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ACTUAL VERSUS DESIGN PERFORMANCE OF SOLAR SYSTEMS IN THE NATIONAL SOLAR DATA NETWORK

September 1984

U.S. DEPARTMENT OF ENERGY
NATIONAL SOLAR DATA PROGRAM

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OF SOLAR SYSTEMS IN THE
NATIONAL SOLAR DATA NETWORK

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FOREWORD

In 1974, the U.S. Department of Energy (DOE) was authorized by Congress to create the National Solar Data Network (NSDN) as part of the National Solar Demonstration Act. Under the NSDN, some 170 solar systems have been instrumented, monitored, and analyzed for periods of up to three years.

The present report was commissioned by DOE to consolidate some of the accumulated knowledge on solar systems specifically relating to design predicted performance versus actual field performance. This report is, therefore, a compendium of the performance of both large and small, public and private solar systems compared to the designer predicted performance. This study is intended to answer the questions:

- How good were the design predictions?
- When solar systems did not perform as predicted, what caused the poorer performance?
- Was performance affected by integration of solar system components?

It should be noted that the data in this report is based on analysis of components and systems designed in the late 1970s and early 1980s; data from later designs was not available for inclusion in this study.

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INTRODUCTION

This report relates field measured performance to the designer predicted performance. The field measured data was collected by the National Solar Data Network (NSDN) over a period of six years. Data from 25 solar systems was selected from a data pool of some 170 solar systems.

The scope of the project extends beyond merely presenting comparisons of data. There is an attempt to provide answers which will move the solar industry forward. As a result of some industry and research workshops, several concerns arose which can be partially allayed by careful study of the NSDN data. These are:

- What types of failures occurred and why?
- How good was the design versus actual performance?
- Why was predicted performance not achieved in the field?
- Which components should be integrated with a system type for good performance?

Since the designs span several years and since design philosophies are quite variable, we have also compared the measured results to f-Chart 5.1 results (see Appendix B). This comparison is a type of normalization in that all systems are modeled with the same process. An added benefit of this normalization is a further validation of the f-Chart model on a fairly large scale. The systems were modeled using equipment design parameters, measured loads, and f-Chart weather data from nearby cities.

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SECTION I

SITE SELECTION AND DESCRIPTION

The NSDN has monitored data from 170 solar systems. However, such a large pool of data did not fit the resources of this project nor is all of the data appropriate to use. Therefore, several selection criteria were developed which could be applied to each site to objectively judge the value of the data.

These selection criteria are listed below:

- The solar systems must have average or above average collector efficiency and solar energy used. The average was determined from all of the NSDN systems monitored with over four months of usable data.
- Design predictions had to be known and available.
- The solar system could either supply hot water or space heating or both. Solar cooling systems were eliminated because the technology is not well enough developed to be cost-effective.

The final selection was made to create a diverse mix of sizes and types of solar systems. The selected systems range in size from 42 square feet to 21,760 square feet of collector area. The solar systems provide Domestic Hot Water (DHW) heating, process hot water heating, space heating of homes, commercial buildings, and institutions, and a combination of space heating and hot water heating for homes, businesses, and institutions. The solar collectors are both air and liquid collectors. The liquid collectors encompass a thermosiphon system, single and double glazing, and flat-black or selective surfaced absorbers.

Table 1 shows several of the important physical characteristics of the selected solar systems. Complete descriptions of the solar systems are given in Appendix A. These descriptions list the major components and operating modes. There are system schematics showing the relative piping or ducting to the subsystems and the NSDN sensor placements. There are also energy flow diagrams showing the major energy flows during the time periods of interest for this study.

Table 1. NATIONAL SOLAR DATA NETWORK SOLAR SYSTEM CHARACTERISTICS

SITE NAME	LOCATION	LOAD SUBSYSTEMS	TYPE *	COLLECTOR PARAMETERS				STORAGE VOLUME
				AREA (Ft ²)	SLOPE	AZIMUTH	NUMBER GLAZINGS	
ARATEX Services	Fresno, CA	Process Hot Water	FP,L	7,050	30°	0°	1	12,500 gal
Bell Telephone of Pennsylvania	West Chester, PA	Space Heating	FP,L	2,112	55°	0°	1	4,600 gal
Cathedral Square	Burlington, VT	Domestic Hot Water	FP,L	2,342	45°	42°W	2	2,699 gal
Facilities Development	San Diego, CA	Domestic Hot Water	FP,L	520	42°	0°	2	1,000 gal
First Manufactured Homes Lot 9	Lubbock, TX	Space Heating & DHW	FP,A	288	45°	0°	1	216 ft ³
First Manufactured Homes Lot 10	Lubbock, TX	Space Heating & DHW	FP,A	288	45°	0°	1	216 ft ³
Forest City Dillon	Washington, DC	Domestic Hot Water	FP,L	2,592	40°	0°	1	3,200 gal
General Electric-Dallas	Dallas, TX	Space Heating & DHW	ET,L	365	22°	0°	N.A.	400 gal
GSA/Federal Youth Center	Bastrop, TX	Space Heating & DHW	FP,L	21,760	25°	30°W	1	4,000 gal
Hei Mai Wong	Honolulu, HI	Domestic Hot Water	FP,L	807	24°	0°	1	1,230 gal
Hogate's Restaurant	Washington, DC	Domestic Hot Water	FP,L	6,254	55°	45°E	2	10,000 gal
Kalin Home	Long Island, NY	Domestic Hot Water	FP,L	42	36°	6°E	1	120 gal
Lake Valley Firehouse	Tahoe Paradise, CA	Space Heating & DHW	FP,L	572	55°	0°	1	1,200 gal
Loudoun County School	Leesburg, VA	Domestic Hot Water	FP,L	1,225	37°	15°W	2	2,056 gal
Loyola University	New Orleans, LA	Domestic Hot Water	FP,L	4,590	38°	16°W	1	5,000 gal
Oakmead Industries	Santa Clara, CA	Space Heating & DHW	FP,L	2,622	45°	0°	1	6,500 gal
Saddle Hill Trust Lot 36	Medway, MA	Space Heating & DHW	FP,L	315	58°	0°	2	750 gal
Saddle Hill Trust Lot 73	Medway, MA	Domestic Hot Water	FP,L	45	45°	0°	1	80 gal
Saddle Hill Trust Lot 77	Medway, MA	Domestic Hot Water	FP,A	78	38°	0°	2	120 gal
South Bridge Tower	New York, NY	Domestic Hot Water	FP,L	3,742	40°	14°W	2	3,750 gal
Spearfish High School	Spearfish, SD	Space Heating & DHW	FP,A	8,034	62°	26°W	2	4,017 ft ³
Summerwood M	Old Saybrook, CT	Space Heating & DHW	FP,L	378	50°	12°W	1	600 gal
Telex Communications	Blue Earth, MN	Space Heating	FP,L	11,520	59°	0°	1	0,000 gal
Terrell E. Moseley	Lynchburg, VA	Space Heating	FP,L	400	50°	0°	1	2,000 gal
Vitro Test Site	Silver Spring, MD	Domestic Hot Water	FP,L	105	45°	0°	1	120 gal

* A = Air
 L = Liquid
 ET = Evacuated-Tube
 FP = Flat-Plate

N.A. Denotes not applicable.

SECTION II

COMPARISON OF DESIGN AND PREDICTED PERFORMANCE VERSUS ACTUAL PERFORMANCE

The main point of comparison will be based on solar fraction¹ and system efficiency². Solar fraction is used because both the f-Chart predictions and most design numbers are available this way.

The solar system efficiency is a more useful number, since it is independent of load. This index of comparison will also be shown. For the f-Chart predictions, solar energy delivered to the load is derived from the predicted solar fraction and the measured load.

The NSDN records do not contain any explanation of how the design solar fractions were predicted. In order to provide a common basis for the predicted (design) values, a solar system model was used. We chose f-Chart for this because it is more widely available and used more than most other solar system models. The version of f-Chart used was 5.1 implemented on an Apple II computer.

Although this simpler predictive model may appear restrictive because solar systems are not modeled as accurately as possible, the smaller amount of input data and the ease of input permitted a much larger sample of solar systems. A larger sample of solar systems was desirable in order to provide greater statistical significance.

Table 2 shows a comparison of the measured solar fractions, designer expected solar fractions, and f-Chart predictions using measured load data and f-Chart supplied SOLMET weather data. The table also contains measured collector efficiency and solar energy utilization. These parameters are referred to on Pages 9 and 10.

The measured data comes from the NSDN site files and usually represents 12 months of monitoring. Solar fractions range from seven percent to 98%. Note that a high solar fraction is not indicative of high system efficiency. The solar fraction merely shows what portion of the system load is provided by solar energy. Comparing the predicted solar fractions to the measured solar fractions can help determine if a solar system is functioning well.

As the reader glances through Table 2, it is quite evident that the systems generally performed more poorly than predicted. This is true whether one compares design predictions or f-Chart predictions to the measured solar fractions. These statements are illustrated by Figure 1 and Figure 2, which show how much each measured solar fraction differs from the design or predicted solar fraction.

¹Solar Fraction = Solar Energy Supplied to Load $\div$ Load x 100%.

²System Efficiency = Solar Energy Supplied to Load $\div$ Solar Energy Incident on Collector x 100%.

Table 2. MEASURED, DESIGN EXPECTED, AND PREDICTED VALUES

(All values in percentages)

SITE	MEASURED SOLAR FRACTION	DESIGN EXPECTED SOLAR FRACTION	F-CHART PREDICTED SOLAR FRACTION	COLLECTOR EFFICIENCY	SOLAR ENERGY UTILIZATION
ARATEX Services	21	20	49	30	83
Bell Telephone of Pennsylvania	64	57	59	26	100
Cathedral Square	28	51	18	31	82
Facilities Development	45	58	57	43	85
Forest City Dillon	43	59	49	28	93
First Manufactured Homes Lot 9	66	75	71	40	64
First Manufactured Homes Lot 10	73	75	93	26	61
General Electric-Dallas	29	64	65	31	41
GSA/Federal Youth Center	16	46	48	16	98
Hei Wai Wong	98	100	96	32	72
Hogate's Restaurant	43	64	46	35	93
Kalin Home	52	60	30	50	100
Lake Valley Firehouse	50	50	81	35	61
Loudoun County School	60	26	64	21	62
Loyola University	37	52	54	29	85
Oakmead Industries	52	86	67	40	52
Saddle Hill Trust Lot 36	53	50	35	40	99
Saddle Hill Trust Lot 73	56	54	49	52	73
Saddle Hill Trust Lot 77	42	43	56	28	51
South Bridge Tower	7	24	15	47	78
Spearfish High School	54	53	62	27	64
Summerwood M	58	84	35	42	80
Telex Communications	82	79	83	28	76
Terrell E. Moseley	80	69	77	28	87
Vitro Test Site	14	24	23	23	94

Figure 1 depicts the difference in actual versus design solar fraction. One system, Loudoun County School, outperformed the design prediction by 34%. Of the 25 solar systems, 12, or 48% were able to meet or exceed design expectations. Two of the solar systems, or eight percent, were less than 10% below design expectations, while 11, or 44% of the systems, were well below design expectations. Note that we have considered any system within two percent of the design goal as meeting the design goal.

Figure 1. Bar Chart of Actual Solar Fraction Minus Design Expected Solar Fraction

Figure 2 is similar to Figure 1 because the difference between two solar fraction percentages is shown. However, Figure 2 shows the difference between the measured solar fraction and the f-Chart predicted solar fraction using measured loads.

In Figure 2, there are nine systems which meet or exceed design expectations, and six of the sites are common to both groups. Also, there are seven sites which are less than 10% below design predictions. Only one site is common to both Figure 1 and Figure 2 from the less than 10% below-design group, but five sites are common to the below-10% group.

Figure 2. Bar Chart of Actual Solar Fraction Minus f-Chart Predicted Solar Fraction

Using the solar fraction as a basis of comparison is very good for an owner interested in the energy savings or economics. Solar fraction evaluates the percent of load not purchased, so savings can be directly calculated. However, solar fraction is load dependent, whereas the solar system efficiency is sunshine dependent.

A system efficiency number is used to compare these solar systems because this value is more consistent from site to site. System efficiency is defined as the solar energy delivered divided by the total solar energy incident on the array. The design system efficiency is developed from the solar fraction of the load times the design load divided by the total long-term solar energy incident on the array area. Likewise, a system efficiency can be determined from the f-Chart solar fraction.

Figure 3 shows the difference in the measured system efficiency minus the design system efficiency. Design system efficiency data was not available for Oakmead Industries and Hogate's Restaurant. Figure 3 shows eight solar energy systems which meet or exceed the design expectations. (The criteria is that a solar system meets or exceeds the design expected performance if the difference between measured and design system efficiency is greater than negative two percent.) Looking back at Figure 1, there

Figure 3. Bar Chart of Actual System Efficiency Minus Design Expected System Efficiency

are only five sites, ARATEX Services, Lake Valley Firehouse, Loudoun County School, Saddle Hill Trust Lot 36, and Terrell E. Moseley, which also met or exceeded the design solar fraction.

As one peruses Figure 3, quite naturally the question is asked, "Why did so many solar systems fail to meet the design goals?" This question will be answered subsequently. However, first there may be solar systems which have performed below expectations, but where the design goals are still realistic. The present criteria of system efficiency does not catch the poorer performers. These sites must be detected by scrutinizing the f-Chart predictions, solar energy utilization, collector efficiency, and specific facts from the site history relating to problems with the collection, storage, and energy transport subsystems.

The two other criteria used to evaluate solar system performance mentioned above were collector efficiency and solar energy utilization, also shown in Table 2. To avoid any confusion, collector efficiency is defined as the percentage of total solar insolation (incident on the gross collector array) which is collected. Another aspect of the collector efficiency is the manufacturer's single-panel test curve. This curve is the result of tests by an independent laboratory which comply with ASHRAE Standard 93-77 (see Reference 3). These tests establish the maximum efficiency,

y-intercept or $F_{RT}\alpha$ for f-Chart and the slope of the curve or losses (F_{RUL} for f-Chart). A recently published report, "Component Report: Performance of Solar Arrays and Collector Controllers in the National Solar Data Network" (Reference 4), compares these test and measured results for many of the same solar systems.

The other criteria mentioned above is solar energy utilization. It is defined as the solar energy delivered to the load divided by the solar energy collected. This concept is useful to determine the efficiency of transport and use of the solar energy after it has been collected. This value is restricted to measured parameters only, since design data is not available and f-Chart does not output the amount of solar energy collected.

As the individual site analyses proceeded, it became evident that there were three groups of solar systems. These are:

- Design Goals Met or Exceeded
- Design Goals Realistic, Performance Less Than Expected
- Design Goals Optimistic

These groups are discussed in detail in the following sections. If the first two groups are added together, there are 14 solar systems out of the 25 which have realistic, achievable design goals.

A. DESIGN GOALS MET OR EXCEEDED

The group of sites which had realistic design goals and performed up to the design expectations is listed below. The basis of comparison for these eight sites is the system efficiency parameter discussed earlier.

ARATEX Services
First Manufactured Homes Lot 9
Kalin Home
Lake Valley Firehouse
Loudoun County School
Saddle Hill Trust Lot 36
Summerwood M
Terrell C. Moseley

The ARATEX Services solar system had a measured system efficiency of 30%, which is two percent less than design expected. Measured collector performance was quite good, with a 30% efficiency. The measured solar energy utilization of 83% was also very good, and the measured solar fraction of 21% was one percent above the design solar fraction. The f-Chart predicted solar fraction was 49% and the predicted system efficiency was 51%, or 19% above the design predictions. Although the long-term solar insolation was 14% sunnier than the measured insolation, the f-Chart predictions are still too optimistic.

The First Manufactured Homes Lot 9 site had good performance with a measured system efficiency of 25% versus the design expected system efficiency of 22%. The system efficiency predicted from the f-Chart solar fraction was 24%. The measured solar fraction for this site is nine percent below the design expected solar fraction, whereas the f-Chart predicted solar fraction is 71%, or five percent greater than measured. Slightly better collector performance and long-term weather which is 16% sunnier than the measured weather account for the difference between f-Chart and the measured values.

The Kalin Home solar system had excellent measured performance. The measured system efficiency was 50% and the collector efficiency was an amazing 50%. (The collectors performed seven percent above the manufacturer's single-panel test curve.) The measured solar fraction of 52% is eight percent below the expected design solar fraction, but, at 50%, the measured system efficiency is two percent above the design expected system efficiency. The f-Chart predicted solar fraction was only 30%, or 22% below the measured value. Likewise, the system efficiency predicted from the f-Chart solar fraction was 22%. Since the measured collector performance was seven percent above the manufacturer's single-panel test result, the f-Chart results would be expected to be smaller, but not to the extent given here. There is no reason to believe the f-Chart input data was in error, but there is no other explanation for the discrepancy. The long-term weather for the f-Chart prediction was eight percent above the measured value.

The performance of the Lake Valley Firehouse solar system was good, at a system efficiency of 22% and a collector efficiency of 35%. The design expected system efficiency was 23% and the solar fraction was 50%, the same as the measured solar fraction. The f-Chart predicted solar fraction was 81%, 31% greater than measured. Comparing the system efficiency predicted from the f-Chart solar fraction with the measured system efficiency, the f-Chart system efficiency of 28% is six percent greater than measured. The f-Chart predictions are above the measured values because the long-term solar insolation data used by f-Chart is 28% sunnier than the measured insolation.

The Loudoun County School solar system performed moderately, but well above design expectations. Measured solar fraction was 60% compared to 26% design expected and 64% f-Chart predicted solar fraction. Comparing system efficiencies, measured was 13% versus nine percent design expected and nine percent for f-Chart. Since the measured collector efficiency of 21% was 10% less than the manufacturer's single-panel test curve, it seems likely that the design expected performance was very conservative. The f-Chart results were low when one would expect higher than measured values because the long-term weather was sunnier than measured and because the collector performance was low. There is no apparent explanation for these differences. The Loudoun County School performance was reduced by large losses from buried pipes between the collector and the school mechanical room.

The measured performance at Saddle Hill Trust Lot 36 was very good. Collector efficiency was 40% and measured solar fraction was 53%. Note that this performance was restricted to the winter-time when the loads were higher. Although the measured solar fraction is only three percent above the design expected, the measured system efficiency of 46% is 10% above the design expected. This difference from measured to design expected performance is reduced to four percent in system efficiency if the measured summer months are included. The f-chart solar fraction of 35% is 18% below the measured solar fraction and f-Chart system efficiency is 10% below measured. One reason the performance at Saddle Hill Trust Lot 36 is so good is because the measured solar insolation is 20% greater than the long-term insolation used by f-Chart. Also, the system has very high utilization of solar energy collected and collector efficiency was five percent above the manufacturer's single-panel test curve.

The Summerwood M solar system has excellent performance during the winter when the loads are high. Measured collector efficiency was 42% which is 16% greater than the manufacturer's single-panel test result. The measured solar fraction of 58% was 26% below the design expected value. However, the measured system efficiency of 29% was the same as the design expected system efficiency. The f-Chart predicted solar fraction of 35% was 23% less than measured. The measured system efficiency was three percent greater than the f-Chart predicted efficiency using the solar fraction values. Measured solar energy utilization was 80% of the measured collected solar energy during the winter. The yearly value for solar energy utilization was 58%. The reduced amount of solar utilization or solar energy delivered to the load on a yearly basis is due to the small summer hot water heating loads.

The Terrell E. Moseley solar system performed well, with a high solar fraction (80%) and 24% measured system efficiency. This performance was 11% above the design expected solar fraction and only one percent below design expected system efficiency. The f-Chart predictions were similar to the measured performance at a 77% solar fraction and 19% system efficiency predicted from f-Chart results. The long-term solar insolation was eight percent below the measured insolation. Solar energy utilization by the Terrell E. Moseley system was very good, but the collectors performed 21% below the manufacturer's single-panel test curve. Accurate design forecasting and the balancing combination of higher solar insolation with lower collector performance provided good results in this case.

B. DESIGN GOAL REALISTIC, PERFORMANCE LESS THAN EXPECTED

The sites which had realistic design expectations but performed below their potential are listed below. Generally, some component of the system was performing at a reduced output due to control malfunction or excessive wear. These six sites are:

Bell Telephone of Pennsylvania
First Manufactured Homes Lot 10
General Electric-Dallas
GSA/Federal Youth Center
Oakmead Industries
Saddle Hill Trust Lot 77

The measured performance of 64% solar fraction and 27% system efficiency at the Bell Telephone of Pennsylvania site was below the design expected performance. However, there were problems with the air vents on the solar system which restricted system filling. After these air vents were replaced, the system performance slightly exceeded the design expected performance. The f-Chart predicted solar fraction was five percent below the measured value, but the predicted system efficiency equalled the measured value. Note that the measured solar insolation was 11% sunnier than the long-term insolation.

The First Manufactured Homes Lot 10 solar system performed much less effectively than its sister system on Lot 9. The measured solar fraction of 73% at Lot 10 was greater than the 66% solar fraction measured at Lot 9. However, the measured system efficiency of 16% at Lot 10 was much lower than the measured value of 25% at Lot 9, and substantially below the design expected value of 22%. At Lot 10, the measured load was 16.5 million BTU compared to 30.3 million BTU at Lot 9. This smaller load was the reason for the improved solar fraction at Lot 10. The real problem at Lot 10 was the much lower collector efficiency of 26% compared to the 40% collector efficiency at Lot 9. The smaller load at Lot 10 did result in storage temperatures 6°F to 7°F warmer in the winter months. Another reason for the reduced performance at Lot 10 was the fact that air flow was 27% less than design.

The f-Chart predicted solar fraction at Lot 10 was 93%, but the f-Chart system efficiency was still only 16%. This is due to the smaller load at Lot 10, because the same system at Lot 9 produced an f-Chart system efficiency of 24%. If the collector performance at Lot 10 was improved so that all or most of the load would be served with solar energy, then the system efficiency would be nearly 21% or within one percent of the design expected value.

The General Electric-Dallas solar system had good collector performance, but poor utilization of collected solar energy. The measured solar fraction of 29% was 35% below the design expected value. The measured system efficiency of 10% was eight percent below the design expected value. An improvement of 37% in the solar energy delivered to the load would result in a system efficiency equal to the design expected value. The f-Chart predicted solar

fraction is 65%, similar to the design expected value, and the predicted system efficiency is 28%, which is 10% above the design expected value. The control interface between the solar and load subsystems is the suspected cause of the low utilization of solar energy.

The GSA/Federal Youth Center solar system had very high solar energy utilization but poor collector performance. This resulted in a solar fraction of 16% and a system efficiency of 14%. The design expected solar fraction was 46% and the system efficiency was 20%. The f-Chart solar fraction is 48%, but the predicted system efficiency is 45% compared to the 20% design expected system efficiency. The large difference between the f-Chart and design expected system efficiency is suspected to be due to an overstatement of collector efficiency by the manufacturer's single-panel test curve. The measured collector performance was degraded due to stagnation damage after installation and subsequent freezing. The stagnation damage was caused when the collectors were installed several months before the system was turned on. The freeze damage was caused by a mislocated check valve which prevented drainback. Both of these problems can be attributed to poor installation practices.

The Oakmead Industries solar system had a measured collector efficiency of 40%. This is slightly better than the manufacturer's single-panel test result. The design solar fraction of 86% is 34% greater than measured. There was no design system efficiency available. Although the design expectations appear optimistic, design solar fraction could be met if the solar utilization could be increased to 85%. The present measured solar energy utilization of 52% is suspected to be due to the oversized storage tank which was often at temperatures too low for utilization by the space heating subsystem.

The f-Chart predicted solar fraction was 67%, 15% better than measured. Likewise, the f-Chart system efficiency predicted from the solar fraction was 24%, or four percent better than the measured data. Some of the increase in f-Chart predicted performance was due to greater solar insolation in the long-term weather records. The increased solar energy delivered to the loads is undoubtedly the major cause for better predicted performance at Oakmead Industries.

At Saddle Hill Trust Lot 77, site performance was reduced primarily because of transport losses. The measured solar fraction of 42% compares favorably with the design solar fraction of 43%. However, the measured system efficiency was only 15%, or nine percent below the design expected value. The f-Chart predicted solar fraction was 56% and the predicted system efficiency of 21% is six percent above the measured value and three percent below the design expected value. Since the measured solar energy utilization was only 51% and collector efficiency was exactly as expected from the manufacturer's single-panel test curve, transport and storage losses were the cause of the poorer performance. These losses are principally due to leaks in the ductwork. Therefore, the design goals are realistic and they can be achieved if the duct leaks are sealed.

C. DESIGN GOALS OPTIMISTIC

This group of sites has design goals which appear to be unattainable by the installed systems. There may have been changes in system size after the designs were completed but we are not aware of any. The primary basis of comparison is the system efficiency augmented by f-Chart predictions, collector efficiency, and solar energy utilization. All of these sites have good performance. The 11 sites considered are listed below:

Cathedral Square	Saddle Hill Trust Lot 73
Facilities Development	South Bridge Tower
Forest City Dillon	Spearfish High School
Hei Wai Wong	Telex Communications
Hogate's Restaurant	Vitro Test Site
Loyola University	

The Cathedral Square solar energy system had good performance with a 28% measured solar fraction and 17% measured system efficiency. On the other hand, the design solar fraction was 51% and the design system efficiency was 41%. The f-Chart solar fraction was 18%, 10% less than the measured value and quite opposite to the design solar fraction. Similarly, the f-Chart predicted system efficiency was 14%, or three percent less than measured. These f-Chart results are even more surprising when one considers that the long-term solar insolation was 17% sunnier than the measured insolation. The measured collector efficiency of 31% is only one percent below the manufacturer's single-panel test result. The design results are clearly optimistic, because, even if 100% of the collected solar energy based on the long-term solar insolation were used, the system efficiency would still only be 31%. It appears that a 51% design solar fraction is just not possible with the present solar system.

The Facilities Development solar system has been a consistently high performer with no major problems. At Facilities Development, collector efficiency was 43% and the solar energy utilization was 85%. However, the measured system efficiency was nine percent less than design expected. The measured solar fraction was 13% less than predicted. If there were no losses, then measured system efficiency would still be two percent smaller than predicted. The design expectations are certainly optimistic. Although the f-Chart predicted solar fraction is 12% greater than the measured solar fraction, the f-Chart system efficiency predicted from the solar fraction is only three percent greater than the measured system efficiency. The f-Chart results appear only slightly optimistic and that may be due to the 15% greater long-term solar insolation.

At the Forest City Dillon site, the solar fraction was 43% and solar energy delivered to the load was 93% of the collected energy. This performance is quite good, but the collector efficiency of 28% was 22% below the manufacturer's single-panel test curve. The system efficiency of 26% was fair, but eight percent below f-Chart predictions and 29% below the design expected value. The difference

between design solar fraction and measured solar fraction was 16% versus a six percent difference in the f-Chart predicted and measured solar fraction. The design expected performance was very optimistic even compared to 100% utilization of the solar energy collected.

The Hei Wai Wong site performed well, although the collector efficiency of 32% was still 12% below the manufacturer's single-panel test value. The solar fraction of 98% was two percent below the design predicted and two percent above the f-Chart prediction. However, the design expected results were quite optimistic when one compares system efficiencies. The measured system efficiency of 23% was 23% below the design expected result, but two percent above the f-Chart result. Seventy-two percent of the collected energy was delivered to the load. At this site, the f-Chart predictions and measured results compare very well. The design expected results appear to be optimistic because the actual load was 50% of the design expected load.

The Hogate's Restaurant solar system performed with a collector efficiency of 35%, which is good but nine percent less than the manufacturer's single-panel test result. The measured solar fraction of 43% was also very good, but 21% below the design predictions. Design system efficiency was unavailable. The large difference in solar fraction between measured and design expected indicates an optimistic design. Since the f-Chart solar fraction of 46% was only three percent above the measured value, this is a further indication that the design expected performance was optimistic. Noting that the measured solar energy utilization was 93% and that the long-term insolation was 13% greater than the measured value, it may be instructive to estimate what the possible highest solar fraction could be. Taking the highest possible values for solar energy incident, solar collector efficiency, and solar energy utilization, one can estimate that a 61% solar fraction is possible. This is still three percent below the design expected solar fraction.

The Loyola University solar system had a collector efficiency of 29%, seven percent below the manufacturer's single-panel test result. However, the solar fraction of 37% was 15% below the design expected value and 17% below f-Chart predictions. This lower performance was partially due to sunnier long-term weather and below-expected collector performance. The measured solar energy utilized was 85% of the collected solar energy. The design is optimistic unless the collector array efficiency can be improved. The system efficiency predicted from the f-Chart solar fraction was 30% versus the 34% system efficiency expected by the designer. The f-Chart predicted system efficiency is seven percent above the 23% measured system efficiency. Although the Loyola University solar system performed quite well, the measured performance was below the predicted f-Chart performance because the measured solar insolation was 83% of the f-Chart long-term insolation and because the collector performance was below expected.

At the Saddle Hill Trust Lot 73 site, overall performance was very good. Collector performance was particularly high with a collector efficiency of 52%, seven percent better than the manufacturer's single-panel test result. Solar energy utilization was also quite good with 73% of the collected energy being used by the load. The system efficiency of 38% was excellent, but was still 13% below the design expected. The measured solar fraction was two percent above design expected, however. The f-Chart results were similar to the measured values, but with a lower solar fraction of 49% and a lower system efficiency of 35%. Perhaps the difference was due to the lesser amount of sunshine for the long-term weather data. The design expected performance is optimistic at Saddle Hill Trust Lot 73 because the design system efficiency is too high. Also, since the long-term average weather is less sunny, the fine performance of the particular measured year may not be repeated. Therefore, the f-Chart results are quite likely representative of long-term average results.

The South Bridge Tower solar system had a high collector efficiency of 47%, due to cool inlet water temperatures during the winter months. The measured solar fraction of seven percent was 17% below the design expected solar fraction and eight percent below the f-Chart predicted solar fraction. Comparing system efficiencies, the measured system efficiency of 26% was 20% below design expected and 30% below the system efficiency predicted from the f-Chart solar fraction. The design expected performance is quite optimistic, but the reason may lie in the overstated collector performance from the manufacturer's single-panel test. Although measured collector efficiency was very high, it was 29% below the performance predicted from the single-panel test. If one uses the f-Chart long-term insolation, which is 23% sunnier than the measured insolation, and the measured collector efficiency, the estimated system efficiency is three percent above the measured system efficiency. Apparently the South Bridge Tower solar system design expectations and f-Chart predictions are very inflated due to the erroneous single collector panel test results.

The Spearfish High School solar system performed more moderately with a measured collector efficiency of 27%. This was eight percent below the manufacturer's single-panel test result. The measured solar fraction of 54% actually was one percent greater than the design expected solar fraction, but the measured system efficiency of 22% was 11% below the design expected system efficiency. This comparison implies that the design expected solar energy delivered to load would be nearly twice the measured value. Comparing f-Chart predictions, the f-Chart solar fraction of 62% was eight percent greater than measured, but the system efficiency predicted from the f-Chart solar fraction was three percent less than measured. The long-term solar insolation was about one percent less than the measured insolation, so this was not a factor. Although the design expected solar fraction is the same as the measured solar fraction, the design loads were more than twice the measured loads. Hence, the expected solar contribution based on solar fraction was also greatly inflated.

The Telex Communications solar system had good performance. Collector efficiency was 28%, but was still two percent above the manufacturer's single-panel test result. Seventy-six percent of the collected solar energy was utilized. The measured solar fraction of 82% was excellent and one of the highest. This solar fraction was three percent above the design value. The f-Chart solar fraction of 83% was similar to the measured value. The design goals are optimistic due to design expected system efficiency, which is 15% greater than measured, and 10% greater than f-Chart.

The Vitro Test Site had relatively poor collector efficiency of 23% versus the manufacturer's single-panel test result of 46%. Due in part to the reduced collector efficiency, the measured solar fraction was only 14%, 10% below the design expected value. However, the measured system efficiency of 22% was 36% below the design expected system efficiency because the estimated design load was 50% too high and collector performance was low. Measured solar energy utilization was very good, with 94% of the collected solar energy being used. The f-Chart predictions were also higher than the measured results because the manufacturer's single-panel test results were used. The f-Chart solar fraction of 23% was nine percent greater than the measured solar fraction. The system efficiency predicted from the f-Chart solar fraction was 39%, 17% higher than the measured value. The optimistic design expectations for the Vitro Test Site were partially due to lower than expected collector performance and overestimation of the design load.

SECTION III

SUMMARY AND CONCLUSIONS

The data presented in Section II illustrates the comparison of measured performance with design expected and f-Chart predicted performance. This section presents the aggregated results and the conclusions.

Table 3 shows the summary performance data of measured versus design expected and f-Chart predicted results. The data is the average sum of the difference between the measured performance and design expected or f-Chart predicted performance.¹ Measured values which are less than the design expected or f-Chart predicted results yield a negative number.

Table 3. MEASURED SUMMARY PERFORMANCE DATA
VERSUS DESIGN EXPECTED AND f-CHART PREDICTED RESULTS

(All values in percentages)

CATEGORY	SOLAR FRACTION		SYSTEM EFFICIENCY	
	DESIGN	f-CHART	DESIGN	f-CHART
All Sites	-8.0	-6.4	-9.0	-4.0
All Sites Except Poor Performers	-5.5	-2.5	-10.0	-2.0
Sites Which Meet or Exceed Design	0.7	3.7	2.0	6.0
Optimistic Design	-9.2	-6.1	-18.0	-7.0

Examining the average differences from Table 3, one can see that the difference between measured and design expected data is usually negative. This means that the design expected results exceeded the measured results. Statistically, this difference is significant for the system efficiency values. If we exclude the below average performers, the differences are smaller for solar fraction but slightly larger on system efficiency.

For those sites with expected performance and realistic design expectations, the average measured performance exceeded the design performance only slightly.

¹ Value = $\frac{\sum (\text{Measured Value} - \text{Design or f-Chart Value})}{\text{Number of Values}}$

However, in the category labeled Optimistic Design, there is no real difference between all the sites and the ones labeled optimistic. The system efficiency from the optimistic category was much higher than when all sites were included. This indicates that the solar fraction parameter is more independent of the groups. The System Efficiency is much worse for the Optimistic Design group because of the greater variability of insolation. This is a strong indication that this category is indeed overdesigned. Recall that most of the error appeared to be due to overestimation of the loads.

The summary results for the f-Chart predicted performance are similar to the design expected values, but somewhat closer to the measured values. In fact, there is no significant difference between the f-Chart predictions and the measured values for System Efficiency for All Sites. This means that, on the average, f-Chart predictions match the measured results. However, bear in mind that these f-Chart predictions are based on measured loads for the input data. Interestingly, there is also no significant difference between the design expectations and f-Chart predictions for System Efficiency for All Sites. The exclusion of below-average measured performance merely brings the f-Chart predictions closer to the measured performance.

For those sites which meet or exceed design expectations, the f-Chart predictions are surprisingly below the measured performance. There is no explanation as to why this might be.

The sites where the design expected performance was optimistic also have f-Chart predictions which are optimistic, but not to the same degree as for the design expected performance. In several instances, the f-Chart predictions were somewhat inflated because the long-term solar insolation exceeded the measured insolation. For all sites in this report, the long-term insolation exceeds the measured insolation by six percent.

The reader should note that, although the average measured and design expected or f-Chart predicted performance values are not greatly different, the range of values represented in the data is quite wide. From Figures 1, 2, and 3, it is obvious that the differences in solar fraction range from +30% to -30%, and the differences in system efficiency range from + four percent to -36%. It is unclear whether this large variability is a general characteristic of solar system performance, or whether it is due to differences in system types and system applications. Study of a larger sample of similar systems would help determine the true range of variability and perhaps the cause.

Design expected performance was found to be significantly greater than actual measured performance by an eight percent solar fraction or a nine percent system efficiency. The f-Chart predicted performance with measured loads was not significantly different from the measured performance or the design expected performance. The f-Chart predictions tended to be greater than the measured performance because the average long-term insolation was 5.7% larger than measured insolation, and because the average measured collector performance was 6.3% below the manufacturer's test results.

Of the 25 selected solar systems, eight sites, or 32%, met or exceeded the design goals, while 11 sites, or 44%, had design goals which were not achievable. The other six sites, 24%, had realistic design goals but below average performance.

The below average measured performance was caused by poor solar energy utilization on three systems, poor collector performance on two systems, and faulty air vents on one system. The collectors appear to have degraded on one system due to excessive stagnation and freezing caused by a misplaced check valve. The other poor collector performance appears to be related to lower than designed air flow. The solar energy utilization problems were caused by low storage temperatures, high duct losses, and a suspected control problem.

Further research into the aspect of solar energy utilization is needed to round out the design process. Predictive models like f-Chart appear to be particularly adept at determining how well the solar collector component will perform. The fact that several solar systems had poor utilization of the collected solar energy indicates a need to better understand the dynamics of integrating solar energy systems with conventional HVAC systems.

The conclusions of this study are summarized below.

- Design expected performance was statistically different from measured performance and eight percent greater in solar fraction, or nine percent greater in system efficiency.
- The f-Chart predictions were not statistically different from measured or design expected results.
- The long-term insolation data was about six percent sunnier than the measured insolation. This inflated the f-Chart predictions.
- The manufacturer's collector test results were six percent above the measured collector efficiency on the average. This higher efficiency also inflated the f-Chart predictions.
- Design expected loads were generally larger than the measured loads. This difference is believed to be the largest source of error in the design expected performance.

DESIGN DO'S AND DON'T'S

The following list of design do's and don't's is suggested from the writer's interpretation of the data. What is proposed in the list is a checklist or "rules of thumb" pertaining to establishing the design concept of a solar system.

1. Do check predictions for reasonableness. Our suggestion here is to determine the average incident solar energy in BTU/ft²-day and the average solar energy delivered to loads in BTU/ft²-day. The ratio of these will yield a system efficiency. The measured NSDN solar systems had an average system efficiency of 25% and the f-Chart predicted average system efficiency was 29%. Predicted system efficiencies over 40% are suspect, although two NSDN solar systems did achieve that level of performance.
2. Do check solar energy utilization. Recall that this is defined as solar energy used divided by solar energy collected. A ratio greater than one is impossible; ratios less than 0.6 should be checked because they are low.
3. Don't use conservative design practice to estimate loads. This was the greatest source of error in the design expected results. Therefore, loads should be carefully determined.
4. NSDN measured insolation data was usually below f-Chart SOLMET insolation data by about six percent on the average. This higher insolation causes some inflation in the predicted values. The designer must be aware of this.
5. Do try to find more than one source of ASHRAE 93-77 collector test results. Also, compare the chosen collector test curve with other generically similar collector curves to alert a designer to a suspect test curve if it is greatly different.

SECTION IV

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APPENDIX A
SYSTEM DESCRIPTIONS

ARATEX SERVICES

The ARATEX Services (formerly Work-Wear) site is an industrial laundry located in Fresno, California. The system was designed so that collected and recycled solar energy would satisfy 20% of a 30,000-gallon per day hot water laundry process demand. Output waters are designed to be maintained at about 180°F; however, conservation efforts have reduced this temperature to 165°F.

The solar collector array consists of 140 flat-plate, single-glazed Ying Collectors Model SP4120 (Ying Manufacturing Corporation, Gardena, California), 90 of which were reglazed with Tedlar, and recoated during a refurbishment project begun in September 1979.

The Ying solar collectors normally have one UV stabilized layer of clear polycarbonate plastic, 0.02 inches in thickness, as a cover. Transmittance of this cover is 0.91. Flat-black paint was used as a surface for the aluminum absorber plate.

Ying controls were used to control the operation of the solar collectors.

The collector area is 7,050 square feet. The collector array faces due south and the collector angle is 30 degrees from the horizontal.

The system, shown schematically in Figure A-1, has three modes of operation for process water heating with solar energy and recycled thermal energy.

Mode 1 - Collector-to-Storage - During this mode of operation, water is pumped from solar thermal storage through the collector array and back into storage. This mode is activated when the temperature of the collector array outlet exceeds the storage temperature by 4.5 degrees and continues until this differential temperature drops below 1.5 degrees. There is a 12-minute delay for circulation pump P2 to turn on or off. This control function eliminates sporadic pump operation during fluctuations of insolation, saving electrical operating energy and increasing the life of the collector pump.

Mode 2 - Hot Water Demand - This mode is activated when there is a demand by the laundry for hot water. City water entering the hot water system is preheated using thermal energy from wastewater in the 16,500-gallon holding tank. The temperature of the city water is raised to a range of 95°F to 110°F before entering solar thermal storage. As water is drawn from solar thermal storage, it passes through a steam heat exchanger (HX2) where auxiliary energy is added to maintain the 4,000-gallon laundry hot water service storage tank at about 180°F. Additional energy is supplied from steam condensate flowing through heat exchanger HX3. Under conditions of elevated demand, valve V3 opens to provide inlet water preheated only by the heat recovery subsystem.

Mode 3 - Storage-to-Wastewater - When the water in the solar thermal storage tank reaches 180°F, it can be circulated by reverse flow through heat exchanger HX1 in the heat recovery subsystem, thus storing any excess solar energy in the wastewater holding tank. This mode is used to prevent overheating the 12,500-gallon fiberglass storage tank and allows the wastewater holding tank to be used as a secondary storage tank.

- D001 WIND DIRECTION
- I001 COLLECTOR PLANE TOTAL INSOLATION
- ▶ T001 OUTDOOR TEMPERATURE
- V001 WIND VELOCITY

Figure A-1. ARATEX Services Solar Energy System Schematic

REVISED 4/5/79

Figure A-2. Energy Flow Diagram for ARATEX Services
December 1979 through November 1980
(Figures in million BTU)

BELL TELEPHONE OF PENNSYLVANIA

The Bell Telephone of Pennsylvania site is a one-story office and warehouse building in West Chester, Pennsylvania. The solar energy system is designed to supply approximately 60% of the annual space heating requirements for the building. The site has an array of Heliotherm flat-plate collectors (DC 24 SC) with a gross area of 2,112 square feet which faces south at an angle of 55 degrees from the horizontal.

The collector panels have a single, 0.10-inch-thick cover and a selective surface manufactured by Heliotherm. The absorber surface has a solar absorptivity of 0.95 and an infrared emissivity of 0.10. Total solar transmissivity of the glazing is 0.92. The absorber surface is composed of 0.04-inch Roll-Bond CDA 122 copper by Olin Brass Company. The fluid circulated through the collectors is water. The collector panels are 0.10-inch-thick covered with plexiglass "G" by Rohm & Haas.

The site utilizes a Honeywell R7412A differential controller to operate the solar collectors. This controller has the capability of adjustment of differential set points on-site as needed.

Solar-heated water is stored in a 6,000-gallon capacity tank, which is believed to contain only 4,600 gallons. The tank is located above ground in the mechanical room. Thermal energy is distributed to the loads by circulating water from the storage tank through forced-air heat exchangers and through 20 individual heat pump evaporators. When solar energy is insufficient to meet the requirements for space heating, auxiliary energy is supplied to the circulating water by electric resistance heating in the boiler.

The system, shown schematically in Figure A-3, has three instrumented modes of solar operation.

Mode 1 - Collector-to-Storage - This mode is entered when the sensed collector absorber plate temperature exceeds the temperature in the middle of storage by at least 18°F. Water from the tank is then circulated through the collectors until this temperature differential is less than 3°F. The collector subsystem has a draindown feature to prevent freezing. Overheat protection is provided by automatic draining of the collector array whenever the collector output temperature exceeds 190°F.

Mode 2 - Storage-to-Space Heating - This mode is entered with a demand for heating from manually preset thermostats in either the office corridors or the warehouse area. Water is circulated by pumps P3 and P4 between the storage tank and the Air-Handling Unit (AHU) heat exchangers and the Forced Flow Heater (FFH) units. The AHU and FFH units are activated to provide heat to the warehouse area and the corridors, respectively. Pumps P3 and P4 are deactivated whenever the space heating demands are satisfied at each respective area.

Mode 3 - Storage-to-Space Heating (Heat Pumps) - This mode is entered when there is a demand for space heating from individual offices and the sensed temperature of the water to the heat pumps is below a nominal 70°F. Valve V10 blends water from the storage tank with the heat pump return flow as required. Flow from the storage tank ceases when the heat pump fluid operating temperature again reaches the 70°F set point. When the sensed storage tank temperature is less than 70°F, the boiler becomes the thermal energy source for the heat pumps by the opening of valve V8 and the closing of valve V9.

MAY 12, 1960

Figure A-3. Bell Telephone of Pennsylvania Solar Energy System Schematic

Figure A-4. Energy Flow Diagram for Bell Telephone of Pennsylvania
November 1979 through March 1980
(Figures in million BTU)

CATHEDRAL SQUARE

The Cathedral Square site is a 10-story building located in Burlington, Vermont. The building has 101 apartments, each containing approximately 500 square feet of living space. Solar energy is used to preheat the Domestic Hot Water (DHW). The solar energy system has an array of flat-plate collectors, Daystar 21-B, with an effective area of 1,798 square feet, requiring a gross area of 2,342 square feet. The array faces 42 degrees west of due south at an tilt of 45 degrees from the horizontal.

The collector array consists of 80 Daystar 21-B collectors. The collectors have a 3/16-inch low-iron content, tempered glass cover plate with a net aperture of 21 square feet. The absorber plate is copper with copper tubing and repainted black. The absorber has an absorptivity of 0.98. Special features include a folded polymer heat trap with transmissivity of 0.94 and an integrated temperature delimiter which maintains internal collector temperatures below 270°F. The optical efficiency is 0.83. (This model is no longer manufactured by Daystar.)

A Rho Sigma Model 106 differential controller is used to control the operation of the solar collectors. Thermistor sensors measure a 10°F "on" differential and a 3°F "off" temperature differential between storage and the collector array.

A 67% propylene glycol/water solution is the transfer medium that delivers solar energy from the collector array to a water storage heat exchanger. The transfer medium that delivers solar energy from storage to the hot water heat exchanger is water. Solar energy is stored in a 2,699-gallon solar storage tank. Energy is exchanged from the solar storage tank to the 865-gallon conventional DHW storage tank when there is a sufficient temperature difference between the two tanks. When there is a hot water demand, cold supply water flows past the solar storage heat exchanger into the DHW storage tank. Two gas-fired boilers supply any auxiliary thermal energy required to satisfy the hot water load.

The solar system, shown schematically in Figure A-5, has two modes of operation.

Mode 1 - Collector-to-Storage - This mode activates when the collector temperature exceeds the solar thermal storage temperature by approximately 10°F. Pumps in the collector heat exchanger/storage loop are activated. The propylene glycol/water solution flows through the collector array and the collector heat exchanger, and water flows through the heat exchanger and solar thermal storage tank. When the collector temperature is within approximately 3°F of the solar energy storage temperature, the pumps are deenergized and the mode is terminated.

Mode 2 - Storage-to-Preheat - This mode activates when the temperature of the solar thermal storage exceeds the temperature on the discharge side of the DHW preheat exchanger by approximately 10°F. Pumps in the solar thermal storage to DHW preheat exchanger loop are activated. The water flows from solar thermal storage through the DHW heat exchanger and back to storage. The city water is preheated, on demand, as it passes through the DHW preheat heat exchanger. This mode terminates when the temperature of the hot water on the discharge side of the DHW preheat heat exchanger is within approximately 3°F of the temperature of solar thermal storage.

JUNE 3, 1981

Figure A-5. Cathedral Square Solar Energy System Schematic

Figure A-6. Energy Flow Diagram for Cathedral Square
October 1981 through September 1982
(Figures in million BTU)

FACILITIES DEVELOPMENT

The Facilities Development Company site is a three-story multi-family condominium consisting of 31 units in San Diego, California. Solar energy is used for preheating Domestic Hot Water (DHW) for the complex. The solar energy system has an array of flat-plate Revere collectors with a gross area of 520 square feet. The array faces south at an angle of 42 degrees to the horizontal.

The Revere Sun-Aid No. 211 collector panels have two glass covers and a nonselective absorber surface. The absorber surface has a solar absorptivity of 0.96 and an infrared emissivity of 0.11. Total solar transmissivity of the glazing is 0.86. The absorber surface is composed of black painted copper. The fluid circulated through the collectors is water.

The differential controller is a Heliotrope General Model DTT200 with freeze protection cycle, 9°F "on" temperature differential and 3°F "off" differential.

Potable water is the transfer medium that transports solar energy from the collector array to an underground insulated 1,000-gallon glass-lined Santa Fe storage tank. Preheated water from the storage tank is supplied, on demand, to 31 conventional Ruudglas 52-gallon DHW tanks. When solar energy is insufficient to satisfy the load, electric heating elements within the individual DHW tanks are energized.

The system, shown schematically in Figure A-7, has two modes of solar operation.

Mode 1 - Collector-to-Storage - This mode activates when the water temperature in the collectors is 9°F higher than the temperature of the storage tank. Water is pumped through the collectors and circulates back to storage until the temperature difference is 3°F or less.

Mode 2 - Storage-to-DHW Tank - This mode activates when there is a demand for hot water replenishment by an individual DHW tank. Water from storage circulates through a supply service loop to the individual DHW tank and returns through a service line to storage. The water temperature in each DHW tank is thermostatically controlled. When required, additional energy is supplied by electric heating elements within each tank.

1001 COLLECTOR PLANE TOTAL SOLAR IRRADIATION
1001 OUTDOOR TEMPERATURE

Figure A-7. Facilities Development Solar Energy System Schematic

Figure A-8. Energy Flow Diagram for Facilities Development
January 1980 through December 1980
(Figures in million BTU)

FIRST MANUFACTURED HOMES LOT 9

The First Manufactured Homes Lot 9 site is a single family residence located in Lubbock, Texas. First Manufactured assembles houses in a factory and wheels them to the desired location. The building has 1,280 square feet of living area. Solar energy is used for space heating and preheating Domestic Hot Water (DHW). The solar energy system has an array of nine Payne #175A408SCS flat-plate collectors, with a gross area of 288 square feet. The array faces south at an angle of 45 degrees from the horizontal.

The collectors have a single 3/16-inch low-iron glass cover with 0.90 solar transmittance. The absorber is corrugated aluminum sheet, painted flat black. This surface has an absorptivity of 0.90 and an emissivity of 0.85. Insulation behind the absorber is one and one-half inch fiberglass. All collectors are ducted in parallel.

The control unit is a B.D. Payne Company 851BSSC solar controller, using thermistor sensors. This unit controls all functions of the solar and auxiliary systems.

The collectors use air to collect and deliver solar energy to 20,520 pounds of rock located in a storage bin located within the house. An air-to-liquid heat exchanger, located near the collector array outlet, is used to heat water in an 82-gallon preheat tank.

Solar energy is supplied to meet the space heating requirements either directly from the collector array or from the rock storage bin. Solar heated water from the 82-gallon preheat tank is supplied to the cold water inlet of a 42-gallon DHW tank. The space heating subsystem uses a heat pump for auxiliary heating (manufactured by B.D. Payne, #541B028SHP). Both the space heating subsystem and the DHW subsystem utilize electric resistance heaters for auxiliary thermal energy.

The system, shown schematically in Figure A-9, has five modes of operation.

Mode 1 - Collector-to-Storage - When the temperature of the collectors is at least 25°F greater than the bottom of the storage bin and the building is not demanding heat, the controller will energize the solar blower and the collector air director motor. Solar energy will then be supplied to the storage bin until the temperature differential drops below 10°F.

Mode 2 - Direct Solar-to-Space Heating - For this operating mode, three conditions must be met. The first is that a 25°F temperature differential must be maintained between the collector sensor and the sensor in the bottom of the storage bin. The second is that the sensor located near the top of the rock storage bin must measure a temperature of 80°F or higher. The third is that the first stage of the building thermostat must demand heat.

When these three conditions have been met, the controller will energize the space heating blower, the solar blower, the solar air director in the collector ducts, and the solar air director in the space heating ducts.

NOTE: The water heating mode will take place concurrently with Mode 1 and Mode 2 when the control sensors indicate that solar energy is available to preheat the domestic hot water.

Mode 3 - Storage-to-Space Heating - To heat the indoor conditioned space using stored solar energy, three conditions must be met. The first is that the building thermostat must demand heat. The second is that the sensor in the top of the rock storage bin must have a temperature greater than 80°F, indicating sufficient energy in the storage bin. The third is that the temperature differential between the collector sensor and the sensor in the bottom of the bin must be less than 25°F, indicating that direct solar energy from the collector is not available.

When these three conditions are met, the controller will energize the indoor space heating air director and blower.

If heat from the storage bin is unable to meet the building demand, the second stage of the building thermostat will energize the electric resistance auxiliary heaters. These will supply auxiliary energy concurrently with the addition of energy from the rock storage bin. To prevent excessive heat pump pressures, the heat pump compressor is locked off whenever some or all the heating requirements can be supplied with solar energy.

Mode 4 - Preheating Domestic Hot Water - When the temperature of the collectors is at least 25°F greater than the preheat tank, system controls energize the solar blower and DHW pump. This mode will continue until the water temperature in the preheat tank reaches 160°F, or the temperature differential drops below 10°F. The water preheating mode receives the highest priority; therefore, it can activate during the summer when no solar energy is added to the rock storage bin.

Mode 5 - Auxiliary Space Heating - When solar energy is not available from either the collectors or storage, heating will be provided by the heat pump. If the outside ambient temperature is below 0°F or if the heat pump cannot supply the heating demand, the electric resistance heaters energize to supply auxiliary heating.

Figure A-9. First Manufactured Homes Lot 9 Solar Energy System Schematic

Figure A-10. Energy Flow Diagram for First Manufactured Homes Lot 9
 October 1981 through February 1982
 (Figures in million BTU)

FIRST MANUFACTURED HOMES LOT 10

The First Manufactured Homes Lot 10 site is a single family residence located in Lubbock, Texas. The building has 1280 square feet of living area. Solar energy is used for space heating and preheating Domestic Hot Water (DHW). The solar energy system has an array of nine Payne #175A408SCS flat-plate collectors, with a gross area of 288 square feet. The array faces south at an angle of 45 degrees from the horizontal. The collectors use air to collect and deliver solar energy to 20,520 pounds of rock located in a storage bin located within the house. An air-to-liquid heat exchanger, located near the collector array outlet, is used to heat water in an 82-gallon preheat tank.

The collectors have a single 3/16-inch low-iron glass cover with 0.90 solar transmittance. The absorber is corrugated aluminum sheet, painted flat black. This surface has an absorptivity of 0.90 and an emissivity of 0.85. Insulation behind the absorber is one and one-half inch fiberglass. All collectors are ducted in parallel.

The controller is a B.D. Payne Company 851BSSC solar controller identical to the one used in First Manufactured Homes Lot 9.

Solar energy is supplied to meet the space heating requirements either directly from the collector array or from the rock storage bin. Solar heated water from the 82-gallon preheat tank is supplied to the cold water inlet of a 42-gallon DHW tank. Both the space heating subsystem and the DHW subsystem utilize electric resistance heaters for auxiliary energy.

The system, shown schematically in Figure A-11, has five modes of operation.

Mode 1 - Collector-to-Storage - When the temperature of the collectors is at least 25°F greater than the bottom of the storage bin and the building is not demanding heat, the controller will energize the solar blower and the collector air director motor. Solar energy will then be supplied to the storage bin until the temperature differential drops below 10°F.

Mode 2 - Direct Solar-to-Space Heating - For this operating mode, three conditions must be met. The first is that a 25°F temperature differential must be maintained between the collector sensor and the sensor in the bottom of the storage bin. The second is that the sensor located near the top of the rock storage bin must measure a temperature of 80°F or higher. The third is that the first stage of the building thermostat must demand heat.

When these three conditions have been met, the controller will energize the space heating blower, the solar blower, the solar air director in the collector ducts, and the solar air director in the space heating ducts.

NOTE: The water heating mode will take place concurrently with Mode 1 and Mode 2 when the control sensors indicate that solar energy is available to preheat the domestic hot water.

Mode 3 - Storage-to-Space Heating - To heat the indoor conditioned space using stored solar energy, three conditions must be met. The first is that the building thermostat must demand heat. The second is that the sensor in the top of the rock storage bin must have a temperature greater than 80°F, indicating sufficient energy in the storage bin. The third is that the temperature differential between the collector sensor and the sensor in the bottom of the bin must be less than 25°F, indicating that direct solar energy from the collectors is not available.

When these three conditions are met, the controller will energize the indoor space heating air director and blower.

If heat from the storage bin is unable to meet the building demand, the second stage of the building thermostat will energize the electric resistance auxiliary heaters. These will supply auxiliary energy concurrent with the addition of energy from the rock storage bin.

Mode 4 - Preheating Domestic Hot Water - When the temperature of the collectors is at least 25°F greater than the preheat tank, system controls energize the solar blower and DHW pump. This mode will continue until the water temperature in the preheat tank reaches 160°F, or the temperature differential drops below 10°F. The water preheating mode receives the highest priority; therefore, it can activate during the summer when no solar energy is added to the rock storage bin.

Mode 5 - Auxiliary Space Heating - When solar energy is not available from either the collectors or storage, heating will be provided exclusively by the electric resistance heaters.

- 1001 COLLECTOR PLANE TOTAL INSOLATION
- ▶ T001 OUTDOOR TEMPERATURE
- ▶ T650 INDOOR TEMPERATURE

Figure A-11. First Manufactured Homes Lot 10 Solar Energy System Schematic

Figure A-12. Energy Flow Diagram for First Manufactured Homes Lot 10
October 1981 through February 1982
(Figures in million BTU)

FOREST CITY DILLON

The Forest City Dillon site is a high-rise apartment building in Washington, D.C. The building has 188 apartments and a total of 124,000 square feet of living space. Solar energy is used to preheat the Domestic Hot Water (DHW).

The solar energy system has 12 arrays of flat-plate collectors with a gross area of 2,592 square feet. The arrays face south at an angle of 40 degrees from the horizontal. The collectors are manufactured by Lennox, Model LSC-18-1S. A light hydrocarbon solution is the transfer medium that delivers solar energy from the collector arrays to a hot water heat exchanger.

The collector panels have one glass cover and a selective absorber surface. The absorber surface has a solar absorptivity of 0.94 and an infrared emissivity of 0.10. Total solar transmissivity of the glazing is 0.96. The absorber surface is composed of a steel absorber plate with a black chrome coating. The fluid circulated through the collectors is Brayco 888 oil.

The control system is manufactured by Rho Sigma, Model RS104.

Preheated water is stored in a 3,200-gallon storage tank and supplied, on demand, to a conventional 400-gallon hot water tank. When solar energy is insufficient to satisfy the total load, three oil-fired boilers provide auxiliary thermal energy.

The system, shown schematically in Figure A-13, has only one mode of solar operation.

Mode 1 - DHW Preheating - This mode activates when the temperature of the collector solar fluid exceeds the water temperature of the preheat storage tank by approximately 25°F. Pumps P1 and P2 are activated. The solar fluid passes through a heat exchanger, where heat is transferred to circulating water. The preheated water then flows through the storage tank until the preheated water temperature approximates the solar fluid temperature within 10 to 15°F. Pumps P1 and P2 then shut off.

As hot water is drawn from the DHW tank, it is replenished with preheated water from the storage tank. When necessary, the water can be heated further by an oil-fired heat exchanger. This conventional heat exchanger is in a DHW circulation loop containing pump P4. Pump P4 is activated when the DHW storage temperature drops below the 135°F service-water temperature requirement.

Pump P5 activates when the recirculation return temperature drops below a nominal 130°F. If the storage temperature is greater than the recirculation return temperature by a nominal 5°F, then recirculation flow is passed through storage to utilize solar energy.

Figure A-13. Forest City Dillon Solar Energy System Schematic

Figure A-14. Energy Flow Diagram for Forest City Dillon
January 1981 through December 1981
(Figures in million BTU)

GENERAL ELECTRIC-DALLAS

The General Electric-Dallas site is a single family residence located in Dallas, Texas. The solar energy system is designed to provide space cooling, space heating, and Domestic Hot Water (DHW) for the residence. The system contains a 400-gallon storage tank and a 365-square-foot collector array containing 21 panels of General Electric Solartron vacuum tube solar collectors, Model TC-100.

The General Electric TC-100 solar collectors utilize florescent lamp tubes fabricated into a thermos bottle unit. Collected energy is removed from the tubes by an independent hydronic copper system. The concentrating ratio is 1.1, with an aluminized glass surface and a vapor deposited surface on the copper tubes.

Solar cooling is provided by a solar-driven Rankine engine which, in turn, drives a vapor compressor chiller/heat pump. An electric motor is used for auxiliary power to the chiller. Solar heating is provided by circulating solar heated water from storage to a water/air heat exchanger. Auxiliary heating is provided by the heat pump and an electric strip heater. Solar preheating of DHW uses a heat exchanger located in the solar storage tank. Auxiliary energy is provided by a gas-fired boiler.

The system shown schematically in Figure A-15, has six modes of solar operation. However, because complete control documentation is presently unavailable, much of this description was written using control logic as seen from data analysis. Thus, control set points should be taken as approximate values only.

Mode 1 - Collector-to-Storage - When the insolation rate reaches 100 BTU/ft²-hr, pump P1 is turned on, initiating collector loop flow. Pump P2 is turned on when the collector outlet temperature rises 10°F above the temperature of the storage tank. This pumps water from storage through the heat exchanger located in the collector loop.

Mode 2 - Solar Cooling - When the temperature of storage reaches 270°F and there is a demand for cooling, pump P3 is activated. Valve V4 is positioned so that water from storage is pumped directly to the Rankine engine. The Rankine engine is used to drive the vapor compressor chiller. The chilled water from the chiller is then delivered to a heat exchanger in the air duct where the air is chilled and delivered to the space.

Mode 3 - Auxiliary Cooling - If, after 15 minutes of Rankine operation, the Rankine is unable to meet the power demand of the compressor, or, if the storage temperature is less than 270°F, the Rankine is decoupled from the chiller and an auxiliary electric motor is used to power the chiller.

Mode 4 - Space Heating, Outside Air Temperature 40°F - When there is a demand for space heating, valve V4 is positioned to allow solar storage flow to a heat exchanger located in the air duct. If the temperature of storage is greater than 105°F, then pump P3 is activated and solar heated water from storage is delivered to the heat exchanger. If the temperature of storage drops below 90°F, this flow will stop. If solar heating is unable to meet the heating demand, the chiller/heat pump is activated and used to heat the space. If this combined energy source is still unable to meet the heating demand, the strip heater located in the air duct is used to meet the deficit.

Mode 5 - Space Heating, Outside Air Temperature Less Than 40°F - This mode is similar to that mentioned above except that the heat pump is not used. Heating is provided by solar energy and heat strip only.

Mode 6 - Preheating Domestic Hot Water - Supply water for DHW is preheated by passing through a heat exchanger located in the solar storage tank. Valve V3 is manually positioned to temper water returning from the heat exchanger with incoming supply water so that the temperature of the water delivered to hot water storage does not exceed 150°F. The DHW storage tank is maintained at 150°F by a gas-fired boiler.

- I001 COLLECTOR PLANE TOTAL INSOLATION
- ▶ T001 OUTDOOR TEMPERATURE
- ▶ T002 3-TON S/A DHF

REVISED 5/23/80

Figure A-15. General Electric-Dallas Solar Energy System Schematic

Figure A-16. Energy Flow Diagram for General Electric-Dallas
 October 1980 through March 1981
 (Figures in million BTU)

GSA/FEDERAL YOUTH CENTER

The GSA/Federal Youth Center solar energy site is located in a prison near Bastrop, Texas. This facility consists of youth housing units, administration offices, prison industries, academic and vocational training, a clinic, recreation, and support services. The "downtown" buildings consist of administrative offices, cafeteria, recreational facilities, and a hospital. The combination of buildings to which solar energy makes a space heating and cooling contribution has a floor area of approximately 149,671 square feet. The solar energy system is designed to provide 46% of the annual heating demand, nine percent of the annual cooling demand, and 97% of the annual Domestic Hot Water (DHW) demand.

The solar energy system consists of 21,760 square feet of single-glazed, selective-coated collectors manufactured by Cole Solar Systems (Model 306-G1S). Orientation is 30 degrees west of south and 25 degrees from the horizontal. The 1,184 collectors are all located on the roof structures and are connected in a series-parallel arrangement. This results in small groups of collectors (four to 10) connected in parallel which have a common output connected in series to the common input of a second identical group. Solar heated water is stored in two interconnected tanks outside the equipment room. Water returning from the collectors enters a 15,000-gallon storage tank. For freeze protection, the collector loop uses the drainback method.

The collector panels have a single 1/8-inch glass cover of tempered water-white glass. The absorber surface has a selective black chrome coating. The absorber riser tubes are copper soldered to the absorber. The heat transfer fluid circulated through the collectors is water. The drainback system design prevents freezing by pumping the water out of the collectors and into the hot storage tank.

The pneumatic control system was manufactured by Powers Regulator Company.

Domestic hot water heating is accomplished by drawing hot water from the smaller, hotter storage tank through a heat exchanger and returning it to the storage tank. The DHW recirculating loop to the "downtown" buildings flows through this heat exchanger and the auxiliary DHW heater.

Space heating is provided by pumping water from the smaller storage tank through a separate heat exchanger. The space heating circulating loop from the dormitories flows through this heat exchanger, then to the auxiliary boilers where additional heat is added if necessary.

Space cooling is supported by circulating water from the smaller storage tank through an absorption chiller. Auxiliary energy may supplement or be used in place of the solar energy through use of

fossil boilers and a heat exchanger. Further auxiliary cooling is provided through two centrifugal chillers.

The system, shown schematically in Figures A-17 and A-18, has four modes of solar operation.

Mode 1 - Collector-to-Storage - This mode is entered when the temperature sensor on the collector absorber plate rises to 20°F above the temperature of storage tank 2. Collection is terminated when the differential temperature falls below 3°F. Collector pump P32 may operate at three possible speeds, depending on the rate of solar energy absorption. As the temperature difference between the collector plate and the storage tank increases, the pump speed increases. Similarly, when possible, the pump speed decreases to the next level as the difference in temperature falls. Whenever storage tank 2 temperature at the pump inlet exceeds 185°F, the pump is turned off.

Mode 2 - Domestic Hot Water Heating - DHW heating is accomplished by circulating water from storage tank 1 by either pump P29 or P30 through heat exchanger HX2. Modulating valves maintain the water leaving the tube section below 145°F and a 3°F temperature loss across the solar side of the heat exchanger. A valve also determines whether larger pump P30 or smaller pump P29 is necessary to provide circulation. Auxiliary DHW heating is supported by boiler 3 and pump P23 which circulate water through a heat exchanger in the DHW heater. DHW heating in the dormitory section is accomplished by means of heat exchangers in the space heating loop in these buildings.

Mode 3 - Space Heating - Space heating is accomplished by circulating water from storage tank 1 by either pump P27 or P28 through heat exchanger HX1. Modulating valves maintain the water leaving the tube section below 145°F and maintain a 3°F temperature loss across the solar side of the heat exchanger. A modulating valve also determines whether larger pump P27 or smaller pump P28 is necessary to provide circulation. Auxiliary space heating during the winter is provided by using pumps P17 and P18 to circulate through boilers 1 and 2. During the summer, boiler 3 is used to provide auxiliary energy instead of boilers 1 and 2. Circulation from the boiler is produced by pump P33 through heat exchanger HX4. A modulating valve maintains a water temperature of 140°F leaving the tube section of the heat exchanger. When boiler 3 is used, circulation in the space heating loop is required during the summer since this loop also provides DHW in the dormitory buildings.

Mode 4 - Space Cooling - Space cooling is accomplished by using pump P31 to circulate hot water from the storage tank through the generator of the absorption chiller. The storage tank temperature necessary to start the absorption chiller varies from 182°F to 196°F and is determined from the sunshine forecast and the overnight low forecast. When the storage tank drops below 175°F or the load is not being met, valve V7 opens, V8 closes, and pumps P31 and P26 start. This allows boilers 1 and 2 to supply energy

to the absorption chiller. Two centrifugal chillers are also available for auxiliary space cooling. Solar heated water, used in this and the previous two modes, returns to the storage tanks through valve V6. Valve V6 compares the temperature of the returning water with the temperature of tank 1, and, if the temperature of the returning water is below that of tank 1, the water is diverted into tank 2.

Figure A-17. GSA/Federal Youth Center Solar Energy System Schematic 1

Figure A-18. GSA/Federal Youth Center Solar Energy System Schematic 2

Figure A-19. Energy Flow Diagram for GSA/Federal Youth Center
 October 1980 through May 1981
 (ECSS and Space Heating Subsystems only)
 (Figures in million BTU)

HEI WAI WONG

The Hei Wai Wong site is a four-story apartment building in Honolulu, Hawaii. Three separate solar energy systems are used to provide solar energy for hot water. One of these systems participated in the NSDN program. This system supplies hot water for six apartments and a laundry used by the occupants of the apartments. The six apartments are occupied by 12 adults and seven children.

The participating NSDN system consists of an array of 807 square feet of flat-plate collectors manufactured by Raypak, Inc. of Westlake Village, California. The collectors face due south at a tilt of 24 degrees from the horizontal.

The SG-18P collectors have one glass cover with a selective absorber surface. The absorber surface has a solar absorptivity of 0.95 and an infrared emissivity of 0.71. Total solar transmissivity of the glazing is 0.91. The absorber surface is composed of aluminum.

No controls were used on the collector array.

Solar energy is stored in a 1,230-gallon tank filled with water. The tank is mounted on a tower on the roof, with the bottom of the tank slightly higher than the top of the collector plates. When the sun heats the water in the collectors to a temperature above that of the water in the tank, a thermosiphon current is created in the collector loop. Because the tank is higher than the collectors, the thermosiphon flow stops when the temperature of the water in the tank is higher than that in the collectors. No electrical power is used to operate the collector system.

The entire solar system operates at city water pressure. Hot water is supplied to the apartments and laundry from the top of the storage tank so that the hottest water available in storage is always used. Cold water supplied from the city water system is fed directly to the bottom of the collector panels. Hot water going to each apartment passes through individual 30-gallon electrical hot water heaters located in each apartment. These heaters boost the temperature of the hot water from the solar storage when solar energy is insufficient to satisfy the hot water requirements. Auxiliary heating of the hot water for the laundry is provided by an 85-gallon gas hot water heater.

The solar energy system is shown schematically in Figure A-20.

Figure A-21. Energy Flow Diagram for Hei Wai Wong
November and December 1979 and April through August 1980
(Figures in million BTU)

HOGATE'S RESTAURANT

The solar energy system of Hogate's Restaurant in Washington, D.C. supplies part of the energy necessary to heat approximately 10,000 gallons of Domestic Hot Water (DHW) each day. The DHW is used by the restaurant's kitchen and must be maintained at a temperature of 150°F.

The solar energy system was added to the existing water heating system and has an array of Sunworks "Solelector" flat-plate collectors with a gross area of 6,254 square feet. The array faces southwest at an angle of 55 degrees from the horizontal. The collector panels have double glass covers and a selective absorber surface. The absorber surface has a solar absorptivity of 0.87 and an infrared emissivity of 0.07. Total solar transmissivity of the glazing is 0.07. The absorber surface is composed of black nonelectrolytic thin-film oxide coated copper. The fluid circulated through the collectors is 40% propylene glycol/water. Insulation is 2.5-inches thick, with an R-value of 10.

Propylene glycol and water is the transfer medium that delivers solar energy from the collector array to storage and to the hot water load. Potable water is isolated from the heat transfer fluid by a liquid-to-liquid heat exchanger. Solar heated water is stored in two insulated 5,000-gallon tanks which are located in the garage. When solar energy is insufficient to satisfy the hot water load, a gas-fired boiler provides auxiliary energy for water heating.

The system, shown schematically in Figure A-22, has two modes of operation.

Mode 1 - Collector-to-Storage - This mode activates when the temperature difference between the collector absorber plate and the water in the bottom of tank T2 exceeds the temperature setting in the controller. Pumps P1 and P3 turn on to circulate the solar heated water; pumps P2 and P4 are backup pumps. Water in the DHW preheat loop circulates from tank T2, through the heat exchanger to tank T1, and returns to tank T2. This mode terminates when the temperature difference between the collector plate and the cooler tank T2 is less than the control setting, or the temperature of tank T1 is higher than 180°F.

Mode 2 - Storage-to-Load - This mode activates when there is a hot water demand. In this mode, makeup water from the cold water supply flows through valves V7 and V6, replacing the preheated water in tank T2. Before entering the DHW recirculation loop, preheated water from tank T1 may be mixed with cold water by tempering valve V1 to maintain the design temperature of 150°F. If there is insufficient solar energy in storage to maintain this design temperature, the water is heated to 150°F by the existing boiler.

1001 COLLECTOR PLANE TOTAL SOLAR IRRADIATION
1001 OUTDOOR TEMPERATURE

APRIL 30, 1980

Figure A-22. Hogate's Restaurant Solar Energy System Schematic

• • 12-MONTH TOTAL EXTRAPOLATED FROM
AVERAGE VALUE FOR SEVEN MONTHS

Figure A-23. Energy Flow Diagram for Hogate's Restaurant
January 1980 through December 1980
(Figures in million BTU)

KALIN HOME

The Kalin Home is a single family residence in East Meadow, Long Island, New York. The home has approximately 1,300 square feet of conditioned space. Solar energy is used for preheating Domestic Hot Water (DHW) and is designed to provide 60% of the DHW requirements. The solar energy has an array of two flat-plate collectors, manufactured by Solar Thermal Systems, a Division of Exxon Corporation, with a gross area of 42 square feet. The array faces six degrees east of south at an angle of 36 degrees from the horizontal.

The controller is a Rho Sigma RS-120.

This system is a drainback solar system. Preheated water is supplied to a solar heat exchanger equipped 120-gallon stone-lined DHW tank. An electrical heating element in the DHW tank provides auxiliary energy for water heating. This site utilizes off-peak power to heat DHW at night on only the upper two-thirds of the 120-gallon tank. The off-peak power is available from midnight to 7:00 a.m. daily. The homeowners are part of a 600-site LILCO (Long Island Light Company) solar project.

The system, shown schematically in Figure A-24, has two modes of solar operation.

Mode 1 - DHW solar heating occurs when the 1/12-hp pump switches on and fills the collector loop from the drainback reservoir. The system is activated when control sensors determine an 8°F to 12°F differential exists between the bottom of the water heater heat exchanger and the collector outlet. The pump turns off when the differential reduces to 2°F.

Mode 2 - On an off-peak timer-relay, auxiliary DHW heating can be provided by a 4.5-kw element heater fitted in the solar storage tank. This element is monitored for "on" time by a Martin timer. The off-peak auxiliary energy is available only from midnight to 7:00 a.m. Hot water from the tank is then tempered for use by the tempering valve with a set point of 120°F to 125°F.

- I001 TOTAL INSOLATION
- T001 OUTDOOR AMBIENT TEMPERATURE
- DS810 SOLAR CIRCUIT BREAKER
- T600 MECHANICAL ROOM TEMP

OCTOBER 23, 1981

Figure A-2L: Kalin Home Solar Energy System Schematic

* Denotes unavailable data

Figure A-25. Energy Flow Diagram for the Kalin Home
October 1981 through September 1982
(Figures in million BTU)

LAKE VALLEY FIREHOUSE

The Lake Valley Firehouse Number 2, located at Tahoe Paradise, California, is a small fire station using solar energy to preheat Domestic Hot Water (DHW) and provide space heating and snow melting. The solar energy system is designed to supply approximately 50% of the space heating and DHW energy requirements for the building. The upstairs dayroom and kitchen are heated by baseboard radiators. The downstairs sleeping quarters and engine room are heated by pipes in the concrete floor. Auxiliary energy is provided by a 325,000 BTU/hr propane-gas-fired boiler, a 52-gallon propane-gas-fired DHW heater, and an upstairs wood stove. In addition, a unique snow-melting capability is provided to the front ramp by circulating solar heated water through coils beneath a specially designed asphalt ramp. Since the ramp can use solar energy at much lower temperatures than is practical for space heating, it is expected to increase the total solar energy used by the system.

The solar energy system has an array of nine flat-plate collectors manufactured by Solargenics, Inc., Model 75-20. The array has a gross area of 572 square feet. The collector array, mounted on an A-frame structure in the backyard, faces south at an angle of 55 degrees from the horizontal. A 20% ethylene glycol solution is used as the medium for delivering solar energy from the collector array to the water thermal storage tank. The collector panels have one glass cover and a selective absorber surface. The absorber surface has a solar absorptivity of 0.91 and an infrared emissivity of 0.08. Total solar transmissivity of the glazing is 0.91. The absorber is composed of an aluminum plate with aluminum flow tubes coated with black chrome on dull nickel.

The water thermal storage tank is located aboveground. The tank has four inches of foam insulation with an R factor of 30 and has a capacity of 1,200 gallons. The actual volume of water is varied from 600 gallons to 1,200 gallons, depending on the season. The DHW subsystem consists of a heat exchanger and a gas-fired DHW heater. Makeup water is preheated by passing through a heat exchanger located in the thermal storage tank prior to entering the DHW heater. Auxiliary energy is supplied by the DHW heater to maintain a DHW temperature of 120°F. Makeup water flows from the cold water supply through heat exchanger HX1 and the DHW heater under city water pressure. The space heating and snow-melting subsystems consist of a heat exchanger in the thermal storage tank, a gas-fired boiler for auxiliary heating, two circulation pumps, and heating coils.

The energy for space heating and snow melting is supplied from either the thermal storage tank or from the gas-fired boiler, but not from both simultaneously. While supplying energy from the gas-fired boiler, solar energy can be concurrently collected to heat water in the thermal storage tank and preheat DHW. If snow melting is desired while space heating is active, both loads must

receive energy from the same source. Space heating cannot be performed with auxiliary energy while using solar energy to melt snow.

The system, shown schematically in Figure A-26, has the following five modes of operation.

Mode 1 - Collector-to-Storage - This mode is entered when the differential temperature between the collector surface and water in the storage tank is greater than 10°F. A Heliotrope General (Delta-T) differential controller then energizes pump P1. Pump P1 maintains circulation of water between the thermal storage tank and collectors until the differential temperature is less than 2°F.

Mode 2 - Storage-to-Space Heating - This mode is entered when any of three thermostats indicates a demand for heating and the temperature of the water in the storage tank is greater than 75°F. Pump P2 is energized and a solution of 28% ethylene glycol and 72% water is circulated from heat exchanger HX2 to any of three heating coils. Valve V1 will allow flow from port A to port AB. Valve V2 will blend flow from ports A and B to port AB. Each of three areas requiring space heating has a thermostat-controlled solenoid valve which allows space heating to be controlled for each area.

Space heating in the upstairs dayroom and kitchen is supplemented with auxiliary energy from a wood stove. The amount of this auxiliary energy supplied for space heating is unknown.

Snow melting from the engine ramp is manually controlled as described in Mode 3. Operation of Mode 3 is possible concurrently with Mode 2, but this is not typical.

Mode 3 - Storage-to-Snow Melting - This mode is manually controlled. Pump P3 is energized and a solution of 28% ethylene glycol and 72% water is circulated from heat exchanger HX2 to the heating coil embedded in an asphalt ramp. Valve V3 will blend flow from ports A and B to port AB.

This mode is inoperative when the auxiliary boiler supplies energy for space heating. Typically this mode would be entered when the temperature of the water in the storage tank was less than 100°F and there was no demand for space heating. Sufficient energy would still be available from water in the storage tank to melt snow from the asphalt engine ramp.

Mode 4 - Storage-to-Domestic Hot Water - This mode is entered when there is a demand for hot water. Makeup water flows from the cold water supply to the DHW heater through heat exchanger HX1 for pre-heating. Auxiliary energy from the DHW heater is supplied to maintain a DHW outlet temperature of 120°F.

Mode 5 - Auxiliary Boiler-to-Space Heating - This mode is entered when the thermostat indicates a demand for heating and the temperature of the water in the storage tank is less than 75°F. Pump P2 is energized and a solution of 28% ethylene glycol and 72% water is

transferred from the auxiliary boiler to the heating coil. Valve V1 will allow flow from port B to port AB. Valve V2 will blend flow from ports A and B to port AB. Each of the three areas requiring space heating has a manually controlled solenoid valve which allows all space heating to be eliminated from any area.

Space heating in the upstairs dayroom and kitchen is supplemented with auxiliary energy from a wood stove. The amount of this auxiliary energy supplied for space heating is unknown.

Operation of Mode 3 is not possible concurrently with Mode 5.

Figure A-26. Lake Valley Firehouse Solar Energy System Schematic

Figure A-27. Energy Flow Diagram for the Lake Valley Firehouse
 March 1981 through June 1981
 (Figures in million BTU)

LOUDOUN COUNTY SCHOOL

The Loudoun County School site is the Charles S. Monroe Vocational Technical School located in Leesburg, Virginia. Solar energy is used for preheating Domestic Hot Water (DHW). The solar energy system has an array of flat-plate collectors with a gross area of 1,225 square feet. The array faces 15 degrees west of south at an angle of 37 degrees from the horizontal.

The collector panels have two low-iron glass covers and a non-selective absorber surface (Nextel black velvet by 3M). The absorber surface has a solar absorptivity of 0.98 and an infrared emissivity of 0.89. Total solar transmissivity of the glazing is 0.72. The absorber surface is composed of two sheets of stainless steel (stainless 439) resistance roll welded. The circulation pump (P1) is rated 1-hp (240-volt, 3-phase).

A silicone oil solution is the transfer medium that delivers solar energy from the collector array to a heat exchanger. Solar energy is stored within the building in a 2,056-gallon water tank.

Preheated water is supplied from the solar storage tank to a 1,000-gallon DHW tank. Hot water from the DHW tank is circulated through the service hot water lines and back to the DHW tank to instantly provide hot water at the service taps. This circulation is controlled by a time clock so that circulation occurs only during hours of normal use. An electrical heating element immersed in the DHW tank provides auxiliary energy, as required, to maintain the desired 140°F service water temperature.

The system, shown schematically in Figure A-28, has four modes of operation, all of which operate independently of one another.

Mode 1 - Collector-to-Storage - This mode activates when there is a temperature difference of 20°F between a control sensor located at the collector and a control sensor located inside the storage tank (near the bottom). At this time, the controller turns on pump P1 which circulates the transport fluid through the collectors and the heat exchanger located inside the storage tank. P1 continues to operate until the temperature difference between the control sensors is less than 5°F. At this point, P1 is turned off and the mode terminates. Mode 1 will also terminate when the storage tank temperature exceeds 200°F, as measured by another control sensor near the top of the storage tank.

Mode 2 - Solar Energy Preheat - This mode activates when there is a temperature difference of 20°F between a control sensor located near the top of the storage tank and a control sensor located near the bottom of the DHW tank. At this time, the controller energizes pump P2, which delivers preheated water from the storage tank to

the DHW tank and recirculates water from the DHW tank to the storage tank. When the temperature difference between the control sensors becomes less than 5°F, pump P2 turns off and the mode terminates. An electrical element in the DHW tank is energized to provide auxiliary water heating when the DHW tank temperature falls below a set point.

Mode 3 - Recirculate - This mode activates (under time-clock control) during hours of normal use, i.e., primarily during daylight and early evening hours every day of the week except Sunday. When activated, pump P3 is energized and hot water circulates from the hot water tank through the service hot water lines and returns to the hot water tank.

Mode 4 - DHW Load - This mode activates when hot water is drawn from any of the hot water taps in the building. The hot water demand is replenished by cold water supplied to the storage tank. The make-up water to the DHW tank from the storage tank goes through P2 (if Mode 2 is active at this time) or bypasses P2 if Mode 2 is inactive. Mode 3 need not be activated to supply the demand at the hot water taps.

Figure A-28. Loudoun County School Solar Energy System Schematic

Figure A-29. Energy Flow Diagram for the Loudoun County School
 July 1979 through June 1980
 (Figures in million BTU)

LOYOLA UNIVERSITY

The Loyola University solar energy system, located in New Orleans, Louisiana, supplies energy necessary to preheat approximately 9,000 gallons of Domestic Hot Water (DHW) each day to Biever Hall Dormitory. Biever Hall is a six-story dormitory that houses 420 students. The system is designed to supply 140°F water to bathrooms, showers, and eight washing machines.

The solar energy system was added to the existing water heating system and has 15 arrays of General Energy Devices Model 2400C flat-plate collectors with a gross area of 4,590 square feet, and a net area of 4,320 square feet. The collectors face 16 degrees west of south at an angle of 38 degrees from the horizontal. The system is an open-loop system which uses potable water as both the collector fluid and storage medium.

A Hawthorne Industries BT-100 controls the solar collector operation.

City water is preheated by the flat-plate collectors on the roof and stored in a 5,000-gallon tank located on the west side of the building at ground level. Upon demand, the preheated water is transported to two existing 1,500-gallon hot water tanks. When solar energy is insufficient to satisfy the hot water load, auxiliary energy is supplied by a central heating plant via a high temperature/high pressure line.

The system, shown schematically in Figure A-30, has five modes of operation.

Mode 1 - Collector-to-Storage - This mode activates when the temperature difference between the collector outlet and the water in the bottom of the storage tank exceeds 16°F. Pump EP100, or back-up pump EP101, turns on to circulate the solar heated water from storage to collector and back to storage. This mode terminates when the temperature difference between the collector outlet and the water in the bottom of the storage tank is less than 3°F.

Mode 2 - Storage-to-Load - This mode activates when there is a hot water demand. In this mode, makeup water from the cold water supply flows through a water softener system and then to the 5,000-gallon storage tank. Solar heated water is then forced out of the top of the tank and transferred to the two 1,500-gallon DHW tanks, where, if not hot enough, auxiliary heat is used to maintain 140°F water temperature.

Mode 3 - Recirculation of DHW - Pump EP300 and, alternately, pump EP301 are used to continuously recirculate the DHW throughout the six-story dormitory. Thus, hot water is always available at the taps.

Mode 4 - Freeze Protection - When the outdoor ambient temperature is less than or equal to 38°F, Mode 4 is then activated. Warm water is pumped through the collector arrays, thus preventing freezing.

Mode 5 - Heat Rejection - When the temperature exiting the collectors equals or exceeds 180°F, a valve is activated, the water is drained and not allowed to enter the storage tank.

Figure A-30. Loyola University Solar Energy System Schematic

Figure A-31. Energy Flow Diagram for Loyola University
February 1981 through June 1981
(Figures in million BTU)

OAKMEAD INDUSTRIES

The Renault and Handley Building, referred to as Oakmead Industries, is one of two nearly identical solar heated buildings located at the Oakmead Industrial Park in Santa Clara, California. This commercial building contains approximately 60,000 square feet of floor area. The solar energy system installation is a retrofit and was originally designed to provide 85% of the annual heating requirements and 90% of the annual hot water demand.

The building has two central heating zones, one for the north zone of the building and the other for the south zone. The north zone is heated by a combination of solar energy from a liquid-based flat-plate collector array and an auxiliary gas-fired furnace. The south zone heating system provides space heating for the warehouse area. The south zone is heated by a hybrid passive/active solar energy system installed on the south wall, solar energy from the liquid flat-plate collectors, and by an auxiliary gas-fired furnace.

Staefa, Inc. (Switzerland) provided the control system for Oakmead Industries.

The Revere Sun-Aid liquid-based solar collectors utilize a 10% solution of propylene glycol in water as the heat transfer medium for collecting solar energy. The flat-plate collector array faces due south at a tilt of 45 degrees from the horizontal and employs a 2,622-square-foot collector array. The collector surface is enhanced with a black chrome selective surface and a single layer of water-white crystal glass.

The system, shown schematically in Figure A-32, has eight modes of solar operation.

Mode 1 - Liquid Collector Subsystem-to-Thermal Control Loop - In this mode, collector loop pump P1 starts if the collector plate stagnation temperature is greater than 120°F. An adjustable time delay provides an off delay for pump P1 (normally five minutes). At the end of the delay period, pump P1 will continue to operate if the collector plate temperature is 5°F greater than the Thermal Control Loop (TCL) temperature. Pump P3 is interlocked with pump P1 to provide constant operation of collector to the TCL. Pumps P1 and P3 are deactivated when the differential temperature between the collector plate and the TCL falls below 5°F.

Mode 2 - Liquid Collector Subsystem Protection - If the collector plate temperature exceeds 240°F or the top of the storage tank is greater than 200°F, valve AV3 connects the solar loop to the heat rejector, energizes the heat rejector fan, deenergizes pump P3, and energizes pump P1. This provides collector protection from extremely high temperatures. This mode is deactivated when the plate temperature falls below 240°F or the storage tank falls below 200°F.

Mode 3 - Thermal Control Loop to Storage (Liquid Subsystem) - In this mode, solar energy is transferred to storage when the TCL temperature exceeds 120°F. Valve AV2 modulates flow to and from storage while valve AV1 provides makeup water from the top or bottom of the storage tank. This mode is completely controlled by the operation of valves AV1 and AV2.

Mode 4 - Thermal Control Loop-to-Space Heating (Liquid Subsystem) - This mode is energized when there is a demand for space heating. Pump P2 is interlocked to operate with pump P3 if the TCL temperature is greater than 80°F or the storage tank top temperature is greater than 80°F. Solar energy is provided to the north and south space heating zones until there is no demand for space heating or the temperature in the TCL and storage tank falls below 80°F.

Mode 5 - Storage-to-DHW Subsystem (Liquid Subsystem) - In this mode, solar energy is transferred from the storage tank to the DHW preheat tank if the DHW preheat tank is less than 160°F, storage tank is greater than 100°F, and the storage tank temperature is 10°F greater than the DHW preheat tank. Pump P4 is activated to deliver energy to the DHW subsystem and deactivates when the difference between the storage tank temperature and the DHW preheat tank falls below 5°F.

Mode 6 - Auxiliary Space Heating (Liquid and Air Subsystems) - This mode activates when there is a need for space heating and solar energy is insufficient to meet the demand. The auxiliary gas-fired furnace will provide the remaining building space heating demand. (There are two gas-fired furnaces for the north and south heating zones.)

Mode 7 - Auxiliary Hot Water Heating (Liquid Subsystem) - In this mode, auxiliary hot water is provided by an electric heater. If solar energy is insufficient, then the electric hot water provides auxiliary energy upon demand. The DHW tank is maintained at a control set point of approximately 140°F.

Mode 8 - Air Collector Subsystem-to-Space Heating - This mode activates when there is a need for space heating in the south zone only. If the temperature in the air collectors is greater than 85°F, then the fan in the auxiliary furnace will activate to deliver heated air to the south zone. This mode is deactivated when the temperature in the air collectors falls below 85°F or there is no space heating demand in the south zone. (The return plenum damper is closed during the summer months.)

- I001 COLLECTOR PLANE TOTAL INSOLATION
- ▶ T001 OUTDOOR TEMPERATURE
- V001 WIND SPEED
- D001 WIND DIRECTION
- RH901 OUTDOOR RELATIVE HUMIDITY

- I002 COLLECTOR PLANE TOTAL INSOLATION
- ▶ T002 OUTDOOR TEMPERATURE

REVISED 12/3/79

Figure A-32. Oakmead Industries Solar Energy System Schematic

| Denotes invalid data.

Figure A-33. Energy Flow Diagram for Oakmead Industries
October 1981 through April 1982
(Figures in million BTU)

SADDLE HILL TRUST LOT 36

The Saddle Hill Trust Lot 36 site is a single family residence in Medway, Massachusetts. Solar energy is used for space heating the home and preheating Domestic Hot Water (DHW). The system has an array of 14 liquid flat-plate Daystar Model 2001 collectors with a gross area of 315 square feet. The array faces south at an angle of 58 degrees from the horizontal.

A Rho Sigma controller operates the solar collector pump.

A 60% glycerol solution is the transfer medium that delivers solar energy from the collector array to storage; water is the transfer medium that delivers solar energy from storage to the space heating and hot water loads. Solar energy is stored in the basement in a 750-gallon storage tank. The tank is made of steel and lined with polyurethane. Preheated city water is supplied, on demand, to a conventional 80-gallon DHW tank. When solar energy is insufficient to satisfy the space heating load, a Friedrich Model QUA-112-AMA oil furnace provides auxiliary energy for space heating. Similarly, the conventional electric Vaughn Model C8N2 80-gallon DHW heater provides auxiliary energy for water heating.

The system shown schematically in Figure A-34, has three modes of operation.

Mode 1 - Collector-to-Storage - This mode activates the collector solar pump when the collector temperature is either more than 40°F higher than storage temperature or higher than 150°F. Solar energy transfer takes place through a heat exchanger located inside the storage tank.

Mode 2 - Storage-to-Space Heating - This mode activates the space heating solar pump when there is a demand for space heating, storage temperature is 70°F or higher, and house temperature is lower than storage temperature. Solar energy transfer takes place through a heat exchanger located inside the air duct.

Mode 3 - Storage-to-DHW Tank - This mode activates the DHW solar pump when storage water is 5°F higher than water in the DHW tank. Solar energy transfer takes place through a heat exchanger located inside the DHW heater.

NOVEMBER 13, 1980

Figure A-34. Saddle Hill Trust Lot 36 Solar Energy System Schematic

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? Denotes unknown value.

* Number in parentheses represents portion of losses which contributes to the space heating load.

Figure A-35. Energy Flow Diagram for Saddle Hill Trust Lot 36
October 1980 through May 1980
(Figures in million BTU)

SADDLE HILL TRUST LOT 73

The Saddle Hill Trust Lot 73 site is a single family residence in Medway, Massachusetts. Solar energy is used for preheating incoming city water. The system has an array of two liquid flat-plate Daystar Model 2001 collectors, with a gross area of 45 square feet, which faces south at an angle of 45 degrees to the horizontal. A 60% glycerol solution is used as the medium for delivering solar energy from the collector array to storage. Water is the transport medium that delivers solar energy to storage and to the Domestic Hot Water (DHW) heater.

The collector panels have one glass cover and a nonselective absorber surface. The absorber surface has a solar absorptivity of 0.97 and an infrared emissivity of 0.97. Between the glass cover and the absorber plate, there is a special "heat trap" which is a thin layer of a high-temperature polymer which is folded in an accordion shape. Total solar transmissivity of the glazing is 0.83. The absorber surface is composed of a black painted copper plate. The fluid circulated through the collectors is a glycerol solution.

A Rho Sigma differential thermostat activates the solar collector pump.

Solar energy is stored in the basement in an 80-gallon preheated tank, Model SWH/TC80 manufactured by Ford Products. This preheated city water is supplied, on demand, to a conventional 40-gallon natural-gas DHW tank, Model SV-40-NRT7 manufactured by State. When solar energy is insufficient to satisfy the hot water requirements, the gas-driven DHW heater provides auxiliary energy for water heating.

The system, shown schematically in Figure A-36, has two modes of solar operation.

Mode 1 - Collector-to-Storage - This mode activates the solar pump when a 40°F temperature difference exists between the collector and the preheated tank. This mode continues operating until the temperature difference drops to 20°F.

Mode 2 - Storage-to-DHW Tank - This mode activates when there is a demand for hot water. Hot water from the top of the preheated tank is transferred to the DHW tank to replace the amount removed. Simultaneously, city water is automatically supplied to the preheated tank.

AUGUST 19, 1980

Figure A-36. Saddle Hill Trust Lot 73 Solar Energy System Schematic

Figure A-37. Energy Flow Diagram for Saddle Hill Trust Lot 73
January 1980 through December 1980
(Figures in million BTU)

SADDLE HILL TRUST LOT 77

The Saddle Hill Trust Lot 77 site is a single family residence in Medway, Massachusetts. Solar energy is used for preheating incoming city water. The solar energy system has an array of Solaron flat-plate collectors with a gross area of 78 square feet. The array faces south at an angle of 38 degrees from the horizontal. Air is used as the medium for delivering solar energy from the collector array to an air-to-liquid heat exchanger located in the collector air duct. Water is the medium used to transport solar energy from the heat exchanger to storage.

The Solaron collector panels have two glass covers and a nonselective absorber surface. The absorber surface has a solar absorptivity of 0.94 and an infrared emissivity of 0.10. Total solar transmissivity of the glazing is 0.89. The absorber surface is composed of black steel. The medium circulated through the collectors is air.

A Robertshaw Solar Commander differential thermostat, Model SD-10, provides control of the solar collectors.

Solar energy is stored in the basement in a 120-gallon preheat storage tank. This preheated city water is supplied, on demand, to a conventional State "Super Lift" Model SV-40-RRT7 40-gallon Domestic Hot Water (DHW) tank. When solar energy is insufficient to satisfy the hot water requirements, the gas-driven DHW heater provides auxiliary energy for water heating.

The system, shown schematically in Figure A-38, has two modes of solar operation.

Mode 1 - Collector-to-Preheat - This mode activates the fan and pump when the difference between the temperature of the collector air and the temperature of the water in the preheat tank exceeds 40°F and the temperature of the water in the tank is below 140°F. This mode continues until the temperature difference drops to 20°F.

Mode 2 - Preheat-to-Domestic Hot Water - This mode activates when there is a demand for hot water. Hot water from the top of the preheat tank is transferred to the DHW tank to replace water removed. Simultaneously, city water is automatically supplied to the preheat tank.

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AUGUST 19, 1980

Figure A-38. Saddle Hill Trust Lot 77 Solar Energy System Schematic

Figure A-39. Energy Flow Diagram for Saddle Hill Trust Lot 77
September 1979 through August 1980
(Figures in million BTU)

SOUTH BRIDGE TOWER

The South Bridge Towers is a high-rise cooperative housing project located in New York City. The solar energy system is used to pre-heat the Domestic Hot Water (DHW) for the 350 apartments in Tower 6. The system of 150 Daystar 21-B flat-plate collectors faces 14 degrees west of south, at a tilt of 40 degrees from the horizontal. The collector array has a gross area of 3,742 square feet and uses a 50% propylene glycol and water solution for the energy transport fluid. Additional freeze protection is provided by electric heat tapes mounted on the collector headers and exposed piping.

The Daystar 21-B Series 1200 solar collectors utilize a "Black Velvet" flat-black absorber plate coating (3M Nextel), an internal plastic heat trap folded into accordion pleats, and double covers of low-iron tempered glass.

The controller is an Independent Energy C-100 Energy Manager.

The collected solar energy is stored in a 3,750-gallon stone-lined storage tank. Preheated water leaving the storage tank is further heated by passing through the condenser cooler which uses the depleted low pressure steam return. Low pressure steam, purchased from the local utility, heats the water to delivery temperature. The water is then circulated to the apartments.

The system, shown schematically in Figure A-40, has two modes of solar operation.

Mode 1 - Collector-to-Storage - This mode activates when the temperature difference between the collectors and storage is 20°F. There is a time delay to keep the collectors from cycling on and off. This mode deactivates when the temperature difference is 3°F or less.

Mode 2 - Storage-to-Load - This mode activates when there is a hot water demand. Incoming city water is preheated in the solar storage tank and then passes through the DHW heater before being delivered to the apartments.

Figure A-40. South Bridge Tower Solar Energy System Schematic

Figure A-41. Energy Flow Diagram for South Bridge Tower
January 1981 through February 1982
(Figures in million BTU)

SPEARFISH HIGH SCHOOL

The Spearfish High School solar energy system consists of a high-volume flat-plate (Solaron, Inc.) collector array of 8,034 square feet mounted at 62 degrees tilt facing 26 degrees west of south, operated by a circulating fan on the outlet duct return to the storage air handler. Upstream of the storage rock bin, capacity 4,150 cubic feet, is a damper system which selects solar heated air flow to a Domestic Hot Water (DHW) preheat heat exchanger (36 inches x 68 inches) directly to the space heating load, to the rock bin for storage, or for simultaneous heating of the conditioned space and the storage rock bin with solar energy.

The Solaron Series 2000 flat-plate collector uses a 28-gauge steel absorber with a flat black ceramic enamel coating. Two 1/8-inch low-iron tempered-glass covers seal the steel collector pan.

Barber-Coleman controls operate the solar and HVAC system.

Auxiliary energy for space and hot water heating is provided by natural-gas-fired packaged boilers.

The system, shown schematically in Figure A-42, has three modes of operation for space heating.

Mode 1 - Collector-to-Storage - The solar energy is transferred to storage after the heating load is satisfied, by repositioning dampers so air flows from the top plenum of the rock box to the bottom plenum and back to the collector array.

Mode 2 - Collector-to-Space Heating - The solar collector air handler circulating fan is activated when the absorber plate temperature reaches 80°F. Solar heated air is moved to the air handler at the rock storage box where control logic, actuated by system demands for heat or DHW or both, determines damper positions. Mode 2 selects direct solar space heating in which solar heated air is provided to roof-mounted air handlers which make up the required thermal energy from conventional hot water boilers to satisfy the load.

Mode 3 - Collector-to-Space Heating and Storage - The collector circulating fan and the storage delivery fan can operate simultaneously in this new mode to provide both stored and direct heated solar energy to the load. This is accomplished by positioning the storage air handler dampers and opening the damper downstream of PCF2.

The DHW subsystem is enabled by operation of the main collector circulating fan. Appropriate damper positions are selected by control logic which senses hot water demand and routes water to be preheated into the air-to-water heat exchanger while damper positions are selected to route solar heated air to the heat exchanger.

Figure A-42. Spearfish High School Solar Energy System Schematic

Figure A-43. Energy Flow Diagram for the Spearfish High School
 September 1980 through May 1981
 (Figures in million BTU)

SUMMERWOOD M

The Summerwood Associates site is a cluster of condominiums overlooking Long Island Sound. Two adjacent units are instrumented: a Madison model designated Summerwood M, and a Guilford model designated Summerwood G. The Summerwood M site is described in this report.

The Summerwood M site is a rowhouse residence in Old Saybrook, Connecticut. The home has approximately 1,375 square feet of conditioned space. Solar energy is used for space heating and pre-heating Domestic Hot Water (DHW). The solar energy system has an array of flat-plate collectors with a gross area of 378 square feet. The array faces 12 degrees west of south at an angle of 50 degrees from the horizontal. Water is the transfer medium that delivers solar energy from the collector array to storage and to the space heating and DHW loads. Draindown provides collector freeze protection.

The collectors have a single 3/16-inch low-iron glass cover with 0.92 solar transmittance. The absorber is copper sheet with a selective black surface manufactured by Enthone. The surface has an absorptivity of 0.90 and an emissivity of 0.12. Fluid passages are 1/4-inch copper tubes spaced 16 inches apart with a one-inch copper manifold. The tubes are soft-soldered to the absorber sheet. Insulation behind the absorber is two and one-half inch fiberglass. The transfer fluid used is water. All collectors are plumbed in parallel. When the collector pump turns off, all fluid drains back into the storage tank.

A Johnson Controls system controls the solar system.

Solar energy is stored in a 600-gallon poured-concrete insulated tank located in a crawl space. Solar heated water is supplied to a liquid-to-air heat exchanger within the space heating duct and to a heat pump for water-to-air operation. A closed heat transfer loop between the solar storage tank and a 120-gallon DHW tank provide solar energy to the DHW supply. When solar energy is insufficient to satisfy the entire space heating load, the heat pump operates in its water-to-air mode, extracting heat from the solar heated water. When the storage tank temperature falls below 40°F, the heat pump automatically disconnects from the solar heated water supply and operates in an air-to-air mode using an outdoor evaporator. An electric heater in the space heating duct provides auxiliary energy for space heating in conjunction with both solar and conventional heating modes. An electrical heating element in the DHW tank provides auxiliary energy for water heating.

The system, shown schematically in Figure A-44, has four modes of solar operation.

Mode 1 - Collector-to-Storage - This mode activates when collector temperature exceeds the storage temperature by 15°F and terminates when a temperature difference of 2°F is reached. Collector loop pump P1 is operated in this mode.

Mode 2 - Storage-to Space Heating - Direct Solar Mode - This mode activates when there is a demand for space heating and solar storage temperature is above 85°F. Circulating pump P2 and the air-handling subsystem blower are operated in this mode.

Mode 3 - Storage-to-Space Heating - Solar-Assisted Heat Pump Mode - This mode activates when there is a demand for space heating and the solar storage temperature is less than 85°F and greater than 40°F. Circulating pump P2, the air-handling subsystem blower, and the heat pump are operated in this mode.

Mode 4 - Storage-to-DHW - This mode activates when the temperature difference between solar storage and the DHW tank exceeds 15°F and terminates when the temperature difference drops below 6°F. Pump P3 is operated in this mode.

FEB 27 1980

Figure A-44. Summerwood M Solar Energy System Schematic

Figure A-45. Energy Flow Diagram for Summerwood M
October 1980 through May 1981
(Figures in million BTU)

TELEX COMMUNICATIONS

The Telex Communications, Inc. site is a single-story manufacturing plant in Blue Earth, Minnesota. The solar energy system is a retrofit designed to provide 70% of the annual space heating requirements for the building, which has 97,000 square feet of conditioned area. The system has an array of 360 flat-plate collectors manufactured by InterTechnology/Solar Corporation. The array has a gross area of 11,520 square feet and faces south at an angle of 59 degrees from the horizontal. Water is used as the medium for delivering solar energy from the collectors to storage. The collected energy is stored in a 20,000-gallon storage tank. Gravity draindown is used for collector freeze protection.

In order to increase the performance of the collectors, a black chrome selective absorber coating and water-white glass are used. The black chrome selective coating is electroplated on a nickel-coated aluminum extension. The solar absorptivity and thermal emissivity of the black chrome coating are nominally 0.95 and 0.12 respectively. The low thermal emissivity results in reduced radiative heat losses from the absorber plate and thus increases efficiency. Honeywell controls are used.

The stored energy is transferred to the space heating subsystem by circulating the solar heated water from the storage tank to 12 parallel water-to-air heat exchangers and back to storage. Nine of the heat exchangers were installed in nine existing air-handler units; three are an integral part of space heaters with motorized fans which were added to the existing system. Fluid flow to each air-handler unit and solar space heater is individually and thermostatically controlled. Auxiliary heat is provided by electrical heat strips in each air-handler unit and by three electrical space heaters located near the solar space heaters. The air-handler units provide ventilation year-round.

The system, shown schematically in Figure A 16, has two modes of solar operation.

Mode 1 - Collector-to-Storage - This mode is entered when the temperature of the collector surface exceeds the water temperature in the water thermal storage by 25°F. Water is circulated from storage through the collectors until the storage temperature reaches 190°F, or until the difference between the collector plate temperature and storage temperature is less than 2°F.

Mode 2 - Storage-to-Space Heating - This mode is controlled by manually preset thermostats. The minimum designed operational temperature in water thermal storage is 100°F, although the control system does not inhibit operation below this temperature. Water is circulated through the heat exchangers and returned to storage until the demand is satisfied.

Figure A-46. Telex Communications Solar Energy System Schematic

Figure A-47. Energy Flow Diagram for Telex Communications
November 1979 through April 1980
(Figures in million BTU)

TERRELL E. MOSELEY

The Terrell E. Moseley, Inc. site is a 1,780-square foot, single-story, commercial office building with attached warehouse in Lynchburg, Virginia. The solar energy system is designed to provide approximately 70% of the space heating and hot water energy requirements of the office building. Because the hot water consumption is very low, only the space heating system is monitored for performance evaluation. The site has a collector array of 16 flat-plate collectors built by T.E. Moseley, Inc. The collector array has a gross area of 400 square feet, and faces south at a tilt angle of 50 degrees from the horizontal. Water is the heat transfer medium throughout the solar energy system. Collected solar energy is delivered to the 2,000-gallon storage tank, which is in an unheated attached warehouse building. The insulation on the tank is four inches of fiberglass.

The collector panels have one 3/16-inch tempered glass cover manufactured by Pittsburgh Plate Glass Co. and a nonselective absorber surface. The absorber surface has an estimated solar absorptivity of 0.95 and an infrared emissivity of 0.90. Total solar transmissivity of the glazing is 0.85 at normal incidence angles. The absorber surface is composed of a 16-gauge aluminum plate with a series of 5/16-inch OD copper tubes fastened to the plate with thermal mastic and pipe straps. The fluid circulated through the collectors is untreated water.

A Dayton differential thermostat which operates the solar collectors is part of the integrated control system for the building.

When solar energy is insufficient to maintain 55°F storage temperatures, a gas-fired boiler (auxiliary heater) provides additional energy to storage. Space heating is provided by circulating storage water through a heat exchanger located in the air distribution system of the building. In addition, a solar-assisted heat pump is employed to provide auxiliary energy to the space heating demand. Since the collector fluid automatically drains into storage after each solar energy collection operation, additional collector freeze protection measures are not required.

The system, shown schematically in Figure A-48, has three modes of solar operation.

Mode 1 - Collector-to-Storage - This mode is entered when the collector absorber plate temperature exceeds the middle storage temperature by 20°F. The transfer fluid is circulated from storage through the collectors and back to storage until this temperature differential drops to less than 3°F.

Mode 2 - Storage-to-Space Heating - This mode is entered when there is a demand for space heating and the sensed temperature of the storage water is greater than 85°F. Water is circulated between storage and liquid-to-air heat exchanger HX1 in the air-handling

unit distribution duct until the space heating demand is satisfied, or the sensed storage temperature drops below 85°F.

Mode 3 - Storage-to-Heat Pump - This mode of operation provides space heating when Mode 2 operation is not available. This mode is entered when there is a demand for space heating and the temperature of the storage water is below 85°F. Energy input to the heat pump is supplied by opening the normally closed valve V2, closing the normally open valve V1, and circulating storage water through heat pump evaporator HX2. This mode is terminated when either the sensed storage temperature rises above 90°F, or when no space heating demand exists.

1001 COLLECTOR PLANE TOTAL SOLAR IRRADIATION
T101 OUTDOOR TEMPERATURE
T601 INDOOR TEMPERATURE

Figure A-48. Terrell E. Moseley Solar Energy System Schematic

Figure A-49. Energy Flow Diagram for Terrell E. Moseley
October 1980 through April 1981
(Figures in million BTU)

VITRO TEST SITE

The Vitro Test Site is a service hot water preheat system providing hot water to a commercial office building located at the Vitro Corporation in Silver Spring, Maryland.

The 105-square-foot collector array faces south at an angle of 45 degrees from the horizontal, and is composed of four flat-plate, single-glazed Sunjammer D-277 solar collectors manufactured by Ametek, Inc., incorporating a selective-coated copper absorber plate. A 120-gallon stone-lined preheat tank with a double-walled heat exchanger provides solar heated water to a conventional electric hot water tank. The preheat tank and auxiliary tank are located in a penthouse equipment room on the roof of the three-story office building. The solar collectors are mounted on the south wall of the penthouse and are connected to the preheat tank by 80 feet of 3/4-inch copper pipe, insulated with 1/2-inch of rubber foam insulation. A propylene glycol/water mixture is circulated from the array to the preheat tank by either a 120V AC pump or a 12V DC pump powered by a small photovoltaic panel. A recirculation loop maintains hot water availability throughout the building.

An Independent Energy C-30 controller operates the AC collector pump.

The system, shown schematically in Figure A-50, has two modes of operation.

Mode 1 - AC Pump Operation - When the temperature at the collectors reaches 20°F above the storage temperature, the AC solar collector pump activates and circulates the heat transfer fluid between storage and the collectors. Pump P2 activates when return water from the recirculation loop drops below 100°F. The solar pump shuts off when the collectors are within 5°F of the storage tank temperature.

Mode 2 - DC Pump Operation - In this mode, the AC pump is switched off manually using the C-30 controller. The photovoltaic panel is directly wired to the DC pump, and when insolation reaches a level sufficient to activate the pump (around 70 BTU/ft²-hr), the heat transfer fluid circulates between storage and the collectors. When insolation drops below 70 BTU/ft²-hr, the DC pump ceases operation.

Figure A-50. Vitro Test Site Solar Energy System Schematic

Figure A-51. Energy Flow Diagram for the Vitro Test Site
January 1982 through December 1982
(Figures in million BTU)

APPENDIX B
THE f-CHART VERSION 5.1

APPENDIX B
THE f-CHART VERSION 5.1

B.1 THEORY

The f-Chart simulation program was developed at the Solar Energy Laboratory at the University of Wisconsin, Madison, Wisconsin, to aid designers and researchers in the selection of the correct size and type of solar collectors to supply a system load at minimum cost (Reference B-1).

The f-Chart was developed to provide a relatively straightforward method of predicting long-term solar system thermal performance, without using a detailed computer simulation directly as a design tool. The approach taken by the authors was to identify the key variables of solar system performance, and to perform detailed computer simulations in order to provide a correlation between the key variables and long-term simulated performance of solar systems. The correlation variables are essentially as follows:

$$y \cong \frac{\text{Absorbed Solar Energy}}{\text{Heating Load}}$$
$$x \cong \frac{\text{Reference Collector Loss}}{\text{Heating Load}}$$

y is the ratio of the total energy absorbed by the solar collectors to the total solar system load over a month; x is essentially a ratio of a standard (reference) collector energy loss to the total system load over the month.

A correlating equation was developed from a large number of computer simulations representing a number of locations over a range of design criteria. The equation provides a fraction, f, of the load which will be met by the solar system. Both x and y are calculated, and substituted into the equation below.

$$f = ay - bx - cy^2 + dx^2 + ey^3$$

for $0 < y < 3$ and $0 < x < 18$

where a, b, c, d, and e are coefficients dependent
on the system type (air, liquid, etc.)

Various mathematical manipulations are required to calculate x and y, including modeling of theoretical collector performance results, provision of insolation values (which require manipulation from horizontal values to values in the plane of the array), ambient temperature, and estimation of heating loads, hot water loads, process loads, etc.

Monthly values of f are calculated, and tiered to provide an estimate of the total annual solar fraction, F.

B.2 THE f-CHART 5.1, MICROCOMPUTER VERSION

The version of f-Chart used in this study is the f-Chart 5.1 Version for Microcomputers,¹ provided by f-Chart Software, 4406 Fox Bluff Rd., Middleton, Wisconsin 53662. The program is written for various microcomputers, including the Apple II² (as in this application), the IBM PC,³ Tandy TRS-80,⁴ and a CP/M version⁵ (Digital Research Corp.).

The program performs the necessary calculations relating to the f-Chart algorithms described in Section B.1 of this appendix.

System performance was modeled using actual parameters from each site, such as measured collector area, measured system loads, measured heat exchanger effectiveness, ASHRAE 93-77 single-panel collector test results, and flow rates. The measured values were taken from site information files and actual performance data.

Weather data, from the f-Chart user files supplied with the program, was used to predict yearly system performance.

The f-Chart 5.1 has the capability of modeling seven generic system types, as listed below.

1. Pebble Bed Storage Space and Domestic Water Heating Systems
2. Water Storage Space and/or Domestic Water Heating Systems
3. Active Collection with Building Storage Space Heating Systems
4. Direct-Gain Passive Systems
5. Collector-Storage Wall Passive Systems
6. Pool Heating Systems
7. General Solar Heating Systems (e.g., process heating systems)

This study utilized system types 1, 2, and 7 to model the 25 sites' performances.

¹The f-Chart 5.1 is a copyrighted program by f-Chart Software.

²APPLE is a registered trademark of Apple Computer, Inc.

³IBM is a registered trademark of International Business Machines.

⁴TRS-80 is a registered trademark of the Tandy Computer Corporation.

⁵CP/M is a registered trademark of Digital Research, Inc.

B.3 COMMENTS ON USE

The program, f-Chart Version 5.1, was implemented on an Apple II Plus microcomputer at Vitro Corporation.

Most sites were easily modeled using the measured/actual system parameters and long-term weather data.

There were some problems with the operation and execution of the program, which were divided into two categories:

1. Problems with definition of parameters to be modeled (conceptual problems)
2. Problems with execution and operation of the program

Category 1 Problems

- a. There appears to be a lack of consistency between the definition of "load" as described in f-Chart and the "load" as defined by the NSDN. For the case of Domestic Hot Water (DHW), for example, system models 1 and 2 (see Section B.2) for combined space heating and DHW systems utilize a load which is based on total energy use by the hot water system, or:

$$\text{DHW Load} = \text{Auxiliary Energy} + \text{Solar Energy}$$

System type 7, however, treats "load" for a hot water only system as:

$$\begin{aligned} \text{DHW Load} = & \text{Consumption in Gallons} \times \text{Density} \\ & \times \text{Specific Heat} \times \text{Temperature} \\ & \text{Rise Across System} \end{aligned}$$

System type 7, when used to model a large DHW system, does not include DHW system losses as part of the load. Solar contribution to losses, therefore, is not calculated, making prediction results suspect.

- b. When running a combined DHW/SH system, as in system types 1 and 2, if the system load is determined using daily hot water consumption (for DHW) and monthly UA x heating degree-days (for space heating), some problems result if the heating load is zeroed during the summer months. Apparently, the f-Chart 5.1 program switches the entire collector output from the main (large) storage system to the DHW tank, and the program stops execution. The solution is to instruct f-Chart to create a small heat load (using a building UA of one, along with a zero value for heating degree-days), which retains the large storage tank in the simulation. When a zero appears

in the monthly values of building UA (as might occur during summer months), the system is assumed to be a DHW-only system, and the simulation goes out of range.

This may not be a severe problem, but this problem causes wasted time reentering data and reloading the program.

Category 2 Problems - Operational

- a. The program has the capability of using five sets of variable monthly input parameters for various factors such as loads, collector angle, etc. There are occasions when the program "locks up" the counter which indicates to the program the number of system parameters which have multiple values, and sticks on five when less than five are in use. This results in a case where, for example, only three multiple values (such as hot water consumption, building UA, and monthly hot water set temperature) are allowed. One must then start the entire model over again from the beginning, since the counter cannot be reset by the user.
- b. Negative values for collector azimuth (i.e., collector azimuth values east of south) are rejected by f-Chart 5.1 as "out of range."
- c. Variable monthly values for all input parameters having different values by month are always zeroed on the parameters list after a run. If one wants to examine the values on the monitor or printout, the data file for the site (assuming it was saved before the run) must be recalled from disc to read monthly values. Again, this is a time-consuming problem, since, once the values are lost, they must be reentered by hand.
- d. When using the printer, the prompts which f-Chart responds with appear after the answers (such as Yes, No, etc.) are typed. One must be familiar with the question/answer sequence to operate the printer feature. (At Vitro Corporation, an Epson FX-100 printer is used.)

APPENDIX B

REFERENCE

- B-1. Beckman, W.A., S.A. Klein, and J.A. Duffie, Solar Heating Design by the f-Chart Method, John Wiley & Sons, New York, 1977.