperature difference
N-S	North-South
N_{Nu}	Nusselt number
n	Day of year
N_{Pr}	Prandtl number
N_{Re}	Reynolds number
OL(t)	Fraction of maximum occupancy load
p	Wetted perimeter
PP	Percent possible sunshine
P	Pressure
Q	Energy
q	Heat transfer rate
Q_{BS}	Battery electrical storage energy
Q_{CS}	Cold thermal storage energy
Q_{ED}	Electrical load demand
Q_{HD}	Heat load demand
Q_{HS}	Hot thermal storage energy
$(q/A)_{ins}$	Insulation heat transfer loss rate
Q_{RD}	Cooling load demand
Q_T	Maximum load constant for building
q_{use}	Usable heat transfer rate
R	Solar distance ratio
R_c	Cycle efficiency ratio
r	Reflectivity
T	Collector tilt angle
$\bar{T}$	Average temperature
t	Time
t_L	Building heating lag time
T_{cell}	Temperature of solar cell
T_{ref}	Reference temperature of solar cell (nominally 28°C)
T_a	Ambient temperature
T_{cnd}	Condenser temperature
T_{ci}	Collector inlet temperature
T_{co}	Collector outlet temperature
T_{ei}	Heat exchanger inlet temperature
T_{eo}	Heat exchanger outlet temperature
T_{cs}	Cold storage temperature
T_{ct}	Cooling tower temperature
T_{mn}	Monthly minimum air temperature
T_{mx}	Monthly maximum air temperature
T_{sp}	Building internal temperature setpoint
T_t	Turbine inlet temperature
U	Overall heat transfer coefficient
V_{sm}	Single media fluid volume
w	Fluid mass flow rate
W_c	Collector (heliostat) width
W	Weight
X	E-W collector (heliostat) spacing
x	Quality
Y	N-S collector (heliostat) spacing
y	Distance coordinate
y_d	Submersion depth of diffuser

GREEK

α', β'	Insolation constants
α	Absorptivity
β	Solar cell temperature loss coefficient
γ	Specific heat ratio
δ	Solar declination angle
ϵ	Void fraction of matrix material
ϵ_c	Emissivity
η	Efficiency
η_{pcs}	Power conversion efficiency
η_{st}	Storage tank thermal efficiency
η_{oc}	Optical efficiency
μ	Viscosity
ρ	Density
σ	Stefan-Boltzman constant
τ	Transmissivity
Δ	Incremental change

CAPITAL

Ω_a	Solar azimuth
Ω_E	Solar elevation angle
Ω_Z	Zenith angle
Φ	Site latitude

ECONOMIC PARAMETERS

$\overline{AC}$	Annualized cost
BECE	Breakeven cost of electricity
CI	Capital investment
CRF	Capital recovery factor
$\overline{FCR}$	Annualized fixed charge rate
g	General inflation
g_f	Fuel escalation rate
k	After tax cost of money
n	Power law exponent
N	Number of years of system life
NO	Number of units
OPM	Recurring cost electricity cost
p	Years to start of operation
RCC	Recurring cost
R O I	Return on investment
Y_{co}	First year of operation

Subscript

pv	Present value
o	Original building
STES	Solar total energy system
max	Maximum

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