305
10/7/77

Dr. 1493

AI-ERDA-13200

MASTER

COMMERCIAL APPLICATIONS OF SOLAR TOTAL ENERGY SYSTEMS

Second Quarterly Progress Report, August 1, 1976—October 31, 1976

April 25, 1977

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

Atomics International Division
Rockwell International
8900 De Soto Avenue
Canoga Park, California 91304

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy ^{6.50}~~\$5.50~~ (domestic)

~~\$8.00~~ (foreign)

Microfiche \$3.00 (domestic)

\$4.50 (foreign)

13.40

SECOND QUARTERLY PROGRESS REPORT
COMMERCIAL APPLICATIONS
OF
SOLAR TOTAL ENERGY SYSTEMS
AUGUST 1, 1976 – OCTOBER 31, 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ISSUED: APRIL 25, 1977

CONTRACT: E(04-3)-1210

Rockwell International

Atomics International Division
8900 De Soto Avenue
Canoga Park, California 91304

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

This report investigates the application of the Solar Total Energy System (STES) to the commercial sector (e. g. , office buildings, shopping centers, retail stores, etc.) in the United States. Candidate solar thermal and solar photovoltaic concepts are considered for providing on-site electrical power generation as well as thermal energy for both heating and cooling applications. The solar thermal concepts include the use of solar concentrators (distributed or central receiver) for collection of the thermal energy for conversion to electricity by means of a Rankine cycle or Brayton cycle power conversion system. Recoverable waste heat from the power generation process is utilized to help meet the building thermal energy demand. Evaluation methodology is identified to allow ranking and/or selection of the most cost-effective concept for commercial building applications.

FOREWORD

This report, submitted by Atomics International (AI), Division of Rockwell International Corporation, to the Energy Research and Development Administration (ERDA), Solar Energy Division, Washington D. C., provides a summary of the technical progress for the second quarter period activities under Contract E(04-3-1210).

The task activities described herein were conducted in the Advanced Programs area with Mr. S. J. Nalbandian, Project Manager. Mr. J. E. Rannels is the ERDA Program Manager. Technical direction for the study is provided by Dr. R. W. Harrigan, the technical monitor at Sandia Laboratories, Albuquerque, New Mexico. Technical support to the study (primarily Task 1) is provided by the Space Division (SD) of Rockwell International, Seal Beach, California, and by two subcontractors, Envirodyne Energy Services, Anaheim, California and The Energy Group, a subsidiary of Welton-Becket Associates, Los Angeles, California.

The study was begun on May 10, 1976, and is scheduled for completion on May 9, 1977. This document presents a summary of activities for the second quarter period from August 1, 1976, through October 31, 1976. The work represents the contributions of several individuals. Dr. M. G. Boobar (AI) is responsible for the application analysis and costing studies. Mr. B. L. McFarland (AI) developed the application analysis computer program and system component definitions. Mr. K. E. Smith (SD) developed the requirements data, and Dr. E. P. French (SD) developed the deterministic solar insolation model. Mr. G. W. Neal, Vice President of Envirodyne Energy Services, and Mr. M. Meckler, President of the Energy Group, have also provided valuable assistance.

LIST OF SYMBOLS

A	Area
A_a	Absorber area that is illuminated
A_c	Collector area
A_r	Absorber area that radiates
A_w	Absorber area that is wetted by heat transport media (coolant)
c	Specific heat
CEL	Coefficient of heat generation from electrical lighting
CHD	Coefficient of process heat
CHL	Coefficient of heat loss
CRL	Coefficient for humidity effects
CVH	Coefficient of heating ventilation
CVR	Coefficient of cooling ventilation
D	Diameter
EL(t)	Fraction of maximum electrical as a function of time
G	Mass flowrate/unit area
g_c	Gravitational constant
h	Heat transfer coefficient
HL(t)	Fraction of maximum process heat as a function of time
J	Mechanical equivalent of heat
k	Thermal conductivity
L	Length
P	Pressure
PL(t)	Fraction of maximum occupancy load
Q	Energy
q	Heat transfer rate
Q_{BS}	Battery electrical storage energy
Q_{CS}	Cold thermal storage energy
$\dot{Q}_{ED}$	Electrical load demand
$\dot{Q}_{HD}$	Heating load demand
Q_{HS}	Hot thermal storage energy
q_{ins}	Insulation heat transfer loss rate
$\dot{Q}_{RD}$	Cooling load demand

Q_T	Maximum load constant for building
q_{use}	Useable heat transfer rate
r	Reflectivity
S	Direct insolation
T	Temperature
$\bar{T}$	Average temperature
t	Time
T_a	Ambient temperature
T_c	Collector inlet temperature
T_h	Collector outlet temperature
T_{SP}	Building internal temperature setpoint
U	Overall heat transfer coefficient
W	Weight
x	Quality
y	Distance coordinate
y_d	Submersion depth of diffuser

GREEK

η_{oc}	Optical efficiency
α	Absorptivity
γ	Specific heat ratio
ϵ	Emissivity
η	Efficiency
μ	Viscosity
ρ	Density
σ	Stefan-Boltzman constant
τ	Transmissivity
η_{st}	Storage tank thermal efficiency
Δ	Incremental change

CONTENTS

	Page
Abstract	iii
Foreword	iv
List of Symbols	v
1.0 Introduction	1
1.1 Program Objectives	1
1.2 Summary of Report Period Accomplishment	1
2.0 Task 1 - Requirements Development	7
2.1 Building Categories	7
2.2 Energy Demand	11
2.3 Site Selection Criteria	16
3.0 Task 2 - Concept Definition and Component Evaluation	19
3.1 Thermal STES Operating Modes	19
3.2 Component Characterization	21
3.2.1 Concentrating Solar Collectors	21
3.2.2 Thermal Storage Subsystems	21
3.2.3 Collector Fluid Storage	26
3.2.4 Dual Material Heat Storage	28
3.2.5 On-Line Storage	28
3.2.6 Remaining Components	30
4.0 Task 3 - Concept Application Evaluation	31
4.1 Solar Total Energy System Evaluation Program (STESEP)	31
4.1.1 Approximation of Building Loads	33
4.1.2 System Parameters	37
5.0 Task 4 - Cost and Market Projections	39
5.1 Program Application	39
5.2 Preliminary Trend Data	42
6.0 Future Work	49
References	51

CONTENTS

Page

Appendices

A.	Computer Simulation Programs for Building Energy Demand Analysis	A-1
B.	Deterministic Insolation Estimates for STES Performance Evaluation	B-1
C.	Cost Algorithms	C-1
D.	Cost Sensitivities of Solar Total Energy Systems	D-1

TABLES

1.	Key Contacts	8
2.	Typical Commercial Building Types	14
3.	HVAC Systems Simulated	15
4.	Characteristics of Candidate STES Sites	18
5.	Control Modes for STES Concepts	20
6.	Solar Collector Characterization	23
7.	Solar System Characterization	23
8.	Subsystem and Component Characterization	24
9.	Solar Concentrating Collectors	25
10.	STES Evaluation Program	33
11.	Typical Building Load Data for a Department Store in San Bernardino	34
12.	Typical Environmental Data for San Bernardino, California	34
13.	Building Load Variability	37
A-1	Example of Computer Simulation Programs	A-2
B-1	Seasonally Varying Solar Radiation Parameters	B-4
B-2	Average Daily Solar Energy Incident on Collector Apertures	B-12
C-1	Preliminary Cost Algorithms for Candidate Capital Equipment Items	C-2
D-1	Weighted Average After-Tax Cost of Capital (k)	D-3
D-2	Capital Recovery Factor (CRF), Fixed Charge Rate ($\overline{FCR}$) and Depreciation Factor (DPF) Sensitivities	D-5
D-3	Effect of Interest Rates, Inflation, and Operating Costs on Annualized System Costs	D-8

FIGURES

	Page
1. Solar Thermal STES Concept Block Diagram	2
2. Photovoltaic STES Concept Block Diagram	2
3. STES Program Schedule	4
4. STES Evaluation Methodology	5
5. Shopping Center Floor Space by Region	9
6. Office Building Floor Space by Region	10
7. Office Building Analysis by Height and Size	10
8. Metered Energy Data – March 1969	12
9. Metered Energy Data – July 1969	12
10. Candidate STES Study Regions and Sites	16
11. Diagram of Solar Thermal STES Concept (Rankine Cycle PCS)	22
12. Diagram of Solar Thermal STES Concept (Brayton Cycle PCS)	22
13. Diagram of Photovoltaic STES Concept	22
14. Distributive Collector Concepts	24
15. Sandia Thermocline Stability Test Plot of Raw Data	27
16. Effect of Charge/Discharge Time on Heat Transfer Area Requirements	29
17. STES Evaluation Program	32
18. Comparison of Department Store Energy Data with Evaluation Program Predictions – Monthly Loads	36
19. Comparison of Department Store Energy Data with Evaluation Program Predictions – Hourly Loads	36
20. Effect of Condenser Temperature on Annualized Cost for Shopping Center	38
21. Typical Data Printout	40
22. Shopping Center Solar Thermal STES Concept	41
23. Cost Parameters	43
24. Effect of Escalation Rates	45
25. Effect of Project Start Year	46
26. Effect of Cost of Money (k)	47

FIGURES

	Page
A-1. Comparison of Simulation Programs	A-6
B-1. Insolation Geometry	B-5
B-2. Insolation "Signatures" for Candidate Sites	B-9
B-3. Hourly Insolation Patterns for Madison, Wisconsin	B-13
C-1. Operations and Maintenance Costs	C-3
D-1. Effect of Recurring Cost Ratio on Annualized System - Resultant Cost Ratio	D-9
D-2. Escalation Rates Based Upon Bureau of Labor Statistics/ Consumer Price Index Data	D-12
D-3. Projected Fuel Costs	D-13

1.0 INTRODUCTION

The application of solar energy to help meet the nation's future energy requirements is a potential alternative to presently used energy sources for the generation of electricity and thermal energy. The purpose of this study contract is to assess the feasibility of using solar energy to provide a significant fraction of the energy needs of the commercial sector. The specific type of application is the Solar Total Energy System (STES) concept where electricity is generated on-site with the recovery of waste heat to help satisfy building heating and/or cooling requirements. Both solar thermal power conversion and solar photovoltaic system concepts are considered. Figures 1 and 2 are block diagram representations of the generalized form of these concepts. The specific system configurations would permit the selection of (on the basis of performance and cost effectiveness) the amount of electricity to be purchased from the utility, type(s) of energy storage, and the split between vapor compression and absorption chiller subsystems. This report summarizes the activities and findings during the second quarter period of the study.

1.1 PROGRAM OBJECTIVES

The objectives of the engineering study relative to the applicability of STES to commercial buildings are:

- 1) Develop conceptual designs and establish requirements data
- 2) Identify key technology items and advanced technology requirements
- 3) Define methodology for configuration and site selection criteria
- 4) Assess performance, cost, and market projections
- 5) Define requirements for demonstration program plan for system capability greater than 200 kWe from solar energy.

1.2 SUMMARY OF REPORT PERIOD ACCOMPLISHMENT

The study effort began on May 10, 1976, with the primary emphasis during the first quarter aimed at developing a data base to support activities associated with meeting the first two program objectives mentioned above. This

effort is summarized in Reference 1. During the second quarter of the study, effort has continued with emphasis on defining conceptual designs, evaluation of requirements data, defining methodology for concept selection criteria as well as costing methodology. The program schedule is shown in Figure 3. The study consists of six tasks with milestones as shown in the schedule. The inter-relationship of the five technical tasks is shown in Figure 4 and discussed in the following paragraphs.

Information regarding commercial buildings is collected and evaluated in Task 1. This data includes building configurations, sizes, energy requirements, operating characteristics, and site characteristics (environmental and solar insolation). Task 2 includes identifying system concepts, configuration, and component characteristics applicable for STES. The Task 3 effort evolves about a methodology to evaluate the various system concepts and application areas using information developed in Tasks 1 and 2 along with system and component cost data developed in Task 4.

The parametric results for concept performance are then evaluated in conjunction with Task 4 economic considerations and commercial building type applicability to establish the potential market penetration for STES. Results from Tasks 1 through 4 will be used in Task 5 to define demonstration project requirements and to recommend further development of key technology items required for a cost-effective STES application for commercial buildings.

During this reporting period, a methodology for simulating the solar thermal power conversion concept, which uses distributive solar concentrators and a Rankine cycle power conversion system (PCS), has been developed. The relatively simple computer model can also be used to evaluate the effectiveness of a central receiver tower concept in lieu of the distributive concentrator, and will be extended to allow simulation of a Brayton cycle PCS. A similar computer program will be developed for evaluation of the solar photovoltaic STES concept. Preliminary trend data for the distributive concentrator - organic Rankine PCS concept indicates potential cost-effective application areas for relatively large (5 to 10 MWe) STES configurations.

A more detailed discussion of activities by task for Task 1 through Task 4 is provided in the following sections of the report.

Figure 3. STES Program Schedule

Figure 4. STES Evaluation Methodology

76-019-49-62

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

2.0 TASK 1 – REQUIREMENTS DEVELOPMENT

Several contacts have been made within the construction, building management, design and utility industries in order to obtain an adequate data base for establishment of requirement data. A list of the key contacts (including the two subcontractors supporting this study) is given in Table 1 along with the specific topics of discussion.

2.1 BUILDING CATEGORIES

Trade publications and other reports have been reviewed to obtain information on commercial building statistics and energy demand requirements. References 2 through 7 provide considerable background information regarding office buildings, shopping centers, hotel or motel, warehouse, retail stores, and other commercial buildings. About 70% of the total square footage (and consequently, the energy consumption) of commercial buildings consists of shopping centers, retail stores, and office buildings. For this reason, these three areas of application have been selected to represent the potential commercial market for STES.

Figure 5 shows the distribution of shopping centers in the four sections of the U. S. for 1972 and 1974. About one-third of the total number of shopping centers in 1974 (about 15,000) was greater than 100,000 ft² (9,294 m²) each (gross leaseable floor area); however, they represent about two-thirds of the total shopping center floor area and account for about 70% of the total energy required by all shopping centers greater than 10,000 ft² (929 m²).

Figure 6 shows the distribution of office buildings in 1973, sampled by Building Owners and Managers Association International (BOMA).⁽²⁾ This total is believed to represent about one-half of the total office floor space in the U. S. Figure 7 shows an analysis of these sample buildings by building height and size, and the amount of energy demand. From this data, office buildings account for about one-fourth of the total square footage of floor area among shopping centers, retail stores, and office buildings. However, only about 5% of the office buildings are under 10 stories (floors), which may limit large-scale applicability of STES for existing buildings due to collector area constraints. Additional effort is planned to define applicable building types for STES.

TABLE 1
KEY CONTACTS

Organization	Purpose
The Energy Group (Subcontract)	Selection, load simulation and sensitivity methodology for six typical buildings
Envirodyne (Subcontract)	Total energy systems data
Electric Power Research Institute (EPRI)	Utilities interface and energy demands
Accurex Corporation	High-temperature collector data
Sandia	Insolation data
Aerospace Corporation	Site selection, climatic data, methodology
Southern California Edison	Metered demand data
Los Angeles City Energy Coordinator	DWP utility interface
City of Pasadena	Results of city STES study
Broadway-Hale Stores, Engineering Department	Operational data
Engineering Supervision Co.	Metered energy demand data and its use in energy management
Alabama Power and Light	Energy demand simulation correlation (AXCESS)
Hengstler and Associates	HVAC systems design
Boston Edison	Energy demands and rate structure
Public Service of New Mexico	Material loads data
Seattle Light	Metered load data and rate structure
TVA	Energy demands and rate structure
Security Pacific National Bank	Commercial building statistics
F. W. Dodge	Commercial building statistics
Southern California Gas	Metered load data
Southern Carolina Electric and Gas	Energy demands and rate structure
Edison Electric Institute (EEI)	Energy demand simulation correlation (AXCESS)
California State University - Fullerton	Demand simulation correlation

76-O25-59-92

Figure 5. Shopping Center Floor Space By Region
(Millions of Square Feet)

76-O25-49-100

Figure 6. Office Building Floor Space by Region (Year 1973)

76-O25-49-94

Figure 7. Office Building Analysis by Height and Size (Year 1973)

2.2 ENERGY DEMAND

Effort is continuing to obtain real building load profile data and modes of operation where possible. A number of metered demand profiles were obtained; however, variations in area loading, operating hours, construction, and many other factors, make any attempt to characterize the data impossible except, again, in terms of general block form. Usually the building design data are not accessible and the report is proprietary.

One exception to the above was provided through the Southern California Edison Company and the Broadway-Hale Stores of Los Angeles. Data from a submetering program conducted in 1974 has been provided and is being evaluated. The program was undertaken in a cooperative attempt to provide more efficient energy management in the Broadway Store in San Bernardino, California.

Figures 8 and 9 show hourly load profiles and ambient air temperatures for this three-story building, which consists of about 145,000 ft² (13,475 m²) of total floor area. The total peak load is not significantly different for the spring and summer days shown even though the air conditioning demand increases during summer.

It appears that during times of cheap energy, peak demand and first 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 interest other than academic. 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 (i. e., AXCESS, E-CUBE) come into general use and, even now, these are not normally used in building design. In designing solar total energy systems, computerized simulation techniques are essential since the load fraction varies continuously and the equipment must be optimally sized to match to solar input.

Appendix A provides additional information on available simulation programs; in particular, the AXCESS program developed by the Edison Electric Institute (EEI). Under subcontract to AI, The Energy Group (TEG), a subsidiary of Welton-Becket Associates, is developing simulated energy demand

9170-1

Figure 8. Metered Energy Data — March 1969
(Figure provided by Southern California Edison Company
and Broadway-Hale Stores of Los Angeles)

9170-2

Figure 9. Metered Energy Data — July 1969
(Figure provided by Southern California Edison Company
and Broadway-Hale Stores of Los Angeles)

profiles for selected buildings. This simulation is being conducted using the AXCESS program on actual buildings defined directly from architectural drawings. Six of about 80 candidate buildings were selected for evaluation and are described in Table 2. This simulation will provide a comparison of energy demand by building type, size, and internal system design. Eleven primary (i. e., energy generation and conversion) and 16 terminal (i. e., distribution, ducting) heating, ventilating, and air conditioning (HVAC) systems that could be installed in these six representative buildings were evaluated. After eliminating 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 HVAC systems that might be installed in the six buildings. These were the systems used in determining the load profiles through computer simulation. A summary of the primary and terminal systems selected and arranged by applicable building type is presented in Table 3. A description of the HVAC system types is contained in the ASHRAE Handbooks.

It must be emphasized again that the simulated loads program is being run to study sensitivity. A parallel methodology is also being developed by TEG which will permit the effect of the following factors on building energy demands to be determined:

- 1) Occupancy
- 2) Construction
- 3) Orientation
- 4) Internal systems
- 5) Set temperature
- 6) Operational
- 7) Location and climate
- 8) Use
- 9) Season

Almost by necessity, simulated profiles are simplified; however, if properly accomplished, major transients, hourly and peak demands and total

TABLE 2
TYPICAL COMMERCIAL BUILDING TYPES
(ACTUAL CONSTRUCTION)

Office Building	Low Rise	High Rise
Floor Area	25,000 ft ² (2,323 m ²)	248,000 ft ² (23,048 m ²)
Completion Date	1964	1970
Location	Los Angeles, California	Los Angeles, California
Description	Three stories plus base- ment; precast concrete and solar bronze glass exterior; precast concrete frame	Fifteen stories; exposed aggregate concrete and solar bronze glass exterior; reinforced concrete frame
Retail Store	Small	Large
Floor Area	55,000 ft ² (5,111 m ²)	260,000 ft ² (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 con- crete 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
Shopping Center	Small	Large
Floor Area	224,000 ft ² (20,876 m ²)	775,000 ft ² (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

TABLE 3
HVAC SYSTEMS SIMULATED

Terminal	Primary
Low-Rise Office Building	
1. Dual duct	1. Boiler and refrigeration
2. Multi-zone	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	
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
Retail Store – Small	
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	
1. Multi-zone	1. Boiler and refrigeration
2. Single zone reheat	2. Furnace and refrigeration
Shopping Center – Small	
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	
1. Unitary cooling units with separate heating	1. Furnace and unitary cooling
2. Multi-zone	2. Boiler and refrigeration
3. Unitary heat pumps	3. Heat pump
4. Single zone reheat	4. Furnace and refrigeration

energy demand can be accurately simulated for a given set of input conditions. This enables simulation techniques to be used effectively to determine trends. While there is generally good comparison in form between predicted and actual demands, there can be vast differences in actual energy usage due to operational variations from that assumed during design of the building.

2.3 SITE SELECTION CRITERIA

For purposes of site evaluation, the continental U. S. has been separated into six regions as shown in Figure 10. The heavy solid boundary lines are defined along average annual insolation lines. The insolation values are given in Langleys/day (1 Langley = 3.69 Btu/ft^2). This appears reasonable since it provides a guide to regions of varying insolation which is a strong driver on

76-O18-49-19B

Figure 10. Candidate STES Study Regions and Sites
(6 Regions, 12 Sites)

the ability to generate power from solar energy. The ambient conditions exert a lesser influence on the relatively massive, internally loaded buildings which generally comprise the commercial applications.^(4 - 7) The dashed lines are based upon the humidity and degree day variances within the equal insolation regimes. Twelve sites have been selected, as shown, for specific application analyses. Characteristics of these 12 sites are summarized in Table 4.

A simplified method for defining characteristics of solar radiation and weather data has been developed for use in this study. The primary problems with existing methods of analysis for application to a conceptual study are:

- 1) Direct solar radiation data available for limited number of U.S. sites.
- 2) Hourly insolation data too costly to use for present STES study.
- 3) Averaged daily insolation data lacks detail needed to assess collector-tracker performance.

As a result, the approach taken for this study was to:

- 1) Evaluate data sources - Aerospace and Sandia tapes, weather atlas, climatological bulletins, etc.
- 2) Summarize data on insolation, degree days and ambient temperature for site evaluation.
- 3) Use deterministic insolation model for analysis of collector performance.

This simple computer model and its application are described in Appendix B. Essentially, it defines two factors: Clearness Number (CN), and Cloud Factor (CF) that can be derived for a site from normally available data found in a weather atlas, climatological bulletins or handbooks. These factors can then be used to develop a simulation of both the total horizontal and the direct normal insolation hourly variations at a particular site.

TABLE 4
CHARACTERISTICS OF CANDIDATE STES SITES

REGION	LOCATION	TOTAL INSOLATION (H) (Btu/ft ² -DAY)			HEATING DEGREE DAY (HDD)*		COOLING DEGREE DAY (CDD)*		^{tdw} DESIGN WINTER TEMPER- ATURE (DRY BULB) (97-1/2 %) (°F)	^{tds} DESIGN SUMMER TEMPER- ATURE (2-1/2 %) (°F)	^{tw} WET BULB TEMPER- ATURE (°F)	HUMIDITY RATIO (W) <div>lb H₂O</div> <div>lb DRY AIR</div>	tm ANNUAL MEAN TEMPER- ATURE (°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	PHEONIX, 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

3.0 TASK 2 – CONCEPT DEFINITION AND COMPONENT EVALUATION

The solar thermal STES concept is shown in Figure 11 for a Rankine PCS. This concept considers three types of energy storage:

- 1) Hot thermal storage (Q_{HS})
- 2) Cold thermal storage (Q_{CS})
- 3) Battery electrical storage (Q_{BS}).

It also considers both cascaded vapor compression and absorption chillers to supply refrigeration (cooling) load demand requirements ($\dot{Q}_{RD}$), auxiliary heating to supply both power ($\dot{Q}_{ED}$) and heating load ($\dot{Q}_{HD}$) requirements.

Figure 12 shows the Brayton cycle thermal concept which will be evaluated. Again, three energy storage modes will be considered in the evaluation. The higher temperature requirements of this cycle will favor a central receiver type of solar collector if the heat transfer problems in the absorber can be solved.

Figure 13 shows the photovoltaic concept to be analyzed. This concept also has three storage modes which will be considered during the evaluation.

3.1 THERMAL STES OPERATING MODES

The operating mode of a STES concept strongly influences the equipment type and size requirements to meet the three, load-demand requirements ($\dot{Q}_{ED}$, $\dot{Q}_{HD}$, $\dot{Q}_{RD}$) for commercial buildings. Consequently, three modes of operation of the STES are being considered.

The first mode assumes a control system for the PCS which will supply the electrical load demand and can use hot and/or cold thermal storage in conjunction with auxiliary fossil fuel to meet the building heating and cooling requirements.

The second mode assumes a control system of the PCS which will supply the building heating and cooling load demands in conjunction with hot and/or cold storage and uses utility power to meet the building electrical requirements not supplied by the PCS.

The third mode assumes a control system of the PCS which will convert all of the solar collector output to electricity and store the excess in batteries. Cold storage and auxiliary fossil fuel are used to meet the building heating and cooling requirements, and utility power is used to meet the building electrical requirements in excess of the PCS output.

Table 5 summarizes the features of these three control modes which are all applicable to the two thermal STES concepts, while only the solar load control is applicable to both the photovoltaic and thermal concepts.

TABLE 5
CONTROL MODES FOR STES CONCEPTS

Mode	Features
PCS Supplies Total Electrical Load	Hot thermal (600° F) storage required No utility electricity used Cold storage optional* (50° F) Auxiliary fuel used Type of chiller optional Not used for photovoltaic STES
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
PCS Accommodates Available Solar Insolation	Applicable for photovoltaic and STES solar thermal For photovoltaic system warm (200° F) 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 trade-off

3.2 COMPONENT CHARACTERIZATION

To evaluate these STES concepts, the component and subsystems shown in Figures 11 through 13 have been characterized in terms of their performance and cost parameters. Tables 6 through 8 list these parameters and give the values selected as state-of-the-art with a probable range of variation for the parameter.

The following discussion describes the derivation of the major component models selected for use in this study.

3.2.1 Concentrating Solar 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. Four basic concepts of distributed concentrating collectors being developed are shown in Figure 14.⁽⁹⁻¹⁹⁾ For these collectors, the thermal losses determine their operating efficiencies and are somewhat different for each concept. For the evaluation of the STES concepts, the losses can be represented by:*

$$q_{use} = \alpha \tau r S A_c - UA_a (\bar{T} - T_a) - \epsilon A_a (\bar{T}^4 - T_a^4) \quad \dots (1)$$

Data from References 9 through 18 have been used for preliminary evaluation of the loss coefficients for these collectors. These are listed in Table 9. It should be noted that data is lacking for most configurations and estimated values will be used until data is available.

3.2.2 Thermal Storage Subsystems

Thermal storage is necessary to:

- 1) Prevent interruption of power due to intermittent cloud cover.
- 2) Extend the usable period of operation of the system to nonsunlight periods.

*See List of Symbols

Figure 11. Diagram of
Solar Thermal STES
Concept (Rankine
Cycle PCS)

76-019-49-54

76-019-49-55

Figure 13. Diagram of Photovoltaic STES Concept

76-019-49-56

TABLE 6
SOLAR COLLECTOR CHARACTERIZATION

Type	Performance Parameter	Value Used	Probable Range
Solar Collector - Distributor			
Concentrator	Optical Efficiency (%)	65	60 - 80
	Concentration Ratio	42	30 - 60
Absorber	End Loss Coefficient (W/m ² -h-°C)	14.1	7 - 30
	Radiation Loss Coefficient	0.6	0.3 - 2
	Tracking Error	0	?
Hydraulic	Pressure Loss (VH)*	30	20 - 60
	Thermal Loss (%)	5	5 - 20
Solar Collector - Central			
Concentrator	Optical Efficiency (%)	0.65	0.6 - 0.8
	Concentration Ratio	1000	500 - 1000
Absorber (Receiver)	End Loss Coefficient (W/m ² -h-°C)	16	7 - 30
	Radiation Loss Coefficient	2	1 - 4
	Tracking Error	0	?
Hydraulic	Pressure Loss (VH)	30	20-60
	Thermal Loss (%)	0	0 - 5

*VH - velocity head

TABLE 7
SOLAR SYSTEM CHARACTERIZATION

Item	Performance Parameters	Value Used	Probable Range
Storage Systems			
Hot Thermal Storage	Input/output Efficiency (%)	70	50 - 90
	Thermal Loss Coefficient (W/m ² -h-°C)	0.28	0.1 - 1
Cold Thermal Storage	Input/output Efficiency (%)	70	50 - 90
	Thermal Loss Coefficient (W/m ² -h-°C)	0.28	0.1 - 1
Battery Storage	Energy Efficiency (%)	72	70 - 80
	Storage Loss Coefficient (%/h)	0	?
Main Heat Exchanger	MTD* Required (°C)	5	5 - 20

*MTD = mean temperature differential

P

TABLE 8
SUBSYSTEM AND COMPONENT CHARACTERIZATION

Component and Subsystem	Performance Parameters	Value Used	Probable Range
Power Conversion Systems			
Organic Rankine	% of Carnot Efficiency	50	40 - 60
Brayton	Compressor/Expander Efficiency (%)	85	80 - 90
Stirling	?	Being Evaluated	?
Photovoltaic	Cell Efficiency (%)	15	13 - 20
Inverters	Cell Efficiency (%)	90	85 - 95
Cooling Systems			
Absorption	% of Carnot Efficiency	35	30 - 50
Vapor Compression	COP	3.5	3.5 - 4.5
Auxiliary Heaters			
Cooling Towers (air)	Thermal Effectiveness (%)	70	60 - 80
Cooling Tower (water)	Not Analyzed

(a) Fixed Stepped Mirror Concept
(General Atomic)

(c) Segmented Mirror Concept
(Sheldahl)

(b) Parabolic Trough Concept
(Honeywell)

(d) Fresnel Lens Concept
(JPL)

42400-10115

Figure 14. Distributive Collector Concepts

TABLE 9

SOLAR CONCENTRATING COLLECTORS

Concept Source	Reference	Concentration Ratio (A_c/A_a)	Optical Efficiency, η_{oc} (%)	Receiver Emissivity (ϵ_A)	Condition Loss Coefficient (UA/A_a)		Wetted Area/Illuminated Area (A_u/A_a)
					W/m ² -h-°C	Btu/ft ² -h-°F	
Segmented Mirror							
Sheldahl-Plane	9, 10	30	64(67)*	1.5	8.5	1.5	2
Sheldahl-V [†]	9, 10	30	(71)	0.37	8.2	1.44	3
Itek	9, 11	46	(75)	1.2	1.4	0.24	3
Parabolic							
Honeywell (NSC)**	9, 12	31	63	1.8	5	0.89	2
Honeywell (SC)**	9, 12	31	60	0.39	5	0.89	2
Sandia (NSC)**	13, 14	42	(65)	2	14.1	2.5	4§
Sandia (SC)**	13, 14	42	(64)	0.3	14.1	2.5	4§
JPL [†]	15	16.8	65	1.0	0.6	0.1	
Fresnel Lens							
McDonnell Douglas	16, 17	(40)	(63)	(1)	(5.6)	(1)	2
Fixed Mirror	9, 18	41	65	(0.3)	(5.6)	(1)	

*Numbers in parenthesis are estimated values.

[†]Evaluated from transient data - solid absorber.

§With plug-in tube

**NSC = nonselective coating, SC = selective coating.

In-line storage can prevent short term interruptions and give time for the off-line storage subsystem to respond. Each type of storage concept has advantages and disadvantages, as described in Reference 16; so this discussion is concerned with the representation of the subsystem.

3.2.3 Collector Fluid Storage

Conceptually, one of the simplest types of system stores preconditioned collector fluid off-line in a separate tank⁽¹⁴⁾ and removes the fluid as needed to heat the power conversion unit working fluid. Since cold fluid will replace the hot fluid following an extraction period, four types of losses occur that need to be estimated. These are:

- 1) Diffuser mixing losses (increases needed charge time and tank volume).
- 2) Heat leak during storage (increases charge time and can degrade PCS efficiency)
- 3) Thermal capacity of tank wall and insulation (increases charge time).
- 4) Thermal conduction in fluid (increases needed tank volume and charge time).

Diffuser losses occur with a conventional thermocline storage unit⁽¹³⁾ because a layer of fluid must be maintained above the outlet diffuser at all times. Thus, the hot fluid entering the tank during charging will mix with the cold fluid above it and produce a temperature profile represented by:*

$$\frac{T_h - T}{T_h - T_c} = \exp(-\Delta y/y_d) \quad \dots (2)$$

This profile is very similar to that presented in Reference 13 and implies that two lengths (diffuser to liquid surface) of fluid will be degraded more than 10% in energy during the charging process. Figure 15 compares Equation 2 with test data from Reference 13.

*See list of symbols

76-D2-49-61A

Figure 15. Sandia Thermocline Stability Test Plot of Raw Data
(First and Last Observations April 2, 1976)

Thermal losses during storage occur through the insulation and tank supports and may or may not be isolated as a thermal layer on the tank walls. If an average heat leak q_{ins}/A is assumed for the insulation, the storage efficiency can be estimated as (flat head tanks for low-pressure storage):*

$$\eta_{st} = 1 - \frac{2(q_{ins}/A)t(2 + D/L)}{\rho D c (T_h - T_c)} \quad \dots (3)$$

The thermal capacity of the insulation and fluid thermal conductivity losses are normally insignificant in comparison with the above losses and will be neglected for this work.

3.2.4 Dual Material Heat Storage

If sufficient heat transfer area exists, excess collector fluid can be used to heat a second material (either sensible or latent heat) and later remove this energy for non-sunlit operation of the STES.

There is a temperature loss associated with this type of storage in order to transfer the required amount of energy to and from storage. Figure 16 shows how the amount of temperature loss affects the number of transfer units required in a latent heat storage subsystem as a function of the charge time to discharge time at a constant flow rate. For sensible heat storage, the relationships are more complicated, as discussed in Reference 19, but storage efficiencies of 80 to 90% are feasible⁽¹⁹⁾ in some cases.

3.2.5 On-Line Storage

On-line storage can also be accomplished with dual media material but a two-tank storage system appears to be most suitable for STES application. Since one tank is used for the hot fluid and another used for the cold fluid, the tank inlet and outlet configuration is not critical. The flow-through arrangement minimizes temperature excursions, and spherical tanks can be used to minimize insulation losses.

*See list of symbols.

Figure 16. Effect of Charge/Discharge Time on Heat Transfer Area Requirements

9170-4

Although the work described later, on concept application, assumed a thermocline storage system for the hot thermal storage, the two-tank system is being added to the evaluation computer program, described under Task 3, in place of the thermocline system.

3.2.6 Remaining Components

The heat exchangers are characterized by their mean temperature difference and checked for "pinch-point," problems which are minor for either an organic Rankine or Brayton PCS.

The Rankine cycle PCS is characterized by the fraction of Carnot efficiency obtained and assumes a 90% effectiveness for the regenerator.

The absorption cycle chiller is characterized by the fraction of Carnot efficiency, while the vapor compression chiller is assumed to have a fixed coefficient of performance (COP).

The cooling tower is assumed to be a dry tower, air cooled, with a 70% effectiveness, since a water tower will produce fog under some conditions and increase maintenance costs for the solar collectors.

4.0 TASK 3 – CONCEPT APPLICATION EVALUATION

Although the component and subsystem characterizations described under Task 2 are simple, combining them to produce a system able to meet a given load profile is a tedious task and has been accomplished here through the use of a small computer program.

The data obtained in Task 1 provides a load profile for the STES to meet, as well as the insolation and environmental conditions for the candidate sites. These have to be combined with the component characteristics and control mode logic from Task 2 to size a system, which then has to be evaluated for cost effectiveness by algorithms described under Task 4 activity. The following discussions describe this program and its planned use.

4.1 SOLAR TOTAL ENERGY SYSTEM EVALUATION PROGRAM (STESEP)

A small computer program has been written in FORTRAN for use on the Honeywell 440 computer to evaluate the STES concept. This program, STESEP, evaluates building loads and collector behavior, and sizes components necessary for the STES concept being evaluated. A program logic diagram for STESEP is shown in Figure 17, which uses hourly energy balances to define the STES operation. Table 10 shows the input requirements for the program and lists the program output in general terms.

The 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 Appendix B, 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 Appendix C.

The annualized system resultant cost then is determined using the procedures described in Reference 20. Appendix D provides a more detailed discussion of the cost methodology.

42400-10116

Figure 17. STES Evaluation Program

TABLE 10
STES EVALUATION PROGRAM

Input Parameters	Output Parameters
Building Data	Load Profiles (monthly and hourly)
Environment (Site) Data	Component Sizes
Component Characteristics and Cost	Capital Investment
Cost Parameters	Recurring Costs
Operational Data	Annualized Cost

4.1.1 Approximation of Building Loads

To define the building loads on an hourly basis, the STESEP program requires an average daily profile of the electrical loads (EL), the occupancy load (PL), and the process heat load (HL) in a form as shown in Table 11, expressed as a fraction of maximum load (Q_T) for the day. The STESEP program also requires a tabular input of the maximum and minimum ambient temperatures and the cloud factor and clearness number for the location of interest by month, as discussed previously and shown in Table 12. Tables 11 and 12 represent the required input for a department store in San Bernardino, California, and are typical of the input necessary to represent any specific building and site combination.

Since the building loads for commercial buildings are primarily a function of the way the building 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 four constants to obtain the balance, as discussed in the following text.

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

For $T_a > T_{SP}$

$$\dot{Q}_{RD} = Q_T \left[CEL \cdot EL(t) + CVR \cdot PL(t) + CHL \cdot CRL \cdot (T_a - T_{SP}) \right]$$

For $T_a < T_{SP}$,

$$\dot{Q}_{HD} = Q_T \left[CVH \cdot PL(t) - CEL \cdot EL(t) + CHL \cdot (T_{SP} - T_a) + CHD \cdot HL(t) \right]$$

*See list of symbols.

TABLE 11
TYPICAL BUILDING LOAD DATA FOR A DEPARTMENT STORE IN SAN BERNARDINO*

Fraction of Total Load	Hour of Day																							
	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	0.23	0.23	0.23	0.23	0.5	0.5	0.5	1	1	1	1	1	1	1	1	1	1	1	1	0.5	0.23	0.23	0.23	0.23
Occupancy Load	0.02	0.02	0.02	0.02	0.02	0.1	0.1	1	1	1	1	1	1	1	1	1	1	1	1	0.2	0.02	0.02	0.02	0.02
Process Heat Load	0	0	0	0	0	0	0	0	0.2	0.5	0.5	0.9	0.9	0.6	0.4	0.2	0.5	0.9	0.9	0.5	0.2	0.1	0	0

*Floor area: 145,000 ft² (13,470 m²)

Maximum electrical load: 1 MW (based on 6.9 W/ft²) exclusive of vapor compression cooling load.

TABLE 12
TYPICAL ENVIRONMENTAL DATA FOR SAN BERNARDINO, CALIFORNIA

Item	Month of Year											
	1	2	3	4	5	6	7	8	9	10	11	12
Maximum Air Temperature (°F)	66	68	71	75	79	87	94	94	92	83	75	68
Minimum Air Temperature (°F)	38	40	41	46	49	53	57	57	54	48	42	38
Cloud Factor (CF)	0.79	0.77	0.87	0.85	0.89	0.90	0.97	0.95	1	1	0.91	0.84
Clearness Number (CN)	0.68	0.64	0.63	0.69	0.63	0.68	0.59	0.63	0.61	0.60	0.54	0.67

The coefficients in these equations have physical significance but are used primarily to adjust the demand profile used by STESEP to agree with metered load data for the building of interest. The coefficient, CEL, corresponds to the conversion of lighting energy to heat, while the coefficients, CVR and CVH, correspond to the ventilation energy requirement for recirculation of building air. The coefficient, CHL, corresponds to the overall energy loss to the environment from the building, and the coefficient, CRL, modifies this loss for humidity effects on the refrigeration load.

It can be seen that these equations do not include capacitance effects or solar heat input effects on the building loads. The effect of building capacitance is approximated by a constant delay time which can be adjusted to produce energy demand peaks corresponding to the metered building loads; while solar loads are implicitly included in the metered data used to adjust the coefficients for that building. It should be noted that the factor (Q_T) allows approximate scaling for building size effects in a straightforward manner.

When actual load data are not available, simulation programs such as AXCESS, E-CUBE, etc., (see Appendix A) can be used to generate the required yearly electrical cooling and heating loads to supply the Tables 11 and 12 type of information. The STESEP coefficients are then adjusted to produce the same yearly loads.

The results obtained by this simplified method provide a building load profile accurate enough for conceptual design studies but are not intended to replace the daily profiles generated by more elaborate programs, such as AXCESS and E-CUBE, which can evaluate different HVAC operational methods. The purpose of this method is to use the synthesized load profiles (when actual load data are missing) to evaluate STES concepts within the scope of this study.

The results of using the data from Tables 11 and 12, in conjunction with the yearly metered load data for a department store in San Bernardino, are shown in Figure 18 for the monthly loads, while Figure 19 shows an hourly load profile comparison for June 30, 1969. In both cases, the calculated loads (indicated by the curves on the figures) are in good agreement with the metered load data (indicated by the symbols).

Figure 18. Comparison of Department Store Energy Data with Evaluation Program Predictions - Monthly Loads

Figure 19. Comparison of Department Store Energy Data with Evaluation Program Predictions - Hourly Loads

In comparing synthesized load profiles with specific daily load data, the variability of the load data must be considered. For this department store, the available data sample was half-hour metered loads for maximum load days during each month of 1969. Using this data in conjunction with the monthly metered loads, allowed estimates of the load variability to be made for this 1 year of operation. Table 13 shows the estimated metered load variability for the building and confirms that the simplified approximation of building loads used in STESEP is a good approximation of average day loads for this building.

4.1.2 System Parameters

The STES operational data are varied to obtain a minimum annualized cost. The program tests for a minimum annualized cost and, when obtained, the results are saved; while other cases are evaluated using different system operating conditions and/or control modes. Typewriter plots of the pertinent parameters can be obtained as desired during these calculations. An example of such a plot is shown in Figure 20, where the condenser temperature is varied for a Rankine cycle STES. Application of the results from this program is discussed under Task 4.

TABLE 13
BUILDING LOAD VARIABILITY
(SAN BERNARDINO DEPARTMENT STORE)
1969 DATA

Energy Demands	Observations
Electrical Loads	<p>Maximum daily load is $6\% \pm 4\%$ greater than average load</p> <p>Maximum monthly load variability is $\pm 7\%$</p> <p>November daily variability is $\pm 8\%$;</p> <p>4% due to nighttime load variations</p> <p>3% due to daytime load variations</p> <p>Average daily load variability is $\pm 5\%$</p> <p>Store open ~ 1 h longer in March, April, December</p> <p>January (high months)</p>
Heating and Cooling Load	<p>Depends on operating conditions (HVAC turned off at night)</p> <p>Monthly HVAC load correlated by degree days</p> <p>Hourly heating load not related to ambient temperature</p> <p>Maximum day cooling load is $22\% \pm 18\%$ greater than average load</p> <p>Maximum day heating load $15\% \pm 16\%$ greater than average load</p>

LEGEND	
CONDENSER TEMPERATURE (°C)	
X	60
O	77
+	94
#	127

76-022-49-85

Figure 20. Effect of Condenser Temperature on Annualized Cost for Shopping Center
(Rankine Cycle STES with Solar Load Control)

5.0 TASK 4 – COST AND MARKET PROJECTIONS

Appendices C and D provide background data on costing performed under this task. These results are used in the Task 3 evaluation program to define concept cost effectiveness.

5.1 PROGRAM APPLICATION

Figure 21 shows the STESEP summary data printout of the minimum annualized cost system for the STES concept application described in Figure 22. As can be seen from the data printout, in the most cost-effective configuration for this example, 1,000,000 ft² (92,900 m²) shopping center application, solar energy will furnish 52.9% of the electrical load and 89.3% of the thermal load, based on the following input assumptions:

1) Start of commercial operations	1986
2) Weighted average after-tax cost of capital	8%
3) Escalation Rates	
Equipment and general	5%
Operations, maintenance, and fuel	8%
4) Amortization period	30 years
5) Cost of fuel (1976)	\$2.50/10 ⁶ Btu (\$2.37/GJ)
6) Cost of purchased electricity	\$0.0512/kWh (\$14.22/GJ)

The size, efficiency, input and output temperatures, and performance are tabulated for each item of equipment. Also shown are the unit cost, installed cost, operating cost (recurring cost), and lifetime assigned to each component. For purposes of this calculation, a "lifetime" of 30 years was assumed for each component. The program currently is being modified to include more realistic lifetimes for the various components, as well as redundancy requirements.

The total capital investment, recurring costs, and annualized costs are summarized on the last two lines of the printouts. For this example, the collectors, storage, and PCS's account for over 90% of the capital costs. Also

STES EQUIPMENT SIZES FOR A LANDOVER MALL

LOCATED IN WASHINGTON D.C.

WITH A FLOOR AREA OF 92900. SQ M AND 96889. KWHR/DAY OUTPUT

RANKINE CYCLE STES CONCEPT WITH PCS CONTROL BY SOLAR LOAD WITH DISTRIBUTED COLLECTOR 1

SOLAR ENERGY FURNISHES 52.9 % OF ELECTRICAL LOAD, AND 89.3 % OF THERMAL LOAD

FOR A 1986 START OF OPERATION. COST PARAMETERS ARE

FCR=0.148 K=0.080 G=0.050 GF=0.080 N= 30 FUEL= 2.37 \$/GJ, ELECT=14.22 \$/GJ (1976 \$)

EQUIP	SIZE	EFF	TIN DEG C	TOUT DEG C	ENERGY KWH/DAY	INST'D CST. \$/UNIT	SIZE.	CAP. INV. K\$	REC'G CST. K\$	CMPT. LIFE YEARS
COLL	133527. SM	0.295	191.	344.	225367.	100.	13353.	0.	30.	
STOR	9301. KW	0.722	0.	0.	11526.	127.	1181.	0.	30.	
HT EX	8973. SM	0.965	344.	191.	252288.	17.	155.	0.	30.	
AUX HT	6033. KW	0.750	185.	338.	35895.	15.	88.	112.	30.	
PCS	6430. KW	0.227	338.	60.	57338.	193.	1244.	409.	30.	
VC RFG	2720. TON	3.500	0.	0.	57495.	194.	527.	0.	30.	
AB RFG	1904. TON	0.652	105.	8.	48194.	222.	422.	0.	30.	
PRO HT	3632. KW	1.000	60.	19.	0.	21.	74.	0.	30.	
CL TWR	18821. SM	0.700	60.	105.	158372.	3.	61.	0.	30.	
CL STO	0. CM	1.000	8.	17.	0.	0.	0.	0.	30.	
AUX EL	7906. KW	0.000	0.	0.	39551.	0.	0.	739.	0.	

TOTAL CAP. INV. IS \$ 0.17105E+08 WITH YEARLY REC'G. COSTS OF \$ 6.12603E+07

ANNUALIZED COST OF \$ 0.74169E+07 WITH A YEARLY SAVING OF \$ 0.83215E+06 R.O.I. = 4.9 %

Figure 21. Typical Data Printout

76-022-49-83

Figure 22. Shopping Center Solar Thermal STES Concept
(Rankine Cycle with Solar Load Control)

shown are: (1) the annualized savings as compared to the cost of purchased electricity at \$0.0512/kWh (1976 dollars), assuming an escalation rate in the cost of power equal to 8%; and (2) the incremental return on investment (ROI), which is defined as the annualized savings divided by the capital investment.

These computer runs cost approximately \$10 for the evaluation of 24 cases and, hence, allow a large number of operational parameters to be surveyed in arriving at the most cost-effective STES for a particular building and site combination. This allows evaluation and comparison of various concept configurations to define potential market applicability.

5.2 PRELIMINARY TREND DATA

The STESEP computer program was employed to develop preliminary trend data on several of the economic parameters for distributive collectors, wherein the PCS is sized to accommodate the available solar insolation. (It should be reemphasized that these trend data are indeed preliminary and were developed primarily as an "exercise" for the program as it exists in its present incomplete development state — e. g. , updates are required for redundancy, etc.)

Figure 23 shows the variation of capital investment (CI), recurring cost, annualized cost ($\overline{AC}$) and savings, and incremental return on investment (ΔROI) as a function of the collector and building total floor area ratio (the floor area remains constant for a given installation). As might be expected, the capital investment increases with increased collector area. The recurring costs initially will decrease as the collector area increases inasmuch as the quantity of purchased power declines. However, the operating and maintenance cost do increase steadily with increased collector area and, hence, the cusp and change in direction of the recurring cost curve. (It should be noted that the collector/floor area ratio ordinate is presented in exponential form on this chart.) The annualized saving is described as the annualized cost of purchasing all the power requirements ($\overline{AC}_0$) less the annualized cost ($\overline{AC}$) of the STES; the incremental return on investment (ΔROI) is the annualized savings capital investment and represents the increase (or decrease) from the return on investment acceptable to the utility or private investor. The values assumed for the various cost parameters are discussed in Appendix D. The additional symbols shown in

76-026-49-107

Figure 23. Cost Parameters (PCS Control by Solar Insolation Availability)

Figure 23 are discussed in detail in Appendix D. They are defined as:

y_{co} = start year

k = capital cost (interest rates)

g = general inflation rate

g_f = fuel escalation rate

Figure 24 shows the effect of escalation rates on annualized cost and ΔROI . For a given collector/floor area ratio, the $\overline{AC}$ increases and ΔROI decreases as the escalation rate increases. (The ΔROI is negative at a collector/floor area ratio of 1 at $g_f = 6\%$.) Also shown is the increase in the percent of the load carried by the STES as a function of the collector/floor area ratio.

Figure 25 presents the effects of project start year through 2006. The minimum annualized cost and ΔROI will increase with time for the assumptions made. Inasmuch as it was assumed that the cost of fuel (and, therefore, purchased power) increases continuously, the optimum collector area is shown to increase annually through approximately 1996.

Figure 26 was developed to explore the impact of "cheap" money. (For example, a " k " of $\sim 6\%$ can be achieved at a debt/equity ratio $\gtrsim 2$ and an interest rate of $\sim 5\%$.) The data show that for the assumptions made (including 10% fuel and power escalation rates), the decrease in annualized cost and potential improvement in ΔROI are nominal for a collector/floor area ratio of $\lesssim 1.5$.

Figure 24. Effect of Escalation Rates (PCS Control by Solar Insolation Availability)

76-O25-49-97

Figure 25. Effect of Project Start Year (PCS Control By Solar Insolation Availability)

LANDOVER MALL

SIZE = 8 MWe
 y_{co} = 1986
 k = 8%
 g = 5%
 g_f = 10%
 FUEL = \$2.37/GJ (\$2.50/10⁶ Btu)
 ELECTRICITY = \$14.22/GJ (5.12 ¢/kWh)

76-026-49-106

Figure 26. Effect of Cost of Money (k)(PCS Control by Solar Insolation Availability)

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

6.0 FUTURE WORK

The activities planned during the next quarter include:

- 1) Continue data collection and catalog information on building types, numbers, size, location, time-related energy demand, etc.
- 2) Identify specific building and energy characteristics for two representative buildings at each of 12 potential sites.
- 3) Develop data for STES equipment and application, e. g., building and system interfaces, utility interfaces, operation and maintenance (redundancy), safety, etc.
- 4) Evaluation program modification to incorporate component life-time data.
- 5) Expand program to include Brayton cycle thermal STES and photovoltaic STES concepts.
- 6) Perform operational parametric studies to evaluate effects of component performance, STES operating conditions, weather variability, and building load variability.
- 7) Update cost algorithms and expand cost data base to include:
 - a) Central towers
 - b) Solar photovoltaic
 - c) Thermal distribution
 - d) Electrical distribution
 - e) Effect of multiple units/outage
 - f) Equipment amortization
- 8) Identify extent of commercial market sector and project market penetration rates.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

REFERENCES

1. Atomics International Letter, 76AT-5556, "Commercial Applications of Solar Total Energy Systems, Contract E(04-3)-1210, Quarterly Progress Report," (August 23, 1976)
2. "Office Building Experience Exchange Report for Calendar Year 1973," Building Owners and Managers Association International (BOMA), 1974
3. "Dollars and Cents of Centers," 6th Edition, The Urban Land Institute, 1975
4. "Solar Heating and Cooling of Buildings--Phase O," NSF-RA-N-74-021E, General Electric Company, Contract Performed for the National Science Foundation, RANN (May 1974)
5. "Solar Heating and Cooling of Buildings--Phase O," NSF-RA-N-74-023C, Westinghouse Electric Corporation, Baltimore, Maryland, Contract Performed for the National Science Foundation, RANN (May 1974)
6. "Solar Climate Control," Project Test Reports (C-75880), Arthur D. Little, Inc. (November 1974)
7. "Solar Heating and Cooling of Buildings--Phase O," NSF-RA-N-74-022C, TRW, Systems Group, Redondo Beach, California, Contract Performed for the National Science Foundation, RANN (May 1974)
8. N75-22903, "Solar Residential Heating and Cooling System Development Test Program," (NASA TMX-64924) (September 1974)
9. ATR-76(7523-07)-1 (II), "Technical Summary of Distributed Collector Concepts," Contract E(04) 1101 (March 1976)
10. "Program to Verify Performance and Cost Effectiveness of a Segmented Line Focus Solar Collector," ERDA Contract E(11-1) 2819
11. Itek 75-8250-1, "Solar Power Collector Breadboard Test," (March 1975)
12. ERDA Semiannual Review: July 21, 1976, ERDA Contract E(11-1) 2993
13. ERDA Semiannual Review: July 1976, Sandia Laboratory Presentation
14. SAND 75-0278, "Solar Total Energy Program Semiannual Report," Contract AT(29-1) 789, Sandia Laboratories (July 1975)
15. TM 33-748, "Performance of a Solar-Thermal Collector," JPL, (NASA-CR-145623) (November 1975)
16. MDC G6383, "Industrial Application of Solar Energy Semiannual Report," Contract E(04-3) 1132 McDonnell Douglas (April 1976)

17. ERDA Semiannual Review: July 1976, Contract 027671-A, McDonnell Douglas Presentation
18. ERDA Semiannual Review: July 1976, Fixed Mirror Solar Concentrator, General Atomic Company
19. MDC G6040, "Central Receiver Solar Power Thermal System Final Report," McDonnell Douglas (January 1976)
20. ERDA/JPL-1012-76/3, "The Cost of Energy from Utility Owned Solar Electric Systems," (JPL 5040-29) (June 1976)

APPENDIX A

COMPUTER SIMULATION PROGRAMS FOR BUILDING ENERGY DEMAND ANALYSIS

The energy demand of a commercial building is determined by a number of factors other than local climatic conditions. These other factors may significantly impact the total energy demands; they include the building use characteristics and the types and internal arrangement of the heating, ventilating, and air conditioning (HVAC) system components. As a consequence, knowledge of the energy demand of a particular building may provide little insight into the energy demand for other buildings located nearby. The best way to determine the energy demand would be to obtain metered data at appropriate intervals over a period of several years. Inasmuch as this would be impractical on a widespread basis for existing buildings (because of the costs involved), and not possible for designing new buildings, a number of computer simulation programs have been developed to define the energy demand for specific buildings. These programs are used by architects, utility personnel, energy management consultants, and others to perform required energy analyses within acceptable limits of accuracies. Table A-1 lists some of the programs available. The type of program best suited to a particular application should consider a number of factors, including the detail level of analysis and simulation cost.

The Energy Group (TEG), a subsidiary of Welton-Becket Associates, utilizes the Alternate Choice Comparison for Energy Systems Selection (AXCESS) program in support of the STES study efforts (subcontract), and considers it reliable and well-documented.

Most of the engineering logic in the formulation of AXCESS was provided by the consulting firm of Seelye, Stevenson, Valve, and Knecht, with the systems simulations and thermal calculation logic written by General American Research Corporation. Additionally, a large group of energy specialists participated as advisors in AXCESS's inception and development. Included in this group were representatives of Edison Electric Institute, the Electric Energy Association, the Duke Power Company, the Alabama Power Company, the Dallas Power and Light Company, the American Electric Power Service Corporation, the Westinghouse Electric Corporation, Southern Services Incorporated, General Electric

TABLE A-1
EXAMPLE OF COMPUTER SIMULATION PROGRAMS

Energy Program	Code Name	Developer
Alternate Choice Comparison for Energy Systems Selection	AXCESS	Edison Electric Institute, New York, New York
Energy Conservation Utilizing Better Engineering	ECUBE	American Gas Association, Arlington, Virginia
Meriweather Energy System Analysis Series	—	Ross F. Meriweather & Association, Inc., San Antonio, Texas
NASA's Energy Cost Analysis Program	NECAP	NASA, Langley Research Center, Hampton, Virginia
Trane Air Conditioning Economics	TRACE	The Trane Company, La Crosse, Wisconsin
Program for Analysis of Energy Utilization in Postal Facilities	—	General American Research Division (GARD) of General American Transportation Corporation, Niles, Illinois

Company, Central Power and Light Company, Florida Power Corporation, the Commonwealth Edison Company, the Pennsylvania Electric Company, and the Kansas City Power and Light Company.

The AXCESS program is designed to provide accurate economic comparisons of different energy systems which may be used in structures of all types. AXCESS is multi-disciplined, including engineering to accurately determine energy usage, and financial to evaluate this energy usage in terms of cost differentials for each of the systems under consideration.

Effectively, a comprehensive feasibility study method, AXCESS is divided into four sections. The first three sections cover the engineering phases, each of which provides monthly and annual monetary values, while the fourth is for financial analysis. The first section has been the primary concern in this study

as it is the energy analysis section which determines all of the energy needs of a building in which alternate mechanical and electrical systems are to be considered.

The purpose of the AXCESS Energy Analysis Computer Program is to provide a valid estimate of the comparative energy uses of alternate methods of meeting the energy requirements of buildings or processes. There are two types of ultimate energy uses to be estimated. In the first, the purchased energy is used directly; for example, lighting by purchased electricity. In these uses, a knowledge of the ultimate use is equivalent to a knowledge of energy used. Thus, 300 kW of installed lighting will use 300 kWh of electricity each hour that the lighting is full on.

The second type of ultimate use, and the main reason for a computer program, requires the conversion of the purchased energy form prior to its end use. This may include a single-step process, such as a gas engine-driven generator which provides electricity for lights, or a multiple stage process where an electrical centrifugal chiller provides chilled water to a dual-duct system for comfort conditioning. For each process, the ultimate use may be predictable, (e. g., lighting and process steam) or may vary as a function of other parameters such as cooling requirements (which are weather-dependent), occupancy, lighting, levels, etc.

The ultimate uses, their determining parameters, the conversion efficiencies and energy usage rates may vary constantly. In order to reasonably approximate this continual variation, the steady-state energy calculations should be repeated as often as possible and each applied to a fairly small time interval. An interval of 1 h was chosen for this purpose because it is the most frequent weather data basis commonly available and because a longer time interval would decrease the accuracy of the calculated electrical demand versus the 15-min integrated demands usually metered.

In essence, the program requests as input, each hour, those ultimate energy uses which are predictable (e. g., 30 kW lighting is on from 3 p. m. to 4 p. m.), the arrangement of the conversion devices (e. g., the chiller serves the dual-duct system's cooling coil and the rejected heat is used to preheat domestic hot

water; the dual-duct system serves Zones 106 through 113), and enough information to calculate each ultimate use that is not predictable (occupancy, weather, design loads, etc., to estimate zone heat gain).

The basic logic of the program revolves around the following five points:

- 1) Using the input design loads, the program calculates hourly zone solar and transmission loads (e. g., through windows, doors, etc.) for the year.
- 2) The program calculates the base energy loads, each hour, as the profile percentage multiplied by the peak usage, taking proper credit for any waste heat application. From these and zone data, it then calculates the zone internal gains and the net zone space conditioning requirements.
- 3) Terminal system operating is simulated in one of 10 subroutines, using input setpoints or "standard" designs. Based on the input performance data, and the calculated loads, each primary system is then simulated in one of three general subroutines.
- 4) All calculated energy usages are summed hourly into "meters." These meters function as electrical usage and demand meters but may be used with any fuel.
- 5) The program output, after playing back the input, consists of the monthly usage and demand for each fuel and any submetering requested. Optional outputs include time of demand, daily or hourly usages, and rejected heat. The submetering capability allows the calculation of actual demand contributions of incremental loads to the total load, permitting alternate fuel source capability within one scheme.

Imbedded in this logic are a number of programming features which extend the utility of this program. They are discussed in the following paragraphs.

For the same building with the same usage, the program permits simultaneous comparison of up to six alternate methods of meeting the energy requirements. Such things as the HVAC system and the lighting level may vary among these six methods, while the building occupancy pattern is assumed to be the same for each scheme.

U. S. Weather Bureau hourly data are input to the program. The user merely selects a weather station and year although it is possible to select a composite weather year if that is considered desirable. Weather data used in the program are hourly readings of dry-bulb temperature, percent relative humidity, and cloud cover factor.

On a block building basis, certain building data are input, such as areas for total roof, net wall, total glass and gross floor. External design conditions are input for the building while internal design conditions may be input for the total building, on a space type basis (e. g. , restaurant versus office area) or zone-by-zone.

Base loads are input in terms of maximum electrical connected load, or peak Btu, together with a profile which describes the percentage use for any of up to nine day-types (seven days of the week plus a holiday and vacation day type.) Typical wall and roof construction weights are selected by the user so that the proper ASHRAE response factor for the input design loads may be utilized in the calculation procedure.

HVAC simulations are broken down by terminal and primary system types. Not only does this afford flexibility in formulating an energy analysis study, but it also provides latitude in updating the program.

The program's basic calculations and reset guidelines conform to standard engineering practice and are consistent with publication of ASHRAE. All of the logic and computer routines used in AXCESS have been thoroughly checked and approved as standard for this area of investigation.

The Edison Electric Institute, References A-1 and A-2, has performed an evaluation of the AXCESS with other simulation programs (not identified due to proprietary reasons) and the Ohio State University (OSU) program, which has been correlated with actual measured data. This comparison is shown in Figure A-1 and indicates good agreement of the simulated data with the OSU data.

Figure A-1. Comparison of Simulation Programs
(Reference A-2)

REFERENCES

- A-1 Private Communication with Mr. George Reeves, Edison Electric Institute, New York, New York
- A-2 ASHRAE Task Group on Energy Requirements for Heating and Cooling of Buildings Subcommittee Report, "The Computer Users Subcommittee," ASHRAE Transactions, 1976, Page 5

APPENDIX B

DETERMINISTIC INSOLATION ESTIMATES FOR STES PERFORMANCE EVALUATION

A. INTRODUCTION

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 TRNSYS (Reference B-1). 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 (Reference B-2). The two sets overlap to a large extent, giving a total of 41 sites for which detailed hourly data is 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 are conveniently available for only a limited number of sites, and even for those, application of the data is a costly process requiring large computer facilities. It has been judged inappropriate to the requirements of the present study of commercial application of solar

*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.

total energy systems (STES) where the primary objective is 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 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 (References B-3 and B-4). More extensive tables are available for average daily values of total horizontal radiation in Reference B-5 (80 sites), and Reference B-6 (117 sites). The Climatic Atlas (Reference B-6) 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 described here is eclectic, incorporating 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.

B. INSOLATION MODEL

1. Extraterrestrial Radiation

Solar radiation reaching the top of the earth's atmosphere may be predicted quite accurately. Its intensity is a near constant, I_{sc} , modified only by a small correction, R , which takes into account the effect of seasonal variations in the earth-sun distance. According to Reference B-7, this distance correction is approximately

$$R = 1.0 + 0.033 \cos (360 n/365) \quad \dots (B-1)$$

where n is the day of the year.

The angle of incidence θ_i upon a surface depends upon the geographic location (latitude ϕ), the surface orientation, the solar declination, δ , and the local solar time, as measured by the hour angle, h. The solar declination is a function of the day of the year and is given approximately by

$$\delta = 23.45 \sin [284 + n (360/365)] \quad \dots (B-2)$$

The angle of incidence of the solar beam on a horizontal surface (equal to the sun's zenith angle) is

$$\cos \theta_z = \sin \delta \cdot \sin \phi + \cos \delta \cdot \cos \phi \cdot \cos h \quad \dots (B-3)$$

Incidence angle formulae for differently oriented surfaces are discussed in the next section.

2. Direct (Beam) Radiation in the Atmosphere

On noncloudy days, most of the extraterrestrial radiation penetrates the atmosphere with negligible change in direction and appears as direct or beam radiation at the earth's surface. A portion of the initial radiation is absorbed by molecular atmospheric constituents such as CO_2 and water vapor; another fraction is scattered out of the beam direction by molecules, droplets, and suspended solid particles. The amount of attenuation depends upon seasonal variations in the amount of absorbers and scatterers in the atmosphere. The ASHRAE Handbook of Fundamentals (Reference B-8) presents a semitheoretical expression for beam radiation through the normal atmosphere. It is expressed in terms of an apparent extraterrestrial irradiation, A, and an extinction coefficient, B, based on air mass. An additional factor, termed the clearness number, CN, corrects for local atmospheric conditions. Thus,

$$I_{DN} = \text{CN} \cdot A \cdot \exp (-B/\cos \theta_z) \quad \dots (B-4)$$

where I_{DN} is the irradiation on a surface normal to the beam. The term A includes the effects of upper atmosphere absorption and of variable earth-sun distance. Table B-1, extracted from Reference B-8, gives monthly values of δ , (A/I_{sc}) , and B. For convenience, the factor R (Equation B-1) is included.

Equation B-4 is applied in the present method. The clearness number, however, is treated as a seasonally variable quantity selected so as to constrain the predicted radiation to agree with the daily average.

3. Diffuse Radiation

A certain amount of the radiation scattered by atmospheric constituents and cloud surfaces reaches a surface at ground level from directions other than that of the direct beam (see Figure B-1). If the surface in question is tilted, it may also receive diffuse radiation from the ground. The amount of diffuse radiation received is a complicated function of the state of the atmosphere, the sun's position, ground reflectance, and surface orientation.

TABLE B-1
SEASONALLY VARYING SOLAR RADIATION PARAMETERS

Date	R	δ (deg)	(A/I_{sc})	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	0.075	+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

76-O18-49-46

Figure B-1. Insolation Geometry

In the present method, a very simple model is used to evaluate diffuse radiation. First, the radiation is assumed to come from the general direction of the sun. This is most closely approximated on bright days in situations where ground reflections are negligible. Secondly, the amount of diffuse radiation is related to the direct normal radiation by means of a linear regression formula derived from actual observations. As employed by Boes (Reference B-3), the formula is

$$I_{DN} = \alpha(PP) + \beta \quad \dots (B-5)$$

where (PP) is the "percent possible," actually the fraction of total (direct plus diffuse) radiation falling on a horizontal surface, compared with the extra-terrestrial value:

$$(PP) = I_h / I_{oh} \quad \dots (B-6)$$

When the directional assumption is made for diffuse radiation, Equations B-1, B-4, B-5, and B-6 combine to give

$$I_{DN} = \frac{\alpha \cdot (I_{DN} + I_{DF}) \cdot \cos \theta_z}{R \cdot I_{sc} \cdot \cos \theta_z} + \beta \quad \dots (B-7)$$

Once I_{DN} is calculated from Equation B-4, I_{DF} may be evaluated from Equation B-7.

It should be pointed out that the linear regression formula (Equation B-5) is used here in an inverse fashion. Ordinarily it is used to estimate I_{DN} from measured values of I_h . Here it is applied to clear air radiation as a means of estimating the diffuse component.

4. Intermittency Due to Cloud Cover

Real solar radiation data contain 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 clear air radiation measured at a given site.

For present purposes, the effect of cloud cover is approximated by a simple model. On the average, for each hour of the day (in a given month), 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 cloud factor CF is applied in the following way: properties of a solar system which depend on hourly variations such as incident energy on a collector, mutual interference or thermal performance are evaluated over a day using the clear air formulas, including the factor CN but excluding CF. When the integrated value is obtained, it is reduced by the factor CF to reflect the average daily effect of cloud cover.

C. EVALUATION OF ATMOSPHERIC PARAMETERS

The expressions for direct and diffuse radiation (for unclouded days) can be multiplied by the cloud factor and integrated over a day to give daily totals for both total horizontal and direct normal radiation. Since the cloud factor is assumed constant with time of day, it may be removed from the integral signs.

1. Direct Normal

From Equation B-4,

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

where $\cos \theta_z$ is a function of time of day according to Equation B-3. The daily total, including cloud effects, becomes

$$\begin{aligned} H_{DN} &= CF \int I_{DN} dt \\ &= CF \cdot CN \cdot \int A \cdot \exp(-B / \cos \theta_z) dt \quad \dots (B-8) \end{aligned}$$

2. Total Horizontal

From Equation B-7,

$$\begin{aligned} I_h &= (I_{DN} = I_{DF}) \cdot \cos \theta_z \\ &= \frac{R \cdot I_{sc}}{\alpha} [CN \cdot A \cdot \exp(-B / \cos \theta_z) - \beta] \cdot \cos \theta_z \quad \dots (B-9) \end{aligned}$$

The daily total with clouds is

$$\begin{aligned} H_h &= \frac{CF \cdot CN \cdot R \cdot I_{sc}}{\alpha} \int A \cdot \exp(-B / \cos \theta_z) \cdot \cos \theta_z dt \\ &\quad - \frac{CF \cdot R \cdot I_{sc} \cdot \beta}{\alpha} \int \cos \theta_z dt \quad \dots (B-10) \end{aligned}$$

The constants α and β are taken from Reference B-3. They are $(\alpha / I_{sc}) = 1.330$, and $(\beta / I_{sc}) = -0.384$.

The left-hand sides of Equations B-8 and B-10 can be regarded as daily averages and identified with those computed from the Aerospace tapes (Reference B-4), for example. The terms on the right-hand sides contain the

constants CN and CF and additional quantities which are known or can be computed by simple numerical integration. Thus, Equations B-8 and B-10 represent two equations in the unknowns CN and CF. When the deterministic method uses the coefficients determined in the above manner, it predicts daily values of direct normal and total horizontal radiation equal to the long-term averages.

The method has been applied to a few sites of widely varying climatology. The results are shown in Figure B-2. It appears that the annual patterns of CN, CF variation may represent a kind of insolation "signature" which would be useful as a basis for estimating coefficients. For example, the upper three sites are all from the Southwest and exhibit nearly equal values of CN and CF for each month. If this is assumed, then Equation B-10 can be used to evaluate coefficients for any site in the same climatic region for which daily average values of total horizontal radiation are known.

D. EVALUATION OF ENERGY INCIDENT ON A COLLECTOR

An appropriate use of the deterministic method is the estimation of the energy incident on a collector aperture. There is a large range of possible orientations and tracking strategies of interest. The present method provides a rapid method of estimating their relative advantages as a function of season and site location. In principle, the method can be applied to any situation in which the aperture orientation can be specified as a function of solar position. Since in the present model the diffuse relation is assumed to come from the solar direction, the effect of orientation is specified by the time-varying incidence angle θ_i of the solar beam.

Denoting either the direct or total (direct plus diffuse) intensity by I , the model predicts a daily total insolation of

$$H = 2 CF \int_{12}^a I \cos \theta_i dt . \quad \dots (B-11)$$

Figure B-2. Insolation "Signatures" for Candidate Sites
(Average Daily Totals Computed from Aerospace
Tapes by Arizona State and Spectrolab)

76-018-49-48

The integration is over the half day from noon to sunset at time

$$t_s = \frac{\cos^{-1} (-\tan \delta \tan \phi)}{15} + 12 \quad \dots (B-12)$$

(The model assumes a symmetrical distribution about solar noon.)

Concentrating collectors generally accept little or no diffuse radiation. For such cases I , in Equation B-11, is equal to I_{DN} in Equation B-4. Flat plate collectors accept both direct and diffuse radiation. In this case, I is given by an equation similar to B-9:

$$I = \frac{R \cdot I_{sc}}{a} [CN \cdot A \cdot \exp (-B/\cos \theta_z) - \beta] \quad \dots (B-13)$$

Time variation of the incidence angle depends upon the tracking pattern of the collector. For south-facing, fixed apertures, the incidence angle is given by an equation similar to Equation B-3 with latitude replaced by $(\phi - T)$:

$$\cos \theta_i = \sin \delta \cdot \sin (\phi - T) + \cos \delta \cdot \cos (\phi - T) \cos h \quad \dots (B-14)$$

where T is the collector tilt angle from the horizontal and h is the hour angle.

$$h = 15 \cdot (12 - t) \quad \dots (B-15)$$

Single axis trackers, in which the axis lies in a north-south plane, form another class. With the axis tilted above the horizontal at angle T , the incidence angle is given by

$$\sin \theta_i = \cos \delta \cdot \sin (\phi - T) \cos h - \sin \delta \cdot \cos (\phi - T) \quad \dots (B-16)$$

An important special case is the polar axis ($T = \phi$) orientation in which $\cos \theta_i = \cos \delta$. In another type collector, the axis is aligned east-west in the horizontal plane. Here the incidence angle is given by

$$\sin \theta_i = \cos \delta \cdot \sin h \quad \dots (B-17)$$

Two-axis trackers, of course, point directly at the sun, so $\cos \theta_i$ is equal to one at all times.

An evaluation was made of the reliability of incident radiation predictions by the deterministic method. Reference B-4 tabulates average daily values for a variety of collector orientations and tracking modes. These values were computed by integrating the hourly radiation incident on each type of collector. The average value for each month was obtained by integrating over the whole month, 2 years running.

The tabulated averages for horizontal flat plates and two-axis trackers (receiving direct normal radiation) were used in Equations B-8 and B-10 to compute CN and CF values. These values in turn were applied in Equations B-4, B-11, and B-13 to predict average daily incident energy for other collector-tracker types. Table B-2 shows the comparison between predicted and "exact" values. The results indicate that the predictions are very good for all types of collectors and for all localities and seasons.

E. APPLICATIONS OF THE DETERMINISTIC METHOD

The method described in the previous sections results in a model which represents the real insolation pattern by means of a smoothly varying synthetic day, as shown in Figure B-3. The intensity at each hour of the day corresponds to the average intensity for unclouded times. Each hour is assumed to be unclouded for a fraction (CF) of the time during the month. In practice, the synthetic day corresponds closely to a typical day on which total insolation matches the daily average for that month.

The deterministic method may be used to estimate the effect of hourly variations in insolation on many aspects of collector performance. For example, the thermal efficiency is a nonlinear function of incident intensity and is underestimated by assuming that the insolation pattern is one of identical days corresponding to the long-term average. In Reference B-5, this error is corrected by means of a use factor derived from an analysis of detailed hourly records. The present method also tends to compensate for this effect

TABLE B-2

AVERAGE DAILY SOLAR ENERGY INCIDENT ON COLLECTOR APERTURES

Site	CN	CF	Month	Incident Solar Energy (kWh./m ² /day)				
				Flat Plate		One-Axis Tracker		
				T = Latitude	T = Lati- tude + 20°	E-W.	N-S Horizontal	N-S Polar
Albuquerque Latitude 35.05°	0.999	0.091	January	5.86* (5.92)	6.34 (6.48)	5.70 (5.55)	4.61 (4.68)	6.36 (6.35)
	0.928	0.953	July	6.64 (6.65)	5.32 (5.16)	6.19 (6.26)	8.29 (8.32)	7.90 (7.61)
Los Angeles Latitude 34.05°	0.940	0.741	January	4.68 (4.77)	5.04 (5.23)	4.47 (4.35)	3.68 (3.69)	5.00 (4.97)
	0.981	1.0	July	7.19 (7.29)	5.73 (5.68)	6.86 (6.90)	9.18 (9.16)	8.73 (8.55)
Seattle Latitude 47.45°	0.742	0.653	January	2.57 (2.61)	2.76 (2.84)	2.37 (2.29)	1.43 (1.50)	2.52 (2.52)
	0.893	0.843	July	5.67 (5.68)	4.54 (4.42)	5.34 (5.32)	7.09 (7.05)	6.98 (6.65)

*Upper values by deterministic method; lower values in parenthesis by hourly integration.

by accounting separately for the clouded hours. Preliminary comparisons have shown that under conditions of low average insolation (Madison, Wisconsin, in January), the deterministic method tends to underestimate thermal efficiency slightly. Further comparisons are desirable for a wide range of climates and seasons in order to arrive at a better assessment.

The deterministic method is well suited to the analysis of various effects associated with the time-varying position of the sun. It may be used to estimate the amount of incident energy lost due to the mutual shading of adjacent collectors. It may also be applied to trade-off studies leading to optimum choices of collector orientation and tracking strategy.

Because the method is formulated in compact analytical form, it is readily adaptable for use by small computers and programmable calculators. Incident energy calculations for fixed, one-axis, and two-axis collectors have been programmed on the Texas Instruments Model SR-52 hand calculator. Similar insolation calculations have been incorporated as a subprogram in the STES evaluation program written for the Honeywell Model 440 computer. The latter program carries out engineering and cost evaluations of STES configurations on a parametric basis.

76-018-49-51

Figure B-3. Hourly Insolation Patterns
for Madison, Wisconsin
(Month of January)

APPENDIX B
REFERENCES

- B-1 "TRNSYS, a Transient Simulation Program," Engineering Experiment Station Report 38, University of Wisconsin, Madison, Wisconsin (March 31, 1975)
- B-2 "Solar Thermal Conversion Mission Analysis, Volume III. South-western United States Insolation Climatology," Aerospace Corporation Report ATR - 74 (7417-16) - 2, Vol. III (November 15, 1974)
- B-3 Eldon C. Boes, et al., "Distribution of Direct and Total Solar Radiation Availabilities for the USA," Sandia Laboratories' Energy Report SAND 76-0411 (1976)
- B-4 "Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Annual Progress Report for period January 1, 1975 to December 31, 1975, ERDA Contract No. E(11-1)-2590, ERDA Report No. CDO-2590-1(2)
- B-5 B. H. Y. Liu and R. C. Jordan, "Availability of Solar Energy for Flat Plate Solar Heat Collectors," in Low Temperature Engineering Application of Solar Energy, ASHRAE, 1968
- B-6 "Climatic Atlas of the United States," U. S. Department of Commerce, pp. 69-70 (June 1968)
- B-7 John A. Duffie and William A. Beckman, Solar Energy Processes, (John Wiley, New York, 1974) pp. 8-18
- B-8 ASHRAE Handbook of Fundamentals, ASHRAE, pp. 386-394, 1972

APPENDIX C

COST ALGORITHMS

A number of algorithms, based on 1976 price estimates, have been developed for the capital costs of candidate capital equipment and items and operations and maintenance costs. They are discussed in the following subsections.

A. CAPITAL EQUIPMENT COSTS

The installed costs for the several candidate capital equipment items considered to date are presented in Table C-1. Preliminary computations indicate that the collector, storage and PCS's will approach 90% of the initial capital outlays.

The several PCS cost algorithms have been compared for a 1-MWe unit. The costs ranged from \$365,000 to \$375,000. (Costs for equivalent "conventional," fossil fuel-fired gas turbine and 900 rpm reciprocating engine installations, derived from Reference C-3, were \$357,000 and \$500,000, respectively.)

B. OPERATIONS AND MAINTENANCE COSTS

The operations and maintenance cost algorithms for both attended and "unattended" plants are shown in Figure C-1. The data were developed by allocating supervision, operations and maintenance labor as a function of plant size and operating hours in accord with the guidelines suggested in Reference C-3. Current quotations were used for labor rates (indirect, direct and contract maintenance); materials and supply costs were estimated in accord with data presented in Reference C-3.

Envirodyne Energy Services provided operations and maintenance cost data on the total energy systems installed in the IRS Complex in Brookhaven, N. Y., and the Landover Mall Shopping Center in suburban Washington, D. C. The data points are shown in Figure C-1. They appear to correlate well with the algorithms which were derived analytically.

TABLE C-1
PRELIMINARY COST ALGORITHMS FOR CANDIDATE
CAPITAL EQUIPMENT ITEMS (INSTALLED)

Unit	Size Range	Algorithm	Reference
Distributive Collectors	—	$\$100/\text{m}^2$	C-1, C-5
Storage			
Hot Storage	150 - 150,000 ft^3	Cost = $\$352 (\text{vol}, \text{ft}^3) 0.515$ + $\$12 (\text{vol}, \text{ft}^3)$	C-2, C-7
Cold Storage	150 - 150,000 ft^3	Cost = $\$352 (\text{vol}, \text{ft}^3) 0.515$	C-7
Battery	—	Cost = $\$50 (\text{size}, \text{kWh})$ + $\$75 (\text{system size}, \text{kWh})$	C-3
Packaged Steam Boilers	$10^4 - 10^5$ lb steam/h-unit	Cost/Unit = $\$3690 (\text{lb}/\text{steam}/\text{h unit}) 0.32$	C-3
Refrigeration			
Centrifugal Chillers (Electric)	250-2,000 tons	Cost/unit = $\$4,240 (\text{tons}/\text{unit}) 0.61$	C-3
Centrifugal Chillers (Engine)	500-2,000 tons	Cost/unit = $\$2,270 (\text{tons}/\text{unit}) 0.745$	C-3
Absorption Chillers (Steam)	250-1,200 tons	Cost/unit = $\$2,194 (\text{tons}/\text{unit}) 0.7$	C-3
Power Conversion Systems			
Sunstrand Organic Rankine Cycle	100-1,000 kW	Cost = $\$3,815 (\text{kW}/\text{unit}) 0.66$	C-4
Rankine Cycle — Steam	1-1,000 kW	Cost = $\$22,700 + \$350 (\text{kW})$	C-5
Rankine Cycle — Steam	1,000-1,000,000 kW	Cost = $\$1,250 (\text{kW}) 0.825$	C-5
Shell and Tube Heat Exchangers	20-2,000 ft^2	Cost/unit = $\$300 (\text{area}, \text{ft}^2) 0.56$	C-6
Cooling Towers — Dry	—	Cost/unit = $\$40 (\text{area}, \text{ft}^2) 0.6$	C-7

76-019-49-70A

Figure C-1. Operations and Maintenance Costs

APPENDIX C
REFERENCES

- C-1 R. W. Harrigan (Sandia Laboratories) personal communication
- C-2 Solar Total Energy Program Semiannual Report, October 1976 - March 1976, Sandia Laboratories (SAND76-0205)
- C-3 Final Report on Total Energy Feasibility Criteria for U. S. Army Engineer Power Group, Fort Belvoir, Virginia, (Contract DAAK02-73-C-0370), by OES, Inc. (Envirodyne), December 1973
- C-4 A. W. Adam (Sunstrand Energy Systems), personal communication
- C-5 R. W. Harrigan, "Application of Solar Total Energy to a Mixed-Load Community," Sandia Laboratories (SAND75-0542), December 1975
- C-6 G. M. Hoerner, Jr., "Nomograph Updates Process Equipment Costs," Chemical Engineering, p. 141, May 24, 1976
- C-7 Estimate Based on Equipment Quotations Received in 1976 for AI Facilities

APPENDIX D

COST SENSITIVITIES OF SOLAR TOTAL ENERGY SYSTEMS

Evaluation of the comparative economic merits of candidate solar total energy systems (STES), as well as projections of the initial date and rate of market penetration, are dependent upon various assumptions such as the cost of money, escalation rates, useful equipment life, etc. In order to provide a consistent basis for comparing the results of this investigation of STES applications in the commercial sector with other on-going ERDA studies, annualized system resultant costs and levelled busbar energy costs will be used as a basis of comparison. These parameters will be determined using the procedures jointly developed by JPL, ERDA, and EPRI, as described in Reference D-1.

The sensitivity of the annualized system cost to variations in the following were explored:

- 1) Weighted average, after-tax cost of capital (k)
- 2) System lifetime (N) and/or accounting lifetime (n)
- 3) Effective corporate income tax rate (τ) and investment tax credit fraction (α)
- 4) Type of depreciation (straight line or sum of digits)
- 5) Inflation or escalation rate (g).

The results indicated that the annualized system-resultant cost ratio (annualized cost/capital investment) increases exponentially as the recurring cost ratio (operating and maintenance plus fuel cost/capital investment) increases. In capital-intensive systems such as solar, nuclear, and hydro, which are characterized by low recurring cost ratios ($\lesssim 2\%$), the annualized cost ratio is equal to about 0.2 (+0.04, -0.03) over a range of interest rates (k) which vary from 8 to 10.5%, inflation rates (g) ranging from 5 to 11%, and system lifetimes (N) of 20 to 30 years. As the recurring cost ratio increases (e.g., fossil fuel systems), the annualized ratio rises most rapidly for the combination which represents the highest N and g , and lowest k . The "drivers" appear to be the system lifetime and projected inflation rate. Typically, the capital investment ratios are dependent upon the anticipated inflation rates and system lifetimes.

The several elements of the sensitivity analyses are presented in the following paragraphs.

A. WEIGHTED AFTER TAX-COST OF CAPITAL

The JPL-ERDA-EPRI expression for the weighted after-tax cost of capital is presented in Reference D-1 as Equation (B-1):

$$k = (1 - \tau) k_d \frac{D}{V} + k_c \frac{C}{V} + k_p \frac{P}{V},$$

where

C/V = common stock fraction

D/V = debt fraction

P/V = preferred stock fraction

k_c = common stockholders' rate of return on investment

k_d = interest rate on corporate debt

k_p = preferred stockholders' rate of return on investment.

The effective corporate income tax rate, τ , is a function of both the state and federal tax rates, as well as any investment tax credits. The nominal tax rate for a developer-owner-investor making a one-time outlay would be on the order of 50%; in the case of a utility, the JPL-ERDA-EPRI document indicates a value of 40%.

Given a current prime interest rate on the order of 7%, utility bonds are bringing 8-1/2 to 10%, depending on the quality of the issue, maturity date, etc.; private investor-owners presently are getting 25 to 30 year bank loans locally for commercial building ventures, at interest rates of 9-1/2 to 10%. If, for purposes of this example, it is assumed that there would be no preferred issues, and if it is further assumed that:

- 1) Utilities would accept a 12 to 15% return (D-1) on equity and be able to negotiate a 50/50 to 60/40 debt-to-equity ratio, and

- 2) Private owner-investors would accept an after-tax return of 15 to 20% on commercial property and currently are getting 70% bank financing for such ventures,

then it can be shown (Table D-1) that the weighted cost of capital (k) will be on the order of 8 to 10.5% for utilities and 8 to 9.5% for investor-owners, based upon these assumptions. The "driver" on the cost of capital, therefore, appears to be the assumed debt/equity ratio.

TABLE D-1
WEIGHTED AVERAGE AFTER-TAX COST OF CAPITAL (k)

k (%)	Utility	Investor-Owner
	8 to 10.5	8 to 9.5
<u>Assumptions</u>		
k_{debt} (%) [*]	9-10	10
k_{common} (%)	12-15	15-20
Effective Corporate Income Tax Rate, τ , (%)	40	50
Debt/Equity Ratio	50/50-60/40	70/30
n , N (years)	20/30	20/20

*Prime Rate = 7%

B. EFFECT OF k , n , N , τ , α , SUM OF THE DIGITS (DPF_{SD}) AND STRAIGHT-LINE DEPRECIATION FACTORS (DPF_{SL}) ON CAPITAL RECOVERY FACTORS (CRF) AND ANNUALIZED FIXED-CHARGE RATES (FCR)

The expressions for computing the CRF, $\overline{FCR}$, and DPF in Reference D-1 are given by the following expressions. (Equation numbers refer to Reference D-1).

$$CRF_{k,n} = \frac{k}{1 - (1+k)^{-N}} \quad \dots (B.36)$$

$$\overline{FCR} = \frac{1}{1-\tau} (CRF_{k,n} - \frac{\tau}{N} + \beta_1 + \beta_2) \quad \dots (B.21)$$

$$= CRF_{k,n} \left[\frac{(1-\tau) (DPF_{m,k,n})}{1 -} \right]^{-\alpha} + \beta_1 + \beta_2 \quad \dots (E.11)$$

where in Equation (E.11):

β_1 = "other" tax fraction

β_2 = insurance fraction

$$DPF_{SL,k,n} = \left[n \cdot CRF_{k,n} \right]^{-1} \quad \dots (E.11)$$

$$DPF_{SD,k,n} = \frac{2 \left(\frac{n-1}{CRF_{k,n}} \right)}{n(n+1)k} \quad \dots (E.12)$$

$$\tau \approx 0.50 \quad \dots (E.14)$$

Shown in Table D-2 are the effects on CRF , DPF_{SD} , DPF_{SL} , and $\overline{FCR}$ of varying:

k from 8 to 9.5%

n , N from 20 to 30 years

τ from 40 to 50%

α from 0 to 4%.

As can be seen, the CRF (which ultimately appears as an operator in the recurring cost segment of Equation (B.20) for computing the annualized system-resultant cost ($\overline{AC}$) varies from 0.0888 to 0.121 over the range of k 's and N 's considered. The $\overline{FCR}$, which is a function of the effective income tax rate, type of depreciation method, amortization period, etc., exhibits a variation on the order of $\approx 10\%$ for the types of depreciation, range of tax rates, and investment tax credits considered for a given k , n , and N . The high and low variance over the whole gamut of parameters considered is on the order of 50%.

TABLE D-2

CAPITAL RECOVERY FACTOR (CRF), FIXED CHARGE RATE ($\overline{FCR}$)
AND DEPRECIATION FACTOR (DPF) SENSITIVITIES.

k (%)	8		9.5		10.5		Assumptions
n = N (years)	20	30	20	30	20	30	
$CRF_{N,k}$	0.101852	0.08883	0.113477	0.101681	0.121493	0.110529	
$DPF_{SL,k,n}$ (Equation E.11)	0.490908	0.375249	0.440618	0.327822	0.411546	0.301580	
DPF_{SD} (Equation E.12)	0.606062	0.503832	0.560784	0.456487	0.533745	0.429136	
Utility Financing							
$\overline{FCR}$ (Equation B.21)	-	0.1483	-	0.1698	-	0.1845	$\beta_1 + \beta_2 = 0.0225$ $\tau = 0.40$
$\overline{FCR}_{DPF/SL}$ (Equation E.11)	-	0.1494	-	0.1729	-	0.1892	N = 30 n = 20 $\alpha = 0.04$ $\tau = 0.50$
$\overline{FCR}_{DPF/SD}$ (Equation E.11)	-	0.1392	-	0.1607	-	0.1757	$\beta_1 + \beta_2 = 0.0225$ N = 30 n = 20 $\alpha = 0.04$ $\tau = 0.5$
$\overline{FCR}_{DPF/SD} (\alpha = 0)$	-	0.1456	-	0.1688	-	0.1846	$\alpha = 0$ N = 30 n = 20 $\tau = 0.5$ $\beta_1 + \beta_2 = 0.0225$
Investor/Owner Financing							
$\overline{FCR}$ (Equation B.21)	0.1589 0.1762	-	0.1783 0.1994	-	0.1917 0.2155	-	$\tau = 0.4$ N = n = 20 $\tau = 0.5$ $\beta_1 + \beta_2 = 0.225$
$FCR_{DPF/SL}$ (Equation E.11)	0.1681	-	0.1904	-	0.2058	-	$\tau = 0.5$ N = n = 20 $\beta_1 + \beta_2 = 0.0225$ $\alpha = 0.04$
$FCR_{DPF/SD}$ (Equation E.11)	0.1563	-	0.1767	-	0.1909	-	$\tau = 0.5$ n = N = 20
$FCR_{DPF/SD} (\alpha = 0)$	0.1645	-	0.1858	-	0.2006	-	$\beta_1 + \beta_2 = 0.0225$

C. ANNUALIZED COST SENSITIVITIES

The annualized system-resultant cost is computed in Reference D-1 according to Equation B.20.

$$\overline{AC} = (1 - g)^{-d} \left[\overline{FCR} \cdot CI_{pv} + CRF_{k, n} (OP_{pv} + MNT_{pv} + FL_{pv}) \right] \dots (B.20)$$

where the present value of capital investment (CI_{pv}) and the present value of recurrent costs (X_{pv}) are:

$$CI_{pv} = (1 + g_c)^p \sum_t \left[CI_t \left(\frac{1 + g_c}{1 + k} \right)^j \right], \dots (B.38)$$

$$X_{pv} = (1 + g_x)^p X_o \left(\frac{1 + g_x}{k - g_x} \right) \left[1 - \left(\frac{1 + g_x}{1 + k} \right)^N \right] \dots (B.39)$$

where:

OP_{pv} = present value of operating cost

MNT_{pv} = present value of maintenance cost

FL_{pv} = present value of fuel cost

$p = Y_{co} - Y_p$ (number of years from the beginning of the price year to the beginning of the first year of commercial operation)

$j = Y_t - Y_{co} + 1$ (number of years between December 31 of a particular year and January 1 of the first year of commercial operations)

$d = Y_{co} - Y_b$ (number of years between January 1 of the base year for constant dollars and January 1 of the year of first commercial operations).

If, for the sake of simplicity, we assume that

$$p = d = j = 0,$$

and that the recurring costs (e.g., operations, maintenance, fuel, etc.) can be represented as a fraction, a , of the capital investment, i.e.,

$$OP_{pv} + MNT_{pv} + FL_{pv} = a \cdot CI_{pv}$$

where:

$$0 < a < 1,$$

Then the annualized cost can be expressed as a function of the capital investment (i.e., the annualized cost ratio):

$$\frac{\overline{AC}}{CI_{pv}} = \left\{ \overline{FCR} + (CRF)(a) \left(\frac{1 + g_x}{k - g_x} \right) \left[1 - \left(\frac{1 + g_x}{1 + k} \right)^N \right] \right\}$$

where:

$$\left(\frac{1 + g_x}{k - g_x} \right) \left[1 - \left(\frac{1 + g_x}{1 + k} \right)^N \right] = N$$

when $k = g_x$.

This ratio has been examined for its sensitivity to variations in:

k from 8 to 9.5%

g_x from 5 to 11%

N from 20 to 30 years

a from 0.0125 to 0.4

and the results are presented in Table D-3 and Figure D-1. It should be noted that:

- 1) In capital-intensive systems (e.g., solar, hydro and nuclear installations) where the recurring cost presumably represents a small fraction of the capital investment (2.5%), the annualized cost will

TABLE D-3
EFFECT OF INTEREST RATES, INFLATION, AND OPERATING COSTS
ON ANNUALIZED SYSTEM COSTS

Interest Costs, k (%)	8						9.5						10.5					
Inflation Rate, g_x (%)	5	8	11	5	8	11	5	8	11	5	8	11	5	8	11	5	8	11
Eff. Interest Rate	2.86	0	(-2.70)	2.86	0	(-2.70)	4.29	1.39	(-1.35)	4.29	1.39	(-1.35)	5.24	2.31	(-0.45)	5.24	2.31	(-0.45)
$\left[\frac{1+k}{1+g_c} - 1 \right] (\%)$																		
Timespan (n yr)	20			30			20			30			20			30		
PV Factor (yr)	15.2	20	27.2	20.5	30	47.2	13.2	17.4	23.5	17.0	24.4	27.2	12.2	15.8	21.0	18.0	21.5	32.3
$\left(\frac{1+g}{k-g} \right) \left[1 - \left(\frac{1+g}{1+k} \right)^n \right]$																		
$\overline{FCR}_{SL}$		0.158			0.149			0.190			0.173			0.206			0.189	
CRF		0.102			0.0888			0.113			0.102			0.121			0.111	
$(O\&M + F)/CI$							1.25%											
$\overline{AC}/CI$	0.187	0.196	0.203	0.172	0.183	0.201	0.209	0.215	0.223	0.195	0.204	0.221	0.224	0.230	0.238	0.210	0.218	0.234
$(O\&M + F)/CI$							2.50%											
$\overline{AC}/CI$	0.207	0.221	0.237	0.195	0.217	0.254	0.227	0.239	0.256	0.216	0.235	0.268	0.243	0.254	0.270	0.231	0.249	0.279
$(O\&M + F)/CI$							5%											
$\overline{AC}/CI$	0.246	0.272	0.307	0.230	0.284	0.359	0.265	0.288	0.323	0.260	0.297	0.363	0.280	0.302	0.333	0.272	0.308	0.368
$(O\&M + F)/CI$							10%											
$\overline{AC}/CI$	0.323	0.374	0.445	0.331	0.417	0.568	0.339	0.387	0.456	0.346	0.422	0.553	0.354	0.397	0.460	0.356	0.428	0.548
$(O\&M + F)/CI$							20%											
$\overline{AC}/CI$	0.478	0.576	0.723	0.513	0.682	0.987	0.468	0.583	0.721	0.520	0.671	0.934	0.501	0.588	0.714	0.522	0.666	0.906
$(O\&M + F)/CI$							30%											
$\overline{AC}/CI$	0.631	0.780	1.000	0.695	0.948	1.406	0.637	0.780	0.987	0.693	0.920	1.314	0.649	0.780	0.968	0.689	0.905	1.265
$(O\&M + F)/CI$							40%											
$\overline{AC}/CI$	0.788	0.984	1.278	0.877	1.215	1.826	0.787	0.976	1.252	0.867	1.169	1.695	0.796	0.971	1.222	0.855	1.144	1.623

76-O18-49-67

Figure D-1. Effect of Recurring Cost Ratio on Annualized System - Resultant Cost Ratio

approximate 20 to 30% of the capital investment and be relatively insensitive to the amortization period (N), capital costs (k), or inflation (g).

- 2) When the recurring cost ratio is relatively high (e.g., $\hat{c} > 25\%$ of the capital investment which might be typified by fossil fuel-fired systems), the annualized cost ratio is strongly dependent upon the projected inflation rate and amortization period.

As an example, if one assumes a recurring cost ratio of 2% for a solar system and 25% for a fossil fuel-fired and/or purchased power total energy system, one can afford a higher capital investment for the solar system and still achieve the same annualized system cost. The solar system capital investment for this case can be seen from Figure D-1 to be three to five times greater, depending upon the projected inflation rates for fuel and/or power over the life (i.e., amortization period) assigned to the project.

As a corollary, it should be noted that the life-cycle costs of a capital-intensive project can be anticipated with a greater degree of confidence (inasmuch as they predominantly consist of amortization charges) in contrast to a system which is characterized by high recurring costs and, therefore, subject to the whims of inflation.

D. ESCALATION RATES

As indicated, annualized costs are particularly sensitive to inflation rates where the recurring cost ratio is high. Additionally, cost data on the various candidate equipment items were compiled from a number of sources. However, the sources are not all referenced to the same time base, and, therefore, the impact of escalation on equipment costs from 1970 to the present was reviewed. The paragraphs which follow present the rationale for selecting an 8%/year increase in equipment costs since 1970, a review of the Bureau of Labor Statistics Consumer Price Index (BLS/CPI) and possible future trends in fuel costs.

1. Updating Equipment Cost Data

Cost data are available from various sources on candidate equipment items. To preclude the need for continually obtaining fresh quotations, a common

procedure (Reference D-2) is employed for normalizing these data to 1976 (base year) using price-ratio values.

Each issue, Chemical Engineering publishes an update of its own Plant Cost Index and the Marshall and Swift (M&S) Equipment Cost Index. The CE Index is based on 1957-59 costs and considers equipment, machinery, supports, construction, labor, buildings, engineering, and supervision. The M&S Index, which is based on 1926 costs, includes both the chemical process and related industries such as electrical, power, mining, milling, refrigeration, and steam power generation. In 1970, the CE Index stood at 125.7; in May 1976 it was 190.1. The M&S Index was 303.3 in 1970; in the second quarter of 1976 the Index stood at 468.5. This would indicate an equipment escalation rate on the order of 8% per year since 1970. Similarly, the Hourly Earnings Index for chemical and allied products (also published in Chemical Engineering) has been compounding at an annual rate of approximately 7.5% since its base year in 1967.

2. Future Escalation Rates for Capital Investments and Recurring Costs

A sample problem presented by JPL in Reference D-1 suggests a generalized escalation rate of 5% per year and a 6% rate for recurring costs. The widely-recognized Consumer Price Index (for urban wage earners and clerical workers) is updated monthly by the Bureau of Labor Statistics. Data are available, by month, since 1913. These data were examined briefly to determine if there was a discernible long-term trend.

The escalation data, grouped by 4-year intervals, are shown in Figure D-2. Other computations indicated that in the 9-year period since 1967 (CPI = 100), the average inflation rate was 6.1% compounded annually; in the 43-year period since the recession trough of 1933 (CPI = 38.1), the compound rate of increase averaged 3.5%.

In 1975, Ford, Bacon, and Davis presented the data shown in Figure D-3 on the projected costs of fossil fuels through 1980. These data indicate that the price of oil and coal will double in the 5-year interval, and that gas (after deregulation) could increase eight-fold. Current projections on the next OPEC round of price increases range from 10 to 25% as reported in the Los Angeles

76-018-49-68

Figure D-2. Escalation Rates Based Upon Bureau of Labor Statistics/Consumer Price Index Data

76-018-49-69

Figure D-3. Projected Fuel Costs (Taken from Ford, Bacon & Davis, Inc. - 1975 Energy Management Guidebook)

Times on September 7, 1976, including a norm of 15% as reported by the Wall Street Journal on September 9, 1976. "New" gas from the Gulf of Mexico is being offered to the pipelines at \$2.75 to \$3.00/ million Btu (\$2.61 to \$2.84 per gigajoule).

The future trend of the CPI (as it might correlate to investment costs) is difficult, if not impossible, to predict. Discussions with BLS personnel disclosed that the Bureau makes no such projections. The trend will, as a minimum, be impacted by future energy costs. (Indeed, Michael Spicer, Managing Director of The Economic Models Group, was quoted in the aforementioned Los Angeles Times as stating that "...a 25% rise in oil prices would increase the U.S. inflation rate from its current level of 5.5% a year to 7.5%.") The parametric range of 5 to 11% for consideration in the previous section of cost escalation rates, therefore, appears justified.

APPENDIX D

REFERENCES

- D-1. J. W. Doane, et al. , "The Cost of Energy From Utility-Owned Solar Electric System," Jet Propulsion Laboratory, Pasadena, California Report JPL 5040-29, ERDA/JPL01012-76/3
- D-2. J. M. Hoerner, Jr. , "Nomograph Updates Process Equipment Costs," Chemical Engineering, p 141, May 24, 1976