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Comparison of Solar Hot Water Systems Simulated in EnergyGauge USA and TRNSYS 15

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Prepared by Michael Anello – June, 2006

Introduction

This document is meant to serve as a detailed summary of the comparison between the simulation methods of EnergyGauge USA and TRNSYS (version 15) relating to solar hot water systems.

The initial motivation behind this comparison was to verify that the f-chart model created for EnergyGauge's solar hot water calculations was reporting the correct results. To this end, models of three systems were created in TRNSYS in order to serve as a baseline for the EnergyGauge results. The three systems modeled were:

- Liquid-active closed loop (LACL)
- Liquid-active open loop (LAOL)
- Integrated collector storage (ICS)

This document will detail each of these systems as they were modeled in TRNSYS as well as the F-chart model that was created for EnergyGauge. The goal of this document is to provide a single source of information about all of the models and a comparison of the results produced by each model.

Comparison of Results

LACL

Average Annual Solar Fraction		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	0.42	0.38
Tampa, FL	0.65	0.63
Portland, OR	0.40	0.33
Hot Water Energy Use (KWh)		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	2332	2522
Tampa, FL	894	939
Portland, OR	2174	2432

LAOL

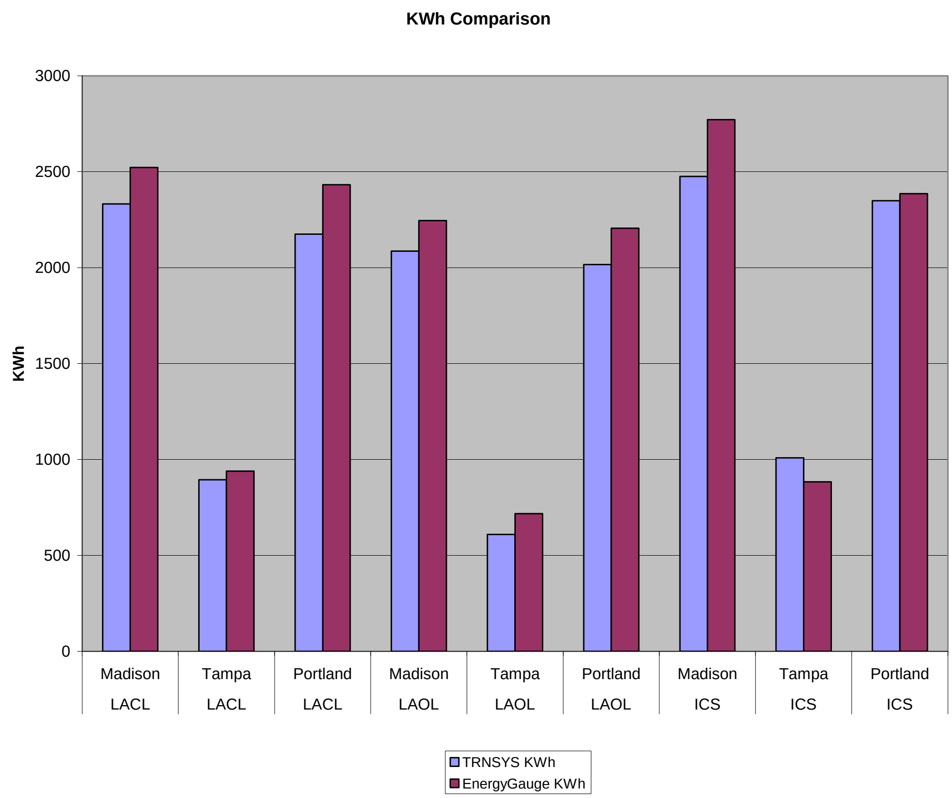
Average Annual Solar Fraction		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	0.48	0.45
Tampa, FL	0.76	0.72
Portland, OR	0.44	0.39
Hot Water Energy Use (KWh)		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	2086	2245
Tampa, FL	610	717
Portland, OR	2016	2205

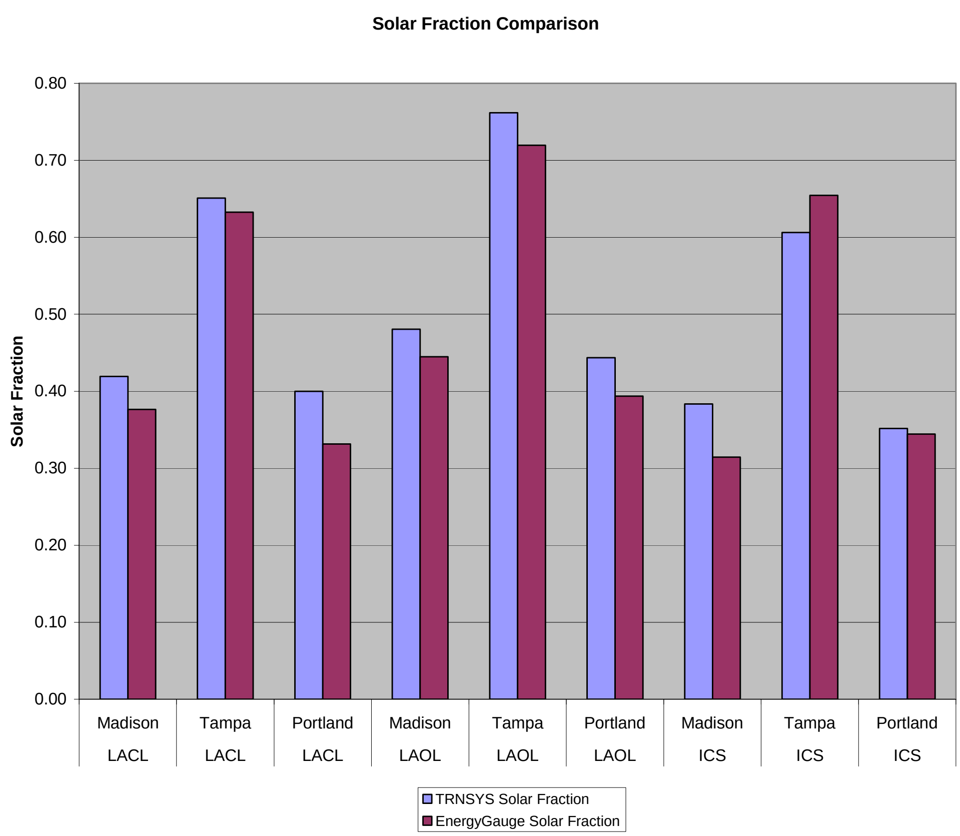
ICS

Average Annual Solar Fraction		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	0.38	0.32
Tampa, FL	0.61	0.65
Portland, OR	0.35	0.34
Hot Water Energy Use (KWh)		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	2476	2772
Tampa, FL	1008	883
Portland, OR	2349	2385

No Solar

Hot Water Energy Use (KWh)		
City	**TRNSYS**	**EnergyGauge USA**
Madison, WI	4016	4044
Tampa, FL	2560	2555
Portland, OR	3623	3638


KWh Comparison
KWh
0
500
1000
1500
2000
2500
3000
Madison LACL
Tampa LACL
Portland LACL
Madison LAOL
Tampa LAOL
Portland LAOL
Madison ICS
Tampa ICS
Portland ICS
TRNSYS KWh
EnergyGauge KWh


Solar Fraction Comparison
Solar Fraction
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
Madison LACL
Tampa LACL
Portland LACL
Madison LAOL
Tampa LAOL
Portland LAOL
Madison ICS
Tampa ICS
Portland ICS
TRNSYS Solar Fraction
EnergyGauge Solar Fraction

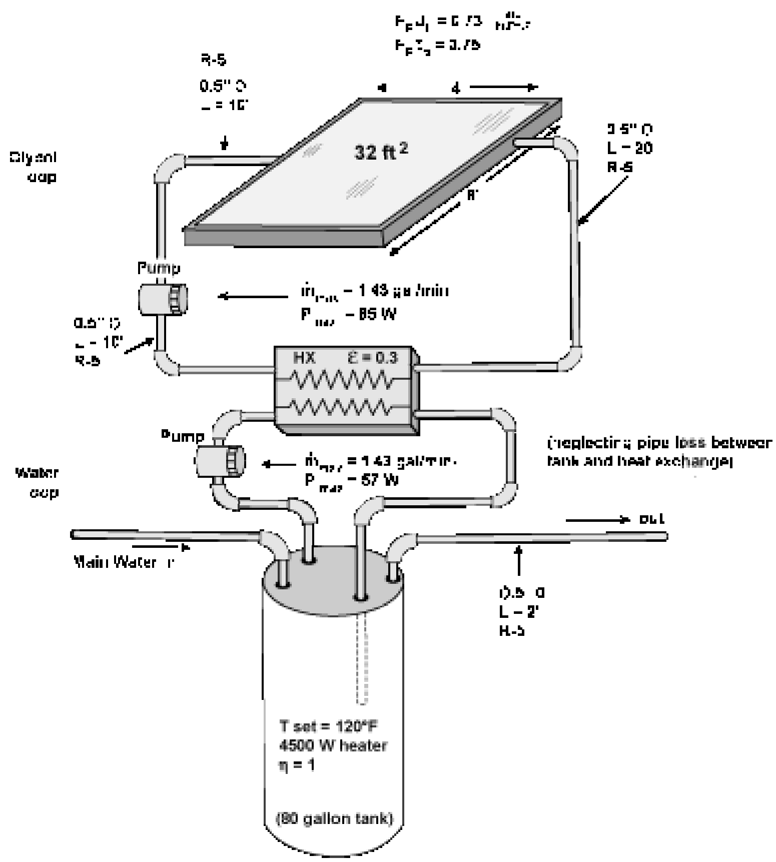
Significant Input Values

Variable	Value (English)	Value (SI)	Source	Model
Aux. heater size		16,198 kJ/hr (4,500 W)		ICS, LACL
Collector azimuth	180	180		LAOL, LACL, ICS
Collector loss coefficient	0.7344 Btu/hr-ft^2-F	4.17 W/m^2-C		LAOL, LACL
Collector surface area	32.29 ft^2	3 m^2		LAOL, LACL
Collector tilt	22.6	22.6		LAOL, LACL, ICS
Cover area	30.14 ft^2	2.8 m^2		ICS
Daily water load	60 gallons	226.5 kg		LACL, LAOL, ICS
Heat Exchanger Correction Factor		0.88		LACL
Loss Temperature	Tampa: 75.24F Madison: 70.56F Portland: 70.22F	Tampa: 24C Madison: 21.4C Portland: 70.22F		LACL, LAOL, ICS
Pump Energy		60 W		LAOL
Pump Energy		85 W		LACL
Set temperature	120 F	48.89 C		ICS
Storage tank surface area	24.97 ft^2	2.32 m^2		LAOL, LACL
Storage tank UA		3.535 kJ/hr-m^2-C		ICS
Storage tank U-value	0.1409 Btu/hr-ft^2-F	0.8 W/m^2-C (2.88 kJ/ hr-m^2-C)		LAOL, LACL
Storage tank volume	80.05 gal	303 L		LAOL, LACL
Storage tank volume	40 gal	0.15 m^3		ICS
Tank Energy Factor		0.90		LACL, LAOL
Tank loss coefficient	17.06 Btu/hr-F	9 W/C		ICS
Transmittance correction	0.96	0.96		LAOL, LACL
Transmittance/absorptance product	0.75	0.75		LAOL, LACL
Transmittance/absorptance product		0.82		ICS
Volumetric capacity	41.22 gal	156 L (0.156 m^3)		ICS

TRNSYS Models

LACL

The liquid-active, closed loop system modeled is displayed below.



The TRNSYS file created for this system is displayed below with comments interspersed:

```
ASSIGN \trnsys15_NEW\ICS_2006 \Madison\LACL.LST      6
ASSIGN \trnsys15_NEW\ICS_2006 \Madison\LACL.PLT     11
ASSIGN \trnsys15_NEW\ICS_2006 \Madison\LACL.OUT     12

* ================= Set TMY2 weather file here
*----- Tampa is 12842, Lat: 28.0, Solar Time Shift = -7.53
*ASSIGN \trnsys15\ICS\TMY2\12842.TM2  20

*----- Miami is 12839, Lat: 25.8
*ASSIGN \trnsys15\ICS\TMY2\12839.TM2  20

*----- Jacksonville is 13889, Lat: 30.5
*ASSIGN \trnsys15\ICS\TMY2\13889.TM2  20
```

```
*----- Madison, WI is 14837, Lat: 43.1, Solar Time Shift = 0.67
ASSIGN \trnsys15_NEW\ICS_2006 ICS\TMY2\14837.TM2  20

*----- Portland, OR is 24229, Lat: 45.6
*ASSIGN \trnsys15\ICS\TMY2\24229.TM2  20

*----- When changing locations, the following things must be updated:
*-----   1. weather file
*-----   2. solar radiation processor latitude (param 5)
*-----   3. solar radiation processor shift in solar time angle (param 7)
*-----   4. input water temperatures

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                     *
*                       Liquid Active Closed Loop                     *
*                       Written by Michael Anello                     *
*                            September, 2004                          *
*                                                                     *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

EQUATIONS 1
TIMESTEP = 1 / 256

*----- Annual simulation
SIMULATION 0.0 8760. TIMESTEP
WIDTH 72

*----- Tolerances
TOLERANCES 0.02  0.02

*----- Limits (maximum iterations)
*      warning  error  trace
LIMITS 25       200    25

*----- This reads in Unit 20 - the TMY2 data
UNIT 20 TYPE 89 CARD READER
PARAMETERS 2
2  20

*----- 5th input is tilt
UNIT 16 TYPE 16 SOLAR RADIATION PROCESSOR
* ================ 5th parameter is latitude
PARAMETERS 9
4      1      1
1      43.1   4871.
0.67   2      1
INPUTS 7
20,4 20,3 20,99 20,100  0,0  0,0  0,0
0.0  0.0  0.0   0.0     0.2  22.6  0.0
```

Solar Radiation Processor

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Horizontal radiation mode	4	n/a	I and I_{dn} are inputs
2	Tracking mode	1	n/a	Fixed surface
3	Tilted surface radiation	1	n/a	Isotropic sky model

4	Day of year to start simulation	1	n/a	
5	Latitude	43.1	Degrees north	Specific to Madison, WI
6	Solar constant	4871	$kJ/m^2 \cdot hr$	
7	Shift in solar time hour angle	0.67	Degrees	Specific to Madison, WI
8	Radiation smoothing	2	n/a	Radiation smoothing disabled
9	IE	1	n/a	Treat simulation time as solar time if IE<0

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	I	Global horizontal radiation from TMY2 file (20,4)	$kJ/m^2 \cdot hr$	
2	I_{dn}	Direct normal beam radiation from TMY2 file (20,3)	$kJ/m^2 \cdot hr$	
3	t_{dl}	Time of last radiation data reading from TMY2 file (20,99)	hr	
4	t_{d2}	Time of next radiation data reading from TMY2 file (20,100)	hr	
5	$\square_g$	0.2	n/a	ground reflectance
6	$\square_i$	22.6	degrees	slope of surface
7	$\square_i$	0.0	degrees	azimuth of surface (facing south)

```
UNIT 1 TYPE 1 COLLECTOR
PARAMETERS 11
1    2.97  3.7
1    50    0.717
18   0.0   2
0.19  0.0
INPUTS 9
32,1 32,2 20,5 16,7 16,4 16,6 0,0 16,10 16,11
20.  0.0  1.1  0.0  0.0  0.0  0.2 0.0   40.0
```

Collector

The collector performance values (parameters 2, 6, 7, 8, 10, and 11) were taken from the FSEC Summary Information Sheet for the AE-32 model collector.

Efficiency Equation: $\eta = 71.7 - 499\left(\frac{T_i - T_a}{I}\right)$

To convert this to TRNSYS inputs, convert all terms by 100 to make fractional, then multiply linear term by 3.6 to convert from C/W-m^2 to kJ/hr-m^2.

Incident Angle Modifier: $K\tau\alpha = 1.0 - 0.19\left(\frac{1}{\cos(\theta)} - 1\right)$ (no conversion necessary)

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	N_s	1	n/a	number of collector in series
2	A	2.97	m^2	collector area
3	c_{pc}	3.7	kJ/kg·C	specific heat of collector fluid (glycol)
4	Efficiency mode	1	n/a	□ vs. $(T_i - T_a) / I_T$
5	G_{test}	50	kg/m^2·hr	flowrate per unit area at test conditions
6	a_0	0.717	n/a	intercept efficiency (F_R(□□)$_n$, F_{av}(□□)$_n$, or F_0(□□)$_n$)
7	a_1	18	kJ/hr·m^2·C	negative of the first-order coefficient of the efficiency curve
8	a_2	0	n/a	negative of the second-order coefficient of the efficiency curve ($F_R U_{L/T}$, $F_{av} U_{L/T}$, or $F_0 U_{L/T}$)
9	Optical mode	2	n/a	use incidence modifiers from ASHRAE
10	□$_0$	0.19	n/a	first-order angle modifier constant from

				ASHRAE test
11	□$_1$	0	n/a	second-order angle modifier constant from ASHRAE test

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	temperature of fluid leaving pipe (from heat exchanger) (32,1)	C	temperature of fluid entering cold side of collector inlet
2	m(dot)$_c$	mass flow rate of fluid leaving pipe (from heat exchanger) (32,2)	kg/hr	collector fluid mass flow rate
3	T_a	ambient temperature from TMY2 data (20,5)	C	
4	I_T	Total radiation on surface 1 from radiation processor (16,7)	$kJ/hr{\cdot}m^2$	incident radiation
5	I	Total radiation on horizontal from radiation processor (16,4)	$kJ/hr{\cdot}m^2$	total horizontal radiation
6	I_d	diffuse radiation on horizontal from radiation processor (16,6)	$kJ/hr{\cdot}m^2$	horizontal diffuse radiation
7	□$_g$	0.2	n/a	ground reflectance
8	□	angle of incidence for surface from radiation processor (16,10)	degrees	incidence angle
9	□	slope of surface from radiation processor	degrees	collector slope

		(16,11)		

```
* Collector pump controller
UNIT 2 TYPE 2 PUMP CONTROLLER
PARAMETERS 2
5  100.
INPUTS 6
1,1  4,1  4,3  2,1  0,0   0,0
15.  60.  60.  0.   10.0  2.0
```

Pump Controller

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	NSTK	5	n/a	number of oscillations of the controller in a timestep after which the output control function ceases to change
2	T_{MAX}	100	C	high limit cut-out temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_H	output temperature from collector (1,1)	C	upper input temperature
2	T_L	output temperature from tank (4,1)	C	lower input temperature
3	T_{IN}	tank temperature to load (4,3)	C	temperature for high limit cut-out monitoring
4	$\square_i$	output control function from controller (2,1)	n/a	input control function
5	ΔT_H	10	C	upper dead band temperature difference
6	ΔT_L	2	C	lower dead band temperature difference

```
* Collector pump
UNIT 3 TYPE 3 PUMP
PARAMETERS 4
* 1.43 gal/min, 85 W
325.  3.7  306.  0.5
INPUTS 3
31,1 31,2 2,1
60.  0.0  0.0
```

Hot Side Pump

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	$m(dot)_{max}$	325	kg/hr	maximum flowrate
2	c_p	3.7	kJ/kg-C	fluid specific heat
3	P_{max}	306	kJ/hr	maximum power consumption (85W)
4	f_{par}	0.5	n/a	fraction of pump power converted to fluid thermal energy

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from pipe from heat exchanger (31,1)	C	inlet fluid temperature
2	$m(dot)_i$	output m(dot) from pipe from heat exchanger (31,2)	kg/hr	inlet mass flowrate
3	□	control function from pump controller (2,1)	n/a	control function

```
*----- Monthly MADISON supply water temperature - from Danny
*-----  Updated 3/30/06 by Mike based on EnergyGaugeUSA values
UNIT 5 TYPE 14 LOAD
PARAMETERS 48
0    5.5  744  5.5
744  4.5  1416 4.5
1416 5.1  2160 5.1
```

```
2160 7.1  2880 7.1
2880 10.0 3624 10.0
3624 13.0 4344 13.0
4344 15.4 5088 15.4
5088 16.6 5832 16.6
5832 16.1 6552 16.1
6552 14.2 7296 14.2
7296 11.4 8016 11.4
8016 8.3  8760 8.3
```

Supply Water Temperatures

The supply water temperatures are specified by using a "time dependent forcing function" (Type 14) within TRNSYS.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	t_0	0	n/a	start hour
2	v_0	5.5	C	initial value
3	t_1	744	n/a	hour at point 1
4	v_1	5.5	C	value at point 1
etc…				

The supply water temperatures are given on a monthly basis – the preceding 4 parameters define the supply water temperature for January (hours 0-744 of the year). These come from correlations developed by NREL (Christiansen and Hendron, 2005). The remainder of the unit is completed by specifying the remainder of the temperatures on a monthly basis.

```
*----- Hourly hot water load - from Danny
UNIT 14 TYPE 14 LOAD
PARAMETERS 88
0   3.6  1   3.6
1   1.8  2   1.8
2   0.0  5   0.0
5   3.6  6   3.6
6   7.3  7   7.3
7   18.2 8   18.2
8   14.5 9   14.5
9   14.9 10  14.9
10  14.5 11  14.5
11  13.1 12  13.1
12  11.6 13  11.6
13  10.2 14  10.2
14  8.7  15  8.7
15  8.0  16  8.0
16  9.4  17  9.4
17  11.6 18  11.6
18  13.8 19  13.8
19  15.3 20  15.3
20  13.8 21  13.8
21  12.3 22  12.3
22  10.9 23  10.9
23  9.4  24  9.4
```

Supply Water Mass Flow Rate

The supply water mass flow rates are specified by using a "time dependent forcing function" (Type 14) within TRNSYS.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	t_0	0	n/a	start hour
2	v_0	3.6	kg/hr	initial value
3	t_1	1	n/a	hour at point 1
4	v_1	3.6	kg/hr	value at point 1
etc…				

The supply water mass flow rates are given on a hourly basis – the preceding 4 parameters define the supply water mass flow rates for the first hour of each day. The remainder of the unit is completed by specifying the remainder of the mass flow rates on an hourly basis. The load profile is then used for each day within the TRNSYS simulation.

```
EQUATIONS 4
*----- 70.56F (average as found in EnergyGauge
LOSSTEMP = (70.56-32)*5/9
SET_TEMP_F = 120
SET_TEMP_C = (SET_TEMP_F-32) * (5/9)
*-----  Heating rate of heater (kJ/hr)
HEAT_RATE = 16198
```

Loss Temperature Equation

This equation is defined in order to specify the temperature of the surroundings for the purpose of tank and piping heat loss calculations. In this case, the "LOSSTEMP" is defined as 70.56F (in Madison). The LOSSTEMP variable is then used within the Tank and Pipe types in the simulation.

Set Temperature Equation

This equation defines the set temperature of the hot water tank auxiliary heater. It is set to 120F.

Heating Rate Equation

This simply defines the heating rate of the tank heater. It is set to 16,198 KJ/hr (15,355 Btu/hr).

```
UNIT 4 TYPE 4 TANK
PARAMETERS 20
1  0.273  4.19  1000  3.332  -1.49  1
4 4 SET_TEMP_C 2 HEAT_RATE
13 13 SET_TEMP_C 2 0
0.0  20.0  100.0
INPUTS 5
7,3   7,4  5,1   14,1  LOSSTEMP
```

```
15.0  0.0  19.4  0.0   21.0
DERIVATIVES 15
SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C
SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C
SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C
```

Hot Water Tank

The overall tank loss coefficient is based on results from the TRNSYS_tankloss.xls spreadsheet by Jay Burch. This spreadsheet takes various values (energy factor, recovery efficiency, rated input power, fuel type, and physical size) as inputs and outputs various (overall tank loss coefficient) TRNSYS inputs for the tank type.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Inlet Position Mode	1	n/a	fixed inlet position
2	V_t	0.273	m^3	effective tank volume (based on 80gal tank)
3	c_{pf}	4.19	kJ/kg-C	specific heat of the fluid
4	ρ_f	1000	kg/m^3	fluid density
5	U_t	3.332	$kJ/hr\text{-}m^2\text{-}C$	overall tank loss coefficient per unit area
6	H_1	-1.49	m	height of node 1 (if negative, all nodes are of equal height)
7	AuxMode	1	n/a	indicates master/slave heating element relationship
8	l_1	4	n/a	node in which first aux. heater is located
9	l_{T1}	4	n/a	node in which first thermostat is located
10	$T_{set,1}$	SET_TEMP_C (from equation)	C	set point of first thermostat
11	$\Delta T_{db,1}$	2	C	first thermostat deadband
12	$Q(dot)_{HE,1}$	HEAT_RATE (from equation)	kJ/hr	max. heating rate of second aux. heater
13	l_2	13	n/a	node in which second aux.

				heater is located
14	l_{T2}	13	n/a	node in which second thermostat is located
15	$T_{set,2}$	SET_TEMP_C (from equation)	C	set point of second thermostat
16	$\Delta T_{db,2}$	2	C	second thermostat deadband
17	$Q(dot)_{HE,2}$	0	kJ/hr	max. heating rate of second aux. heater (since 0, heater is effectively disabled)
18	$(UA)_f$	0	kJ/hr-C	total conductance for heat loss to gas flue when auxiliary is not operating (since 0, no loss)
19	T_{flue}	20	C	average flue temperature when auxiliary is not operating
20	T_{boil}	100	C	boiling point of fluid in tank

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_h	output temperature heat exchanger (7,3)	C	temperature of fluid from the heat source
2	$m(dot)_h$	output m(dot) from heat exchanger (7,4)	kg/hr	mass flowrate from the heat source
3	T_L	supply water temperature (5,1)	C	temperature of the replacement fluid
4	$m(dot)_L$	supply water mass flow rate (14,1)	kg/hr	mass flow rate of the replacement fluid
5	T_{env}	result from the LOSSTEMP	C	temperature of the environment

		equation		

```
* Heat exchanger
UNIT 7 TYPE 91 HEAT EXCHANGER
PARAMETERS 3
*effectiveness CpHot  CpCold
0.3           3.7    4.19
INPUTS 4
*HotInletTemp HotMassFlowRate ColdInletTemp ColdMassFlowRate
30,1           30,2           43,1           43,2
55.0          325.0           30.0           325.0
```

Heat Exchanger

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	□	0.3	n/a	heat exchanger effectiveness
2	c_{ph}	3.7	kJ/kg-C	specific heat of the fluid (hot side)
3	c_{pc}	4.19	kJ/hr-C	specific heat of the fluid (cold side)

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_{hi}	output temperature from pipe from collector (30,1)	C	hot side inlet temperature
2	$m(dot)_h$	output m(dot) from pipe from collector (30,2)	kg/hr	hot side mass flowrate
3	T_{ci}	output temperature from pipe from tank (43,1)	C	cold side inlet temperature
4	$m(dot)_c$	output m(dot) from pipe from tank (43,2)	kg/hr	cold side mass flowrate

```
* Heat exchanger pump
* this pump is controlled by the collector pump controller
UNIT 43 TYPE 3 PUMP
PARAMETERS 4
```

```
* 1 gal/min, 57 W
227.  4.19  205.  0.5
INPUTS 3
4,1  4,2  2,1
60.  0.0  0.0
```

Cold Side Pump

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	$m(dot)_{max}$	227	kg/hr	maximum flowrate
2	c_p	4.19	kJ/kg-C	fluid specific heat
3	P_{max}	205	kJ/hr	maximum power consumption
4	f_{par}	0.5	n/a	fraction of pump power converted to fluid thermal energy

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from pipe from tank (4,1)	C	inlet fluid temperature
2	$m(dot)_i$	output m(dot) from pipe from tank (4,2)	kg/hr	inlet mass flowrate
3	□	control function from pump controller (2,1)	n/a	control function

```
* Return pipe from collector to heat exchanger
UNIT 30 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  6.096     1.14   1000 3.7  20
INPUTS 3
*Tin Mdot Tenv
1,1  1,2  LOSSTEMP
30.  0.   20.
```

Pipe From Collector to Heat Exchanger

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	6.096	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	3.7	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from collector (1,1)	C	inlet fluid temperature
2	m(dot)	output m(dot) from collector (1,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
* Supply pipe from heat exchanger to collector pump
UNIT 31 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  3.048     1.14   1000 3.7  20
INPUTS 3
*Tin Mdot Tenv
7,1  7,2  LOSSTEMP
15.  0.   20.
```

Pipe From Heat Exchanger to Hot Side Pump

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	3.048	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density

5	c_p	3.7	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from heat exchanger (7,1)	C	inlet fluid temperature
2	m(dot)	output m(dot) from heat exchanger (7,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
* Supply pipe from pump to collector
UNIT 32 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  3.048     1.14   1000 3.7  20
INPUTS 3
*Tin Mdot Tenv
3,1  3,2  LOSSTEMP
60.  0.   20.
```

Pipe From Hot Side Pump to Collector

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	3.048	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	3.7	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature	C	inlet fluid temperature

		from hot side pump (3,1)		
2	m(dot)	output m(dot) from hot side pump (3,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
* Supply pipe from tank to load
UNIT 33 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  0.6096    1.14   1000 4.19 60
INPUTS 3
*Tin Mdot Tenv
4,3  4,4  LOSSTEMP
60.  0.   20.
```

Pipe From Tank to Load

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	0.6096	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	60	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from tank (4,3)	C	inlet fluid temperature
2	m(dot)	output m(dot) from tank (4,4)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
UNIT 24 TYPE 24 INTEGRATOR
```

```
PARAMETERS 1
24
INPUTS 5
16,6  1,3  4,5  4,3  4,6
0.0   0.0  0.0  0.0  0.0
```

Daily Integrator

The integrator type is used to sum values across a given time period. In this model, there are two integrators: a daily integrator and an hourly integrator. Their purpose is to compile the results in a manner that makes sense – daily and hourly data for an entire year.

NOTE: the 2nd row of inputs in both integrators are initial values for the integration – they are always set to zero for the purposes of this model.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_R	24	hours	a value of 24 causes results to be integrated over each day

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	16,6	kJ/m^2-hr	total solar radiation on surface 1
2	X_2	1,3	kJ/hr	collector rate of energy gain
3	X_3	4,5	kJ/hr	tank rate of energy loss to environment
4	X_4	4,3	kJ/hr	temperature to load from top node
5	X_5	4,6	kJ/hr	tank rate of energy removal to supply the load less the rate of energy supplied from the load

```
UNIT 25 TYPE 25 PRINTER
*----- PRINT RUNNING TOTALS OF INTEGRATION RESULTS EVERY 24 HOURS
PARAMETERS 5
24.  24.  8760.  12  1
INPUTS 8
24,1   24,2  24,3  24,4  24,5
TOTSOL TOTQU QENV  QTANK TQREQ
```

```
KJ      KJ     KJ     KJ     KJ
```

Daily Printer

The printer type is used to output the results to a text file. In this model, there are two printers: a "daily" printer and an "hourly" printer.

NOTE: the 2nd row of inputs in both printers are labels for each column of results. The 3rd row of inputs is a units label for each column as well.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_p	24	hours	time interval at which printing is to occur
2	t_{on}	24	hours	time at which printing is to start
3	t_{off}	8760	hours	time at which printing is to stop
4	L_{unit}	12	n/a	logical unit number to which to print to (refers to LACL.OUT)
5	UNITS	1	n/a	a value of 1 prints out the user supplied units (the 3rd row of inputs mentioned previously)

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	24,1	kJ/m^2-hr	daily total solar radiation on surface 1
2	X_2	24,2	kJ/hr	daily collector rate of energy gain
3	X_3	24,3	kJ/hr	daily tank rate of energy loss to environment
4	X_4	24,4	kJ/hr	daily required heating rate by heater
5	X_5	24,5	kJ/hr	daily tank rate of

				energy removal to supply the load less the rate of energy supplied from the load

```
UNIT 27 TYPE 24 INTEGRATOR
PARAMETERS 1
1
INPUTS 9
* 1,1: collector outlet temp
* 3,3: collector pump power
* 32,1: collector supply pipe outlet temp
* 4,3: tank outlet temp
* 20,5: ambient dry bulb temp
* 16,6: total radiation on surface
* 43,3: HX pump power
* 1,3: collector rate of energy gain
* 4,8: aux heater heating rate
1,1 3,3 32,1 4,3 20,5 16,6 43,3 1,3 4,8
0.0 0.0 0.0  0.0 0.0  0.0  0.0  0.0 0.0
```

Hourly Integrator

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_R	1	hours	a value of 1 causes results to be integrated over each hour

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	1,1	C	collector outlet temperature
2	X_2	3,3	kJ/hr	collector pump power
3	X_3	32,1	C	collector supply pipe (from pump) outlet temperature
4	X_4	4,3	C	tank outlet temperature
5	X_5	20,5	C	ambient dry bulb temperature
6	X_6	16.6	kJ/m^2-hr	total radiation on collector surface
7	X_7	43,3	kJ/hr	heat exchanger pump power

8	X_8	1,3	kJ/hr	collector rate of energy gain
9	X_9	4,8	kJ/hr	auxiliary heater heating rate

```
UNIT 26 TYPE 25 PRINTER
PARAMETERS 5
1.  0.  8760.  11  2
INPUTS 9
27,1 27,2 27,3 27,4 27,5 27,6 27,7 27,8 27,9
na   na   na   na   na   na   na   na   AUX_Heating_Rate
```

Hourly Printer

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_p	1	hours	time interval at which printing is to occur
2	t_{on}	0	hours	time at which printing is to start
3	t_{off}	8760	hours	time at which printing is to stop
4	L_{unit}	11	n/a	logical unit number to which to print to (refers to LACL.PLT)
5	UNITS	2	n/a	a value of 2 prints out the TRNSYS supplied units

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	27,1	C	hourly collector outlet temperature
2	X_2	27,2	kJ/hr	hourly collector pump power
3	X_3	27,3	C	hourly collector supply pipe (from pump) outlet temperature
4	X_4	27,4	C	hourly heater outlet

				temperature
5	X_5	27,5	C	hourly ambient dry bulb temperature
6	X_6	27,6	kJ/m^2-hr	hourly total radiation on collector surface
7	X_7	27,7	kJ/hr	hourly heat exchanger pump power
8	X_8	27,8	kJ/hr	hourly collector rate of energy gain
9	X_9	27,9	kJ/hr	hourly auxiliary heater heating rate

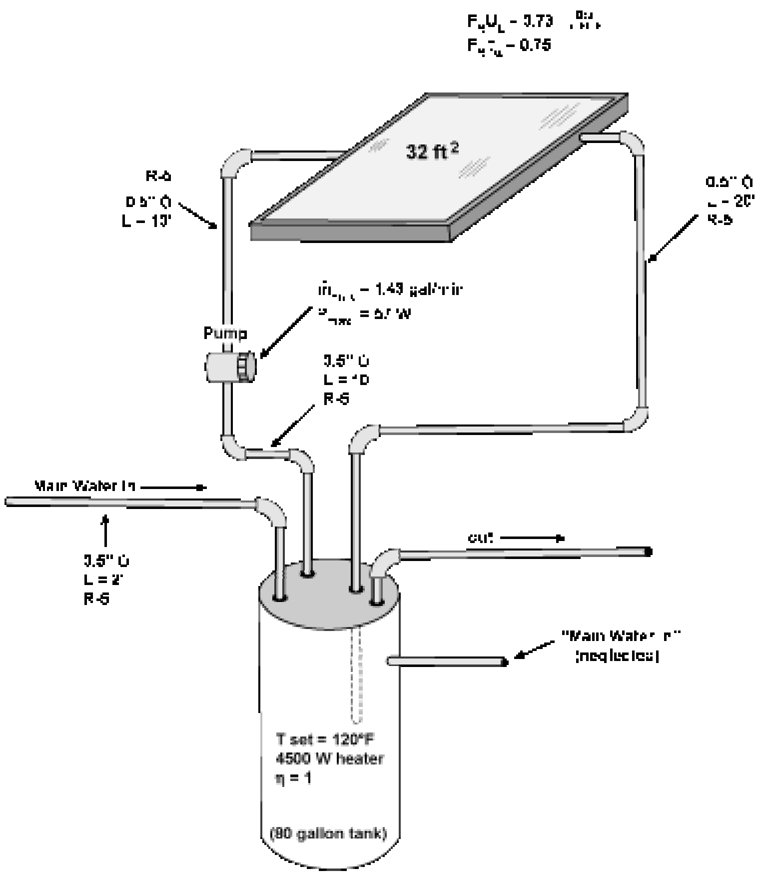
```
END
```

The "END" statement signifies the end of the input file.

LAOL

The liquid-active, open loop system modeled is displayed below.

LAOL (Liquid Active Open Loop Solar System)



The TRNSYS file created for this system is displayed below with comments interspersed:

```
ASSIGN \trnsys15_NEW\ICS_2006 \Madison\LAOL.LST     6
ASSIGN \trnsys15_NEW\ICS_2006 \Madison\LAOL.PLT    11
ASSIGN \trnsys15_NEW\ICS_2006 \Madison\LAOL.OUT    12
* ================ Set TMY2 weather file here
*----- Tampa is 12842, Lat: 28.0, Solar Time Shift = -7.53
*ASSIGN \trnsys15\ICS\TMY2\12842.TM2  20

*----- Miami is 12839, Lat: 25.8
*ASSIGN \trnsys15\ICS\TMY2\12839.TM2  20

*----- Jacksonville is 13889, Lat: 30.5
*ASSIGN \trnsys15\ICS\TMY2\13889.TM2  20

*----- Madison, WI is 14837, Lat: 43.1, Solar Time Shift = 0.67
ASSIGN \trnsys15_NEW\ICS_2006 \TMY2\14837.TM2  20

*----- Portland, OR is 24229, Lat: 45.6
*ASSIGN \trnsys15\ICS\TMY2\24229.TM2  20

*----- When changing locations, the following things must be updated:
*-----   1. weather file
*-----   2. solar radiation processor latitude (param 5)
*-----   3. solar radiation processor shift in solar time angle (param 7)
*-----   4. input water temperatures

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                     *
*                       Liquid Active Open Loop                       *
*                      Written by Michael Anello                      *
*                           September, 2004                           *
*                                                                     *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

EQUATIONS 1
TIMESTEP = 1 / 256

*----- Annual simulation
SIMULATION 0.0 8760. TIMESTEP
WIDTH 72

*----- Tolerances
TOLERANCES 0.02  0.02

*----- Limits (maximum iterations)
*      warning  error  trace
LIMITS 25       200    25

*----- This reads in Unit 20 - the TMY2 data
UNIT 20 TYPE 89 CARD READER
PARAMETERS 2
2  20

*----- 5th input is tilt
UNIT 16 TYPE 16 SOLAR RADIATION PROCESSOR
* ================ 5th parameter is latitude
PARAMETERS 9
4      1      1
1      43.1   4871.
0.67   2      1
INPUTS 7
20,4 20,3 20,99 20,100  0,0  0,0  0,0
0.0  0.0  0.0   0.0     0.2  22.6  0.0
```

Solar Radiation Processor

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Horizontal radiation mode	4	n/a	I and I_{dn} are inputs
2	Tracking mode	1	n/a	Fixed surface
3	Tilted surface radiation	1	n/a	Isotropic sky model
4	Day of year to start simulation	1	n/a	
5	Latitude	43.1	Degrees north	Specific to Madison, WI
6	Solar constant	4871	$kJ/m^2 \cdot hr$	
7	Shift in solar time hour angle	0.67	Degrees	Specific to Madison, WI
8	Radiation smoothing	2	n/a	Radiation smoothing disabled
9	IE	1	n/a	Treat simulation time as solar time if IE<0

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	I	Global horizontal radiation from TMY2 file (20,4)	$kJ/m^2 \cdot hr$	
2	I_{dn}	Direct normal beam radiation from TMY2 file (20,3)	$kJ/m^2 \cdot hr$	
3	t_{dl}	Time of last radiation data reading from TMY2 file (20,99)	hr	
4	t_{d2}	Time of next radiation data reading from TMY2 file (20,100)	hr	
5	$\square_g$	0.2	n/a	ground reflectance
6	$\square_i$	22.6	degrees	slope of surface
7	$\square_i$	0.0	degrees	azimuth of surface (facing south)

```
UNIT 1 TYPE 1 COLLECTOR
PARAMETERS 11
1    2.97  4.19
1    50    0.717
18   0.0   2
0.19  0.0
INPUTS 9
32,1 32,2 20,5 16,7 16,4 16,6 0,0 16,10 16,11
20.  0.0  1.1  0.0  0.0  0.0  0.2 0.0   40.0
```

Collector

The collector performance values (parameters 2, 6, 7, 8, 10, and 11) were taken from the FSEC Summary Information Sheet for the AE-32 model collector.

Efficiency Equation: $\eta = 71.7 - 499\left(\frac{T_i - T_a}{I}\right)$

To convert this to TRNSYS inputs, convert all terms by 100 to make fractional, then multiply linear term by 3.6 to convert from C/W-m^2 to kJ/hr-m^2.

Incident Angle Modifier: $K\tau\alpha = 1.0 - 0.19\left(\frac{1}{\cos(\theta)} - 1\right)$ (no conversion necessary)

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	N_s	1	n/a	number of collector in series
2	A	2.97	m^2	collector area
3	c_{pc}	4.19	kJ/kg·C	specific heat of collector fluid (water)
4	Efficiency mode	1	n/a	□ vs. $(T_i - T_a) / I_T$
5	G_{test}	50	kg/m^2·hr	flowrate per unit area at test conditions
6	a_0	0.717	n/a	intercept efficiency (F_R(□□)$_n$, F_{av}(□□)$_n$, or F_0(□□)$_n$)
7	a_1	18	kJ/hr·m^2·C	negative of the first-order coefficient of the efficiency curve

8	a_2	0	n/a	negative of the second-order coefficient of the efficiency curve ($F_RU_{L/T}$, $F_{av}U_{L/T}$, or $F_0U_{L/T}$)
9	Optical mode	2	n/a	use incidence modifiers from ASHRAE
10	□$_0$	0.19	n/a	first-order angle modifier constant from ASHRAE test
11	□$_1$	0	n/a	second-order angle modifier constant from ASHRAE test

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	temperature of fluid leaving pipe (from heat exchanger) (32,1)	C	temperature of fluid entering cold side of collector inlet
2	m(dot)$_c$	mass flow rate of fluid leaving pipe (from heat exchanger) (32,2)	kg/hr	collector fluid mass flow rate
3	T_a	ambient temperature from TMY2 data (20,5)	C	
4	I_T	Total radiation on surface 1 from radiation processor (16,7)	kJ/hr·m^2	incident radiation
5	I	Total radiation on horizontal from radiation processor (16,4)	kJ/hr·m^2	total horizontal radiation
6	I_d	diffuse radiation on horizontal from radiation processor (16,6)	kJ/hr·m^2	horizontal diffuse radiation

7	$\square_g$	0.2	n/a	ground reflectance
8	$\square$	angle of incidence for surface from radiation processor (16,10)	degrees	incidence angle
9	$\square$	slope of surface from radiation processor (16,11)	degrees	collector slope

```
UNIT 2 TYPE 2 PUMP CONTROLLER
PARAMETERS 2
5  100.
INPUTS 6
1,1  4,1  4,3  2,1  0,0   0,0
15.  60.  60.  0.   10.0  2.0
```

Pump Controller

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	NSTK	5	n/a	number of oscillations of the controller in a timestep after which the output control function ceases to change
2	T_{MAX}	100	C	high limit cut-out temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_H	output temperature from collector (1,1)	C	upper input temperature
2	T_L	output temperature from tank (4,1)	C	lower input temperature
3	T_{IN}	tank temperature to load (4,3)	C	temperature for high limit cut-out monitoring
4	$\square_i$	output control function from	n/a	input control function

		controller (2,1)		
5	ΔTH	10	C	upper dead band temperature difference
6	ΔTL	2	C	lower dead band temperature difference

```
UNIT 3 TYPE 3 PUMP
PARAMETERS 4
* 1 gal/min, 57 W
227.  4.19  205.  0.5
INPUTS 3
31,1 31,2 2,1
60.  0.0  0.0
```

Pump

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	$m(dot)_{max}$	227	kg/hr	maximum flowrate
2	c_p	4.19	kJ/kg-C	fluid specific heat
3	P_{max}	205	kJ/hr	maximum power consumption
4	f_{par}	0.5	n/a	fraction of pump power converted to fluid thermal energy

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from pipe from heat exchanger (31,1)	C	inlet fluid temperature
2	$m(dot)_i$	output m(dot) from pipe from heat exchanger (31,2)	kg/hr	inlet mass flowrate
3	□	control function from pump controller	n/a	control function

		(2,1)		

```
*----- Monthly MADISON supply water temperature - from Danny
*-----  Updated 3/30/06 by Mike based on EnergyGaugeUSA values
UNIT 5 TYPE 14 LOAD
PARAMETERS 48
0    5.5  744  5.5
744  4.5  1416 4.5
1416 5.1  2160 5.1
2160 7.1  2880 7.1
2880 10.0 3624 10.0
3624 13.0 4344 13.0
4344 15.4 5088 15.4
5088 16.6 5832 16.6
5832 16.1 6552 16.1
6552 14.2 7296 14.2
7296 11.4 8016 11.4
8016 8.3  8760 8.3
```

Supply Water Temperatures

The supply water temperatures are specified by using a "time dependent forcing function" (Type 14) within TRNSYS.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	t_0	0	n/a	start hour
2	v_0	5.5	C	initial value
3	t_1	744	n/a	hour at point 1
4	v_1	5.5	C	value at point 1
etc…				

The supply water temperatures are given on a monthly basis – the preceding 4 parameters define the supply water temperature for January (hours 0-744 of the year). The remainder of the unit is completed by specifying the remainder of the temperatures on a monthly basis.

```
*----- Equation for tank and pipe loss temp
EQUATIONS 1
LOSSTEMP = (70.56-32)*5/9
```

Loss Temperature Equation

This equation is defined in order to specify the temperature of the surroundings for the purpose of tank and piping heat loss calculations. In this case, the "LOSSTEMP" is defined as 70.56F (in Madison). The LOSSTEMP variable is then used within the Tank and Pipe types in the simulation.

```
*----- Hourly hot water load - from Danny
UNIT 14 TYPE 14 LOAD
```

```
PARAMETERS 88
0   3.6  1   3.6
1   1.8  2   1.8
2   0.0  5   0.0
5   3.6  6   3.6
6   7.3  7   7.3
7   18.2 8   18.2
8   14.5 9   14.5
9   14.9 10  14.9
10  14.5 11  14.5
11  13.1 12  13.1
12  11.6 13  11.6
13  10.2 14  10.2
14  8.7  15  8.7
15  8.0  16  8.0
16  9.4  17  9.4
17  11.6 18  11.6
18  13.8 19  13.8
19  15.3 20  15.3
20  13.8 21  13.8
21  12.3 22  12.3
22  10.9 23  10.9
23  9.4  24  9.4
```

Supply Water Mass Flow Rate

The supply water mass flow rates are specified by using a "time dependent forcing function" (Type 14) within TRNSYS.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	t_0	0	n/a	start hour
2	v_0	3.6	kg/hr	initial value
3	t_1	1	n/a	hour at point 1
4	v_1	3.6	kg/hr	value at point 1
etc…				

The supply water mass flow rates are given on a hourly basis – the preceding 4 parameters define the supply water mass flow rates for the first hour of each day. The remainder of the unit is completed by specifying the remainder of the mass flow rates on an hourly basis. The load profile is then used for each day within the TRNSYS simulation.

```
EQUATIONS 3
SET_TEMP_F = 120
SET_TEMP_C = (SET_TEMP_F-32) * (5/9)
*-----  Heating rate of heater (kJ/hr)
HEAT_RATE = 16198
```

Set Temperature Equation

This equation defines the set temperature of the hot water tank auxiliary heater. It is set to 120F.

Heating Rate Equation

This simply defines the heating rate of the tank heater. It is set to 16,198 KJ/hr (15,355 Btu/hr).

```
UNIT 4 TYPE 4 TANK
PARAMETERS 20
1  0.273  4.19  1000  3.332  -1.49  1
4  4  SET_TEMP_C 2 HEAT_RATE
13 13 SET_TEMP_C 2 0.0
0.0  20.0  100.0
INPUTS 5
30,1 30,2  5,1   14,1  LOSSTEMP
15.0  0.0  19.4  0.0   21.0
DERIVATIVES 15
SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C
SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C
SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C SET_TEMP_C
```

Hot Water Tank

The overall tank loss coefficient is based on results from the TRNSYS_tankloss.xls spreadsheet by Jay Burch. This spreadsheet takes various values (energy factor, recovery efficiency, rated input power, fuel type, and physical size) as inputs and outputs various (overall tank loss coefficient) TRNSYS inputs for the tank type.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Inlet Position Mode	1	n/a	fixed inlet position
2	V_t	0.273	m^3	tank volume
3	c_{pf}	4.19	kJ/kg-C	specific heat of the fluid
4	$\square_f$	1000	kg/m^3	fluid density
5	U_t	3.332	$kJ/hr\text{-}m^2\text{-}C$	overall tank loss coefficient per unit area
6	H_1	-1.49	m	height of node 1 (if negative, all nodes are of equal height)
7	AuxMode	1	n/a	indicates master/slave heating element relationship
8	l_1	4	n/a	node in which first aux. heater is located
9	l_{T1}	4	n/a	node in which first thermostat is located

10	$T_{set,1}$	SET_TEMP_C (from equation)	C	set point of first thermostat
11	$\Delta T_{db,1}$	2	C	first thermostat deadband
12	$Q(dot)_{HE,1}$	HEAT_RATE (from equation)	kJ/hr	max. heating rate of second aux. heater (since 0, heater is effectively disabled)
13	l_2	13	n/a	node in which second aux. heater is located
14	l_{T2}	13	n/a	node in which second thermostat is located
15	$T_{set,2}$	SET_TEMP_C (from equation)	C	set point of second thermostat
16	$\Delta T_{db,2}$	2	C	second thermostat deadband
17	$Q(dot)_{HE,2}$	0	kJ/hr	max. heating rate of second aux. heater (since 0, heater is effectively disabled)
18	$(UA)_f$	0	kJ/hr-C	total conductance for heat loss to gas flue when auxiliary is not operating (since 0, no loss)
19	T_{flue}	20	C	average flue temperature when auxiliary is not operating
20	T_{boil}	100	C	boiling point of fluid in tank

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_h	output temperature from pipe from collector	C	temperature of fluid from the heat source

		(30,1)		
2	m(dot)$_h$	output m(dot) from pipe from collector (30,2)	kg/hr	mass flowrate from the heat source
3	T_L	supply water temperature (5,1)	C	temperature of the replacement fluid
4	m(dot)$_L$	supply water mass flow rate (14,1)	kg/hr	mass flow rate of the replacement fluid
5	T_{env}	result from the LOSSTEMP equation	C	temperature of the environment
6	$\square_{htr,1}$	0 (heater always off)	n/a	enable signal for first heating element
7	$\square_{htr,2}$	0 (heater always off)	n/a	enable signal for second heating element

```
* Return pipe from collector to tank
UNIT 30 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  6.096     1.14   1000 4.19 20
INPUTS 3
*Tin Mdot Tenv
1,1  1,2  LOSSTEMP
30.  0.   20.
```

Pipe From Collector to Tank

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	6.096	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info

1	T_i	output temperature from collector (1,1)	C	inlet fluid temperature
2	m(dot)	output m(dot) from collector (1,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
* Supply pipe from tank to pump
UNIT 31 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  3.048     1.14   1000 4.19 20
INPUTS 3
*Tin Mdot Tenv
4,1  4,2  LOSSTEMP
15.  0.   20.
```

Pipe From Tank to Pump

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	3.048	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from tank (4,1)	C	inlet fluid temperature
2	m(dot)	output m(dot) from tank (4,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
* Supply pipe from pump to collector
UNIT 32 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  3.048     1.14   1000 4.19 20
INPUTS 3
*Tin Mdot Tenv
3,1  3,2  LOSSTEMP
60.  0.   20.
```

Pipe From Pump to Collector

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	3048	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from pump (3,1)	C	inlet fluid temperature
2	m(dot)	output m(dot) from pump (3,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
* Supply pipe from tank to load
UNIT 33 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  0.6096    1.14   1000 4.19 60
INPUTS 3
*Tin Mdot Tenv
4,3  4,4  LOSSTEMP
60.  0.   20.
```

Pipe From Tank to Load

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	0.6096	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	60	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from tank (4,3)	C	inlet fluid temperature
2	m(dot)	output m(dot) from tank (4,4)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
UNIT 24 TYPE 24 INTEGRATOR
PARAMETERS 1
24
INPUTS 5
16,6  1,3  4,5  4,3  4,6
0.0   0.0  0.0  0.0  0.0
```

Daily Integrator

The integrator type is used to sum values across a given time period. In this model, there are two integrators: a daily integrator and an hourly integrator. Their purpose is to compile the results in a manner that makes sense – daily and hourly data for an entire year.

NOTE: the 2nd row of inputs in both integrators are initial values for the integration – they are always set to zero for the purposes of this model.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_R	24	hours	a value of 24 causes results to be integrated over each day

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	16,6	kJ/m^2-hr	total solar radiation on surface 1
2	X_2	1,3	kJ/hr	collector rate of energy gain
3	X_3	4,5	kJ/hr	tank rate of energy loss to environment
4	X_4	4,3	kJ/hr	tank output temperature (top node)
5	X_5	4,6	kJ/hr	tank rate of energy removal to supply the load less the rate of energy supplied from the load

```
UNIT 25 TYPE 25 PRINTER
*----- PRINT RUNNING TOTALS OF INTEGRATION RESULTS EVERY 24 HOURS
PARAMETERS 5
24.  24.  8760.  12  1
INPUTS 5
24,1   24,2  24,3  24,4  24,5
TOTSOL TOTQU QENV  TQREQ QTANK
KJ     KJ    KJ    KJ    KJ
```

Daily Printer

The printer type is used to output the results to a text file. In this model, there are two printers: a "daily" printer and an "hourly" printer.

NOTE: the 2nd row of inputs in both printers are labels for each column of results. The 3rd row of inputs is a units label for each column as well.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_p	24	hours	time interval at which printing is to occur

2	t_{on}	24	hours	time at which printing is to start
3	t_{off}	8760	hours	time at which printing is to stop
4	L_{unit}	12	n/a	logical unit number to which to print to (refers to LACL.OUT)
5	UNITS	1	n/a	a value of 1 prints out the user supplied units (the 3rd row of inputs mentioned previously)

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	24,1	kJ/m^2-hr	daily total solar radiation on surface 1
2	X_2	24,2	kJ/hr	daily collector rate of energy gain
3	X_3	24,3	kJ/hr	daily tank rate of energy loss to environment
4	X_4	24,4	kJ/hr	daily required heating rate by heater
5	X_5	24,5	kJ/hr	daily tank rate of energy removal to supply the load less the rate of energy supplied from the load

```
UNIT 27 TYPE 24 INTEGRATOR
PARAMETERS 1
1
INPUTS 9
* 1,1: collector outlet temp
* 3,3: pump power
* 32,1: collector supply pipe outlet temp
* 4,3: tank outlet temp
* 20,5: ambient dry bulb temp
* 16,6: total radiation on surface
```

```
* 1,4: collector outlet temp2
* 1,3: collector rate of energy gain
* 4,8: aux heater heating rate
1,1 3,3 32,1 4,3 20,5 16,6 1,4  1,3 4,8
0.0 0.0 0.0  0.0 0.0  0.0  0.0  0.0 0.0
```

Hourly Integrator

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_R	1	hours	a value of 1 causes results to be integrated over each hour

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	1,1	C	collector outlet fluid temperature (from collector heat exchanger)
2	X_2	3,3	kJ/hr	collector pump power
3	X_3	32,1	C	collector supply pipe (from pump) outlet temperature
4	X_4	4,3	C	tank heater outlet temperature
5	X_5	20,5	C	ambient dry bulb temperature
6	X_6	16.6	kJ/m^2-hr	total radiation on collector surface
7	X_7	1,4	C	collector outlet fluid temperature
8	X_8	1,3	kJ/hr	collector rate of energy gain
9	X_9	4,8	kJ/hr	auxiliary heater heating rate

```
UNIT 26 TYPE 25 PRINTER
PARAMETERS 5
1.  0.  8760.  11  2
INPUTS 9
27,1 27,2 27,3 27,4 27,5 27,6 27,7 27,8 27,9
na   na   na   na   na   na   na   na   na
```

Hourly Printer

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_p	1	hours	time interval at which printing is to occur
2	t_{on}	0	hours	time at which printing is to start
3	t_{off}	8760	hours	time at which printing is to stop
4	L_{unit}	11	n/a	logical unit number to which to print to (refers to LACL.PLT)
5	UNITS	2	n/a	a value of 2 prints out the TRNSYS supplied units

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	27,1	C	hourly collector outlet temperature (from collector heat exchanger)
2	X_2	27,2	kJ/hr	hourly collector pump power
3	X_3	27,3	C	hourly collector supply pipe (from pump) outlet temperature
4	X_4	27,4	C	hourly heater outlet temperature
5	X_5	27,5	C	hourly ambient dry bulb temperature
6	X_6	27,6	kJ/m^2-hr	hourly total radiation on collector surface
7	X_7	27,7	C	collector outlet fluid

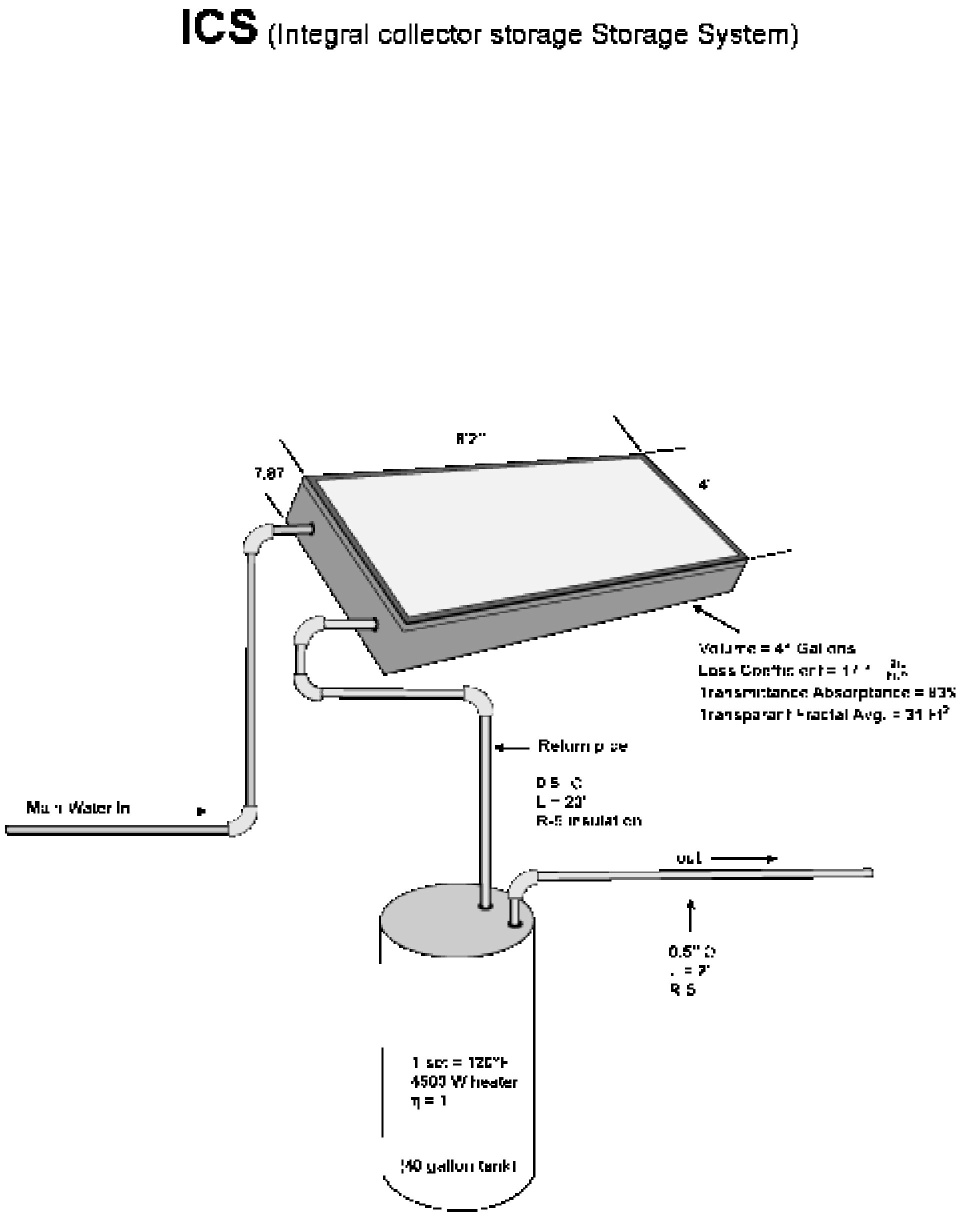
				temperature
8	X_8	27,8	kJ/hr	hourly collector rate of energy gain
9	X_9	27,9	kJ/hr	hourly auxiliary heater heating rate

```
END
```

The "END" statement signifies the end of the input file.

ICS

The integral collector storage system modeled is displayed below.



The TRNSYS file created for this system is displayed below with comments interspersed:

```
ASSIGN \trnsys15_NEW\ICS_2006\Madison\ICS.LST     6
ASSIGN \trnsys15_NEW\ICS_2006\Madison\ICS.PLT    11
ASSIGN \trnsys15_NEW\ICS_2006\Madison\ICS.OUT    12
* ================ Set TMY2 weather file here
*----- Tampa is 12842, Lat: 28.0, Solar Time Shift = -7.53
*ASSIGN \trnsys15_NEW\ICS_2006\TMY2\12842.TM2  20

*----- Miami is 12839, Lat: 25.8
*ASSIGN \trnsys15_NEW\ICS_2006\TMY2\12839.TM2  20

*----- Jacksonville is 13889, Lat: 30.5
*ASSIGN \trnsys15_NEW\ICS_2006\TMY2\13889.TM2  20

*----- Madison, WI is 14837, Lat: 43.1, Solar Time Shift = 0.67
ASSIGN \trnsys15_NEW\ICS_2006\TMY2\14837.TM2  20

*----- Portland, OR is 24229, Lat: 45.6
*ASSIGN \trnsys15_NEW\ICS_2006\TMY2\24229.TM2  20

*----- When changing locations, the following things must be updated:
*-----   1. weather file
*-----   2. solar radiation processor latitude (param 5)
*-----   3. solar radiation processor shift in solar time angle (param 7)
*-----   4. input water temperatures

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                       *
*                   Integrated Collector System (ICS)                   *
*                       Written by Michael Anello                       *
*                             August, 2004                              *
*                                                                       *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

EQUATIONS 1
TIMESTEP = 1 / 256

*----- Annual simulation
SIMULATION 0.0 8760. TIMESTEP

*----- Output file width (number of characters)
WIDTH 72

*----- Tolerances
*----- see page 2-3 of manual
TOLERANCES 0.02  0.02

*----- Limits (maximum iterations)
*      warning  error  trace
LIMITS 25       200    25

*----- This reads in Unit 20 - the TMY2 data
UNIT 20 TYPE 89 CARD READER
PARAMETERS 2
2  20

*----- 5th input is tilt
UNIT 16 TYPE 16 SOLAR RADIATION PROCESSOR
* ================ 5th parameter is latitude
PARAMETERS 9
4      1      1
1      43.1   4871.
0.67   2      1
```

```
INPUTS 7
20,4 20,3 20,99 20,100  0,0  0,0  0,0
0.0  0.0  0.0   0.0     0.2  22.6  0.0
```

Solar Radiation Processor

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Horizontal radiation mode	4	n/a	I and I_{dn} are inputs
2	Tracking mode	1	n/a	Fixed surface
3	Tilted surface radiation	1	n/a	Isotropic sky model
4	Day of year to start simulation	1	n/a	
5	Latitude	43.1	Degrees north	Specific to Madison, WI
6	Solar constant	4871	$kJ/m^2 \cdot hr$	
7	Shift in solar time hour angle	0.67	Degrees	Specific to Madison, WI
8	Radiation smoothing	2	n/a	Radiation smoothing disabled
9	IE	1	n/a	Treat simulation time as solar time if IE<0

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	I	Global horizontal radiation from TMY2 file (20,4)	$kJ/m^2 \cdot hr$	
2	I_{dn}	Direct normal beam radiation from TMY2 file (20,3)	$kJ/m^2 \cdot hr$	
3	t_{dl}	Time of last radiation data reading from TMY2 file (20,99)	hr	
4	t_{d2}	Time of next radiation data reading from TMY2 file (20,100)	hr	
5	ρ_g	0.2	n/a	ground reflectance

6	□$_i$	22.6	degrees	slope of surface
7	□$_i$	0.0	degrees	azimuth of surface (facing south)

```
*----- EQUATIONS FOR ICS
*----- used in ICS COLLECTOR
*----- equation from Thornton
EQUATIONS 1
UTOP=(18.45250 + 0.1598663*[1,15] - 0.00061446*[1,15]*[1,15])
```

This equation defines the U-value for the top of the collector based on an equation provided by Jeff Thornton of Tess, Inc.

```
*-----  Equation for solargain and cover losses fraction for each node
EQUATIONS 5
NUM_TUBES = 8
*----- Number of nodes in entire ICS unit
NUM_NODES = 32
NODE_FRAC = 1 / NUM_NODES
TUBE_LEN = 2.41
TUBE_DIA = 0.1
```

These equations define the number of tubes within the ICS collector and the total number of nodes within the entire collector as well as the size of the tubes. Also, the node fraction is defined for use in the ICS Type 550.

```
*----- ICS COLLECTOR - TYPE 550
UNIT 1 TYPE 550 ICS COLLECTOR
PARAMETERS 16
NUM_TUBES NUM_NODES 2.41   1.18
0.2       4.19      1000   6.23
5.0       0.5       5.0    5.0
TUBE_LEN  TUBE_DIA  0.0    1
INPUTS 80
5,1   14,1   20,5   16,7
16,6  16,4   16,10  16,2
16,3  16,11  0,0    0,0
20,5  0,0    UTOP   0,0
*----- Fraction of solar gain for each of the 32 nodes
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
*----- Fraction of additional cover losses for each of the 32 nodes
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
0,0  0,0  0,0  0,0  0,0  0,0  0,0  0,0
*----- Initial values for inputs
20.0  0.0      40.0  0.0
0.0   0.0      0.0   0.0
0.0   0.0      0.0   0.2
```

```
0.0   8.2E-01  6.15  0.0
*----- Fraction of solar gain for each of the 32 nodes
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
*----- Fraction of additional cover losses for each of the 32 nodes
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC NODE_FRAC
DERIVATIVES 32
*----- Initial temperature in each of the 32 nodes
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
```

Collector

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Number of tubes	NUM_TUBES (8)	n/a	number of unique storage tubes that comprise the IC collector
2	Number of nodes	NUM_NODES (32)	n/a	total number of nodes in the collector (note that this isn't per tube)
3	collector length	2.41	m	length of housing along the length of tubes
4	collector width	1.18	m	length of housing across the tube diameters
5	collector depth	0.2	m	depth of enclosure
6	c_p	4.19	kJ/kg·K	fluid specific heat
7	ρ	1000	kg/m^3	fluid density
8	k	6.23	kJ/hr·m·K	fluid thermal conductivity
9	edge loss coefficient	5	kJ/hr·m^2·K	
10	back loss coefficient	0.5	kJ/hr·m^2·K	
11	heat transfer coefficient	5	kJ/hr·K	between corresponding nodes

12	heat transfer coefficient	5	kJ/hr·K	between adjacent nodes
13	tube length	TUBE_LEN (2.41)	m	
14	tube diameter	TUBE_DIA (0.1)	m	
15	additional capacitance	0	kJ/K	additional capacitance of the system provided by the storage fluid (walls, glass, fins, etc)
16	IAM mode	1 (no off-normal effects are considered)	n/a	

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	temperature of fluid leaving pipe (from heat exchanger) (5,1)	C	temperature of fluid entering cold side of collector inlet
2	$m(dot)_c$	mass flow rate of fluid leaving pipe (from heat exchanger) (14,1)	kg/hr	collector fluid mass flow rate
3	T_a	ambient temperature from TMY2 data (20,5)	C	
4	I_T	Total radiation on surface 1 from radiation processor (16,7)	$kJ/hr{\cdot}m^2$	incident radiation
5	I_d	diffuse radiation on horizontal from radiation processor (16,6)	$kJ/hr{\cdot}m^2$	horizontal diffuse radiation
6	I	Total radiation on horizontal from radiation processor (16,4)	$kJ/hr{\cdot}m^2$	total horizontal radiation

7	incidence angle	16,10	degrees	
8	solar zenith angle	16,2	degrees	
9	solar azimuth angle	16,3	degrees	
10	collector slope	16,11	degrees	
11	surface azimuth	0.0	degrees	facing south
12	$\square_g$	0.2	n/a	ground reflectance
13	edge and back loss temperature	20,5 (ambient temperature)	degrees	
14	$\tau\alpha$	0.82	n/a	transmittance-absorption product
15	top loss coefficient	6.15	$kJ/hr{\cdot}m^2{\cdot}K$	
16	additional top losses	0	$kJ/hr{\cdot}m^2$	any additional hours from the collector cover per unit area – losses from the system are positive values
17-48	fraction of solar gain for node i	NODE_FRAC (1/32)	n/a	
49-80	fraction of additional losses for node i	NODE_FRAC (1/32)		

```
*----- Monthly MADISON supply water temperature - from Danny
*-----  Updated 3/30/06 by Mike based on EnergyGaugeUSA values
UNIT 5 TYPE 14 LOAD
PARAMETERS 48
0    5.5  744  5.5
744  4.5  1416 4.5
1416 5.1  2160 5.1
2160 7.1  2880 7.1
2880 10.0 3624 10.0
3624 13.0 4344 13.0
4344 15.4 5088 15.4
5088 16.6 5832 16.6
5832 16.1 6552 16.1
6552 14.2 7296 14.2
7296 11.4 8016 11.4
8016 8.3  8760 8.3
```

Supply Water Temperatures

The supply water temperatures are specified by using a "time dependent forcing function" (Type 14) within TRNSYS. The values are identical to the values used in the corresponding EnergyGauge calculation for each city.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	t_0	0	n/a	start hour
2	v_0	5.5	C	initial value
3	t_1	744	n/a	hour at point 1
4	v_1	5.5	C	value at point 1
etc…				

The supply water temperatures are given on a monthly basis – the preceding 4 parameters define the supply water temperature for January (hours 0-744 of the year). The remainder of the unit is completed by specifying the remainder of the temperatures on a monthly basis.

```
*----- Hourly hot water load - from Danny
*----- each line correspons to a single month of input temps
*----- start hour, flow rate (L/hr), end hour, flow rate (C)
*----- 60 gal/day
UNIT 14 TYPE 14 LOAD
PARAMETERS 88
0   3.6  1   3.6
1   1.8  2   1.8
2   0.0  5   0.0
5   3.6  6   3.6
6   7.3  7   7.3
7   18.2 8   18.2
8   14.5 9   14.5
9   14.9 10  14.9
10  14.5 11  14.5
11  13.1 12  13.1
12  11.6 13  11.6
13  10.2 14  10.2
14  8.7  15  8.7
15  8.0  16  8.0
16  9.4  17  9.4
17  11.6 18  11.6
18  13.8 19  13.8
19  15.3 20  15.3
20  13.8 21  13.8
21  12.3 22  12.3
22  10.9 23  10.9
23   9.4  24  9.4
```

Supply Water Mass Flow Rate

The supply water mass flow rates are specified by using a "time dependent forcing function" (Type 14) within TRNSYS.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	t_0	0	n/a	start hour
2	v_0	3.6	kg/hr	initial value
3	t_1	1	n/a	hour at point 1
4	v_1	3.6	kg/hr	value at point 1

etc…				

The supply water mass flow rates are given on a hourly basis – the preceding 4 parameters define the supply water mass flow rates for the first hour of each day. The remainder of the unit is completed by specifying the remainder of the mass flow rates on an hourly basis. The load profile is then used for each day within the TRNSYS simulation. The values used are identical to the load used in the corresponding EnergyGauge simulation.

```
*----- Equations
EQUATIONS 7
*----- 70.56F (average as found in EnergyGauge)
LOSSTEMP = (70.56-32)*5/9
SET_TEMP_F = 120
SET_TEMP_C = (SET_TEMP_F-32) * (5/9)

*see TRNSYS_tankloss.xls (based on EF of 0.88)
*-----  Tank UA (kJ/(hr-C-m^2)
TANK_UA = 3.535
* (equivalent to 40gal)
TANK_V_M3 = 0.136
TANK_HGT = -1.68
*-----  Heating rate of heater (kJ/hr)
HEAT_RATE = 16198
```

Equations

Loss Temperature: This equation is defined in order to specify the temperature of the surroundings for the purpose of tank and piping heat loss calculations. In this case, the "LOSSTEMP" is defined as the average temperature as used in the corresponding EnergyGauge calculation for each city. The LOSSTEMP variable is then used within the Tank and Pipe types in the simulation.

Set Temperature Equation: This equation defines the set temperature of the hot water tank auxiliary heater. It is set to 120F.

Tank UA: The UA of the tank is set to 3.535 kJ/hr-C. This was calculated with the TRNSYS_tankloss.xls spreadsheet.

Tank Size: The volume of the tank is set to 40 gallons.

The tank height is set to 5.51ft, and the set temperature is 120F. The heating rate of the internal tank heater is 16,198 kJ/hr.

Heating Rate Equation: This simply defines the heating rate of each tank heater. It is set to 16,198 KJ/hr (15,355 Btu/hr).

```
* ----- Hot Water Tank
UNIT 4 TYPE 4 TANK
```

```
PARAMETERS 20
1     TANK_V_M3   4.19  1000  TANK_UA  TANK_HGT  1
4     4     SET_TEMP_C   2      HEAT_RATE
13    13    SET_TEMP_C   2      HEAT_RATE
0.0   20.0  100.0
INPUTS 5
0,0  0,0   30,1 30,2  LOSSTEMP
0.0  0.0   50.0  0.0  20.0
DERIVATIVES 15
SET_TEMP_C  SET_TEMP_C  SET_TEMP_C  SET_TEMP_C  SET_TEMP_C
SET_TEMP_C  SET_TEMP_C  SET_TEMP_C  SET_TEMP_C  SET_TEMP_C
SET_TEMP_C  SET_TEMP_C  SET_TEMP_C  SET_TEMP_C  SET_TEMP_C
```

Hot Water Tank

The overall tank loss coefficient is based on results from the TRNSYS_tankloss.xls spreadsheet by Jay Burch. This spreadsheet takes various values (energy factor, recovery efficiency, rated input power, fuel type, and physical size) as inputs and outputs various (overall tank loss coefficient) TRNSYS inputs for the tank type.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Inlet Position Mode	1	n/a	fixed inlet position
2	V_t	TANK_V_M3 (0.15)	m^3	tank volume
3	c_{pf}	4.19	kJ/kg-C	specific heat of the fluid
4	□$_f$	1000	kg/m^3	fluid density
5	U_t	TANK_UA (3.535)	$kJ/hr\text{-}m^2\text{-}C$	overall tank loss coefficient per unit area
6	H_1	TANK_HGT (1.68)	m	height of node 1 (if negative, all nodes are of equal height)
7	AuxMode	1	n/a	indicates master/slave heating element relationship (meaningless since both elements are disabled)
8	l_1	4	n/a	node in which first aux. heater is located
9	l_{T1}	4	n/a	node in which first thermostat is located
10	$T_{set,1}$	SET_TEMP_C	C	set point of first

				thermostat
11	$\Delta T_{db,1}$	2	C	first thermostat deadband
12	$Q(dot)_{HE,1}$	HEAT_RATE (16,198)	kJ/hr	max. heating rate of second aux. heater (since 0, heater is effectively disabled)
13	l_2	13	n/a	node in which second aux. heater is located
14	l_{T2}	13	n/a	node in which second thermostat is located
15	$T_{set,2}$	SET_TEMP_C	C	set point of second thermostat
16	$\Delta T_{db,2}$	2	C	second thermostat deadband
17	$Q(dot)_{HE,2}$	HEAT_RATE (16,198)	kJ/hr	max. heating rate of second aux. heater (since 0, heater is effectively disabled)
18	$(UA)_f$	0	kJ/hr-C	total conductance for heat loss to gas flue when auxiliary is not operating (since 0, no loss)
19	T_{flue}	20	C	average flue temperature when auxiliary is not operating
20	T_{boil}	100	C	boiling point of fluid in tank

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_h	n/a (no external heat source)	C	temperature of fluid from the heat source
2	$m(dot)_h$	n/a (no external heat source)	kg/hr	mass flowrate from the heat source

3	T_L	output temperature from pipe from collector (30,1)	C	temperature of the replacement fluid (not actually used, replacement fluid comes from ICS)
4	m(dot)$_L$	output m(dot) from pipe from collector (30,2)	kg/hr	mass flow rate of the replacement fluid (not used, replacement fluid comes from ICS)
5	T_{env}	result from the LOSSTEMP equation	C	temperature of the environment

```
*----- Return pipe from ICS to tank
*----- 4/11/06 from Dan - 50' of 3/4" copper pipe with R5.2 insulation
UNIT 30 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U      DENS CP   T0
 0.01905 15.24     1.09   1000 4.19 20
INPUTS 3
*Tin Mdot Tenv
1,1  1,2  LOSSTEMP
30.  0.   20.
```

Pipe From Collector to Tank

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.01905	m	pipe inside diameter
2	L	15.24	m	pipe length
3	U	1.09	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	20	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature	C	inlet fluid temperature

		from collector (1,1)		
2	m(dot)	output m(dot) from collector (1,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
*----- Supply pipe from heater to load
UNIT 33 TYPE 31 PIPE OR DUCT
PARAMETERS 6
*DIA(M) LENGTH(M) U(R-5) DENS CP   T0
0.0127  0.6096    1.14   1000 4.19 60
INPUTS 3
*Tin Mdot Tenv
4,1  4,2  LOSSTEMP
60.  0.   20.
```

Pipe From Tank to Load

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	d	0.0127	m	pipe inside diameter
2	L	6.096	m	pipe length
3	U	1.14	kJ/m^2-hr-C	overall loss coefficient based on inside pipe surface area
4	□	1000	kg/m^3	fluid density
5	c_p	4.19	kJ/kg-C	fluid specific heat
6	T_I	60	C	initial fluid temperature

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	T_i	output temperature from tank (4,1)	C	inlet fluid temperature
2	m(dot)	output m(dot) from tank (4,2)	kg/hr	fluid mass flowrate
3	T_{env}	result from the LOSSTEMP equation	C	environmental loss temperature for losses

```
*----- Quantity integrator - used for integrating stuff
UNIT 24 TYPE 24 INTEGRATOR
PARAMETERS 1
*-----
24
INPUTS 5
*----- total solar radition on surface (kJ/m^2 - hr)
*----- collector rate of delivered energy (kJ/hr)
*----- rate of energy loss to the environment by tank (kJ/hr)
*----- required heating rate of internal heater (kJ/hr)
*----- rate of energy removal to supply the load less the rate of energy
supplied from the load by tank (kJ/hr)
16,6  1,8  4,5  4,8  4,6
0.0   0.0  0.0  0.0  0.0
```

Daily Integrator

The integrator type is used to sum values across a given time period. In this model, there are two integrators: a daily integrator and an hourly integrator. Their purpose is to compile the results in a manner that makes sense – daily and hourly data for an entire year.

NOTE: the 2nd row of inputs in both integrators are initial values for the integration – they are always set to zero for the purposes of this model.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_R	24	hours	a value of 24 causes results to be integrated over each day

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	16,6	kJ/m^2-hr	total solar radiation on surface 1
2	X_2	1,8	kJ/hr	collector rate of delivered energy
3	X_3	4,5	kJ/hr	tank rate of energy loss to environment
4	X_4	4,8	kJ/hr	required heating rate by heater
5	X_5	4,6	kJ/hr	tank rate of energy removal to supply the load less the rate of energy supplied from

				the load

```
UNIT 25 TYPE 25 PRINTER
*----- PRINT RUNNING TOTALS OF INTEGRATION RESULTS EVERY 24 HOURS
PARAMETERS 5
24.  24.  8760.  12  1
INPUTS 8
24,1   24,2  24,3  24,5  24,4
TOTSOL TOTQU QENV  QTANK TQREQ
KJ     KJ    KJ    KJ    KJ
```

Daily Printer

The printer type is used to output the results to a text file. In this model, there are two printers: a "daily" printer and an "hourly" printer.

NOTE: the 2nd row of inputs in both printers are labels for each column of results. The 3rd row of inputs is a units label for each column as well.

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_p	24	hours	time interval at which printing is to occur
2	t_{on}	24	hours	time at which printing is to start
3	t_{off}	8760	hours	time at which printing is to stop
4	L_{unit}	12	n/a	logical unit number to which to print to (refers to LACL.OUT)
5	UNITS	1	n/a	a value of 1 prints out the user supplied units (the 3rd row of inputs mentioned previously)

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	24,1	kJ/m^2-hr	daily total solar radiation on surface 1
2	X_2	24,2	kJ/hr	daily collector

				rate of energy gain
6	X_3	24,3	kJ/hr	daily tank rate of energy loss to environment
7	X_4	24,4	kJ/hr	daily required heating rate by heater
8	X_5	24,5	kJ/hr	daily tank rate of energy removal to supply the load less the rate of energy supplied from the load

```
UNIT 27 TYPE 24 INTEGRATOR
PARAMETERS 1
1
INPUTS 9
*1,1: collector outlet temp
*30,1: collector return pipe outlet temp
*5,1: collector supply pipe outlet temp
*4,1: heater outlet temp
*20,5: ambient dry bulb temp
*16,4: total radiation on horizontal
*1,2: flow rate exiting ICS
*1,8: collector rate of delivered energy
*4,8: aux heater heating rate
1,1 30,1 5,1  4,1 20,5 16,4  1,2  1,8  4,8
0.0 0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
```

Hourly Integrator

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_R	1	hours	a value of 1 causes results to be integrated over each hour

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	1,1	C	collector outlet fluid temperature (from collector heat exchanger)
2	X_2	30,1	C	collector return pipe outlet temperature
3	X_3	5,1	C	collector supply

				pipe outlet temperature
4	X_4	4,1	C	tank outlet temperature
5	X_5	20,5	C	ambient dry bulb temperature
6	X_6	16,4	kJ/m^2-hr	total radiation on horizontal
7	X_7	1,2	kg/hr	collector outlet flow rate
8	X_8	1,8	kJ/hr	collector rate of delivered energy
9	X_9	4,8	kJ/hr	tank heater heating rate

```
UNIT 26 TYPE 25 PRINTER
PARAMETERS 5
1.  0.  8760.  11  2
INPUTS 9
27,1 27,2 27,3 27,4 27,5 27,6 27,7 27,8 27,9
na   na   na   na   na   na   na   na   AUX_Heating_Rate
```

Hourly Printer

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1	Δt_p	1	hours	time interval at which printing is to occur
2	t_{on}	0	hours	time at which printing is to start
3	t_{off}	8760	hours	time at which printing is to stop
4	L_{unit}	11	n/a	logical unit number to which to print to (refers to LACL.PLT)
5	UNITS	2	n/a	a value of 2 prints out the TRNSYS supplied units

Description of Inputs

Number	Input Name	Value Used	Units	Info
1	X_1	27,1	C	hourly collector

				outlet temperature (from collector heat exchanger)
2	X_2	27,2	C	collector return pipe outlet temperature
3	X_3	27,3	C	collector supply pipe outlet temperature
4	X_4	27,4	C	hourly tank heater outlet temperature
5	X_5	27,5	C	hourly ambient dry bulb temperature
6	X_6	27,6	kJ/m^2-hr	hourly total radiation on collector surface
7	X_7	27,7	kg/hr	flow rate existing ICS
8	X_8	27,8	kJ/hr	hourly collector rate of delivered energy
9	X_9	27,9	kJ/hr	hourly tank heater heating rate

```
UNIT 28 TYPE 65 ONLINE PLOTTER
PARAMETERS 10
2    2
-40  120
0    4000
52  7
-1    -1
INPUTS 4
20,5   1,1     1,8    4,8
TAMB   TCOLL   QCOLL  QAUX
LABELS 5
C    kJ/hr
Temperatures
Energy
ICS Plots
```

Online Plotter

The online plotter is used to interactively view various datapoints during the actual calculation of the model. It is useful for debugging the model. Once the model is verified, the online plotter is normally turned "off".

Description of Parameters

Number	Parameter Name	Value Used	Units	Info
1		2		
2		2		
3		-40		
4		120		
5		0		
6		4000		
7		52		
8		7		
9		-1		
10		-1		

Description of Inputs

Number	Input Name	Value Used	Units	Info
1		20,5	C	ambient temperature
2		1,1	C	temperature of collector
3		1,8		
4		4,8		

Description of Labels

Number	Input Name	Value Used	Info
1		C	
2		kJ/hr	
3		Temperatures	
4		Energy	
5		ICS Plots	

```
END
```

The "END" statement signifies the end of the input file.

EnergyGauge Models

EnergyGauge USA uses the DOE2 simulation engine to predict building energy loads. An f-chart routine was written as a DOE2 function that models the three solar hot water systems of interest.

LACL/LAOL/ICS

The SDHW function, as detailed below, is embedded within the DOE-2 input deck and is used by DOE-2 to calculate the "domestic hot water kilowatts" (DHWKW) variable based on the type of solar hot water heating system used.

This function is based on the f-chart method as detailed in Solar Engineering of Thermal Processes (Duffie, John A. and Beckman, William A., Wiley-Interscience, 1980), Section 14.5.

```
FUNCTION NAME = SDHW ..
```

Declares the function in DOE-2

```
       ASSIGN
```

Begins the "Assign" section of the function

```
         DHWKW = DHWKW
         DHWFL = DHWFL
         EXMCKW = EXMCKW
         DHWGAL = DHWGAL
         DHWTMP = DHWTMP
         TGARAG = XXX28
```

Brings in the necessary variables from the current iteration of the DOE-2 engine

Variable	Description	Units
DHWKW	domestic hot water kilowatt hours	kw
DHWFL	domestic hot water fuel energy use	Electric, Natural Gas, Fuel Oil
EXMCKW	pump power	kw
DHWGAL	domestic hot water load	gallons/minute
DHWTMP	domestic hot water temperature	F
TGARAG	garage temperature (NOTE: this variable is dependent on the hot water tank location as specified by the user – might also be "TLIVIN")	F

```
         $--- SOLAR HEATER PROPERTIES
         $--- --- 0: NONE, 1: LACL, 2: LAOL, 3: ICS
         SOLAR_TYPE = 1
```

Declares the type of solar hot water system to be modeled. In this case, it is set to "1", or "LACL".

```
SI_COLLECTOR_AREA = 3.72
FrUl = 4.17
SI_REF_TEMP = 100
FrTauAlphaN = 0.75
TauAlphaOverTauAlphaN = 0.96
TANK_SURF_AREA_SI = 3.26
TANK_U_VALUE_SI = 0.70
E_SET_POINT = 120.00
TRANS_ABSORP = 0.54
A_STRAT_CORRECTION = 0.326
TankTurnovers = 1.46
SI_UATANK = 9.00
PUMPW = 0.11
SOLARTANK_L= 303.00
```

Sets variables based on user input in EnergyGauge USA as well as various assumptions.

Variable	Description	Source	Units
SI_COLLECTOR_AREA	collector area	user input	m^2
FrUl	collector thermal loss coefficient	user input	W/m^2-C
SI_REF_TEMP	empirically derived reference temperature (=100C)	Solar Engineering of Thermal Processes	C
FrTauAlphaN	collector solar transmittance coefficient	user input	dimensionless
TauAlphaOverTauAlphaN	Transmittance correction factor	user input	dimensionless
TANK_SURF_AREA_SI	surface area of tank	user input	m^2
TANK_U_VALUE_SI	U-value of tank	user input	W/m^2-C
E_SET_POINT	hot water set point	user input	F
TRANS_ABSORP	collector transmittance-absorptance product	user input	dimensionless
A_STRAT_CORRECTION	tank stratification correction (=0.326)	Constant correlation parameter	Dimensionless
TankTurnovers	number of daily tank turnovers	calculated from user input	dimensionless
SI_UATANK	Total tank loss coefficient of tank	user input	W/C
PUMPW	pump size	user input	W
SOLARTANK_L	tank volumetric capacity	user input	L

```
$--- AVERAGING STUFF
NUM_HOURS = 24
```

The NUM_HOURS variable is used to average the following variables over the specified previous period for use within the function:

SI_AVG_TEMP (average temperature in C)
SI_AVG_SOL (average solar radiation in kJ/hr-m^2)
SI_DHWLOADT (average total hourly domestic hot water load in kJ/hr)
DHWKG (average domestic hot water load in kg)

```
$--- WEATHER VALUES
CURR_HOUR = IHR
CURR_DAY = IDAY
CURR_MONTH = IMO
CLDAMT = CLDAMT
E_TAMB = DBT
E_WBULB = WBT
E_INPUT_WATER_TEMP = HTTIN
SI_AVG_TEMP = XXX30
E_AVG_SOL = XXX31
SI_DHWLOADT = XXX32
RFLAG = XXX33
SI_AVG_SOL = XXX34
AVG_DHWKG = XXX35 ..
```

Brings in more variables from the current iteration of the DOE-2 engine:

Variable	Description	Units
CURR_HOUR	current hour	n/a
CURR_DAY	current day	n/a
CURR_MONTH	current month	n/a
CLDAMT	cloud cover for the current time step (0-10: 0=no clouds, 10=full cloud cover)	n/a
E_TAMB	dry bulb temperature	F
E_WBULB	wet bulb temperature	F
E_INPUT_WATER_TEMP	supply water temperature	F
SI_AVG_TEMP	average dry bulb temperature from previous iteration	C
E_AVG_SOL	average solar radiation from previous iteration	btu/hr-ft^2
SI_DHWLOADT	average total hourly domestic hot water load from previous iteration	kJ/hr
RFLAG	Rain flag (rain=1) from previous iteration	n/a
SI_AVG_SOL	average solar radiation from previous iteration	kJ/hr-m^2
AVG_DHWKG	average domestic hot water load from previous iteration	kg

```
         CALCULATE ..
```

Begins the calculations portion of the function

```
         SI_SET_POINT = (E_SET_POINT -32)*5/9
         SI_INPUT_WATER_TEMP = (E_INPUT_WATER_TEMP - 32) * 5 / 9
         SI_TAMB = (E_TAMB - 32) * 5 / 9
         SI_WBULB = (E_WBULB - 32) * 5 / 9
```

Converts the hot water set point, supply water temperature, ambient temperature, and wet bulb temperature to SI units.

```
         STO_COR = 0.93
```

This is an empirical correction for 'X' from the original F-chart correlations.

```
C        $----- CALCULATE THE DEW POINT
         P = 101.3
         A = 0.00066 * (1.0 + 0.00115 * SI_WBULB)
         ESWB = EXP((16.78 * SI_WBULB - 116.9) / (SI_WBULB + 237.3))
         ED = ESWB - A * P * (SI_TAMB - SI_WBULB)
         ESDB = EXP((16.78 * SI_TAMB - 116.9) / (SI_TAMB + 237.3))
         RH = (100.0* (ED / ESDB))

         ES = 6.11 * 10.0**(7.5 * SI_TAMB / (237.7 + SI_TAMB))
         E = (RH * ES) / 100
C        SI_DEWPOINT = (-430.22 + 237.7 * ALOG(E)) / ((-ALOG(E)) + 19.08)

         T1 = (-430.22 + 237.7 * ALOG(E))
         T2 = ((-ALOG(E)) + 19.08)
         SI_DEWPOINT = T1 / T2
         K_DEWPOINT = SI_DEWPOINT + 273.15
C        $----- END OF DEWPOINT CALCULATION
```

This correlation calculates the dewpoint based on psychometric principles. This is only used for the ICS calculation.

```
C        $----- CALCULATE THE AVERAGE TEMP FOR THE PAST 36 HOURS
         SI_AVG_TEMP = (SI_AVG_TEMP * 35  + SI_TAMB) / 36
         IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1))
     1      SI_AVG_TEMP = SI_TAMB
```

Calculates the average temperature for the past NUM_HOURS. The reason this was done was to take into account the fact that there is strong interaction between load history and weather history in order to offset loads in the current hour. The file "123" is generated earlier by the DOE2 "SOLAR" function (see details at the end of this section).

```
C        $----- GET THE SOLAR RADIATION AND AVERAGE IT FOR THE
C        $-----   PAST NUM_HOURS
         IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1) .AND.
     1       (CURR_MONTH .EQ. 1) .AND. (RFLAG .EQ. 0))
```

```
     1      REWIND 123
         IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1) .AND.
     1       (CURR_MONTH .EQ. 1))
     1      RFLAG = 1
         READ (123, 500) TEMP1, TEMP2, TEMP3, E_SOL
C        E_AVG_SOL = (E_AVG_SOL * (NUM_HOURS - 1) + E_SOL) /
C    1                  NUM_HOURS
C        IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1))
C    1      E_AVG_SOL = E_SOL

         SI_SOL = E_SOL * 11350
         SI_AVG_SOL = (SI_AVG_SOL * (NUM_HOURS - 1) + SI_SOL) /
     1                  NUM_HOURS
         IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1))
     1      SI_AVG_SOL = SI_SOL
C        PRINT 400, NUM_HOURS, E_SOL, SI_SOL, E_AVG_SOL
```

Calculates the solar radiation for the past NUM_HOURS. This algorithm reads in the solar radiation from a text file (generated earlier in the DOE2 deck). Again, this was done to take into account that there is strong interaction between load history and weather history in order to offset loads in the current hour.

```
C        $----- BEGIN THE WATER HEATING CALCULATION

C        $----- WATER HEATING CONSUMPTION BY HOUR IS DETERMINED
         DHWFR= .2
         IF (CURR_HOUR .EQ. 2) DHWFR=.1
         IF (CURR_HOUR .EQ. 3) DHWFR=.0
         IF (CURR_HOUR .EQ. 4) DHWFR=.0
         IF (CURR_HOUR .EQ. 5) DHWFR=.0
         IF (CURR_HOUR .EQ. 6) DHWFR=.2
         IF (CURR_HOUR .EQ. 7) DHWFR=.4
         IF (CURR_HOUR .EQ. 8) DHWFR=1.0
         IF (CURR_HOUR .EQ. 9) DHWFR=.8
         IF (CURR_HOUR .EQ. 10) DHWFR=.82
         IF (CURR_HOUR .EQ. 11) DHWFR=.8
         IF (CURR_HOUR .EQ. 12) DHWFR=.72
         IF (CURR_HOUR .EQ. 13) DHWFR=.64
         IF (CURR_HOUR .EQ. 14) DHWFR=.56
         IF (CURR_HOUR .EQ. 15) DHWFR=.48
         IF (CURR_HOUR .EQ. 16) DHWFR=.44
         IF (CURR_HOUR .EQ. 17) DHWFR=.52
         IF (CURR_HOUR .EQ. 18) DHWFR=.64
         IF (CURR_HOUR .EQ. 19) DHWFR=.76
         IF (CURR_HOUR .EQ. 20) DHWFR=.84
         IF (CURR_HOUR .EQ. 21) DHWFR=.76
         IF (CURR_HOUR .EQ. 22) DHWFR=.68
         IF (CURR_HOUR .EQ. 23) DHWFR=.6
         IF (CURR_HOUR .EQ. 24) DHWFR=.52
```

Determines the current hot water load fraction for each hour of the day. Based on data from the hot water demand profiles used in EnergyGauge USA (Fairey and Parker, 2004).

```
         DHWLOAD = DHWGAL * 60 * DHWFR * 8.3 *
     1     (DHWTMP-E_INPUT_WATER_TEMP)
```

Calculates the hot water load in Btu/hr.

$$DHWLOAD\frac{Btu}{hr} = DHWGAL\frac{gal}{\min}\cdot 60\frac{\min}{hr}\cdot DHWFR\cdot 8.3\frac{lbs}{gal}\cdot \left(DHWTEMP\frac{F}{1} - E\_INPUT\_WATER\_TEMP\frac{F}{1}\right)$$

```
C        $----- STANDBY LOSSES ARE COMPUTED
         ESTDBY = 5.26 * (120.00 - TGARAG)
C        $----- ESTDBY IS FOR ELECTRIC; NESTDBY IS NON_ELECTRIC
         NESTDBY = 0.00 * (120.00 - TGARAG)
```

Both the ESTDBY and NESTDBY equations are formulated based on user input in EnergyGauge USA. If the auxiliary hot water heater fuel source is electric, then NESTDBY become 0, if it is not electric then ESTDBY become zero. Again, the variable TGARAG depends on the location of the tank as specified by user input (it may also be "TLIVIN").

The multiplier for each equation is based on the UA and the insulation of the tank, as well as the "Heat Trap" and "Pipe Loss" values as found in the "Set_Standby_Values" procedure in EnergyGauge USA. The temperature difference is that between the thermostat set point and the temperature of where the hot water tank is located.

The next lines calculate the total load in Btu/hr, then converted to KJ/hr.

```
C        $----- 'DHWLOADT' IS YOUR TOTAL HOURLY WATER HEATING LOAD IN BTU/HR
         DHWLOADT= DHWLOAD + ESTDBY + NESTDBY
         SI_DHWLOADT = DHWLOADT * 1055.0
```

Next, calculate the average hot water load (KJ/hr) and hot water load (gallons) for the past NUM_HOURS.

```
C        $----- AVERAGE THE SI_DHWLOADT FOR THE PAST NUM_HOURS (LACL, LAOL)
         AVG_DHWLOADT = (AVG_DHWLOADT * (NUM_HOURS - 1) +
     1                   SI_DHWLOADT) / NUM_HOURS
         IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1))
     1      AVG_DHWLOADT= SI_DHWLOADT

C        $----- AVERAGE THE DHWGAL FOR THE LAST NUM_HOURS (ICS)
         DHWKG = DHWGAL * DHWFR * 60 * 8.3 * 0.454
         AVG_DHWKG = (AVG_DHWKG * (NUM_HOURS - 1) + DHWKG) /
     1               NUM_HOURS
         IF ((CURR_HOUR .EQ. 1) .AND. (CURR_DAY .EQ. 1))
     1      AVG_DHWKG = DHWKG

C        PRINT 400, CURR_DAY, CURR_HOUR, AVG_DHWKG, DHWKG

C        $----- SET DEFAULT VALUE FOR F
         F = 0

         IF (SOLAR_TYPE .EQ. 1) GO TO 10
```

```
         IF (SOLAR_TYPE .EQ. 2) GO TO 10

         IF (SOLAR_TYPE .EQ. 3) GO TO 30
```

Due to the if-statement above, the next statements are executed after the solar fraction for the system (LACL, LAOL, or ICS) are determined.

Next, if the solar radiation greater than the critical start irradiance of 60 W/m^2 then the DOE2 pump power (EXMCKW) is equal to the pump power (watts) from the solar hot water routine, else it is equal to 0.

The final hot water load (kilowatts) is then found by adding the current standby losses and subtracting the amount of load that the solar system will meet. The final two lines in this section are for auxiliary heaters whose fuel is electricity. If gas, then they would be replaced with:

DHWFL = DHWFL + (NESTDBY – SOLARADJ)
DHWKW = 0

```
C        $----- TAKE F (SOLAR FRACTION), AND MODIFY DHWKW
44       SOLARADJ = DHWLOADT * F
         IF (E_SOL .GT. 60)EXMCKW = PUMPW
         IF (E_SOL .LT. 60)EXMCKW = 0
C        PRINT 400, CURR_DAY, CURR_HOUR, ESTDBY/3413, DHWKW
         DHWKW = DHWKW + (ESTDBY - SOLARADJ) / 3413
         DHWFL = 0
```

These lines are for debugging and for returning control back to the main DOE2 engine.

```
C        PRINT 400, CURR_DAY, CURR_HOUR, ESTDBY/3413, DHWKW
500      FORMAT(1X, F3.0, 2X, F3.0, 2X, F3.0, 2X, F6.2)
C        PRINT 400, TEMP1, TEMP2, TEMP3, TEMP4

C        WRITE (55,400) CURR_HOUR, CURR_DAY, SI_TAMB, SI_AVG_TEMP
C        WRITE (60,400) SI_TAMB, SI_DEWPOINT, CURR_HOUR

400      FORMAT(1H ,4F12.3)
         RETURN
```

This is the beginning of the LACL/LAOL f-chart routine. The only difference between LAOL and LACL in f-chart is the value of $\frac{F_R'}{F_R}$ (FrpFr within the code) (collector/heat exchanger correction factor) variable. For LAOL systems (SOLAR_TYPE=2), since there is no heat exchanger, $\frac{F_R'}{F_R}$ is set to 1.0. For LACL systems (SOLAR_TYPE=1), the value is user defined.

```
C        ----- BEGIN LACL/LAOL

10       IF (SOLAR_TYPE .EQ. 1) FrpFr = 1.0

         IF (SOLAR_TYPE .EQ. 2) FrpFr = 1.0
```

This next section of code is from "Solar Engineering of Thermal Processes", Duffie and Beckman, Wiley and Sons, New York, 1980, pages 486-505.

```
C        ----- AVERAGE DHW LOAD (SI)
         AVG_LOAD = AVG_DHWLOADT

         X = FrUl * FrpFr * (SI_REF_TEMP - SI_AVG_TEMP) * 3600 *
     1      SI_COLLECTOR_AREA / AVG_LOAD

         CORR_X = X * (11.6 + (1.18 * SI_SET_POINT) +
     1           (3.86 * SI_INPUT_WATER_TEMP) -
     2           (2.32 * SI_AVG_TEMP)) / (100 - SI_AVG_TEMP)
         CORR_X = X * STO_COR
         Y = FrTauAlphaN * FrpFr * TauAlphaOverTauAlphaN *
     1       1.0 * SI_AVG_SOL * SI_COLLECTOR_AREA / AVG_LOAD


         F = 1.029 * Y - 0.065 * CORR_X - 0.245 * Y * Y +
     1       0.0018 * CORR_X * CORR_X + 0.0215 * Y * Y * Y
```

These next two lines are small corrections – if for some reason the value of the solar fraction is not between 0 and 1, we fix it.

```
         IF (F .LT. 0) F = 0
         IF (F .GT. 1) F = 1
```

Debugging and return control to the rest of the function.

```
C        PRINT 300, CURR_HOUR, AVG_LOAD, SI_AVG_SOL, SI_INPUT_WATER_TEMP
C        PRINT 300, DHWKW, CORR_X, Y, F
         GO TO 44
         RETURN
C        ----- END OF LACL/LAOL
```

The ICS f-chart routine comes from the paper, "A Performance Prediction Methodology for Integral Collection-Storage Solar Domestic Hot Water Systems", Zollner A., Klein S. A., and Beckman W. A., Journal of Solar Energy Engineering, November, 1985, Vol. 107.

```
C        ----- BEGIN ICS

C        30     PRINT 200, 'ICS'

30       SI_KG_AVG_LOAD = AVG_DHWKG

C        ----- CALCULATE SKY TEMPERATURE
         K_TAMB = SI_AVG_TEMP + 273.15

         CLOUD_EFFECT = 1
     1                  + 0.0224 * CLDAMT
     2                  - 0.0035 * CLDAMT**2
     3                  + 0.00028 * CLDAMT**3

         SI_CLRSKYEMIS = 0.787 + 0.764 * ALOG(K_DEWPOINT / 273)
         SI_CDYSKYEMIS = SI_CLRSKYEMIS * CLOUD_EFFECT
         K_SKYTEMP = SI_CDYSKYEMIS**0.25 * K_TAMB
         SI_SKYTEMP = K_SKYTEMP - 273.15
C        ----- END OF CALCULATE SKY TEMPERATURE
```

```
C        ----- CALCULATE STUFF FOR F
         K_INLET_WATER_TEMP = SI_INPUT_WATER_TEMP + 273.15
         K_SINK_TEMP =(K_TAMB)-((1/4)*(K_TAMB-K_SKYTEMP))
```

Zollner, S.A. Klein and W.A. Beckman, "A Performance Prediction Methodology for Integral Collection Storage Solar Domestic Hot Water Systems," Journal of Solar Energy Engineering, Nov. 1985, Vol. 107, p. 265-272.

```
C        ----- CONVERT SI_UATANK FROM W/C TO KJ/(HR C)
         SI_KJ_UATANK = SI_UATANK * 3.6

         SI_ICS_UL = SI_UATANK/SI_COLLECTOR_AREA
         K_DELIVERED_WATER_TEMP =((SI_AVG_SOL/1000*SI_COLLECTOR_AREA
     1                           *TRANS_ABSORP)+(SI_KG_AVG_LOAD
     2                           *4.19*K_INLET_WATER_TEMP)+(SI_ICS_UL
     3                           *SI_COLLECTOR_AREA*1*K_SINK_TEMP))
     4                           /((SI_KG_AVG_LOAD*4.19)
     5                           +(SI_ICS_UL*SI_COLLECTOR_AREA*1))

         K_SET_POINT = SI_SET_POINT + 273.15

C        ----- CALCULATE F, Equation 16 from Zollner
         F = (K_DELIVERED_WATER_TEMP-K_INLET_WATER_TEMP)
     1       /(K_SET_POINT-K_INLET_WATER_TEMP)

C        ----- CALCULATE CORRECTIONS FOR F
         STRAT_F_CORR =F*(1+(A_STRAT_CORRECTION/TankTurnovers)*(1-F))

C        1.894 IS THE CONVERSION OF BTU/HR-F TO SI_KJ_HR-K
         SI_KJ_UATANKAUX = 6.94 * 1.894
C        K_TENV = TEMPERATURE SURROUNDING AUXILIARY TANK
         K_TENV = (TLIVIN - 32) / 1.8 + 273.15
C        ----- Aux. jacket loss correction from Zollner Example
         CORR_LSUBO = SI_KJ_UATANKAUX * (K_SET_POINT - K_TENV)
         CORR_LOAD = SI_KG_AVG_LOAD * 4.19
     1             * (K_SET_POINT - K_INLET_WATER_TEMP)

         JACKETLOSS_F_CORR = ((STRAT_F_CORR-(CORR_LSUBO/CORR_LOAD))
     1                     *CORR_LOAD+CORR_LSUBO)
     2                     /(CORR_LOAD+CORR_LSUBO)

         FINAL_F = JACKETLOSS_F_CORR

         IF (SI_AVG_TEMP .LT. 0.55) FINAL_F = 0
         IF (SI_KG_AVG_LOAD .LE. 0) FINAL_F = 0
         IF (FINAL_F .GT. 1) FINAL_F = 1
         IF (FINAL_F .LT. 0) FINAL_F = 0

C        PRINT 100, SI_UATANK, K_SET_POINT, K_TAMB, FINAL_F

         F = FINAL_F


         GO TO 44
         RETURN
C        ----- END OF ICS

100      FORMAT(1H ,4F12.3)
```

```
200      FORMAT(A)
250      FORMAT(30A)
300      FORMAT(10X, 4F12.3)
         END

         END-FUNCTION ..
```

The next function is the "Solar" function – this simply creates a file of data (named "fort.123" that the SDHW function uses. The 4 columns of data in the file are: month, day of month, hour of day, and solar radiation on the surface (Btu/ft^2 in DOE-2.1).

```
FUNCTION NAME = SOLAR ..
ASSIGN IMO=IMO, IDAY=IDAY, IHR=IHR, SOLI=SOLI ..
CALCULATE ..
        WRITE (123,100) IMO, IDAY, IHR, SOLI
C       PRINT 100, IMO, IDAY, IHR, SOLI
        ENDFILE 123
100     FORMAT(1X, F3.0, 2X, F3.0, 2X, F3.0, 2X, F6.2)
101     FORMAT(1H, 4F12.3)
        END
END-FUNCTION ..
```

Equations and Unit Conversions

Definition of solar fraction

$$F = 1 - \frac{aux_{solar}}{aux_{nosolar}}$$

where aux_{solar} is equal to the amount of auxiliary power added to the solar system to meet the hot water load (heater and pump) and $aux_{nosolar}$ is equal to the amount of the power needed to meet the load in a non-solar system (heater).

Weather and Location-Specific Data

The following weather data was used for both the TRNSYS and EnergyGauge USA (F-chart) models.

TMY2 Data

City	TMY2 data file
Madison, WI	14837.TM2
Miami, FL	12839.TM2
Portland, OR	24229.TM2

Monthly Supply Water Temperature

Madison, WI

Month	Supply Water Temperature (C)
January	5.5
February	4.5
March	5.1
April	7.1
May	10.0
June	13.0
July	15.4
August	16.6
September	16.1
October	14.2
November	11.4
December	8.3

Tampa, FL

Month	Supply Water Temperature (C)
January	21.6
February	21.9
March	23.2
April	25.1
May	27.2
June	28.8
July	29.7
August	29.5
September	28.3
October	26.4
November	24.3
December	22.6

Portland, OR

Month	Supply Water Temperature (C)
January	11.3

February	10.9
March	11.5
April	13.0
May	15.0
June	16.9
July	18.2
August	18.7
September	18.2
October	16.7
November	14.8
December	12.9

Hourly Hot Water Load Data

Although the hourly hot water load data was not location-specific, it is included here for completeness-sake.

Hour Ending At	**Hot Water Load (kg/hr)**
1:00 AM	3.6
2:00 AM	1.8
3:00 AM	0
4:00 AM	0
5:00 AM	0
6:00 AM	3.6
7:00 AM	7.3
8:00 AM	18.2
9:00 AM	14.5
10:00 AM	14.9
11:00 AM	14.5
12:00 PM	13.1
1:00 PM	11.6
2:00 PM	10.2
3:00 PM	8.7
4:00 PM	8.0
5:00 PM	9.4
6:00 PM	11.6
7:00 PM	13.8
8:00 PM	15.3
9:00 PM	13.8
10:00 PM	12.3
11:00 PM	10.9
12:00 AM	9.4

Miscellaneous Location-Specific Data

City	**Latitude (degrees)**	**Shift in Solar Time Hour Angle (degrees)**
Madison, WI	43.1	0.67
Tampa, FL	28.0	-7.53
Portland, OR	45.6	-2.60

References

Craig Christiansen and Bob Hendron, "Building America Analysis Spreadsheet," http://www.eere.energy.gov/buildings/building_america/pa_resources.html, 2005.

John A. Duffie and William A. Beckmann Solar Engineering of Thermal Processes, Wiley and Sons, New York, 1980.

Philip Fairey and Danny Parker, A Review of Hot Water Draw Profiles Used in Performance Analysis of Residential Domestic Hot Water Systems, FSEC-RR-56-04, Florida Solar Energy Center, Cocoa, FL, July 2004.

TRNYSYS: A Transient Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, WI, 1994, Version 15, 2005.

A. Zollner, S.A. Klein and W.A. Beckman, "A Performance Prediction Methodology for Integral Collection-Storage Solar Domestic Hot Water Systems", Journal of Solar Energy Engineering, November, 1985, Vol. 107.

Additional Resources

- www.trnsys.com
- www.tess-inc.com
- David Bradley, bradley@tess-inc.com, 608-274-2577
- Jeff Thornton, thornton@tess-inc.com, 608-274-2577
- TMY2 elements: http://rredc.nrel.gov/solar/pubs/tmy2/tab3-2.html
- Michael Anello, michael@OneToMany.com