FLORIDA SOLAR ENERGY CENTER®

FSEC STANDARD

Solar Thermal System and Components Test Protocols

FSEC Standard 105-10

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2.0 Generic System Classes

The following list summarizes some of the generic systems that have been considered in the development of the test protocols. Note that some systems may incorporate more than one of these generic system classes. In these cases, testing may proceed under the provisions of Section 5.1.3 (Innovative Solar Equipment) of FSEC Standard 101-10 Operation of the Solar Thermal Collector Certification Program.

A:	System with an integral auxiliary heater or separate auxiliary heater. This test protocol assumes that the auxiliary heater is electric. If this is not the case, an additional recovery efficiency test will be needed. A solar system with an integral electric heater shall be required to undergo additional tests due to the affect on stratification caused by the heater.
DC:	System making use of a differential controller
HP:	Heat pipe collector with integral storage
HX:	System utilizing a heat exchanger (EHX: External, IHX: Internal, MHX: Integral Mantle HX, WHX: Wrap Around Integral Wrap around HX)
ICS:	ICS type of system
NCL:	System utilizing a natural convection loop that is not within the collector loop
PV:	Photovoltaic Panel in photovoltaic driven pump system/ PU: Pump (Only DC pump is currently considered)
SP:	Self pumped (phase change) system
T:	System utilizing a timer controller
TO:	System with tubular optics
TS:	System utilizing a collector that incorporates NCL

3.0 Nomenclature and Definitions

Term	Definition
C_{heated}	Thermal capacitance of the electrically heated fluid volume
C_{solar}	Thermal capacitance of the solar heated fluid volume
C_{total}	Thermal capacitance of the entire tank fluid volume
C_p	Heat capacity
Delta T ambient	The temperature difference between the specified control volume and the ambient
F	Friction factor
G	Total irradiance
G_{dh}	Horizontal diffuse irradiance
H_{pump}	Pump head
I	Current
K_t	Daily clearness index for validation tests
K_T	Average clearness index for specified test
M_{drawn}	Mass withdrawn from the domestic hot water (DHW) System
M_{pump}	Pump mass flow rate

M_{tank}	Tank fluid mass volume at T_{max}
Q_{aux}	Auxiliary heating element energy use rate
Q_{coll}	Collected energy
$Q_{initial}$	Initial charge energy of a tank or system when subjected to an instantaneous purge between two set temperatures.
Q_{net}	The energy delivered from a solar system without auxiliary heating
Rho	Density
T_{amb}	Ambient temperature
$T_{amb\ ave}$	Average ambient temperature
$T_{amb\ final}$	Final ambient temperature at the end of a test
$T_{amb\ orig}$	Original ambient temperature at the start of a test
T_{ave}	Average temperature
T_{del}	Temperature of the water delivered from the DHW system at the outlet of the system
T_{high}	Temperature of the water in a test system at the beginning of a high-temperature test (typically 55 - 60°C (131 - 140°F))
$T_{initial}$	Temperature of the water in the test system at the beginning of a test (heat loss or warm-up)
T_{low}	Temperature of the water in a test system at the beginning of a low-temperature test (typically 20 - 25°C (68 - 77°F))
T_{mains}	Temperature of the water mains inlet into the DHW system at the point of entry after an initial purge of stagnant water in the delivery piping.
T_{max}	Maximum temperature of a tank
T_{purge}	Purge temperature of the system (T_{low} or T_{high})
T_{pv}	Photovoltaic panel temperature
T_{set}	The setpoint of the activated auxiliary heating element
T_{sink}	Heat sink average temperature
T_{source}	Heat source temperature
$T_{tank\ ave}$	Average tank fluid temperature
$T_{tank\ ave\ final}$	Final average tank fluid temperature after the decay, irradiation, charge, or purge period.
$T_{tank\ ave\ orig}$	Original average tank fluid temperature before the decay, irradiation, charge, or purge period
$T_{tank\ ave\ purge}$	Final average tank fluid temperature after the purge period. This value is usually estimated by averaging the tank inlet temperature and $T_{del.}$
$Time_{draw}$	Draw duration
$Time_{decay}$	Decay test duration
TRNSYS	A system simulation software program
$UA_{hx\ loss}$	UA loss from the heat exchanger to environment
$UA_{hx\ trans}$	UA transfer from the hot side to the cold side of the heat exchanger
UA_{other}	Installed total UA loss of the storage tank piping or fittings
UA_{pipe}	Installed total UA loss of the NCL loop piping
V	Voltage
V_{rate}	Volumetric flowrate
Dwell time	Time required to exchange the capacity of the storage tank one time.

Similar — A system which differs from another only in component size, capacity rating, etc.

5.0 Testing Policy

To expedite the testing and certification of solar DHW systems, FSEC will to test the most common system size to be sold. If the range of collector area/storage tank volume ratios for the similar systems is large, additional system sizes may be tested. The decision about which tests are required shall be at the discretion of the certifying body.

Different configurations that will require at least one unique test include: different collector absorber coating, the use of a different HX, and any other significant model changes. Systems utilizing a separate collector (e.g. TS) may require a separate collector test. Similar systems incorporating more than one generic component may not require a full array of additional tests. Data for each system component will be required for all configurations unless existing analytical techniques can be used to extrapolate it from previous data or if one of the components can be modeled within another (e.g. internal HX in ICS).

6.0 General Testing Procedures

All system or component test objects shall be mounted in a manner that is similar to the intended usage. This requirement would include the use of such devices as reflectors and roof support structures. The intent is that all thermal and optical characteristics are reproduced during the test. Structural issues may be evaluated secondarily.

Delivery energy instrumentation shall be positioned so that the mixing valve has no effect on the test results. On systems utilizing a NCL loop, the use of strap-on loop temperature sensors would be useful for obtaining information about NCL flow rates and comparing these to those predicted by the best available TRNSYS models. For these types of systems, the instrumentation shall not impede the fluid flow as this could adversely impact the performance of the system. Systems that have some type of self-draining mechanism shall be plumbed in such a manner that a physical head of 4.88 m (16.0’) is achieved. Any other required plumbing (heat traps, safety valves, drain lines, etc.) shall also be installed. A bypass loop, plumbed in parallel to the test object be utilized to precondition the test loop before making purges.

On systems where an internal tank probe(s) can be inserted, this would be useful information for determining the satisfaction of the test criteria and for comparison with the TRNSYS models. One suggested method for determining average tank temperature is a line averaging RTD. When this method is used to measure average tank temperature, it is important to note that the cross sectional area of the tank perpendicular to the line of the RTD needs to be constant.

The applicability of extrapolating these test results to fluids other than water is limited. When testing with a fluid other than water, fluid composition tests shall be performed to ensure that the specified fluid composition exists. At a minimum, a hygrometer test or its equivalent shall be performed and checked with the fluid specification before proceeding with the experiment.

Any system with a HX loop and a closed storage/HX unit (usually with an IHX or MHX) containing more than 2.5% (by volume) of the storage tank fluid shall be preheated to the same temperature as the rest of the system for all warm-up and tank tests prior to system operation. In most cases, desirable preheating of the closed storage unit will occur during the heating of the adjacent fluid. For atmospheric systems, the rate of filling may be limited by the system’s components. Note that these loops are not to be directly purged at the end of the test. However, the energy within the loops shall be purged in the normal operating fashion. This may require extended draw periods.

No test shall be performed in excess of a manufacturer’s recommended operating conditions. This may necessitate the adjustment of certain test operating conditions to conform to the intent of the test.

6.1 Instrumentation Accuracy/ Resolution

Table 1 indicates the accuracies for the instrumentation required in the following tests. The radiation measurements shall be performed with devices that meet the standards of the World Meteorological Organization for a first class pyranometer or pyrheliometer. The data resolution shall be no lower than the stated accuracy.

Value to be Measured	Accuracy SI Units (±)	Accuracy IP Units (±)
Temperature	0.1^{o} C (precision 0.1^{o} C)	0.2 ^{o} F (precision 0.2 ^{o} F)
Temperature Difference	0.1^{o} C (precision 0.1^{o} C)	0.2^{o} F (precision 0.2 ^{o} F)
Mass	1%	1%
Fossil Fuel Usage	1%	1%
Electric Energy Usage	Max (1%, 15Wh)	Max (1%, 511 Btu)
Air Flow	1%	1%
Liquid Flow	1% measured mass value	1% measured mass value

Table 1 Instrumentation Accuracies

6.2 Data Time Step

Unless otherwise indicated, all data shall be collected with a maximum fifteen-second-time step. This data shall be averaged and reported at a maximum rate of 5 minutes for long-term tests (duration is longer than 1 day) or 0.5 minutes for short-term tests. Due to the interaction with TRNSYS, which uses a fixed time step, all data shall be collected in fixed time steps. Any test using an energy purge shall be measured with the highest practical data resolution.

6.3 Instrument Calibration

All instrumentation used in the experimental setup needs to be calibrated to an accepted standard on a regular basis. The maximum time betweens calibration is:

- yearly for radiation measuring devices
- yearly for temperature measuring devices
- yearly for mass measurements (scales)
- by tested unit for flow measurements (pre testing and post testing)

The temperature sensors have a Temperature Check performed pre and post testing to ensure stability of the sensors over the duration of the test.
Calibrations may occur more frequently if non-conforming data is observed, significant changes occurred during the testing or when requested by the engineer.

6.4 Required Experimental Data

The minimum real time data to be collected for the tests shall consist of those listed below (in order) in SI/TRNSYS units. For ease of modeling, all data channels shall be recorded on a regular interval, even if not used. A log indicating such things as draw, purge, and irradiation start and stop times shall be included. Other data including site elevation, longitude, latitude, and test sample orientation shall also be supplied. The certifying body shall reject any data that does not meet these minimum requirements.

1. Data collection time (both local and solar) and date yyyymmdd. hh.hhhh
2. Inlet temperature (^{o}C)

3. Outlet temperature (^oC)
4. Ambient temperature (e.g." Outside", if applicable) (^oC)
5. Environmental temperature (e.g. "Inside", if applicable) (^oC)
6. Flow Rate(s) (Kg/h)
7. Wind velocity (m/s)
8. Auxiliary energy usage (if applicable) (kWh)
9. Radiation measurements, if applicable (see below) (W/m^2)
   a. Total surface
   b. Total horizontal
   c. Horizontal diffuse
   d. Horizontal infrared (ICS)
   e. Surface diffuse (ICS-TO)

The radiation measurements shall include at least a through c above. Measurements d and e will depend upon the system types being tested.

7.0 Standard Experimental Procedures

7.1 Tank Charge

Fill Method:

a. The fill may occur at any rate up to the manufacturer's recommended maximum flow rate.

b. Heat and fully mix the tank to $T_{initial}$, where $T_{initial} = T_{low}$ or T_{high}.

c. Fill the tank until $|T_{initial} - T_{del}| \leq 0.2°C(0.4°F)$ or

$$\frac{\partial |T_{initial} - T_{del}|}{\partial t} \leq 0.05°C(0.09°F)$$ for a 10-minute period. Tank shall be maintained at this temperature for a minimum of the tank dwell (fill) time.

7.2 Tank Purge

Test Method:

a. Purge the energy in the system by circulating water through the system.

b. The purge shall occur at 0.125- 0.189 l/s (2-3 GPM) until $|T_{in} - T_{del}| \leq 0.2°C(0.4°F)$ or

$$\frac{\partial |T_{in} - T_{del}|}{\partial t} \leq 0.05°C(0.09°F)$$ for a 10-minute period.

NOTE: If it is not possible to purge the water at T_{high} for the duration of the purge, then the alternative method is to conduct the purge with T_{in}=T_{low}, with a mathematical re-adjustment. To adjust the delivered energy, subtract $Q_{delta\ tank}$ from the measured Q_{del}.

c. Conduct real time measurement of M_{drawn} , T_{in} T_{del} and T_{amb}

Analysis Method:

The analysis of all tank energy purges shall utilize the following equations:

a. $$Q_{del} = \int Rho(t) * C_p(t) * V_{rate} * \left[T_{del}(t) - T_{mains}(t)\right] dt$$

b. $$T_{used} = \frac{T_{tank} + T_{mains}}{2}$$, Extrapolated tank temperature range.

c. $$T_{orig} = \frac{T_{tank} + T_{mains}}{2}$$, Original tank temperature range.

d. $$Q_{initial} = Q_{del} * \frac{Rho(T_{used}) * Cp(T_{used})}{Rho(T_{orig}) * Cp(T_{orig})} * \frac{(T_{tank\ ave\ orig} - T_{mains\ end})_{Used}}{(T_{tank\ ave\ orig} - T_{mains\ end})_{Orig}}$$

Where Q_{del} is the instantaneous purge energy and 'orig' refers to the initial purge conditions and 'used' refers to the conditions this value is extrapolated to. For the initial purge, $Q_{initial} = Q_{del}$.

7.3 Capacitance And Draw Stratification Test

This test is to be performed indoors, preferably in an environment with a nearly constant temperature. The unit is to be installed in a manner consistent with the intended system design as outlined in Section 6.0. Piping connections are to be made, but isolated via valving. This test is typically performed before the loss tests (see 7.4) so that a baseline tank capacitance can be determined. This test shall also be used in conjunction with the solar testing (see 7.5) to determine initial charge energy for a High Temperature warm-up test (see 7.5.2). In these cases, the test does not necessarily have to be performed immediately before the system test if the tank and surroundings are maintained at similar temperatures before starting this and the subsequent warm-up tests.

a. Charge tank to T_{high} (see 7.1).
b. Measure ambient temperatures during the entire test period.
c. Purge the energy in the tank (see 7.2) with $T_{in} = T_{amb}$

The resulting capacitance energy calculation from this test is used as the basis for the initial tank energy figure in tests 7.4 and 7.5 when the construction characteristics of the tank make the analytical determination of this value difficult.

7.4 Heat Loss Test [Standard Decay Method]

Test Method:
This test is to be performed indoors, preferably in an environment with a nearly constant temperature. If the environmental temperature variation is greater than 10% (approximately 3.5°C for these conditions using a 22°C ambient) of the estimated difference between the tank and ambient temperatures, then the use of internal probes shall be used for determining a run-time UA value. If significant stratification is anticipated, the use of internal tank temperature probe(s) is required.

a. Charge the tank (see 6.1) until $T_{initial} = T_{high}$.

b. Wait until:

$$\frac{T_{tank\,aveorig} - T_{ambave}}{3} \leq (T_{tank\,ave\,final} - T_{ambave}) \leq \frac{2 * (T_{tank\,aveorig} - T_{ambave})}{3}.$$

This will be estimated before the test is run using the known tank volume and estimated environmental temperatures. Measure the environment temperature during the entire test period.

c. Purge the remaining energy in the tank (see 7.2) with $T_{in} = T_{amb}$.

Analysis Method:
A real time numerical loss calculation is to be used if the variation in the ambient temperature exceeds 10% of the initial average tank to ambient temperature difference during the test or if the tank is not fully mixed due to varying or large insulation levels. This requires the use of internal tank temperature measurements and is the preferred calculation method when this instrumentation can be installed.

a. $Q_{loss} = Q_{initial} - Q_{del}$ (the delivered energy after the purge)

b. Numerically solve for UA, $Q_{loss} = \sum UA * (T_{ank\ ave} - T_{amb}) * \Delta t$

If the variation in the ambient temperature is below the 10% level, the following calculations which assume an ideal exponential temperature decay can be used.

a. Determine the tank thermal capacitance from either $Q_{initial}$ or a theoretical calculation.

   1. Experimental Method (preferred)

   $$M_{tank} * C_P\ (@T_{hot}) = \frac{Q_{initial}}{T_{tank\ ave\ orig} - T_{tank\ ave\ final}}$$

   2. Theoretical Method
   $M_{tank} * C_P = M_{tank} * C_p\ (@T_{hot})$

b. Determine the steady state ideal heat loss (UA).

   1. $$T_{tank\ ave\ final} = T_{tank\ ave\ purge} + \frac{Qdel}{M_{tank} * C_p}$$

   2. $$UA = \frac{M_{tank} * C_p}{Time_{decay}} * \ln\left[\frac{(T_{tank\ ave\ orig} - T_{amb\ ave})}{(T_{tank\ ave\ final} - T_{amb\ ave})}\right]$$

Data from this test can be used to determine the $UA_{installed\ loss\ total}$. The $UA_{isolated\ loss\ total}$ value is to be used in the TRNSYS tank model. This value is to be used as the other UA of the TRNSYS tank models. For systems such as ICS where this value is implicit in the overall re-normalization of the model, this experiment is not required. A calculated value is used instead of this test due to the variability of this value with system to ambient temperature difference. Note the availability of the experimentally determined $Q_{initial}$ value in test 7.3.

7.5 Solar System Warm-Up Test

This is the primary test used to calibrate a TRNSYS model to the experimental results.

An implicit consideration in these protocols are that the systems are sized on the order of 60-80 l/m^2 (1.5-2 gal/ft^2) of storage per collector area, which is typical of residential solar DHW systems used in the United States. If a particular system design falls outside of this range, the test exposure times and temperature rises (see 7.5.1 and 7.5.2) shall be adjusted with respect to this ratio.

These tests are to be performed on the actual solar pre-heat system installed in a conventional manner (with added instrumentation).   If the system is a one-tank system with an integral heating element, then the system will be tested with and without the element in operation. In the test with the element, set Tset = 50^{o}C (122^{o}F) and energize the element for the first hour of each test.

For active systems, an additional constraint is that the system pump shall be activated during purges to extract any uncaptured energy within the hydronic system. This shall occur normally in most cases.   For PV pump driven systems, the PV panel shall not be covered during the purge period, so that all of the collected energy can be purged.

Because of the variability of these tests, it may be necessary to extract summary information from a previous test in order to set the operating conditions of a succeeding test. This is necessary so that the minimum temperature and/or radiation requirements are met. If the criteria are not met, it will be necessary to perform additional test(s) in order to satisfy the diversity of data. In general, the Clear, Low Temperature tests (see 7.5.1) are setup to give the "high" performance when the test is run at "cool" temperatures (T_{low}), and the Cloudy, High Temperature tests (see 7.5.2) are setup to give the "low" performance when the test is run at "high" temperatures. On the low temperature tests, the initial temperature is typically the mains temperature, while the high temperature test uses an elevated starting temperature (T_{hot}). In addition to meeting the specified solar radiation requirements, each individual test also shall have a minimum of 5^{o}C (9 ^{o}F) tank temperature rise to minimize the effect of errors in the experimental data.

In tests utilizing an end of period purge, a cover shall be placed on the thermal collector at the beginning of the purge process. The cover shall consist of 0.04 m (1.6") insulation board, preferably with foil-covered surfaces. The cover shall extend at least 0.08 m (3.1") beyond the gross horizontal collector aperture and cover any vertically exposed optical components. The exposed side of the cover shall be backed with any appropriate material required for structural rigidity and exposure to the weather (e.g. plywood and plastic).

Before starting the warm up tests, pre-heat the entire system to a uniform temperature. In systems with an integral collector and storage components (ICS), this is accomplished by fully mixing the system heat transfer fluid. In systems utilizing a heat exchanger between the collector and storage components, it may be necessary to take additional steps to ensure that the collector is pre-heated to the tank temperature. For active systems, the pumps shall be activated manually in order to fully mix the heat transfer fluid(s). The following are a few recommendations:

a. When the desired tank temperature is close to the ambient temperature:
    1. TS: Uncover the collector during the mixing period (about 10 minutes prior to the start of exposure)
    2. Others: Cover the collector
b. When the desired tank temperature is lower than the ambient temperature:
    1. All: Cover the collector
c. When the desired tank temperature is higher than the ambient temperature:
    1. TS: Uncover the collector during the mixing period (about 10 minutes prior to the start exposure)
    2. Others: Partially uncover the collector during mixing to allow some heating, do not allow stagnation.

All systems shall be positioned and fixed facing due south. The recommended tilt for the systems is such that that the collection portion of the systems be normal to the sun at solar noon ± 4^o on the day of the test, unless this contradicts the manufacturer's recommended tilt. For systems such as TS or SP, the manufacturer may recommend a minimum tilt to ensure adequate flow, in these cases, use the manufacturer's recommended tilt that is nearest the normal tilt value at solar noon. For active systems, the operation of the controllers and pumps shall be automatic once the manual mixing has been completed.

These procedures assume that T_{mains} is relatively constant during the test period(s) and close to ambient temperature. With the exception of TO, all other warm-up tests can be performed 1 to 2 times per day as meteorological and experimental conditions allow.

A 3.4 +/- .8 m/s (7.6 +/- 1.8 mph) wind speed shall be required for the testing of units with integral storage tanks and/or unglazed collectors that have not been tested with a measured wind blowing across them.

For simulator testing, there are two different profiles for each of the "cloudy" days. The clear day is a constant 800 W/M^2 for 4 hours. The first cloudy day is a constant 400 W/M^2 for 6 hours. The second cloudy day is also 4 hours long consisting of rotating 30-minute periods of 200 W/M^2 and 600 W/M^2.

The warm-up tests are expected to yield a minimum of 4 data points (2 each Clear, Low Temperature and 2 each Cloudy, High Temperature). A data point (test) is considered to meet the criteria if the radiation condition is met and the minimum 5^oC ($9\,^oF$) tank temperature rise is achieved. The goal of the tests is to expose the collector to approximately 13,000 kJ/m^2 (12,322 Btu/ft^2) of radiation in each test to equalize relative experimental errors and to equally weight the various conditions. $T_{initial}$ shall be selected so that T_{high} does not exceed T_{max}. (Cloudy test length shall be adjusted to not exceed this value.)

Measure insolation, infrared irradiance, and ambient temperature during the test.

7.5.1 Clear, Low Temperature

This test is to be performed on a minimum of 2 clear (K_T>0.65) days. For simulator testing, only one test needs to be performed.

a. Charge the system (see 7.1) until $T_{initial} = T_{low.}$ T_{low} needs to be low enough that the T_{high} requirement (see 7.5.2) can be met.
b. Expose the collector for 3-4 hours.
c. At the conclusion of the irradiation period, cover the collector and purge (see 7.2) the gathered energy from the tank with $T_{in} = T_{low}$.
d. Check radiation requirements (see 7.5) to see if further data is required.

7.5.2 Cloudy, High Temperature

This test is to be performed on a minimum of 2 cloudy (K_T<0.65) days.

a. Charge the system (see 7.1) until $T_{initial} = T_{high,}$ where $T_{high.} = T_{low}$+30° C.
b. Expose the collector for 5-6 hours.
c. At the conclusion of the irradiation period, cover the collector and purge (see 7.2) the gathered energy from the tank with $T_{in} = T_{high}$.
d. Check the radiation requirements (see 7.5) to see if further data is required.

7.6 Nighttime Decay Tank Loss Test (System loss fit)

Perform the heat loss test (see 7.4) on installed system outdoors and uncovered. The test shall be started within 1 hour of dusk and completed within 1 hour of dawn. Constraints regarding constant temperature and length of decay period are not considered for this version of the test. However, the test shall be conducted when the average outdoor sky temperature is at least 10° C below the average ambient temperature.

8.0 Data Analysis Methods

The analysis consists of two steps; 1.) determining a physical parameter from the test and, 2.) re-normalizing a TRNSYS model of the test or specifying a TRNSYS parameter based upon the test results. The basic analysis method is given either in Section 7 above for standard experimental procedures or in the method provided below for each system type.

The calculation of temperature dependent densities and heat capacities shall be done using real-time data. The Q_{del} value is to be used when matching net delivered energy with TRNSYS. Normally it is not necessary to adjust this value as the TRNSYS model accounts for tank energy changes (due to different starting and ending temperatures) and losses from the unit during the purge period.

It is necessary to adjust some of the experimental data so that it is consistent with the testing being done. For example, to account for the covering of the collector during the purge period, it is necessary to zero the visual radiation and adjust the sky infrared radiation to an equivalent sky radiation if the pyranometer and pyrheliometer are not covered by the collector cover.

9.0 Integral Collector Storage and Thermosiphon Systems

9.1 Qualification tests

Conduct the initial (measurements, pressure, etc.) and qualification (stagnation, shock, etc.) tests as specified by the certification program.

9.2 Heat loss tests

Conduct a capacitance test (see 7.3).

Conduct a heat loss test (see 7.4).

On ICS systems, conduct a nighttime decay loss test (see 7.6)

9.3 Warm-up tests

Conduct the solar system warm-up tests (see 7.5).

9.4 Analysis Method

a. The tank parameters from the tank tests (if applicable), the heat exchanger parameters from the heat exchanger tests (if applicable), the pump and PV panel parameters (if applicable), and the data from the flat plate thermal performance test (if applicable) will be used to create an audit TRNSYS model of the complete system. Minor variations of this model will be created for each of the data points to be evaluated.

b. The data from each of the individual data points in the test will be used to calibrate the TRNSYS model using the FR_{TA} and FR_{UL} isothermal initial conditions. A fitting routine will be used to fit the observed net energy deliveries (or auxiliary energy if an integral auxiliary element is a part of the system) to the observed data points (one per test). For ICS system types, the FR_{UL} knob is actually a UA_{loss} knob since there is no FR_{UL} data point. (Note that the ICS night time loss test shall be fit as part of the data set.)

10.0 Storage Tanks

In general, these tests are to be performed for any storage tank that can be physically separated from the solar component. Any integral heat exchanger shall be filled with the specified operating fluid and external connections shall be sealed and insulated. If required, preheating of the specific operating fluid shall also be done. Conventional, commercially available water heaters are modeled in TRNSYS without additional testing for a specific system certification. All others shall undergo the tests specified here.

A 3.4 +/- .8 m/s (7.6 +/- 1.8 mph) wind shall be blown across the face of any tank unit that is to be used outdoors and is not to be tested in outdoor warm-up tests.

10.1 Physical Tank Measurements (Modeling Parameters)

Measure all easily accessible significant characteristics of the tank, including:

a. Diameters or lengths and widths (internal and external).
b. Heights (internal and external), denote any minimum and maximum water levels.
c. Thickness (insulation, tank shell, tank vessel).
d. Volumes (at T_{mains}) of the tank and any integral heat exchanger(s).
e. Provide a diagram indicating geometry including vessel, shell, and any protrusions such as HX's and plumbing connections.
f. Indicate materials used for vessel, insulation, shell, tank liner, heat exchangers.

10.2 Capacitance Test

Conduct a capacitance test (see 6.3).

10.3 Heat Loss Test

Conduct a heat loss test (see 6.4).

10.0 Heat Exchangers

These tests are to be performed with the heat transfer fluid(s) to be used in the actual installation. If multiple fluids are to be used, multiple tests will be required. A minimum of 10 minutes shall be allowed for the stabilization of fluid flows and temperatures for each set of data points collected in the thermal performance tests. Data during the thermal performance tests shall be reported in 30-second intervals or less. The preferred testing conditions are indoors, although outdoor tests may be performed if the system is covered during the test. For systems (IC, TS) that incorporate a collector side HX, the explicit HX test is not usually required as these affects will show up in the system testing.

11.1 Physical Measurements (Physical Parameters)

Measure all easily accessible significant characteristics, including the items below. Note that these details are especially critical for NCL modeling.

a. Diameters or appropriate lengths (internal and external).
b. Lengths (internal and external) and spacing of tubes and/or fins.
c. Thicknesses (insulation, piping, shell, fins, etc.).
d. Volumes (at T_{mains}) (supply and load sides).
e. Diagram indicating geometry, including vessel, shell, and any protrusions such as plumbing connections, and fins.
f. Indicate materials used in the heat exchanger and surrounding insulation.

Report all measurements in a consistent set of units.

11.2 Pressure Integrity Tests

The Test pressure shall be 1100 kPa Gauge (160 PSIG) for street pressurized portions of the heat exchanger.

For non street pressurized portions of the unit rated above 550 kPa gauge (80 PSIG), the test pressure is the smaller of one and one half times the manufacturer's rated pressure or 1100 kPa gauge (160 PSIG).

For non-street pressurized portions of the unit rated below 550 kPa gauge (80 PSIG), a pressure of one and one half times the manufacturer's rated pressure with a minimum of 170 kPa Gauge (25 PSIG) is required.

For unpressurized portions of the unit, the pressure will be set by the certification body using the manufacturer's design pressure as a guideline.

The result of this test is "pass" if no observable pressure change has occurred.

11.2.1 Supply side of Heat Exchanger (As applicable)

1. A pressure gauge is attached to the exit port of the heat exchanger and the outlet is sealed.
2. The supply side is filled with unheated water.
3. Hydraulic pressure is applied to the inlet port until the gauge indicates the test pressure has been reached.
4. The inlet pressure port is then closed and the pressure is monitored for 15 minutes.
5. The final pressure is recorded.

11.2.2 Load side of Heat Exchanger (As applicable)

1. A pressure gauge is attached to the exit port of the heat exchanger and the outlet is sealed.
2. The supply side is filled with unheated water.

3. Hydraulic pressure is applied to the inlet port until the gauge indicates the test pressure.
4. The inlet pressure port is then closed and the pressure is monitored for 15 minutes.
5. The final pressure is recorded.

11.3 Pressure Drop Test

These tests shall be conducted at 38^{o}C (100^{o}F) +/- 5^{o}C (9^{o}F). The flow rates used for testing the heat exchanger shall adequately represent the anticipated laminar, transition, and turbulent flow regimes experienced during operation. For NCL testing, the unit shall be oriented horizontally.

The temperatures and heat transfer fluids used in the heat exchanger shall represent what is expected during actual system use. A minimum of three valid data points shall be collected for each specified temperature/flow/fluid combination.

a. Supply Side of Heat Exchanger (As applicable)
   1. Heat the fluid to a specified operating temperature at the specified flow rate.
   2. Allow the pressure transducers to stabilize and measure the pressure drop.
   3. Repeat steps 1 and 2 for each specified flow rate.

b. Load Side of Heat Exchanger (As applicable)
   1. Heat the fluid to a specified operating temperature at the specified flow rate.
   2. Allow the pressure transducers to stabilize and measure the pressure drop.
   3. Repeat steps 1 and 2 for each specified flow rate.

Report all measurements in SI consistent set of units. A second order pressure drop curve shall be generated for both the supply side and load side coils. For NCL modeling, the flow shall be reported in mass units.

11.4 Performance Tests

The flow rates used for testing the heat exchanger shall adequately represent the anticipated laminar, transition, and turbulent flow regimes experienced during system operation.

The temperatures and heat transfer fluids used in the heat exchanger shall represent what is expected during actual system use. A minimum of ten minutes of data (30 minutes for NCL) shall be collected for each specified temperature/flow/fluid combination.

For heat exchangers tested under low flow operating conditions (NCL), special care shall be taken to ensure the accuracy of flow and temperature measurements. The use of a thermopile is required for measuring the temperature difference between inlet and outlet ports. The preferred method is to operate the heat exchanger with the NCL loop in operation. In these cases, the flow rate will have to be backed out of the energy balance of the “tank” and “collector” loops. No flow meter shall be used in the NCL test loop in these cases. When the energy balance technique cannot be used to measure the flow, use a forced flow and a low flow meter.

11.4.1 External Doubly Pumped Heat Exchangers

Test Method:

a. Stabilize flows to within +/- 0.006 l/s (0.1 GPM) and temperature to +/- 0.1 ^{o} C (0.2 ^{o} F).

b. Commence data collection at 15-second intervals. The rate of data collection and/or stabilization time shall be increased for any flows at or below 0.0315 l/s (0.5 GPM). The data will include the two inlet and outlet temperatures, ambient temperature, and the two flow rates. Additional temperature measurements may be required because of the non-linear nature of the heat transfer in long heat exchangers. If necessary, this can be accomplished by using three surface probes (assumed to be on the outer surface) and two internal probes at the inlet and outlet ports.

c. Adjust the temperatures and/or flow rates and proceed to step a above until the proper number of valid data points have been collected.

Analysis Method:

a. Only data collected from the first portion of the test (approximately 1 hour) shall be selected. The goal is to obtain data prior to the energy purge.

b. The data from each of the data point sets in the test will be used to calibrate the TRNSYS model using the UA knob(s) in the selected heat exchanger model. A linear regression routine will be used to fit the observed net energy deliveries to the observed data points (one per data point). If additional temperature probes are used (NCL), then the curve fit form from the three surface mounted probes shall be used to interpolate the corresponding internal temperature from the inlet and outlet temperature probes. If NCL is used for HX evaluation, the flow rate shall be determined from an energy balance, adjusted from estimated losses.

c. The UA knob(s) shall be used for modeling the HX in TRNSYS.

11.4.2 External NCL Heat Exchangers - Empirical Parameter Method

Test Method:

a. Connect heat exchanger, tank and piping together, allowing for the external control of tank and collector temperatures.

b. Start data collection in 15-second intervals. The data will include the two inlet and outlet temperatures, ambient temperature, the collector-side flow rate, and the flow rate through the tank (not between the tank and the heat exchanger). Additional temperature measurements may be needed because of the non-linear nature of the heat transfer in long heat exchangers. If necessary, this can be accomplished by using three surface probes (assumed to be on the outer surface) and two internal probes at the NCL inlet and outlet ports.

c. Maintain the tank at T_{mains} by using a measured flow of tempered water.

d. Stabilize collector flow to within +/- 0.006 l/s (0.1 GPM) and temperature to +/- 0.1 ^{o} C (0.2 ^{o} F) of that specified.

e. Measure all heat exchanger temperatures, heat exchanger hot side flow rate, and energy required to maintain the tank at a constant temperature.

f. Every 15 minutes, raise the heat exchanger inlet temperature by 15 ^{o} C (8.333^{o} F) until it reaches 95 ^{o} C (203^{o} F).
g. Stop flow to the tank.
h. Maintain heat exchanger inlet temperature at 95 ^{o} C (203^{o} F).
i. Measure all heat exchanger temperatures and collector-side flow rate.
j. Stop the test when the tank is within 1 ^{o} C (1.8 ^{o} F) of the temperature of the fluid entering the collector side of the heat exchanger. This may take up to 1 day.

Analysis Method:
a. The use of linear regression software is a necessary component of data analysis.

b. Use the data from both portions of the test along with material properties to generate a fit in the following form: $UA = P1Gr^{P2}Re^{P3}Pr^{P4}$

Where P1 through P4 are coefficients from the fit and the Gr, Re, and Pr are calculated dimensionless values. UA is calculated using standard heat transfer forms for the geometry of the heat exchanger and its plumbing connections. The thermosiphon flow rate is calculated from an energy balance on the system. (This may require that other losses be quantified first).

11.4.3 External NCL Heat Exchangers- Modified Effectiveness Method

Test Method:
a. Connect the heat exchanger, tank and piping together, allowing for external control of tank and heat exchanger hot side temperature. The collector loop will be supplied with a controllable hot water loop.
b. Measure the heat loss coefficient of the heat exchanger.
c. Start data collection at 60-second intervals. The data will include the two heat exchanger inlet and outlet temperatures, ambient temperature, and the collector loop flow rate.
d. Stabilize collector flow to within +/- 0.006 l/s (0.1 GPM) and temperature to +/- 0.1 ^{o} C (0.2 ^{o} F) of that specified.
e. Measure all heat exchanger temperatures, heat exchanger hot side flow rate, and ambient temperature.
f. Set the collector and tank loop temperatures for each of the following sample cases. Additional cases may be required for different fluids, flow rates, etc. Collect data for the indicated periods.

Sample Case	**Collector**	**Tank**	**Length (hr)**
1	80	15	4
2	65	40	4

g. A second order fit of pressure drop (Pa) vs. flow (kg/Hr) will be generated for both the supply and load sides of the HX .

h. Thermosiphon flow rates shall be calculated from an energy balance on the heat exchanger, using measured temperatures and collector flow rates. Allowances shall be made for thermal losses. Plot thermosiphon flow versus time for the various tests.

i. Generate plots and fits of heat exchanger performance in terms of modified effectiveness vs. flow rate and modified capacity ratio.

Analysis Method:

a. A second order fit of pressure drop (Pa) vs. flow (kg/Hr) will be generated for both the supply and load sides of the HX.

b. Thermosiphon flow rates shall be calculated from an energy balance on the heat exchanger, using measured temperatures and collector flow rates. Allowances shall be made for thermal losses. Plot thermosiphon flow versus time for the various tests.

c. Generate plots and fits of heat exchanger performance in terms of modified effectiveness vs. flow rate and modified capacity ratio. Calculations will be based upon Equations 2 and 4 of the Lin/Harrison analysis.

Equation 2: $$\varepsilon_{mod} = \frac{(M_{tank} * CP_{tank}) * (T_{tankout} - T_{tankin})}{(M_{coll} * CP_{coll}) * (T_{tankin} - T_{tankout})}$$

Equation 4: $$Crmod = \frac{M_{tank} * CP_{tank}}{M_{col}l * CP_{coll}}$$

11.4.5 Immersed Heat Exchanger – Internal Load Side

Test Method:

a. Charge the tank to the specified temperature. Two tests are typically conducted. One with the tank slightly above ambient and one with the tank near T_{max}

b. Stabilize heat exchanger flow to within +/- 0.006 l/s (0.1 GPM) and temperature (T_{max}) to +/- 0.1^{o} C (0.2^{o} F).

c. Start data collection at 15-second intervals. The rate of data collection and/or stabilization time shall be increased for any flows at or below 0.0315 l/s (0.5 GPM). The data will include the inlet and outlet temperatures, ambient temperature, and the flow rate.

d. Run the test for approximately 15 minutes, so that there is only a small change in tank temperature.

e. Repeat steps 1 through 4 for various flow rates (laminar, transition, and turbulent) and tank temperatures.

Analysis Method:

a. The data from each of the data point sets in the test will be used to calibrate the TRNSYS model using the UA value and exponent in the tank coil heat exchanger model. A fitting routine will be used to fit the observed energy deliveries to the observed data points (one per data point

b. The UA knob(s) shall be used for modeling the HX in TRNSYS.

11.4.6 Immersed Heat Exchanger – Internal Supply Side

Test Method:

a. Charge the tank to the specified temperature, typically above ambient.
b. Stabilize heat exchanger flow to within +/- 0.006 l/s (0.1 GPM) and temperature (T_{max}) to +/- 0.1^o C (0.2^o F).
c. Commence data collection at 15-second intervals. The rate of data collection and/or stabilization time shall be increased for any flows at or below 0.0315 l/s (0.5 GPM). The data will include the inlet and outlet temperatures, ambient temperature, and the flow rate.
d. Run the test for approximately 60 minutes, so that there is only a significant change in tank temperature. Ideally, the time period shall be set so that the amount of input energy is the same for each test and enough energy (2000 kJ minimum) is input to avoid experimental error.
e. Repeat steps 1-4 for various flow rates (laminar, transition, and turbulent) and tank temperatures.

Analysis Method:

a. The data from each of the data point sets in the test will be used to calibrate the TRNSYS rating model using the UA value and exponent in the tank coil heat exchanger model. A fitting routine will be used to fit the observed energy input to the observed data points (one per data point)
b. The UA knob(s) shall be used for modeling the HX in TRNSYS.

12.0 Solar Photovoltaic Component Tests

12.1 Photovoltaic Panel Performance Map (I and V Vs G curves and T_{pv})

Test Method:

The current analysis method does not integrate the panel temperature into the empirical curve fit. Therefore, it is required that the panel temperatures be maintained within the range of 35-45^o C (95-113^{o}F).

a. Expose the panel to varying amounts of solar radiation between 100-1000 W/m^2 (32-317 Btu/h-ft^2) by varying the azimuth and tilt of the collector or the irradiance level if tested indoors. Obtain data at irradiance levels no greater than 150 W/m^2 apart.
b. For each irradiance level, ramp the panel through a series of voltages from open circuit to short circuit using a controllable load.
c. Measure the observed current, voltage, irradiance, panel temperature, and ambient temperature for each set of data.

Analysis Method:
For each set of irradiance data, generate empirical curve fits relating current to voltage. (Note that the panel temperature relationship is not currently fit.

12.2 DC Pump Performance Map (P_{pump} Vs H_{pump})

Test Method:
All pumps shall be tested with the specified fluids at a temperature of 37.78 ^{o} C (100 ^{o} F).

a. Subject the pump to a series of system pressure drops by adjusting the throttle on the system loop containing the pump.
b. For each throttle adjustment, subject the pump to varying voltages by using a variable power supply.
c. Measure the observed flow rate, pressure increase across the pump, pump voltage and current draw.

Analysis Method:
See Appendix A for additional information on this method.
a. Generate empirical curve fits relating pump head to flow and voltage.
b. Generate empirical curve fits relating pump head to flow and current.
c. Determine the system pressure drop curve based on the certification program assumptions for plumbing.
d. Generate an empirical curve fit relating pump flow to irradiance for the specified PV module and DC pump combination for the system.
e. In order to model PV pumping, the plots of flow vs. irradiance and power vs. flow are used in the TRNSYS model, along with the starting radiation and average pump flow rate to model PV pumping.

Appendix A

Analysis Method for Evaluating PV Powered DC Pumps in Solar Water Heating Systems

To model the performance of solar water heating system (SWHS) using photovoltaic PV driven pumps it is necessary to characterize the operation of the fluid circulation system. Outlined below is a method to mathematically combine measured and modeled performance of individual components in a PV pumped system to predict the collector loop flow rate as a function of solar intensity. The fits are set up to discard any data that is not interpolated, so the data sets shall have ranges exceeding the desired system operation.

The performance of a system comprised of multiple components can be predicted if the performance of the individual components is known. A PV pumped system has three main components. These components are the pump, the system piping, and the PV panel. The variables associated with each component are:

Pump – current (I), voltage (V), flow (F), and head (H)
System piping – flow (F) and head (H)
PV Panel – current (I), voltage (V), irradiance (G), PV panel temperature (Tpv)

The performance of each component can be empirically described as functions of these variables. The form of the equations representing the functions varies with the specific components. Some can be represented by simple quadratics while others are more complex. The attached figures illustrate one specific example.

Pump performance can be measured directly under various conditions in a test stand. All four pump variables can be measured simultaneously. Surface fitting the data yields two functions:

{1} H as a function of F and V (fig. 1)

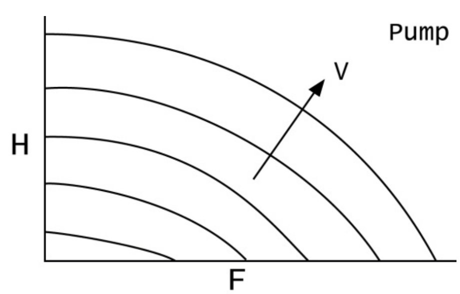

Figure 1

{2}	H as a function of F and I	(fig. 2)

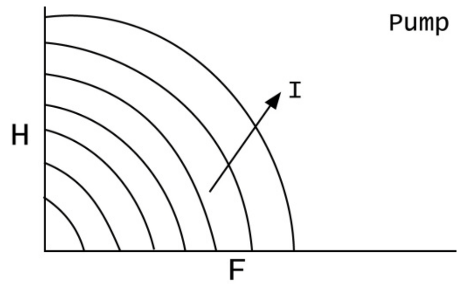

Figure 2

The system piping performance can be predicted using a pipe distribution analysis program. [1] However, most commercial programs are not well suited for laminar flow applications, because of the relative differences in fitting losses and the correlations used to predict them. Curve fitting the data yields on function:

{3}	H as a function of F	(fig. 3)

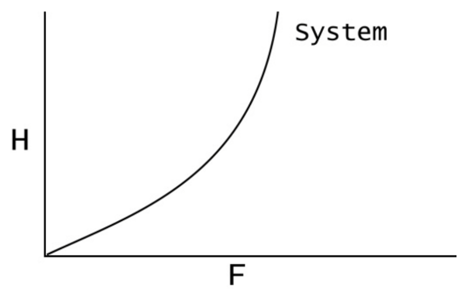

Figure 3

The PV panel parameters can be measured at various reference conditions. A modeling program can predict parameters under other conditions. [2] This yields one function:

{4}	I as a function of V, G, and Tpv	(fig. 4)

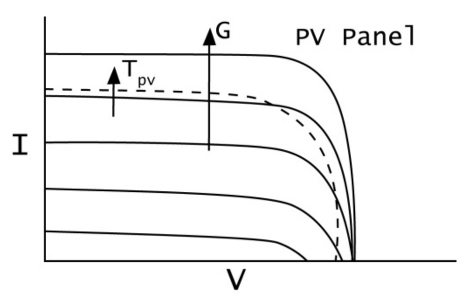

Figure 4

Note that Tpv is currently not being evaluated.

With each component's curve fit known, the functions can be combined to eliminate unnecessary variables. The steps used in the analysis are outlined below.

Pump function {1} combined with system function {3} (fig. 5A) eliminates H as a variable leaving:

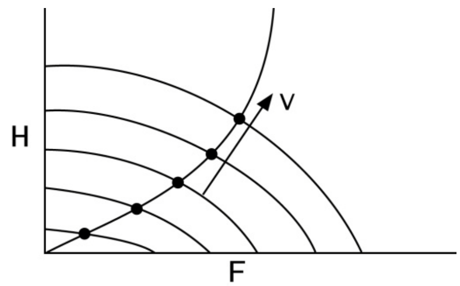

Figure 5a

{5} F as a function of V (fig. 5B)

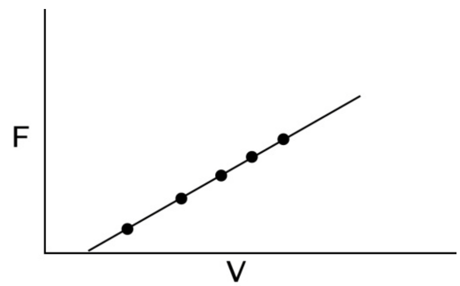

Figure 5b

Pump function {2} combined with system function {3} (fig. 6A) eliminates H as a variable leaving:

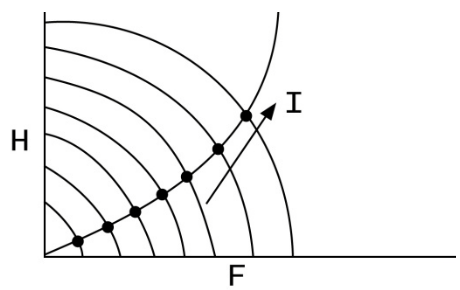

Figure 6a

{6} F as a function of I (fig. 6B)

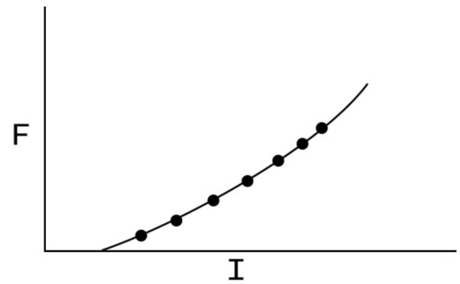

Figure 6b

Pump/system function {5} combined with pump/system function {6} eliminates F as a variable leaving:

{7} I as a function of V (fig. 7)

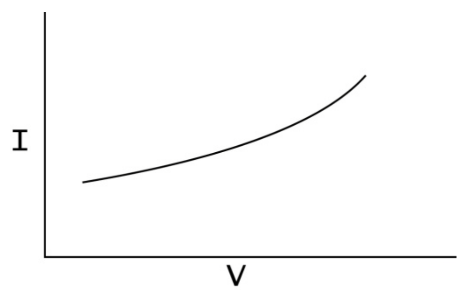

Figure 7

PV function {4} combined with pump/system function {7} (fig. 8A) eliminates I as a variable leaving:

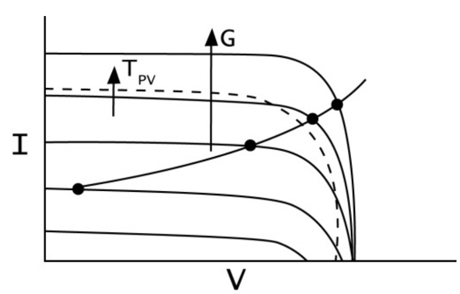

Figure 8a

{8} V as a function of G and Tpv (fig 8b)

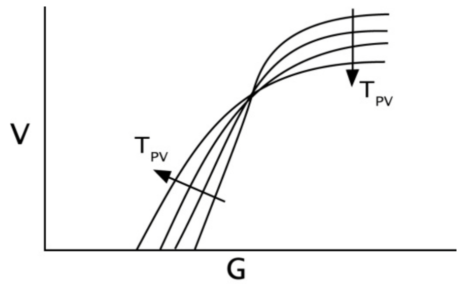

Figure 8b

Pump/system function {5} combined with PV/pump/system function {8} changes the dependent variable from voltage to flow leaving:

{9} F as a function of G and Tpv (fig. 9)

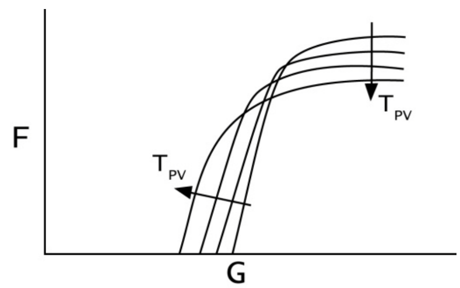

Figure 9

An empirical formula exists which relates Tpv to both Tamb and G. [3] This formula together with function {9} above describes the flow through the collector loop as a function of solar irradiance and ambient air temperature, although this has not been implemented.

Combining (1) and (2) yields dynamic pump power:

{10} P as a function of F

An empirical formula exists which relates P as a function of F. This formula describes the power used by the pump.

Integrating this curve fit into TRNSYS requires the determination of several values from the fit:

The start-up radiation is usually read from the F vs. G graph. In some cases, this may need to be adjusted manually.
Average PV flow (for stratification) is usually taken from the F vs. G graph and is usually an average of the minimum and maximum flow rates.
A total of six parameters for the flow and power are input into TRNSYS from fits 9 and

10. In some cases, the minimum pump current or voltage must be manually adjusted for a specific system. The likely cause is that there are multiple solutions to the empirical fits, one of which is not desired.

References:

[1] Cybernet, Waterbury, CT: Haestad Methods, Inc. 1992

[2] Buresch, Matthew, Photovoltaic Energy Systems, New York: McGraw-Hill, Inc. 1993, p. 87

[3] Ibid., p.76