A solar water heater that has stood the test of time

Buying an off-the-shelf solar water heater is certainly the easiest way to get one, but if you have the skill, making one can be a cheaper alternative. Lindsey Roke describes his impressive system

When I was studying for my engineering degree in the early '60s, solar heating of domestic hot water was a new technology catching people's imagination. When my prospective father-in-law was building a house, he was looking at installing a solar water heater and obtained a couple of publications put out by the DSIR (the New Zealand equivalent of CSIRO). So when, in my final year of study, we had to do a presentation, I picked solar water heating (it pays to keep in with your prospective father-in-law!).

While he never did install a solar heater, I was hooked on the subject as well as on his daughter. Seven years later when we designed and built our own home, it was time to build my own solar water heater.

As you will see by the glorious mix of units, this was the time when New Zealand was going metric. The first units are those I specified. Those in brackets are the metric conversion for those who are not bilingual.

Almost 30 years old and still working! A well made home-built solar water heater can last as long as a commercial product.

No freezing

Where we live in Auckland at latitude 37° south, the temperature rarely hits 30°C. Frosts (at least where we live, beside a tidal estuary) are rare and light. Indeed over the last few years, since global warming has really started to kick in, our banana palms have survived without being burned off by winter frosts.

In this climate, freezing of water pipes is not a problem (even though we occasionally get frost on the glass of the solar heater).

I'm a firm believer in the KISS principle (Keep It Simple, Stupid) so, with no freezing to contend with, I was able to avoid much of the complexity that is often associated with water heaters. I avoided secondary circuits with the attendant valves and double-walled heat exchangers, pumps, a second hot water tank to preheat the main cylinder, and roof penetrations and loads.

At the time we built our house, the usual hot water system in New Zealand was a 30 imperial gallon (140 litre) copper cylinder with about 2" (50mm) of cotton flock insulation. These are normally designed to operate at a 25' water head (75kPa) pressure. Forty foot head (120kPa) cylinders were also quite common. Where the water supply pressure is greater than this, a pressure reducing valve supplies the cylinder. Either a vent pipe 25 feet high or a pressure relief valve is standard.

To prevent scolding, regulations for new installations now also require a tempering valve to be fitted to the outlet of the cylinder. This is a thermostatic mixing valve that adds cold water to the hot water coming from the cylinder to give a maximum downstream temperature of 55°C, whatever the cylinder water temperature.

Cylinder set-up

When we built the house, I specified a somewhat different main hot water cylinder (we also have a very small electrically heated cylinder under the kitchen sink).

The main cylinder is a 70 gallon (320 litre), 40' head cylinder. It has the element and thermostat positioned '20 gallons' (90 litres) up from the bottom of the cylinder. I had two 1" (25mm) wetback stove connections put on the side. One is just below the element and the other is at the bottom of the side. The solar heater is connected to these and heats the water at the bottom until it is up to the temperature of the water above it. Then the convection process in the cylinder adds the next layer to the water being heated.

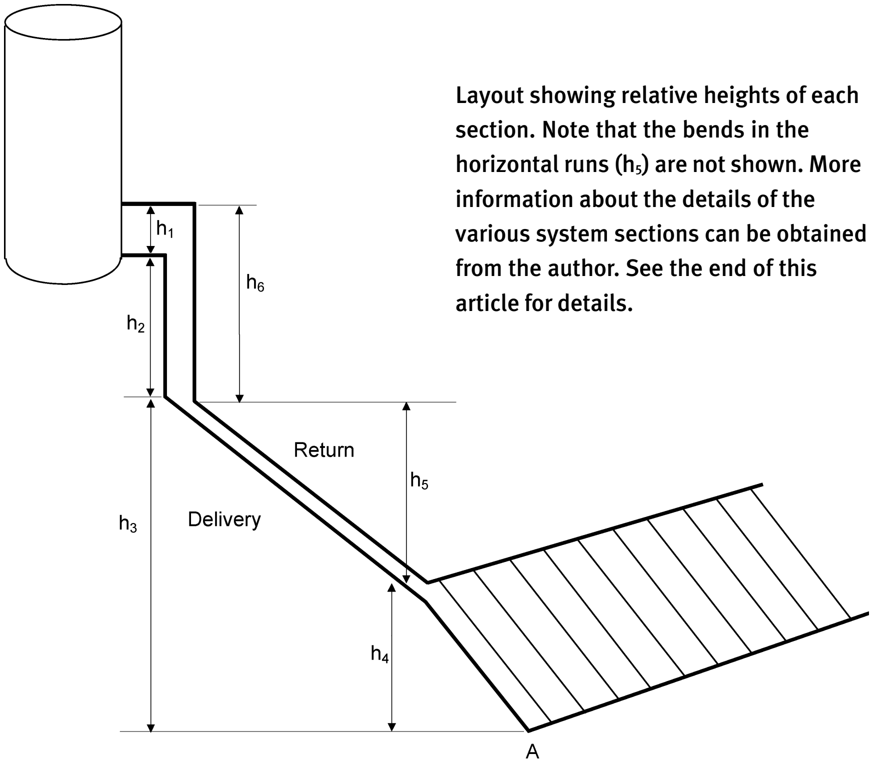
This set-up has a number of advantages:

• When the sun is shining, the water keeps being heated until we need it. It doesn't get transferred to a second cylinder where it would either cool down or have to be maintained by some other means. This is one of the problems with connecting the solar heater to a pre-heating cylinder feeding the main cylinder. Thus, when we come home from our summer holiday we get hot water out of our taps without either having to dump a cylinder of cold water or heat it with electricity.

• There is one cylinder rather than two to lose heat from.

• The water layers better (mixes less with the hotter water above) in a vertical cylinder than it does in a horizontal one.

• The 40' head option allows higher hot water pressure for showers et cetera. I had thought we might need this for when the cylinder is relatively cool and providing almost the total shower flow, then we would still have an adequate flow. In practice, the flow restrictor in the showerhead is screwed in reasonably well and a 25' head cylinder would probably have been fine.



Layout showing relative heights of each section. Note that the bends in the horizontal runs (h_5) are not shown. More information about the details of the various system sections can be obtained from the author. See the end of this article for details.

Lindsey is happy about how little electricity his hot water systems uses for boosting.

Collector and pipework

All the pipework is copper. In New Zealand domestic copper pipe is specified by its inside diameter (ID). Thus 1" pipe has an ID of 1". Normal household reticulation is ½" (12.7mm). With metrication actual sizes have not changed. They are simply called 12mm et cetera.

The runs to and from the solar heater are in 1" domestic copper pipe. All permanent joints are silfossed—silfos is the normal phosphorous-copper-silver alloy used for brazing copper to copper. There are a few joints that are designed to be dismantled, such as around the isolating valves on the cylinder. These are made with standard crox fittings. Crox fittings are compression fittings that seal on a rib formed around the tube with a special hand tool.

The collector itself faces slightly west of true north. It is a horizontal ladder configuration made of copper refrigeration pipe. This pipe is specified by the outside diameter (OD). The two long runs of the ladder are 1" OD copper while the 'rungs' are ½" OD. There were a couple of reasons for this decision. Because the refrigeration pipe has a slightly smaller OD and a thinner wall, it is less expensive. The panel is well supported so does not need the extra strength of the thicker walls. Also the ½" OD of the rungs made life simpler when finding something to form the fins around (as described later). The 1" OD refrigeration tube slides neatly into the 1" ID domestic copper tube for silfossing.

Various reports of solar heaters not working illustrated that air-locking could defeat thermo-siphoning. This is a consequence of either slipshod installation or designs where the requirements were not fully understood.

Our 'horizontal' runs are carefully arranged so that there is a one in 100 fall from the cylinder to the far end of the collector. This is true both in the runs to and from the collector and in the two long sides of the collector itself. I fitted a drain valve at the lowest point (the bottom of the collector at the far end).

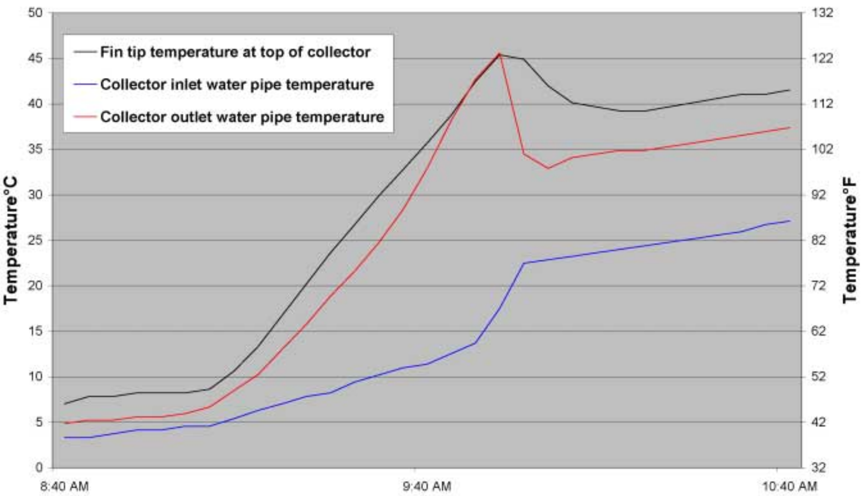
A press was used to form the channels in the aluminium fins.

Insulation

One can buy various types and configurations of insulation for pipes. Because solar heater pipes operate above ambient temperature it is not necessary to hermetically seal the outside to prevent water vapour ingress, but it is necessary to keep the weather out.

The insulation I chose was fibreglass preformed for 25mm OD pipe. It has an overall diameter of 75mm and came in 1 metre lengths. This is supplied cut almost in half lengthwise and is designed to be fitted around a single pipe. I ran my two pipes, (over and under) with about 10mm clearance between them. I split the fibreglass into two separate pieces. I put one piece on top of the top pipe and the other under the bottom pipe. I then filled the gaps between them with fibreglass ceiling insulation.

Inside, I held this all in place with either of two methods. Where the pipe was up against a floor joist, I used a few sheet-metal straps about 10mm wide. I used two for each length of insulation. Where the pipes were in free space I used string binding. Outside, as well as the string binding, I wrapped the fibreglass with old calico sheeting. I stuck the sheeting lap down with a neoprene contact adhesive. I painted over all this cotton covering with Fosters Sealfas 30-36.



Water and collector temperatures during the first two hours of heating on a typical day.

The steel collector casing and the collector fins were made from scrap or offcuts from work. The collector case is made from reject ends of coils of zinc coated pre-paint steel originally bought to make refrigerator wrappers. Now, 28 years later, it is beginning to show some signs of rust in a few places and will need some attention soon.

Collector details

The collector 'ladder' itself is 3.6m long and has 24 'rungs' (risers) 1m long spaced at 150mm. It was made by simply silfossing the rungs into the long members

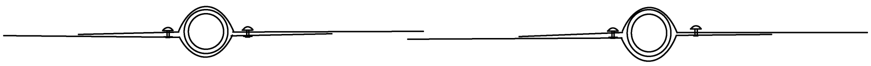


Figure 1. Fitting the fins around the collector pipes. Lithium grease is used to reduce corrosion and help transfer heat.

(header pipes). I drilled both long members with a drill a little under the ID size of the tube. I then belled the tube out lightly around each hole with a suitable pry tool. Because of the strength and gap-filling ability of silfos, all that is necessary is to get enough shape to support—as an assembly aid—the end of the ½" tube. I laid out the pipework on the concrete workshop floor, starting from one end and keeping everything lined up with a rafter square. As I progressed the long tubes tended to banana outwards but it was not difficult to pull the ends together as I went.

I used 150mm wide aluminium sheet offcuts for the collector surface. First I formed a ½" semicircular groove in them. Then I coated the inside of the formed groove where it would mate with the tube with lithium-based grease. Next I pop-riveted a pair around each tube (see Figure 1). The logic of using aluminium rather than copper is that it is a better thermal conductor per dollar—even if, unlike mine, it isn't free!

The logic of fin rather than continuous sheet construction is that heat does not need to flow between rungs. Indeed, halfway between rungs can be regarded as a 'thermal watershed'. The closer to the tube, the more heat that has to be conducted, hence the use of two layers closer to the pipe. The use of fins rather than continuous sheet also solved any problems that might have otherwise arisen due to differential expansion between the collector surface and the tubes.

The lithium-based grease is normally used in large copper/aluminium crimped power cable joints to prevent corrosion. Logic says that it will do the same in a solar collector. It will also conduct heat from the aluminium to the copper. While the lithium-based grease is certainly not fit for human consumption, should a leak occur, the water will come out rather than the grease go in.

Once I had assembled the collector, and checked its fit on its mounts in the collector casing, I suspended it upside-down and 'painted' it with soot using an air/acetylene paint-burning torch with the air holes nearly all blocked off.

Subsequently, when I've needed to re-coat areas, I have found it harder, but not impossible, to make the sooty flame blow down onto the collector. I have needed to do this when the collector was rained on after the outer glass sheet was broken.

The advantages of soot is that it is a completely non-selective black. It absorbs superbly but when it gets hot it also re-radiates superbly. Thus, when the water is cold, the collector catches all the energy that is thrown at it but when it is hot, it self-limits. Thus, even when we have been away on holiday for three weeks over the summer, the water will not be boiling when we come home.

The glass cover used was the biggest size of agricultural glass available, normally used for horticultural glasshouses. It is clipped onto standard aluminium glasshouse extrusion and seals reasonably well against the standard flexible plastic insert in that extrusion. Apart from being relatively inexpensive and quick and easy to install, it has the advantage of being very easy to take sheets off.

What I would do differently next time

Cylinder modifications and location

After three days of normal hot water usage with no sunshine, it is necessary to turn the power on if we want hot water. As originally configured, the element heated the whole 50 gallons (230 litres) in the cylinder from just above the top solar heater connection. It does this even if we only want one shower. If the following day turns out to be sunny, this is rather a waste of electricity. It also takes a while, even with a 3kW element.

The first modification was to take the cylinder out and cut in a second element and thermostat '20 gallons' (90 litres) from the top. This heats the top section (and only this top section) from cold in 20 minutes. We now never use the bottom element and so it could be left out unless I were in an area with a very intermittent supply of electricity.

While we had the cylinder out, I took

Pipe-work and fin expansion

From 0°C to 80°C the pipe runs and collector together (a total length of 12m) will expand by 16mm. The collector itself will get longer by 4.9mm. It will get wider by 1.36mm. The coefficient of expansion of aluminium is 23×10^{-6}/K. That of copper is 17×10^{-6}/K. Added to that, the fins experience a slightly greater temperature swing than do the tubes. Thus, expansion has to be taken into account.

The runs from the cylinder have three right-angle corners and so are free to expand. (Had they been straight, they would have needed some way of expanding such as the inclusion of a horizontal 'U'). I mounted the collector rigidly at only one point. This is at the top corner where the water returns to the cylinder. At all the other nine points I suspended it in wire 'swings'. This lets the collector grow or shrink in any direction. The fins can also slide up and down the tubing and were deliberately made not quite full length.

the opportunity to remove all the cotton flock insulation and re-insulate it with polyurethane foam. To resist the 5psi (35kPa) foaming pressure, we pressurised the internal cylinder with air. We provided external support to the flat ends of the case only. The sides had enough hoop strength to support themselves.

With cylinders insulated this well, there is no warming in the cupboard. To save space, it could have been mounted above the ceiling. Incidentally, this would have also given a better thermosiphon head differential to recirculate the water faster. The temperature plot shows quite a wide difference between flow and return temperatures and a higher recirculation rate could improve collection efficiency.

Lagging of the pipes

I had assumed that the old cotton sheeting around the insulation on the pipes outside was virtually redundant once the Fosters coating had been applied. I was wrong as this cotton covering developed splits. I have now replaced the covering with old fibreglass curtaining. It is surviving well though it will still need recoating with Fosters from time to time.

Coating of the collector

I would seriously consider coating the collector with high temperature matt black paint such as is used for spraying engine manifolds, as it would probably be more durable.

If rain gets in when a sheet of glass is broken or moves out of place, the soot tends to wash off. I plan to do a comparative heat emissivity test on two pieces of aluminium in the sun, one with paint and the other with soot. If the paint performs better, I will paint one panel of the heater and see how the paint stands up over time. If it passes that test I will use paint rather than soot when re-coating is required.

Durability

The timber for the support frame was purchased from one of my colleagues who had it left over after building a house. This frame is showing some deterioration. I would make sure that the timber (appropriately treated if necessary) was more appropriate for outdoor use.

Tilt angle

The original logic was that the collector tilt angle would be set up for midsummer. Reflector panels were fitted to the deck balustrade behind (when the grape vine was bare) for the winter half of the year. The combined angle was approximately optimised for midwinter. In practice, the reflectivity of the aluminised plastic surfacing of the reflectors degraded quite quickly. Also, at the end of the day the sun was mainly reflected past the ends of the collector.

Putting these reflectors up and taking them down was a hassle. They have been retired. If I had realised I was not going to use a reflector, I would have set the collector at a steeper angle, probably optimised towards the middle of winter.

Service valves

The 1” gate valves and the ½” drain valves have only ever been used once. I should have omitted them (the KISS principle) and used crox nipples instead of the gate valves and a ½” crox plug instead of the ½” ball valve.

Vegetation

Trees do grow. A lemon tree should have been planted further away. Other trees have been cut back.

30 years of hot water

Even with the low price of electricity in New Zealand (now about NZ$0.17 per kWh) the system has paid for itself several times over. Given the opportunity I'd certainly do it again!

Creating the semi-circular form in the fins

While there would be a variety of ways of forming these—such as using a vibrosheer or a press brake—let me describe the method I used.

I scrounged the bottom half of an old steel die-set from work (a die-set is the standard top and bottom parts of a press tool. It is used to support the punches and form blocks etc that a toolmaker fits to it to create a press tool for producing metal components). I welded appropriate bits of scrap steel onto this bottom half to form the male half of the semicircular form for pressing into the flat sheet. The semicircular form for the section was 12.7mm (½”) diameter rod. Because the tool would not do a full length form in one hit, I had to make it so I could form the shape progressively.

I ground the bottom of the 12.7mm rod away tapering from a grind up to the centre line at the end to nothing ground off about 150mm in (in other words, there is a 150mm long taper on one end but which only goes halfway through the thickness of the rod). I then bent the rod slightly where the grinding ended. Then, when I'd welded the rod to the die set between two 6.3mm (¼”) packers, the form went from nothing above the packers at the end to full semicircular depth over 150mm.

For the top half, I used a short section of a small 'I' beam. I welded two strips of steel to the bottom of this to come down on the horizontal part of the section. (I did not bother providing a female form across the top of the curve.) As I intended to mount this in a fly press, I turned down an old pipe socket to the right diameter to fit into the top clamp of the press. I welded this to the top of the 'I' section. I also organised some crude guides so that the top and bottom halves stayed lined up. Note that a typical workshop hydraulic press could do the job that the fly press did.

North-south and east-west

As an aside, when considering a northern hemisphere house plan for the southern hemisphere (or vice versa) don't turn the plan around through 180°, flip it over. While north and south orientations 'swap' east and west do not. As can be seen from the overview photo, the solar heater is cantilevered off the deck. I had originally planned to fit it above the garage door to the left of the deck. Once the house was built I realised that the wing to the left of that position (from which the overview photo was taken) would shade it from the morning sun. Morning sun, not afternoon sun as explained previously.

Start-up of the recirculation process

I have noticed an interesting phenomenon with this system when it starts recirculating from cold—particularly when the water in the cylinder is warm or hot. Natural convection relies on the water in one leg (the one from the cylinder in this case) exerting a higher pressure on the water in the ladder rungs than the water in the return leg. You can ignore the pressure in the cylinder above the top (return) pipe as it is common to both legs.

The height in the delivery path equals the height in the return path, i.e.

$$h_1 + h_2 + h_3 = h_4 + h_5 + h_6$$

During normal circulation any theoretical pressure difference is lost in the friction associated with the water flow. Imagine, however, that we block the flow at point A. Then the pressure in the delivery line will be greater than in the return line. This is because the average density is higher because the water is colder. So, when ñ is the corresponding specific gravity (density) in each section, pressure at A on the delivery side ($h_1\tilde{n}_1 + h_2\tilde{n}_2 + h_3\tilde{n}_3$) is greater than the pressure at A on the return side ($h_4\tilde{n}_4 + h_5\tilde{n}_5 + h_6\tilde{n}_6$):

$$(h_1\tilde{n}_1 + h_2\tilde{n}_2 + h_3\tilde{n}_3) > (h_4\tilde{n}_4 + h_5\tilde{n}_5 + h_6\tilde{n}_6)$$

When there is no sunshine (such as at night) the warmest water—and hence that at lowest density—is that in the cylinder (h_1). In my configuration this is at the highest point in the circuit so back-flow does not occur.

Consider now the start-up process. Let us use known or estimated temperatures around the circuit and (from a table, below) corresponding water densities.

When water first heats in the collector and starts providing a lower density in h_4 than the water in h_2 and h_3, water at 23°C comes out of the cylinder into h_2. This is at a lower density than the cold water in h_6. It 'fights'—together with the lower density water in the cylinder (h_1)—against the recirculation. Ie the '>' in the equation above is pointing in the wrong direction.

To get it started the '>' sign in the equation above hast to be at least an '=' sign, ie:

$$(h_1\tilde{n}_1 + h_2\tilde{n}_2 + h_3\tilde{n}_3) = (h_4\tilde{n}_4 + h_5\tilde{n}_5 + h_6\tilde{n}_6)$$

We can solve this equation to find what the temperature in the collector has to rise to for recirculation to start. h_3 at this stage is being filled with water at the outlet temperature of the cylinder. This is at the 23°C that we see at the inlet to the collector once recirculation starts.

Solving for $\tilde{n}_4$ and substituting the values above, ñ4 = 0.9902

The temperature that corresponds to this density is 46°C (115°F). This is indeed about what we see as the start-up spike on the actual plot of temperatures on a clear winter day in early July.

While it is extremely unlikely that I am the first to discover this phenomenon, I have never seen it reported, let alone analysed.

It would be possible to build a thermosiphon collector/cylinder arrangement with so much height close to the cylinder and so little elsewhere that in some conditions circulation would never start.

		Height		Temperature		
		mm	inch	(°C)	(°F)	Corresponding specific gravity
Cylinder (average estimated temperature over h_1)	h_1	300	12	26	79	0.99670
Pipe run in/under the house initially	h_2	1040	41	15	59	0.99913
Pipe run in/under the house just before circulation starts	h_2	1040	41	23	73	0.99750
Pipe run outside	h_3	650	26	5	41	0.99999
Collector	h_4	250	10	4	39	1.00000
Pipe run outside	h_5	400	16	5	41	0.99999
Pipe run in/under the house	h_6	1340	53	15	59	0.99913