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Compact hot water storage systems combining copper tube with high conductivity graphite and phase change materials

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Abstract

The low thermal conductivity of wax-based phase-change material has limited its application in latent heat thermal energy storage (TES) systems. This paper compares two ways to increase the thermal conductivity of wax by a factor of more than 100. The first involves embedding a modified copper tube/aluminum fin heat exchanger of the type typically used in room air conditioners in a container filled with wax-based phase change material. The second and more unconventional approach is to embed copper tube circuits into a high-conductivity graphite-wax composite. Both types of systems demonstrated excellent performance, however the prototype graphite-wax composite TES system offers the added advantages of leak-free operation and greater flexibility in the shape of the TES unit.

This paper covers the design, performance and economics for using a TES unit to replace a conventional hot water storage tank in a heat pump water heater and a solar thermal water heater. TES unit optimization for a HPWH allowed for lower return temperature to the compressor, constant exit water temperature, faster charging time and reduced unit size by as much as 60% compared to a conventional water tank. TES unit optimization for a solar thermal application permits replacement of large water tanks with lighter weight TES units that can be placed on interior or exterior walls.

Overall, this paper describes how optimized designs of thermal energy storage systems for domestic hot water delivery now in development are compact, have flexible form factor for applications in buildings where space is at a premium, deliver hot water at a constant output temperature, operate for a longer time for the same volume, or have increased efficiency over conventional systems.

Some additional applications of copper heat exchangers embedded in PCM will also be mentioned, including air and ground source heat pump space heating and cooling in which the use of a compact TES unit offers higher COP due to condenser and evaporator temperature optimization.

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Keywords: phase change materials, heat exchanger, solar thermal energy storage, wax, graphite, ground source heat pumps

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1. Background

Currently, solar water heaters utilize a water tank for hot water storage as shown in Figure 1(a). Of interest is the possibility to replace the water tank with a more compact space-saving phase change material - heat exchanger (PCM-HX) as shown in Figure 1(b). The PCM is typically a paraffin wax that changes phase from solid to liquid and vice-versa. Phase-change materials deliver energy at a constant temperature [1, 2]. This means that water outlet temperature from the unit will maintain a constant temperature for the required delivery time as opposed to water delivered from a water tank that decreases in temperature over time. This work investigates the feasibility and economics of PCM-based hot water storage as a replacement to the conventional water tank.

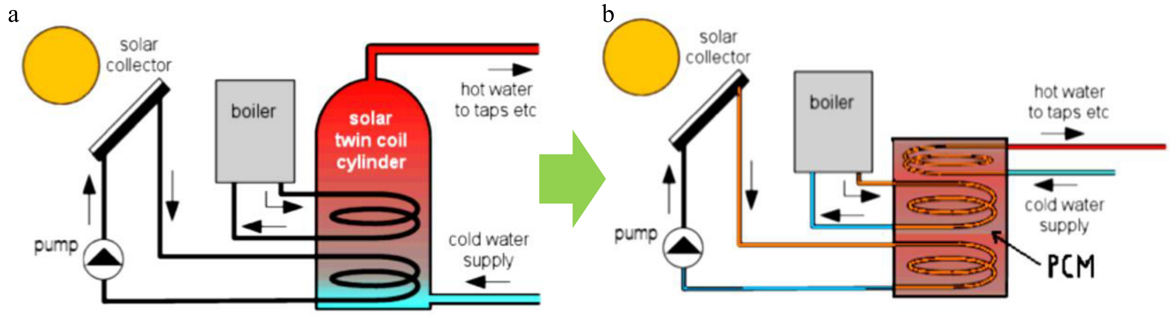

Figure 1. (a) System with water tank; (b) System

Water tank baseline determination and PCM unit required performance:

- Water temperature: Inlet 10°C, outlet 40°C
- Water flow, 10 litres/min (lpm)
- Hot water supply duration: 12 minutes (Total 10 lpm x 12 minutes = 120 litres)
- Solar inlet temperature, 50 to 70°C

The operation requirement is for usable water at 40°C. When a water tank is heated up, it may provide water at a temperature higher than 40°C.

However, water at temperature below 40°C is not useful, therefore:

- Energy required to heat water up to 40°C is wasted energy. PT48 wax has half the specific heat of water so less energy is wasted to bring the wax to the minimum useful temperature.
- Between the useful temperatures of 40°C and 52°C, PCM has 5 times the energy capacity of water as shown in Figure 3.

Usable water from a water tank is between 40°C and 52°C. Therefore, the energy capacity of water vs. PCM between 40°C and 52°C is compared as follows:

Energy stored in water: E = Cp*dT between 40°C and 52°C,

E_{water} = 4.178kJ/kg-K * (52-40°C) = 50.136kJ/kg

Energy stored in PT48 PCM is latent heat between 46°C and 50°C, which is the phase change range, and sensible heat between 40°C and 46°C and 50°C and 52°C.

PT48 specific heat, solid = 2.1 kJ/kg-K, liquid = 2.27 kJ/kg-K

$E_{sensible}$ = 2.1kJ/kg-K * (46-40°C) = 12.6kJ/kg (Sensible heat when temperature is below phase change)

$E_{sensible}$ = 2.27kJ/kg-K * (52-50°C) = 4.54kJ/kg (Sensible heat when temperature is above phase change)

E_{latent} = 245kJ/kg (Phase change)

$E_{PCM(48C)} = E_{sensible} + E_{latent}$ = 12.6 + 4.54 + 245 = 262.14 kJ/kg

The energy ratio between the PCM and water can be determined as follows:
262.14kJ/kg / 50.136kJ/kg = 5.22
This means PT48 has 5.22 times more thermal capacity than water between 40°C and 52°C.

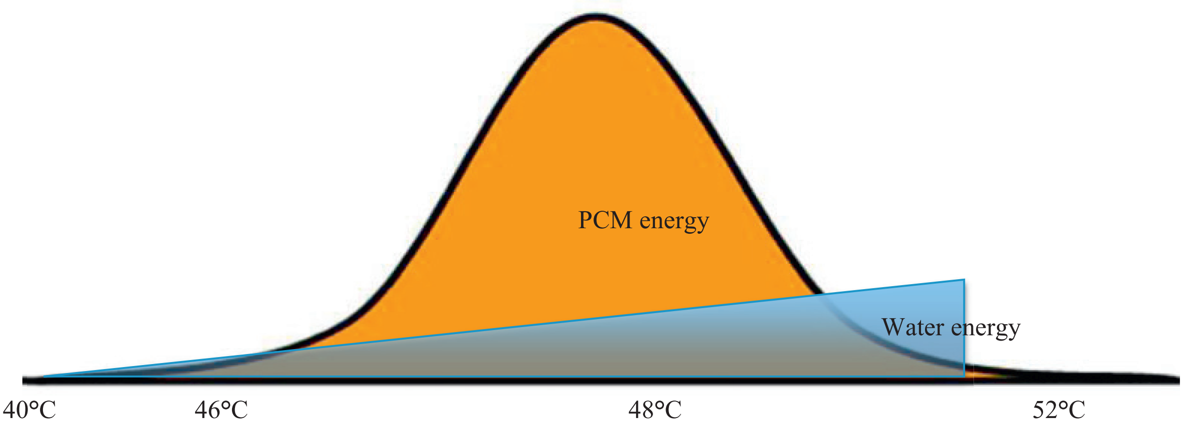

Figure 3. Graph showing energy difference between PT48 PCM and water from 40°C to 52°C

2. Heat exchanger modelling

The modelling work for the heat exchanger was performed on Dassault Solidworks in 3-Dimensions. The heat exchanger is built in a similar manner as an air-conditioning heat exchanger. Round copper tubes are inserted and expanded into flat aluminium fins. There are two main circuits in the heat exchanger: The "demand" water circuit and the solar "charging" circuit. Each circuit consists of 3 tubes. The water tubes were selected as 12mm diameter each and the solar circuit tubes are currently 8mm each. Figure 4 shows the 3 cold-water inlet tube depicted by 3 blue arrows. Next to them, the 3 smaller solar "charging" tubes can be seen. The PCM is "sandwiched" between the 131 fins at a pitch of 1.79 mm.

The current circuiting configuration was found to be the best performing of the many circuit variations that were tried. The "demand" water tubes weave their way from the inlet on the top right to the top left, and via the large "U" connections, change direction until they exit at the bottom left of the unit. The smaller solar charging tubes exist between the "demand" water tubes.

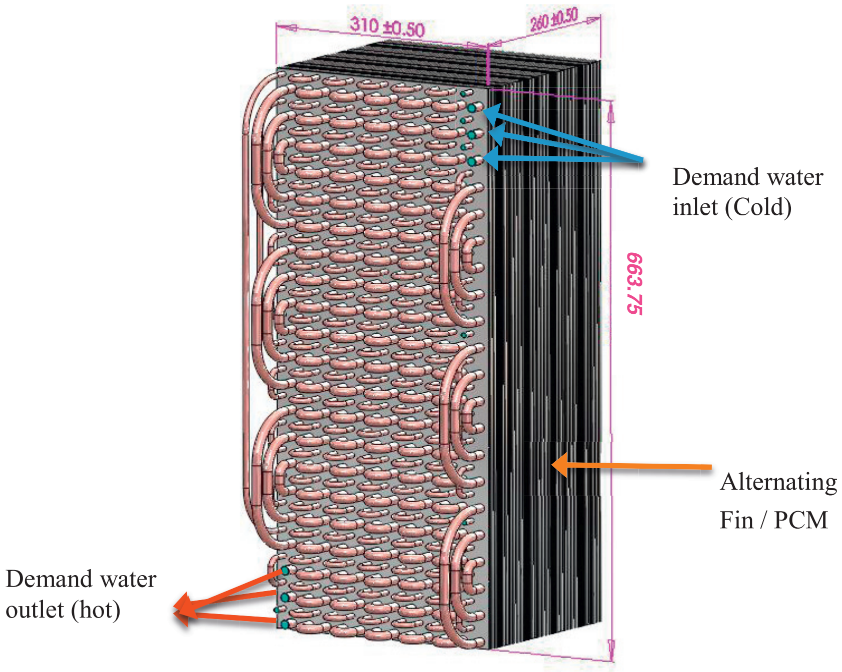

Figure 4. Heat exchanger Solidworks model

3. PCM material selection

Pure Temp [4] is a supplier of wax PCM. Their website shows the properties of various wax PCM in Table 1:

Table 1. Pure Temp PCM material properties

PCM Type (Pure Temp)	PCM Temperature (°C)	PCM Temperature (°F)	Density (g/cm^3)	Density (lb/ft^3)	Latent heat (J/g)	Latent heat (BTU/lb)	Specific Heat (J/g °C)		Specific Heat (BTU/lb °F)	
PT40	40	104	0.85	53.1	198	85	1.98	2.12	0.473	0.508
PT43	43	109	0.88	55.1	180	78	1.87	1.94	0.447	0.463
PT48	48	118	0.82	51.1	245	106	2.1	2.27	0.502	0.543
PT50	50	122	0.86	53.8	200	86	1.82	1.94	0.435	0.463
PT56	56	133	0.81	50.7	237	102	2.47	2.71	0.59	0.648
PT61	61	142	0.84	52.4	199	86	1.99	2.16	0.475	0.516
PT68	68	154	0.87	54.3	198	85	1.84	1.91	0.441	0.455

PT48 was chosen due to its high latent heat of fusion value of 245 kJ/kg. PT43, which is closer to the desired outlet temperature of 40°C, has a lower latent heat of 180 kJ/kg. Since the specific heat of the solid wax with 2.1kJ/kg-K has less value than the latent heat, it is advantageous to use the higher latent heat PT48 wax.

4. Simulation

The model developed above was entered into a Comsol Multiphysics computer simulation program with the heat transfer module for the simulation work also done in 3-D.

4.1. Discharging cycle scenario simulation

The simulation starts with the PCM fully "charged" where the PCM and the solar circuit tubes are all at 52°C (Figure 5). This temperature which is 4°C higher than the PCM type was selected to ensure the PCM is completely in its liquid phase. In practice, the unit can be at higher temperature as delivered from the solar panel thus providing additional sensible heat.

Charged system scenario assumptions:

- The charging of all the PCM capacity is complete
- The system has stopped and the water in the "charging tubes" is also at 52°C
- There are no heat losses from the system – it is perfectly insulated from the surroundings
- PCM exists only between the aluminium fins. There is no PCM around any of the "U" bends or connections as would be when the heat exchanger is immersed in wax

4.2. Discharging cycle simulation results

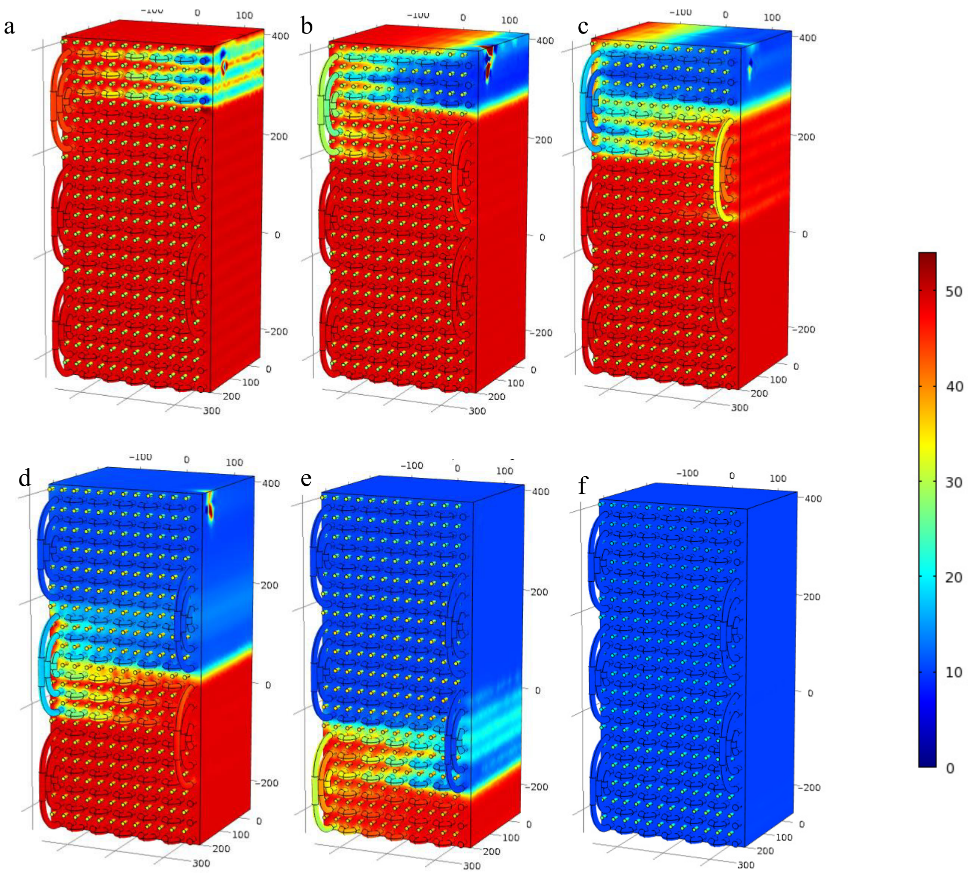

Figure 5. Discharge cycle temperature distribution results a. 100s b. 200s c. 300s d. 500s e. 720s f. 1800s

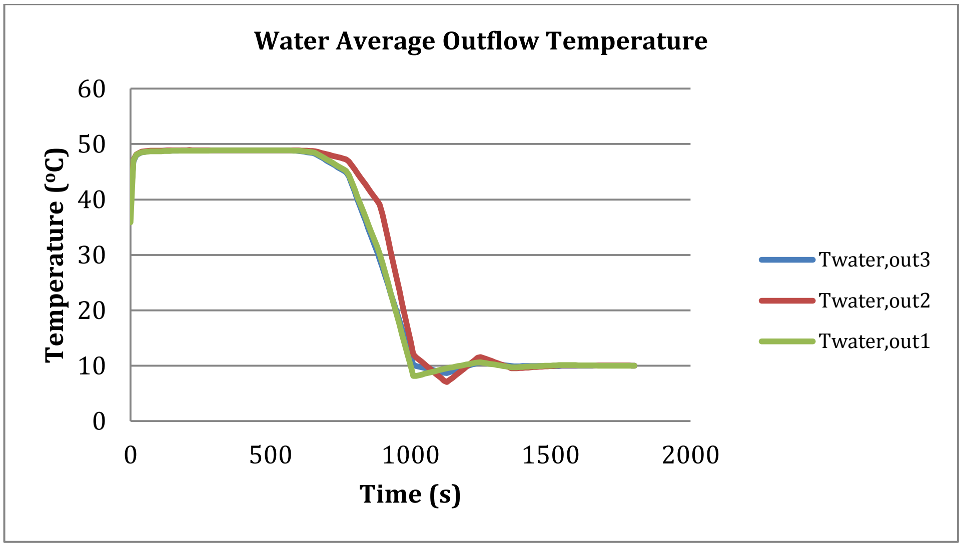

Figure 6. PCM-HX unit water outlet temperature

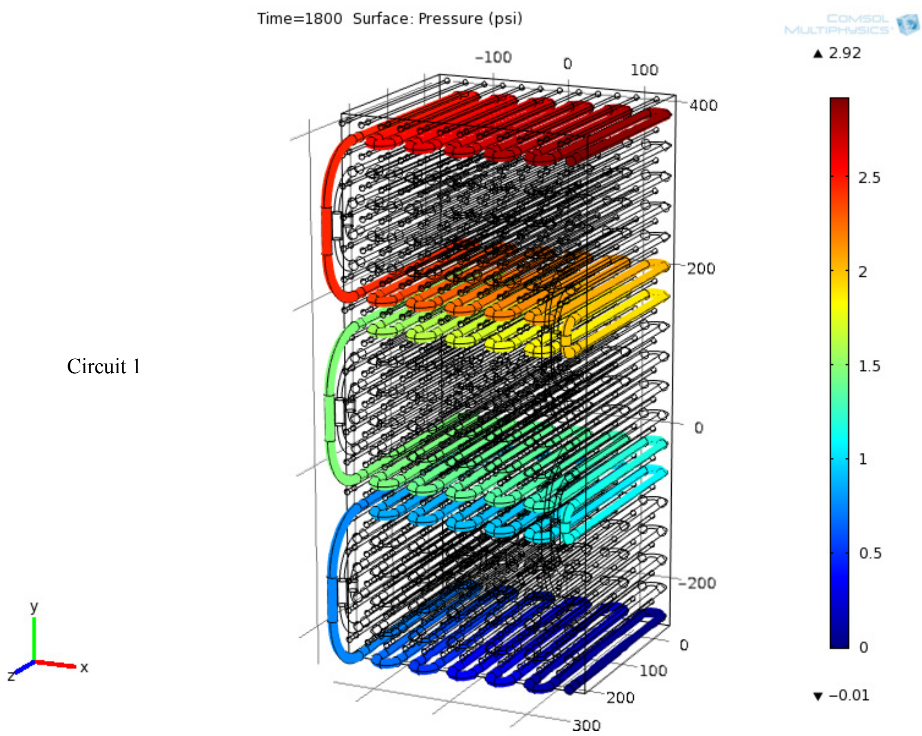

Figure 7. Water pressure drop profile during discharge

5. Discussion of results

The discharge simulation results in Figure 5 clearly depict the temperature change of the PCM as cold water flows through the unit as a function of time shown. The temperature change also reveals the circuitry of the copper pipes in the system. After about 300 seconds, the top PCM "block" is depleted of its heat, all transferred to the water. After 500 seconds, 3 "blocks" are depleted. The water outlet temperature graph shows that after 100 seconds, water exiting the unit is 10°C. The pressure drop for each of the water circuits is 2.92 psi or 0.20 Bars in Figure 7.

It can be seen from the water outflow chart in Figure 6 that the water outlet temperature equals the PCM temperature of 48°C. The simulation does a good job of simulating the PCM as can be noted from the steady temperature directly related to the PCM depleting its latent heat of fusion over time. The simulation also shows the quick drop in temperature once the PCM has depleted its latent heat and now has only sensible heat to supply. The unit total volume is calculated inclusive of the "U" bends. This inclusion changes the unit depth from 260mm to 260 mm resulting in a total unit volume of 0.0576 m^3. The unit flow rate as simulated is 10 litres/minute. It delivers water at 48°C outlet temperature for 12 minutes and water at temperature > 40°C for 15 minutes. The unit thus delivers 150 litres of water at temperature >40°C. As a comparison, a 150 litre water tank occupies a volume of 0.15m^3. The PCM HX unit thus occupies only 38% of the volume of a 150 litre water tank.

The PCM-fin matrix resulted in an equivalent thermal conductivity of 23W/m-K. Considering the PCM has thermal conductivity of 0.2W/m-K, it can be seen that the use of aluminium fins immersed in the wax and the fin pitch selected dramatically increased the overall thermal conductivity of the matrix. The unit water pressure drop at 10 litres/minute is 0.2bars (3psi) and is considered acceptably low.

6. Graphite wax PCM

Graphite PCM composite with a thermal conductivity of 23 W/m-K is expected to produce similar results to PCM-HX with the added advantage of the PCM being integral with the graphite. No container is necessary further reducing the system cost. The shape of the unit can now be tailored to the application.

7. Ground source heat pump application

Ground source systems [3] can be designed with a hot side and a cold side where each unit contains a copper heat exchanger in PCM, which eliminates the need for an expensive stainless steel plate heat exchanger, as shown in Figure 8. The condenser and evaporator are embedded in their respective PCMs. The refrigerant cycle is exposed to fixed temperatures therefore improving system COP (coefficient of performance). Cold water is sent to the air handlers instead of refrigerant. Excess cold or heat is absorbed by the ground loop. The hot side produces hot water in PCM storage and has a dual purpose in winter for hot water and space heating by sending hot water through the air handlers.

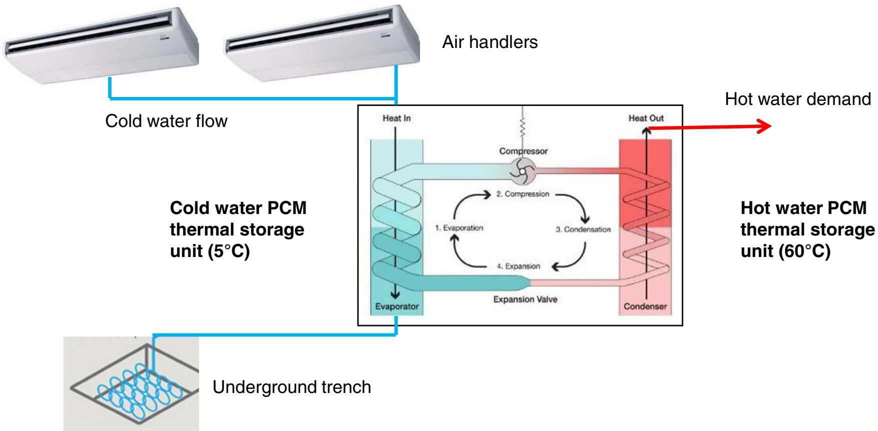

Figure 8. PCM thermal storage heat pump system with ground loop

8. Conclusions

- Immersing a heat exchanger in wax as means of water thermal storage by can significantly reduce the volume of water storage systems
- The unit performs like a 150 litre water tank size unit performs within the required parameters. It delivers water over 40°C for 15 minutes. The phase-change process delivers the required amount of energy in a stable and uniform manner.
- The water pressure drop is at an acceptable level of 0.2 bars (3 psi).
- The PCM unit can store 5 times more energy than water in the useful range of 40°C to 52°C.
- The sensible energy needed to raise the PCM temperature to 48°C is half that needed for water
- The use of extended surfaces in the form of aluminium fins and the fin pitch selected provided an equivalent thermal conductivity of 23W/m-K
- This PCM thermal storage technology is applicable to air conditioning systems, and heat pumps with ground loops.

References

[1] Al-Abidi AA, Sohif Bin Mat, Sopian K, Sulaiman MY, Lim CH, Abdulrahman Th, Review of Thermal Energy Storage for Air Conditioning, Renewable and Sustainable Energy Reviews 2012; 16:5802-5819.
[2] Sharma A, Tyagi VV, Chen CR, Buddhi D, Review of Thermal Energy Storage with Phase Change Materials and Applications, Renewable and Sustainable Energy Reviews 2009; 13:318 – 345.
[3] Lund J, Sanner B, Rybach L, Curtis R, Hellstrom G, Geothermal (Ground source) Heat Pumps – A World Overview, GHC Bulletin Sept 2004: 1.
[4] http://www.puretemp.com/technology.html