Integral Passive Solar Water Heaters

David A. Bainbridge

The flat-plate collector water heating system is the predominant type being used today, and most people think immediately of flat-plate collectors when they think of solar heating. But there is an alternative and in many cases better solar water heating system - the integral passive solar water heater.

The integral passive solar water heater (IPSWH) combines solar collection with storage. A typical IPSWH includes one or a series of tanks which are painted black to absorb heat from the sun. They are enclosed in an insulated box and covered with glazing material.

A wide variety of configurations are possible, with differing cost and performance. The performance of a good IPSWH approaches that of a flat plate system. And the IPSWH will usually be more economical, thanks to the much lower construction cost for similar performance. A recent comparison study found the IPSWH to be the most cost effective solar water system even in a cold 6,000 Degree day climate. They do even better in warmer climates.

Currently, most operating IPSWHs are simple home-built systems constructed from inexpensive materials such as recycled electric water heater tanks. In almost every case, the IPSWH heater will be the cheapest solar water heater for homeowners to build and install. They also have good potential for mass marketing in tract houses and/or commercial applications. Activity in this sector has increased dramatically in the last two years.

The first patents on solar water heaters in the U.S. were taken in 1891 for the Climax heater and in 1898 for Frank Walker's system. These early IPSWHs were used widely in California and Florida during the early 1900's and performed well. They gradually disappeared as artificially cheap natural gas became available and was aggressively promoted. Ken Butti and John Perlins describe the early history of Solar Water Heaters in the Fall 1977 issue of Co-Evolution Quarterly.

December 8, 1981

F.A. Brooks tested several IPSWHs in 1936 at the University of California in Berkeley. He demonstrated that they were capable of producing water over 48 C (120 F). He also found that upright tanks placed on an incline deliver hotter water than horizontal tanks. He concluded that IPSWHs were efficient solar energy absorbers and provided solar hot water at a cost consistently below that of a flat plate system. Their one drawback was lower morning temperatures.

Figure 1

Contemporary investigators have improved on Brooks' original heaters by reducing night heat loss. IPSWH designers have placed manual and automatic insulated lids on the heaters. These lids can also reflect additional solar radiation onto the tanks during the day. Horace McCracken wrapped the tanks in transmissive insulation to prevent nighttime heat losses, but this insulation also decreases the daytime collection efficiency. The author, John Burton, Peter Zweig, and several others have used selective surfaces and selective glazings to reduce night heat loss.

Figure 2

Despite their attractive price and performance, IPSWHs have received very little attention in the research and development field. There is currently surprisingly little information describing integral passive solar water heater performance and cost in different climates. There is little doubt, however, that they will play an important role in solar water heating. IPSWHs will surely be the focus for increased activity in the near future, with tremendous potential for commercial kits and installations. Many firms are now approaching large scale production of IPSWHs, up to several hundred units per month. Four major producers are Servomatic, Cornell, SAV, and CCPM. In California, more Servomatic IPSWHs were sold in the first six months of 1981 than any active system.

Figure 3

Five of the many types of integral passive solar water heaters are described in the following section. These include the single tank horizontal IPSWH, the triple tank vertical, the greenhouse IPSWH, the inverted IPSWH, and a super low cost bag heater.

The Single-Tank Integral Passive Solar Water Heater

The single tank heater with lid is often called a breadbox heater (because it looks like a breadbox). It can be constructed using readily available materials and employing simple conventional construction techniques. A standard electrical water heater tank is painted black and enclosed in a well-insulated box. Glass or another glazing material covers the south side and top of the box. Operating lids reduce night cool down to increase performance of the breadbox. Incoming water from the main line enters the breadbox at a low point. The solar heated warm water is drawn from a high point and routed to the existing back-up water heater.

The horizontal tank position provides the lowest performance, but it is easiest to build and less visible than the vertical types of IPSWHs. By using vertical tilted tanks, the stratification of the water in the tank is greater and hotter water is provided.

The Three Tank Vertical Integral Passive Solar Water Heater

The vertical three-tank integral passive solar water heater can also be easily constructed using readily available materials and conventional construction techniques. Three standard glass-lined water heater tanks are painted black or covered with selective surface tape, and enclosed in a well-insulated box. Glass or other glazing material covers the south side of the box. Lids or interior insulated drapes can be installed to increase performance of the heater. The tanks are plumbed in series with the central tank as the final stage.

Figure 4

The tilted vertical position and series operation provide better heating than the horizontal single tank systems. In Davis, California this type of system has provided about 70 percent of yearly hot water demand.

The simplicity, durability and performance of this type of system makes it a good bet for commercial use. The Table below looks at possible costs for a three tank system.

Table 1

A Greenhouse Heater

Better IPSWH performance can be achieved in colder climates by setting up the IPSWH in a protected space, most commonly in a solar greenhouse. Most IPSWH configurations can be used inside a greenhouse. The heater can be placed near the peak of the greenhouse to take advantage of the warmest air temperatures. The water tank of the collector should be painted black or coated with selective surface tape. An insulated enclosure with glazing (and lids) is still necessary.

Upside Down

Another method for reducing night heat loss is turning the heater over. The upside-down heaters seem almost absurd at first - but they have been demonstrated successfully in several areas. Facing the heater glazing down virtually eliminates night sky cooling and enables the heaters to stay much warmer. A reflector or series of reflectors brings the sun to the heater.

A Low Cost ($2) Integral Passive Solar Water Heater

The final system described here was developed by the Minimum Cost Housing Group at McGill University in Canada. It uses off-the-shelf hardware, a garbage bag and PVC pipe and fittings, and can be built by the homeowner with available tools, a wrench and lighted cigarette for welding the plastic. Temperatures of over 100 F were reached with just the exposed bag. When placed in an insulated box with a glass cover, temperatures reached 132 F.

These are only four of the many types and configurations of integral heaters. Evaluation and testing of different systems has only recently begun and is still incomplete. However, any of the systems will work and provide hot water. Build one and let me know how it performs.

Build Your Own Integral Passive Solar Water Heater

The integral passive solar water heater uses a very simple design to heat water. Water flow is provided by routing the cold water intake line through the heater and on to the back-up (natural gas or electric) water heater. The backup heater should be off and bypassed in the summer. The simple system eliminates the need for expensive pumps and/or controls. The heater may serve as a preheater or provide all of the hot water needed. The following list of basic considerations can help you design and install an integral passive solar water heater for your own home or business.

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Design Suggestions for an Integral Passive Solar Water Heater

Find a sunny location for the IPSWH (facing south) preferably close to the back-up water heater (to minimhze pipe run). Make sure it will be exposed to the sun all year. Next, determine how the IPSWH will be installed. Keep in mind that a three tank system, filled with water, weighs approximately 1,000 pounds.

In many houses the heater can be built on the ground. This makes installation easier and also makes shuttering more straightforward (if a shutter is used).

There are numerous other possibilities for placement of the IPSWH. It can be put on a carport, patio, or roof if it is strong enough. If necessary, it can be placed on a special platform, or bracing can be added.

Determine what type and size of integral heater you want Either single Ob multi-tank systems can be used. Figure 30 gallons of capacity per person for maximum performance. However, even a small, undersized system will preheat water and provide economical solar water heating.

Decide what type of tank(s) will be used for the water heater. Tanks come in a wide variety of sizes and shapes. Almost any size and shape will work, but long and thin tanks will work best. This configuration has a greater surface area to water volume ratio, which will improve solar heating. New glass-lined water heater tanks (minus the heating element, insulation and sheet metal cover) can be ordered from several manufacturers. Used water heater tanks can be obtained for little or no charge and stripped down to the bare tank with the heating element taken off. Be sure to test the tanks thoroughly for leaks and rust, and patch them carefully. Replace the sacrificial anode if it is consumed. A new anode costs only $12-$15 and it will add to the longevity of your system.

Other types of tanks, i.e., range boilers, pipe, etc., may also be used, but stainless steel or glass lined tanks are preferable. Acrylic or latex black paint can be used on the outside or for better performance coat the tank with selective surface tape.

Develop the system schematics. Your plan will depend on number of tanks, placement of plugs in tanks, utilization of dip tubes, etc. Remember, draw the warm water from the top of the tanks through the fittings or dip tubes. Include plans to connect to the water main and to return to the back-up water heater. Be sure to include a drain at the bottom of the system for draining the water heater if is is necessary for repairs or for protection from freezing. Tests have shown that it can take 72 hours to freeze a tank at 12 F. The pipes are more sensitive and should be well insulated, and possibly heat taped. Tank protection with a collapsible ball has been successful in tests at NCAT. Also add a pressure/temperature relief valve and vacuum breaker at the top of the system.

Design a support structure for the water heater. The tanks may be placed horizontally, vertically with a reflector, or tilted for maximum heat capture. The tilt for the tanks should be roughly equal to the degrees of latitude where the system will be installed, although some variation is allowable.

Figure 5

Make sure that the box is well sealed and insulated with fiberglass or foam.

There are a number of options for glazing. 1) Single or double pane tempered glass; 2) Tedlar coated fiberglass exterior with Teflon film interior glazing; 3) Acrylic or polycarbonate glazings; and 4) Heat Mirror, at R-3.6, looks promising in tests but may be marred by high stagnation temperatures, or 5) other glazing materials.

In most areas it is advisable to use two panes of glazing material to provide for maximum heat retention. Be sure to caulk and tightly seal the glazing. Davis Alternative Technology Associates suggest that about 2.5 gallons of water per square foot of glazing is a maximum for good heating; less water will speed heating.

Operating lids are optional in the milder climates of the U.S., but essential for year round use where freezing temperatures occur commonly in the winter. The lids should be well-insulated and designed to seal tightly. They may be manually operated or automatically opened and closed using a heat motor, freon transfer system, or mechanical operator. Garage door openers have been used on several IPSWHs.

Reflectors may be used to increase the solar heat gain. Foil, or other material with a shiny surface, can be installed around the water tanks at an angle that will focus additional solar energy on the tanks. A variety of materials can be used to construct reflectors. If operating lids are installed, it is usually simple to make them reflectors as well.

The installation of the integral passive solar water heater is straightforward. Conventional building practices and the common sense employed in other building projects are all that is required.

Below is a partial listing of installation precautions.

Obtain required building permits and approvals.

Be sure that water lines leading from the home to the water heater are well insulated and protected. Use armaflex (and coating) or urethane with aluminum jacket.

When the water heater is installed, it is important to bleed the air out of the system to assure good performance. Use the T & P valve to do this or leave a plug out at the top until the system is full.

If galvanized tanks are used with copper pipe, make sure they are separated properly with dielectric fittings to prevent accelerated corrosion.

Water Heater Maintenance

Excessively high hot water bills often reflect poor maintenance of your existing hot water heater. Four areas of neglect are: 1) Exposing the water heater to the weather or poorly insulating the room in which it is housed; 2) Setting very high water temperature or faulty thermostat control; 3) Failing to insulate tank properly (insulation is easily added); and 4) Buildup of sediment within the tank. It makes good sense to tune-up your water heater even if you don't install a solar water heater.

The Future

Ongoing research and development activity will present many new and different design options for IPSWHs. Currently, the field is wide open for experiments, innovative designers, installers and manufacturers. Developments are needed in ways of increasing the collecting area of the tank as well as in ways of insulating the tank in colder climates. I hope to present results of tests later this

Table 1. IPSWH Manufacturers

CCMP SOLAR 1001 C Prairie Drive Austin, TX 78758 512-836-2066 Contact: Paolo Minissi	Manufacture the SK81 integral heater. A 30 gallon tank in double-glazed box. Selective surface tank. A very good buy for arond $600. A useful owners manual is included.
Sharpe Solar 4300 Easton Drive, Suite 4 Bakersfield, CA 93309 805-325-4220 Contact: Charles Sharpe	Manufacture the MagicBox integral heater. Sixty gallon heater, double-glazed, with selective surface on second tank.
Solar Components Corporation P.O. Box 237 Manchester, NH 03105 603-668-8186	Manufacture the Sun-Lite Water Heater with two 30-gallon lined steel tanks in an insulated metal framed case, double glazed. Freeze protection device available. $995 FOB
Sun Miner Corporation 1850 W. Grant Road, Suite 101 Tucson, AZ 85705 602-623-5486	Manufacture the SM1000 integral heater. One glass lined 30-gallon tank in R-16 insulated box. Uses low iron glass. $995 retail.
Hasco Solar 214-222 14th Ave. Bayside, NY 11360	Manufacture the Thermosol heater. A 35-gallon heater with serpentine flow under a double glazed dorm covering.
Western States Energy Management Marketing Systems P.O. Box 2005 Kirkland, WA 98033	Manufactures a post mounted integral water heater with reflector. $2 for information packet.

Note: Rapidly changing market; there may be others I have missed, and some of these may be out of business now.

December 9, 1981 David A. Bainbridge

PLANS (p&h: postage and handling)

Integral Design 4708 Raley Blvd Sacramento, CA 95838	$15; horizontal and vertical two-tank designs $5, onetank design.
Zomeworks Box 712 Albuquerque, NM 87103	$5 + $1 p&h; one tank vertical two tank with lids
Ted Lucas 10371 Stone River Court Fountain Valley, CA 92708	$5; horizontal tank with reflector lining
The Crystal City Collector Center for Maximum Potential Building Systems 8604 Webberville Rd. Austin, TX 78729	$5.50; one tank with reflector underneath
Solstice Publications Box 2043 Evergreen, CO 80439	$22 + $1.50 p&h
Union Electric-Solar Preheater P.O. Box 149 St. Louis, MO 63166	free; two tanks with reflector behind
Horace McKracken How to Build a Passive Solar Water Heater 329 W. Carlos Alturas, CA 96101	$6; Horizontal system with one or more tanks
John Golder Solar Capsule Water Heater P.O. Box 854 Santa Cruz, CA 94061	One-tank $6 horizontal
TVA SUNBOX TVA Office of Power Division of Energy Conservation Chattanooga, Tennessee 37104	free

Plans, continued

Farallones Institute $1
15290 Coleman Valley Rd.
Occidental, CA 95465

NCAT -- Booklet with Plans free
Box 3838
Butte, MT 59702

Published Plans:

Frederic Langa (1980) "Sun on Tap: Pure and Simple," New Shelter, vol. 1, no. 7, October.

Bonnie Speer (1981) "Build a Solar Water Preheater," Handyman, January.

VICTOR ATIYEH
GOVERNOR

Department of Energy

LABOR & INDUSTRIES BUILDING, ROOM 102, SALEM, OREGON 97310 PHONE 378-4040

January 14, 1982

David A. Bainbridge
1625 Curtis Street
Berkeley, CA 94702

Dear David:

Thank you for sending me some of your information on IPSWHs. As you may know, the Oregon Department of Energy must certify solar systems on the basis of predicted energy yield, which has caused us to cast about for predictive techniques for IPSWH's. This type of solar is enjoying some commercial success here and there is considerable pressure from manufacturers for someone to define a simple predictive test. In addition, the Bonneville Power Administration (BPA) is in a position to subsidize the installation solar DHN systems, but is reluctant to recognize IPSWH's without credible engineering test results.

On the national level the need for good testing of IPSWH has been rcognized by SRCC (Solar Rating and Certification Corporation) which has recommended use of the ASHRAE 95 test for this type unit. While the SRCC test will give good comparative results, it has not been specified how to translate these results from the test conditions to a particular segment of the real world.

So in concert with all the above, we have devised (and tested) a reasonably simple test and associated analytical techniques for predicting IPSWH performance, which I have enclosed for your review. BPA is also reviewing this proceedure as an interim means of including this type of DHW in their program. Please don't be put off by the visual complexity of this proceedure; it is basically very simple and getting simpler. So far we have examined several different types of units. In one case there was an ASHRAE 93-77 test for a unit we tested, which led to the remarkable result that for a "classical IPSWH (one without night covers), the coefficients derived from the ASHRAE 93-77 test can be used to predict system performance if the T used is (Tinlet water -- Tambient). The tests we have been conducting use a draw pattern representative of an average "dull witted" family, and the system performance could be improved by a more conscious hot water use, but these results are intended to be conservative enough for utility acceptance.

I would appreciate it if you could review this proceedure and let me know how it looks to you. Any questions or comments -- my number is 503-378-5263.

Sincerely,

Howdy Reichmuth, Renewable Resource
Specialist
Renewable Resources Division

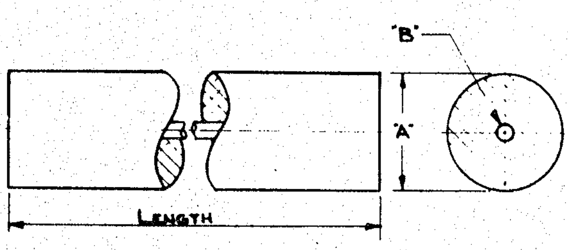
HR:kgg/8970B

KAISER MAGNESIUM

MAGNESIUM
EXTRUDED
ANODES

SECTION 1-6
EFFECTIVE 4-1-71
Supersedes Sec. 5 pg. 2, 10-1-70

ROD
PRODUCT DATA & AVAILABILITY



Core Wire located within 1/16" of center of Rod.

A Dia. Inches	B Wire Core Size[1]	Weight Per Foot Pounds
2.012	10 ga (1)	2.50
1.561	10 ga	1.50
1.315	10 ga	1.06
1.050	10 ga	.68
.840	10 ga	.45
.750	10 ga	.36

.675

(1) ¼" dia black annealed wire available on request

Spectrographic Chemical Analysis

Aluminum	2.5 — 3.5%	Copper (Maximum)	0.040%
Zinc	0.7 — 1.3%	Iron (Maximum)	0.002%
Manganese (Minimum)	0.200%	Nickel (Maximum)	0.001%
Silicon (Maximum)	0.050%	Total Other Impurities (Max.)	0.300%

Delivery: 2 to 3 weeks A.R.O.
Packing: Cut to length—12" through 25' banded bundles.

INTERIM PROCEDURE FOR ESTIMATING THE YEARLY SOLAR YIELD FOR INTEGRAL (BATCH) SOLAR WATER HEATERS OR THERMOSYPHON WATER HEATING SYSTEMS AT OREGON (OR ARBITRARY) SITES

1. This test and analysis procedure was developed to provide an interim capability to estimate the solar yield of batch type and thermosyphon type solar domestic hot water heating systems. These types of solar DHW systems have significant night heat losses and unknown fluid flow rates which are not consistently measured and which cannot be adequately accounted for in existing solar DHW system simulations (such as F chart).

2. An integral solar water heater for these purposes is one where the thermal storage is acting as the solar absorber (tank in a box) and this thermal storage is exposed to night conditions in the same manner as day conditions. In the case of the thermosyphon, unit exposure to night conditions will be different than to day conditions.

3. Use of this procedure requires that thermal performance tests on a full DHW system be done as follows:

   a. A DHW systems thermal performance test according to ASHRAE 95-81S~~##~~ by an accredited laboratory using SRCC rating conditions, or

   b. A system thermal performance test of 10 days duration be performed as in attachment 1, and

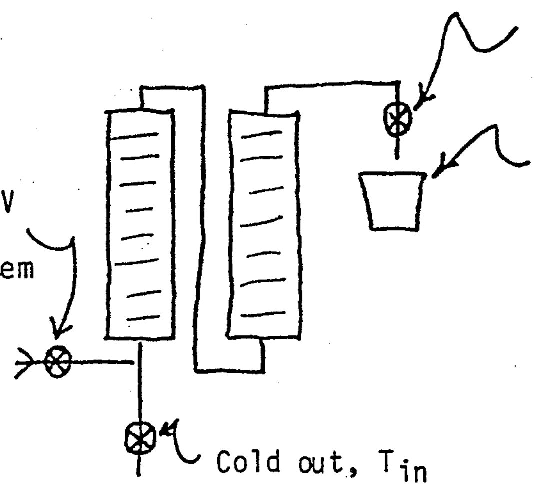
   c. A collector cool down test on a single collection unit be performed as in attachment 2.

4. The results of the thermal performance tests will be used to compute the system annual yield per gross square foot of aperture, which in turn will be used to determine the minumum system size required for Oregon tax credit eligibility. The computations of system annual yield will be carried out as described in attachment 3.

5. One-of-a-kind systems or systems built into a residence for which a prototype cannot be tested prior to installation, will be assigned heat loss and optical efficiency factors by ODOE staff from inspection of plans in lieu of the thermal tests in #3 above. These factors will be used to compute the system's annual yield as in #4 above.

ATTACHMENT #1
10-day Test for Thermal Performance

1. System should be set up for test as in the diagram:



Where:

T_{in} is the temperature* of the inlet water

T_{out} is the temperature* of the water out (measured with same thermometer as Tin)

$T_{ambient}$ is the air temperature* in the shade at the aperture

Solar Is the total solar intensity measured in the plane of the aperture by an integrating pyranometer equivalent to LICOR 200S or better.

*temperatures should be measured by a thermometer with an accuracy of $\pm$ 3^{o}F or better

2. The test is run continuously for 10 days as follows for each day:

   a. at 8 a.m. draw 30 gallons of hot water into the measuring container, stir and note the temperature. Note ambient temperature.

   b. at 12 p.m. draw 10 gallons of hot water into the measuring container, stir and note the temperature. Draw 2 gallons of cold water into the measuring container, stir and note temperature using same thermometer as that was used to measure the hot water. Note ambient temperature.

   c. at 5 p.m. draw 25 gallons of hot water into the measuring container, stir, and note temperature. Note ambient temperature.

   d. after sundown note the total solar for the day.

3. The last draw on the last day of the test will be at 8 a.m. on day 11. After this draw, drain each unit in the array in 5 gallon intervals, noting the temperature of each interval.

4. Assemble data each day on a form as follows:

Day __1__ Solar _____ Btu/ft^2day T_{in} _____ ^oF

Time	T_{out} ^oF	$T_{ambient}$ ^oF
8 a.m.	______	______
12 p.m.	______	______
4 p.m.	______	______

Day __2__ Solar _____ Btu/ft^2day T_{in} _____ ^oF

etc.

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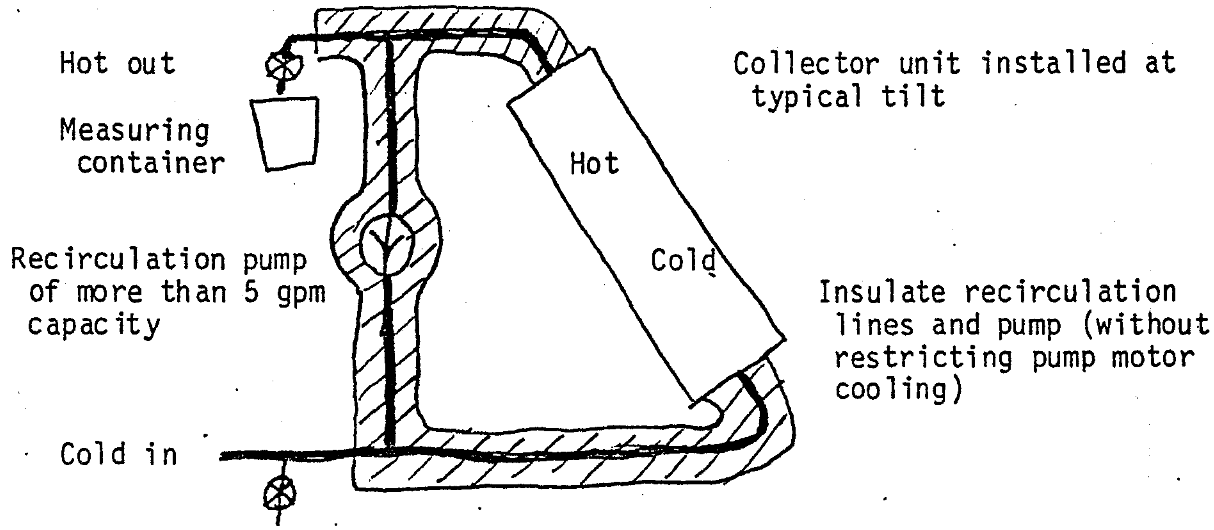
ATTACHMENT #2
Collector Cool Down Test

1. Collector should be set up for test as in the diagram:



2. Starting at sunset the test is conducted as follows:

   a. allow the collector to heat itself to 40-60°F above ambient during the day or fill the collector with hot water.

   b. depending on the volume of the tank and capacity of the pump, run the pump long enough to circulate the tank volume once.

   c. withdraw ½-gallon from hot outlet of the tank into the measuring container, noting the temperature of the hot water, the ambient temperature and the time. Repeat every two hours for 10 hours.

   d. withdraw ½-gallon of cold inlet water into measuring container and note temperature. This measurement of the inlet water temperature is used to make a correction for the temperature measurements which involve withdrawing hot water.

   e. Mix water with pump at end of test and repeat c.

3. Assemble the data as follows:

Inlet Water Temperature _____ °F

Time	Water Temp °F	Ambient Temp °F
______	______	______
______	______	______
______	______	______
______	______	______
______	______	______

ATTACHMENT #3

Method For Estimating Annual Yield From A Thermal Performance Test And A Cool Down Test

1. This method is a first order approximation based on the following simplifications and assumptions:

   a. the daily draw is approximately equal to the storage of the system.

   b. The heat removal factor $F_r = 1$. This assumption greatly simplifies the equations. It is recognized that in the real world heat transfer requirements will cause the aperture to be at a higher temperature than the heated fluid during solar input. This effect will be accounted for in the collection efficiency E_c derived from the thermal performance data. This method essentially ratios actual thermal performance data from the test solar/weather conditions to other solar/weather using the same E_c for both cases. Though there may be some absolute errors in E_c introduced by using it to catch the system optical and heat transfer efficiencies, it is assumed here the E_c so derived will be sufficiently accurate to develop a servicable ratio from the test to arbitrary conditions.

2. The system thermal performance over a full diurnal interval where there is an insignificant storage residual (as in an ASHRAE 95 series test with convergence or in the average daily performance from a long term performance test) can be described to a first order by an energy balance for the interval as follows:

$$Q_s E_c = M\Delta t + L_d U_d \left(T_{in} + f_d \Delta t - T_d\right) + L_n U_n \left(T_{in} + f_n \Delta t - T_n\right) \quad (1)$$

Where the energy balance interval has been normalized to one day and one square foot of gross aperture and,

Q_s = average incident solar on the aperture plane Btu/ft^{2}day

E_c = collection parameter no units 0 E_c 1

Δt = average temperature increase $T_{draw} - T_{in}$, ^oF

Q_{out} = average useful thermal output Btu/ft^{2}day...(If 10-day test is used this includes the storage residual)

L_d = effective day length, hours

U_d = aperture heat loss during solar input, Btu/ft^{2}hr^{o}F. This is estimated from inspection of glazing, aborber and insulation for thermosyphon units (this should be the same as F_rU_l from the ASHRAE 93-77 test of a similar collection surface). For Batch heaters it is equal to U_n as measured in attachment 2.

L_n = effective night length, hours

U_n = aperture night heat loss, Btu/ft^{2}hr^{o}F (measured as in attachement 2, note for Batch heaters of the tank in a box variety $U_n = U_d$.

T_{in} = average temperature of cold inlet water ^oF

T_d = average day temperature during interval ^oF

T_n = average night temperature during interval ^oF

M = thermal mass flow Btu/^{o}F day/ft^2 gross aperture

f_n, f_d = draw pattern factors these relate the average draw fluid temperature during the day, f_d, or night, f_n, to the draw temperature. These factors are given in the table below for the best and worst case draw patterns.

	f_d	f_n
Best case - all draw during day	.5	0
Worst case - all draw the following morning	.5	1

Test results on individual Batch solar heaters by several researchers have yielded a good linear relationship between collection efficiency and the parameter $\Delta t/I$. It is importanat to recognize in these tests that Δt was generally measured directly as the average of several temperature sensors directly mounted on the surface of the tank less ambient temperature. This contrasts with the definition of Δt as used in the ASHRAE 93-77 test or the common Hottel-Whillier-Bliss equation where Δt is the difference between the inlet fluid temperature and the ambient. This prior research has shown that the essential energy balance relationship of the H-W-B equation can be applied to batch systems if care is taken in the definition of Δt and its associated parameter, the heat removal factor f_r.

This proposed test and modeling procedure uses the full day/night cycle as the heat balance interval (rather than instantaneous) in order to include the full effect of the night heat loss.

A modified heat removal parameter f has been introduced with the essential function of accounting for variations in the absorber temperature from point to point on the absorber and with time in order to account for variation in water use patterns. Conceptually, this parameter can be seen as follows: every unit of water withdrawn from the batch heater emerging at a temperature $T_{in} + \Delta t$, will have an "average detention temperature = $T_{in} + f\Delta t$"

During the past day that unit of water was in the process of being heated to $T_{in} + \Delta t$ and was generally at a temperature $T_{in} + \Delta t^1$ lower than $T_{in} + \Delta t$. f is then the ratio

$$f = \frac{\int_{\text{time}}^{24 \text{ hrs.}} \Delta T^1 (t)\, dt}{24 \Delta t}$$

For the case where the daily draw is approximately equal to the storage, the average absorber temperature is $T_{in} + f\Delta t$, where Δt = average draw temp. - T_{in}. In general it is very difficult to estimate f accurately but this will not seriously compromise this method because a) the best and worst case values for f can be reasonably identified with the real f lying in between and b) the form an use of the energy balance equation (eq.2) is resonably insensitive to variations in f for the case where the draw pattern is the same at the test and candidate sites and the heat losses of the unit are low as is typical in most batch heaters.

To establish the best case draw pattern factor assume a full storage draw at the end of the day and that storage heats uniformly. The daily average absorber temperature cannot be less than $T_{in} + \Delta t/2$, and the night absorber temperature will be not more than T_{in} so that fd = .5 and fn = 0. The estimate of the worst case is made by assuming that the full draw takes place at the end of night so that the absorber has been at a temperature of $T_{in} + \Delta t$ (or slightly higher) all night, hence Fn = 1 and during the day the absorber was at an average temperature greater than $T_{in} + \Delta t/2$ and probably lower than $T_{in} + \Delta t$. A good performance case is assumed here and fd = .5. For the SRCC test draw, (30 gallons at 8 a.m., 10 gallons at 12 p.m., 25 gallons at 5 p.m.) and total daily draw approximately equal to storage, the effect of the draw pattern is assumed to be the mean of the best and worst cases.

For cases where the draw is considerably less than storage f should be closer to the worst case f and for cases where draw is greater than storage f should be closer to best case f.

3. Equation (1) is solved for Δt then Q_{out} = M t. Equation (2) results giving Q_{out} as a function of environmental and system parameters. E_c is the only parameter on the right side of equation (2) that is unknown and it is derived from the thermal performance and cool down test data for the experimental case where Q_{out} and U_d, U_n are reasonably known.

$$Q_{out} = \frac{M}{M + X}\left[E_c Q_s - L_d U_d (T_{in} - T_d) - L_n U_n (T_{in} - T_n)\right] \qquad (2)$$

Where

$$X = f_d + f_n$$

$$X = .5L_d U_d + .5L_n U_n$$

(the parameter X is dependent on the draw pattern factors and is here averaged for the best and worst case -- best case X would be $.5L_dU_d$ and worst case would be $.5L_dU_d + L_nU_n$)

Note here that the parameter X varies from month to month through the day and night length L_d and L_n. This seasonal variation can be removed by assuming that $L_d = L_n = 12$ hrs to give equation (3).

$$Q_{out} = \frac{M}{M + 6U_d + 6U_n}\left[E_c Q_s - 12U_d (T_{in} - T_d) - 12U_n (T_{in} - T_n)\right] \qquad (3)$$

4. Equation (3) is used as follows to give an approximation of the yearly system yield:

   a. Q_{out}, U_d, U_n, T_{in}, T_d, T_n and Q_s are derived from the system thermal performance and cool down test, as follows:

From cool down test

$$U_n = \frac{\text{(water temp begin - water temp end) x storage mass (lbs.)}}{\text{elapsed time x gross aperture x (aver. water temp - aver. ambient temp)}}$$

(This is a linear approximation of the cooling curve -- in extreme cases an exponential fit could be used.)

From 10-day test

U_d = derived by inspection for thermosyphon or = U_n for batch

$T_{in} = \overline{T}_{in}$

$$T_d = \frac{1}{n}\sum_{n=1}^{10} \frac{T^a_8 + T^a_{12} + T^a_5}{3}$$

where T^a_8 T^a_{12} T^a_5 are the ambient temperatures at 8:00, 12:00, and 5:00.

$$T_n = \frac{1}{n}\sum_{n=1}^{10} \frac{T_5^a + T_8^a}{2}$$

$$Q_s = \frac{1}{n}\sum_{n=1}^{10} Q_{s,n}$$ where $Q_{s,n}$ is the total daily solar on day n

$$Q_{out} = \left[\left(\frac{1}{n}\sum_{n=1}^{10} \frac{T_8^0 + T_{12}^0 + T_5^0}{3}\right) - \frac{1}{n}\sum_{n=1}^{10} T_n^i\right] \times M + \text{residual } Q$$

where T_8^0, T_{12}^0 T_5^0 are the average draw temperatures at 8:00, 12:00, 5:00 and T_n^i is the inlet temperature on day n and,

$$\text{residual } Q = \left(\frac{\text{system storage gallon} \times 8.33}{\text{gross aperture}}\right) \cdot \left(\overline{T}_{drain} - \overline{T}_{in}\right)$$

where $\overline{T}_{drain}$ is the average temperature of the storage at drain out.

b. Equation (3) is used to solve for E_c.

c. Monthly system yields are then estimated using E_c by inputting the monthly values for Q_s, T_d, T_n, T_{in} with the sum of the monthly yields bing the yearly yield estimate.

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