ENERGY ANALYSIS ALGORITHMS FOR DUAL CAPACITY GSHP SYSTEMS FOR HOT 2000™

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ABSTRACT

This is a report of efforts to develop normalised capacity and efficiency curves, as a function of entering water temperature (EWT), for use in a performance prediction algorithm for dual capacity (2 speed or dual compression) ground source heat pumps (GSHPs). The report describes current products in the market and how they operate and develop normalized capacity and efficiency equations from performance characteristics of two-speed and dual compressor systems. Attempts to develop similar equations for direct-expansion GSHPs were unsuccessful as there is limited reliable test data at this time.

RÉSUMÉ

Le rapport fait état des efforts déployés dans le but d'élaborer des courbes de capacité et d'efficacité normalisées en tant que fonction de la température de l'eau d'arrivée, que l'on utilisera ensuite dans un algorithme de prévision de performance d'une pompe géothermique à deux vitesses. Le rapport décrit les produits actuellement disponibles sur le marché et comment ils fonctionnent; il décrit l'élaboration d'équations de capacité et d'efficacité se rapportant aux caractéristiques de performance des systèmes à deux vitesses et à double compression. Des tentatives pour élaborer des équations semblables concernant les pompes géothermiques à détente directe ont échoué parce qu'il n'existe pas, à l'heure actuelle, de résultats d'essais fiables.

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INTRODUCTION

In order to reduce computational times when modelling ground source heat pumps in Hot 2000™, simplified capacity and efficiency algorithms are required. These algorithms have already been developed for single capacity heat pumps[1], but are still required for dual capacity (2 speed or dual compressor) systems.

This report presents normalized capacity and efficiency curves as a function of entering water temperature (EWT) which can be applied to both well water and closed-loop ground source heat pumps.

Inlet refrigerant conditions were also examined relative to outdoor air temperature for direct expansion (DX) heat pump systems. Capacity and efficiency curves versus entering refrigerant temperatures could not be developed, since no Canadian or United States manufacturers of DX heat pumps have tested their equipment to the new CSA performance standard[2] at the time this report was written.

COMPRESSOR OPERATION

The capacity of the heat pumps examined in this report are varied by two different methods. The first method employs dual compressors, and the second utilizes two-speed compressors to vary the capacity. The systems are produced by three different manufacturers.

Dual Compressors

Two compressors provide the capacity modulation for these units. One compressor is used at low capacity while two are used when high capacity is required. Variable speed indoor blowers are used to adjust the air flow to the units heating or cooling output. A single-speed pump is assumed for these models because the one manufacturer of this particular type of system recommends that the flow rate of the secondary fluid not be varied with unit capacity since they believe it will detrimentally affect the units operation and life.

The system operation is controlled in relation to the indoor space thermostat setting. In the heating mode, the unit operates at low capacity (one compressor) until the temperature drops 1.5 °C below the thermostat setting at which point the unit goes into high capacity operation (both compressors). If the indoor temperature continues to fall, at 3 °C below the temperature setpoint, supplemental electric resistance heat is brought on as required to provide for any shortfall in output relative to the heating load. The description of operation presented here was based on ClimateMaster's Ultra TR series GSHPs.

Two-Speed Compressors

High-low speed compressors/motors are used in these units with variable speed blowers to match the air flow to the units heating or cooling output. Both manufacturers recommend their units operate with high and low flow circulation of secondary fluids in residential applications. Reducing the secondary fluid flow rate reduces the pumping energy and improves the over-all system efficiency.

The two-speed unit's operation is also controlled by the indoor space thermostat. One manufacturer employs a complicated algorithm which combines the indoor space temperature with the rate of change of the indoor temperature. Essentially, when the indoor temperature is above or below the setpoint temperature, the rate of change in temperature is continuously monitored. If the temperature is not moving back to its operating range at an acceptable rate, the compressor moves into high speed and the high flow circulation pump is also engaged. If, in high-speed in the heating mode, and the space temperature is below its setpoint and not recovering at a satisfactory rate, the resistance heat will be engaged.

The other manufacturer uses discrete temperature measurements similar to the control strategy of ClimateMaster's dual compressor units. When the indoor setpoint temperature is outside its range, the compressor will go into high-speed operation. If the high-speed heating capacity is inadequate, then the resistance heat will make-up the shortfall.

This description of two-speed compressor unit operation was based on Waterfurnace's AT Series and Florida Heat Pump's SX series, both consisting of three models.

INDOOR BLOWER OPERATION

ClimateMaster Ultra TR - In the 1st stage of heating, the blower "ramps" up to low speed 3 minutes prior to the 1st compressor being engaged. If the heating load is not satisfied by the 1st stage of heating, the blower "ramps" up to high speed prior to the 2nd compressor being engaged. If the 3rd stage of heating is required (auxiliary electric resistance heat), the blower remains at high speed. When the 2nd stage heating load is satisfied, the blower "ramps" down to low speed prior to the 2nd compressor being de-energized. Similarly, 1st stage cooling calls for low indoor blower speed and 2nd stage cooling calls for high indoor blower speeds.

WaterFurnace Premier AT - On a call for 1st stage heating (low speed compressor), the blower runs on medium speed. If the thermostat setting is still not satisfied, and 2nd stage heating is called for (high speed compressor), the blower runs at high speed. If 3rd stage heating is called for, the blower remains on high speed. When the compressor cycles off, the blower remains on low speed for 60 seconds before shutting off. Similarly, 1st stage cooling calls for medium indoor blower speed. 2nd stage cooling has the blower operating at high speed.

Florida SX - On a call for 1st stage heating (low speed compressor), the blower "ramps" up to low speed in 15 seconds, after which the compressor is engaged. If the thermostat setting is not satisfied by 1st stage heating, the blower is "ramped" up to high speed over 15 seconds. The high speed compressor stage of heating is then engaged. If the 3rd stage of heating is required (auxiliary electric resistance heat), the blower increases to back-up speed over 15 seconds. On shutdown the blower operates at 45% of low speed operation for 60 seconds, before turning off. In the cooling mode, 1st stage calls for low indoor blower speed and 2nd stage cooling calls for high indoor blower speed. The "ramp" up time is 30 seconds for cooling instead of the 15 seconds required in heating mode.

EWT ALGORITHM

The EWT algorithms were developed in Reference [1] for both groundwater and ground-source systems. For information purposes, portions of Reference [1] dealing with the EWT algorithms are included in Appendix B of this report. Because the EWT varies with outdoor air temperature and not system capacity, these algorithms are also applicable for dual capacity GSHP systems.

NORMALIZED HEATING CAPACITY AND COP EQUATIONS

Figures 1 and 2 illustrate the heating capacity and COP, respectively, of 6 two speed compressor systems at high and low operating conditions. The equations which follow were normalized to 10°C EWT. The normalized heating capacity and COP equations for the **two-speed compressor systems** are as follows:

$$Q_{hp,high} = CAP_{h,r}(0.770 + 1.91\,10^{-2} xEWT + 5.60\,10^{-4} xEWT^2 - 1.73\,10^{-5} xEWT^3)$$

$$Q_{hp,low} = CAP_{l,r}(0.742 + 2.16\,10^{-2} xEWT + 6.40\,10^{-4} xEWT^2 - 1.98\,10^{-5} xEWT^3)$$

$$COP_{high} = COP_{h,r}(0.856 + 1.47\,10^{-2} xEWT + 4.67\,10^{-4} xEWT^2 - 5.60\,10^{-5} xEWT^3)$$

$$COP_{low} = COP_{l,r}(0.794 + 1.53\,10^{-2} xEWT + 7.67\,10^{-4} xEWT^2 - 2.23\,10^{-5} xEWT^3)$$

Figures 3 and 4 illustrate the heating capacity and COP, respectively, of 6 dual compressor systems at high and low capacity. The equations were normalized to 10°C EWT. While this is only the standard heating rating condition for an open or groundwater system it is used for a closed-loop groundsource, as well. Insufficient data was available to normalize about O°C EWT. The normalized heating capacity and COP equations for the **dual compressor systems** are as follows:

$$Q_{hp,high} = CAP_{h,r}(0.765 + 2.41\,10^{-2} xEWT - 2.13\,10^{-5} xEWT^2$$

$$Q_{hp,low} = CAP_{l,r}(0.726 + 2.92\,10^{-2} xEWT - 3.02\,10^{-4} xEWT^{2})$$

$$COP_{high} = COP_{h,r}(1.19 - 2.03\,10^{-2} xEWT + 1.01\,10^{-4} xEWT^{2})$$

$$COP_{low} = COP_{l,r}(1.21 - 2.25\,10^{-2} xEWT + 1.22\,10^{-4} xEWT^{2})$$

The symbols for the heating capacity and COP equations are interpreted as follows:

$Q_{hp,high}$ = heat pump heating capacity in high capacity mode at EWT corresponding to the bin midpoint temperature (BTU/hr)

$Q_{hp,low}$ = heat pump heating capacity in low capacity mode at EWT corresponding to the bin midpoint temperature (BTU/hr)

COP_{high} = heat pump COP in high capacity mode at EWT corresponding to the bin midpoint temperature

COP_{low} = heat pump COP in low capacity mode at EWT corresponding to the bin midpoint temperature

$CAP_{h,r}$ = heat pump heating capacity in high capacity mode at standard rating condition (10 °C EWT) (BTU/hr)

$CAP_{l,r}$ = heat pump heating capacity in low capacity mode at standard rating condition (10 °C EWT) (BTU/hr)

$COP_{h,r}$ = heat pump COP in high capacity mode at standard rating condition (10 °C EWT)

$COP_{l,r}$ = heat pump COP in low capacity mode at standard rating condition (10 °C EWT)

EWT = temperature of the water or liquid entering the heat pump corresponding to the bin midpoint temperature of the outdoor air

The manufacturers' data for the normalized heating curves can be seen in Appendix A.

NORMALIZED COOLING CAPACITY AND EER EQUATIONS

Figures 5 and 6 illustrate the cooling capacity and EER, respectively, of 6 two speed compressor systems at high and low capacity mode conditions. The equations were normalized to 10°C EWT. The normalized cooling capacity and EER equations for the **two-speed compressor systems** are as follows:

$$Q_{hpc,high} = CAPC_{h,r}(1.136 - 1.28\,10^{-2} x EWT + 5.77\,10^{-4} x EWT^{2})$$

$$Q_{hpc,low} = CAPC_{l,r}(1.06 - 5.17\,10^{-2} x EWT - 8.74\,10^{-4} x EWT^{2})$$

$$EER_{high} = EER_{h,r}(1.282 - 2.93\,10^{-2} x EWT + 2.58\,10^{-4} x EWT^{2})$$

$$EER_{low} = EER_{l,r}(1.22 - 2.32\,10^{-2} x EWT + 1.32\,10^{-4} x EWT^{2})$$

Figures 7 and 8 illustrate the cooling capacity and EER, respectively, of 6 dual compressor systems at high and low capacity mode conditions. The equations were normalized to 10°C EWT because data were not available at the 0°C EWT standard rating condition. The normalized cooling capacity and EER equations for the **dual compressor systems** are as follows:

$$Q_{hpc,high} = CAPC_{h,r}(1.04 - 3.06\,10^{-3}xEWT - 8.12\,10^{-5}xEWT^{2}$$

$$Q_{hpc,low} = CAPC_{l,r}(1.04 - 3.06\,10^{-3}xEWT - 8.12\,10^{-5}xEWT^{2})$$

$$EER_{high} = EER_{h,r}(0.829 + 1.78\,10^{-2}xEWT - 6.23\,10^{-4}xEWT^{2})$$

$$EER_{low} = EER_{l,r}(0.795 + 2.21\,10^{-2}xEWT - 1.78\,10^{-4}xEWT^{2})$$

The symbols for the cooling capacity and EER equations are interpreted as follows:

$Q_{hpc,high}$ = heat pump cooling capacity in high capacity mode at EWT corresponding to the bin midpoint temperature (BTU/hr)

$Q_{hpc,low}$ = heat pump cooling capacity in low capacity mode at EWT corresponding to the bin midpoint temperature (BTU/hr)

EER_{high} = heat pump EER in high capacity mode at EWT corresponding to the bin midpoint temperature

EER_{low} = heat pump EER in low capacity mode at EWT corresponding to the bin midpoint temperature

$CAPC_{h,r}$ = heat pump cooling capacity in high capacity mode at standard rating condition (10 °C EWT) (BTU/hr)

$CAPC_{l,r}$ = heat pump cooling capacity in low capacity mode at standard rating condition (10 °C EWT) (BTU/hr)

$EER_{h,r}$ = heat pump EER in high capacity mode at standard rating condition (10 °C EWT)

$EER_{l,r}$ = heat pump EER in low capacity mode at standard rating condition (10 °C EWT)

EWT = temperature of the water or liquid entering the heat pump corresponding to the bin midpoint temperature of the outdoor air

The manufacturers' data for the normalized cooling curves can be seen in Appendix A.

DIRECT-EXPANSION ALGORITHM

The difference between conventional GSHPs and direct expansion heat pumps is the fluid being circulated through the ground heat exchangers. Direct expansion systems circulate refrigerant directly through the ground heat exchanger, eliminating the need for a secondary/anti-freeze heat exchanger.

Because the secondary anti-freeze heat exchanger introduces a temperature drop, direct expansion systems should have a higher capacity and efficiency compared with a conventional GSHP, all else being equal.

Currently there are no direct expansion systems in Canada or the United States which have been tested according to the recently published CSA Performance Standard C748-94. The only testing that has been documented was performed by US Power in 1992[3]. These tests were based on similar procedures to those on which the CSA performance standard was based. However, there are some discrepancies and erroneous data in these test results and the accuracy is questionable.

A number of direct-expansion manufacturers may commence testing in the near future. Consequently, it would be prudent to postpone the development of an accurate, yet simplified direct expansion model until reliable test data is available.

CONCLUSIONS

The capacity and efficiency normalized equations, presented for both dual compressor and two-speed GSHPs, include the effects of fan/motor power input and pump input. For now, the user must provide the performance (capacity and COP) at the 10°C EWT for either cooling or heating. While Caneta realize that this is not a standard rating point for closed-loop systems, insufficient data was available on all units to permit normalization about 0°C in heating. The EWT must still be approximated for ground water or ground-coupled systems as outlined by Caneta Research[1].

At present there is no reliable performance data for DX GSHPs and for that reason, it is suggested that the development of a simplified direct expansion model be postponed.

REFERENCES

[1] Caneta Research Inc., "Simplified Energy Analysis Algorithms for GSHP Systems for HOT 2000 ™", Efficiency and Alternative Energy Technology Branch, Natural Resources Canada. Ottawa, Ontario. 1994.

[2] CSA, "CSA Standard C748-94: Performance of Direct-Expansion (DX) Ground-Source Heat Pumps". Canadian Standards Association Rexdale, Ontario. 1994.

[3] Optimum Controls Corporation, "Test Certification - US Power Climate Control GSDX2 Heat Pump/GSDX4 Heat Pump". US Power Climate Control Corporation. Reading, Pennsylvania. 1992.

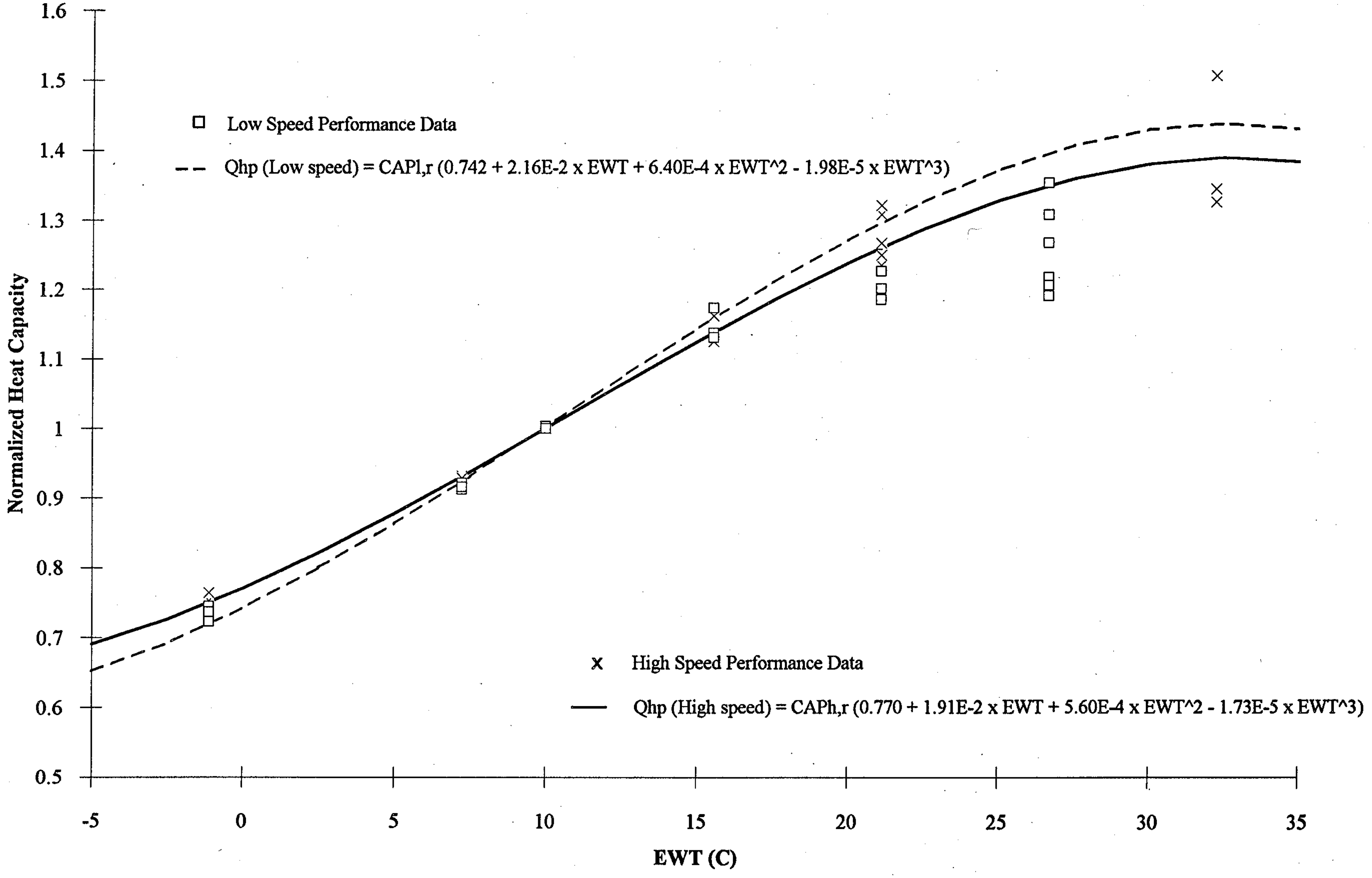


Figure 1: Heating Capacity Normalized WRT 10 C Entering Water Temperature With a 2 Speed Compressor

Figure 2: COP Normalized WRT 10 C Entering Water Temperature
2 Speed Compressors

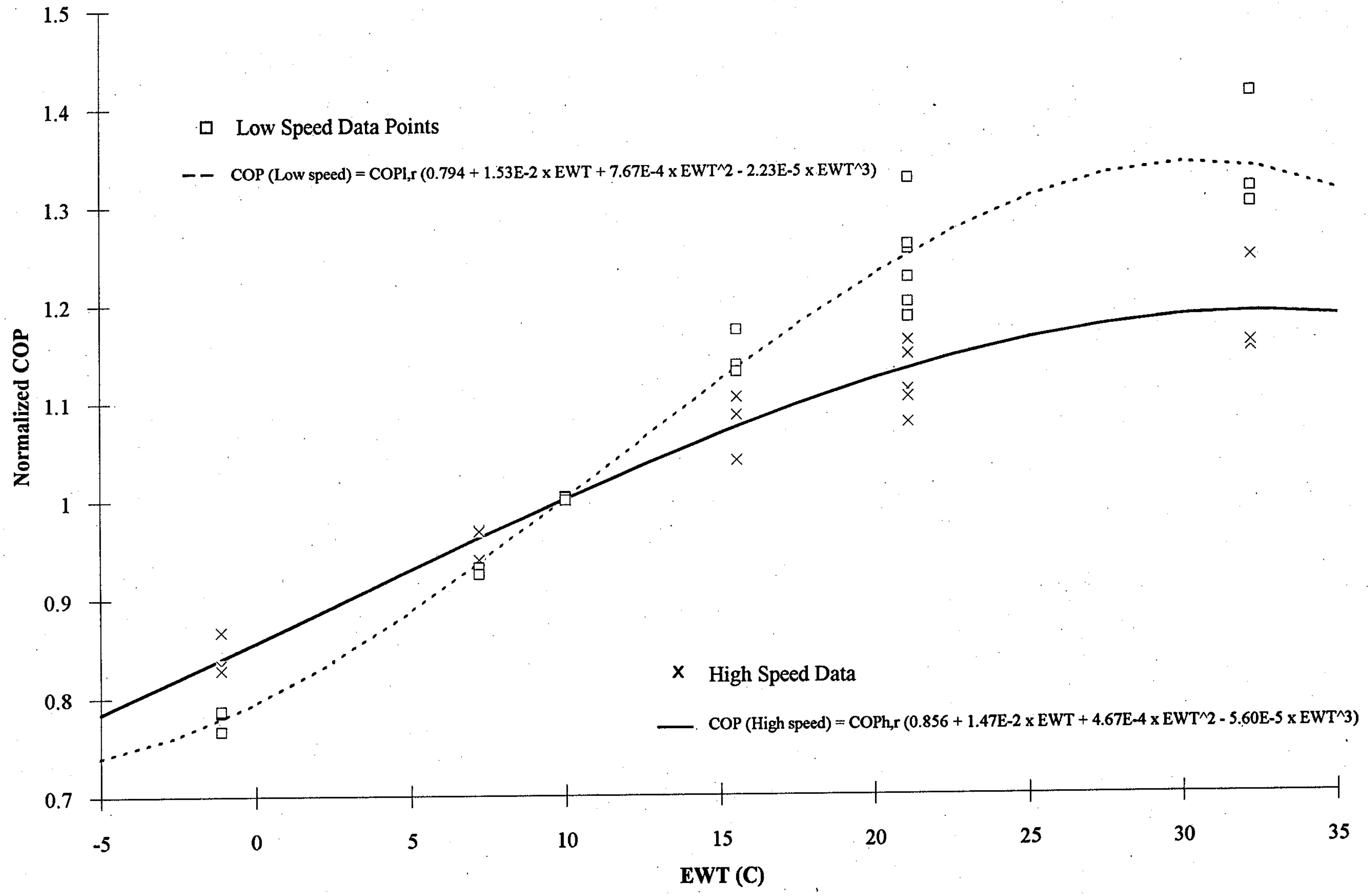


Figure 3: Heading Capacity Normalized WRT 10 C Entering Water Temperature With Dual Compressors

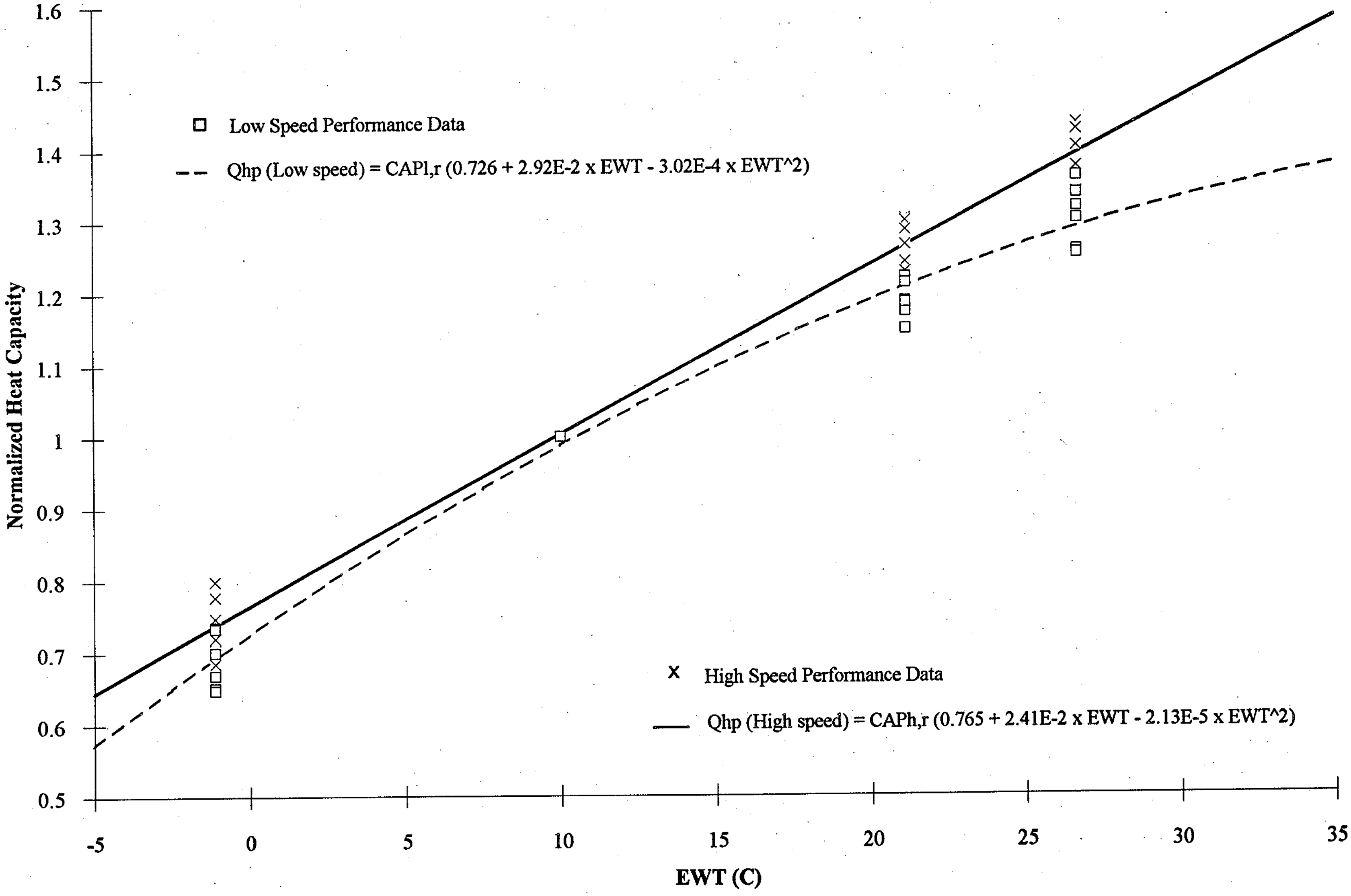


Figure 4: COP Normalized WRT 10 C Entering Water Temperature With Dual Compressors

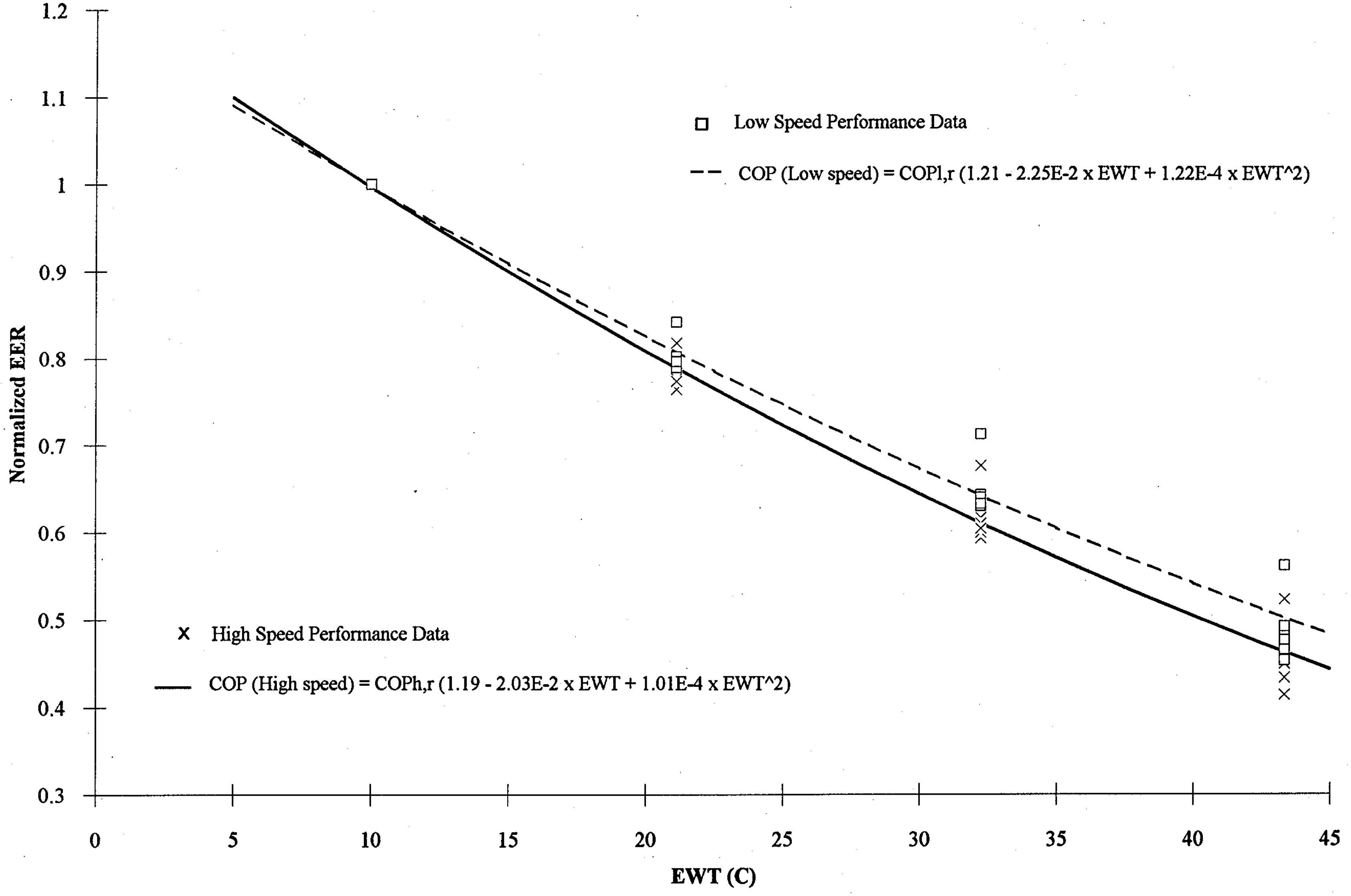


Figure 5: Cooling Capacity Normalized WRT 10 C Entering Water Temperature With a 2 Speed Compressor

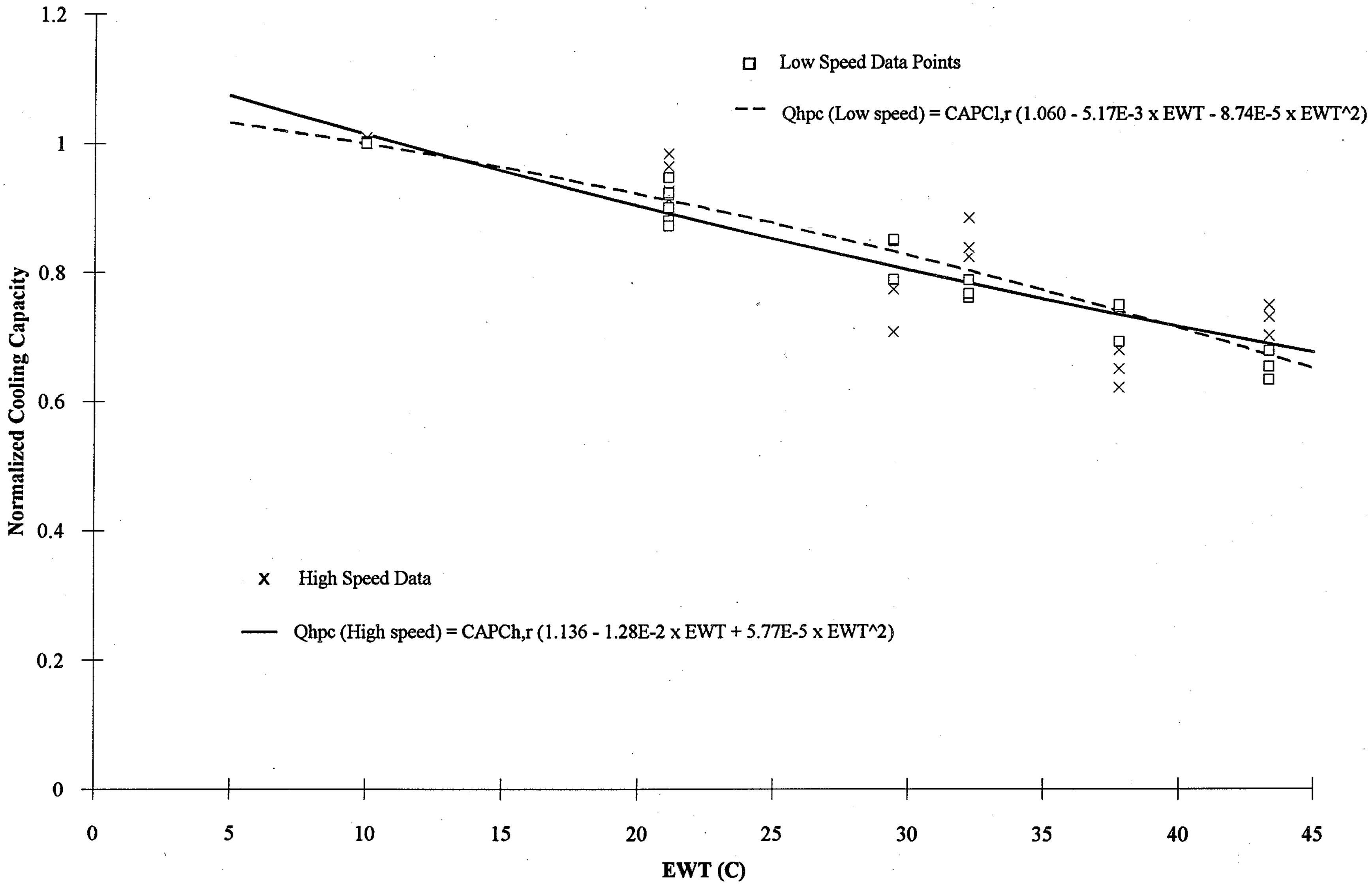


Figure 6: EER Normalized WRT 10 C Entering Water Temperature With a 2 Speed Compressor

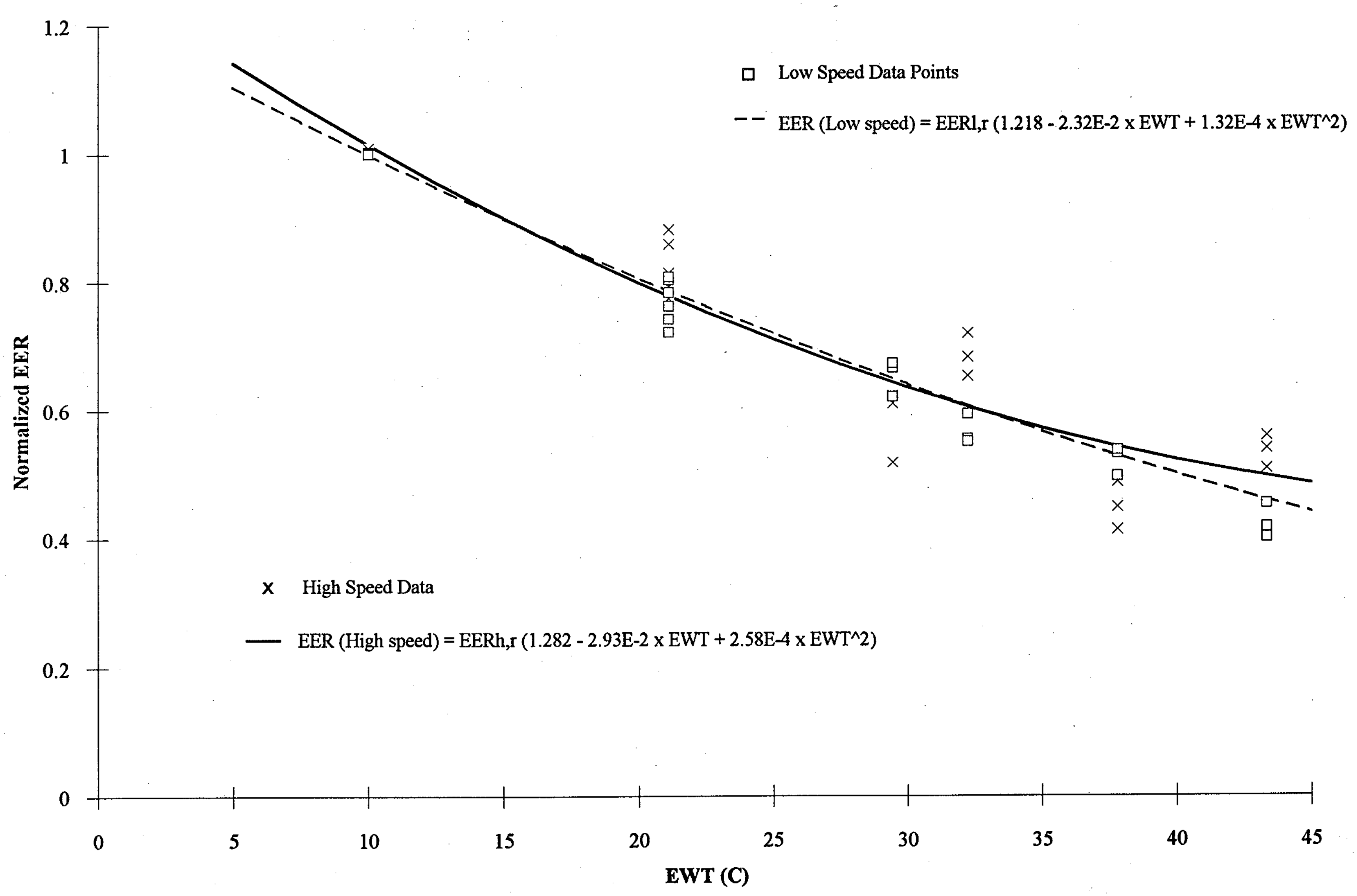


Figure 7: Cooling Capacity Normalized WRT 10 C Entering Water Temperature With Dual Compressors

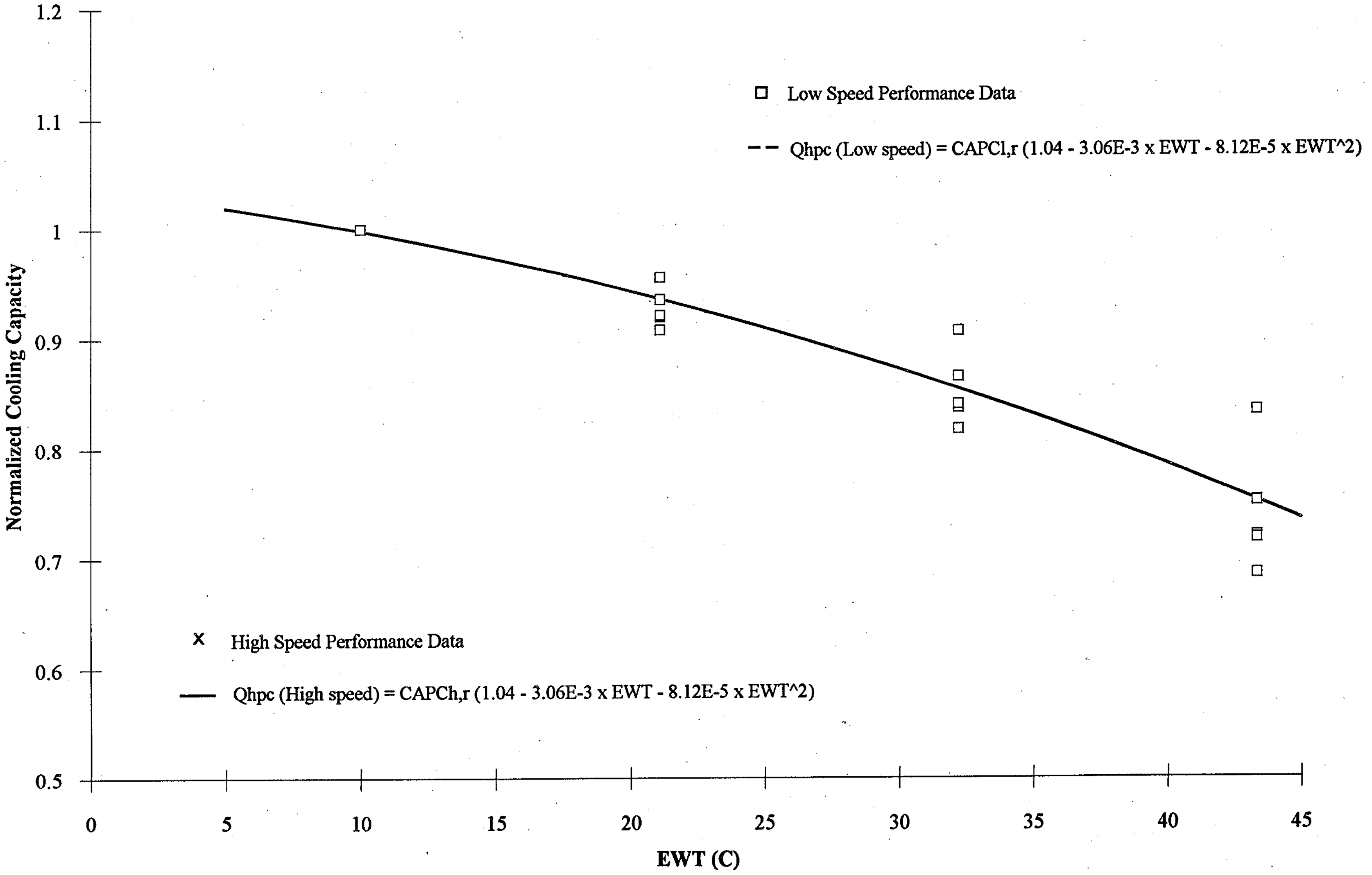
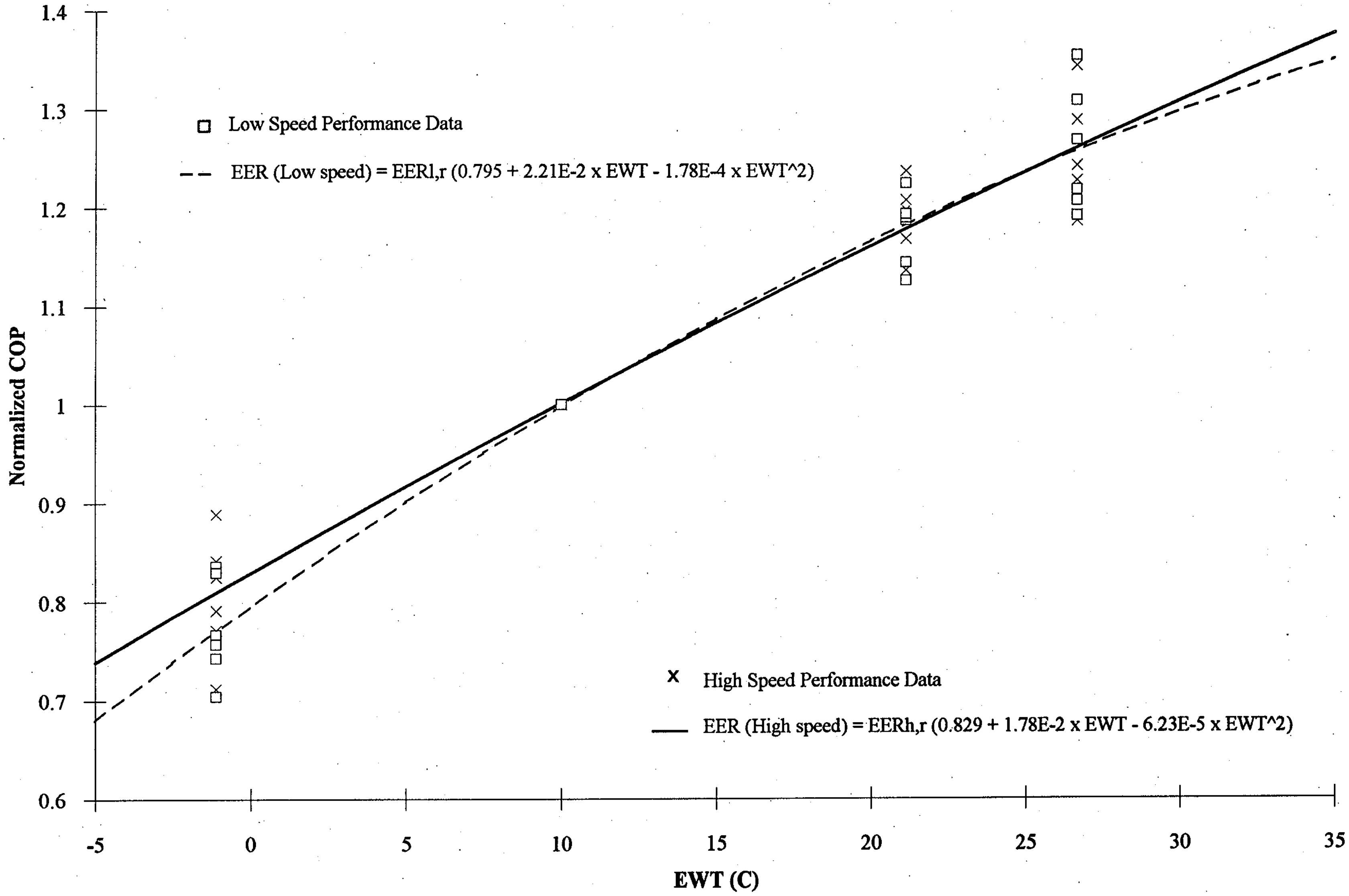


Figure 8: EER Normalized WRT 10 C Entering Water Temperature With Dual Compressors



APPENDIX A

Manufacturer's Data for Normalized Heat Pump Equations

2 Speed Compressor Heating Performance Data - Normalized with Respect to ARI 325 Ratings

				ARI 325 (50 F)			EWT (F) =			30/45 F				EWT (F) =	50					
		GPM	CFM	HC (kBTH)	COP	Pump (kW)	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP
Waterfurnace	AT045-High	6	1,500	40.5	3.4	0.6	-1.1	30.5	8.9	0.8	3.4	2.8	0.8	10.0	40.5	11.9	1.0	4.0	3.4	1.0
	AT057-High	8	1,800	53.5	3.3	0.7	-1.1	39.1	11.5	0.7	3.3	2.7	0.8	10.0	53.5	15.7	1.0	3.9	3.3	1.0
	AT070-High	10	2,200	64.5	3.0	0.6	-1.1	49.3	14.4	0.8	2.9	2.6	0.9	10.0	64.5	18.9	1.0	3.3	3.0	1.0
Florida	SX048-High	6	1,600	42.0	3.6	0.4	7.2	39.1	11.5	0.9	4.0	3.5	1.0	10.0	42.0	12.3	1.0	4.1	3.6	1.0
	SX060-High	8	2,000	56.0	3.3	0.5	7.2	52.2	15.3	0.9	3.6	3.2	1.0	10.0	56.0	16.4	1.0	3.7	3.3	1.0
	SX-072-High	10	2,200	68.0	3.0	0.8	7.2	63.2	18.5	0.9	3.2	2.8	0.9	10.0	68.0	19.9	1.0	3.4	3.0	1.0
Waterfurnace	AT045-Low	3	1,000	20.6	3.8	0.2	-1.1	14.9	4.4	0.7	3.5	2.9	0.8	10.0	20.6	6.0	1.0	4.5	3.8	1.0
	AT057-Low	5	1,200	28.2	3.7	0.4	-1.1	21.0	6.2	0.7	3.6	2.9	0.8	10.0	28.3	8.3	1.0	4.6	3.7	1.0
	AT070-Low	7	1,400	35.4	3.4	0.6	-1.1	26.1	7.6	0.7	3.5	2.7	0.8	10.0	35.5	10.4	1.0	4.3	3.4	1.0
Florida	SX048-Low	3	1,100	20.6	4.0	0.2	7.2	18.8	5.5	0.9	4.3	3.7	0.9	10.0	20.6	6.0	1.0	4.6	4.0	1.0
	SX060-Low	5	1,400	28.2	3.8	0.3	7.2	26.0	7.6	0.9	4.2	3.5	0.9	10.0	28.2	8.3	1.0	4.5	3.8	1.0
	SX-072-Low	7	1,600	33.4	3.3	0.6	7.2	30.6	9.0	0.9	3.8	3.1	0.9	10.0	33.4	9.8	1.0	4.1	3.3	1.0

				ARI 325 (50 F)			EWT (F) 70/60							EWT (F) 90/80						
		GPM	CFM	HC (kBTH)	COP	Pump (kW)	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP
Waterfurnace	AT045-High	9	1,500	40.5	3.4	0.6	21.1	53.0	15.5	1.3	4.6	4.0	1.2	32.2	61.1	17.9	1.5	4.9	4.2	1.2
	AT057-High	11	1,800	53.5	3.3	0.7	21.1	66.1	19.4	1.2	4.2	3.7	1.1	32.2	72.0	21.1	1.3	4.4	3.8	1.2
	AT070-High	13	2,200	64.5	3.0	0.6	21.1	76.9	22.5	1.2	3.6	3.3	1.1	32.2	85.6	25.1	1.3	3.8	3.5	1.2
Florida	SX048-High	6	1,600	42.0	3.6	0.4	15.6	48.8	14.3	1.2	4.5	4.0	1.1	21.1	55.5	16.3	1.3	4.8	4.3	1.2
	SX060-High	11	2,000	56.0	3.3	0.5	15.6	63.5	18.6	1.1	4.0	3.6	1.1	21.1	71.0	20.8	1.3	4.2	3.8	1.1
	SX-072-High	13	2,200	68.0	3.0	0.8	15.6	76.5	22.4	1.1	3.5	3.1	1.0	21.1	85.0	24.9	1.3	3.6	3.2	1.1
Waterfurnace	AT045-Low	9	1,000	20.6	3.8	0.2	21.1	26.2	7.7	1.3	5.5	4.7	1.2	32.2	30.6	9.0	1.5	6.3	5.4	1.4
	AT057-Low	11	1,200	28.2	3.7	0.4	21.1	35.4	10.4	1.3	5.4	4.4	1.2	32.2	40.1	11.8	1.4	5.9	4.9	1.3
	AT070-Low	13	1,400	35.4	3.4	0.6	21.1	44.3	13.0	1.3	5.0	4.0	1.2	32.2	49.7	14.6	1.4	5.5	4.4	1.3
Florida	SX048-Low	9	1,100	20.6	4.0	0.2	15.6	24.1	7.1	1.2	5.4	4.7	1.2	21.1	27.6	8.1	1.3	6.1	5.3	1.3
	SX060-Low	11	1,400	28.2	3.8	0.3	15.6	32.7	9.6	1.2	5.1	4.3	1.1	21.1	37.2	10.9	1.3	5.6	4.8	1.3
	SX-072-Low	13	1,600	33.4	3.3	0.6	15.6	39.0	11.4	1.2	4.6	3.7	1.1	21.1	44.5	13.0	1.3	5.1	4.2	1.3

Dual Compressor Heating Performance Data - Normalized with Respect to ARI 325 Ratings

			ARI 325 (50 F)			EWT (F) = 30 F							EWT (F) = 50 F						
	GPM	CFM	HC (kBTH)	COP	Pump (kW)	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP
ClimateMaster VT-030-High	6	1,050	26.4	3.9	0.4	-1.1	18.1	5.3	0.7	3.6	2.8	0.7	10.0	26.4	7.7	1.0	5.0	3.9	1.0
VT-036-High	6	1,200	33.0	3.8	0.4	-1.1	24.7	7.2	0.7	3.6	3.0	0.8	10.0	33.0	9.7	1.0	4.5	3.8	1.0
VT-042-High	8	1,400	39.5	3.9	0.6	-1.1	28.4	8.3	0.7	4.1	3.2	0.8	10.0	39.5	11.6	1.0	4.8	3.9	1.0
VT-048-High	8	1,600	40.0	3.7	0.6	-1.1	32.0	9.4	0.8	4.1	3.3	0.9	10.0	40.0	11.7	1.0	4.5	3.7	1.0
VT-060-High	10	2,000	50.5	3.5	0.6	-1.1	36.4	10.7	0.7	3.2	2.7	0.8	10.0	50.5	14.8	1.0	4.1	3.5	1.0
VT-072-High	10	2,200	63.5	3.5	0.8	-1.1	49.4	14.5	0.8	3.5	2.9	0.8	10.0	63.5	18.6	1.0	4.1	3.5	1.0
ClimateMaster VT-030-Low	6	600	13.0	3.1	0.4	-1.1	8.5	2.5	0.7	3.6	2.2	0.7	10.0	13.0	3.8	1.0	4.9	3.1	1.0
VT-036-Low	6	600	16.3	3.3	0.4	-1.1	11.4	3.3	0.7	3.6	2.5	0.8	10.0	16.3	4.8	1.0	4.5	3.3	1.0
VT-042-Low	8	800	19.5	3.2	0.6	-1.1	12.6	3.7	0.6	3.9	2.5	0.8	10.0	19.5	5.7	1.0	4.8	3.2	1.0
VT-048-Low	8	900	20.0	3.1	0.6	-1.1	14.7	4.3	0.7	4.0	2.6	0.8	10.0	20.0	5.9	1.0	4.5	3.1	1.0
VT-060-Low	10	1,200	25.3	3.0	0.6	-1.1	16.9	5.0	0.7	3.0	2.2	0.7	10.0	25.3	7.4	1.0	3.9	3.0	1.0
VT-072-Low	10	1,400	31.8	3.0	0.8	-1.1	23.3	6.8	0.7	3.5	2.5	0.8	10.0	31.8	9.3	1.0	4.0	3.0	1.0

			ARI 325 (50 F)			EWT (F) 70 F							EWT (F) 80 F						
	GPM	CFM	HC (kBTH)	COP	Pump (kW)	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	COP	Modified COP	Normal. COP
ClimateMaster VT-030-High	6	1,050	26.4	3.9	0.4	21.1	34.4	10.1	1.3	6.1	4.8	1.2	26.7	37.9	11.1	1.4	6.6	5.2	1.3
VT-036-High	6	1,200	33.0	3.8	0.4	21.1	41.0	12.0	1.2	5.2	4.4	1.2	26.7	45.1	13.2	1.4	5.5	4.7	1.2
VT-042-High	8	1,400	39.5	3.9	0.6	21.1	50.0	14.7	1.3	5.3	4.4	1.1	26.7	55.4	16.2	1.4	5.5	4.6	1.2
VT-048-High	8	1,600	40.0	3.7	0.6	21.1	52.0	15.2	1.3	5.3	4.4	1.2	26.7	55.0	16.1	1.4	5.4	4.5	1.2
VT-060-High	10	2,000	50.5	3.5	0.6	21.1	65.0	19.1	1.3	4.9	4.2	1.2	26.7	72.0	21.1	1.4	5.2	4.5	1.3
VT-072-High	10	2,200	63.5	3.5	0.8	21.1	78.0	22.9	1.2	4.6	4.0	1.1	26.7	85.0	24.9	1.3	4.8	4.2	1.2
ClimateMaster VT-030-Low	6	600	13.0	3.1	0.4	21.1	15.9	4.7	1.2	6.0	3.8	1.2	26.7	17.7	5.2	1.4	6.6	4.2	1.4
VT-036-Low	6	600	16.3	3.3	0.4	21.1	19.7	5.8	1.2	5.3	3.9	1.2	26.7	21.8	6.4	1.3	5.6	4.2	1.3
VT-042-Low	8	800	19.5	3.2	0.6	21.1	22.8	6.7	1.2	5.3	3.7	1.1	26.7	25.3	7.4	1.3	5.5	3.9	1.2
VT-048-Low	8	900	20.0	3.1	0.6	21.1	23.8	7.0	1.2	5.3	3.7	1.2	26.7	25.2	7.4	1.3	5.4	3.8	1.2
VT-060-Low	10	1,200	25.3	3.0	0.6	21.1	29.9	8.8	1.2	4.7	3.5	1.2	26.7	33.3	9.8	1.3	5.1	3.9	1.3
VT-072-Low	10	1,400	31.8	3.0	0.8	21.1	36.5	10.7	1.1	4.6	3.4	1.1	26.7	39.8	11.7	1.3	4.8	3.6	1.2

2 Speed Compressor Cooling Performance Data - Normalized with Respect to ARI 325 Ratings

				ARI 325 (50 F)			EWT (F) = 50 F							EWT (F) = 70						
		GPM	CFM	TC (kBTH)	EER	Pump (kW)	EWT (C)	TC (kBTH)	TC (kW)	Normal. HC	EER	Modified EER	Normal. EER	EWT (C)	TC (kBTH)	TC (kW)	Normal. HC	EER	Modified EER	Normal. EER
Waterfurnace	AT045-High	6	1,500	54.0	16.5	0.5	10.0	54.4	15.9	1.0	19.5	16.6	1.0	21.1	49.2	14.4	0.9	15.4	13.4	0.8
	AT057-High	8	1,800	65.0	14.4	0.6	10.0	65.6	19.2	1.0	16.7	14.5	1.0	21.1	62.7	18.4	1.0	14.0	12.4	0.9
	AT070-High	10	2,200	77.0	12.0	0.8	10.0	77.1	22.6	1.0	13.7	12.0	1.0	21.1	75.8	22.2	1.0	11.9	10.6	0.9
Florida	SX048-High	6	1,600	56.0	17.6	0.4	10.0	56.0	16.4	1.0	20.3	17.6	1.0	21.1	50.5	14.8	0.9	16.3	14.3	0.8
	SX060-High	8	2,000	69.0	15.1	0.6	10.0	69.0	20.2	1.0	17.2	15.1	1.0	21.1	63.0	18.5	0.9	13.4	12.0	0.8
	SX-072-High	10	2,200	82.0	13.1	0.6	10.0	82.0	24.0	1.0	14.6	13.1	1.0	21.1	76.0	22.3	0.9	11.1	10.1	0.8
Waterfurnace	AT045-Low	3	1,000	30.8	23.0	0.2	10.0	30.8	9.0	1.0	27.5	23.0	1.0	21.1	27.1	7.9	0.9	19.8	17.1	0.7
	AT057-Low	5	1,200	39.0	21.1	0.4	10.0	39.1	11.5	1.0	26.5	21.2	1.0	21.1	35.1	10.3	0.9	19.4	16.1	0.8
	AT070-Low	7	1,400	47.5	18.5	0.6	10.0	47.6	14.0	1.0	23.6	18.5	1.0	21.1	43.7	12.8	0.9	18.3	14.9	0.8
Florida	SX048-Low	3	1,100	31.2	24.8	0.2	10.0	31.2	9.1	1.0	29.5	24.8	1.0	21.1	27.2	8.0	0.9	20.6	17.9	0.7
	SX060-Low	5	1,400	39.0	21.2	0.3	10.0	39.0	11.4	1.0	26.0	21.2	1.0	21.1	36.0	10.6	0.9	19.7	16.6	0.8
	SX-072-Low	7	1,600	47.0	19.3	0.5	10.0	47.0	13.8	1.0	24.1	19.3	1.0	21.1	44.5	13.0	0.9	18.8	15.6	0.8

				ARI 325 (50 F)			EWT (F) 85/90 F							EWT (F) = 100/110 F						
		GPM	CFM	TC (kBTH)	EER	Pump (kW) (kW	EWT (C)	TC (kBTH)	TC (kW)	Normal. HC	EER	Modified EER	Normal. EER	EWT (C)	TC (kBTH)	TC (kW)	Normal. HC	EER	Modified EER	Normal. EER
Waterfurnace	AT045-High	9	1,500	54.0	16.5	0.5	32.2	44.5	13.0	0.8	12.2	10.8	0.7	43.3	37.9	11.1	0.7	9.4	8.4	0.5
	AT057-High	11	1,800	65.0	14.4	0.6	32.2	54.5	16.0	0.8	11.0	9.8	0.7	43.3	47.5	13.9	0.7	8.6	7.8	0.5
	AT070-High	13	2,200	77.0	12.0	0.8	32.2	68.1	20.0	0.9	9.6	8.6	0.7	43.3	57.7	16.9	0.7	7.4	6.7	0.6
Florida	SX048-High	6	1,600	56.0	17.6	0.4	29.4	39.6	11.6	0.7	10.1	9.1	0.5	37.8	34.8	10.2	0.6	8.0	7.3	0.4
	SX060-High	8	2,000	69.0	15.1	0.6	29.4	54.2	15.9	0.8	10.4	9.4	0.6	37.8	44.9	13.2	0.7	7.4	6.8	0.4
	SX-072-High	10	2,200	82.0	13.1	0.6	29.4	63.4	18.6	0.8	8.7	8.0	0.6	37.8	55.7	16.3	0.7	6.9	6.4	0.5
Waterfurnace	AT045-Low	9	1,000	30.8	23.0	0.2	32.2	23.4	6.9	0.8	14.5	12.8	0.6	43.3	19.5	5.7	0.6	10.3	9.2	0.4
	AT057-Low	11	1,200	39.0	21.1	0.4	32.2	29.9	8.8	0.8	13.6	11.6	0.6	43.3	25.5	7.5	0.7	10.1	8.8	0.4
	AT070-Low	13	1,400	47.5	18.5	0.6	32.2	37.4	11.0	0.8	13.1	11.0	0.6	43.3	32.2	9.4	0.7	9.8	8.4	0.5
Florida	SX048-Low	3	1,100	31.2	24.8	0.2	29.4	24.6	7.2	0.8	17.6	15.4	0.6	37.8	21.6	6.3	0.7	13.9	12.3	0.5
	SX060-Low	5	1,400	39.0	21.2	0.3	29.4	33.1	9.7	0.8	16.5	14.1	0.7	37.8	29.1	8.5	0.7	13.0	11.3	0.5
	SX-072-Low	7	1,600	47.0	19.3	0.5	29.4	40.0	11.7	0.9	15.4	13.0	0.7	37.8	35.2	10.3	0.7	12.1	10.4	0.5

Dual Compressor Cooling Performance Data - Normalized with Respect to ARI 325 Ratings

			ARI 325 (50 F)			EWT (F) = 50 F							EWT (F) = 70 F						
	GPM	CFM	HC (kBTH)	EER	Pump (kW)	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	EER	Modified EER	Normal. EER	EWT (C)	HC (kBTH)	HC (kW)	Normal. HC	EER	Modified EER	Normal. EER
ClimateMaster VT-030-High	6	1,050	31.0	21.0	0.3	10.0	31.0	9.1	1.0	27.0	21.0	1.0	21.1	29.0	8.5	0.9	19.7	16.1	0.8
VT-036-High	6	1,200	38.5	19.7	0.4	10.0	38.5	11.3	1.0	24.5	19.7	1.0	21.1	35.4	10.4	0.9	18.5	15.4	0.8
VT-042-High	8	1,400	45.0	19.8	0.5	10.0	45.0	13.2	1.0	25.3	19.8	1.0	21.1	43.0	12.6	1.0	19.9	16.2	0.8
VT-048-High	8	1,600	50.5	19.9	0.5	10.0	50.5	14.8	1.0	24.8	19.9	1.0	21.1	46.5	13.6	0.9	18.2	15.2	0.8
VT-060-High	10	2,000	65.0	17.8	0.7	10.0	65.0	19.1	1.0	21.8	17.8	1.0	21.1	59.0	17.3	0.9	16.4	13.8	0.8
VT-072-High	10	2,200	77.0	17.8	0.7	10.0	77.0	22.6	1.0	21.4	17.8	1.0	21.1	72.0	21.1	0.9	16.0	13.8	0.8
ClimateMaster VT-030-Low	6	600	15.3	17.2	0.3	10.0	15.3	4.5	1.0	27.2	17.2	1.0	21.1	14.3	4.2	0.9	19.9	13.7	0.8
VT-036-Low	6	600	19.0	16.5	0.4	10.0	19.0	5.6	1.0	24.8	16.5	1.0	21.1	17.5	5.1	0.9	18.7	13.3	0.8
VT-042-Low	8	800	22.2	16.3	0.5	10.0	22.2	6.5	1.0	25.5	16.3	1.0	21.1	21.2	6.2	1.0	20.1	13.7	0.8
VT-048-Low	8	900	24.9	16.6	0.5	10.0	24.9	7.3	1.0	25.0	16.6	1.0	21.1	22.9	6.7	0.9	18.4	13.1	0.8
VT-060-Low	10	1,200	32.0	15.1	0.7	10.0	32.0	9.4	1.0	22.0	15.1	1.0	21.1	29.0	8.5	0.9	16.6	12.0	0.8
VT-072-Low	10	1,400	38.0	15.3	0.7	10.0	38.0	11.1	1.0	21.6	15.3	1.0	21.1	35.5	10.4	0.9	16.2	12.2	0.8

			ARI 325 (50 F)			EWT (F) = 90 F							EWT (F) = 110 F						
	GPM	CFM	TC (kBTH)	EER	Pump (kW) (kW	EWT (C)	TC (kBTH)	TC (kW)	Normal. HC	EER	Modified EER	Normal. EER	EWT (C)	TC (kBTH)	TC (kW)	Normal. HC	EER	Modified EER	Normal. EER
ClimateMaster VT-030-High	6	1,050	31.0	21.0	0.3	32.2	26.8	7.9	0.9	14.7	12.5	0.6	43.3	23.3	6.8	0.8	9.9	8.7	0.4
VT-036-High	6	1,200	38.5	19.7	0.4	32.2	32.2	9.4	0.8	14.2	12.1	0.6	43.3	27.7	8.1	0.7	10.2	8.9	0.5
VT-042-High	8	1,400	45.0	19.8	0.5	32.2	40.8	12.0	0.9	16.0	13.4	0.7	43.3	37.5	11.0	0.8	12.0	10.4	0.5
VT-048-High	8	1,600	50.5	19.9	0.5	32.2	42.4	12.4	0.8	13.9	11.9	0.6	43.3	36.2	10.6	0.7	9.8	8.6	0.4
VT-060-High	10	2,000	65.0	17.8	0.7	32.2	53.1	15.6	0.8	12.6	10.9	0.6	43.3	44.5	13.0	0.7	9.1	8.0	0.4
VT-072-High	10	2,200	77.0	17.8	0.7	32.2	66.6	19.5	0.9	12.2	10.8	0.6	43.3	57.8	16.9	0.8	9.2	8.2	0.5
ClimateMaster VT-030-Low	6	1,000	15.3	17.2	0.3	32.2	13.2	3.9	0.9	14.8	10.8	0.6	43.3	11.5	3.4	0.8	10.0	7.8	0.5
VT-036-Low	6	1,200	19.0	16.5	0.4	32.2	15.9	4.7	0.8	14.3	10.6	0.6	43.3	13.7	4.0	0.7	10.3	8.0	0.5
VT-042-Low	8	1,400	22.2	16.3	0.5	32.2	20.1	5.9	0.9	16.2	11.6	0.7	43.3	18.5	5.4	0.8	12.1	9.1	0.6
VT-048-Low	8	1,100	24.9	16.6	0.5	32.2	20.9	6.1	0.8	14.0	10.5	0.6	43.3	17.8	5.2	0.7	9.9	7.7	0.5
VT-060-Low	10	1,400	32.0	15.1	0.7	32.2	26.1	7.7	0.8	12.8	9.6	0.6	43.3	21.9	6.4	0.7	9.2	7.2	0.5
VT-072-Low	10	1,600	38.0	15.3	0.7	32.2	32.9	9.6	0.9	12.3	9.7	0.6	43.3	28.5	8.4	0.8	9.3	7.5	0.5

APPENDIX B

Entering Water Temperature Algorithm from Reference [1]

DESCRIPTION OF THE SIMPLIFIED ALGORITHM

The HOT 2000™ computer program currently has a ground-source model that requires monthly soil temperature to predict heat pump performance. If the EWT entering the ground source heat pump could be derived, as a function of the outdoor air temperature, a procedure more suited to bin and hour-by-hour analysis would result.

For the **well-water heat pump** the model is simple. The EWT is constant and is simply equal to the mean annual air temperature for the location under analysis. In HOT 2000™ currently, the well-water temperature is allowed to vary monthly. This is an unnecessary complication.

For the **closed-loop ground source** model one can define a relationship for EWT as follows:

Winter Heating Operation

- when heating operation begins in fall the entering liquid temperature will be approximately equal to the mean annual soil temperature (EWT mean) which is also equal to the mean annual air temperature for a locale. The outdoor temperature at this time would be approximately 10 to 15°C.

- the minimum entering liquid temperature, EWT_{min}, is assumed to occur at the coldest or high load heating condition. This occurs at the outdoor heating design temperature for a locale and depends on the sizing of the heat exchanger. Longer heat exchanger lengths result in higher EWT_{min}; shorter heat exchanger lengths result in lower EWT_{min}. The value of EWT_{min} is typically between -5°C and 0°C.

- characteristically the EWT_{min} remains constant in the cold months evidence that ice is forming around the heat exchanger pipes. To this end, the EWT is held constant below an outdoor temperature of -5°C.

Summer Cooling Operation

- under low or no load cooling conditions typical of late April and through early June, the $EWT = EWT_{mean}$, as described earlier for heating in the fall. This assumes that any ice build-up around the heat exchanger has melted during April, May and early June, before the heat pump is required to operate in cooling.

- under high load cooling, in the design cooling month, EWT will reach a maximum value, EWT_{max}. For most Canadian residential applications, the EWT_{max} will be fairly moderate, as the heat exchanger is generally sized for heating and oversized for cooling. A typical value of EWT_{max} would be about 25°C or less and would occur at the outdoor cooling design temperature for the locale.

The closed-loop ground-source equations for EWT based on the preceding discussion are shown in Figure 1.

EWT is determined using the equations in Figure 1 at each bin temperature by interpolating between EWT_{mean} and EWT_{min} in winter and between EWT_{mean} and EWT_{max} in summer. The user specifies or the program provides values for EWT_{min}, EWT_{max}, TA_{min}, TA_{max}, EWT_{mean}, TA_{mean}. Suggested default values for EWT_{min} and EWT_{max} are -5°C and 25°C. The other values are already provided by HOT 2000^{TM} or can be determined from HOT 2000^{TM} as in the case of TA_{mean}, the house balance point for heating.

Figure 1: Closed-Loop Ground Source Equations for EWT

Winter

$$EWT = EWT_{min} + \frac{[EWT_{mean} - EWT_{min}]\ [TA - TA_{min}]}{[TA_{mean} - TA_{min}]}$$

$$EWT = EWT_{min} + EWT_{mean}\ \frac{[TA - TA_{min}]}{TA_{mean} - TA_{min}} - EWT_{min}\ \frac{[TA - TA_{min}]}{TA_{mean} - TA_{min}}$$

$$EWT = EWT_{min} \times \frac{[1 - (TA - TA_{min})]}{TA_{mean} - TA_{min}} + EWT_{mean}\ \frac{[(TA - TA_{min})]}{TA_{mean} - TA_{min}}$$

$$EWT = EWT_{min} \times \frac{[TA_{mean} - TA]}{TA_{mean} - TA_{min}} + EWT_{mean}\ \frac{[TA - TA_{min}]}{TA_{mean} - TA_{min}}, \text{ if } TA \geq -5°C$$

$$EWT = EWT\ (TA = -5°C), \text{ if } TA < 5°C$$

Where:

EWT_{min} = minimum entering liquid temperature, °C
EWT_{mean} = local mean annual air temperature, °C
TA_{min} = design heating outdoor air temperature for locale, °C
TA_{mean} = house balance point outdoor air temperature, °C
TA = bin temperature - outdoor air, °C.

Summer

$$EWT = EWT_{mean} \times \frac{[TA_{max} - TA]}{TA_{max} - TA_{mean}} + EWT_{max}\ \frac{[TA - TA_{mean}]}{TA_{max} - TA_{mean}}$$

EWT_{max} = 25°C
EWT_{mean} = local mean annual air temperature, °C
TA_{max} = design cooling outdoor air temperature for locale, °C
TA_{mean} = house balance point outdoor air temperature, °C
TA = bin temperature - outdoor air, °C