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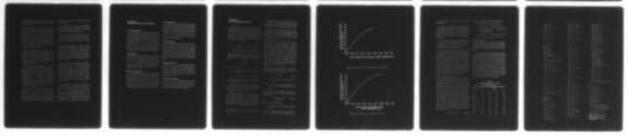

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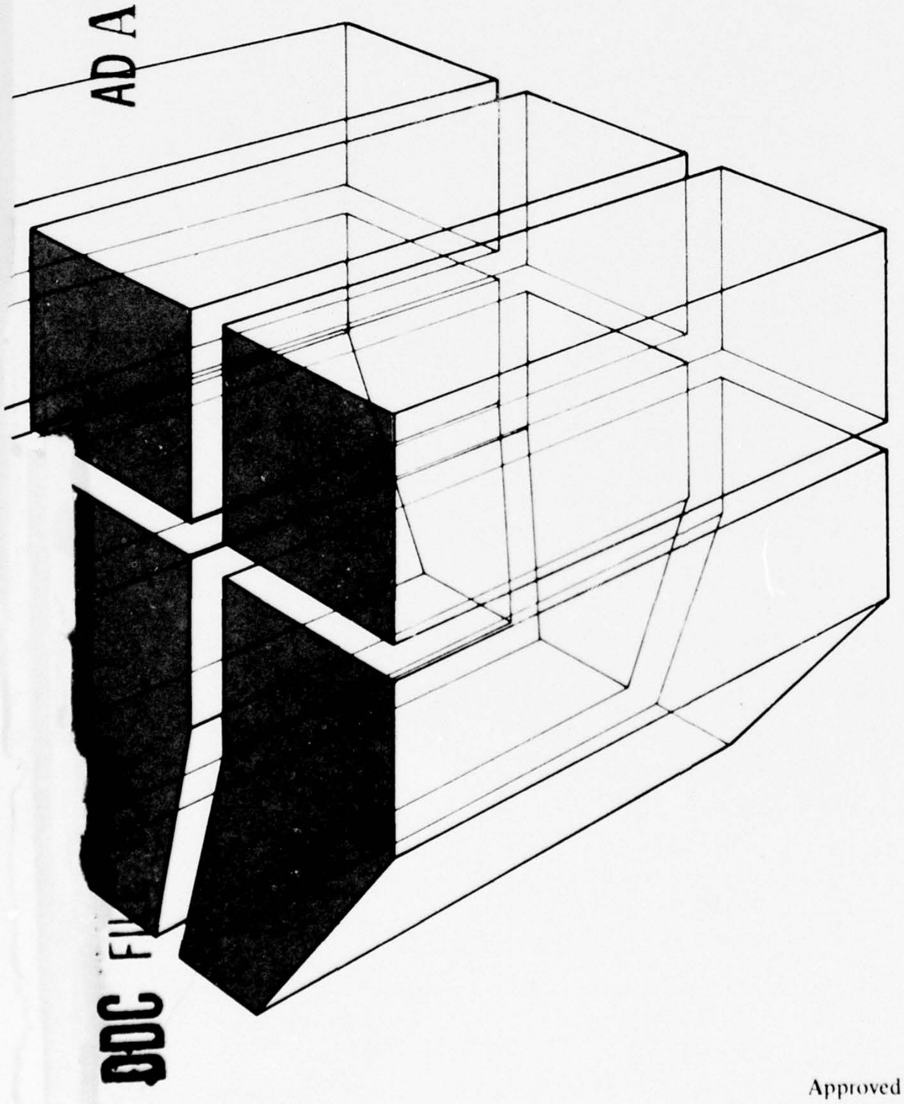
MARKET EVALUATION STUDY: SOLAR HEATING AND DOMESTIC HOT WATER HEATING IN DOD BUILDINGS



by
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This study assesses the potential market for combined solar space heating and domestic hot water heating in Department of Defense (DOD) buildings. The study considers eight building categories: family housing, bachelor enlisted quarters, bachelor officers' quarters, administration, training, operational, community support, and recreational, which together contain 683 million sq ft (61.5 million m^2), or 40 percent of the DOD inventory. All buildings were assumed to be oil heated. NEXT Page

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The buildings were grouped by climatological/solar regions, and the loads for each building type were determined by using the Energy Utilization Index (EUI) method. Solar system performance in each region was obtained by using the U.S. Army Construction Engineering Research Laboratory universal curve method. The life-cycle costs of providing solar space heating and domestic hot water heating were analyzed, and the DOD market potential for installed solar system costs of \$9, \$15, and \$20 per square foot were determined.

The study shows that at an estimated initial fuel cost of \$3.50 per MBtu for oil heating, a 10 percent cost of money, and an 8.5 percent overall fuel inflation factor, solar systems for space heating and domestic hot water heating become economically feasible when installed system costs are \$14/sq ft (\$150/m^2). When installed system costs reach \$9/sq ft (\$97/m^2), the market potential becomes 172 million sq ft (15.5 million m^2) of solar collectors. The study also shows the largest potential market at these economic conditions to be family housing, which contains a total of 102 million sq ft (9.2 million m^2). M SQ.

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FOREWORD

This study was performed for the Federal Energy Administration (FEA) under Project Order No. CG-05-50083-00(1). Mr. Alex Haynes, FEA Solar Energy Division, was the FEA government technical representative.

The research was performed by the Energy Systems Branch (EPE), Energy and Power Division (EP), U. S. Army Construction Engineering Research Laboratory (CERL).

Appreciation is expressed to Dr. D. M. Joncich (CERL) for deriving many of the mathematical expressions used in this study, and Mr. A. Mech (CERL) for assistance in computational analysis.

Dr. D. J. Leverenz is Chief of EPE, and Mr. R. G. Donaghy is Chief of EP. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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MARKET EVALUATION STUDY: SOLAR HEATING AND DOMESTIC HOT WATER HEATING IN DOD BUILDINGS

1 INTRODUCTION

Background and Problem Statement

Like all energy users, the Federal government is faced with rapidly increasing energy costs and, in some locations, shortage or curtailment of its energy supplies. It is therefore searching for a new and abundant natural energy source. Solar energy may be ideal due to its abundance, widespread distribution, and absence of recurring fuel cost.

The technical feasibility of using solar energy gathered by flat-plate collectors for hot water and space heating has been established both in theory and practice.[1] Although [illegible] design phase is somewhat more complex, [illegible] installation phase requires little more skill than [illegible] required to install conventional systems. Thus, the major consideration in solar system application is economics.

The high initial cost of solar system components is the major barrier to economical use of large-scale solar system application. Initial cost is high because most solar system components are now practically handbuilt. The market demand for these systems has not been large enough to encourage the capital expenditures necessary to promote full application of automated production techniques, which can significantly reduce the cost of solar components.

Since solar energy could be important in fulfilling future energy needs of the United States, the Federal Energy Administration (FEA) is developing a comprehensive program[2] which will provide a substantial initial solar component demand through applications on Federally owned buildings. This demand is expected to encourage the use of automated production techniques, thereby lowering the first cost of solar components.

Since the Department of Defense (DOD) owns approximately 80 percent of the buildings controlled by the Federal government, it is the greatest single potential government user of solar systems. As a first step in determining the overall DOD market, the market potential for solar domestic hot water heating in DOD bachelor enlisted and bachelor officer quarters (barracks) was examined, since it appeared to provide a significant trial for solar systems.[3] Based on the results of that study, the program was expanded to include space heating in barracks and other DOD buildings.

Objective

The objective of this project was to assess the market potential for solar space heating and solar domestic water heaters in DOD buildings by determining the number of solar collectors which could be economically installed in the buildings, based on several estimated installed system life-cycle costs.

Approach

A real property inventory of DOD buildings within the United States was performed to determine the total floor area of buildings which could be potential candidates for solar heating and solar domestic hot water heating systems. The heating load and domestic hot water load for each selected building type was then determined for four different climatic regions. The portion of the load that could be satisfied by using solar energy was determined for each climatic region; then the most economical collector area per square foot of building area was found by performing a life-cycle cost analysis for various solar system costs. The overall market potential was determined for each region and summed for the entire United States.

Chapter 2 describes the analysis methods used to determine the building inventory and building loads and to perform the solar system simulation and economic evaluation. Chapter 3 describes the findings and shows the tabulated results. Chapter 4 gives the conclusions drawn from the results. Detailed descriptions of the building load determination and solar simulation techniques are provided in the appendices.

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[1] J. A. Duffie and W. A. Bechman, *Solar Energy Thermal Processes* (Wiley, 1974).

[2] *Solar Energy Government Buildings Program, Policy and Implementation Plan* (The Mitre Corporation, January 1977).

[3] L. M. Windingland, G. N. Walton, and D. C. Hittle, *Market Potential Study: Solar Domestic Water Heaters in DOD Barracks*, Technical Report E-102/ADA036479 (U. S. Army Construction Engineering Research Laboratory [CERL], February 1977).

2 METHOD OF ANALYSIS

Building Inventory

The 1.8 billion sq ft (162 million m^2) of DOD buildings in the United States offers great potential for solar energy application. The Army, Air Force, and Navy (Marine Corps property is included in Navy property) maintain computerized real property inventory data bases which list buildings by category, location, date acquired, number of square feet, type of construction, and, in the case of living quarters, number of persons per building. Analysis of the various building category codes showed more than 40 different building categories; of these, eight were chosen for their potential use of solar energy for combined space heating and hot water heating.

The building types selected, which represent more than 50 percent of the DOD inventory, are: family housing, bachelor enlisted quarters, bachelor officers' quarters, administrative buildings, training buildings, operation buildings, community support buildings, and recreational buildings. These types of buildings are also potential solar users in civilian applications.[4]

The Directorates of Real Property of the Army, Air Force, and Navy provided specialized inventories for buildings in each category whose permanent construction was less than 20 years old. This was done to eliminate buildings that might not be amenable to solar heating equipment because of structural inadequacy or a decreased economically useful life. These limitations restricted the study to approximately 40 percent of the total DOD building inventory. The Army, Air Force, and Navy inventories reported the area of each building category; these areas were summed to obtain the DOD total area for each selected building type.

The United States was then segmented into four general climatic/solar insolation regions, whose boundaries were the state lines as shown in Figure 1. These regions were selected along average solar radiation intensity lines. One city was selected in each region whose climatic conditions were typical of that region; the solar and climatological data were then obtained for that city.

Load Determination

The heating load of each building was analyzed to determine the performance of solar energy heating systems. Since actual measured heating and hot water load data for the eight building types were not available for this project, the Energy Utilization Index (EUI)[5] was used to predict these energy requirements. EUI is a manual computational method specifically designed to analyze the heating and cooling energy requirements of Army buildings. Appendix A provides a brief description of the EUI method, which uses a variety of physical building data and specific meteorological data to determine the monthly and annual building heating loads. The pertinent data required for the EUI are:

1. Monthly heating degree days*[6]
2. Incident solar radiation per month*[7]
3. Monthly average wind velocity*[8]
4. Exterior walls, roof and floor composition and area
5. Window and glass area
6. Number of doors and windows
7. Underground floor and wall composition
8. Inside set-point temperature
9. Mechanical ventilation rate
10. Occupancy levels
11. Boiler/furnace efficiency.

This information was supplied for each building type so a monthly load determination per square foot of building could be calculated. Monthly building loads were required for the solar simulation techniques used in this study.

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[4] *Solar Energy Government Buildings Program, Policy and Implementation Plan* (The Mitre Corporation, January 1977).

[5] L. M. Windingland and D. C. Hittle, *Energy Utilization Index Method for Predicting Building Energy Use*, Technical Report E-105 (CERL, May 1977).

*Data are for the four climatic regions indicated in Figure 1.

[6] *Climatic Atlas of the United States* (U. S. Department of Commerce, 1968).

[7] *Climatic Atlas of the United States* (U. S. Department of Commerce, 1968).

[8] *Engineering Weather Data*, AFM 88-8, Chapter 6 (Department of the Air Force, 15 June 1967).

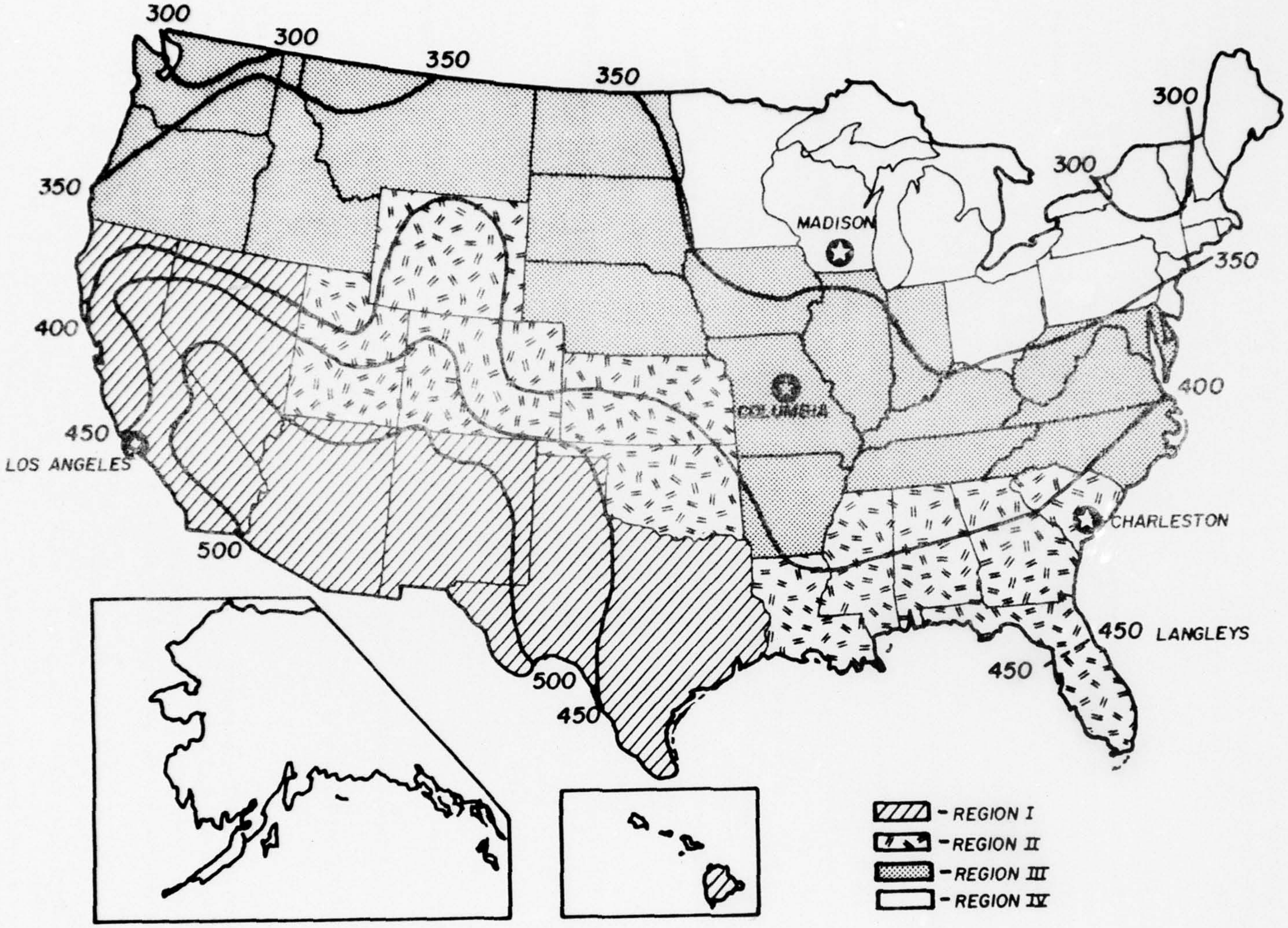

Figure 1. Solar insolation and climatic regions.

Note: lines indicate average annual mean daily solar radiation in langleys.

A typical building in each category group was selected on which to base the heating loads analysis; Appendix B describes buildings selected. These buildings are typical of many structures throughout the DOD and should exhibit a reasonable average of heating load per unit area.

Solar System Performance

The performance of a solar system in meeting the loads was determined by using a manual method developed by CERL that computes the percentage of the load met by solar energy for various collector areas. This method (see Appendix C) is based on the fact that, with proper normalization for load size and local solar insolation, the performance of a given solar system for a given building in any location can be represented by a universal performance curve.[9] Its development was based on established technology and calculation methods and provides sufficient accuracy for feasibility studies. The universal curve assumes use of a single, glazed, selective-surface, flat-plate, water collector. (The collector areas given in this report are for this type of collector.) Figure 2 shows the universal curve for space heating, which was used to determine the amount of load that could be satisfied by solar energy. Use of this curve requires calculation of building energy loads and compilation of on-site weather data. Using this information, the curve relates solar system performance to the collector area. This curve (shown in Appendix C) can be represented by a general equation:

$$\rho = aP_s + bP_s^2 \qquad \text{[Eq 1]}$$

where a and b = constants

ρ = percent load satisfied by solar

P_s = (collector area × solar insolation)/building load.

Economic Analysis

The method used to define the optimal collector area for each building type in each region analytically compares the capital costs involved in solar system acquisition and installation with the present worth of the fuel saved by using a solar system. The Office of the Chief of Engineers' (OCE) life-cycle costing (LCC) instructions[10] were combined with the building loads, conventional system efficiencies, solar insolation values, and collector areas to derive a closed-form equation (Eq 12) that could be used to determine the economically optimum collector areas for each building type in each region.

The net life-cycle cost is defined as the difference between capital costs (CC) for solar system acquisition and the present worth (PWC_s) of fuel saved by using the solar system, as shown in Eq 2.

$$LCC = CC - PWC_s \qquad \text{[Eq 2]}$$

In this study, capital cost is assumed to include all equipment costs, installation costs, and the present worth cost of operation and maintenance. It is assumed that these costs vary directly with collector areas, as shown in Eq 3.

$$CC = YBA_c \qquad \text{[Eq 3]}$$

where B = the solar system cost per sq ft of collector

A_c = the collector area

Y = a factor which reflects the current DOD time value of money.

Y can be determined using Eq 4:

$$Y = \frac{i(1+i)^n n}{(1+i)^{n}-1} \qquad \text{[Eq 4]}$$

where i = DOD time value of money

n = facility life (years).

The capital cost represents money spent for the solar system which is in excess of costs associated with the conventional heating; the conventional system is assumed to be auxiliary to the solar system.

The present worth of fuel saved by the solar system is given in Eq 5.

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[9] D. Hittle, D. Holshouser, and G. Walton, *Interim Feasibility Assessment Method for Solar Heating and Cooling of Army Buildings*, Technical Report E-91/ADA026588 (CERL, May 1976) and D. Hittle, G. Walton, D. Holshouser, and D. Leverenz, *Predicting the Performance of Solar Energy System Simulation*, Interim Report E-98/ADA035608 (CERL, January 1977).

[10] *OCE Life Cycle Costing Instructions* (Department of the Army, May 1971).

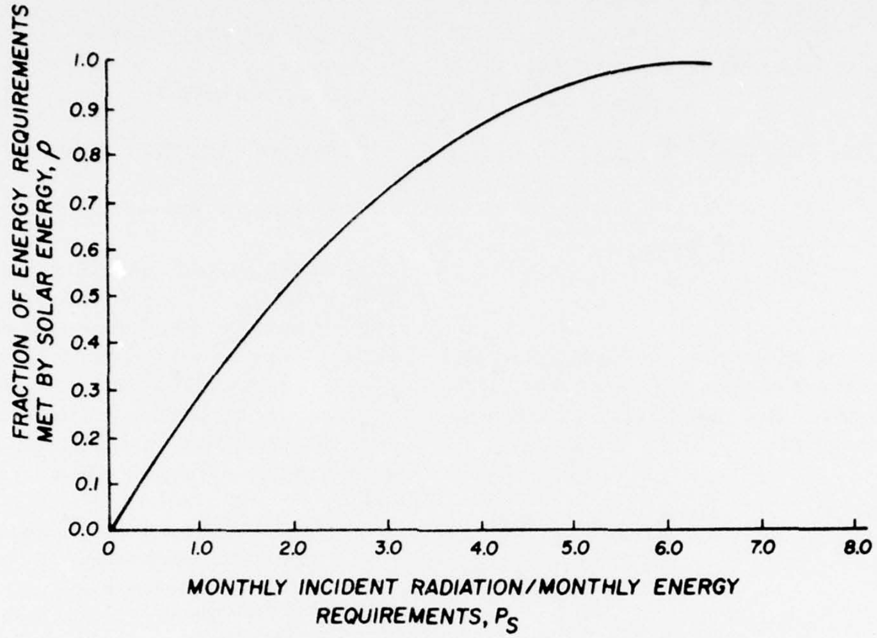

Figure 2. Universal curve for solar heating systems.

$$PWC_s = \frac{MD}{n} \sum_{m} \rho_m Q_{Lm} \qquad \text{[Eq 5]}$$

where ρ_m = the monthly percent of load met by solar as given in Eq 1

D = the cost of energy/Btu

n = the efficiency of the conventional heating system

Q_{Lm} = the monthly heating load

M = a factor which reflects the overall cost of fuel at a specific inflation rate over the facility life.

M is given in Eq 6.

$$M = \frac{(1 + i)^n - 1}{1} \qquad \text{[Eq 6]}$$

where i = the overall inflation rate of fuel

n = the number of years.

The universal curve presented in the solar simulation section is described in Eq 7:

$$\rho_m = aP_{sm} + bP_{sm}^2 \qquad \text{[Eq 7]}$$

where a, b = constant derived from the universal curve

ρ_m = the Y value determined on a monthly basis

$$P_{sm} = \frac{A_c Q_{cm}}{Q_{Lm}} \qquad \text{[Eq 8]}$$

where Q_{cm} = monthly solar radiation energy on the collector

Q_{Lm} = monthly energy requirements

P_{sm} = the X value given on a monthly basis.

Inserting Eq 7 into Eq 5 yields Eq 9:

$$PWC_s = \frac{MD}{n} \sum_m (aP_{sm} + bP^2_{sm})\, Q_{Lm} \qquad \text{[Eq 9]}$$

Substituting for P_{sm} from Eq 8 and CC from Eq 3 yields Eq 10:

$$LCC = YBA_c - \frac{aMD}{n} \sum_m A_c Q_{cm} - \frac{bMD}{n} \sum_m \frac{A_c{}^2 Q^2_{cm}}{Q_{Lm}} \qquad \text{[Eq 10]}$$

Savings are maximized when the slope of the LCC curve is zero. This is obtained by differentiating Eq 10 with respect to collector area and setting it equal to zero, as shown in Eq 11:

$$\frac{dLCC}{dA_c} = YB - \frac{aMD}{n} \sum_m Q_{cm} - \frac{2bMD}{n} \sum_m \frac{Q^2{}_{cm}}{Q_{Lm}} A_c = 0 \qquad \text{[Eq 11]}$$

The normalized area where this occurs is obtained by solving for A_c and is given by Eq 12:

$$A_{c/\text{optimum}} = \frac{nYB - aMD \sum_m Q_{cm}}{2bMD \sum_m \left(\frac{Q_{cm}{}^2}{Q_{Lm}} \right)} \qquad \text{[Eq 12]}$$

Eq 12 can be substituted into Eq 10 to determine the life cycle cost at the optimum collector area. The value obtained for the life-cycle cost represents the savings of a solar energy system only if it is negative, i.e., the money saved over the facility life exceeds the additional money spent for the solar equipment.

Figure 3 shows the life cycle cost of solar systems versus collector area based on the above formulae. The lowest point on the curve represents the collector area which maximizes the dollar savings $A_{c_{opt}}$, as given in Eq 12. The crossover point represents the collector area which maximizes the fuel savings at zero dollar payback.

The following information is required in order to use Eqs 10 and 12 to determine solar system economic feasibility:

1. Installed solar system component costs
2. DOD time value of money
3. Present cost of fuel
4. Projected fuel inflation rates
5. Efficiency of conventional heating system.

This study was performed for various values of solar system costs. The Federal Energy Administration's proposed installed solar system costs of \$9, \$15, and \$20 per square foot were used. These costs include the collectors, pumps, piping, heat exchangers, storage, and controls. Annual operating and maintenance costs are assumed to be offset by the reduced cost of maintaining the conventional heating system.

The DOD time value of money assumed in this study was 10 percent* (a comparison of data for a 6.5 percent DOD time value of money is included in Chapter 3); this assumes that the money could be invested at these rates and therefore requires solar systems to achieve that rate of return.

When the cost data have been determined, it is necessary to establish the life-cycle cost for the fuel used by the conventional system and for the fuel saved by using solar energy for a portion of the building load based on the estimated solar system performance. The present fuel cost used in this analysis was \$3.50 per million Btus, which is comparable to approximately \$.50/gallon of No. 2 fuel oil.

The fuel cost differences associated with the conventional system building loads and solar system contributions were determined, and fuel inflation rates (including general inflation) of 10 percent and 8.5 percent for the 20-year system life were applied.

3 FINDINGS

Building Inventory

Building inventory data were obtained by state, and solar radiation and climatic data for building load

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*Generally, the Office of Management and Budget also requires the use of 10 percent real rate of discount for the evaluation of government investment projects.

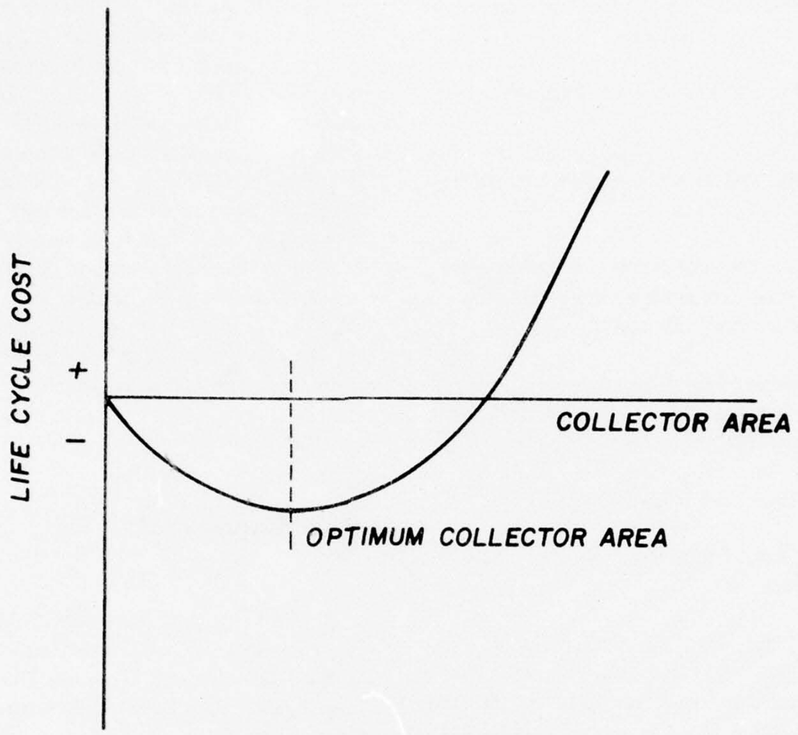

Figure 3. Life cycle cost vs. collector area.

determination were obtained for four cities representative of each climatic region (Figure 1).

The area of each building category in each region was determined by summing individual state inventories (see Table 1). The table shows that approximately 700 million sq ft (63 million m^2) of DOD buildings (40 percent of total DOD inventory) have been considered in this report. It was not possible to determine either the actual roof area available for mounting a solar system or the building orientation from these inventories. It was therefore assumed that if a building did not have the proper roof area or orientation, portions of the solar system could be installed at ground level.

Load Determination

The monthly building heating loads for the eight building types were determined for the four solar insolation/climatic regions by the EUI method.

The monthly loads were then normalized by dividing the load by floor area of the considered building (see Tables 2, 3, 4, and 5). The tables show the monthly heating and domestic hot water heating load for each building type in thousands of Btus per square foot of building area. The building's normalized loads were then multiplied by the total area of buildings of that type. Table 6 shows the total estimated loads by region and building type.

These tables show only average regional figures based on the particular structure that was analyzed and do not represent actual building loads for all locations in the region.

Economic Analysis

Since the building inventories did not include the number of buildings, but rather the total area of each building type, building loads were normalized to square foot of floor area. Similarly, the optimum solar collector area was calculated on a per square foot of building basis for each region, using Eqs 10 and 12. Tables 7 through 10 give results of these calculations; these tables represent optimum collector area only for the four cities studied. These collector areas were used as averages for the building types studied for each region to determine the potential market.

The assumptions and factors used to calculate these tables were:

1. Installed solar system costs can be described on a basis of square foot of collector.

2. Building loads for each region are based on average climatic and solar data from a specific city, and are used as an average for the entire region.

3. Buildings selected for load determination are representative and can be expected to exhibit loads which are average for most buildings of that type.

4. Initial fuel costs are \$3.50 per MBtu.

5. Total inflation rates used in the study were 10 percent and 8.5 percent.

Based on a 10 percent DOD cost of money and a fuel inflation rate of 8.5 percent, Table 7 shows that a solar collector area is not optimum until the installed system cost approaches \$9/sq ft. As the economic assumptions become less stringent (Tables 8, 9, and 10), the optimum collector area increases for the three system costs, and solar system applications become feasible at higher installed system costs. In addition, the tables also show that solar system cost-effectiveness is extremely sensitive to both the time value of money and the predicted fuel inflation rates.

The cost of installed solar systems required to produce cost-effective solar utilization was determined by setting Eq 11 to zero and solving for B (installed system cost). Table 11 gives the results of this calculation. The installed solar heating system becomes cost-effective when the price reaches the value shown in the table. These values are considerably lower than current costs for installed solar systems.

Market Potential

The market potential for solar heating system utilization was determined for each region by multiplying the optimum collector areas by the regional area (in square feet) of the building type being considered. Tables 12 through 14 show the sensitivity of the market potential for three system costs for one economic scenario (i.e., 10 percent DOD time value of money and 10 percent total fuel inflation rate). Tables 15 through 20 show the market potential for variations of the DOD time value of money and total fuel inflation. The regions of greatest market potential for solar systems fluctuate based on installed system cost. This is due to the various insolation and building load ratios which determine the amount of fuel that can be saved. The tables show that a significant market potential for solar heating and hot water systems does not occur until the installed system costs decline to less than \$20/sq ft (\$215/m^2). Table 21 shows the total market potential for the eight building categories for each of the four economic condition scenarios.

4 CONCLUSIONS

The building types included in this study consisted of 683 million sq ft (61.5 million m^2), or 40 percent of the DOD building inventory. The annual estimated space-heating and domestic hot water load for these buildings is 103×10^{12} Btus, which is equivalent to \$360 million of \$.50/gal heating oil.

Family housing, by virtue of its large area (319 million sq ft [23.7 million m^2]), consumes more than 40 percent of the estimated DOD space-heating and domestic hot water load of the buildings studied in each region.

For the FEA-recommended economic parameters (i.e., 10 percent time value of money and 8.5 percent total fuel inflation rate), solar space heating and hot water heating is not economical in comparison to oil heat until total installed solar system costs become \$14/sq ft (\$150/m^2). When installed system costs reach \$9/sq ft, the potential market becomes 172 million sq ft (15.5 million m^2) of solar collectors.

For all economic scenarios considered, family housing provides the largest single market potential for solar space heating and domestic hot water heating. At the recommended economic parameters, this market potential becomes 102 million sq ft at \$9/sq ft (10.2 million m^2 at \$97/m^2).

Table 1
Building Area for Each
Insolation/Climatological Region (Sq Ft × 10^6)

Building Type	Region I	II	III	IV	Total
Family Housing	78.0	85.3	78.6	77.4	319.3
Bachelor Enlisted Quarters (BEQ)	34.8	34.0	28.9	25.3	123.0
Bachelor Officers' Quarters (BOQ)	5.2	7.4	4.5	4.1	21.2
Administration Building	14.3	13.5	20.3	24.1	72.2
Training	4.0	6.0	6.6	9.8	26.4
Operational	11.5	13.8	12.7	14.4	52.4
Community Support	1.9	2.1	2.1	2.4	8.5
Recreational	16.1	16.4	13.2	15.2	60.9
Total	165.8	178.5	166.9	172.7	683.9

(SI Conversion Factor: 1 sq ft = .09 m^2

Table 2
Region I (Los Angeles, CA)
Estimated Heating Load per Building
(kBtu/Sq Ft)

Month Bldg. Type	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Administration	2.77	4.30	10.02	16.28	19.41	16.35	16.10	10.75	7.56	101.54
BEQ	3.22	3.77	5.21	7.02	7.97	7.01	7.30	5.84	4.81	49.19
BOQ	1.83	2.41	4.01	5.91	6.91	5.90	6.19	4.66	3.56	41.38
Operations	2.66	4.15	10.09	15.77	18.77	15.83	15.57	10.38	7.29	100.11
Training	2.56	4.01	9.35	15.27	18.14	15.31	15.08	10.02	7.03	96.77
Family Housing	2.11	2.57	5.03	8.62	10.70	8.50	9.01	6.19	4.28	57.01
Support	0.10	0.10	0.10	0.24	0.46	0.12	0.10	0.10	0.10	0.63
Recreation	1.62	2.01	3.94	6.33	7.68	6.36	5.88	4.22	2.80	40.85

(SI Conversion Factors: 1 sq ft = .09 m^2
1 kBtu = 1.055 J × 10^3)

Table 3
Region II (Charleston, SC)
Estimated Heating Load per Building
(kBtu/Sq Ft)

Month / Bldg. Type	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Administration	0.24	4.50	17.30	27.14	27.95	23.71	18.72	4.31	0.24	124.11
BEQ	2.87	4.37	7.93	11.69	11.91	10.77	9.02	4.27	2.87	65.70
BOQ	1.37	3.00	6.79	10.65	10.87	9.71	7.92	2.90	1.37	54.58
Operations	0.24	4.34	16.77	26.29	27.09	23.04	18.20	4.15	0.24	120.36
Training	0.25	4.19	16.26	25.46	26.24	22.37	17.68	4.01	0.25	116.71
Family Housing	2.11	3.05	10.04	10.37	16.57	13.89	11.34	2.93	2.11	72.41
Support	0.10	0.10	0.71	2.04	2.09	1.51	1.11	0.10	0.10	7.76
Recreation	0.95	2.19	6.96	10.99	11.30	9.29	7.32	2.25	0.95	52.20

(SI Conversion Factors: 1 sq ft = .09 m^2
1 kBtu = 1.055 J × 10^3)

Table 4
Region III (Columbia, MO)
Estimated Heating Load per Building
(kBtu/Sq Ft)

Month / Bldg. Type	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Administration	3.51	14.57	35.68	51.00	58.02	46.35	41.13	20.17	8.32	278.75
BEQ	3.60	7.22	15.22	20.99	23.56	19.21	18.82	9.66	5.33	123.61
BOQ	2.21	6.07	14.24	20.02	22.60	18.23	17.84	8.57	4.06	113.84
Operations	3.38	14.14	34.58	49.56	56.49	44.97	40.03	19.62	8.06	268.81
Training	3.27	13.72	33.49	48.12	54.97	43.60	38.74	19.08	7.82	262.81
Family Housing	2.11	8.66	21.36	30.69	34.55	27.64	25.67	12.28	4.80	167.76
Support	0.10	0.56	3.53	6.84	8.22	6.62	4.34	1.54	0.10	31.86
Recreation	2.05	5.84	14.73	22.24	25.88	23.03	16.43	8.03	3.44	121.37

(SI Conversion Factors: 1 sq ft = .09 m^2
1 kBtu = 1.055 J × 10^3)

Table 5
Region IV (Madison, WI)
Estimated Heating Load per Building
(kBtu/Sq Ft)

Month Bldg. Type	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Administration	12.06	28.20	54.05	75.38	83.33	74.17	64.30	38.16	20.43	450.08
BEQ	6.16	12.37	22.90	29.66	34.81	30.65	26.67	17.29	9.72	190.23
BOQ	4.98	11.33	21.93	28.70	33.87	29.70	25.71	16.30	8.63	181.15
Operations	11.71	27.34	52.58	73.75	81.65	72.51	62.70	37.06	19.84	439.14
Training	11.36	26.49	51.12	72.12	79.97	70.86	61.10	35.97	19.26	428.25
Family Housing	6.62	16.97	32.98	44.72	51.09	43.97	38.60	23.25	11.32	269.52
Support	0.37	1.88	7.33	11.96	13.34	11.25	9.25	4.03	0.65	60.06
Recreation	4.87	10.94	21.80	34.19	37.74	32.69	27.86	15.18	7.40	192.67

(SI Conversion Factors: 1 sq ft = .09 m^2
1 kBtu = 1.055 J × 10^3)

Table 6
Total Estimated Heating Load by Building Category
Btu × 10^{12}

	Region				
Building Type	I	II	III	IV	Total
Family Housing	4.4	6.1	13.2	20.8	44.5
BEQ	1.7	2.2	3.6	4.8	12.3
BOQ	0.2	0.4	0.5	0.7	1.8
Administration	1.5	1.7	5.7	10.3	19.2
Training	0.4	0.7	1.7	4.2	7.0
Operations	1.2	1.7	3.4	6.3	12.6
Support	–	–	–	0.1	0.1
Recreational	0.6	0.9	1.6	2.9	6.0
Total	10.0	13.7	29.7	50.1	103.5

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 7
Optimum Collector Area Per Square Foot of Building Area

Region	I			II			III			IV		
Building Type	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**
Administration	0.260	*		0.175			0.479			0.618		
BEQ	0.183	–	–	0.128	–	–	0.331	–	–	0.286	–	–
BOQ	0.142	–	–	0.098	–	–	0.249	–	–	0.254	–	–
Operations	0.250	–	–	0.169	–	–	0.463	–	–	0.598	–	–
Training	0.242	–	–	0.163	–	–	0.449	–	–	0.580	–	–
Family Housing	0.133	–	–	0.113	–	–	0.282	–	–	0.354	–	–
Support	0.017	–	–	–	–	–	0.025	–	–	0.028	–	–
Recreation	0.118	–	–	0.082	–	–	0.234	–	–	0.246	–	–

Time Value of Money = 10%, Fuel Inflation Rate = 8.5%

*The values obtained were negative, indicating that the solar system was not cost effective.

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 8
Optimum Collector Area Per Square Foot of Building Area

Region	I			II			III			IV		
Building Type	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**
Administration	0.414	0.213	0.045	0.456	0.089	–*	0.805	0.380	0.026	1.000	0.206	–
BEQ	0.292	0.150	0.032	0.334	0.065	–	0.557	0.263	0.018	0.913	0.095	–
BOQ	0.226	0.117	0.025	0.256	0.050	–	0.418	0.197	0.014	0.810	0.085	–
Operations	0.400	0.206	0.044	0.441	0.086	–	0.778	0.367	0.025	1.000	0.199	–
Training	0.385	0.199	0.042	0.426	0.083	–	0.754	0.356	0.024	1.000	0.193	–
Family Housing	0.251	0.097	–	0.295	0.058	–	0.474	0.224	0.015	1.000	0.118	–
Support	0.031	0.012	–	0.028	–	–	0.089	.006	–	0.089	0.009	–
Recreation	0.188	0.097	0.021	0.214	0.042	–	0.392	0.185	0.013	0.784	0.082	–

Time Value of Money = 10%, Fuel Inflation Rate = 10%

*The values obtained were negative, indicating that the solar system was not cost effective.

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 9
Optimum Collector Area Per Square Foot of Building Area

Region	I			II			III			IV		
Building Type	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**
Administration	0.365	0.131	–*	0.336	–	–	0.701	0.206	–	1.00	–	–
BEQ	0.257	0.092	–	0.268	–	–	0.485	0.143	–	0.712	–	–
BOQ	0.199	0.072	–	0.205	–	–	0.364	0.107	)	0.638	–	–
Operations	0.352	0.126	–	0.353	–	–	0.667	0.199	–	1.00	–	–
Training	0.339	0.122	–	0.342	–	–	0.656	0.193	–	1.00	–	–
Family Housing	0.213	0.034	–	0.237	–	–	0.413	0.121	–	0.880	–	–
Support	0.027	0.004	–	0.011	–	–	0.069	–	–	0.070	–	–
Recreation	0.166	0.060	–	0.171	–	–	0.342	0.100	–	0.612	–	–

Time Value of Money = 6.5%, Fuel Inflation Rate = 8.5%

*The values obtained were negative, indicating that the solar system was not cost effective.

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 10
Optimum Collector Area Per Square Foot of Building Area

Region	I			II			III			IV		
Building Type	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**	**9**	**15**	**20**
Administration	0.484	0.329	0.200	0.583	0.300	0.065	0.952	0.624	0.352	1.00	1.00	0.087
BEQ	0.341	0.232	0.141	0.427	0.220	0.047	0.658	0.432	0.243	1.00	0.565	0.040
BOQ	0.264	0.180	0.109	0.327	0.168	0.036	0.494	0.324	0.183	1.00	0.501	0.036
Operations	0.467	0.317	0.192	0.563	0.290	0.062	0.920	0.603	0.340	1.00	1.00	0.084
Training	0.450	0.306	0.186	0.544	0.280	0.060	0.891	0.585	0.329	1.00	1.00	0.082
Family Housing	0.304	0.186	0.087	0.377	0.194	0.042	0.561	0.368	0.207	1.00	0.699	0.050
Support	0.038	0.023	0.011	0.052	–	–	0.118	0.054	–	0.117	0.055	0.004
Recreation	0.220	0.150	0.091	0.273	0.141	0.030	0.464	0.304	0.171	1.00	0.485	0.035

Time Value of Money = 6.5%, Fuel Inflation Rate = 10%

*The values obtained were negative, indicating that the solar system was not cost effective.

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 11
Solar System Cost Required for Maximum Dollar Savings*

Time Value of Money/ Fuel Inflation Rate	Region I	Region II	Region III	Region V
10%/8.5%	$14.20	$10.90	$11.70	$10.40
10%/10%	$21.40	$16.50	$17.70	$15.70
6.5%/8.5%	$18.40	$14.20	$15.20	$13.60
6.5%/10%	$27.80	$21.40	$23.00	$20.40

*Based on collector area that optimizes use of solar energy for heating and domestic hot water heating.

Table 12
Potential Market*–$9/Sq Ft
Sq Ft × 10^6

	Region				
Building Type	**I**	**II**	**III**	**IV**	**Total**
Family Housing	19.6	25.2	37.3	87.4	169.5
BEQ	10.1	11.3	16.1	23.1	60.5
BOQ	1.2	1.9	1.9	3.3	8.3
Administration	5.9	6.2	16.3	47.5	75.9
Training	1.5	2.5	5.0	18.1	27.1
Operations	4.6	6.1	9.9	27.6	48.2
Support	0.1	0.1	0.2	0.2	0.6
Recreational	3.0	3.5	5.2	11.9	23.6
Total	46.0	56.8	91.9	219.1	413.8

*DOD Time Value of Money = 10%

Total Fuel Inflation = 10%

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 13
Potential Market*–$15/Sq Ft
Sq Ft × 10^6

	Region				
Building Type	**I**	**II**	**III**	**IV**	**Total**
Family Housing	7.6	4.9	17.5	9.1	39.1
BEQ	5.2	2.2	7.6	2.4	17.4
BOQ	0.6	0.4	0.9	0.3	2.2
Administration	3.0	1.2	7.7	5.0	16.9
Training	0.8	0.5	2.4	1.9	5.6
Operations	2.4	1.2	4.6	2.9	11.1
Support	–	–	–	–	–
Recreational	1.5	0.7	2.4	1.2	5.8
Total	12.1	11.1	43.1	22.8	98.1

*DOD Time Value of Money = 10%

Total Fuel Inflation = 10%

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 14
Potential Market*–$20/Sq Ft
Sq Ft × 10^6

	Region				
Building Type	**I**	**II**	**III**	**IV**	**Total**
Family Housing	–	–	1.2	–	1.2
BEQ	0	–	0.5	–	0.6
BOQ	0.1	–	0.1	–	0.2
Administration	0.6	–	0.5	–	1.1
Training	0.2	–	0.2	–	0.4
Operations	0.5	–	0.3	–	0.8
Support	–	–	–	–	–
Recreational	0.4	–	0.2	–	0.6
Total	1.9	–	3.0	–	4.9

*DOD Time Value of Money = 10%

Total Fuel Inflation = 10%

(SI Conversion Factor: 1 sq ft = .09 m²)

Table 15
Potential Market*–$9/Sq Ft
Sq Ft × 10^6

	Region				
Building Type	**I**	**II**	**III**	**IV**	**Total**
Family Housing	23.7	32.2	44.0	114.3	214.2
BEQ	11.9	14.5	19.0	30.2	75.6
BOQ	1.4	2.4	2.2	4.4	10.4
Administration	6.9	7.9	19.3	62.2	96.2
Training	1.8	3.2	5.9	23.6	34.6
Operations	5.4	7.8	12.7	36.1	61.9
Support	0.1	0.1	0.2	0.3	0.7
Recreational	3.5	4.5	6.1	15.6	29.7
Total	54.7	72.6	109.4	286.7	523.4

*DOD Time Value of Money = 6.5%

Total Fuel Inflation = 10%

(SI Conversion Factor: 1 sq ft = .09 m²)

Table 16
Potential Market*–$15/Sq Ft
Sq Ft × 10^6

	Region				
Building Type	**I**	**II**	**III**	**IV**	**Total**
Family Housing	14.5	16.6	28.9	54.1	114.0
BEQ	8.1	7.5	12.5	14.3	42.3
BOQ	0.9	1.2	1.5	2.1	5.7
Administration	4.7	4.1	12.6	29.4	50.8
Training	1.2	1.7	3.9	11.2	18.0
Operations	3.6	4.0	7.6	17.1	32.3
Support	0.04	0.1	–	0.1	0.2
Recreational	2.4	2.3	4.0	7.4	16.1
Total	35.4	37.5	71.0	135.7	279.5

*DOD Time Value of Money = 6.5%

Total Fuel Inflation = 10%

(SI Conversion Factor: 1 sq ft = .09 m²)

Table 17
Potential Market*–$20/Sq Ft
Sq Ft × 10^6

	Region				
Building Type	**I**	**II**	**III**	**IV**	**Total**
Family Housing	6.8	3.6	16.3	3.8	30.5
BEQ	4.9	1.6	7.0	1.0	14.5
BOQ	0.6	0.3	0.8	0.1	1.8
Administration	2.8	0.9	7.1	2.1	12.9
Training	0.7	0.4	2.2	0.8	4.1
Operations	2.2	0.9	4.3	1.2	8.6
Support	–	–	–	–	0.0
Recreational	1.5	0.5	2.3	0.5	4.7
Total	19.5	8.2	40.0	9.5	77.1

*DOD Time Value of Money = 6.5%

Total Fuel Inflation = 10%

(SI Conversion Factor: 1 sq ft = .09 m²)

Table 18
Potential Market*–$9/Sq Ft
Sq Ft × 10^6

Building Type	I	II	III	IV	Total
			Region		
Family Housing	10.4	9.6	22.2	27.4	69.6
BEQ	6.4	4.4	9.6	7.2	27.6
BOQ	0.7	0.7	1.1	1.0	3.5
Administration	3.7	2.4	9.7	14.9	30.7
Training	1.0	1.0	3.0	5.7	10.7
Operations	2.9	2.3	5.9	8.6	19.7
Support	–	–	0.1	0.1	0.2
Recreational	1.9	1.3	3.1	3.7	10.0
Total	27.0	21.7	54.7	68.6	172.0

*DOD Time Value of Money = 10%

Total Fuel Inflation = 8.5%

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 19
Potential Market*–$9/Sq Ft
Sq Ft × 10^6

Building Type	I	II	III	IV	Total
			Region		
Family Housing	16.6	20.2	32.5	68.1	137.4
BEQ	8.9	9.1	14.0	18.0	50.0
BOQ	1.0	1.5	1.6	2.6	6.7
Administration	5.2	4.5	14.2	24.1	48.0
Training	1.4	2.1	4.3	9.8	17.6
Operations	4.0	4.9	8.5	14.4	31.8
Support	0.1	–	0.1	0.2	0.4
Recreational	2.7	2.8	4.5	9.3	19.3
Total	39.9	45.1	79.7	146.5	311.2

*DOD Time Value of Money = 6.5%

Total Fuel Inflation = 8.5%

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 20
Potential Market*–$15/Sq Ft
Sq Ft × 10^6

Building Type	I	II	III	IV	Total
			Region		
Family Housing	2.7	–	9.5	–	12.2
BEQ	3.2	–	4.1	–	7.3
BOQ	0.4	–	0.5	–	0.9
Administration	1.9	–	4.2	–	6.1
Training	0.5	–	1.3	–	1.8
Operations	1.5	–	2.5	–	4.0
Support	–	–	–	–	–
Recreational	1.0	–	1.3	–	2.3
Total	11.2	–	23.4	–	34.6

*DOD Time Value of Money = 6.5%

Total Fuel Inflation = 8.5%

(SI Conversion Factor: 1 sq ft = .09 m^2)

Table 21
Market Potential for Solar Heating and Hot Water
Sq Ft × 10^6

Time Value of Money	**10%**	**10 %**	**6.5%**	**6.5%**
Total Fuel Inflation	**10%**	**8.5%**	**10 %**	**8.5%**
Installed System Cost				
$ 9/Sq Ft	413	172	523	320
$15/Sq Ft	98	–	279	34
$20/Sq Ft	5	–	77	–

(SI Conversion Factor: 1 sq ft = .09 m^2)

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APPENDIX A: ENERGY UTILIZATION INDEX (EUI) METHOD

EUI is a manual computational method specifically designed to analyze the heating and cooling energy requirements of Army buildings. The method uses a variety of physical building data and specific meteorological data to determine the monthly and annual building heating loads. The pertinent data required to use this method are:

1. Monthly heating degree days
2. Incident solar radiation per month
3. Monthly average wind velocity
4. Exterior walls and roof composition and area
5. Window and glass area
6. Number of doors and windows
7. Underground floor and wall composition
8. Floor areas
9. Inside set-point temperature
10. Mechanical ventilation rate
11. Occupancy levels
12. Boiler/furnace efficiency.

The EUI method, developed from extensive computer simulations, disaggregates the total heating load into five individual load components:

1. QH_{ENV} = building envelope heating load
2. QH_{INF} = infiltration heating load
3. QH_{RAD} = solar radiation heat gain
4. QH_{FLOOR} = heating load due to underground floors and walls
5. QH_{INT} = internal heat gain.

The total monthly heating load, QH_{TOTAL}, is then determined by using Eq A1:

$$QH_{TOTAL} = QH_{ENV} + QH_{INF} - QH_{RAD} + QH_{FLOOR} - QH_{INT} \quad \text{[Eq A1]}$$

Values for separate equations for each factor in Eq A1 are obtained from building data, weather data, and tables and curves presented in the EUI method.

The heating load from conductive heat transfer through the building envelope, QH_{ENV}, is primarily a function of (1) the envelope area, (2) the conductance of envelope materials, (3) the inside temperature, and (4) the outside temperature.

The building envelope is defined as the total area of all building surfaces (walls, roofs, windows, floors, and doors) which are exposed to the outside air.

The conductance of envelope materials, or the building equivalent U-value, is the weighted average thermal conductance for the exposed building envelope area. This value is determined as follows:

1. The areas of each surface type are calculated.
2. Each surface is multiplied by its U-value from ASHRAE tables.[11]
3. The products of the structural envelope areas and U-value are summed and divided by the total envelope area to obtain the building envelope and equivalent U-value.

Each monthly heating load is determined by using the number of heating degree days (HDDs) per month. This load is then adjusted for buildings of different equivalent U-values by using a correlation factor provided in the EUI method which is based on envelope load variations with envelope equivalent conductances. In addition, correction for variations in envelope areas is made by using the ratio of the building envelope area to the EUI characteristic building envelope area. Finally, the envelope heating load is adjusted by using a correlation factor based on inside set-point temperatures.

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[11] *ASHRAE Handbook of Fundamentals* (American Society of Heating, Refrigerating, and Air Conditioning Engineers, 1972).

The infiltration load, QH_{INF}, is a function of the air change rate, outside weather conditions, and the inside set-point temperature.

In family housing, the infiltration is dominated mainly by wind velocity and factors such as door openings, furnace exhaust, and bathroom fan operation. The barracks and administration buildings are assumed to be pressurized and therefore have no infiltration rate. Instead, their actual ventilation rates are used in the calculations. If the buildings do not use outside air and are not pressurized, standard infiltration rates are used. The support and recreational buildings are assumed to be partially pressurized, but door openings result in an equivalent infiltration rate of 1.25 cu ft/min (.035 m^3/min) per opening.

The variation of infiltration heating loads due to climatic effects and inside set-point temperatures is accounted for by a correlation between infiltration heating loads and monthly HDDs. This correlation is not altered by secondary effects such as solar gain and building mass. Again, the EUI method allows for correction based on the inside set-point temperature for the building being considered.

Solar radiation heat gain, QH_{RAD}, through the windows of the building depends on three primary variables: (1) the total area of windows, (2) the incident solar radiation available per location, and (3) the solar angle. Radiation gain through windows is considered to be directly proportional to total window areas. Incident solar radiation on a horizontal plane varies greatly by location, and depends on latitude, time of year, elevation above sea level, weather, and atmospheric pollution conditions. The EUI method presents tables which provide the average daily incident radiation (in langleys per day) for each month by location.

The solar angle varies with latitude and time of the year; therefore, solar radiation through windows was determined by season, and different curves are used depending on the month being considered. The only other factor that significantly affects solar radiation heat gain is building and glass orientation. The method was developed by assuming an even glass distribution around the building; glass distribution and orientation of the building can therefore be considered by adjusting the window area.

The heating load due to floors and underground walls, QH_{FLOOR}, is a function of the area and U-values of these components and the difference between inside set-point and average ground temperature.

The heat flow through floors and underground walls is treated as a steady-state conduction heat transfer, with the temperature difference being the difference between inside set-point and average ground temperature.

This heating load component is adjusted by using a correlation between HDDs and the number of hours the building is in the heating mode. The heat flow is calculated for each month that the building stays in the heating mode using equations and curves presented in the EUI method. Secondary effects such as the effect of changes in building equivalent U-value and infiltration rates on the duration of heating mode are assumed to be minor.

The internal heat generation, QH_{INT}, in a building is a function of the level of occupancy, lighting, and equipment operation, as well as the number of hours during which the building is in the heating mode. The schedules of occupancy, lighting, and equipment which define the load factors for the different hours of the day are considered when calculating the amount of internal heat generation occurring during the heating mode. This gain is adjusted for by using a correlation between the monthly heating degree days and the internal heat gain.

The internal gain varies, depending on the level of occupancy in the family residences and the occupants' appliance and lighting usage habits. The internal gain in the barracks is directly related to the level of occupancy since occupancy variations change the occupant load as well as equipment and lighting loads. At occupancy levels less than full capacity, the usage per occupant changes, since some lighting and equipment loads are independent of occupancy levels. To adjust for these variations, an occupancy correction factor is used.

APPENDIX B:
BUILDING PHYSICAL DESCRIPTION

Administration Building

The administration building selected for analysis was a two-battalion headquarters and classroom building. This building is a channel-shaped, one-story structure, with a ground floor area of 14,140 sq ft (1272.6 m^2) and a basement floor area of 3000 sq ft (270 m^2). The length and width are 176 and 80 ft (52.8 and 24 m), respectively. The total exterior wall area is 7854 sq ft (706.9 m^2), of which 7 percent (554 sq ft [498.6 m^2]) is comprised of single-glazed windows and glass doors. This building was constructed in 1974 and has a total equivalent envelope U-value of 0.21 Btu/°F-hr-sq ft.

Family Housing

The family housing building selected was a one-story, single-family house. Its total floor area is 1573 sq ft (141.5 m^2), and its length and width are 50 and 41 ft (15 and 12.3 m), respectively. The total exterior wall area is 1767 sq ft (159 m^2) of which 17 percent (303 sq ft [27.2 m^2]) is glass area. This building was constructed in 1957 and has a total equivalent envelope U-value of 0.28 Btu/°F-hr-sq ft.

Bachelor Enlisted Quarters

The bachelor enlisted quarters selected for analysis was a four-module, three-story barracks. This structure has a total floor area of 24,762 sq ft (2208.6 m^2); its length and width are 216 and 46 ft (65 and 14 m), respectively. The total exterior wall area is 11,348 sq ft (1021 m^2), of which 11 percent (1199 sq ft [108 m^2]) is comprised of single-glazed windows. This building was constructed in 1973, and has a total equivalent envelope U-value of 0.26 Btu/°F-hr-sq ft.

Community Support

The community support building selected is a recently built (1973) commissary. This rectangular-shaped building has a length and width of 450 and 200 ft (135 and 60 m), respectively, accounting for its 90,000 sq ft (8100 m^2) of floor area. The total exterior wall area is 24,600 sq ft (2214 m^2) of which 24 percent (5952 sq ft [536 m^2]) is comprised of window or glass door area. The total equivalent envelope U-value for this building is 0.21 Btu/°F-hr-sq ft.

Recreation Building

The recreation building selected for analysis was an enlisted men's club that was constructed in 1958. This one-story structure has a total floor area of approximately 28,607 sq ft (2675 m^2). The length and width of this building are 256 and 148 ft (76.8 and 44.4 m), respectively. The total exterior wall area is 11,940 sq ft (1075 m^2) of which 12 percent (1488 sq ft [134 m^2]) is composed of windows. The total equivalent envelope U-value for this building is 0.24 Btu/°F-hr-sq ft.

Operations, Classrooms

The operations and classrooms buildings were modified versions of the administration building described previously. In analyzing the operations building, the occupancy level was increased to 1.5 times that of the administration building. In the classroom analysis, the occupancy level was increased to 2.0 times that of the administration building.

Bachelor Officers Quarters

The bachelor officers quarters analyzed was a modified version of the bachelor enlisted quarters previously described. In analyzing the bachelor officers quarters, the occupancy level was decreased to one-third of the occupancy level of bachelor enlisted quarters.

APPENDIX C: USE OF UNIVERSAL CURVES

Figures C1 and C2 show universal curves for solar hot water heating and building heating. The X axis of the curve is the solar system performance parameter. The Y axis, ρ is the fraction of Q_L supplied by the solar collector system. Use of the universal curve permits determination of the percentage of the load which can be met by any selected area of collectors. The general equation for these curves is:

$$\rho = aP_s + bP_s^2 \qquad \text{[Eq C1]}$$

where ρ = percent of load satisfied by solar energy

P_s = incident radiation/energy requirements.

P_s is defined as the ratio of annual or monthly incident radiation on the collector array to the annual or monthly energy requirements of the buildings; this is given by Eq C2:

$$P_s = \frac{Q_C A_C}{Q_L} \qquad \text{[Eq C2]}$$

where A_C = collector area

Q_C = annual or monthly incident solar radiation flux density

Q_L = annual and monthly energy requirements.

To apply the universal curves requires an understanding of the terms Q_C and Q_L.

1. Q_C—annual or monthly incident solar radiation flux density. This is the solar flux density on the tilted collector array in Btu/sq ft/month or Btu/sq ft/year (langleys/month or langleys/year).

Average solar radiation data for many sites in the United States are published in the National Oceanic and Atmospheric Administration (NOAA) *Climatic Atlas of the United States*.[12] Since the radiation values provided in these maps are given in daily means, the annual and monthly values are obtained by multiplying by the number of days in the year or month.

The *Climatic Atlas of the United States* also contains tabulated summaries of radiation data for specific sites. More detailed summaries are frequently available from NOAA, local weather services, or state agencies.

Note that solar data for a particular site are usually given in terms of horizontal radiation densities. These numbers must be corrected for the tilt angle of the collector array, since the tilt angle of the collector plate greatly affects the amount of solar radiation striking the surface of the plate.

Once the collector tilt angle is known, the radiation flux density on the tilted collector surface can be determined from horizontal radiation data. Fortunately, there is an optimum collector tilt angle (measured from horizontal) for each type of system. For heating systems, this optimum tilt angle, ν_c, is roughly the latitude plus 10 degrees; for domestic hot water systems, it is approximately the same as the latitude. These angles enable collection of the greatest amount of solar energy in each application. Variations of ± 5 degrees affect performance only slightly. In all cases, the optimum azimuth angle is due south; again, slight deviations from due south (± 10 degrees) do not significantly reduce system performance.

When the optimum tilt angle has been determined, the annual radiation flux density, Q_C, on the optimally tilted surface can be estimated from Eq C3:

$$Q_C = KH_\nu \qquad \text{[Eq C3]}$$

where K = a correction factor which depends on the collector tilt

H_ν = the annual or monthly radiation flux density on a horizontal surface (Btu/sq ft or J/m^2).

For solar systems using annual solar radiation data (domestic hot water), the correction factor, K, is given approximately by:

$$K = \frac{\cos(\nu_L - 7 - \nu_c)}{\cos(\nu_L - 7)} \qquad \text{[Eq C4]}$$

where ν_L = the latitude in degrees

ν_c = the optimum angle from the horizontal in degrees.

Eq C3 is an empirically derived equation based on the results of simulation studies and is valid only for

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[12] *Climatic Atlas of the United States* (U. S. Department of Commerce, 1968).

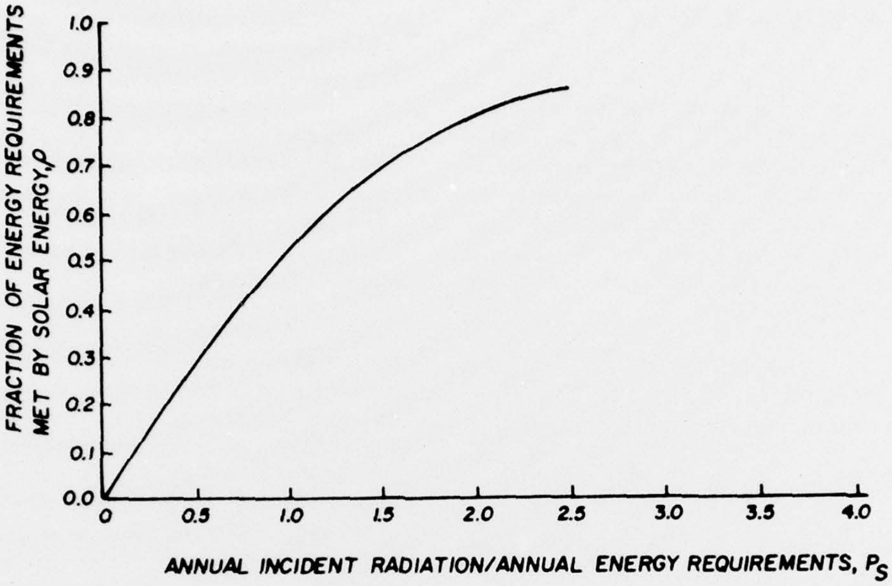

Figure C1. Universal curve for hot energy heating with solar energy.

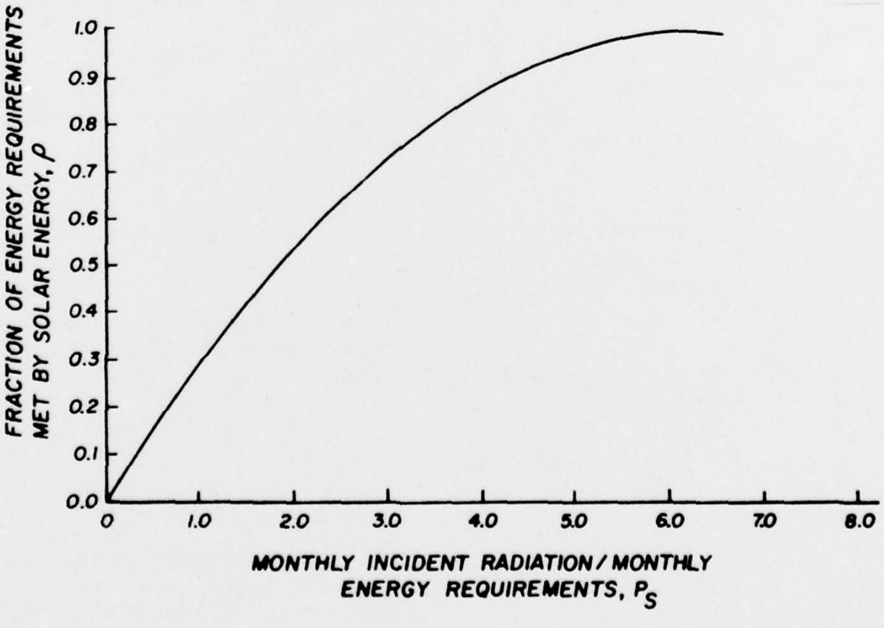

Figure C2. Universal curving for heating with solar energy.

near-optimum collector tilt angles and annual solar radiation data.

For solar heating applications in which monthly radiation figures must be used, the correction factor may not be expressed in closed form. In this case, K must be determined from Table C1, which gives monthly values of this correction factor for four different latitudes. Table C1 is valid only for optimum collector tilt angles.

2. Q_L annual and monthly energy requirements. For using the universal curve, the energy requirements are defined as the total thermal energy in the form of hot water required by the building's domestic hot water heating system or space heating system.

The type of data required to determine Q_L and the sources of that data depend on the type of system being considered. Since solar energy systems produce thermal energy in the form of hot water (or hot air in the case of hot air solar heating systems), consumption or energy requirements in any other terms gallons of oil, cubic feet of gas supplied to a boiler, or gallons of hot water used must be converted to thermal energy in the form of hot water (or hot air if a hot air system is used). This usually requires accounting for the efficiency of conversion equipment as well as the appropriate conversion factors. The following paragraphs describe the determination of Q_L for the solar domestic hot water system and the solar heating systems.

Solar Domestic Hot Water System

Use of the universal curve for domestic hot water systems requires determination of the annual energy needed for heating the hot water. The best source of information is metered consumption data from the building to be heated or from an identical or similar building at the same location. The data can be for either energy or fuel input to the hot water heater or gallons of hot water consumed. When fuel consumption is known, corrections for boiler efficiency must be accounted for as discussed above. When actual consumption data cannot be obtained, data can be derived from various handbooks or from local or national plumbing codes. However, care must be exercised in using per capita consumption data, since they are usually developed for design purposes and are therefore often more closely related to peak demand than to average hot water consumption. When annual hot water demand is determined, the annual energy consumption can be obtained from Eq C5

$$Q_L = DwCp(T_{out} - T_{in}) \qquad \text{[Eq C5]}$$

where Q_L = annual energy consumption in Btu (J)

D = annual hot water demand in gal (ℓ)

w = density of water = 8.33 lb/gal (1.00 kg/ℓ)

C_p = specific heat of water = 1 Btu/1bm °F (4.1868 kJ/kg °K)

T_{out} = temperature of hot water supply in °F (°C)

T_{in} = temperature of supply water in °F (°C).

Solar Heating Systems

Since the length of the heating season varies significantly by site, the universal curve for solar heating systems (liquid or air) must be used on a monthly basis; this requires obtaining the monthly energy demand for heating.

The best source of this information is measured data for the building to be heated or for similar or identical buildings at the same location. These data may only be available in terms of the amount of fuel oil used per month or the amount of gas consumed in heating the building or buildings. If so, the fuel consumption data must be adjusted to account for the efficiency of the boiler or furnace supplying the heat to the space. If measured load data for the building being considered are not available, they must be estimated. Typically, solar heating systems include heating both the building and its domestic hot water. This can be accounted for in the energy requirement by adding the monthly domestic hot water load to the heating load.

Table C1
Monthly Correction Factors (K) for
Heating-Only Systems
(for collector tilt equal to latitude plus 10 degrees)

Month	Latitude			
	30°	35°	40°	45°
Jan	1.64	1.84	2.12	2.49
Feb	1.42	1.55	1.71	1.93
Mar	1.18	1.25	1.33	1.44
Apr	.97	1.00	1.03	1.07
May	.84	.84	.85	.87
Jun	.78	.78	.78	.78
Jul	.80	.80	.80	.81
Aug	.90	.91	.93	.96
Sep	1.07	1.11	1.17	1.24
Oct	1.29	1.40	1.51	1.66
Nov	1.54	1.70	1.93	2.23
Dec	1.70	1.93	2.24	2.64

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