SRCC DOCUMENT TM-1
SDHW SYSTEM AND COMPONENT TEST PROTOCOLS

Version 1.12: July 2008

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1.0 Introduction

These test protocols are intended to address the specific requirements for the testing of solar water heating systems and their auxiliary components. The results of these tests are intended to be used as input into the current TRNSYS simulation program as required by SRCC and FSEC certification.

The intent of these protocols is to address system performance. Consequently, these tests should be conducted at the conclusion of the specified durability tests. Currently, SRCC Standard 100-86 (RA 92) {Sections 4.2-4.6} addresses these issues for flat plate collectors. SRCC OG-300 also specifies these performance tests for solar collectors in section 6.1.2.1. OG-300 currently does not clarify what durability requirements are to be met for auxiliary system components. Therefore, it is recommended that any of these auxiliary components (e.g. heat exchangers) used in the system also be subjected to any of the relevant durability tests (e.g. pressurization of the collector loop of the heat exchanger) before the system is tested for performance. Additional durability tests may be required as specified to determine operation under extreme conditions such as freezing or overheating.

Where applicable (e.g. warm-up tests), these tests have been designed for outdoor conditions. This version incorporates recommended simulator conditions. However, the use of a simulator requires that considerations for infrared radiation, diffuse radiation, ambient airflow, sky temperature, and the view of the collector be made when taking and/or analyzing the data. These test methods have been developed as an alternative to the more extensive ISO methods. The intent is to speed up and simplify the collection and analysis of data. Note that some of the methods have been adapted from the ISO tests.

This set of protocols is intended to be an outline of the type of tests required for a particular class of generic systems. Most of the systems to be tested may not need to undergo many of the tests specified in this document. The decision upon which tests to be conducted will be based upon a variety of factors including:

1. The generic system class being considered
2. Uncertainty in the modeling of these systems in the current SRCC/TRNSYS rating program
3. Previous experience in the performance of a particular class of system
4. The fundamental relationships regarding optics and thermodynamics that govern a system's performance.

2.0 Generic System Classes

The following list summarizes some of the generic systems that have been considered in the development of the following protocols. Note that some of the systems tested may actually incorporate more than one of these generic system classes; In these cases, some additional testing may be required. However, if a system falls into multiple classes, but the second class is a part of the other's "black box" model, then only the first system class needs to be considered. The exception would be when the second class is used to extrapolate results for other system configurations. As new generic system classes are encountered, these protocols will be expanded to accommodate them.

A: System with an integral auxiliary heater or separate auxiliary heater. This test protocol assumes that the auxiliary 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: PV pump driven system/ PV Panel
PU: Pump (Only DC 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 NCL

3.0 Nomenclature

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	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}	Temperature of a charged tank or pre-heated system inlet used for High Delta T warm-up and tank tests = {typically 57.22° C (135 ° F) or recommended maximum temperature of tank)}
T_{purge}	Purge temperature of the system (T_{mains} or T_{hot})
T_{pv}	Photovoltaic panel temperature
T_{set}	The setpoint of the activated auxiliary heating element
T_{sink}	Heat sink average temperature (estimate from $\frac{T_{in} + T_{out}}{2}$)
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
$UA_{hx\ loss}$	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
$UA_{isolated\ loss\ aux}$	Isolated total UA loss of auxiliary heated portion of the storage tank
$UA_{isolated\ loss\ solar}$	Isolated total UA loss of solar heated portion of the storage tank
$UA_{isolated\ loss\ total}$	Isolated total UA loss of the storage tank from a decay test
$UA_{installed\ loss\ total}$	Installed total UA loss of the storage tank from a decay test
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

4.0 Referenced Documents

Qin Lyn, Stephen Harrison and Mikael Lagerquist, "Analysis and Modeling of Compact Heat Exchangers for Natural Convection Loop Applications,"Eurosun 2000, Third ISES-European Solar Congress, Copenhagen, Denmark, 2000.

TRNSYS: "A Transient System Simulation Program," Solar Energy Laboratory, University of Wisconsin – Madison, 1303 Engineering Research Building, 1500 Engineering Drive, Madison, WI 53706 WI, March 2000. <http://sel.me.wisc.edu/trnsys/default.htm>

5.0 Testing Policy

In order to expedite the testing and certification of solar DHW systems, the current policy will be to test the most common system to be sold and possibly one extreme (with respect to the collector area/storage tank volume ratio). If the results from the first two model re-normalization exercises are not reasonably consistent, the other extreme will be tested. The decision about which tests to run and some of the specifics of the operating parameters is at the discretion of SRCC in accordance with section 6.1.2.1 of OG300.

Different configurations that will require at least one test (not necessarily both of the tests) include: different collector absorber coating, the use of a supply side or load side HX, integral heater in the solar tank as well as any significant model changes. Systems utilizing a separate collector (e.g. TS) may require a separate OG-100 type of 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 to those predicted by the TRNSYS models. For these types of systems, the instrumentation should not impede the fluid flow as this may adversely impact the performance of the system. Systems that have some type of self-draining mechanism shall be plumbed in such a manner so that the SRCC rating 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. It is recommended that 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. If this is not possible, it may be possible to “correct” the measurement by physically weighting the RTD probe.

The applicability of extrapolating these test results to fluids other than water is limited. When testing with a fluid other than water, it is recommended that fluid composition tests be performed to ensure that the specified fluid composition exists. At a minimum, a hygrometer test or its equivalent should 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 the fill rate 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 them should be purged in the normal operating fashion. This may required extended draw periods.

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

6.1 Recommended Instrumentation Accuracy/ Resolution

Table 1 indicates the recommended assurances 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 Minimum Data Time Step

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

6.3 Instrument Calibration

All instrumentation used in the experimental setup needs to be re-calibrated to an accepted standard on a regular basis. The recommended minimum re-calibration times are yearly for radiation measuring devices, and monthly for all temperature, mass, and energy measuring devices. Additional re-calibration should be performed when any significant experimental or data acquisition changes have been made or the experimental setup has not been used for an extended period of time.

6.4 Required Experimental Data

6.4.1 Required Numerical Data

The minimum real time data to be collected for the comprehensive tests shall consist of the following (in order) in SI/TRNSYS units. For ease of modeling, all data channels shall be reported 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. SRCC/FSEC reserves the right to reject any data that does not meet these minimum requirements.

1. Data collection time (both local and solar) and date (YYYYdddhh.hhhhh)
2. Inlet temperature (ºC)
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/hr)
7. Wind velocity (m/s)
8. Auxiliary energy usage (if applicable) (kWh)
9. Radiation measurements (see below) (if applicable) (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.

6.4.2 Required Physical Data

Measure all easily accessible significant characteristics of the component or system, including:

a. Diameters and/or lengths and/or widths (internal and external).
b. Heights (internal and external), denote any minimum and maximum water levels.
c. Thickness (insulation, tank shell, tank vessel, fins, etc).
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.
g. Indicate piping lengths and orientations.
h. Indicate slope of components.
i. Lengths (internal and external) and spacing of tubes and/or fins.
j. Volume(s) @ T_{mains}.

Measurements shall be reported in consistent sets of units, unless convention overrides this.

6.5 Data Processing Methods

The goal of these tests methods is to provide data for TRNSYS modeling of systems and or system components. For components, the data is to be used directly in the TRNSYS model. For system or system components, a group of warm up tests is fit via linear regression to generate the gain and loss factors that are used for the modeling for that system.

The calculation of temperature dependent densities and heat capacities shall be done using real-time data. Data reduction shall include the filtering out of any bad 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.

The experimental work consists of several steps:

1. Determine physical parameter from the tests (e.g. length)
2. Determine intermediate or components measurements from component tests (e.g heat exchanger UA). The system parameter is determined as part of this effort.
3. Collect extended test data from a warm up test that along with items 1 and 2 are used to fit a TRNSYS model for a series of these tests. The warm up data is summarized and processed into data files as part of this effort.

At the completion of this phase, experimental data is then used for the TRNSYS modeling and/or calibration.

6.6 TRNSYS Processing for System Model Calibration

Upon receipt of the processed data, a series of TRNSYS model is created. This is usually performed by the Certification agency. One model is created for each test. This model is called the “audit” model. Each of the audit models is then fir to the test data as indicated below:

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.).

c. If the tank is initially stratified, a separate set of tests and fits will be done. This is typically done when a heater is located within the storage tank of a thrmosiphon system.

The net result of this process are two points that are using in the rating model.

7.0 Standard Experimental Procedures

7.1 Tank charge

Fill Method:

a. Fill may occur at any rate up to manufacturer's recommended maximum flow rate.
b.. Heat and fully mix tank to T_{max}.
c. Fill until $|T_{mains} - T_{del}| = 0.2° C\ (0.4° F)$ or $\frac{\partial |T_{mains} - T_{del}|}{\partial t} = 0.05° C\ (0.09° F)$ 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. Draw should occur at 0.125- 0.189 l/s (2-3 GPM) until $|T_{mains} - T_{del}| = 0.2°C(0.4°F)$ or

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

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

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 Installed Capacitance And Draw Stratification/ Test (Q Initial)

This test is to be performed indoors, preferably in an environment with nearly constant temperature. This unit is to be installed in a manner consistent with the intended system design. Piping connections are to be made, but isolated via valving. This test is typically performed before the loss tests so that a baseline tank capacitance can be determined. This test should also be used in conjunction with the solar testing to determine initial charge energy for a High Delta T warm-up test. 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 commencing this test 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 unit is to be installed in a manner consistent with the intended system design. This test is to be performed indoors, preferably in an environment with nearly constant temperature. Any source of heating including resistance heaters and or solar radiation are to be shut off or blocked. If the +/- temperature variation is greater than 10% (approximately 3.5 ^{o} C for these conditions using a 22 ^{o}C ambient) of estimated tank to ambient delta T, then the use of internal probes is recommended for determining a run-time UA value. If significant stratification is anticipated, the use of internal tank temperature probe(s) is recommended.

a. Charge the tank (see 7.1) until $T_{initial} = T_{high}$.
b. Piping connections are to be made, but isolated via valving.
c. Wait until:

$$\frac{T_{\text{tank}aveorig} - T_{ambave}}{3} \le \left(T_{\text{tank}ave\,final} - T_{ambave}\right) \le \frac{2 * \left(T_{\text{tank}aveorig} - T_{ambave}\right)}{3} \ .$$

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.

d. Piping connections are to be made and opened via valving.
e. 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. The real time method 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 is below the 10% level, the following calculations can be used, which assume an ideal exponential temperature decay.

a. Determine tank thermal capacitance from either Qinitial or a theoretical calculation.

  1. Experimental Method (preferred, see 7.3)

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

  2.. Theoretical Method

$$M_{tank} * C_P = M_{tank} * C_p\ (@T_{max})$$

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 $UA_{installed\ loss\ total}$. $UA_{isolated\ loss\ total}$ value is to be used in the TRNSYS tank model. This value is to be used in 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 performed. 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 Tests

These are the primary set of tests used to calibrate the TRNSYS models to the experimental results. Due to the variation in the factors that influence the operation of the solar component of the different generic systems, there is one primary set of tests. Several additional sets of tests (included in Appendix A) may also be specified as needed.

An implicit consideration in these protocols are that the systems are sized on the order of 60-80.3 l/m^2 (1.5-2 gal/ft^2) storage per collector area, which is typical of residential SDHW 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 pre-heat system installed in a conventional manner (with added instrumentation and bypass loops for preconditioning). If the system is a one-tank system with an integral heating element, then this system will be tested with and without the element in operation. In the test with the element, set Tset = 50°C (122°F) and energize the element for the first hour of each test if a stratified start is desired.

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 should 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 delta T tests are setup to give the "high" performance when the test is run at "cool" temperatures, and the cloudy, high delta T tests are setup to give the "low" performance when the test is run at "high" temperatures. On the low delta T tests, the initial temp is typically the mains temperature, and the high delta T test uses elevated starting temps. In addition to meeting the specified solar radiation, each individual test also shall have a minimal 5° C (9 ° 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 component at the beginning of the purge process. The cover should consist of 0.04 m (1.6") insulation board, preferably with foil-covered surfaces. The cover should extend at least 0.08 m (3.1") beyond the gross horizontal collector aperture cover any vertically exposed optical components. The exposed side of the cover should be backed with any appropriate material required for structural rigidity and exposure to the weather (e.g. plywood and plastic).

Before commencing the warm up tests, it is necessary to 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 should be activated manually in order to fully mix the heat transfer fluid(s). The following are a few recommendations:

a. Desired tank temperature is close to the ambient temperature:

   1. Thermosyphon (TS): Uncover collector during mixing period (about 10 minutes prior to exposure start)
   2. Others: Cover collector

b. Desired tank temperature is lower than the ambient temperature:

   1. All: Cover collector

c. Desired tank temperature is higher than the ambient temperature:

   1. TS: Uncover collector during mixing period (about 10 minutes prior to exposure start)
   2. Others: Partially uncover the collector during mixing to allow some heating, do not allow stagnation.

All systems shall be positioned and fixed at 0^o azimuth (due South). The recommended tilt for the systems is that the systems should normal to the sun at solar noon +/- 4^o on the day of the test, unless this contradicts the manufacturers 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 recommended tilt that is nearest the normal tilt value at solar noon. For active systems, the operation of the controllers and pumps should 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 1-2 times/day as meteorological and experimental conditions allow.

A 3.4 +/- .8 m/s (7.6 +/- 1.8 mph) wind 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 has only one profile. 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 warmup tests are expected to yield a minimum of 4 data points (2 clear, low temperature differential and 2 cloudy, high temperature differential, where the differential is measured from the tank average temperature to the ambient average temperature). A data point (test) is considered to meet the criteria if the radiation condition is met and the minimal 5^o C ($9\,^o$ F) tank temperature rise is achieved. The goal of the tests is to gather approximately 13,000 kJ/m^2 (12,322 Btu/ft^2) of radiation for all tests (cloudy test length shall be adjusted to not exceed this value) to equalize relative experimental errors and to equally weight the various conditions. T_{mains} should be selected so that T_{hot} does not exceed T_{max}. (Cloudy test length shall be adjusted to not exceed this value.)

Measure insolation, infrared irradiance, and ambient temperature during all the tests.

Appendix B contains some other tests developed for non-standard systems.

7.5.1 Warm Up Test: Clear, Low Temperature Differential, Isothermal Tank

This test is to be performed on a minimum of 2 clear ($0.65<K_T$) 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 [typically 20 ^{o} C (68 ^{o} F)].so 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 Warm Up Test: Cloudy, High Temperature Differential, Isothermal Start

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 (approximately).
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

Perform the heat loss test (see 7.4) on an installed systems outdoors. The system should be 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, one test shall be conducted when the average outdoor sky temperature is at least 10° C below the average ambient temperature. The other test shall be conducted when the average outdoor sky temperature is within 2° C of the average ambient temperature.

7.6 Warmup and Decay Test Analysis

The analysis is implicit in the fitting process for the test data. This is accomplished by the means of a least squares fit (using the simplex method) to a set of data based upon minimizing the residual difference between the Qnet experimental and the Qnet TRNSYS. In this case, Qnet is defined as the sum of the draw, estimated tank losses during the draw period, and the DE that occurs during the test. As a default the following weighting of data is used (other adjustments may be need if data problems occur):

1. Two low DT warm-up tests and two **high** DT warm-up tests (Typical): Each test is weighted equally. More tests can be used, but the “extra” data set should be “thrown-out” or weighting adjusted to maintain an equal weighting.
2. Two low DT warm-up tests. two nighttime decay tests, and two high DT warm-up tests (ICS units only): Each test is weighted equally. More tests can be used, but the “extra” data set should be “thrown-out” or weighting adjusted to maintain a 1/3 weighting of each type of test.

The result of this analysis are the FR_{TA} and FR_{UL} multipliers that are used for modeling these systems for a given set of design parameters. These values are generated from the OG-300 rating software when configured to fit a set of data.

8.0 Passive (Integral Collector Storage and Thermosiphon) Systems

8.1 Passive System Qualification Tests

Collect physical data (see 6.4.2).
Conduct qualification (pressure, stagnation, shock, etc.) tests as specified by the certification program.

a. Supply side of Heat Exchanger (Or entire system As applicable): This side shall be pressure tested in the same fashion as the collector testing specified in SRCC Standard 100-86 (RA 92) {Sections

4.2-4.6}. If the system has been previously tested by this or a comparable standard, then re-testing is not required.

b. Load side of Heat Exchanger (As applicable): This side of the heat exchanger and system components shall be pressure tested in the same fashion as the collector testing specified in SRCC Standard 100-86 (RA 92) {Sections 4.2-4.6}. If the system has been previously tested by this or a comparable standard, then re-testing is not required.

8.2 Passive System Heat Loss Tests

Conduct a capacitance test (see 7.3).

Conduct a heat loss test (see 7.4). This test may not be required for ICS systems.

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

8.3 Passive System Warm-up Tests

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

If a thermosiphon system contains a tank with an integral heater, an additional set of tests shall be preformed. The tests shall be identical to the set in 7.5.1, with the following change to allow for stratified operation due to the heater operation:

a. For the first hour of the warm up test, the heating element shall be activated.

Test 7.5.2 does not need to be repeated as the same data is used for the fitting process.

9.0 Storage Tank Tests

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.

9.1 Storage Tank Qualification Tests

Collect physical data (see 6.4.2).

9.2 Storage Tank Pressure Integrity Tests

This tests is only required if the tank has not undergone similar testing by an approved certification agency.

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.

9.2.1 Storage Tank Supply side of Tank Heat Exchanger Pressure Integrity Test

a. A pressure gauge is attached to the exit port of the heat exchanger or tank and the outlet is sealed.
b. The supply side is filled with unheated water.
c. Hydraulic pressure is applied to the inlet port until the gauge indicates the test pressure has been reached.
d. The inlet pressure port is then closed and the pressure is monitored for 15 minutes.
e. The final pressure is recorded.

9.2.2 Storage Tank Load side of Tank Heat Exchanger Pressure Integrity Test

a. A pressure gauge is attached to the exit port of the heat exchanger and the outlet is sealed.
b. The supply side is filled with unheated water.
c. Hydraulic pressure is applied to the inlet port until the gauge indicates the test pressure.
d. The inlet pressure port is then closed and the pressure is monitored for 15 minutes.
e. The final pressure is recorded.

9.3 Storage Tank Capacitance Test

Conduct a capacitance test (see 7.3).

9.4 Storage Tank Heat Loss Test

There are two recommended methods for determining tank losses: the decay test and the constant temperature loss test. The decay test is recommended for most applications. However, when there is a significant degree of stratification during the test that cannot be measured by an internal probe, the constant temperature loss test may be used. Note that this test will tend to increase the loss value slightly due to the movement of the fluid in the tank.

a. Conduct a heat loss test (see 7.4).

b. Constant Temperature Loss Test [Optional Method] see Appendix B.

10.0 Heat Exchanger Tests

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. However, the load side HX and tank shall be tested under a variety of temperatures and flows expected in normal operation independent of the system testing.

10.1 Heat Exchanger Qualification Tests

Collect physical data (see 6.4.2).

10.2 Heat Exchanger 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.

10.2.1 Supply side of Heat Exchanger Pressure Integrity Test (As applicable)

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

10.2.2 Load side of Heat Exchanger Pressure Integrity Test (As applicable)

a. A pressure gauge is attached to the exit port of the heat exchanger and the outlet is sealed.
b. The supply side is filled with unheated water.
c. Hydraulic pressure is applied to the inlet port until the gauge indicates the test pressure.
d. The inlet pressure port is then closed and the pressure is monitored for 15 minutes.
e. The final pressure is recorded.

10.3 Heat Exchanger Pressure Drop Test

These tests shall be conducted at 37.78 ^{o} C (100 ^{o} F) +/- 5^{o} C (9 ^{o} F). The flow rates used for testing the heat exchanger should satisfy the following criteria: They should adequately represent the anticipated laminar, transition, and turbulent flow regimes experienced during operation. For NCL testing, the unit should be oriented horizontally.

The temperatures and heat transfer fluids used in the heat exchanger should represent what is expected during 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 fluid to 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 fluid to 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.

A second order pressure drop curve shall be generated for both the supply side and load side coils.

For NCL modeling, thermosiphon flow rates shall be calculated from an energy balance on the heat exchanger, using measured temperatures and collector flow rates. A second order fit of pressure drop (Pa) vs. flow (kg/Hr) will be generated for the NCL side of the HX.

10.4 Heat Exchanger 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 should represent what is expected during 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 for the accuracy of flow and temperature information. 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.

10.4.1 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:

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.

10.4.2 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 °C (8.333° F) until it reaches 95 °C (203° F).
g. Stop flow to the tank.
h. Maintain heat exchanger inlet temperature at 95 °C (203° F).
i. Measure all heat exchanger temperatures and collector-side flow rate.
j. Stop the test when the tank is within 1° C (1.8 ° 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: $UA = P1 Gr^{P2} Re^{P3} Pr^{P4}$

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).

10.4.3 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 temperatures to +/- 0.1 °C (0.2 °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	2
2	65	40	2

Analysis Method:
a. 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 from the HX. Plot thermosiphon flow versus time for the various tests.

b. Calculate the driving pressure using average tank and HX (NCL loop) temperatures, along with the density of the fluids as a function of temperature. Fit the flow to:

Equation 1: $M = C_1 * \Delta P^{C2}$

Plot Flow vs DP for the test period.

c. Generate 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: $$\varepsilon_{\text{mod}} = \frac{(M_{\text{tank}} * CP_{\text{tank}}) * (T_{\text{tankout}} - T_{\text{tankin}})}{(M_{\text{coll}} * CP_{\text{coll}}) * (T_{\text{collin}} - T_{\text{tankout}})}$$

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

Using these values, calculate a fit for Crmod as in Equation 5:

Equation 5: $$\varepsilon_{\text{mod}} = C_1 * Cr\,\text{mod}^2 + C_2 * Cr\,\text{mod}$$

Plot ε_{mod} as a function of Crmod for the test period.

10.4.4 Immersed Heat Exchanger (Wrap around or Wand)– 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° C (0.2° 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 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.

10.4.5 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_{mains}) 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.

11.0 Solar Photovoltaic Component Tests

11.1 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^oF).

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 for each radiation data set. Note that the panel temperature relationship is not currently fit.

11.2 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 using the fits in a-c and the results of 11.1.
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 and maximum pump flow rate to model PV driven 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)
{2} H as a function of F and I (fig. 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. Hence, a spreadsheet with the appropriate laminar flow correlations is recommended. Curve fitting the data yields on function:

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

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:

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

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

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

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

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

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:

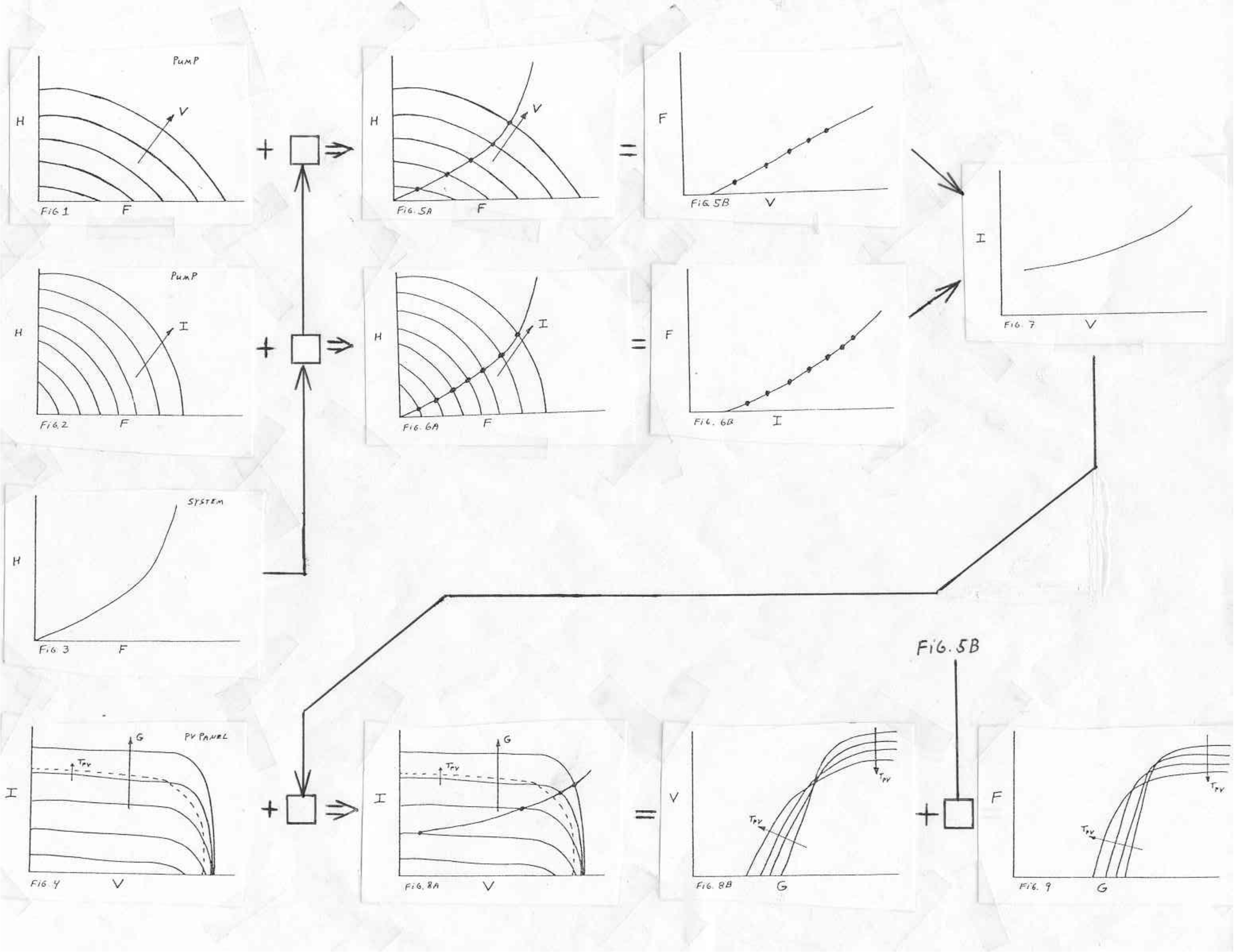
The start-up radiation is usually read from the F vs. G graph. In some cases, this may need to be adjusted manually. Average PV flow (for stratification) is usually taken from the F vs. G graph and is usually an average of the minimum and maximum flow rates. A total of six parameters for the flow and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



PUMP
H
V
F
FIG 1
PUMP
H
I
F
FIG. 2
SYSTEM
H
F
FIG. 3
+
+
H
V
F
FIG. 5A
H
I
F
FIG. 6A
=
=
F
V
FIG. 5B
F
I
FIG. 6B
I
V
FIG. 7
PV PANEL
G
T_{PV}
I
V
FIG. 4
+
G
T_{PV}
I
V
FIG. 8A
=
V
T_{PV}
T_{PV}
G
FIG. 8B
FIG. 5B
+
F
T_{PV}
T_{PV}
G
FIG. 9

Appendix B

Additional Tests

B.1 Constant Temperature Loss Test

Test Method
This test is typically used when the assumptions for the exponential decay cannot be maintained and the impact of the increased heat transfer is not significant on system performance. This test is to be performed indoors, preferably in an environment with nearly constant temperature. This test functions by fully mixing the tank whenever the element comes on. An insulated external loop with a pump is used to fully mix the tank. The flow rate of this loop should be at least 15 l/m (4 GPM). The use of a thermostat with a 3^{o} C (5^{o} F) deadband or less is recommended.

a. Charge tank (see 7.1)
b. Allow element to cycle for a minimum of 5 Cycles.
c. Measure Q_{aux} and the ambient temperatures during the test period.
d. Test is finished at the end of the fifth cycle.

Analysis
Calculate the following to determine the loss.
a. $Q_{loss} = Q_{aux}$
b. Numerically solve for UA, $Q_{loss} = \sum UA * (T_{ank\ ave} - T_{amb}) * \Delta t$

The Q_{aux} can be equated to the internal energy input for the last four cycles. This assumes a constant delta T and a fully mixed tank. Adjustments may need to be made to the input energy to account for the pumping energy, the additional piping losses, and the change in the film coefficient during pump operation.

B.2 Isolated Heat Loss Test [Standard Decay Method]

This method is used when the losses due to the fluid connections is desired.

Test Method
This test is similar to Test 7.4, with one exception:

a. Instead of just closing the valves during the duration of the test, the actual piping should be isolated using quick disconnects or similar.

Analysis
Analysis is the same as Test 7.4. The result is $UA_{isolated\ loss\ total}$.

B.3 Isolated Delayed Purge (Vertical Conductivity)

Test Method

This test is to be performed indoors, preferably in an environment with nearly constant temperature. This test functions by fully mixing the tank whenever the element comes on. An insulated external loop with a pump is used to fully mix the tank. The flow rate of this loop should be at least 15 l/m (4 GPM). The use of a thermostat with a 3^o C (5^o F) deadband or less is recommended.

a. Charge tank (see 7.1)
b. Draw 1/2 of tank volume @ 5 l/min. (1.3 GPM) or less to avoid destratifying the tank, measuring ambient temperature during the entire test period.
c. Disconnect piping connections
d. Wait until:

$$T_{\text{tank ave final}} \leq T_{\text{tank ave orig}} - 5^o \text{ C } (9\ ^o \text{ F}) \text{ and } T_{\text{tank ave final}} \geq T_{\text{amb ave}} + 5^o \text{ C } (9\ ^o \text{ F})$$

These will be estimated before the test is run using the known tank volume and estimated environmental temperatures. Measure Q_{aux} and the ambient temperatures during the test period.

e. Reconnect piping connections.
f. Purge the remaining energy in the tank at $T_{mains.}$.

Analysis
The data from this test will be used to adjust the vertical conductivity of the TRNSYS tank modeling based on energy matching of the data.

B.4 Isolated Auxiliary Capacitance

Test Method
This test is used to determine the heater height and T set when these values are not known. This test is to be performed indoors, preferably in an environment with nearly constant temperature.

a. Charge tank (see 7.1)
b. Disconnect piping connections
c. Activate power and let tank heat up to T_{set} [set to T_{max} +/- 5^o C (9^o F)]. Measure Q_{aux} during the warm-up and the ambient temperatures during the test period.
d. Reconnect piping connections
e. Disconnect the element and purge the energy in the tank.

Analysis

a. The heater set point is determined from the initial asymptote of the draw after stabilization and before the "hot fluid plug" has been purged.

b. The effective height of a horizontal heater is determined by estimating:
$Q_{aux} = C_{heated} * (T_{set} - \text{Tank\_} T_{ave\_orig})$

c. T_{set} is determined from step a and T_{start} is the mixed tank temperature. A TRNSYS model is then used to iterate on Q_{aux}, adjusting the height of the heater until the height / volume are physically reasonable and the DT rms. of the purge is less than TBD.

d.. $C_{solar} = C_{total} - C_{heated}$. The solar volume can be derived from this step. The solar volume is the volume of water in a solar storage tank which is not heated by the auxiliary element.

B.5 Isolated UA Fraction

Test Method
This test is used to determine the thermostat deadband and the UA of the solar heated portion of the tank. This test is to be performed indoors, preferably in an environment with nearly constant temperature. Note that this test can be combined test B.1.

a. Charge tank (see 7.1)
b. Disconnect piping connections
c. Allow element to cycle for a minimum of 5 Cycles.
d. Measure the temperature range of the heated portion using an internal tank probe. Measure Q_{aux} and the ambient temperatures during the test period.
e. Test is finished at the end of the fifth cycle.

Analysis
a. Determine the average high and low temperatures from the internal tank temperature data. These are used to determine the water basis thermostat deadband for use with TRNSYS.

b. The deadband information is then used as the basis for comparison to the TRNSYS model. The model would incorporate the measured deadband, setpoints, heater location, nodes as determined from the other tests. The Q_{aux} from the test will be matched to the TRNSYS model to determine $UA_{\text{isolated loss aux}}$.

c. $UA_{isolated\,loss\,solar} = UA_{isolated\,loss\,total}(\text{testB.2}) - UA_{isolated\,loss\,aux}(TestTBD)$. Note that this equation is only valid for a fully mixed tank. If decay loss test 7.1 is used, it is recommended that the simulation be used (with stratification) to back out these values using the same formula. A simplified approach (when internal tank measurements are available) for either test is to determine the solar fraction of the losses from the dimensions of the tank.

d. Iterate on tests the Isolated Loss Aux test and B.5 until all of the parameters are physically reasonable and match the test data.

B.6 Installed Draw Stratification Test

This method is used to determine the draw mixing parameter, which is typically the size or number of the entry nodes.

Test Method
This test is similar to Test 7.3.

Analysis

a. The data from this test will be used to adjust the tank entry node dimension (usually the bottom node) parameter of the tank modeling. The graph of the draw temperature versus time will be used to extrapolate the estimated heated volume of the tank. This will indicate the relative size of the entry node during a heavy draw for the TRNSYS model. For an ICS type of system, this value will be determined from a physical parameter (e.g. number of tanks in series). This value may be affected by the present limitations of the computer model.

B.7 Mantle Heat Exchangers

This method is used to determine the heat exchanger performance parameters. Note that if this is type of a thermosiphon system, this is separate test is not usually required.

Test Method

a. Charge the internal tank to T_{max} temp.
b. Stabilize flow in the mantle HX to within +/- 0.006 l/s (0.1 GPM) and temperature to +/- 0.1° C (0.2° F).
c. Commence data collection on 15 second intervals. The rate of data collection and/or stabilization time should be increased for any flows at or below 0.0315 l/s (0.5 GPM). The data includes the inlet and outlet temperatures, ambient temperature, and the flow rates. Additional temperature measurements may be required for long heat exchangers or heat exchangers used in NCL because of the non-linear nature of the heat transfer. If necessary, this can be accomplished by using three surface probes (if accessible) and two internal probes on the NCL inlet and outlet ports. What tank temperatures should be specified?? or should tank be isothermal??
d. Adjust the temperatures and/or flow rate and proceed to step 1 until the proper number of valid data points has been collected. Adjust tank temperatures and or flow within the tank or tank stratification?? *Use Graham Morrison's methods for this section.*

Analysis

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.

B.8 Warm Up Tests: Low Radiation, Partially Diffuse, Isothermal Start

Test Method

This method is used to determine system operation at conditions between the standard cloudy and clear conditions. Some systems may operate differently than the standard fit due to the quality of radiation received.

Each of these two tests are to be performed on a minimum of 2 cloudy days ($0.2<K_T<0.65$) with ($0.6<G_d/G<0.9$. This is expected to yield a minimum of 2 data points

a. Charge the system (see 7.1) until $T_{initial} = T_{low.}$ T_{low} needs to be low enough [typically 20 ° C (68 ° F)].so that the T_{high} requirement (see 7.5.2) can be met.
b. Expose the collector for 4-5 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.

Analysis

a. The data from this test and from 7.5.1 are combined to form set of 4 data points.
b. Analysis is the same as for the other warmup tests (7.5).

B.9 Warm Up Tests: Low Radiation, Partially Diffuse, Stratified Start

Test Method

This method is used to determine system operation at conditions between the standard cloudy and clear conditions. Some systems may operate differently than the standard fit due to the quality of radiation received.

Each of these two tests is to be performed on a minimum of 2 clear ($0.65<K_T$) days. This is expected to yield a minimum of 2 data points

a. Charge the system (see 7.1) until $T_{initial} = T_{low.}$ T_{low} needs to be low enough [typically 20 ^{o} C (68 ^{o} F)].so that the T_{high} requirement (see 7.5.2) can be met.
b. Energize electric heater for the first hour of the test.
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 $T_{in} = T_{high}$.
d. Check the radiation requirements (see 7.5) to see if further data is required.

Analysis

a. The data from this test and from 7.5.2 are combined to form set of 4 data points.
b. Analysis is the same as for the other warmup tests (7.5).

B.10 Warm Up Tests: Low Radiation, Totally Diffuse, Isothermal Start

Test Method

This method is used to determine system operation for systems sensitive to the sun angle (tubular optics). Some systems may operate differently than the standard fit due to the quality of radiation received.

These tests are to be performed on a minimum of 2 cloudy ($0.2<K_T<0.65$) days with ($0.9<G_d/G$). This is expected to yield a minimum of 2 data points

a. Charge the system (see 7.1) until $T_{initial} = T_{low.}$ T_{low} needs to be low enough [typically 20 ^{o} C (68 ^{o} F)].so that the T_{high} requirement (see 7.5.2) can be met.
b. Expose the collector for 4-5 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.

Analysis

a. The data from this test and from 7.5.2 are combined to form set of 4 data points.
b. Analysis is the same as for the other warmup tests (7.5).

B.11 Warm Up Tests: High Radiation, Transverse IAM specification, Isothermal Start

Test Method

This method is used to determine system operation for systems sensitive to the sun angle (tubular optics). Some systems may operate differently than the standard fit due to the quality of radiation received.

These tests are to be performed on a minimum of 2 clear ($.65<K_T$) days The determination of data points will be based upon the angles with high uncertainty. For angles < 30^{o}, the incidence angles should be within 2% of the nominal incidence angle. These tests assume that the large IAM discrepancies are in the transverse angles. If longitudinal discrepancies are also in question, another test procedure will be required. The irradiation schedule will need to be created to satisfy the following requirements:

a. Minimum Two hour testing period (e.g. minimum angle resolution is 30^{o}).

b. Staggering the testing periods so that different angle ranges are measured in the morning and afternoon.

c. Accounting for the time of year and latitude of the testing site so that the appropriate angles will measured at the appropriate test times.

d. Staggering the testing times on multiple days so that effective resolution from multiple tests can be increased.

e. The weighting of the data as it applies to d.

f. The values for solar noon have already been tested in the primary warm-up test.

This is process is expected to yield a minimum of 2 data points

a. Charge the system (see 7.1) until $T_{initial} = T_{low.}$ T_{low} needs to be low enough [typically 20^{o} C (68^{o} F)].so that the T_{high} requirement (see 7.5.2) can be met.
b. Irradiate for the daily specified solar times, at least 2 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.

Analysis

a. The data from this test and from 7.5.2 are combined to form set of 4 data points.
b. Analysis is the same as for the other warmup tests (7.5).