CHAPTER IV

A Thermal Analysis of Three-Season SDHW Systems

4.1 Introduction

It became apparent in the preceding chapter that performing economic analyses is something of a game. Because numerous variables have a significant effect upon the final outcome of the analysis, it is easy to tweak a few to obtain the desired answer. Furthermore, it is necessary to estimate the values of all the variables, which may vary significantly from location to location. For these reasons, generalized findings are difficult to report with any certainty. The benefit of an economic analysis is that the associated performance indicators are easily understood and compared. However, it was found that a purely thermal analysis is much less dependent on variable estimation and gives results that are easily comparable.

The basic idea of a thermal analysis is that turning off the SDHW system during the winter reduces the amount of energy collected annually. On the other hand, removing the heat exchanger from the system raises the operating efficiency of the collectors, meaning that more energy is collected annually. This chapter describes a series of performance predictions that were carried out in order to generate a map of the entire United States showing the penalty paid in annual solar fraction due to choosing a three-season operating period.

4.2 The *f*-Chart Method

Most residential sized solar collector systems fall into a few standard configuration categories that have been studied in great detail. Because of this wealth of information, it is possible to design such systems using short-cut methods such as *f*-Chart (Klein and Beckman, 1993) instead of by running numerous hourly simulations. The *f*-Chart method is essentially a curve fit of solar water heating system performance data and it is used in predicting the fraction of a total heating load that will be supplied by solar energy in a given system. Its advantages are numerous, stemming primarily from its simplicity. The system parameters in the curve fit equation are easily obtainable from manufacturer specifications. The only weather data needed are the average monthly temperature and the monthly average daily solar radiation. Monthly average daily radiation is defined as monthly total radiation divided by the number of days in the month (Duffie and Beckman, 1991). Another advantage of the *f*-Chart method is that it does not require any understanding of the underlying thermal processes so that anyone can make use of it. Once set up, only twelve monthly calculations are needed to obtain the annual performance, allowing a number of system alternatives to be evaluated and compared. Lastly, the end result of an *f*-Chart analysis leads very neatly into an economic analysis.

There are also a number of disadvantages to *f*-Chart. It must be remembered that the final result is only an estimate of the monthly and annual performance. Two factors come into play. First, the weather data used is under 30 year average conditions and there is no guarantee that any given year will conform to the average. Second, *f*-Chart is itself is an estimation method. Furthermore, the curve fit is only valid over a limited range of parameters and is limited to standard system configurations on which the curve fit was based.

The *f*-Chart method was developed by correlating a large amount of solar thermal simulation data. The conditions in the simulations were varied over appropriate ranges and then reduced to an equation that predicts the fraction of a heating load met by solar as a function of two dimensionless parameters. The primary design variable used is collector area but secondary parameters such as collector type, fluid type and flowrates, heat exchanger size and load are also included.

F-Chart correlations are available for three system types; a system using liquid heat transfer and storage media, an air system, and a system for water heating only. The later system was used in evaluating the three-season SDHW alternative. (Figure 4.2.1).

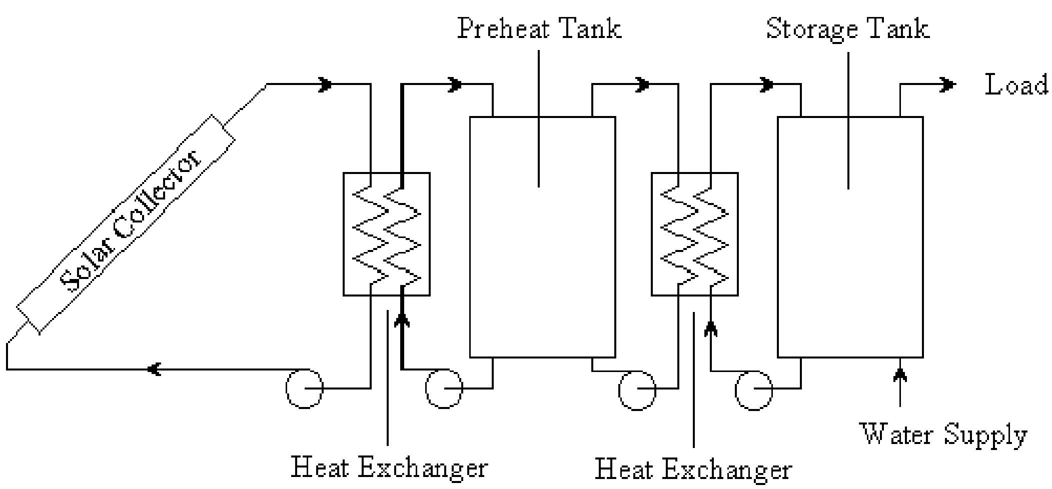


Figure 4.2.1: Water Heating System Schematic Modeled by *f*-Chart

Only the water heating correlation has been used in this analysis, for which the dimensionless parameters as presented by Duffie and Beckman (1991) are shown in equations 4.2.1 and 4.2.2. The X parameter is related to the ratio of collector losses to the heating loads while the Y parameter is related to the ratio of absorbed solar radiation to the heating load.

$$X = \frac{A_C F_R' U_L \left(T_{ref} - \overline{T_a}\right) \Delta t}{L} \tag{4.2.1}$$

$$Y = \frac{A_c F_R' \left(\overline{\tau \alpha}\right) \overline{H_T} N}{L} \tag{4.2.2}$$

A_C = collector area (m^2)
F'_R = collector heat exchanger efficiency factor
U_L = collector overall loss coefficient (W/m^2C)
T_{REF} = empirically derived reference temperature (100 C)
$\overline{T_a}$ = monthly average ambient temperature (C)
Δt = total number of seconds in the month (s)
L = total monthly heating load (J)
$\tau\alpha$ = monthly average transmittance absorbtance product
H_T = monthly average daily radiation incident on the collector surface per unit area (J/m^2)
N = number of days in the month (days)

A correction factor is normally applied to the X parameter for water heating systems (Beckman, Duffie and Klein, 1977). The (T_{REF} - T_a) factor in equation 4.2.1 is multiplied by equation 4.2.3.

$$\frac{\left(11.6 + 1.18 T_W + 3.86 T_m - 2.32 \overline{T_a}\right)}{\left(100 - T_a\right)} \tag{4.2.3}$$

In which T_W is the desired water temperature and T_m is the temperature of mains water.

The above equations can be rewritten as equations 4.2.4 and 4.2.5 respectively. The format in these equations allows the user to directly read the parameters given in a manufacturer's literature and plug them into the formula.

$$X = F_R U_L \times \frac{F_R'}{F_R} \times \left(T_{ref} - \overline{T}_a\right) \times \Delta t \times \frac{A_C}{L}$$

(4.2.4)

$$Y = F_R (\tau\alpha)_n \times \frac{F_R'}{F_R} \times \frac{\left(\overline{\tau\alpha}\right)}{(\tau\alpha)_n} \times \overline{H}_T N \times \frac{A_C}{L}$$

(4.2.5)

The overall *f*-chart correlation for liquid systems is shown in equation 4.2.6.

$$f = 1.029Y - 0.06X + 0.245Y^2 + 0.0018X^2 + 0.0215Y^3$$

(4.2.6)

The annual solar fraction (*f*) can then be determined by the use of equation 4.2.7

$$\Im = \frac{\sum f_i L_i}{\sum L_i}$$

(4.2.7)

As previously mentioned, the *f*-chart method is valid over a limited range of parameters as described in Table 4.2.2

Table 4.2.2: Design Parameters Ranges Used in Developing *f*-Chart for Liquid Systems

0.6	<	$(\tau\alpha)_n$	<	0.9	-
5	<	$F'_R A_C$	<	120	m^2
2.1	<	U_L	<	8.3	W/m2C
30	<	β	<	90	^{o}
83	<	$(U_A)_h$	<	667	W/C

By fixing the value of solar fraction (*f*) and varying one of the two parameters to determine the other, a useful design plot can be created. Once the plot is obtained, a designer can determine the X and Y parameters for a suggested system, and quickly determine the expected solar fraction for the month. Twelve such calculations will yield the annual solar fraction. It can occur that the calculated parameters fall outside of the acceptable range. Beyond a value of X = 15, equation 4.2.6 is no longer applicable, and an extremely incorrect answer will be given. The solid line in figure 4.2.2 shows equation 4.2.6 in both the acceptable and unacceptable regions. As a safeguard against such results, the equation was modified such that the dotted line predicts *f* when X > 15.

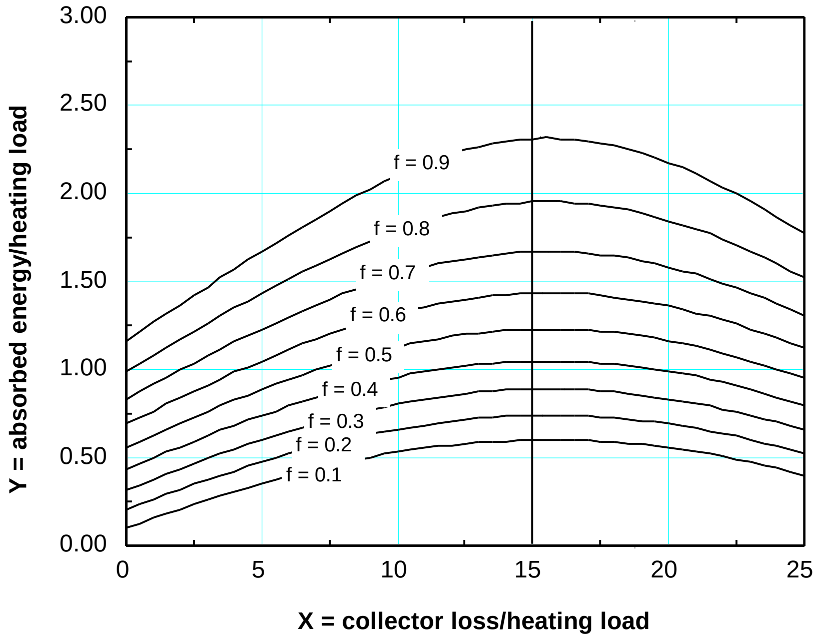


Figure 4.2.2: *f*-Chart Correlation

4.3 Weather Data

The *f*-Chart method bases its estimation of solar gain upon the monthly average daily radiation and the monthly average temperature. While such data are readily available, it was noticed that there are discrepancies between various sources. In some cases the difference was a great as 20% in solar radiation. The difference is a result of the data collection method. Solar irradiation data (global radiation on a horizontal surface) was taken over a period of 30 years between 1951 and 1975 at approximately 60 locations. The data were digitized at each station following instructions that changed over the collection period, and were sent to the National Climatic Data Center (NCDC). A host of problems arose during the course of the experiment stemming partly from each station being equipped differently. Some stations recorded continuous data on strip chart recorders while others only measured total daily radiation. Once the data had been reduced, only data from 26 of the locations were deemed accurate enough for inclusion in a database. During 1976, data collection ceased and the equipment underwent a recalibration overhaul. Data were again collected between 1977-1980 whereupon funding became inadequate to maintain the network and what data were collected, were not controlled for quality (NREL, 1992). Much of the equipment deteriorated during this period as well, including the pyranometers.

The simplest pyranometer consists of two concentric rings. The outer ring is coated with magnesium oxide that has a high reflectance of radiation in the solar energy spectrum. The inner ring is coated with a material such as Parson's Black that has a very high absorptance of radiation in the solar energy spectrum. Thermopiles are then used to measure the temperature difference between the two rings. At the end of the collection period, it was noticed that the Parson's Black coating had turned somewhat green so that the absorptance was no longer the same as the calibration indicated.

Since 1980 time, a great deal of effort has gone into salvaging the vast quantity of data and into making it useful. National Renewable Energy Labs now puts out a widely accepted data base of solar radiation data collected between 1961 and 1990 which is based upon a corrected interpolation of the NCDC data.

Other data necessary to the evaluation of three-season systems were estimates of the first and last date of freezing temperatures in each location. The first and last occurrences of freezing temperatures were obtained from the Weather Atlas of the United States. No mention is made as to the source of the data but it is assumed that the dates and maps presented represent average conditions over some extended period of time.

In calculating the load, it is also necessary to choose a temperature for mains water entering the system. There is much variability in this temperature from location to location but two cases cover the entire spectrum of possibilities. If water is drawn from a deep source, such as a well, then its temperature is nearly equal to the average yearly ambient temperature. If, on the other hand it is drawn from a surface source, such as a reservoir, then it is nearly equal to the monthly average ambient temperature (Klein, 1997).

4.4 The *f*-Chart Method Applied to Three-Season System Analysis

Using the *f*-Chart method, the concept of a three-season system has been examined for various locations throughout the United States. In general, a solar energy collection system that operates year round is designed to meet a desired percentage of a heating load. A comparable system that operates during the freeze free months without a heat exchanger will have a different annual solar fraction. However, the reduction in solar fraction is not as simple as the ratio of time that the collector is shut off. One location for instance may have a long, clear winter (such as Albuquerque, NM) while another may have a short cloudy winter (Sault Saint Marie, MI). In the former case, a system without a heat exchanger cannot operate during six months of the year because of freezing, but the winter months are months in which a large amount of solar energy could have been collected, overcoming the losses associated with the heat exchanger. Thus the reduction in solar fraction would perhaps be more than simply half of the original design value. In the latter case, however, there is little radiation to be collected in the winter and operating during that period does not make up for the year round energy penalty paid by using a heat exchanger.

The overall goal is to answer the question: Given the location of an SDHW system, how much worse will a system operating for three seasons without a heat exchanger perform, than a standard system with a heat exchanger operating year round?

It is first necessary to design a four-season system that will meet a desired percentage of the heating load. The percentage met depends on a variety of factors such as the customer’s desired investment level, the space available for installing the system, and the price of alternative methods of meeting the load. Taking all these factors into account, a four-season system can be designed with a collector area, a storage tank size, and a heat exchanger. The primary design variable is the collector area, which has a direct effect upon the annual solar fraction and system cost. A great deal of work has been carried out to analyze such systems and the optimum slope of the collector panels has been determined to be equal to the latitude of the collector location (Duffie and Beckman, 1991). Because of the earth sun geometry, this slope means that the beam radiation from the sun will be normal to the collector surface at solar noon on the equinoxes (September 21 and March 22) when the incidence angle of beam radiation is zero. Essentially, the collector is sloped at the sun’s average annual declination angle.

The four-season collector area is fixed such that the system meets a certain percentage of the annual load (25%, 50% or 75% for our purposes).

The next step is to design a three-season system, and compare the two in order to determine the thermal penalty. The three-season system design is slightly more complicated. In order to compare the three-season system to the four-season system, the area of the three-season system was set to be equal to that of the corresponding four-season system. The slope of the three-season collector was set to be the average solar declination during the system's operating period (see function slope3_(FF,LF,lat) in Appendix B). The rest of the system parameters were kept the same. The inputs to the *f*-Chart method are shown in figure 4.4.1a and 4.4.1b

Active Domestic Hot Water System - E:\FCHART\M4.FC

Location	MADISON WI	
Water volume / collector area	81.49	liters/m^2
Fuel	Elec	
Efficiency of fuel usage	100.00	%
Daily hot water usage	300	liters
Water set temperature	60.0	C
Environmental temperature	20.0	C
UA of auxiliary storage tank	4.00	W/C
Pipe heat loss	Yes	
Inlet pipe UA	2.00	W/C
Outlet pipe UA	2.00	W/C
Collector-store heat exchanger	Yes	
Tank-side flowrate/area	0.015	kg/sec-m^2
Heat exchanger effectiveness	0.25	

Flat-Plate Collector

Number of collector panels	2	
Collector panel area	2.75	m^2
FR*UL (Test slope)	4.860	W/m^2-C
FR*TAU*ALPHA (Test intercept)	0.741	
Collector slope	43.1	degrees
Collector azimuth (South=0)	0	degrees
Incidence angle modifier calculation	Glazings	
Number of glass covers	1	
Inc angle modifier constant	0.050	
Inc angle modifier value(s)	0.000	
Collector flowrate/area	0.015	kg/sec-m^2
Collector fluid specific heat	3.35	kJ/kg-C
Modify test values	No	
Test collector flowrate/area	0.015	kg/sec-m^2
Test fluid specific heat	4.19	kJ/kg-C

Figure 4.4.1a: Four-Season System *f*-Chart Inputs

Active Domestic Hot Water System - E:\FCHART\M3.FC

Location	MADISON WI	
Water volume / collector area	81.49	liters/m^2
Fuel	Elec	
Efficiency of fuel usage	100.00	%
Daily hot water usage	300	liters
Water set temperature	60.0	C
Environmental temperature	20.0	C
UA of auxiliary storage tank	4.00	W/C
Pipe heat loss	Yes	
Inlet pipe UA	2.00	W/C
Outlet pipe UA	2.00	W/C
Collector-store heat exchanger	No	
Tank-side flowrate/area	0.015	kg/sec-m^2
Heat exchanger effectiveness	0.50	

Flat-Plate Collector

Number of collector panels	2	
Collector panel area	2.75	m^2
FR*UL (Test slope)	4.860	W/m^2-C
FR*TAU*ALPHA (Test intercept)	0.741	
Collector slope	Monthly	degrees
Collector azimuth (South=0)	0	degrees
Incidence angle modifier calculation	Glazings	
Number of glass covers	2	
Inc angle modifier constant	0.050	
Inc angle modifier value(s)	0.000	
Collector flowrate/area	0.015	kg/sec-m^2
Collector fluid specific heat	4.19	kJ/kg-C
Modify test values	No	
Test collector flowrate/area	0.015	kg/sec-m^2
Test fluid specific heat	4.19	kJ/kg-C

Figure 4.4.1b: Three-Season System *f*-Chart Inputs

While the *f*-Chart method exists in a software form that combines worksheet style inputs with a simple summary and plotting tool output, it is limited in that it is designed to evaluate one system at a time (Klein and Beckman, 1993). Since, for the purposes of the three-season analysis, it is desirable to evaluate a large number of cities sequentially, it was deemed worthwhile to re-code the *f*-Chart equations into a program that could be tailored to the desired output. Engineering Equation Solver (EES), an equation solver software package (Klein, 1997) was used. The program appears in Appendix B at the end of this report. Figure 4.4.2 shows a comparison between *f*-Chart software results and the equation solver based program in Appendix B.

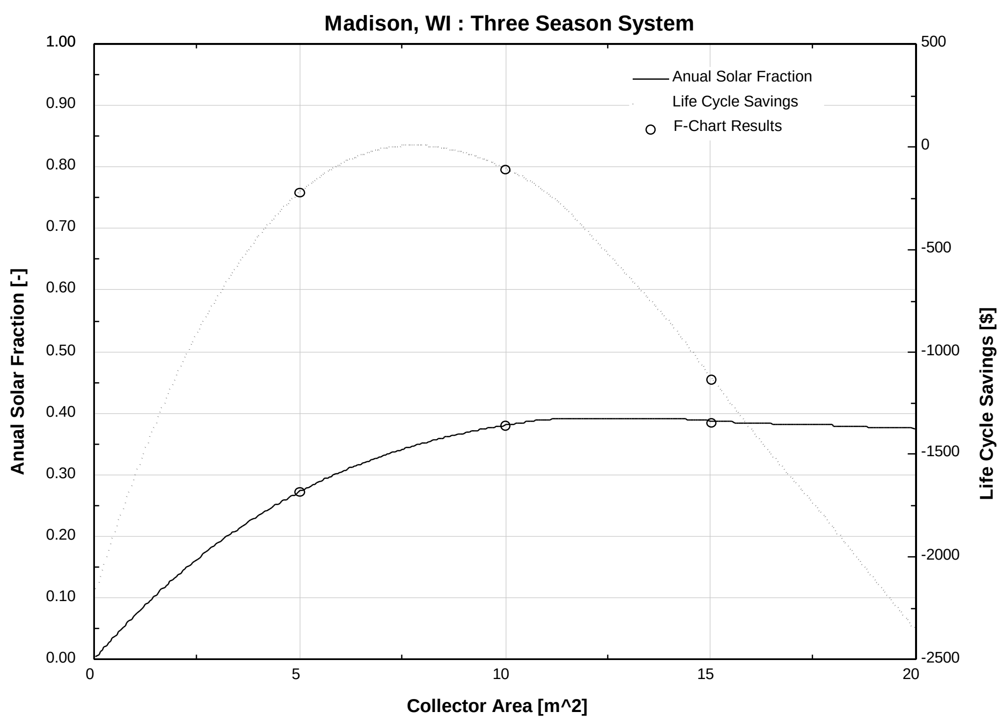


Figure 4.4.2: Comparison of Results between Equation Solver Results and *f*-Chart Software Results

4.5 Three Season Thermal Penalty

A number of tables follow that show the thermal penalty associated with a three-season system in various locations across the United States. Three systems were designed in each location, each based on a four-season system meeting 25, 50 and 75% of an annual water heating load.

- *City Number:* A reference number identifying each city in the NREL data file

- *City:* City name and state of each location analyzed

- *Location:* latitude and longitude of each location

- *Weather:* the first (FF) and last (LF) month in which freezing is an issue are noted. A value of 0 in the LF category denotes the absence of a spring freeze and a value of 13 in the FF category indicates the lack of an autumn freeze.

- *Collector Angles:* The collector slopes of the four-season and three-season systems are noted. The four-season slope is equal to the latitude of the system, and the three-season slope is equal to the average solar declination during the operating period.

- *Three Season Solar Fraction:* These columns show the three-season solar fraction for a system having the same area as a four-season system designed to meet the load shown in the column heading. For example, the first sub column is based upon a four-season system that meets 25% of the load.

Table 4.5.1 Three Season Thermal Penalties for Various Locations

#	City		location		Weather		Collector angles		Three Season Solar Fraction		
			latitude	longitude	LF	FF	slope 4	slope 3	F = 25%	F = 50%	F = 75%
1	Abilene	TX	32.43	99.68	3	11	32.43	28.55	24.32	45.93	62.77
2	Akron	OH	40.92	81.43	4	11	40.92	37.04	21.94	40.28	49.29
3	Albany	NY	42.75	73.8	4	10	42.75	33.3	18.80	34.50	41.91
4	Albuquerque	NM	35.05	106.62	5	11	35.05	31.01	15.65	29.70	40.82
5	Allentown	PA	40.65	75.43	5	11	40.65	36.61	17.28	32.07	40.67
6	Alpena	MI	45.07	83.43	5	10	45.07	35.45	15.12	27.79	33.19
7	Amarillo	TX	35.23	101.7	4	11	35.23	31.35	19.01	35.94	48.98
8	Annette	AK	55.03	131.57	4	10	55.03	45.58	21.54	36.29	37.41
9	Apalachicola	FL	29.73	85.2	1	13	29.73	29.89	31.51	59.45	81.33
10	Asheville	NC	35.43	82.53	3	11	35.43	31.55	22.42	42.02	62.89
11	Astoria	OR	46.15	123.88	3	12	46.15	45.64	26.78	48.94	65.34
12	Atlanta	GA	33.65	84.43	3	12	33.65	33.14	24.69	46.44	68.63
13	Augusta	GA	33.37	81.97	2	12	33.37	32.86	27.37	51.51	75.83
14	Austin	TX	30.3	97.7	3	12	30.3	29.79	24.45	46.00	68.03
15	Bakersfield	CA	35.42	119.05	1	12	35.42	35.37	30.65	57.68	80.62
16	Baltimore	MD	39.18	76.67	3	11	39.18	35.3	23.48	43.66	62.50
17	Barrow	AK	71.3	156.78	6	7	71.3	48.56	0.00	0.00	0.00
18	Baton Rouge	LA	30.53	91.15	2	12	30.53	30.02	29.39	51.68	75.40
19	Bethel	AK	60.78	161.8	5	9	60.78	45.19	12.05	22.07	25.21
20	Bettles	AK	66.92	151.52	6	8	66.92	46.24	1.97	7.18	8.49
21	Big Delta	AK	64	145.73	5	9	64	48.41	13.40	24.24	25.21
22	Billings	MT	45.8	108.53	4	10	45.8	36.35	18.39	33.99	41.92
23	Binghamton	NY	42.22	75.98	4	10	42.22	32.77	18.93	34.63	41.84
24	Birmingham	AL	33.57	86.75	3	11	33.57	29.69	22.88	42.68	57.05
25	Bismarck	ND	46.77	100.75	4	10	46.77	37.32	18.33	34.05	41.84
26	Boise	ID	43.57	116.22	4	11	43.57	39.69	22.18	40.95	49.80
27	Boston	MA	42.37	71.3	4	11	42.37	38.49	20.64	38.35	49.29
28	Brownsville	TX	25.9	97.43	1	13	25.9	26.06	31.51	59.36	81.01
29	Bryce Canyon	UT	37.7	112	4	10	37.7	28.25	16.69	31.49	41.92
30	Buffalo	NY	42.93	78.73	4	11	42.93	39.05	21.85	40.16	49.06
31	Burlington	IA	40.78	91.2	4	10	40.78	31.33	20.18	36.59	41.92
32	Burlington	VT	44.47	73.15	4	10	44.47	35.02	19.07	34.97	41.92
33	Burns	IA	43.58	119.05	5	9	43.58	27.99	12.39	22.50	25.21
34	Cape Hatteras	NC	35.27	75.55	2	12	35.27	34.76	27.60	51.85	70.40
35	Caribou	ME	46.87	68.02	5	9	46.87	31.28	11.64	21.42	25.21
36	Casper	WY	42.92	106.47	5	10	42.92	33.3	14.67	27.21	33.42
37	Cedar City	UT	37.7	113.1	4	10	37.7	28.25	17.39	32.49	41.92
38	Charleston	SC	32.9	79.97	2	12	32.9	32.39	29.24	54.22	69.49
39	Charleston	WV	38.37	81.6	4	11	38.37	34.49	20.95	38.70	49.29
40	Charlotte	NC	35.22	80.93	3	11	35.22	31.34	24.80	45.58	57.14
41	Chattanooga	TN	35.03	85.2	3	11	35.03	31.15	23.25	43.27	57.08
42	Cheyenne	WY	41.15	104.82	5	10	41.15	31.53	14.00	26.12	33.42
43	Chicago	IL	41.78	87.75	4	11	41.78	37.9	21.51	39.74	49.39
44	Cincinnati	OH	39.07	84.52	4	11	39.07	35.19	22.59	41.12	49.67

#	City		location		weather		Collector angles		Three-Season Solar Fraction		
			latitude	longitude	LF	FF	slope 4	slope 3	F = 25%	F = 50%	F = 75%
45	Clayton	NM	36.45	103.1	4	10	36.45	27	16.35	30.84	41.64
46	Cleveland	OH	41.4	81.85	4	11	41.4	37.52	22.18	40.64	49.20
47	Colorado Springs	CO	38.82	104.72	4	10	38.82	29.37	16.69	31.35	41.61
48	Columbia	SC	33.95	92.37	3	11	38.82	34.94	23.66	44.10	57.15
49	Columbia	MO	38.82	79.97	2	12	33.95	33.44	28.68	53.62	69.49
50	Columbus	OH	40	82.88	3	11	40	36.12	23.35	43.63	57.10
51	Concord	NH	43.2	71.5	4	10	43.2	33.75	18.03	33.40	41.80
52	Corpus Christi	TX	27.77	97.5	1	12	27.77	27.72	29.65	55.65	75.40
53	Cut Bank	MT	48.6	122.37	5	9	48.6	33.01	12.27	22.33	25.21
54	Dagget	CA	34.87	116.78	3	11	34.87	30.99	22.34	42.11	57.31
55	Dallas	TX	32.85	96.85	3	12	32.85	32.34	24.96	46.80	62.34
56	Dayton	OH	39.9	84.22	4	11	39.9	36.02	21.52	39.71	49.41
57	Daytona Beach	FL	29.18	81.05	1	12	29.18	29.13	31.53	58.52	74.32
58	Del Rio	TX	29.37	100.78	1	12	29.37	29.32	29.34	55.31	75.53
59	Denver	CO	39.75	104.87	4	10	39.75	30.3	16.73	31.45	41.79
60	Des Moines	IA	41.53	93.65	4	11	41.53	37.65	20.86	38.86	49.48
61	Detroit	MI	42.42	83.02	4	11	42.42	38.54	21.87	40.24	49.23
62	Dillon	MT	45.25	112.8	6	9	45.25	29.66	8.40	15.28	16.99
63	Dodge City	KS	37.77	99.97	4	11	37.77	33.89	19.49	36.74	49.06
64	Duluth	MN	46.83	92.18	5	10	46.83	37.21	14.36	26.77	33.02
65	Eagle	CO	39.65	106.92	6	9	39.65	24.06	7.39	13.78	16.99
66	Eau Claire	WI	44.87	91.48	5	9	44.87	29.28	11.98	21.92	25.21
67	El Paso	TX	31.8	115.78	5	9	40.83	25.24	11.89	21.79	25.21
68	Elko	NV	40.83	106.4	3	11	31.8	27.92	21.79	41.22	56.69
69	Ely	NY	39.28	114.85	5	9	39.28	23.69	11.00	20.46	25.21
70	Erie	PA	42.08	80.18	4	11	42.08	38.2	22.17	40.65	49.19
71	Evansville	IN	38.05	87.53	3	11	38.05	34.17	24.19	44.84	57.28
72	Fairbanks	AK	64.82	147.87	5	9	64.82	49.23	13.68	24.23	25.21
73	Fargo	ND	46.9	96.8	4	10	46.9	37.45	18.55	34.39	41.79
74	Farmington	NM	36.75	108.23	5	10	36.75	27.13	13.51	25.42	33.42
75	Flint	MI	42.97	83.73	4	10	42.97	33.52	19.58	35.61	41.92
76	Fort Smith	AR	35.33	94.37	3	11	35.33	31.45	22.86	42.77	56.64
77	Fort Wayne	IN	41	85.2	4	11	41	37.12	18.55	35.12	48.35
78	Fort Worth	TX	32.83	97.05	3	11	32.83	28.95	23.40	43.57	56.85
79	Fresno	CA	36.77	119.72	1	12	36.77	36.72	30.97	58.27	76.60
80	Glasgow	MT	48.22	106.53	5	10	48.22	38.6	15.25	28.12	33.42
81	Goodland	KS	39.37	101.7	4	10	39.37	29.92	17.19	32.17	41.68
82	Grand Island	NE	40.97	98.32	4	10	40.97	31.52	17.81	33.13	41.78
83	Grand Junction	CO	39.12	108.53	5	10	39.12	29.5	14.77	27.32	33.34
84	Grand Rapids	MI	42.88	85.52	4	11	42.88	39	19.68	37.07	49.21
85	Great Falls	MT	47.48	104.8	4	10	47.48	38.03	18.82	34.64	41.92
86	Green Bay	WI	44.48	88.13	4	10	44.48	35.03	18.67	34.40	41.73
87	Greensboro	NC	36.08	79.95	3	11	36.08	32.2	26.01	47.64	57.00
88	Greensville	SC	34.9	82.22	3	12	34.9	34.39	26.82	49.56	60.99
89	Gulkana	AK	62.15	145.45	6	9	62.15	46.56	8.69	15.88	16.99

#	City		location		weather		collector angles		Three-Season Solar Fraction		
			latitude	longitude	LF	FF	slope 4	slope 3	F = 25%	F = 50%	F = 75%
90	Harrisburg	PA	40.22	76.77	3	11	40.22	36.34	23.79	44.17	56.92
91	Hartford	CT	41.93	72.65	4	11	41.93	38.05	20.65	38.37	49.14
92	Helena	MT	46.6	112	4	10	46.6	37.15	19.15	35.16	41.92
93	Hilo	HI	19.72	155.08	0	13	19.72	19.88	33.28	62.93	86.44
94	Homer	AK	59.63	151.5	5	10	59.63	50.01	16.06	28.92	33.17
95	Honolulu	HI	21.33	157.92	0	13	21.33	21.49	33.36	63.32	87.69
96	Huntington	WV	38.37	95.35	1	12	29.98	29.93	29.66	55.69	80.96
97	Huron	SD	44.38	82.5	4	11	38.37	34.49	24.19	44.70	49.32
98	Houston	TX	29.98	98.22	4	10	44.38	34.93	18.67	34.52	41.92
99	Indianapolis	IN	39.73	86.28	4	11	39.73	35.85	21.35	39.50	49.41
100	International Falls	MN	48.57	93.38	5	9	48.57	32.98	11.87	21.86	32.97
101	Jackson	MS	32.32	90.08	2	11	32.32	29.52	25.73	48.09	70.58
102	Jacksonville	FL	30.5	81.7	1	12	30.5	30.45	29.92	56.26	81.39
103	Juneau	AK	58.37	134.58	4	11	58.37	54.49	24.33	41.65	51.40
104	Kansas City	MO	39.3	94.58	3	11	39.3	35.42	23.57	43.96	62.82
105	King Salmon	AK	58.68	156.65	5	9	58.68	43.09	12.44	22.29	32.87
106	Knoxville	TN	35.82	83.98	3	11	35.82	31.94	23.48	43.62	62.94
107	Kodiak	AK	57.75	152.48	5	10	57.75	48.13	15.72	28.02	39.38
108	Korror Island	PN	7.33	225	0	13	7.33	7.495	33.26	62.78	86.02
109	Kotzebue	AK	66.87	162.63	6	9	66.87	51.28	5.48	13.07	16.99
110	Kwajelein Island	PN	8.73	195	0	13	8.73	8.895	33.30	63.02	86.70
111	Lacrosse	WI	43.87	91.25	4	10	43.87	34.42	21.80	40.26	49.64
112	Lake Charles	LA	30.12	93.22	2	12	30.12	29.61	27.57	51.74	70.14
113	Laredo	TX	27.53	99.45	1	12	27.53	27.48	29.60	55.65	75.48
114	Las Vegas	UT	36.08	115.17	2	11	36.08	33.28	25.25	47.66	64.97
115	Lewiston	ID	46.38	117.02	5	10	46.38	36.76	15.46	28.32	33.42
116	Lewiston	MT	47.05	109.45	5	9	47.05	31.46	12.34	22.40	25.21
117	Lexington	KY	38.03	84.6	3	11	38.03	34.15	24.18	44.75	57.29
118	Lihue	HI	21.98	159.35	0	13	21.98	22.14	33.32	63.11	87.03
119	Little Rock	AR	34.73	92.24	3	11	34.73	30.85	25.99	48.53	64.21
120	Long Beach	CA	33.82	118.15	1	12	33.82	33.77	29.33	55.41	75.93
121	Los Angeles	CA	33.93	118.4	0	13	33.93	34.09	33.38	63.47	88.19
122	Louisville	KY	38.18	85.73	3	11	38.18	34.3	26.86	49.87	64.37
123	Lovelock	NV	40.07	118.55	5	9	40.07	24.48	11.14	20.71	25.21
124	Lubbock	TX	33.65	101.82	3	11	33.65	29.77	22.01	41.54	56.77
125	Lufkin	TX	31.23	94.8	3	11	31.23	27.35	22.89	42.66	56.68
126	Macon	GA	32.7	83.65	2	12	32.7	32.19	27.44	51.61	70.31
127	Madison	WI	43.13	89.33	4	11	43.13	39.25	20.81	38.75	48.91
128	Mason City	IA	43.15	93.33	4	10	43.15	33.7	18.57	34.32	41.92
129	Massena	NY	44.93	74.85	4	10	44.93	35.48	18.65	34.38	41.79
130	McGrath	AK	62.97	155.62	5	9	62.97	47.38	12.57	23.16	25.21
131	Medford	OR	42.37	122.87	4	11	42.37	38.49	23.21	42.38	49.80
132	Memphis	TN	35.05	90	3	11	35.05	31.17	23.49	43.70	57.14
133	Meridian	MS	32.33	88.75	2	11	32.33	29.53	25.62	47.85	64.31
134	Miami	FL	25.8	80.27	0	13	25.8	25.96	33.32	63.11	87.02

#	City		location		weather		collector angles		Three-Season Solar Fraction		
			latitude	longitude	LF	FF	slope 4	slope 3	F = 25%	F = 50%	F = 75%
135	Midland	TX	31.93	102.18	3	11	31.93	28.05	24.82	46.86	64.41
136	Miles City	MT	46.43	105.87	4	10	46.43	36.98	18.57	34.37	41.92
137	Milwaukee	WI	42.95	87.9	4	11	42.95	39.07	21.24	39.37	49.18
138	Minneapolis	MN	44.88	93.22	4	10	44.88	35.43	18.46	34.16	41.77
139	Minot	ND	48.27	101.35	5	9	48.27	32.68	12.08	22.14	25.21
140	Missoula	MT	46.92	114.08	5	9	46.92	31.33	13.39	23.82	25.21
141	Mobile	AL	30.68	88.25	2	12	30.68	30.17	27.36	51.33	69.58
142	Moline	IL	41.45	90.52	4	10	41.45	32	18.82	34.57	41.92
143	Montgomery	AL	32.3	86.37	2	12	32.3	31.79	27.54	51.76	70.40
144	Mount Shasta	CA	41.32	122.32	5	9	41.32	25.73	12.72	22.90	25.21
145	Nashville	TN	36.12	86.68	3	11	36.12	32.24	23.69	44.02	57.28
146	Needles	CA	34.77	114.62	2	12	34.77	34.26	27.38	51.82	71.38
147	Newark	NJ	40.7	74.17	4	11	40.7	36.82	20.64	38.30	49.26
148	New Orleans	LA	29.98	90.25	1	12	29.98	29.93	29.61	55.67	75.71
149	New York (central park)	NY	40.78	73.97	3	11	40.78	36.9	23.79	44.17	57.07
150	New York (laguardia)	NY	40.77	73.9	3	11	40.77	36.89	23.80	44.18	57.07
151	Nome	AK	64.5	165.43	5	9	64.5	48.91	12.20	22.44	25.21
152	Norfolk	VA	36.9	76.2	3	12	36.9	36.39	26.12	48.82	62.26
153	North Bend	OR	43.42	124.25	6	9	43.42	27.83	8.37	14.88	16.99
154	North Omaha	NE	41.37	96	3	11	41.37	37.49	25.23	46.05	57.22
155	North Platte	NE	41.13	100.68	4	10	41.13	31.68	19.83	35.55	41.92
156	Oakland	CA	37.73	122.32	0	13	37.73	37.89	33.36	63.35	87.46
157	Oklahoma City	OK	46.97	97.6	3	11	35.4	31.52	25.43	47.79	64.00
158	Olympia	WA	35.4	122.9	4	11	46.97	43.09	23.51	42.03	48.08
159	Orlando	FL	28.55	81.38	1	13	28.55	28.71	31.06	58.71	75.00
160	Pendleton	OR	45.68	118.85	4	10	45.68	36.23	20.46	36.96	49.65
161	Philadelphia	PA	39.88	75.25	3	12	39.88	39.37	25.33	47.40	62.48
162	Phoenix	AZ	33.43	112.02	1	12	33.43	33.38	29.44	55.81	77.16
163	Pierre	SD	44.38	100.28	4	10	44.38	34.93	18.50	34.25	41.92
164	Pittsburgh	PA	40.5	80.22	4	11	40.5	36.62	21.71	39.93	49.34
165	Pocatello	ID	42.92	112.6	4	10	42.92	33.47	19.25	35.35	41.92
166	Port Arthur	TX	29.95	94.02	2	12	29.95	29.44	29.68	54.79	69.04
167	Portland	OR	43.65	70.32	4	10	43.65	34.2	17.89	33.17	41.87
168	Portland	ME	45.6	122.6	2	12	45.6	45.09	26.91	50.95	69.42
169	Prescott	AZ	34.65	112.43	4	10	34.65	25.2	16.52	31.06	41.59
170	Providence	RI	41.73	71.43	3	11	41.73	37.85	23.63	43.95	56.99
171	Pueblo	CO	38.28	104.48	4	10	38.28	28.83	16.94	31.77	41.77
172	Raleigh	NC	35.87	78.78	3	12	35.87	35.36	24.59	46.26	62.89
173	Rapid City	SD	44.05	103.07	4	10	44.05	34.6	19.34	35.31	41.92
174	Red Bluff	CA	40.15	122.3	2	12	40.15	39.64	29.45	55.01	70.14
175	Redmond	OR	44.27	121.15	5	8	44.27	25.09	8.45	15.19	16.71
176	Reno	NV	39.5	119.78	4	10	39.5	30.05	18.09	33.56	41.92
177	Richmond	VA	37.5	77.33	3	11	37.5	33.62	23.08	43.02	56.82
178	Roanoke	VA	37.32	79.97	4	11	37.32	33.44	19.79	36.99	49.08
179	Rochester	MN	43.92	92.5	5	9	43.92	28.33	12.07	22.04	25.21

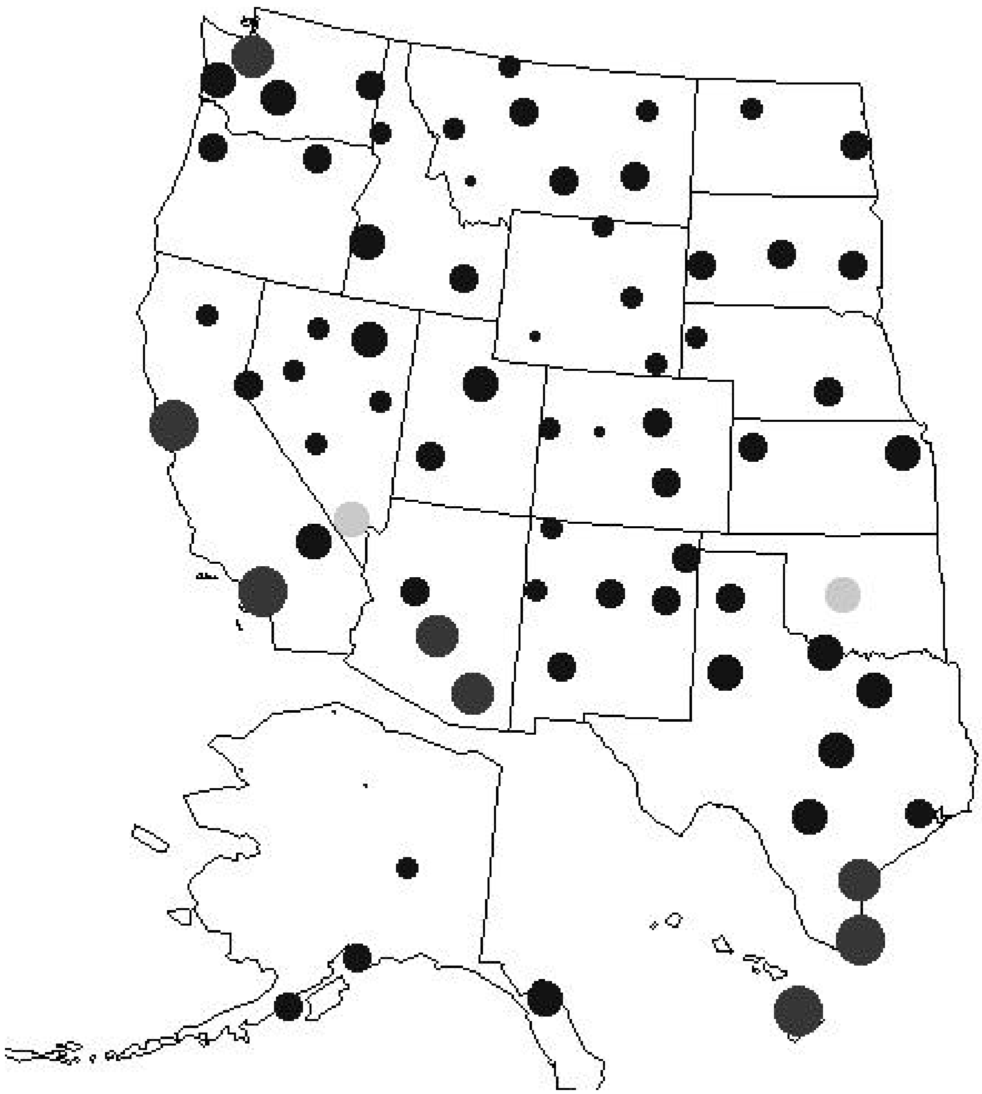
#	City		location		weather		collector angles		Three-Season Solar Fraction		
			latitude	longitude	LF	FF	slope 4	slope 3	F = 25%	F = 50%	F = 75%
180	Rochester	NY	43.12	77.67	4	11	43.12	39.24	20.98	39.08	49.07
181	Rock Springs	WY	41.6	109.07	5	8	41.6	22.42	6.85	12.77	16.71
182	Roswell	NM	33.4	104.53	3	11	33.4	29.52	22.15	41.87	57.27
183	Sacramento	CA	38.52	121.5	1	12	38.52	38.47	30.90	58.07	76.16
184	Salem	OR	44.92	123.02	3	11	44.92	41.04	26.23	47.63	57.30
185	Salt Lake City	UT	40.77	111.97	3	11	40.77	36.89	24.47	45.53	57.44
186	San Angelo	TX	31.37	100.4	3	12	31.37	30.86	23.98	45.39	62.62
187	San Antonio	TX	29.53	98.47	2	11	29.53	26.73	25.12	47.25	64.13
188	San Diego	CA	32.73	117.17	0	13	32.73	32.89	33.40	63.53	88.38
189	San Francisco	CA	37.62	122.38	0	13	37.62	37.78	33.34	63.24	86.69
190	San Juan	PR	18.43	66.12	0	13	18.43	18.59	33.34	63.22	87.35
191	Santa Maria	CA	34.9	120.45	3	11	34.9	31.02	25.06	47.12	64.29
192	Sault Saint Marie	MI	46.47	84.37	5	10	46.47	36.85	14.55	27.00	32.88
193	Savannah	GA	32.13	81.2	2	12	32.13	31.62	27.28	51.31	69.89
194	Scottsbluff	NE	41.87	103.6	5	10	41.87	32.25	11.57	22.24	31.53
195	Seattle	WA	47.45	122.3	2	12	47.45	46.94	30.41	55.55	67.31
196	Sheridan	WY	44.77	106.97	5	10	44.77	35.15	14.71	27.24	33.42
197	Sherman	TX	33.72	96.67	3	11	33.72	29.84	23.26	43.31	56.57
198	Shreveport	LA	32.47	93.82	2	12	32.47	31.96	27.65	51.93	70.12
199	Sioux City	IA	42.4	96.38	4	10	42.4	32.95	18.44	34.09	41.87
200	Sioux Falls	SD	43.57	96.73	4	10	43.57	34.12	18.07	33.54	41.83
201	South Bend	IN	41.7	86.32	4	11	41.7	37.82	21.80	40.12	49.25
202	Spokane	WA	47.63	117.52	4	10	47.63	38.18	20.23	36.64	41.92
203	Springfield	IL	39.83	89.67	3	11	39.83	35.95	21.98	41.57	56.90
204	Springfield	MO	37.23	93.38	3	11	37.23	33.35	22.63	42.60	57.20
205	St. Louis	MO	38.75	90.38	3	11	38.75	34.87	23.78	44.23	57.14
206	Summit	AK	63.33	150	6	8	63.33	42.65	4.73	8.49	8.49
207	Syracuse	NY	43.12	76.12	4	10	43.12	33.67	19.39	35.32	41.92
208	Tallahassee	FL	30.38	84.37	2	12	30.38	29.87	27.16	51.12	75.53
209	Tampa	FL	27.97	82.53	0	13	27.97	28.13	33.33	63.20	87.32
210	Toledo	OH	41.6	83.8	4	11	41.6	37.72	24.95	46.06	57.20
211	Tonopah	NV	38.07	117.08	5	10	38.07	28.45	14.08	26.30	33.42
212	Topeka	KS	39.07	95.63	3	11	39.07	35.19	23.42	43.73	57.02
213	Traverse City	MI	44.73	85.58	5	10	44.73	35.11	15.62	28.49	33.31
214	Truth or Consequences	NM	33.23	107.2	4	11	33.23	29.35	18.45	35.08	48.70
215	Tucson	AZ	32.12	110.93	2	12	32.12	31.61	26.90	51.00	70.60
216	Tucumcari	NM	35.18	103.6	4	11	35.18	31.3	19.07	36.04	49.15
217	Tulsa	OK	36.2	95.9	3	11	36.2	32.32	22.99	42.97	56.59
218	Waco	TX	31.62	97.22	3	11	31.62	27.74	22.59	42.27	56.29
219	Wake Island	PN	19.28	200	0	13	19.28	19.44	33.35	63.30	87.59
220	Washington	DC	38.95	77.03	3	11	38.95	35.07	27.33	50.48	64.29
221	West Palm Beach	FL	26.68	80.1	0	13	26.68	26.84	33.35	63.26	87.49
222	Wichita	KS	37.65	97.42	4	10	37.65	28.2	20.67	38.47	49.50
223	Wichita Falls	TX	33.97	98.48	3	11	33.97	30.09	23.83	44.37	57.09

#	City		location		weather		collector angles		Three-Season Solar Fraction		
			latitude	longitude	LF	FF	slope 4	slope 3	F = 25%	F = 50%	F = 75%
224	Willkes-Barre	PA	41.33	75.73	5	10	41.33	31.71	15.33	27.97	33.40
225	Wilmington	DE	39.67	75.6	4	11	39.67	35.79	20.47	38.07	49.17
226	Winnemucca	NV	40.9	117.8	5	10	40.9	31.28	15.17	27.94	33.42
227	Winslow	AZ	35.02	110.73	4	11	35.02	31.14	19.05	36.11	49.41
228	Yakima	WA	46.57	120.53	4	11	46.57	42.69	22.29	41.02	49.58
229	Yakutat	AK	59.52	139.67	4	10	59.52	50.07	20.06	35.38	38.82
230	Youngstown	OH	41.27	80.67	4	10	41.27	31.82	19.81	35.82	41.92

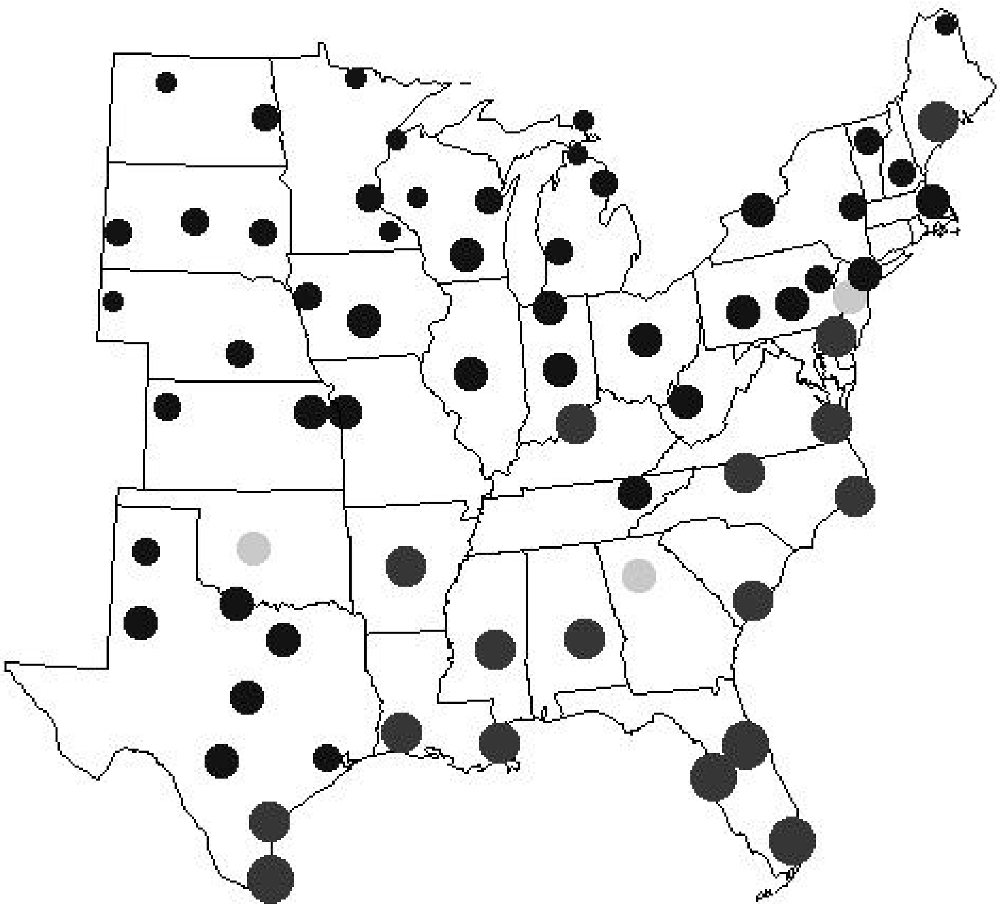
4.6 Three-Season System Thermal Penalty Maps

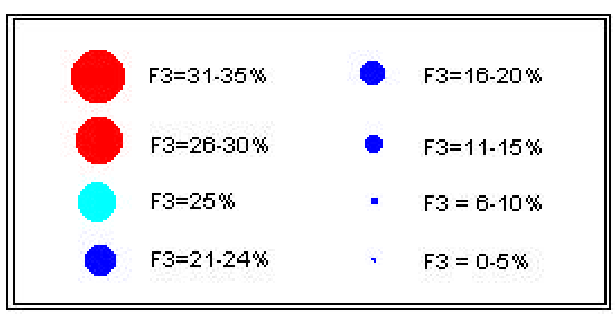
Since the above tables are somewhat cumbersome to use and do not show geographic trends in three-season system performance, a number of cities have been selected and placed on maps for clarity. The figures on the following pages show the three-season system annual solar fraction that can be expected by duplicating the area of a four-season system meeting 25, 50 and 75% of an annual water heating load. The system parameters are as shown in 4.4.1a and 4.4.1b.

Thermal Performance of a Three-Season System Based on a Four Season System Meeting 25% of the Annual Load (Western United States)



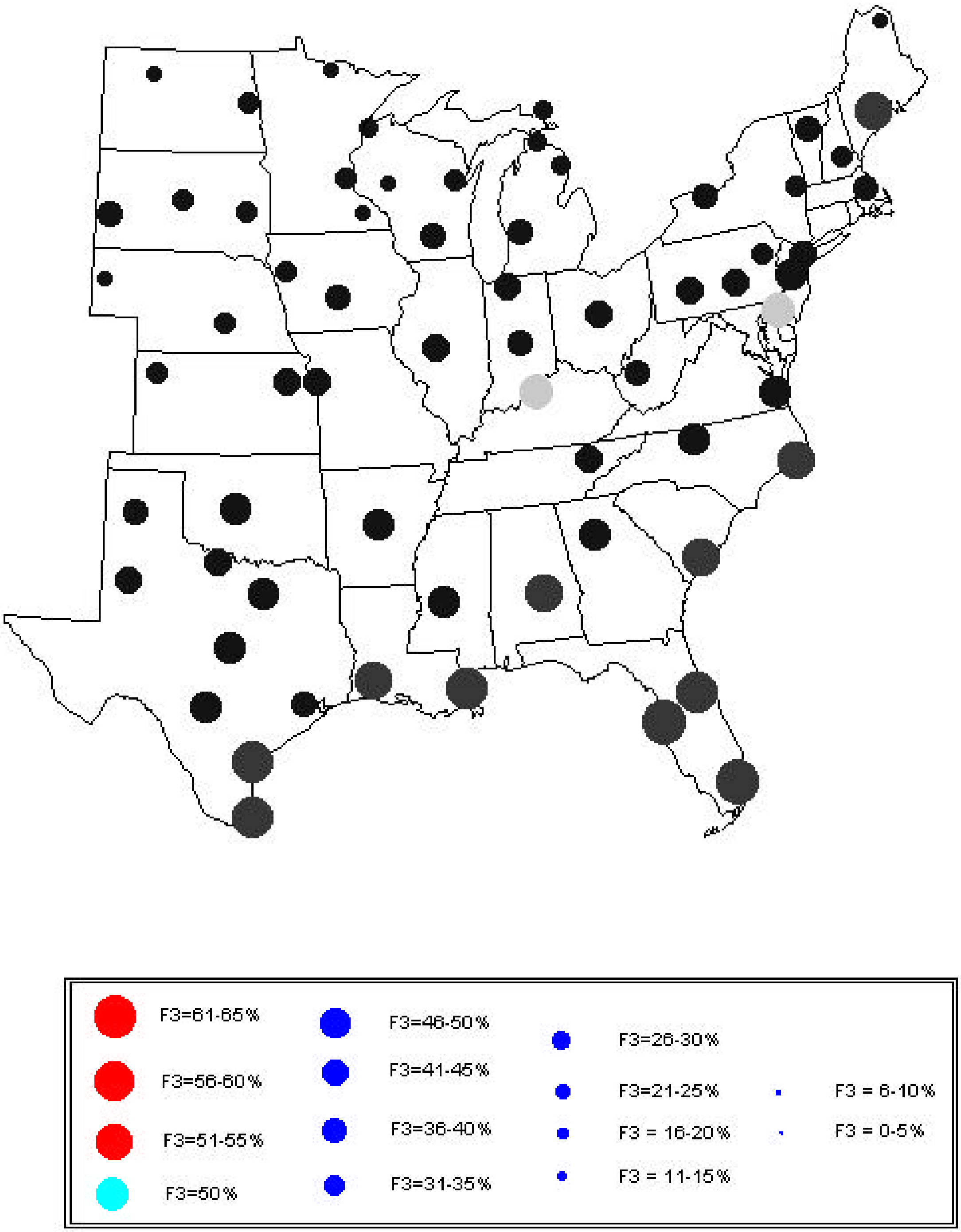
Thermal Performance of a Three-Season System Based on a Four Season System Meeting 25% of the Annual Load (Eastern United States)



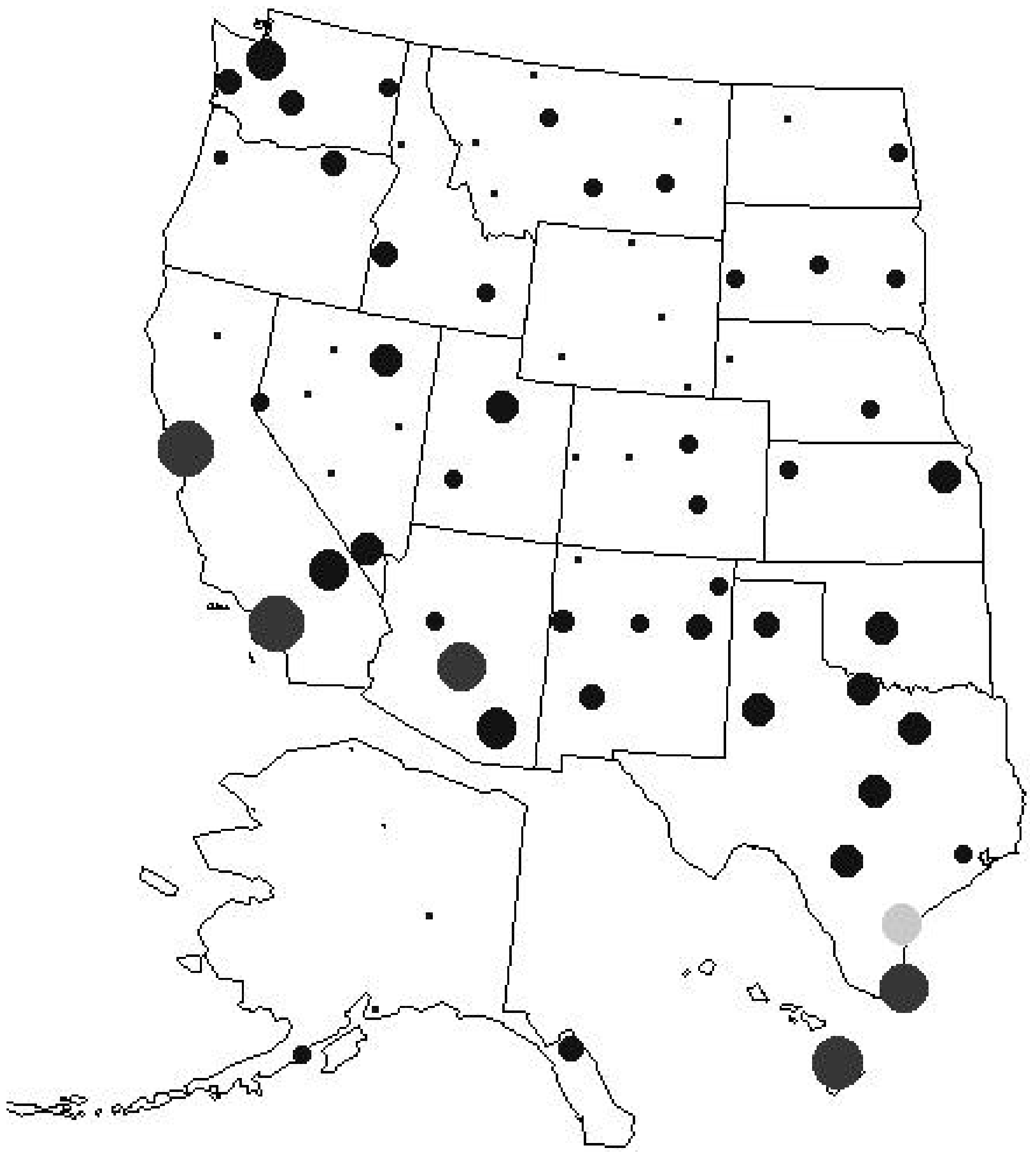


Thermal Performance of a Three-Season System Based on a Four Season System Meeting 50% of the Annual Load (Western United States)

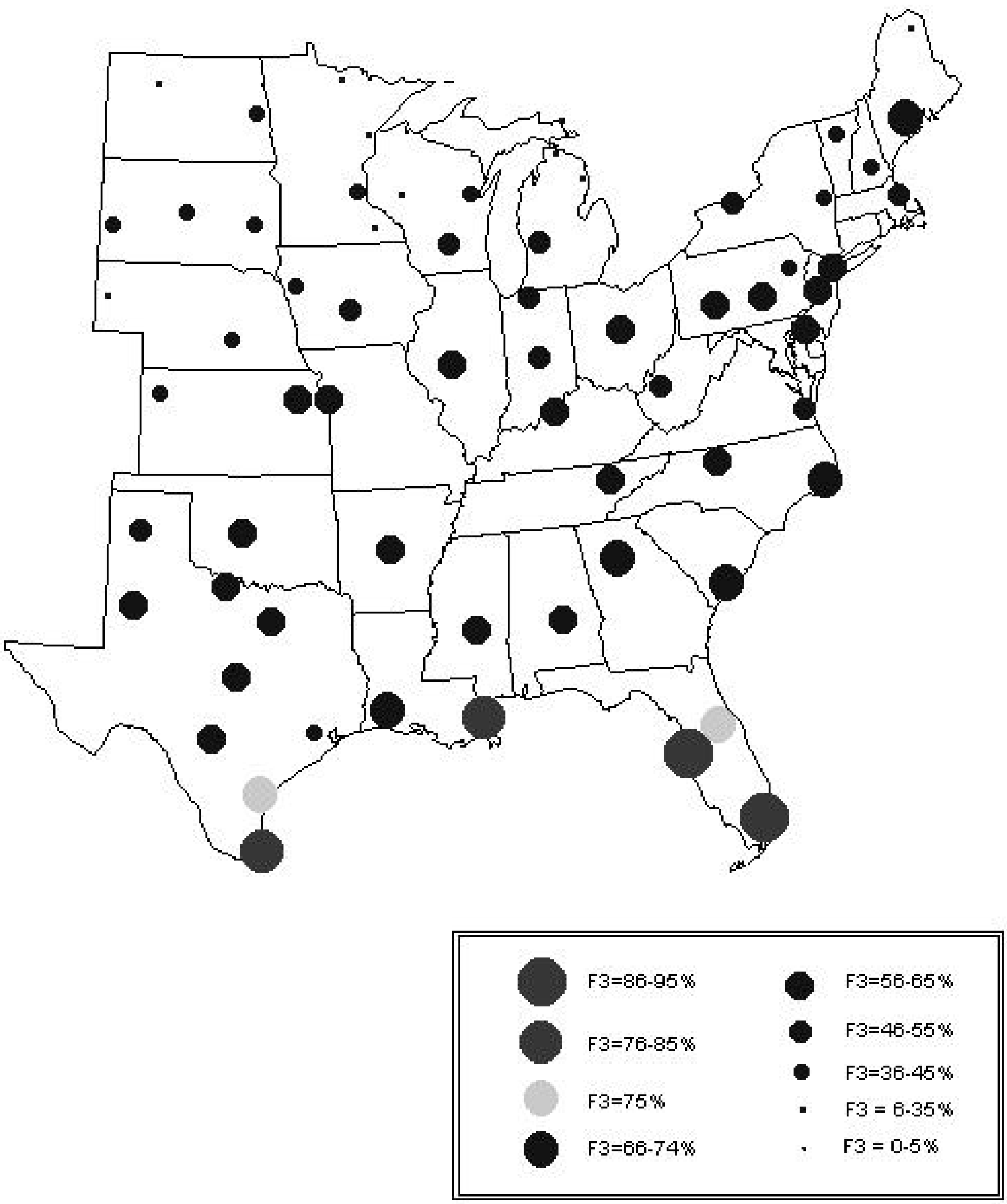
Thermal Performance of a Three-Season System Based on a Four Season System Meeting 50% of the Annual Load (Eastern United States)



Thermal Performance of a Three-Season System Based on a Four Season System Meeting 75% of the Annual Load (Western United States)



Thermal Performance of a Three-Season System Based on a Four Season System Meeting 75% of the Annual Load (Eastern United States)



4.7 Discussion

There were no huge surprises in the thermal analysis of three-season systems. There was, as expected, a decrease in annual solar fraction for most locations associated with shutting down the system for a certain portion of the year. Furthermore, the penalty was closely related to the length of shutdown, modified somewhat by the relative cloudiness of the location during the shutdown time. The cloudier a region during the winter, the less solar energy is available for collection to the four-season system and the smaller the penalty to shutting down. In a clear winter location there is a lot of energy to be collected during the off months, and the four-season system comes out ahead.

Examination of the thermal penalty maps, however, indicates some interesting trends. Three-season system solar fractions in maritime and southern locations tend to be either slightly less than or slightly greater than the four-season system solar fractions. This trend makes some sense in that freezing is rare in southern locations, and the energy lost by shutting down the system for the one month when freezing is a problem, is preferable to losing energy in a heat exchanger all year long. As to the maritime locations, the ocean provides temperature regulation, which means warmer winter temperatures. Furthermore, as cold inland air meets the warmer moist air near the ocean, clouds form and keep the winter clearness indices low (Lutgens and Tarbuck, 1995). The total amount of energy collected during the winter months by the four-season system is almost the same as the energy lost in the heat exchanger throughout the entire year. Thus removing the heat exchanger and shutting down the system for a portion of the year has little or no adverse effect upon the thermal performance of the system and has a positive effect upon the cost of the system.

The second category of locations are those in which the three-season system alternative is undesirable due to a significant thermal penalty. Predictably inland locations in Alaska fall into this category. In these locations, the freeze free period is so short (sometimes as short as a single month) that the three-season system has no hope of comparing favorably. Coincidentally, the same locations are poor candidates for SDHW anyway and the question of whether to install a three or four-season system is somewhat overshadowed by the decision whether or not to install an SDHW system at all. It should be stated that the results for any location with latitude of greater than 66^o should be taken with a grain of salt as the equations for absorbed solar radiation begin to break down at this point. The complication arises from the fact that above the Arctic Circle, the sun never sets during part of the summer and never rises during part of the winter. The other locations in which three-season systems are a bad choice tend to be high altitude locations in the Rocky Mountains. Again the sheer length of the winter severely limits the ability of the three-season system to perform.

The final category is by far the largest and contains those locations in which there is a significant but not detrimental penalty to running a three-season system. The category can be divided into two subcategories. The first subcategory contains locations in which the thermal penalty is slight enough that you would definitely choose a three-season system with its lower first cost. In the second, the thermal penalty is significant enough that a system designer would have to look carefully at local economics to make a decision. Favorable economic conditions such as high summertime electricity prices could make an otherwise thermally poor choice work well.

The thermal penalty maps also shed light on some interesting features of the three-season system alternative. In the maps based upon a four-season 25% system, general weather trends are visible in the performance of the three-season systems. The high altitude Rocky Mountains can be seen as a diagonal line of poorly performing locations stretching from Montana southeast into Colorado. The warm southeastern United States can also clearly be seen. In a great number of locations, these small area three-season systems perform better than their four-season counterparts, and would cost less to install. If there is a thermal penalty associated with the three-season system, it tends to be small.

As the system size increases to meeting near 50% of the annual heating load, local weather conditions become more important than general geographic areas. It is more difficult to divide the country into a few well-defined zones because there are outlying results scattered throughout. Another noticeable trend is that the size of the three-season thermal benefit zone in the southeastern United States has begun to shrink.

As system size passes F=50%, the three season alternative becomes less and less attractive and the thermal penalties are accentuated. Of course the locations in which freezing is a rarity will still perform well but it can be plainly seen from the map that the three-season system penalty is detrimental in all but the southeast. The reason behind the accentuated penalty is that the larger the collector area, the more energy is collected. Since the load remains unchanged, the four-season system is able to overcome the heat exchanger penalty essentially by collecting a surplus of energy and then throwing away the unnecessary portion through the heat exchanger. Were it not for the heat exchanger, the tank water would be continually above the set point temperature. Increasing the area of the three-season system, on the other hand, means that the winter down time becomes more costly from a thermal point of view.

There are a number of sources of error involved with the *f*-Chart results that bear mention. First, the results are only as good as the confidence in the radiation data, which is somewhat shaky (see section 4.3). However, since this analysis is primarily a comparison of SDHW system alternatives, both of which were subjected to the same (perhaps incorrect) weather conditions, this source of error is less important. Second, most of the locations used were in urban areas that tend to be slightly warmer than the surrounding countryside. This heat island effect means that the results indicated for Chicago, IL may not apply well just outside of Chicago. Lacking environmental data for the surrounding areas, there is really no cure for this source of error. The designer should, however, be aware of its existence and should allow for some safety factor in predicting three-season performance near large urban areas. Lastly, the *f*-Chart performance prediction results are intended to be 10-year average results and there may be some significant variation from year to year depending on current conditions.

4.8 Conclusions

The *f*-Chart method has left us with a thorough analysis of the thermal penalty incurred by choosing to run an SDHW system without a heat exchanger for only those months during which freezing is not a worry. A system designer is able to use the generated maps in section 4.6to get a good feeling for the practicality of installing a three-season system in a given location. The locations on the map divide themselves into approximately three categories. First, there are a number of southern and maritime locations in which a three-season system has a higher annual solar fraction. At the other end of the spectrum, there are high latitude and high altitude locations in which the three-season system is barely turned on at all and performs abysmally. The large majority of locations fall into the third category, which is made up of locations in which the thermal penalty is an issue, but is not huge. In these locations the designer would probably need to examine local economics to determine whether the thermal penalty is warranted by the potential decrease in system initial cost and in system operating cost.

For all the success that was met using the *f*-Chart method, there are some important shortcomings. First, it would be helpful if the *f*-Chart results could be confirmed by some other means short of a ten-year experiment in order to increase the confidence with which the results are presented. Second, *f*-Chart is limited to modeling a few standard system configurations and there are a number of variations to the general three-season system design which are worth investigating. A third problem is the confidence level in the weather data. These data were not measured; they are based upon measurements at a few locations and were then interpolated using related data in order to obtain the final set for 230 locations. Recent radiation measurements have shown the data set to have some serious inaccuracies, however, it is the best weather data available. In order to draw conclusions confidently from the results presented in this chapter, it is necessary to repeat them using a method different from *f*-Chart.