G-HEADS: a computer package for Ground Heat Exchanger Analysis, Design and Simulation

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SAINT MARY'S UNIVERSITY

Division of Engineering

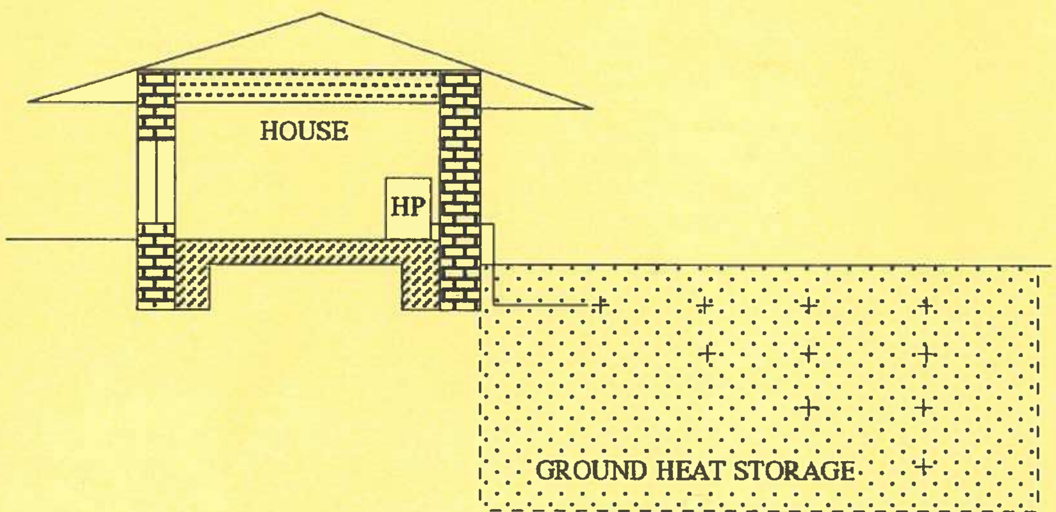
G-HEADS

A Computer Package for

Ground Heat Exchanger Analysis, Design and Simulation*

by

Vlodek R. Tarnawski and Wey H. Leong



March 30, 1990

*Performed under contract to the National Research Council, Ottawa, Canada

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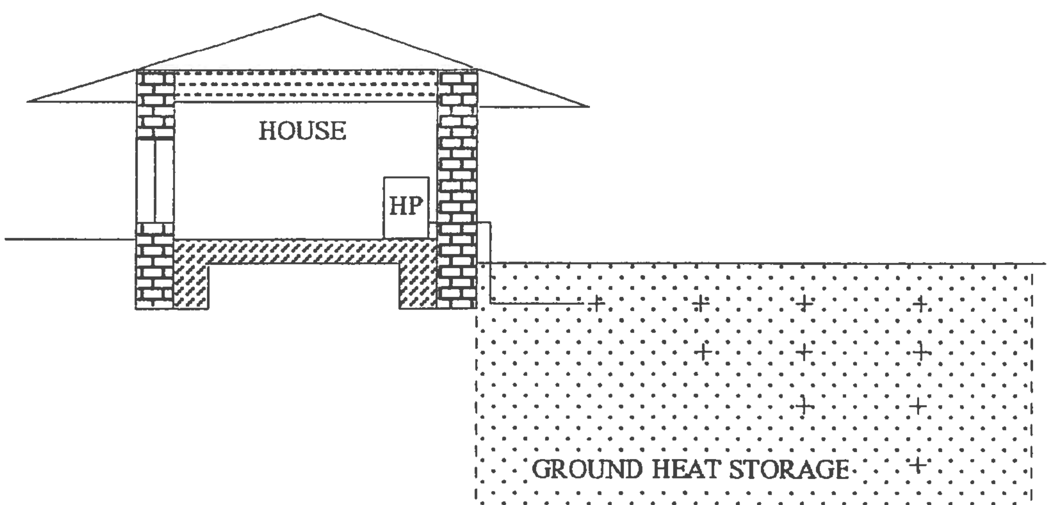

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I G-HEADS - Introduction

G-HEADS is a computer software package developed at Saint Mary's University by Dr. Vlodek Tarnawski and Mr. Wey Herng Leong (B.Eng). This is the first completely computerized approach to ground heat pump engineering and as implied by the name (G-HEADS = Ground Heat Exchanger Analysis, Design and Simulation) it helps to perform the following tasks:

Analysis of ground heat storage to elucidate interactions between a ground heat exchanger (GHE) - surrounding soil - heat pump unit - house. The analysis enables proper selection of the horizontal GHE configuration i.e., single layer, double or multiplelayer, and pipe arrangement (series or parallel).

Design of the GHE is achieved by testing the performance of the entire system described by different design parameters such as: pipe spacing (horizontal and vertical), pipe length, pipe material/diameter, ground coil fluid, different soil (backfill), heating/cooling load etc. These parameters are entered into a microcomputer by the designer of the ground heat pump system.

Simulation of the thermal performance of the system and temperature and soil-moisture regimes around the GHE can be performed on a half-day basis over any time length from one day up to any number of years.

II G-HEADS - Competence

The present version of this package is limited to a horizontal GHE configuration and provides the following features:

- Analyzing heat and moisture migration in unsaturated soils in two different modes

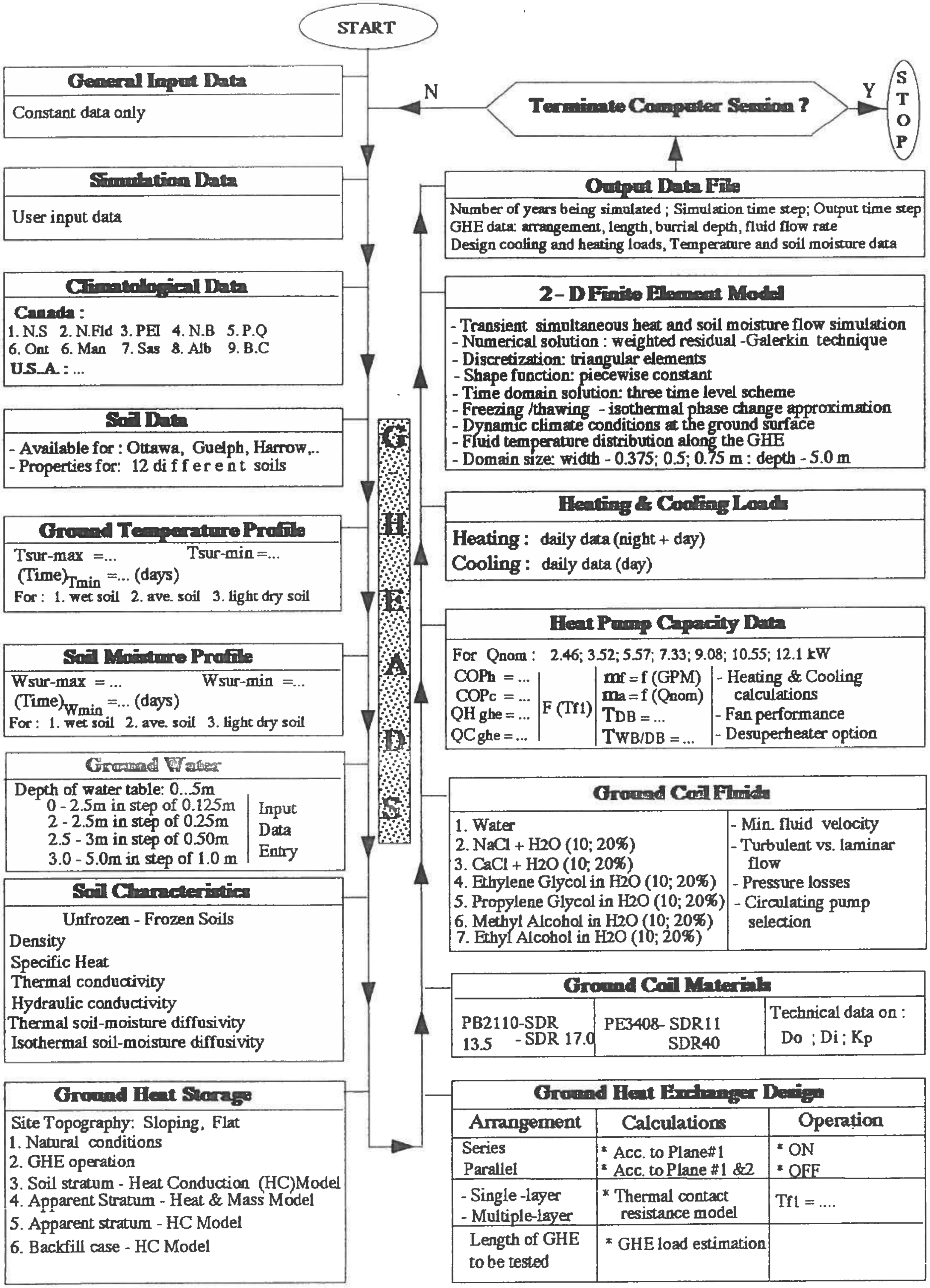
* a coupled model - simultaneous flow of heat and soil-moisture
* a decoupled model - pure heat conduction only

- Analyzing heat transfer in unsaturated /saturated soils with the presence of a water table
- Large variety of different soils - any soil from sand to clay
- Modeling any soil stratum using decoupled model
- Modeling freezing/thawing and drying/rewetting of soil-moisture
- Frost heave warnings
- Calculating real fluid flow in the ground coil
- Selection of all available ground coil fluids
- Calculation for pipe wall thermal resistance
- Modeling thermal contact resistance between tube and surrounding soil (to be developed)
- Selection of all available pipe sizes and materials
- Wide range of GHE design parameters such as:
  * single, double or multiple-layer system
  * series or parallel arrangement
  * length of GHE
  * burial depths (vertical spacing)
  * horizontal spacing
- Selection of heat pump models manufactured by Water Furnace International. Possibility of continued update of this file if other companies are able to provide comprehensive heat pump capacity data
- Sizing the heat pump system
- Modeling on/off operation of the heat pump unit
- Selecting a ground coil fluid circulation pump
- Longitudial variation of ground coil fluid temperature
- Sizing of air distribution system (to be developed)

- Comprehensive climatological data, on a daily basis, including: ambient temperature, short -and longwave solar radiation, wind velocity, rainfall, evapotranspiration, snowfall, cloudiness, etc. These files are available for Ottawa, Fredericton, Kentville (N.S.). There is a possibility of creating additional files for selected places in Canada.
- Topography of the ground heat storage surface (level, inclined)
- Heating and/or cooling load on a daily basis as supplied by the designer
- Possibility of full or partial coverage of heating and/or cooling requirements
- Unlimited simulation time, i.e., from 12 hrs up to any number of years under consideration
- Seasonal Performance Factor (SPF) is currently calculated and displayed along with other useful data important for the design of the ground heat pump system
- Optimum design option could also be available saving a designer a lot of time (to be developed). The designer would enter a range of design parameters such as:
  * single layer - double layer
  * series - parallel arrangement
  * vertical spacing: 0.5 to 2.00 m in step of 0.25 m
  * horizontal spacing: 0.5 to 1.50 m in step of 0.50 m
  * pipe length: 200 to 500 m in step of 50 m
  * pipe diameter/material
  * ground coil fluid
  * type of soil
  * simulation time

  G-HEADS will calculate all possible design cases and select the best one displying on the monitor all design parameters involved
- User friendly menu driven program.

The general structure of G - HEADS computer package and its potential capacity is shown on the next page.


START
General Input Data
Constant data only
Simulation Data
User input data
Climatological Data
Canada :
1. N.S 2. N.Fld 3. PEI 4. N.B 5. P.Q
6. Ont 6. Man 7. Sas 8. Alb 9. B.C
U.S.A. : ...
Soil Data
- Available for : Ottawa, Guelph, Harrow,..
- Properties for: 12 different soils
Ground Temperature Profile
Tsur-max =... Tsur-min =...
(Time)Tmin =... (days)
For : 1. wet soil 2. ave. soil 3. light dry soil
Soil Moisture Profile
Wsur-max = ... Wsur-min =...
(Time)Wmin =... (days)
For : 1. wet soil 2. ave. soil 3. light dry soil
Ground Water
Depth of water table: 0...5m
0 - 2.5m in step of 0.125m
2 - 2.5m in step of 0.25m
2.5 - 3m in step of 0.50m
3.0 - 5.0m in step of 1.0 m
Input Data Entry
Soil Characteristics
Unfrozen - Frozen Soils
Density
Specific Heat
Thermal conductivity
Hydraulic conductivity
Thermal soil-moisture diffusivity
Isothermal soil-moisture diffusivity
Ground Heat Storage
Site Topography: Sloping, Flat
1. Natural conditions
2. GHE operation
3. Soil stratum - Heat Conduction (HC)Model
4. Apparent Stratum - Heat & Mass Model
5. Apparent stratum - HC Model
6. Backfill case - HC Model
GHEADS
N
Terminate Computer Session ?
Y
STOP
Output Data File
Number of years being simulated ; Simulation time step; Output time step
GHE data: arrangement, length, burrial depth, fluid flow rate
Design cooling and heating loads, Temperature and soil moisture data
2 - D Finite Element Model
- Transient simultaneous heat and soil moisture flow simulation
- Numerical solution : weighted residual -Galerkin technique
- Discretization: triangular elements
- Shape function: piecewise constant
- Time domain solution: three time level scheme
- Freezing /thawing - isothermal phase change approximation
- Dynamic climate conditions at the ground surface
- Fluid temperature distribution along the GHE
- Domain size: width - 0.375; 0.5; 0.75 m : depth - 5.0 m
Heating & Cooling Loads
Heating : daily data (night + day)
Cooling : daily data (day)
Heat Pump Capacity Data
For Qnom : 2.46; 3.52; 5.57; 7.33; 9.08; 10.55; 12.1 kW
COPh = ...
COPc = ...
QH ghe = ...
QC ghe = ...
F (Tf1)
mf = f (GPM)
ma = f (Qnom)
TDB = ...
TWB/DB = ...
- Heating & Cooling calculations
- Fan performance
- Desuperheater option
Ground Coil Fluids
1. Water
2. NaCl + H2O (10; 20%)
3. CaCl + H2O (10; 20%)
4. Ethylene Glycol in H2O (10; 20%)
5. Propylene Glycol in H2O (10; 20%)
6. Methyl Alcohol in H2O (10; 20%)
7. Ethyl Alcohol in H2O (10; 20%)
- Min. fluid velocity
- Turbulent vs. laminar flow
- Pressure losses
- Circulating pump selection
Ground Coil Materials
PB2110-SDR 13.5 - SDR 17.0
PE3408- SDR11 SDR40
Technical data on : Do ; Di ; Kp
Ground Heat Exchanger Design
Arrangement
Calculations
Operation
Series
Parallel
* Acc. to Plane#1
* Acc. to Plane #1 &2
* ON
* OFF
- Single -layer
- Multiple-layer
* Thermal contact resistance model
Tf1 = ...
Length of GHE to be tested
* GHE load estimation

III G-HEADS - Applications to other related fields of engineering

This computer package after, relatively simple modifications, may become a powerful tool in the designing of engineering structures and installations in other fields of engineering such as:

- District heating underground pipes
- Gas and oil pipe lines
- Utilization of waste heat from power plants in soil warming (extension of the growing season)
- Buried high voltage power cables
- Long-term storage of high-level radioactive waste from nuclear reactors
- Roads and airfields in northern climates (frost heave)
- Artificial freezing of the ground for special mining and civil engineering applications

IV G-HEADS in Design Office

A serious designer of a ground heat pump system by using this package, can carry out a detailed computer analysis of the entire system being designed i.e., house - heat pump - ground heat exchanger - soil - climatic conditions, in order to select the most efficient solution. G-HEADS allows the designer to test the full range of design possibilities. Once the final solution is obtained its performance is tested over a long period of time, in the range of 1-3 years.

V G-HEADS - How to use it ?

The G-HEADS user need not be knowledgeable about computing and shall only enter the following data from a keyboard by answering the following questions:

Q1: Please type the output file name

Notice: You can type a file name consisting up six characters, but the first one must be a letter, followed by the extension .DAT . Press RETURN {**R**}

Example: SAND.DAT {**R**}

Q2: Please enter the number of years to be simulated (whole number)

Notice: The minimum number is 1 but you may enter also a larger number. This, however, will lead to longer computation time, which for 1 year would be about 150 minutes on the IBM PC.

Example: 1 {**R**}

Q3: Please enter the simulation time increment (STI)

Notice: Recommended values are: 12 or 24 (hours)

Example: 12 {**R**}

Q4: Please enter the output time step for the output data (multiplication of STI)

Notice: If you want to screen the output data every simulation time increment, then type the same number as in Q.2.

Example: 12 {**R**}

Notice: If you want to control the output data over a longer simulation time step, then enter multiplication of STI e.g.: 120, 180, 600,...

Example: 120 {**R**}

Q5: Please enter the time (multiplication of STI) for a specific time date

Notice: If you want to know the the ground heat exchanger performance at a specific date , then enter

the number of hours counted from the begining of simulation (multiplication of STI).

Example: Date of the begining of simulation :15th of August (Fixed date for G-HEADS)

Specific time date : 13th of October

The number to be entered : (17+30+13)*12*2 = 1440 {R}

If you do not have any specific date to control, enter: 9999 {R}

Q6: Select the case number for horizontal pipe spacing

1... HORIZONTAL PIPE SPACING of 0.5 m (1.5 ft)

2... HORIZONTAL PIPE SPACING of 1.0 m (3.5 ft)

3... HORIZONTAL PIPE SPACING of 1.5 m (5.0 ft)

Example: If you want to investigate the pipe spacing of 1.0 m, then enter

2 {R}

Q7: Enter the code number of the city for which the climatological data is available

1... FREDERICTON, New Brunswick

2... KENTVILLE, Nova Scotia

3... OTTAWA, Ontario

Example: If you want to simulate a site located in Ottawa, then enter

3 {R}

Q8: Enter the simulation mode

1...SOIL LAYERS with fixed values of MOISTURE CONTENT

(Model 1: pure heat conduction)

2... SOIL LAYERS - converted into apparent uniform soil domain

(Model 2: pure heat conduction)

3... SOIL LAYERS - converted into apparent uniform soil domain

(Model 3: coupled heat and moiture flow)

Model 1: The ground can be divided into a number of different soil type layers each having a fixed and different moisture content throughout the entire simulation time.

Model 2: Soil layers are replaced by an apparent uniform soil in the entire domain. Software automatically calculates the following apparent parameters according to contribution of each layer : porosity, density, clay fraction, silt fraction. The initial soil moisture content in the entire domain is predicted by the computer for the 15th of August.

Model 3: Soil layers are, as above, replaced by uniform soil and simultaneous heat and moisture flow is taken into account. This model predicts dynamic changes of soil moisture and soil temperature in ground heat storage due to heat extraction or deposition.

Exapmle: If you want to use the model of coupled heat and moisture flow, then enter:

3 {R}

Q9: Enter the code number of the city for which the soil stratum data is available

Notice: The following data is provided: soil type, layer thicknesses, density, silt and clay mass fractions, and moisture content

1... GUELPH, Ontario

2... HARROW, Ontario

3... OTTAWA, Ontario

4... Other (self-entered data)

Example: If you intend to use ready soil stratum data for Ottawa, then enter:

3 {R}

If you have your own soil stratum data to enter, then select :

4 {R}

and answer next two questions

Q10: Enter the number of layers for soil stratum between 0 and 5.0 m

Notice: The maximum number of soil layers is 21 within the ground depth of 5.0 m

The minimum number of soil layers is 1

Example: If you intend to use a uniform stratum throughout the domain, then enter:

1 {R}

Q11: Enter the following data for layer #1 of 1

			Dry bulk density
I	Soil Type	1... SAND:	1480 - 1785 kg/m^3
		2... LOAMY SAND:	1410 - 1775 kg/m^3
		3... SANDY LOAM:	1290 - 1760 kg/m^3
		4... LOAM:	1270 - 1695 kg/m^3
		5... SILT LOAM:	1230 - 1550 kg/m^3
		6... SILT:	1120 - 1600 kg/m^3
		7...SANDY CLAY LOAM:	1405 - 1725 kg/m^3
		8... CLAY LOAM:	1270 - 1560 kg/m^3
		9... SILTY CLAY LOAM:	1260 - 1565 kg/m^3
		10...SANDY CLAY:	1395 - 1710 kg/m^3
		11...SILTY CLAY:	1200 - 1545 kg/m^3
		12...CLAY:	1265 - 1535 kg/m^3

II Layer thickness (up to total ground depth of 5.0 m)

III Dry bulk density of soil

IV Mass fraction of silt (If you don't know, enter the number 9)

V Mass fraction of clay (If you don't know, enter the number 9)

Example: For SAND, one layer of soil throughout the domain, sand density 1650, and mass fractions of silt and clay assigned by G-HEADS, your entry has the following form:

1	{R}
5	{R}
1650	{R}
9	{R}
9	{R}

Q12: Enter the data for the initial profile of soil temperature

1. MAXIMUM ground SURFACE TEMPERATURE in a year
2. MINIMUM ground SURFACE TEMPERATURE in a year
3. The day (number of days) since January 1st when MINIMUM GROUND SURFACE TEMPERATURE was recorded

Example: This data is taken from a Monthly Record of Soil Temperature and can be obtained from the Atmospheric Environment Service of Environment Canada.

For Ottawa records from 1987 the following data is entered:

21	{R}
-1.5	{R}
30	{R}

Q13: Enter expected soil moisture condition in ground heat storage in a year

1... WET Soil

2... AVERAGE Soil

3... LIGHT DRY Soil

Example: Graphical interpretation of soil moisture conditions can be found in Appendix UM#1. Selecting the average soil, the entry is as follows:

2	{R}

Q14: Enter the data for the initial profile of soil moisture content

1. MAXIMUM ground SURFACE MOISTURE CONTENT (% dry mass) in a year
2. MINIMUM ground SURFACE MOISTURE CONTENT (% dry mass) in a year
3. The day (number of days) since January 1st when MINIMUM GROUND SURFACE MOISTURE CONTENT was recorded

Example: This data is taken from Technical Bulletin # 84 (1975) which can be obtained from LRRC, Agmet Section, Agriculture Canada

For Ottawa soil conditions at the Agrometeorological Station the following data is entered:

35 {R}

7 {R}

194 {R}

Q15: Is ground water table within the depth range of 0 to 5.0 m ?

1... YES

2... NO

Example: If you expect ground water in the site, then enter 1

1 {R}

Q16: Enter the average depth of water table in the site, in a year

Notice: The following standard water table depths are allowed by G-HEADS

Within the depth of 0 to 2.0 m you may enter data with depth increment of 0.125m

Remaining standard water table depths are: 2.25 m, 2.50 m, 3.0 m, 4.0 m, 5.0 m

Example: If you have information that the water table depth is about 1.5 m, then

1.5 {R}

Q17: Please enter the type of site topography

1... Slightly sloping (intense rainfall or snow melt will produce surface runoff)

2... Level (intense rainfall or snow melt will produce surface ponding)

Example: If the site under investigation has sloping configuration, then enter 1.

1 {R}

Q18: Do you want to carry out simulation for site natural conditions ?

Notice: Site natural conditions mean no ground heat pump operation

1... YES

2... NO

Example: If you do not intend to investigate the thermal and moisture regime in the ground under natural conditions then enter the number 2.

2 {R}

Q19: Please select the system of the ground coil

Single-layer:	1... SERIES
	2... PARALLEL
Double-layer	3... SERIES - Counterflow
	4... PARALLEL - Counterflow
	5... PARALLEL - Parallelflow
Three-layer	6... PARALLEL - Parallelflow
Four-layer	7... SERIES - Counterflow
	8... PARALLEL - Counterflow
	9... PARALLEL - Parallelflow

Notice: Schematics of all above systems are presented in Appendix UM#2

Example: If you intend to investigate the system #1, then enter

1 {R}

Q20: Please select the method of approximating the length of the GHE

(GHE - Ground Heat Exchanger)

1... LINE SOURCE THEORY (see Q37...Q41)

2... DIMENSIONS of site surface area

Example: If you intend to consider the size of the site under investigation, then

2 {R}

Q21: Enter the site LENGTH and WIDTH assigned for ground heat storage

Notice: The number of pipes in parallel arrangement is computed on the basis of site breadth.

Example: If for instance LENGTH = 25, and WIDTH = 20 then

25 {R}

20 {R}

Q22: Please enter the pipe depth for pipe layer #1 of 1 (≤ 2.0 m)

Notice: Within the depth of 2.0 m, you may theoretically select any value in steps of 0.125 m.

Example: For the pipe buried at a depth of 1.0 m, you shall enter

1.0 {R}

Q23: Please select the pipe code number

Notice: The code number is taken from the Table 1.

Please note that the first 10 pipes are made of Polyethlene, whereas the remaining are of Polybutylene

Example: For the pipe described by code #1, enter as follows

1 {R}

Table 1 Plastic Pipe Sizes and Pipe Thermal Conductivity

Code #	Description	Nominal Size	D_o	D_i	K_p
	-	inch	mm	mm	W/mK
1	SDR - 11	3/4	26.67	21.84	0.3899
2	"	1	33.40	27.35	0.3899
3	"	1 1/4	42.16	34.49	0.3899
4	"	1 1/2	48.26	39.47	0.3899
5	"	2	60.325	49.35	0.3899
6	SCH - 40	3/4	26.67	20.93	0.3915
7	"	1	33.40	26.64	0.3915
8	"	1 1/4	42.16	35.05	0.3915
9	"	1 1/2	48.26	40.89	0.3915
10	"	2	60.325	52.50	0.3915
11	SDR-17 (IPS)	1 1/2	48.26	42.57	0.2159
12	"	2	60.325	53.21	0.2159
13	SDR-13.5 (CTS)	1	28.57	24.31	0.2210
14	"	1 1/4	34.92	29.74	0.2210
15	"	1 1/2	41.27	35.18	0.2210
16	"	2	53.97	46.00	0.2210

Q24: Please enter the code number of the ground coil fluid

Notice: The following ground coil fluids are covered by G-HEADS (Table 2)

Example: For the ground coil fluid marked by 2, enter as follows

2 {**R**}

Table 2. Ground Coil Circulating Fluids

Code #	Fluid Description	Concentration % by mass of water	Freezing Point T_f - °C
1	Methyl Alcohol in Water	10	- 4.14
2	" " "	20	- 12.22
3	Ethyl Alcohol in Water	10	- 4.25
4	" " "	20	-10.00
5	Sodium Chloride in Water	10	- 6.70
6	" " "	20	- 17.00
7	Calcium Chloride in Water	10	- 5.00
8	" " "	20	-16.40
9	Ethylene Glycol in Water	10	- 4.00
10	" " "	20	- 9.00
11	Propylene Glycol in Water	10	- 2.50
12	" " "	20	- 7.80
13	Water	100	0.00

Q25: Please enter the data about the heating season :

- the DESIGN HEATING LOAD (kW)
- Heat Pump TOTAL OPERATING TIME (months) in the heating season

Example: For the design heating load of 8.0 kW, and a heating season of 5.5 months, the entry is as follows.

8 {R}

5.5 {R}

Q26: Please enter the data about the cooling season :

- the DESIGN COOLING LOAD (kW)
- Heat Pump TOTAL OPERATING TIME (months) in the cooling season

Notice: The total heat pump operating time ≤ 12 months

Example: For a design cooling load of 4.5 kW, and a cooling season of 3.5 months, the entry is as follows.

4.5 {R}

3.5 {R}

Q27: Please select the code number corresponding to the heat pump model

Monitor display: Select the nearest number to WX027.

Notice: The number 27 was obtained by converting the design heating load expressed in kW into * 10^3 BTU/hr, i.e. 8.0 * 3.412 ≈ 27. The heat pump models covered by G-HEADS are listed in Table 3.

Table 3. Heat pump models covered by G-HEADS

Code #	Model Type	Nominal Cooling	Ground Flow	Coil Rate	Fluid V_f
-	-	kW	m^3/h {1}	m^3/h {2}	m^3/h {3}
1	WX009	2.636	0.341	0.454	0.568
2	WX012	3.52	0.341	0.568	0.795
3	WX019	5.565	0.568	0.795	1.022
4	WX025	7.322	0.681	1.022	1.363
5	WX031	9.086	0.908	1.363	1.817
6	WX036	10.55	1.022	1.590	2.044
7	WX041	12.008	1.135	1.817	2.498

Example: The nearest heat pump model to WX027 is WX031, having a code number of 5.

5 {R}

Q28: Please select the ground coil fluid volumetric flow rate

Monitor display:

1... 4.00 GPM; REY= 2540. ; v_f = 0.67 m/s at T_{wf} = -10.2 °C (RECOMMENDED)

2... 6.00 GPM; REY= 3810. ; v_f = 1.01 m/s at T_{wf} = -10.2 °C (RECOMMENDED)

3...8.00 GPM; REY= 5080. ; v_f = 1.35 m/s at T_{wf} = -10.2 °C (RECOMMENDED)

where: $T_{wf} = T_{f*} + 2$ °C ; T_{f*} = freezing point of ground coil fluid temperature

Comments: For the selected diameter of the GHE, working fluid, and the heat pump model, the Reynolds numbers (REY) show the turbulent flows. Therefore each volumetric flow rate is recommended.

If the flow regime in the pipe is laminar, the user still has an oportunity to modify the previous selections by changing:

1... Pipe diameter

2... Ground coil fluid

3... Depth(s) of pipe(s) and fractions of flow rates for the multiple-layer system

4... GHE system

5... No change

Example: The case number 1 from the computer display is selected.

1 {R}

Q29: Please enter the entering air temperatures to the heat pump unit

Notice: The entering air may be 100% return air, 100% outdoor air, or a mixture of both

Monitor display: For the summer :: 1... 24 °C Dry Bulb & 17 °C Wet Bulb

2... 27 °C Dry Bulb & 19 °C Wet Bulb

3... 29 °C Dry Bulb & 22 °C Wet Bulb

Example: For the $T_{DB} = 24$ °C and $T_{WB} = 17$ °C, the entry is as follows:

1 {R}

Monitor display: For the winter :: 1... 16 °C Dry Bulb

2... 21 °C Dry Bulb

3... 27 °C Dry Bulb

Example: For the $T_{DB} = 16$ °C, the entry is as follows:

1 {R}

Q30: Please indicate how the heating and/or the cooling load will be obtained

1...Heating and Cooling Load File (H&CL) - see Appendix UM#3 for details

2...SIMPLIFIED FORMULA

Example: If the simplified formula is selected, then

2 {R}

Q31: For the heating season, please enter T_{1H}, A_1, and A_2.

The formula used is as follows: $Q_h(W) = A_1 + (T_{1H} - T_A) + A_2 * Wv * (T_{1H} - T_A)$

Example: For $T_{1H} = 21.1$; $A_1 = 100$; $A_2 = 11$, the entry has the following form:

21.1 {R}

100 {R}

11 {R}

Q32: For the cooling season, please enter T_{1C}, A_1, and A_2, A_3, and A_4.

The formula used is as follows: $Q_c(W) = A_1 + (T_A - T_{1C}) + A_2 * Wv * (T_A - T_{1C}) + A_3 * Q_{si} + A_4$

Example: For $T_{1C} = 24.4$; $A_1 = 1400$; $A_2 = 50$; $A_3 = 9.54$; $A_4 = 500$

the entry has the following form:

24.4 {R}

1400 {R}

50 {R}

9.54 {R}

500 {R}

Q33: Enter the minimum outdoor temperature turning the heat pump unit from COOLING to HEATING mode.

Notice: This value should be obtained from practical recommendations

Example: For the turning temperature of 10 °C, the entry is as follows:

10 {R}

Q34: Enter the min.heating load (kW), above which the heat pump begins to operate

Notice: This value should be obtained from practical recommendations

Example: For the input value of 1.0 kW, the entry is as follows:

1.0 {R}

Q35: Enter the min.cooling load (kW), above which the heat pump begins to operate

Notice: This value should be obtained from practical recommendations

Example: For the input value of 1.0 kW, the entry is as follows:

1.0 {R}

Q36: Do you wish to get the data output after each "on - time" operation ?

1... YES

2... NO (Data output is after each Simulation Time Increment, i.e. 12 or 24hrs)

Example: If you want to investigate the GHE performance after each "on - time" then, enter option 1.

1 {R}

Q37: Please enter the number of hrs for continuous heating operation

Notice: This number shall be obtained from experience, for a particular geographical location.

Example: For 3000 hrs of continuous heating operation, the entry is as follows

3000 {R}

Q38: Please enter the number of hrs for continuous cooling operation

Notice: This number shall be obtained from experience, for a particular geographical location.

Example: For 1500 hrs of continuous cooling operation, the entry is as follows

1500 {R}

Q39: Please enter the heating run fraction

Notice: The heating run fraction is defined as:: (Heating Season Run Hours) /(Total Time of Heating Season)

Example: For the heating run fraction of 0.51, the entry is as follows:

0.51 {R}

Q40: Please enter the cooling run fraction

Notice:The cooling run fraction is defined as::(Cooling Season Run Hours) /(Total Time of Cooling Season)

Example: For the cooling run fraction of 0.60, the entry is as follows:

0.60 {R}

Q41: Calculated length of the GHE

Monitor display: The length of the GHE required for the heat pump heating capacity at

T_{f1}= EWT= -1.1 °C is:: 1082 m.

The length of the GHE required for the heat pump cooling capacity at

T_{f1}= EWT= 43.3 °C is:: 613 m.

Please enter the modified length of the GHE

Notice: The designer shall decide which length is more appropriate for a particular climatic and site conditions and make the necessary length adjustment.

Example: If average length is selected, then the entry is as follows:

850 {R}

VI SAMPLE of OUTPUT DATA FILE

Simulation Data

Number of year(s) being simulated is:	1.0	year(s)
Simulation time step is:	24.0	hrs
Output time step is:	24.0	hrs
Pipe code number is:	1	
Pipe outside diameter is:	0.027	m
Pipe inside diameter is:	0.022	m
Pipe thermal conductivity is:	0.390	W/mK
Design cooling load is:	3.5	kW
Design heating load is:	8.0	kW
Heat pump code number is	5	
Ground coil fluid flow rate is:	0.908	m^3/h
The code of the GHE system is:	1	
Total length of the GHE is:	850	m
Area of the site is:	500	m^2
The depth of the pipe layer #1 is	1.00	m

VII G-HEADS - Computer Hardware Requirements

(i) IBM PC XT/AT or compatible

(ii) Minimum 512 kB RAM

(iii) $5\frac{1}{4}$ or $3\frac{1}{2}$ inch disk drive

(iv) Optional Math Co-Processor

(v) Optional Hard Drive

Due to the large number of mathematical calculations (finite element model), the speed of G-HEADS will be greatly increased if it is run on an AT class computer with math co-processor.

Notice: The hard drive is optional, but loading the program into memory will be again much faster if one is used.

To Start: Place the program diskette in the drive A and type

A> *** {R}

The package may also be run from the drive B or the hard drive.

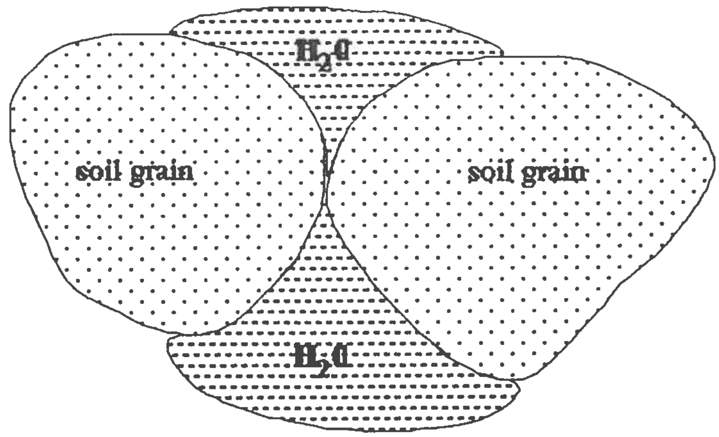
VIII G-HEADS - Enhancement

In the near future this package will be upgraded by adding the following features:

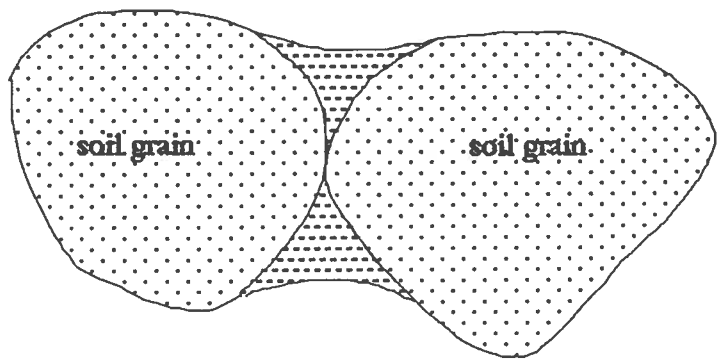
- Implementation of current suggestions from industry
- Vertical configuration of ground heat exchangers with series or parallel arrangement
- Ground heat pump design criteria
- Additional climatological files for selected places in Canada
- Hourly simulation of the entire system
- Mathematical model of a direct expansion system
- Dynamic model of the entire ground heat pump system (GHE - Heat Pump Unit - House - Ambient Conditions)
- Technical and economical analysis
- "Stratospherically safe" new refrigerants and hardware components as applied to a new generation of ground heat pumps.

APPENDIX UM#1 : Types of soil conditions encountered in ground heat storage

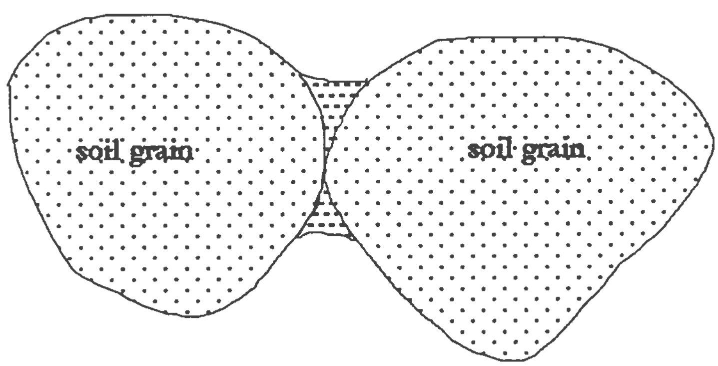
saturated soil



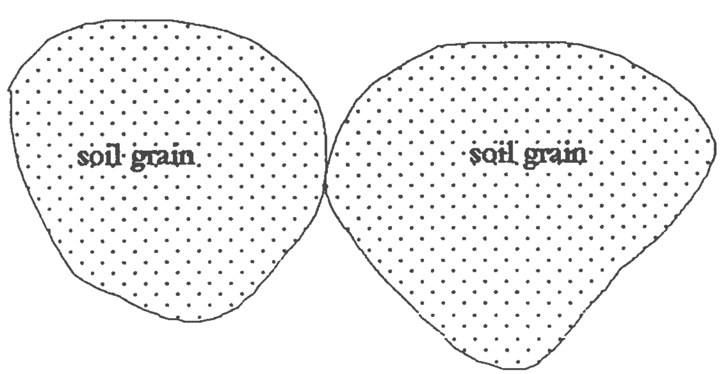
wet soil



average soil

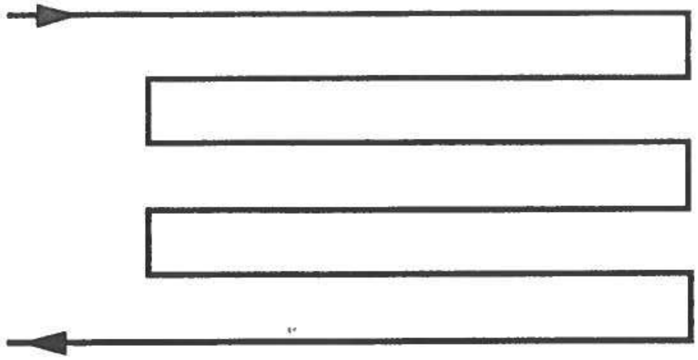


dry soil



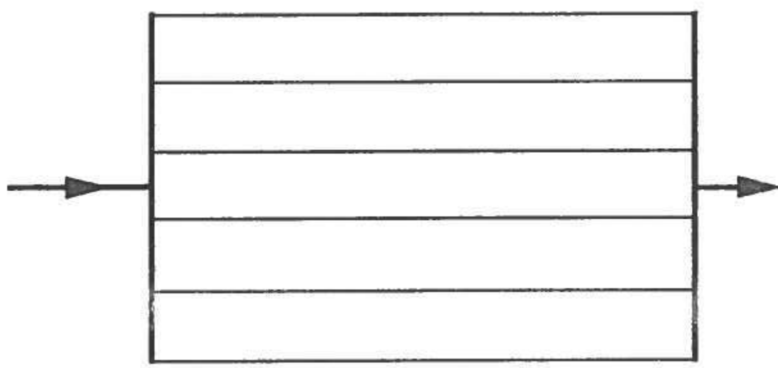
APPENDIX UM#2: Systems of Horizontal Ground Heat Exchangers

1. Single layer - series system



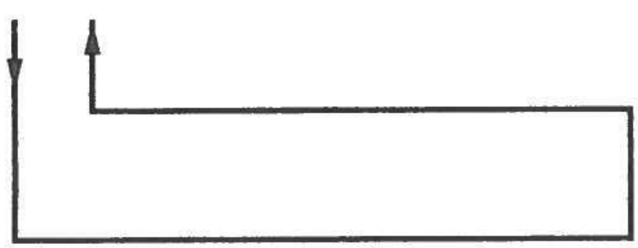
(Top view)

2. Single layer - parallel system



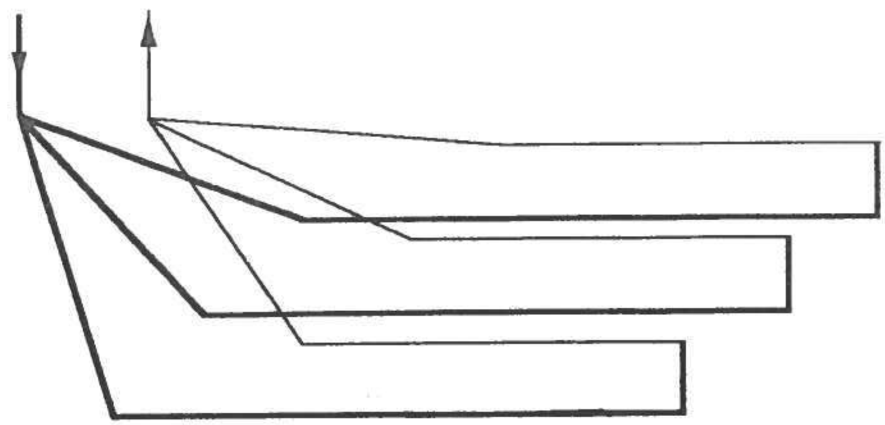
(Top view)

3. Double layer - series - counterflow

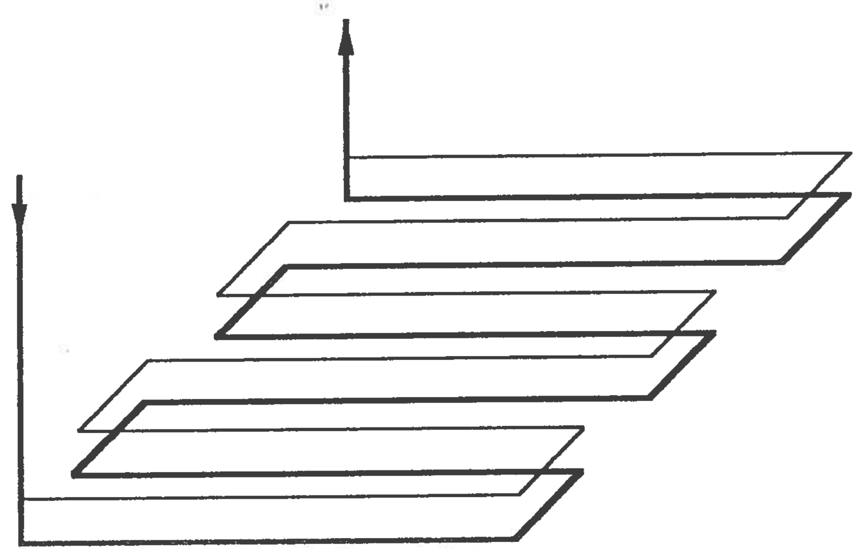


(Front view)

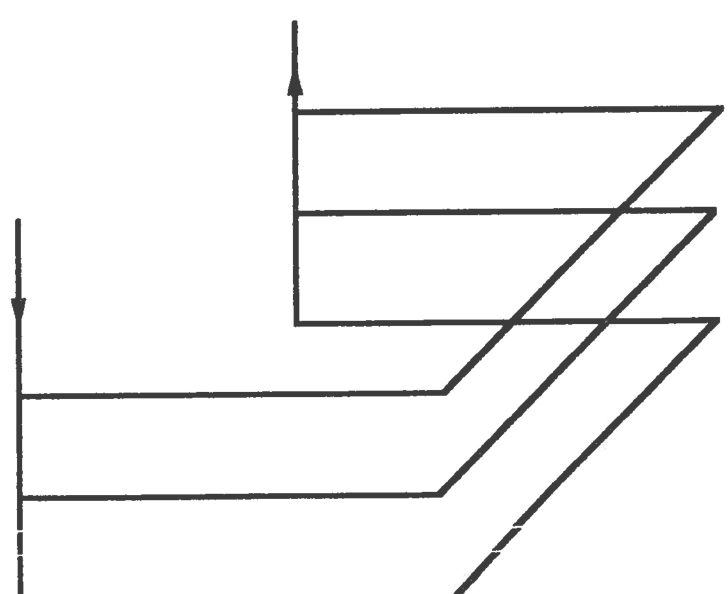
4. Double layer - parallel - counterflow



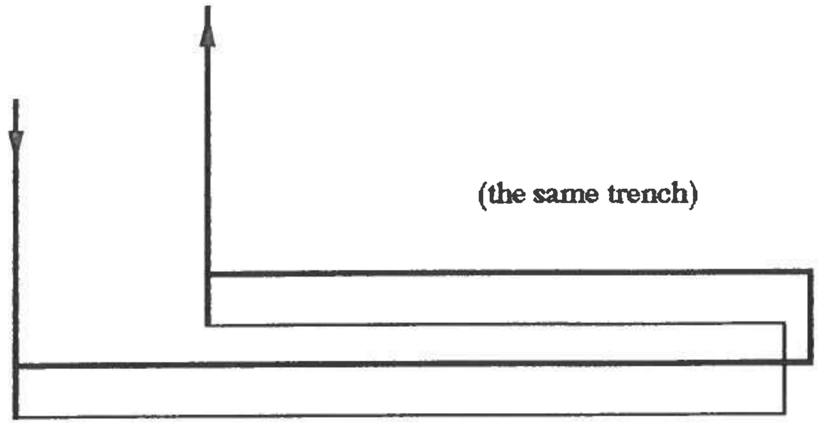
5. Double layer - parallel - parallel flow



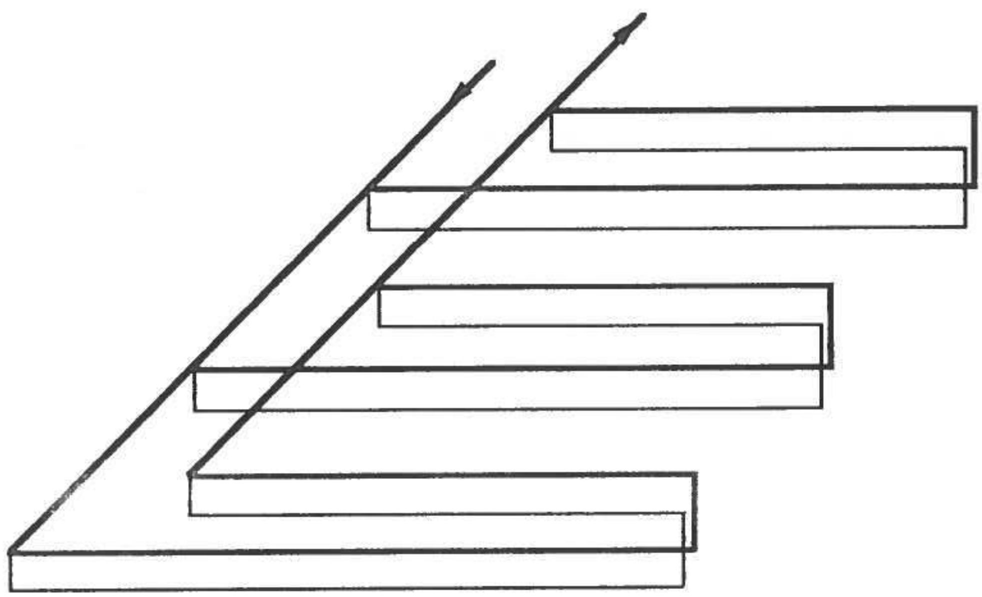
6. Triple layer - parallel - parallel flow



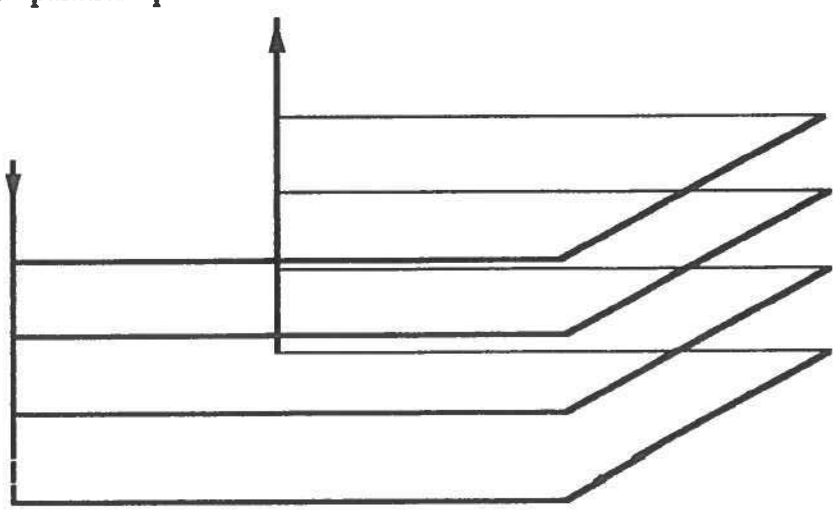
7. Four - layer - series - counterflow



8. Four - layer - parallel - counterflow



9. Four - layer - parallel - parallel flow



APPENDIX UM#3: Heating and Cooling Load File

You may create this file using any text editing software. Two columns shall be created, the first one is the day number (number one is corresponding to the date of August 15) and the second one is the heating or the cooling load expressed in Watts (W). The heating load shall be marked with negative sign, whereas the cooling load is a positive one.

A sample of heating and cooling load file named HCOTTA.DAT is shown below for first 40 days:

```
 1        0.00
 2     5360.36
 3     5670.80
 4     3326.13
 5     3310.73
 6     2382.61
 7     2687.52
 8     1609.60
 9        0.00
10        0.00
11        0.00
12     2581.13
13     1705.98
14     2104.40
15     2178.47
16     2190.41
17        0.00
18        0.00
19        0.00
20     2341.40
21     2777.08
22     2329.35
23     2037.82
24     2527.04
25        0.00
26        0.00
27     2310.58
28        0.00
29        0.00
30        0.00
31        0.00
32     1672.85
33     1665.25
34        0.00
35    -1569.19
36    -1884.65
37    -1924.95
38        0.00
39        0.00
40        0.00
```

APPENDIX UM#4: Computer Run Sample

A sample of user interaction is shown below:

```
-------------------------------------------------------------
|                                                           |
|                      G - H E A D S                        |
| (Ground Heat Exchanger Analysis, Design and Simulation)   |
|                                                           |
|            This software has been developed by            |
|              Dr. V.R. Tarnawski & W.H. Leong              |
| Saint Mary's University, Halifax, N.S., Canada B3H 3C3    |
|                                                           |
|       Enquiries regarding its use should be made to       |
|            National Research Council of Canada            |
|            Institute for Research in Construction         |
|            Ottawa, Ontario                                |
|            Canada K1A 0R6                                 |
|                                                           |
-------------------------------------------------------------

Please type the output-file name (up to 6 letters)
Ottawa.Sim

Please enter the number of years to be simulated (whole number)
(Minimum value of 1 (year) is required)
1

Please enter the simulation time increment(STI)
(Recommended values are 12 and 24 (hours))
24

Please enter the output time step for the output data
(Multiplication of STI)
240

Please enter the time (multiplication of STI)
for a specific time date
(If do not have any, please enter 9999)
4416

Please select the case number for horizontal pipe spacing

   1...HORIZONTAL PIPE SPACING OF 0.5 m (1.5 ft)
   2...HORIZONTAL PIPE SPACING OF 1.0 m (3.5 ft)
   3...HORIZONTAL PIPE SPACING OF 1.5 m (5.0 ft)
2

Please enter the city for which the climatological data is available

   1...FREDERICTON, NEW BRUNSWICK
   2...KENTVILLE, NOVA SCOTIA
   3...OTTAWA, ONTARIO
3

Please enter the simulation mode
```

```
    1...SOIL LAYERS WITH FIXED VALUES OF MOISTURE CONTENT
        (Model 1: Pure heat conduction)
    2...SOIL LAYERS-CONVERTED INTO APPARENT UNIFORM SOIL DOMAIN
        (Model 2: Pure heat conduction)
    3...SOIL LAYERS-CONVERTED INTO APPARENT UNIFORM SOIL DOMAIN
        (Model 3: Coupled heat and moisture flow)
3

Enter the code number of the city for which the soil stratum data is available
(i.e. soil type, layer thicknesses, density, silt & clay mass fractions,
moisture content)

    1...GUELPH, ONTARIO
    2...HARROW, ONTARIO
    3...OTTAWA, ONTARIO
    4...OTHER (self-entered data)
4

Enter the number of layers for soil stratum between 0 and 5 m
2

Enter the following data for layer #1 of 2:

    1. SOIL TYPE ( 1...SAND, 1480-1785 kg/m^3
                   2...LOAMY SAND, 1410-1775 kg/m^3
                   3...SANDY LOAM, 1290-1760 kg/m^3
                   4...LOAM, 1270-1695 kg/m^3
                   5...SILT LOAM, 1230-1550 kg/m^3
                   6...SILT, 1120-1600 kg/m^3
                   7...SANDY CLAY LOAM, 1405-1725 kg/m^3
                   8...CLAY LOAM, 1270-1560 kg/m^3
                   9...SILTY CLAY LOAM, 1260-1565 kg/m^3
                  10...SANDY CLAY, 1395-1710 kg/m^3
                  11...SILTY CLAY, 1200-1545 kg/m^3
                  12...CLAY, 1265-1535 kg/m^3)
    2. LAYER THICKNESS (up to 5.000 m)
    3. DRY BULK DENSITY OF SOIL
    4. MASS FRACTION OF SILT (If do not know, enter 9 for both)
    5. MASS FRACTION OF CLAY
7
0.45
1418.7
9
9

Enter the following data for layer #2 of 2:

    1. SOIL TYPE ( 1...SAND, 1480-1785 kg/m^3
                   2...LOAMY SAND, 1410-1775 kg/m^3
                   3...SANDY LOAM, 1290-1760 kg/m^3
                   4...LOAM, 1270-1695 kg/m^3
                   5...SILT LOAM, 1230-1550 kg/m^3
                   6...SILT, 1120-1600 kg/m^3
                   7...SANDY CLAY LOAM, 1405-1725 kg/m^3
                   8...CLAY LOAM, 1270-1560 kg/m^3
                   9...SILTY CLAY LOAM, 1260-1565 kg/m^3
                  10...SANDY CLAY, 1395-1710 kg/m^3
```

```
                    11...SILTY CLAY, 1200-1545 kg/m^3
                    12...CLAY, 1265-1535 kg/m^3)
   2. LAYER THICKNESS (up to 4.550 m)
   3. DRY BULK DENSITY OF SOIL
   4. MASS FRACTION OF SILT (If do not know, enter 9 for both)
   5. MASS FRACTION OF CLAY
1
4.55
1600
0.10
0.07

Enter the data for the initial profile of soil temperature:

   1. MAXIMUM GROUND SURFACE TEMPERATURE IN A YEAR
   2. MINIMUM GROUND SURFACE TEMPERATURE IN A YEAR
   3. THE DAY SINCE JANUARY 1st WHEN MINIMUM GROUND
      SURFACE TEMPERATURE WAS RECORDED
25
-1.5
18

Enter expected soil moisture condition in ground heat storage in a year

   1...WET SOIL
   2...AVERAGE SOIL
   3...LIGHT DRY SOIL
2

Enter the data for the initial profile of soil moisture content:

   1. MAXIMUM GROUND SURFACE MOISTURE CONTENT (% DRY MASS) IN A YEAR
   2. MINIMUM GROUND SURFACE MOISTURE CONTENT (% DRY MASS) IN A YEAR
   3. THE DAY SINCE JANUARY 1st WHEN MINIMUM GROUND SURFACE MOISTURE
      CONTENT WAS RECORDED
29
9
180

Is ground water table within the depth range of 0 to 5 m ?

   1...YES
   2...NO
1

Enter the average depth of water table in a year
from one of the following:
From 0 to 2 m with increment of 0.125 m, 2.25, 2.50, 3, 4, or 5 m
3

Please enter the type of site topography

   1...Slightly slopping
   2...Level
2

Do you want to carry out simulation for site natural conditions ?
(i.e. without ground heat pump operation)
```

```
    1...YES
    2...NO
2

Please select the arrangement of the ground coil

  Single layer:
    1...SERIES
    2...PARALLEL

  Double-layer:
    3...SERIES/COUNTERFLOW
    4...PARALLEL/COUNTERFLOW
    5...PARALLEL/PARALLEL-FLOW

  Three-layer:
    6...PARALLEL/PARALLEL-FLOW

  Four-layer:
    7...SERIES/COUNTERFLOW
    8...PARALLEL/COUNTERFLOW
    9...PARALLEL/PARALLEL-FLOW
1

Please select the method of approximating the length
of the ground heat exchanger

    1...LINE SOURCE THEORY
    2...DIMENSIONS OF SITE SURFACE AREA
1

You will be asked to enter the length of ground heat exchanger later
with providing more information according to line source theory.

Please enter the pipe DEPTH for pipe layer #1 of 1 (<= 2 m)
1

Please select the pipe code number

  Polyethylene:
    1...SDR-11    20mm (3/4")
    2...SDR-11    25mm (1")
    3...SDR-11    30mm (1.25")
    4...SDR-11    40mm (1.5")
    5...SDR-11    50mm (2")
    6...SCH 40    20mm (3/4")
    7...SCH 40    25mm (1")
    8...SCH 40    30mm (1.25")
    9...SCH 40    40mm (1.5")
   10...SCH 40    50mm (2")

  Polybutylene:
   11...SDR-17    40mm (1.5")
   12...SDR-17    50mm (2")
   13...SDR-13.5 25mm (1")
   14...SDR-13.5 30mm (1.25")
   15...SDR-13.5 40mm (1.5")
```

```
   16...SDR-13.5 50mm (2")
2

Please select the code number of the ground coil fluid

    1...10% METHANOL-IN-WATER SOLUTION, FP= -4.14 C
    2...20% METHANOL-IN-WATER SOLUTION, FP=-12.22 C
    3...10% ETHANOL-IN-WATER SOLUTION, FP= -4.25 C
    4...20% ETHANOL-IN-WATER SOLUTION, FP=-10.00 C
    5...10% SODIUM CHLORIDE-IN-WATER SOLUTION, FP= -6.70 C
    6...20% SODIUM CHLORIDE-IN-WATER SOLUTION, FP=-17.00 C
    7...10% CALCIUM CHLORIDE-IN-WATER SOLUTION, FP= -5.00 C
    8...20% CALCIUM CHLORIDE-IN-WATER SOLUTION, FP=-16.40 C
    9...10% ETHYLENE GLYCOL-IN-WATER SOLUTION, FP= -4.00 C
   10...20% ETHYLENE GLYCOL-IN-WATER SOLUTION, FP= -9.00 C
   11...10% PROPYLENE GLYCOL-IN-WATER SOLUTION, FP= -2.50 C
   12...20% PROPYLENE GLYCOL-IN-WATER SOLUTION, FP= -7.80 C
   13...WATER, FP= 0.00 C
4

Please enter the data about the heating season:
    1. the DESIGN HEATING LOAD (kW)
    2. heat pump TOTAL OPERATING TIME (months) in the heating season
8
7.1

Please enter the data about the cooling season:
    1. the DESIGN COOLING LOAD (kW)
    2. heat pump TOTAL OPERATING TIME (months) in the cooling season
5.5
3.5

Your design heating load is   8.00 kW, and total heating time is  6.0 months.
Your design cooling load is   5.50 kW, and total cooling time is  3.5 months.
Please select the code number corresponding to the heat pump model
with the nearest number to WX027

    1...WX0 9, NOMINAL COOLING=   2.64 kW
    2...WX012, NOMINAL COOLING=   3.52 kW
    3...WX019, NOMINAL COOLING=   5.57 kW
    4...WX025, NOMINAL COOLING=   7.32 kW
    5...WX031, NOMINAL COOLING=   9.08 kW
    6...WX036, NOMINAL COOLING=  10.55 kW
    7...WX041, NOMINAL COOLING=  12.01 kW
5

Please select the code number of ground coil fluid volumetric flow rate

    1... 4.00GPM; REY= 1532., V= 0.43m/s AT TWF=  -8.0C
    2... 6.00GPM; REY= 2298., V= 0.64m/s AT TWF=  -8.0C
    3... 8.00GPM; REY= 3064., V= 0.86m/s AT TWF=  -8.0C (RECOMMENDED)
3

Please select the entering air temperatures to the heat pump unit.
Note: The entering air may be 100% return air, 100% outdoor air,
      or a mixture of both.

 For the summer:
```

```
   1...24 DEG. C DRY BULB & 17 DEG. C WET BULB
   2...27 DEG. C DRY BULB & 19 DEG. C WET BULB
   3...29 DEG. C DRY BULB & 22 DEG. C WET BULB
2

 For the winter:
   1...16 DEG. C DRY BULB
   2...21 DEG. C DRY BULB
   3...27 DEG. C DRY BULB
1

Please indicate how the heating and/or cooling load will be obtained:

   1...READ FROM AN EXISTING FILE
   2...SIMPLIFIED FORMULA FOR HEATING AND COOLING LOAD
2

For the heating season, please enter TIH, A1, and A2 for
Qh(W)= A1*(TIH-TA) + A2*WV*(TIH-TA)
21.1
100
11

For the cooling season, please enter TIC, A1, A2, A3 and A4 for
Qc(W)= A1*(TA-TIC) + A2*WV*(TA-TIC) + A3*QSI + A4
24.4
1400
50
9.54
500

Please enter the minimum outdoor temperature
turning the heat pump unit from COOLING to HEATING mode
(This value should be obtained from experience)
10

Please enter the minimum heating load (kW)
above that heat pump begins to operate
1

Please enter the minimum cooling load (kW)
above that heat pump begins to operate
1.5

Please enter the number of hours of continuous heating operation
3000

Please enter the number of hours of continuous cooling operation
1500

Enter the heating run fraction
.51

Enter the cooling run fraction
.6

The length of ground heat exchanger required for the heating capacity
at EWT= -1.1 Deg.C is   747. m.
```

```
The length of ground heat exchanger required for the cooling capacity
at EWT= 43.3 Deg.C is   309. m.
Please enter the modified length of ground heat exchanger
530

Do you wish to get the data output after each "on-time" operation ?

   1...YES
   2...NO
2
```

A sample of the data output file named OTTAWA.SIM is partially shown in below which provides the results of ground temperatures, volumetric water and ice contents.

```
 ------------------------------------------------------------
|                                                            |
|                      G - H E A D S                         |
| (Ground Heat Exchanger Analysis, Design and Simulation)    |
|                                                            |
|            This software has been developed by             |
|              Dr. V.R. Tarnawski & W.H. Leong               |
| Saint Mary's University, Halifax, N.S., Canada B3H 3C3     |
|                                                            |
|        Enquiries regarding its use should be made to       |
|             National Research Council of Canada            |
|             Institute for Research in Construction         |
|             Ottawa, Ontario                                |
|             Canada K1A 0R6                                 |
|                                                            |
 ------------------------------------------------------------

                   SIMULATION DATA
                   ===============

Number of year(s) being simulated is     1. year(s)
Simulation time step is   24. h
Output time step is  240. h

Pipe code number is     2
Pipe outside diameter is  0.033 m
Pipe inside diameter is  0.027 m
Pipe thermal conductivity is  0.390 W/m.K

Design heating load is   8.0 kW
Design cooling load is   5.5 kW
Heat pump code number is     5
Volumetric flow rate is   8.0 GPM

Ground loop working fluid code number is     4
Freezing point of this working fluid is  -10.00 Deg. C

The design indoor-air temperature for  winter is   21.1 Deg. C
The heat loss coefficients of the simplified formula are:
   AH1=   100.0 W/K    AH2=    11.0 J/m.K
```

The design indoor-air temperature for summer is 24.4 Deg. C
The heat gain coefficients of the simplified formula are:

```
   AC1= 1400.0 W/K   AC2=   50.0 J/m.K   AC3=    9.5 m**2   AC4=  500.0 W
```

The minimum heating load that heat pump begins to operate is 1.0 kW
The minimum cooling load that heat pump begins to operate is 1.5 kW

The code of pipe loop arrangement is 1
Total length of ground heat exchanger is 530.0 m
Ground heat storage surface area required is 530. m**2
The depth of pipe layer #1 is 1.000 m

```
  Time= 240.000  dt= 24.000  TA= 13.1  QSI=  266.32  EA=  7.33  WV=  3.18
  RF=  0.00  SD= 0.00
  QHHE=     0.0  QGHE=     0.0  QDTMT=     0.0  COP= 0.00
  TW2= 40.30  TW1M= 20.57
  FON=0.000  PL= 530.00  FG= 530.00
  OFF-TIME
```

ENTRANCE OF GROUND LOOP-TW2

```
 0.00  14.5  14.3  14.4  14.3  0.3760  0.3763  0.3763  0.3766  0.0000  0.0000
0.0000  0.0000
 0.25  17.7  17.7  17.7  17.6  0.3690  0.3691  0.3690  0.3690  0.0000  0.0000
0.0000  0.0000
 0.50  19.9  19.9  19.8  19.5  0.3545  0.3544  0.3544  0.3541  0.0000  0.0000
0.0000  0.0000
 0.75  20.7  20.6  20.4  20.0  0.3429  0.3429  0.3430  0.3429  0.0000  0.0000
0.0000  0.0000
 1.00  20.1  20.6  20.1  19.5  0.3414  0.3416  0.3419  0.3421  0.0000  0.0000
0.0000  0.0000
 1.25  19.0  18.9  18.8  18.3  0.3462  0.3463  0.3464  0.3466  0.0000  0.0000
0.0000  0.0000
 1.50  17.2  17.2  17.1  16.8  0.3523  0.3523  0.3523  0.3523  0.0000  0.0000
0.0000  0.0000
 1.75  15.5  15.5  15.4  15.3  0.3583  0.3583  0.3583  0.3583  0.0000  0.0000
0.0000  0.0000
 2.00  14.1  14.1  14.1  14.0  0.3643  0.3643  0.3643  0.3642  0.0000  0.0000
0.0000  0.0000
 2.50  12.3              12.2  0.3758                  0.3755  0.0000
0.0000
 3.00  11.1              11.1  0.3865                  0.3854  0.0000
0.0000
```

EXIT OF GROUND LOOP-TW1

```
 0.00  14.4  14.2  14.2  14.2  0.3760  0.3762  0.3762  0.3765  0.0000  0.0000
0.0000  0.0000
 0.25  17.2  17.2  17.2  17.2  0.3690  0.3690  0.3690  0.3690  0.0000  0.0000
0.0000  0.0000
 0.50  19.0  19.0  18.9  18.8  0.3545  0.3544  0.3543  0.3541  0.0000  0.0000
0.0000  0.0000
 0.75  19.4  19.3  19.2  18.9  0.3431  0.3430  0.3430  0.3429  0.0000  0.0000
0.0000  0.0000
 1.00  18.7  19.0  18.7  18.3  0.3418  0.3419  0.3420  0.3421  0.0000  0.0000
0.0000  0.0000
 1.25  17.7  17.6  17.5  17.3  0.3464  0.3464  0.3465  0.3466  0.0000  0.0000
0.0000  0.0000
```

```
 1.50  16.2  16.2  16.2  16.0  0.3523  0.3523  0.3523  0.3523  0.0000  0.0000
0.0000  0.0000
 1.75  14.9  14.9  14.9  14.8  0.3583  0.3583  0.3583  0.3583  0.0000  0.0000
0.0000  0.0000
 2.00  13.8  13.8  13.8  13.7  0.3643  0.3643  0.3642  0.3642  0.0000  0.0000
0.0000  0.0000
 2.50  12.2              12.1  0.3758                  0.3754  0.0000
0.0000
 3.00  11.1              11.0  0.3865                  0.3854  0.0000
0.0000

  Time= 480.000  dt= 14.877  TA= 12.0  QSI=  280.00  EA=  8.98  WV=  1.30
  RF=  0.00  SD= 0.00
  QHHE=  2562.1  QGHE=-10397.5  QDTMT=-10325.9  COP= 3.14
  TW2= 37.95  TW1M= 28.65
  FON=0.325  PL= 530.00  FG= 530.00
  OFF-TIME

ENTRANCE OF GROUND LOOP-TW2
 0.00  17.8  17.9  17.9  17.9  0.3845  0.3846  0.3846  0.3848  0.0000  0.0000
0.0000  0.0000
 0.25  17.9  17.9  17.8  17.8  0.3843  0.3844  0.3845  0.3847  0.0000  0.0000
0.0000  0.0000
 0.50  18.9  18.8  18.7  18.6  0.3788  0.3789  0.3789  0.3790  0.0000  0.0000
0.0000  0.0000
 0.75  20.9  20.4  19.8  19.2  0.3671  0.3671  0.3671  0.3670  0.0000  0.0000
0.0000  0.0000
 1.00  23.1  22.6  20.6  19.3  0.3551  0.3560  0.3564  0.3564  0.0000  0.0000
0.0000  0.0000
 1.25  20.2  19.8  19.2  18.6  0.3523  0.3524  0.3524  0.3525  0.0000  0.0000
0.0000  0.0000
 1.50  17.9  17.8  17.7  17.5  0.3536  0.3536  0.3537  0.3537  0.0000  0.0000
0.0000  0.0000
 1.75  16.5  16.5  16.4  16.4  0.3573  0.3573  0.3573  0.3574  0.0000  0.0000
0.0000  0.0000
 2.00  15.2  15.2  15.2  15.2  0.3619  0.3618  0.3618  0.3618  0.0000  0.0000
0.0000  0.0000
 2.50  13.2              13.1  0.3711                  0.3708  0.0000
0.0000
 3.00  11.7              11.7  0.3800                  0.3787  0.0000
0.0000

EXIT OF GROUND LOOP-TW1
 0.00  17.5  17.6  17.6  17.6  0.3844  0.3845  0.3845  0.3847  0.0000  0.0000
0.0000  0.0000
 0.25  17.2  17.2  17.2  17.1  0.3843  0.3843  0.3844  0.3847  0.0000  0.0000
0.0000  0.0000
 0.50  17.8  17.8  17.7  17.6  0.3788  0.3788  0.3789  0.3790  0.0000  0.0000
0.0000  0.0000
 0.75  18.9  18.6  18.3  18.0  0.3671  0.3671  0.3671  0.3670  0.0000  0.0000
0.0000  0.0000
 1.00  20.0  19.7  18.6  17.9  0.3559  0.3563  0.3565  0.3564  0.0000  0.0000
0.0000  0.0000
 1.25  18.2  17.9  17.6  17.2  0.3525  0.3525  0.3525  0.3525  0.0000  0.0000
0.0000  0.0000
 1.50  16.6  16.5  16.5  16.4  0.3537  0.3537  0.3537  0.3537  0.0000  0.0000
0.0000  0.0000
```

1.75	15.5	15.5	15.5	15.4	0.3574	0.3574	0.3574	0.3573	0.0000	0.0000	0.0000	0.0000
2.00	14.5	14.5	14.5	14.5	0.3618	0.3618	0.3618	0.3618	0.0000	0.0000	0.0000	0.0000
2.50	12.9			12.8	0.3711			0.3707	0.0000			0.0000
3.00	11.6			11.6	0.3800			0.3787	0.0000			0.0000

APPENDIX UM#5: Technical Data of Water-to-Water Heat Pumps

In this user manual, the characteristics of water-source-type heat pumps manufactured by WaterFurnace International are used. The heat pump data is presented, however, in the form of graphs for different unit sizes, volumetric water flow rates, and heating & cooling operation. The following technical data is used to generate the necessary information for modelling of the GHPS:

- coefficient of performance (COP)
- total heat rejected to the ground(HR) - QC_{HE}
- total heat extracted from the ground (HE) - QH_{HE}
- temperature of ground-coil fluid (water) entering a heat pump unit (EWT) - T_{f1}.

The temperature T_{f1} is the main factor that determines other capacity data listed above. Other factors that effect heat pump capacity data are: the type of the ground coil fluid, its mass flow rate, and entering air temperature ($EA = T_{air}$).

A balanced operation of the heat pump unit is considered i.e., the condensing temperature, T_{con}, in winter, and evaporating temperature, T_{evp}, in summer, are constant. Therefore all capacity data of the selected heat pump unit, are functions of the T_{f1}, and valid only for fixed values of the air flow rate V_a, ground coil fluid flow rate V_f, entering air wet bulb temperature T_{WB}, and dry bulb temperature T_{DB} for summer and winter. The following approximations were obtained and are listed on each chart:

Heating operation

$$COP_h = COPh(1) + COPh(2) * T_{f1} + COPh(3) * T_{f1}^2 \quad (5.1)$$

$$QH_{HE} = HE(1) + HE(2) * T_{f1} + HE(3) * T_{f1}^2 \quad (5.2)$$

Cooling operation

$$COP_c = COPc(1) + COPc(2) * T_{f1} + COPc(3) * T_{f1}^2 \quad (5.3)$$

$$QC_{HE} = HR(1) + HR(2) * T_{f1} + HR(3) * T_{f1}^2 \quad (5.4)$$

To obtain other useful characteristics the following relations are used:

Heating Mode

Temperature of ground coil fluid entering the GHE, °C

$$T_{f2} = T_{f1} - \frac{QH_{HE}}{m_f\ c_f} \tag{5.5}$$

Total heat pump heating capacity (TH) - Q_h

$$Q_h = QH_{HE} \frac{COP_h}{COP_h - 1} \tag{5.6}$$

Power input to the compressor

$$W_{co} = QH_{HE} \frac{1}{1 - COP_h} \tag{5.7}$$

Cooling Mode

Temperature of ground coil fluid entering the GHE, °C

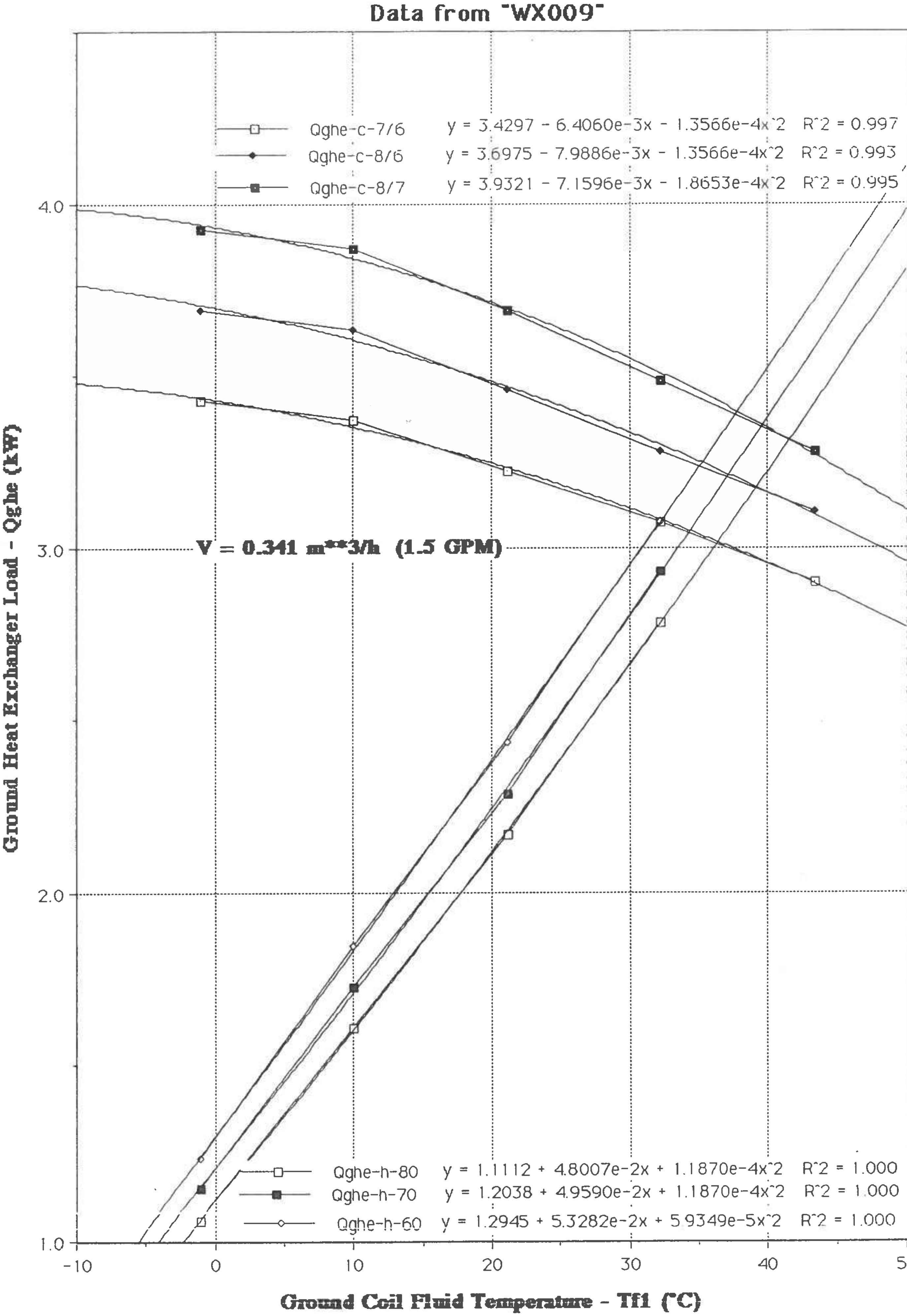
$$T_{f2} = T_{f1} + \frac{QC_{HE}}{m_f\ c_f} \tag{5.8}$$

Total heat pump cooling capacity (TC) - Q_c

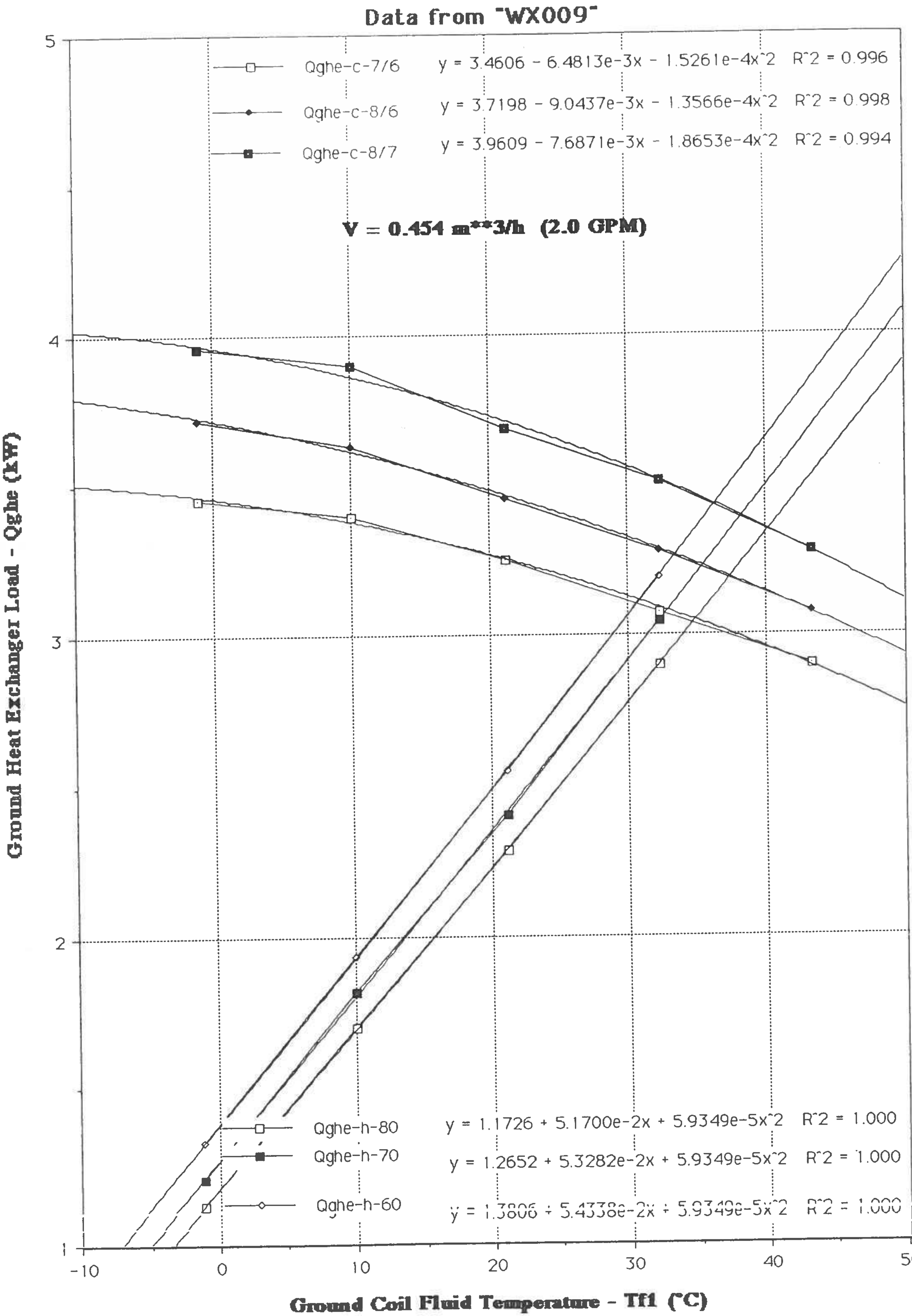
$$Q_c = QC_{HE} \frac{COP_c}{COP_c - 1} \tag{5.9}$$

Power input to the compressor

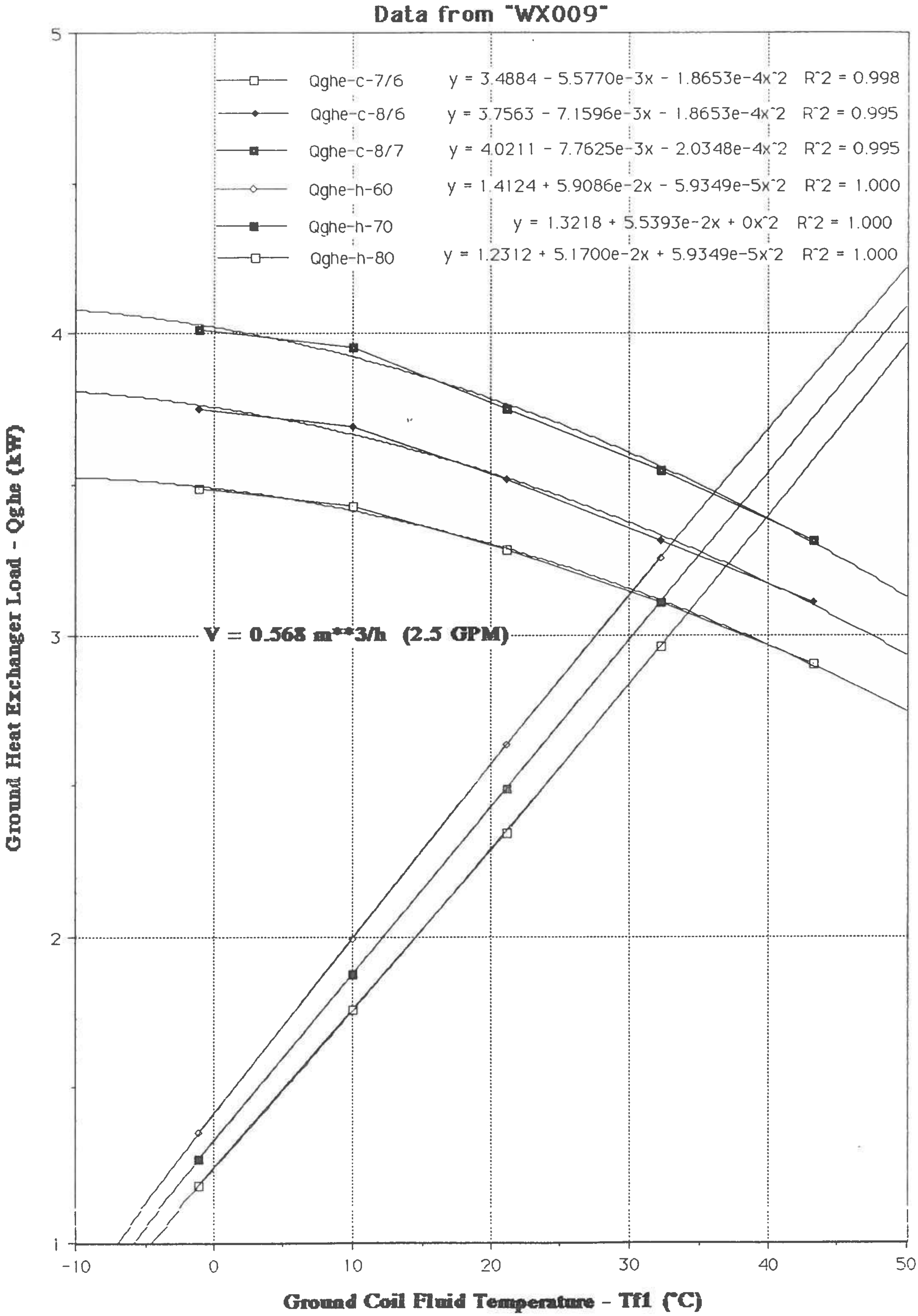
$$W_{co} = QC_{HE} \frac{1}{COP_c - 1} \tag{5.10}$$



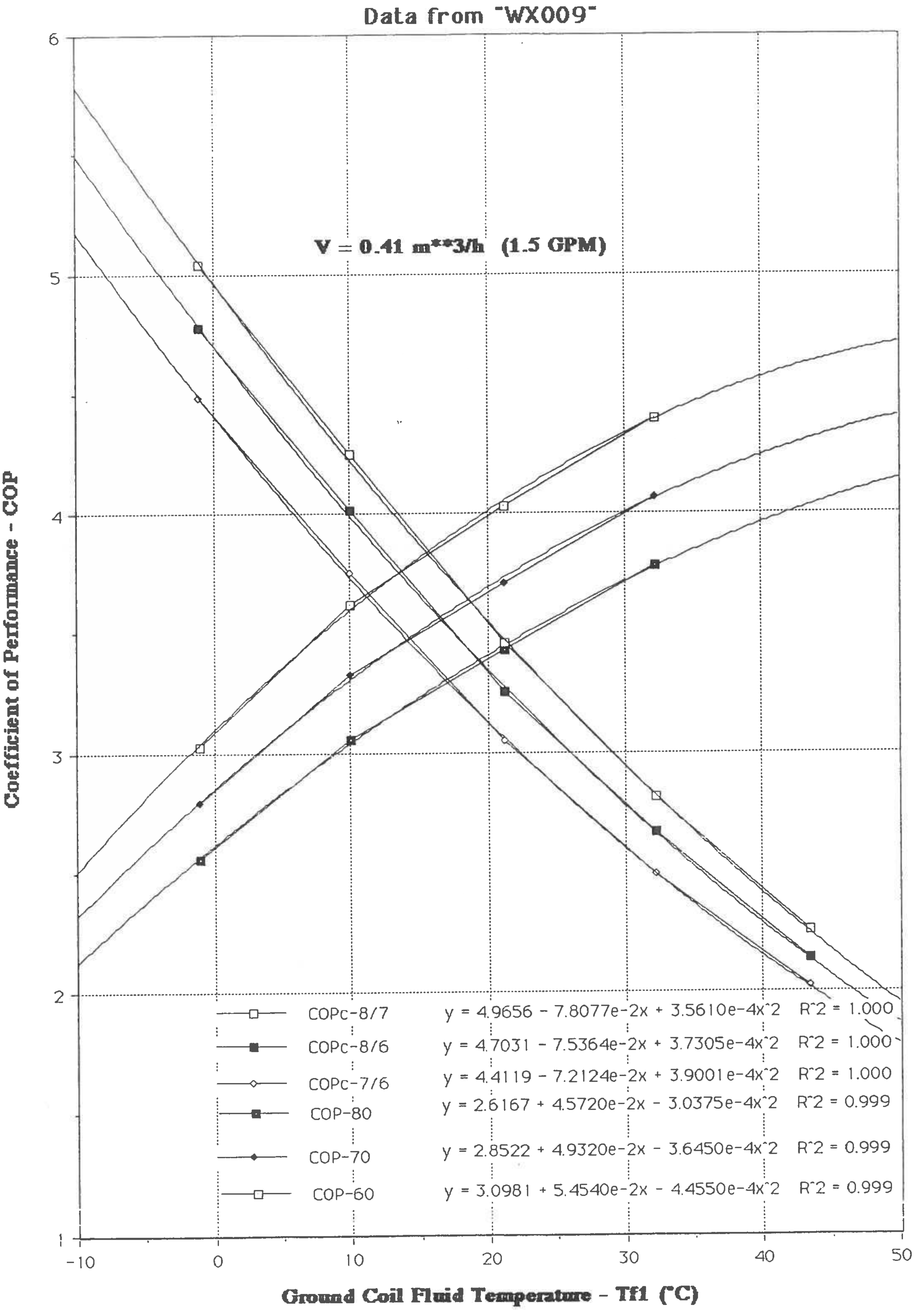
Data from "WX009"
Qghe-c-7/6 y = 3.4297 - 6.4060e-3x - 1.3566e-4x^2 R^2 = 0.997
Qghe-c-8/6 y = 3.6975 - 7.9886e-3x - 1.3566e-4x^2 R^2 = 0.993
Qghe-c-8/7 y = 3.9321 - 7.1596e-3x - 1.8653e-4x^2 R^2 = 0.995
V = 0.341 m**3/h (1.5 GPM)
Qghe-h-80 y = 1.1112 + 4.8007e-2x + 1.1870e-4x^2 R^2 = 1.000
Qghe-h-70 y = 1.2038 + 4.9590e-2x + 1.1870e-4x^2 R^2 = 1.000
Qghe-h-60 y = 1.2945 + 5.3282e-2x + 5.9349e-5x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)



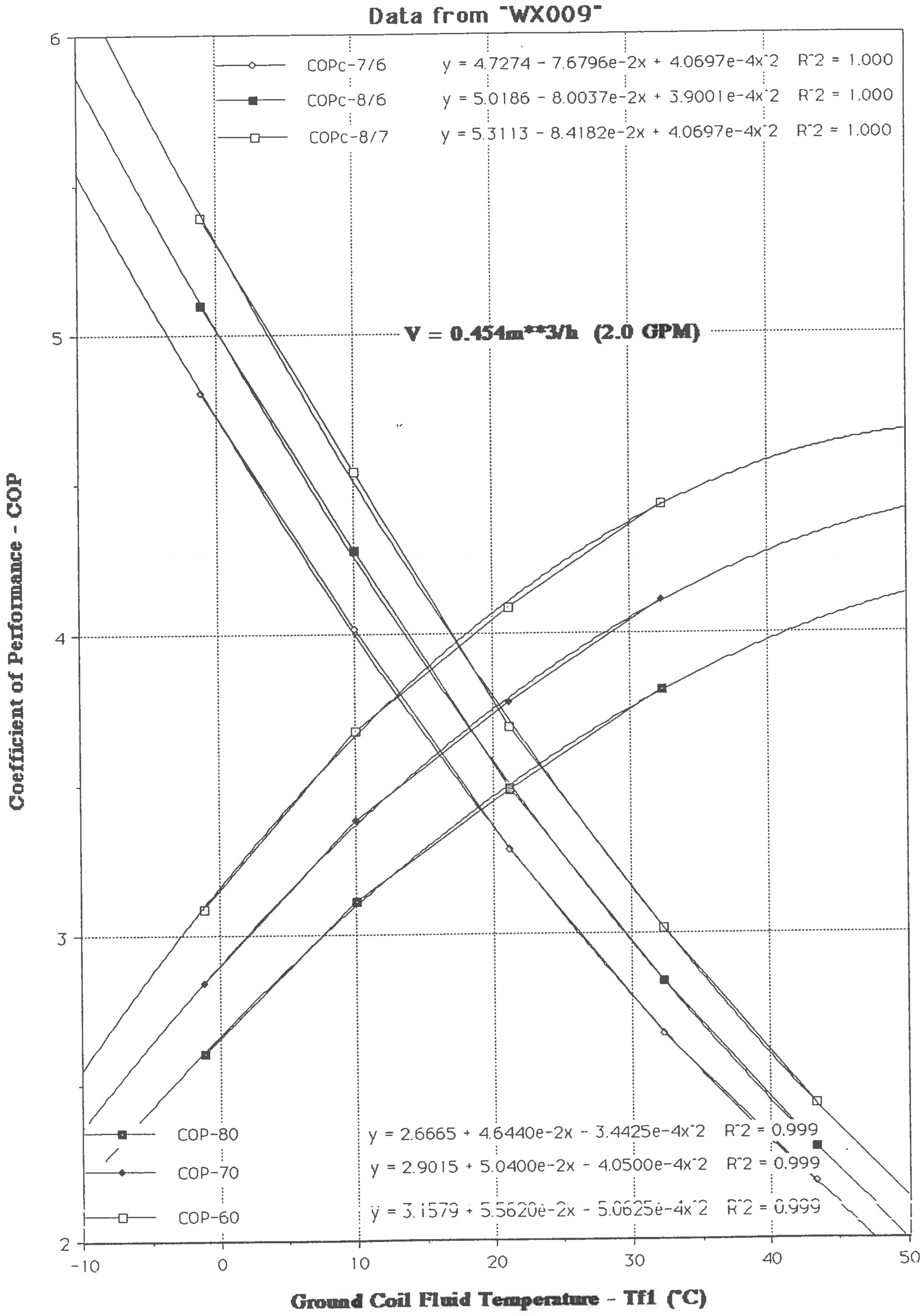
Data from "WX009"
Qghe-c-7/6
y = 3.4606 - 6.4813e-3x - 1.5261e-4x^2 R^2 = 0.996
Qghe-c-8/6
y = 3.7198 - 9.0437e-3x - 1.3566e-4x^2 R^2 = 0.998
Qghe-c-8/7
y = 3.9609 - 7.6871e-3x - 1.8653e-4x^2 R^2 = 0.994
V = 0.454 m**3/h (2.0 GPM)
Qghe-h-80
y = 1.1726 + 5.1700e-2x + 5.9349e-5x^2 R^2 = 1.000
Qghe-h-70
y = 1.2652 + 5.3282e-2x + 5.9349e-5x^2 R^2 = 1.000
Qghe-h-60
y = 1.3806 + 5.4338e-2x + 5.9349e-5x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
5
4
3
2
1
-10
0
10
20
30
40
50



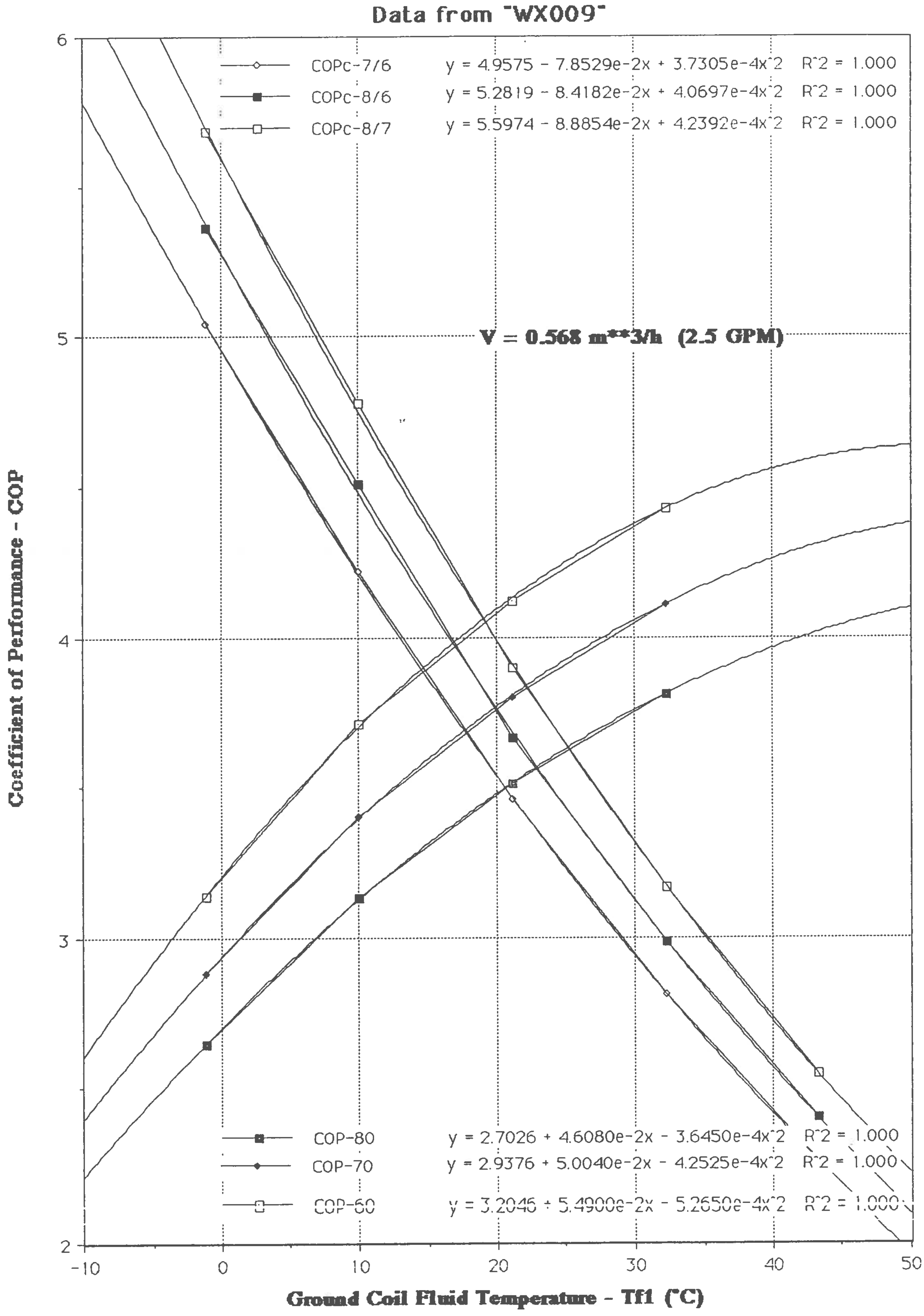
Data from "WX009"
Qghe-c-7/6
y = 3.4884 - 5.5770e-3x - 1.8653e-4x^2 R^2 = 0.998
Qghe-c-8/6
y = 3.7563 - 7.1596e-3x - 1.8653e-4x^2 R^2 = 0.995
Qghe-c-8/7
y = 4.0211 - 7.7625e-3x - 2.0348e-4x^2 R^2 = 0.995
Qghe-h-60
y = 1.4124 + 5.9086e-2x - 5.9349e-5x^2 R^2 = 1.000
Qghe-h-70
y = 1.3218 + 5.5393e-2x + 0x^2 R^2 = 1.000
Qghe-h-80
y = 1.2312 + 5.1700e-2x + 5.9349e-5x^2 R^2 = 1.000
V = 0.568 m**3/h (2.5 GPM)
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
5
4
3
2
1
-10
0
10
20
30
40
50



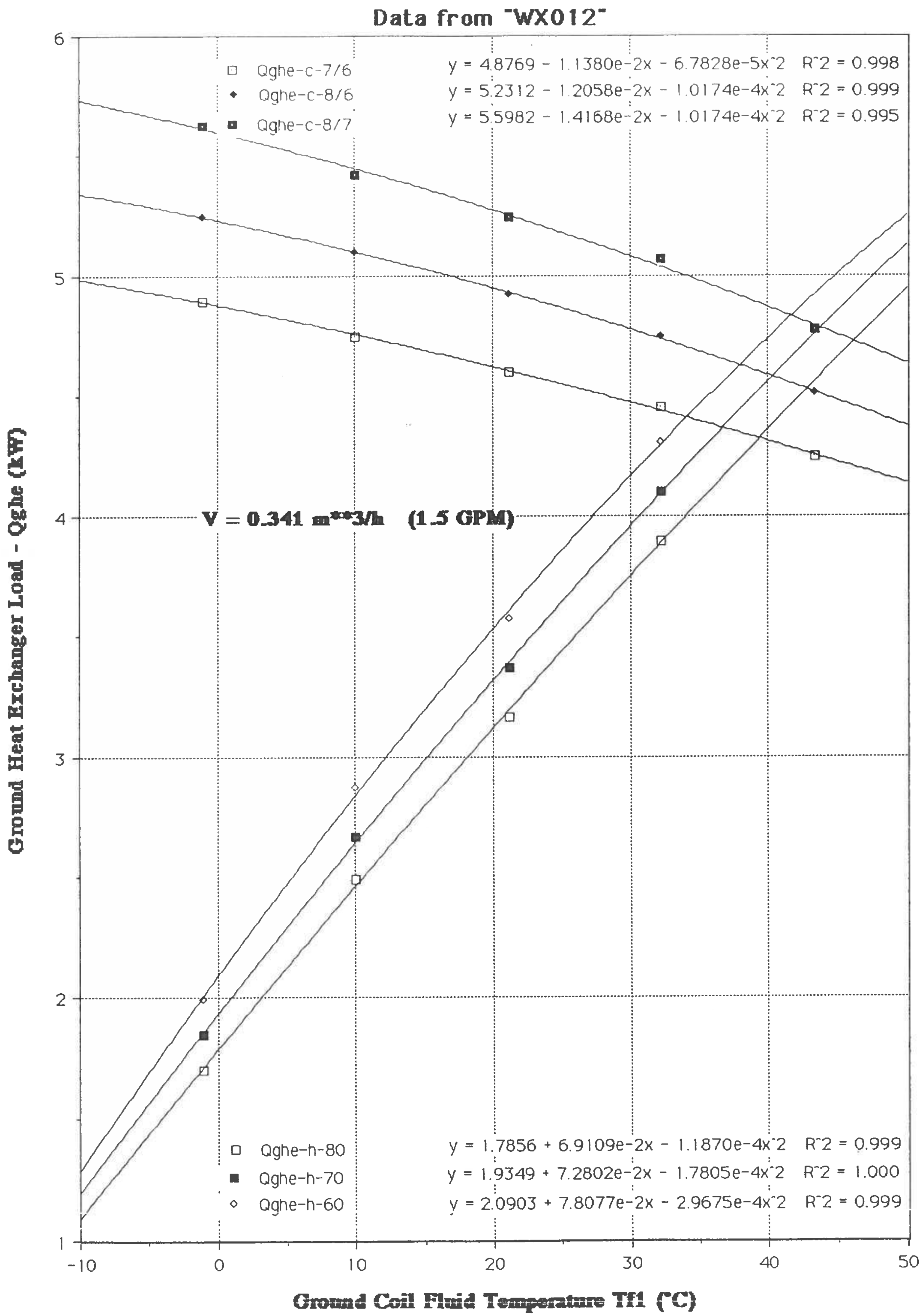
Data from "WX009"
V = 0.41 m**3/h (1.5 GPM)
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
COPc-8/7 y = 4.9656 - 7.8077e-2x + 3.5610e-4x^2 R^2 = 1.000
COPc-8/6 y = 4.7031 - 7.5364e-2x + 3.7305e-4x^2 R^2 = 1.000
COPc-7/6 y = 4.4119 - 7.2124e-2x + 3.9001e-4x^2 R^2 = 1.000
COP-80 y = 2.6167 + 4.5720e-2x - 3.0375e-4x^2 R^2 = 0.999
COP-70 y = 2.8522 + 4.9320e-2x - 3.6450e-4x^2 R^2 = 0.999
COP-60 y = 3.0981 + 5.4540e-2x - 4.4550e-4x^2 R^2 = 0.999



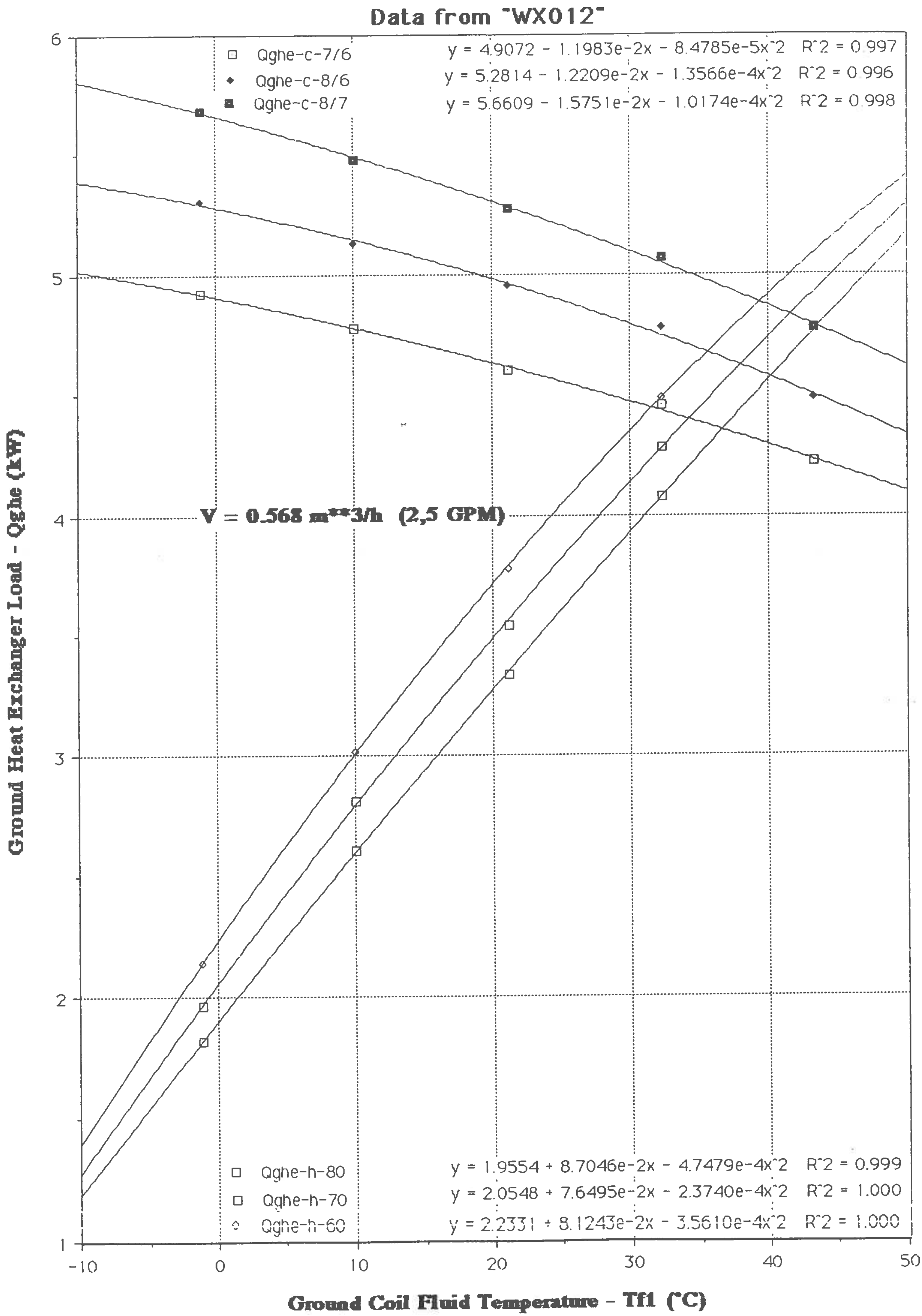
Data from "WX009"
COPc-7/6
y = 4.7274 - 7.6796e-2x + 4.0697e-4x^2 R^2 = 1.000
COPc-8/6
y = 5.0186 - 8.0037e-2x + 3.9001e-4x^2 R^2 = 1.000
COPc-8/7
y = 5.3113 - 8.4182e-2x + 4.0697e-4x^2 R^2 = 1.000
V = 0.454m**3/h (2.0 GPM)
COP-80
y = 2.6665 + 4.6440e-2x - 3.4425e-4x^2 R^2 = 0.999
COP-70
y = 2.9015 + 5.0400e-2x - 4.0500e-4x^2 R^2 = 0.999
COP-60
y = 3.1579 + 5.5620e-2x - 5.0625e-4x^2 R^2 = 0.999
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50



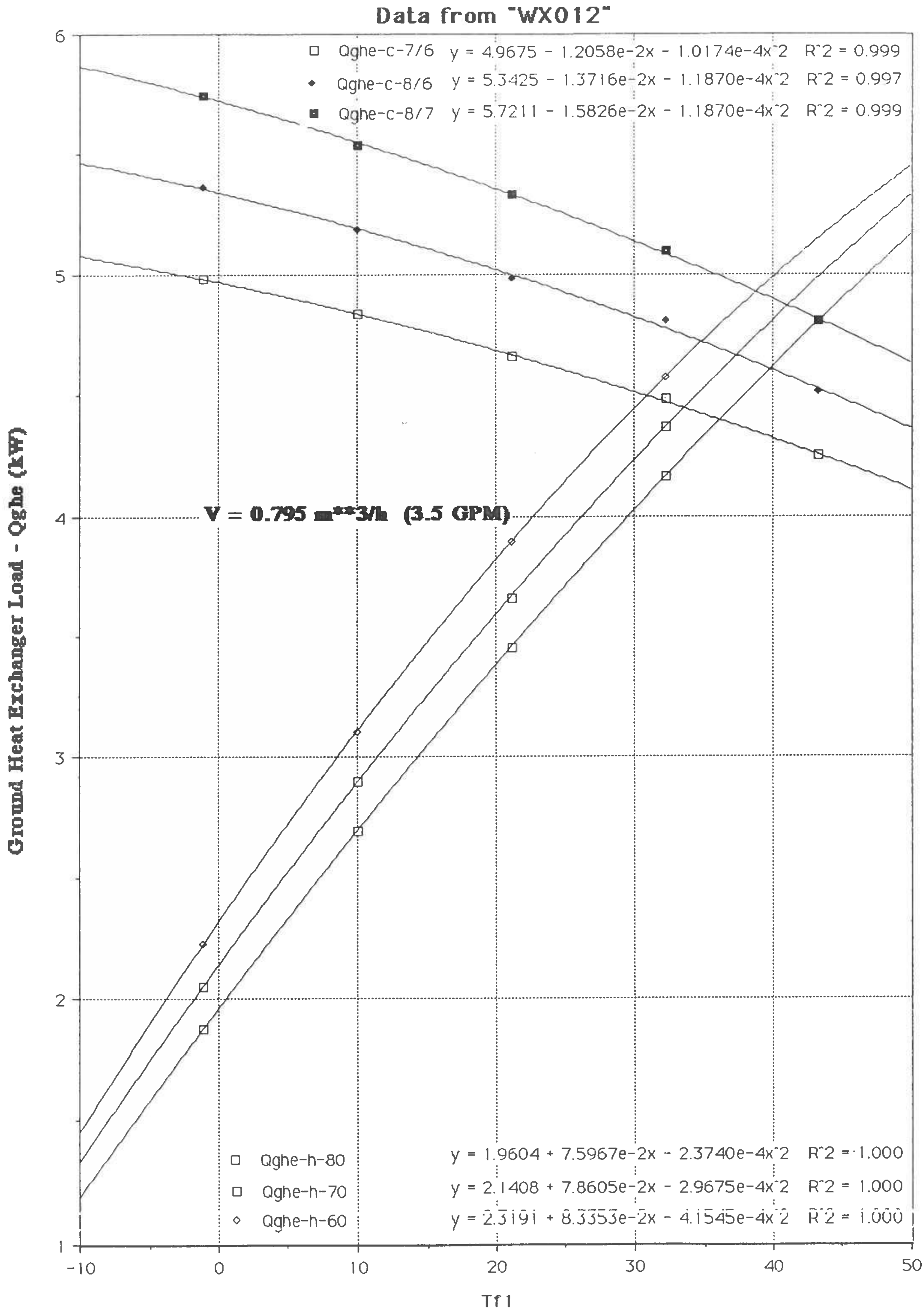
Data from "WX009"
COPc-7/6
COPc-8/6
COPc-8/7
y = 4.9575 - 7.8529e-2x + 3.7305e-4x^2 R^2 = 1.000
y = 5.2819 - 8.4182e-2x + 4.0697e-4x^2 R^2 = 1.000
y = 5.5974 - 8.8854e-2x + 4.2392e-4x^2 R^2 = 1.000
V = 0.568 m**3/h (2.5 GPM)
COP-80
COP-70
COP-60
y = 2.7026 + 4.6080e-2x - 3.6450e-4x^2 R^2 = 1.000
y = 2.9376 + 5.0040e-2x - 4.2525e-4x^2 R^2 = 1.000
y = 3.2046 + 5.4900e-2x - 5.2650e-4x^2 R^2 = 1.000
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50



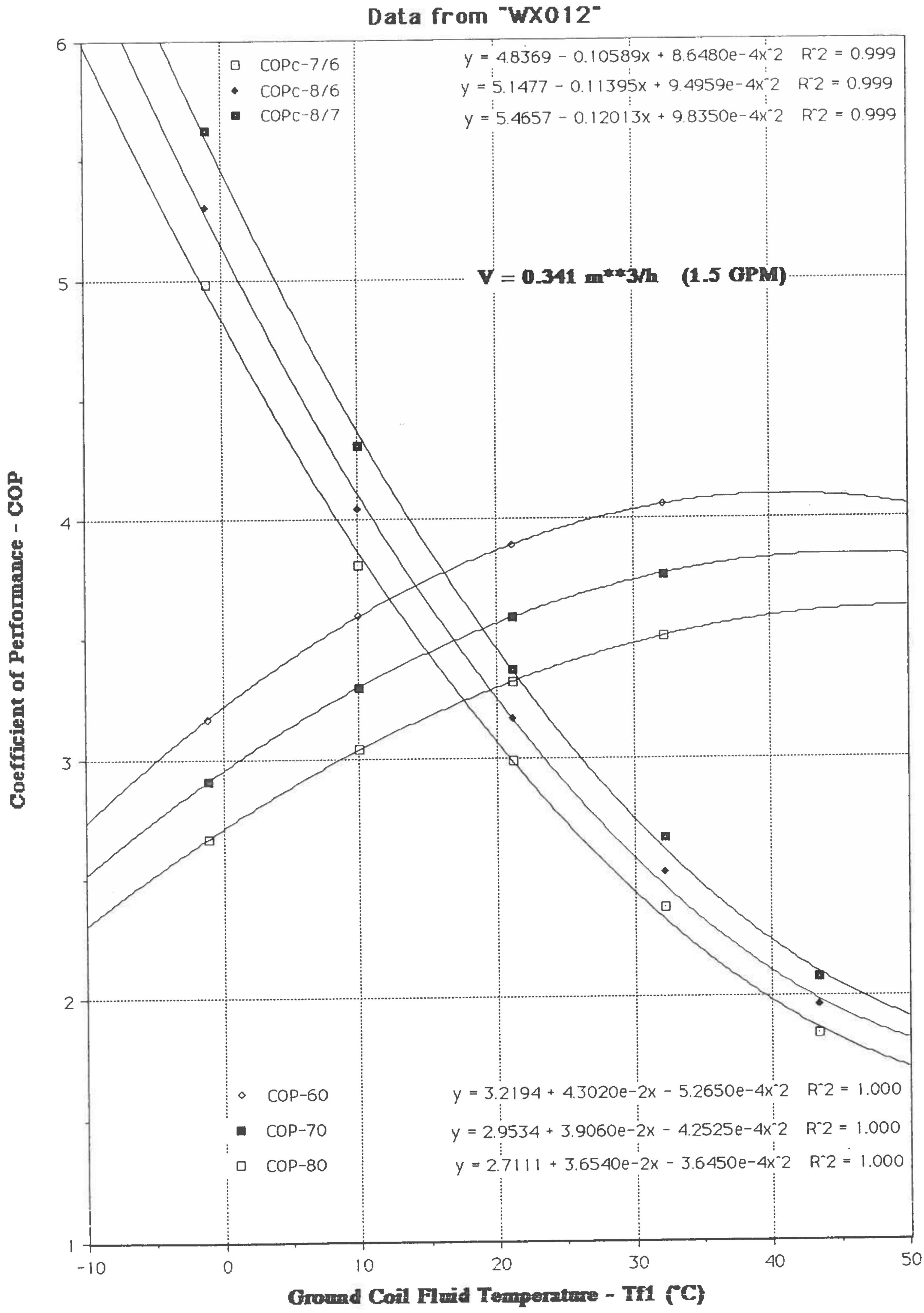
Data from "WX012"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 4.8769 - 1.1380e-2x - 6.7828e-5x^2 R^2 = 0.998
y = 5.2312 - 1.2058e-2x - 1.0174e-4x^2 R^2 = 0.999
y = 5.5982 - 1.4168e-2x - 1.0174e-4x^2 R^2 = 0.995
V = 0.341 m**3/h (1.5 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 1.7856 + 6.9109e-2x - 1.1870e-4x^2 R^2 = 0.999
y = 1.9349 + 7.2802e-2x - 1.7805e-4x^2 R^2 = 1.000
y = 2.0903 + 7.8077e-2x - 2.9675e-4x^2 R^2 = 0.999
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature Tf1 (°C)



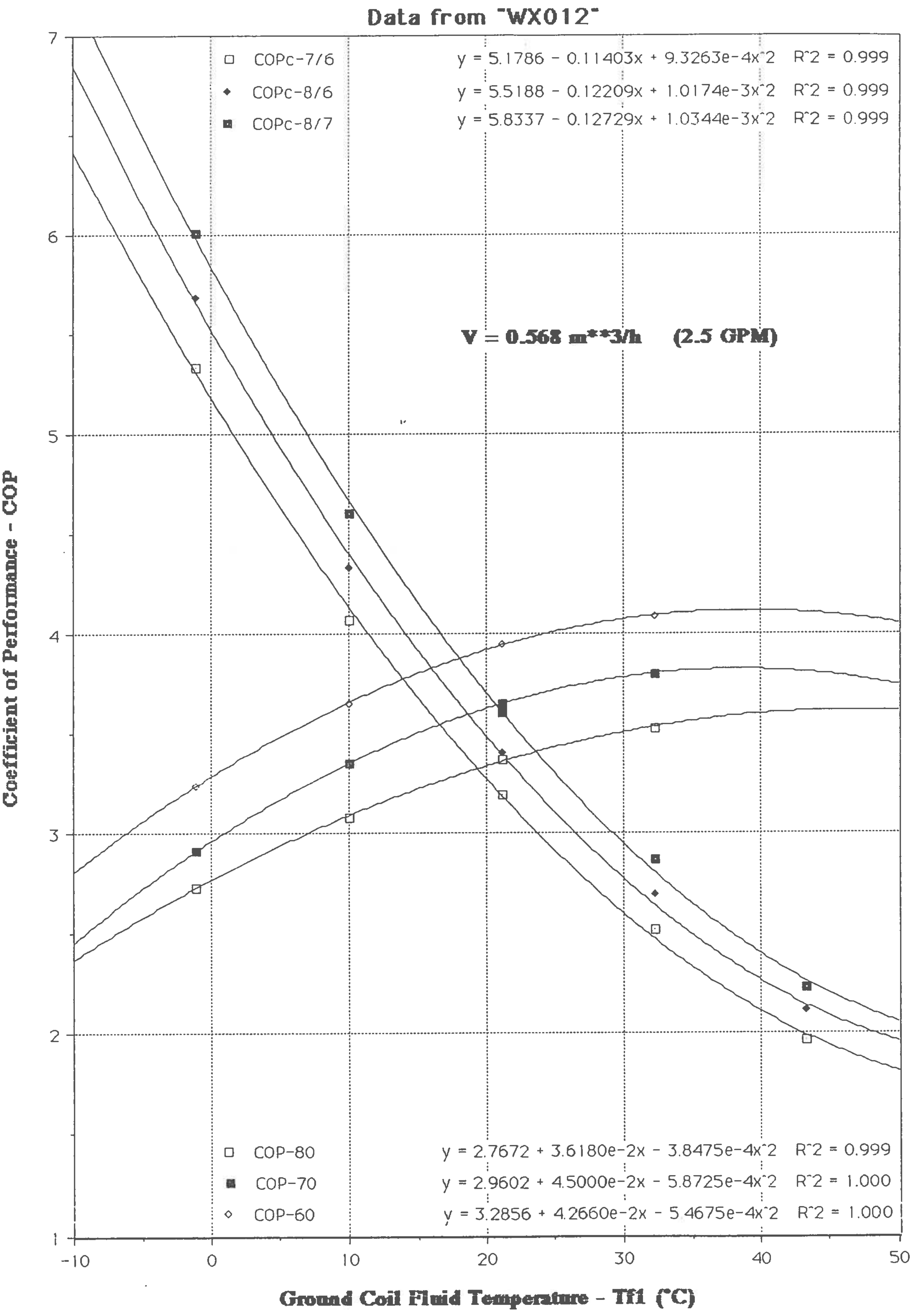
Data from "WX012"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 4.9072 - 1.1983e-2x - 8.4785e-5x^2 R^2 = 0.997
y = 5.2814 - 1.2209e-2x - 1.3566e-4x^2 R^2 = 0.996
y = 5.6609 - 1.5751e-2x - 1.0174e-4x^2 R^2 = 0.998
V = 0.568 m**3/h (2,5 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 1.9554 + 8.7046e-2x - 4.7479e-4x^2 R^2 = 0.999
y = 2.0548 + 7.6495e-2x - 2.3740e-4x^2 R^2 = 1.000
y = 2.2331 + 8.1243e-2x - 3.5610e-4x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
1
2
3
4
5
6
-10
0
10
20
30
40
50



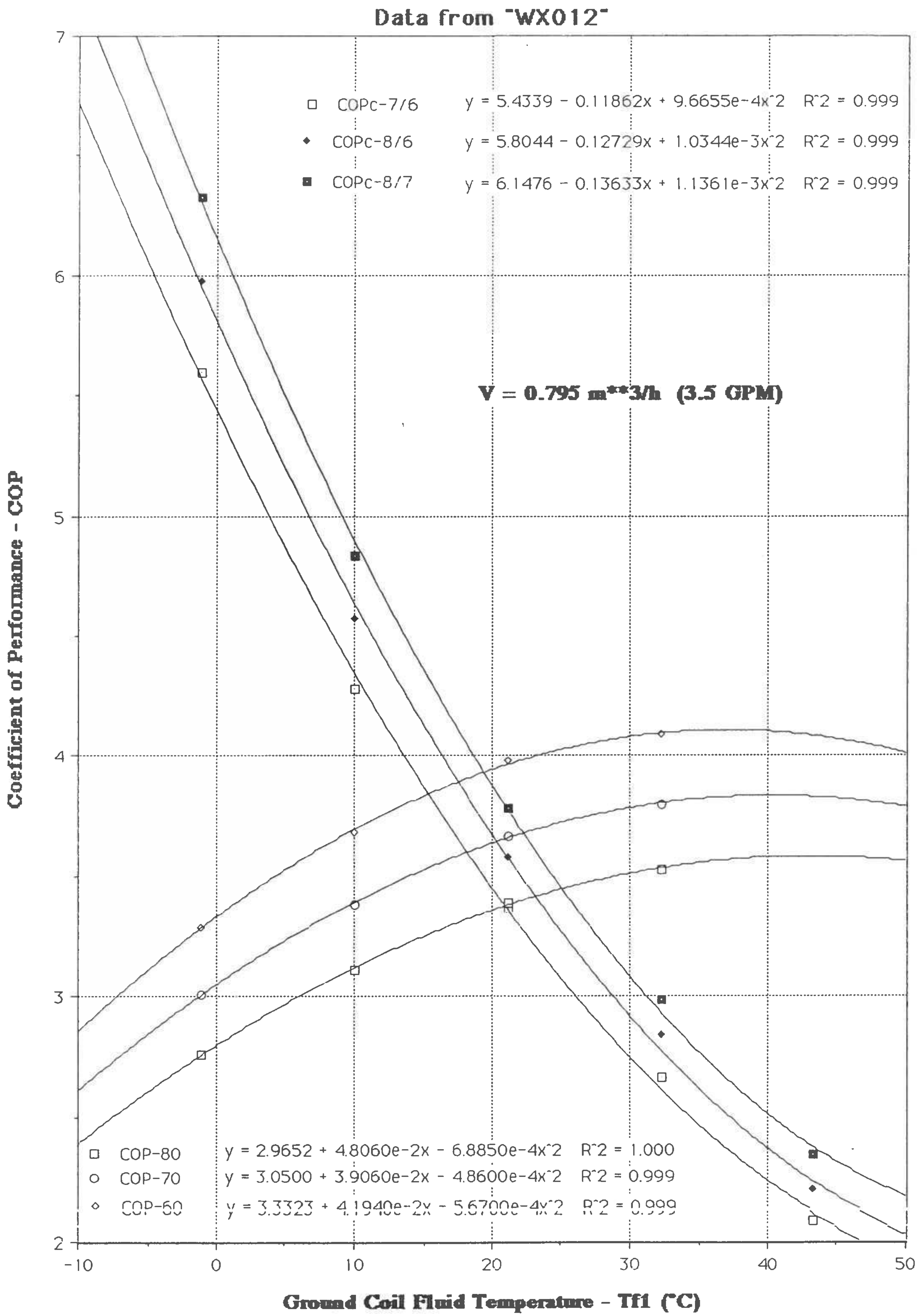
Data from "WX012"
Qghe-c-7/6 y = 4.9675 - 1.2058e-2x - 1.0174e-4x^2 R^2 = 0.999
Qghe-c-8/6 y = 5.3425 - 1.3716e-2x - 1.1870e-4x^2 R^2 = 0.997
Qghe-c-8/7 y = 5.7211 - 1.5826e-2x - 1.1870e-4x^2 R^2 = 0.999
V = 0.795 m**3/h (3.5 GPM)
Qghe-h-80 y = 1.9604 + 7.5967e-2x - 2.3740e-4x^2 R^2 = 1.000
Qghe-h-70 y = 2.1408 + 7.8605e-2x - 2.9675e-4x^2 R^2 = 1.000
Qghe-h-60 y = 2.3191 + 8.3353e-2x - 4.1545e-4x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Tf1
1
2
3
4
5
6
-10
0
10
20
30
40
50



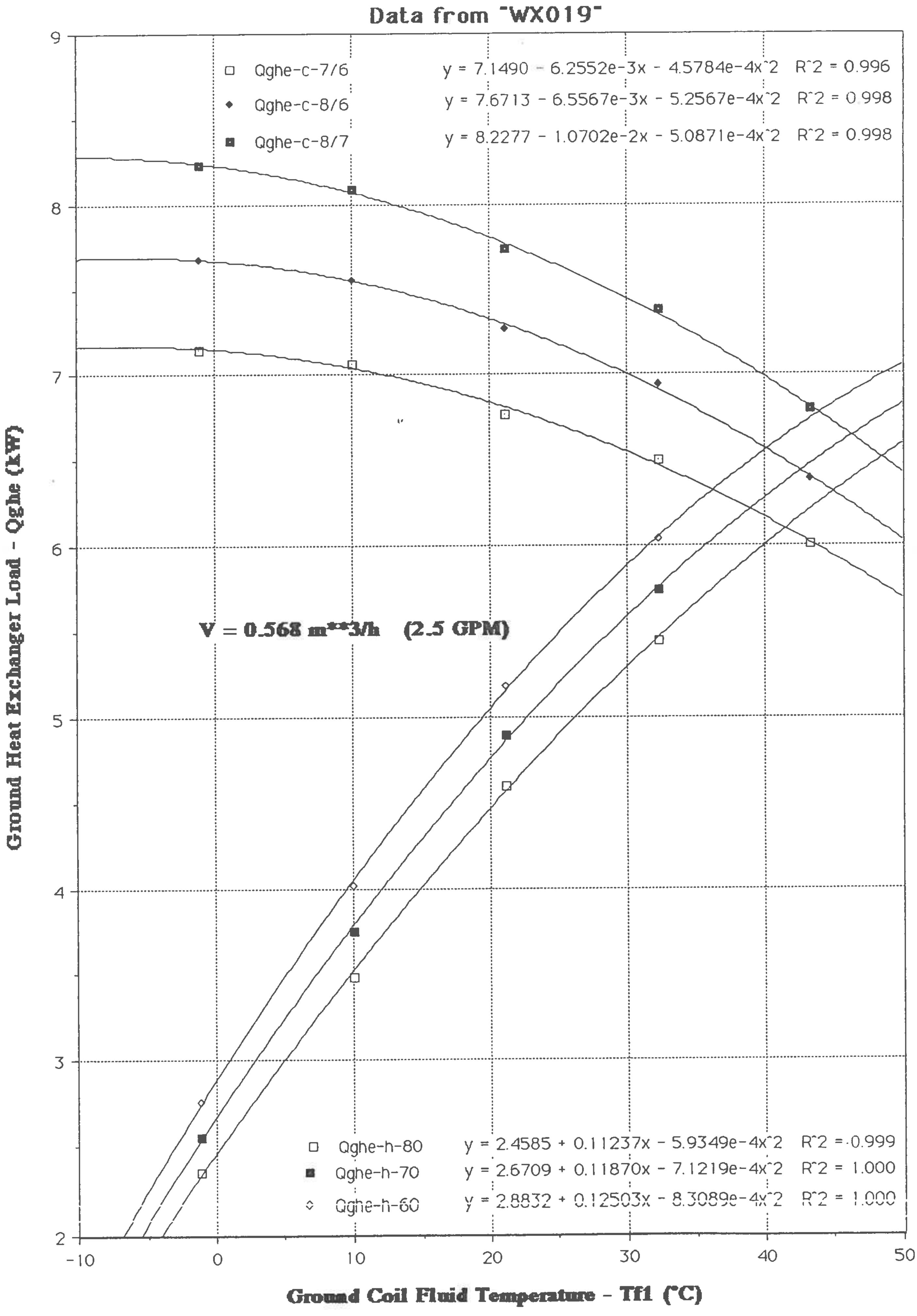
Data from "WX012"
COPc-7/6
COPc-8/6
COPc-8/7
y = 4.8369 - 0.10589x + 8.6480e-4x^2 R^2 = 0.999
y = 5.1477 - 0.11395x + 9.4959e-4x^2 R^2 = 0.999
y = 5.4657 - 0.12013x + 9.8350e-4x^2 R^2 = 0.999
V = 0.341 m**3/h (1.5 GPM)
COP-60
COP-70
COP-80
y = 3.2194 + 4.3020e-2x - 5.2650e-4x^2 R^2 = 1.000
y = 2.9534 + 3.9060e-2x - 4.2525e-4x^2 R^2 = 1.000
y = 2.7111 + 3.6540e-2x - 3.6450e-4x^2 R^2 = 1.000
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
1
-10
0
10
20
30
40
50



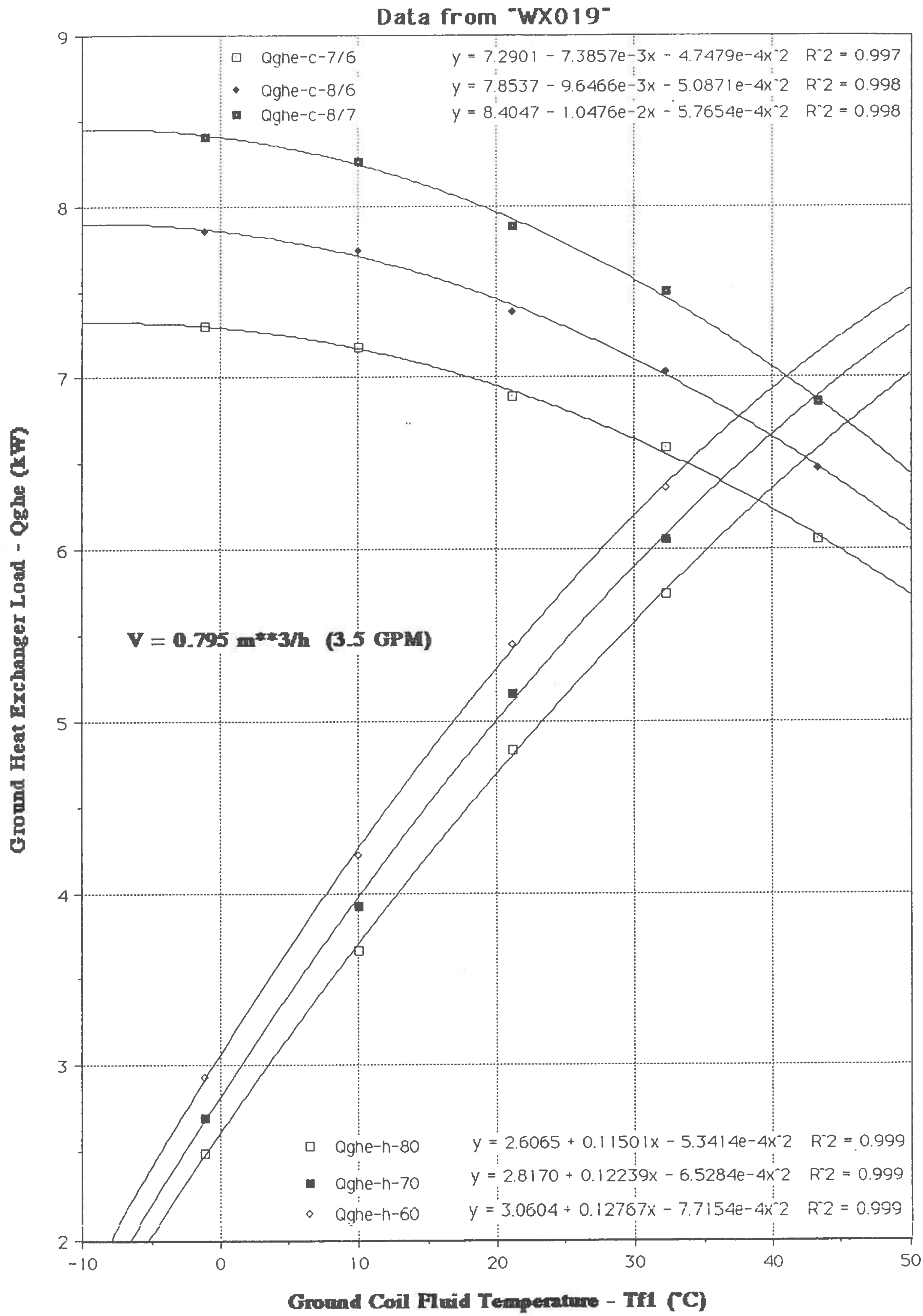
Data from "WX012"
COPc-7/6
COPc-8/6
COPc-8/7
y = 5.1786 - 0.11403x + 9.3263e-4x^2 R^2 = 0.999
y = 5.5188 - 0.12209x + 1.0174e-3x^2 R^2 = 0.999
y = 5.8337 - 0.12729x + 1.0344e-3x^2 R^2 = 0.999
V = 0.568 m**3/h (2.5 GPM)
COP-80
COP-70
COP-60
y = 2.7672 + 3.6180e-2x - 3.8475e-4x^2 R^2 = 0.999
y = 2.9602 + 4.5000e-2x - 5.8725e-4x^2 R^2 = 1.000
y = 3.2856 + 4.2660e-2x - 5.4675e-4x^2 R^2 = 1.000
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)



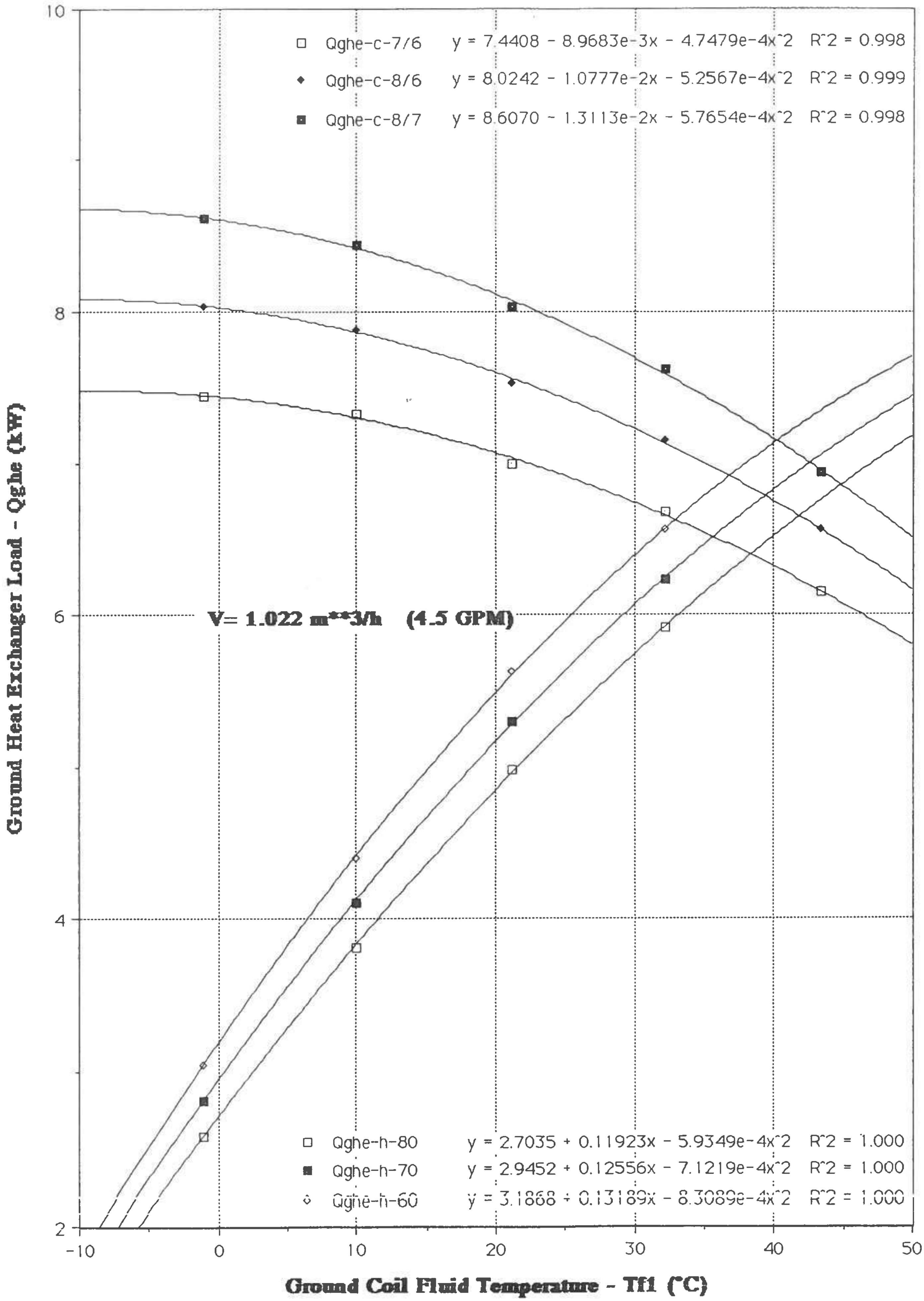
Data from "WX012"
COPc-7/6
y = 5.4339 - 0.11862x + 9.6655e-4x^2 R^2 = 0.999
COPc-8/6
y = 5.8044 - 0.12729x + 1.0344e-3x^2 R^2 = 0.999
COPc-8/7
y = 6.1476 - 0.13633x + 1.1361e-3x^2 R^2 = 0.999
V = 0.795 m**3/h (3.5 GPM)
COP-80
y = 2.9652 + 4.8060e-2x - 6.8850e-4x^2 R^2 = 1.000
COP-70
y = 3.0500 + 3.9060e-2x - 4.8600e-4x^2 R^2 = 0.999
COP-60
y = 3.3323 + 4.1940e-2x - 5.6700e-4x^2 R^2 = 0.999
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
7
6
5
4
3
2
-10
0
10
20
30
40
50

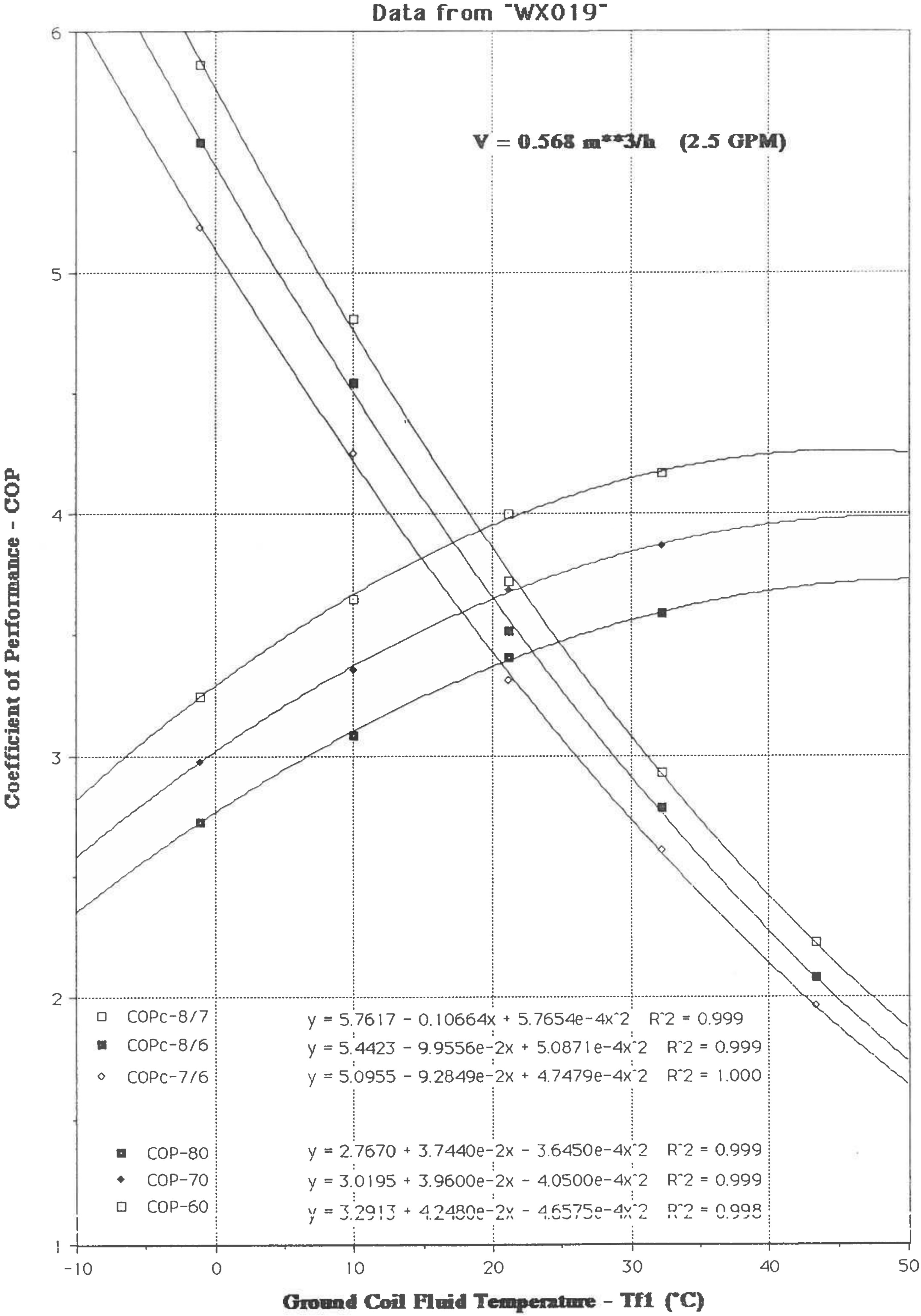


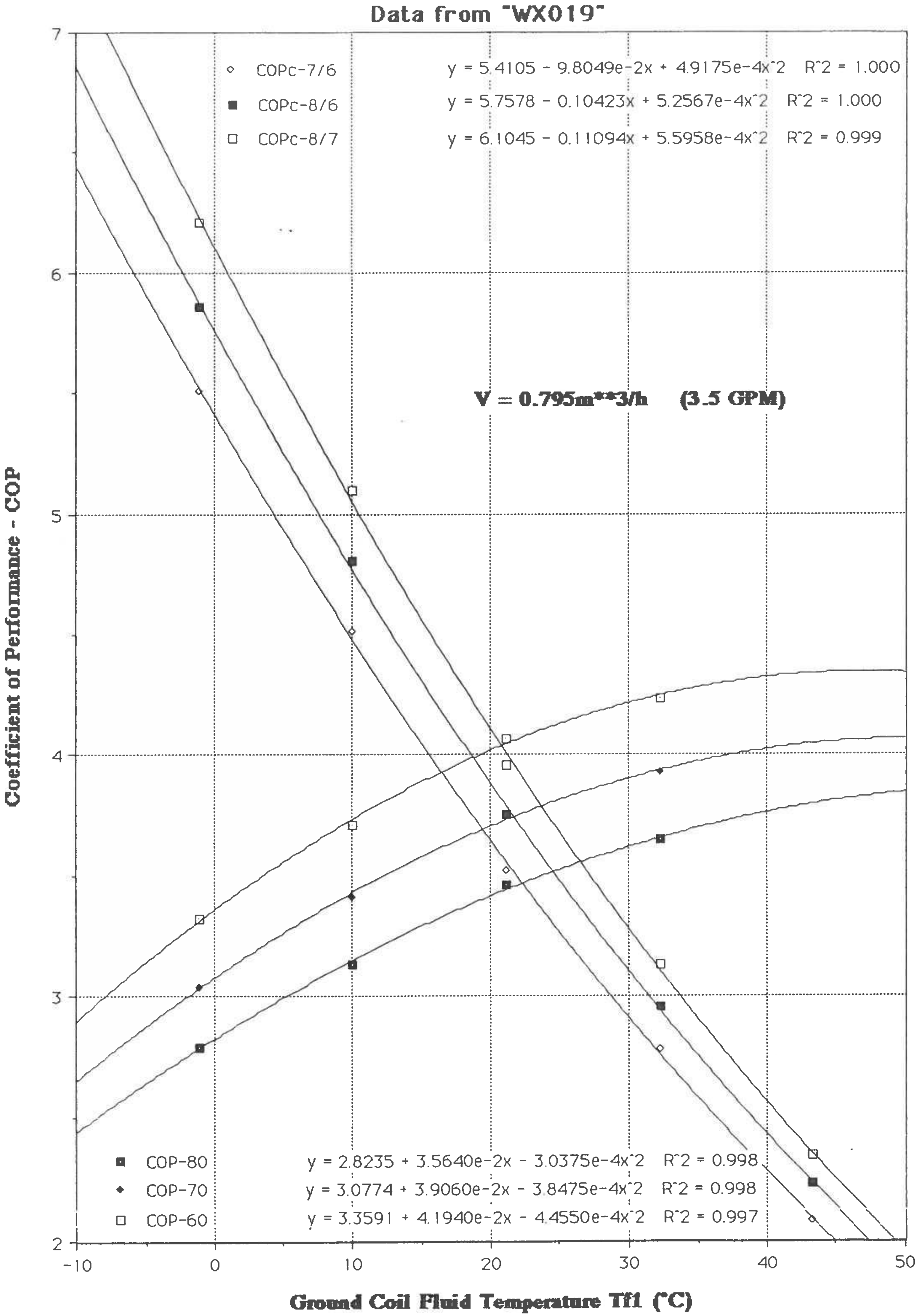
Data from "WX019"
Qghe-c-7/6
y = 7.1490 - 6.2552e-3x - 4.5784e-4x^2 R^2 = 0.996
Qghe-c-8/6
y = 7.6713 - 6.5567e-3x - 5.2567e-4x^2 R^2 = 0.998
Qghe-c-8/7
y = 8.2277 - 1.0702e-2x - 5.0871e-4x^2 R^2 = 0.998
V = 0.568 m**3/h (2.5 GPM)
Qghe-h-80
y = 2.4585 + 0.11237x - 5.9349e-4x^2 R^2 = 0.999
Qghe-h-70
y = 2.6709 + 0.11870x - 7.1219e-4x^2 R^2 = 1.000
Qghe-h-60
y = 2.8832 + 0.12503x - 8.3089e-4x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)

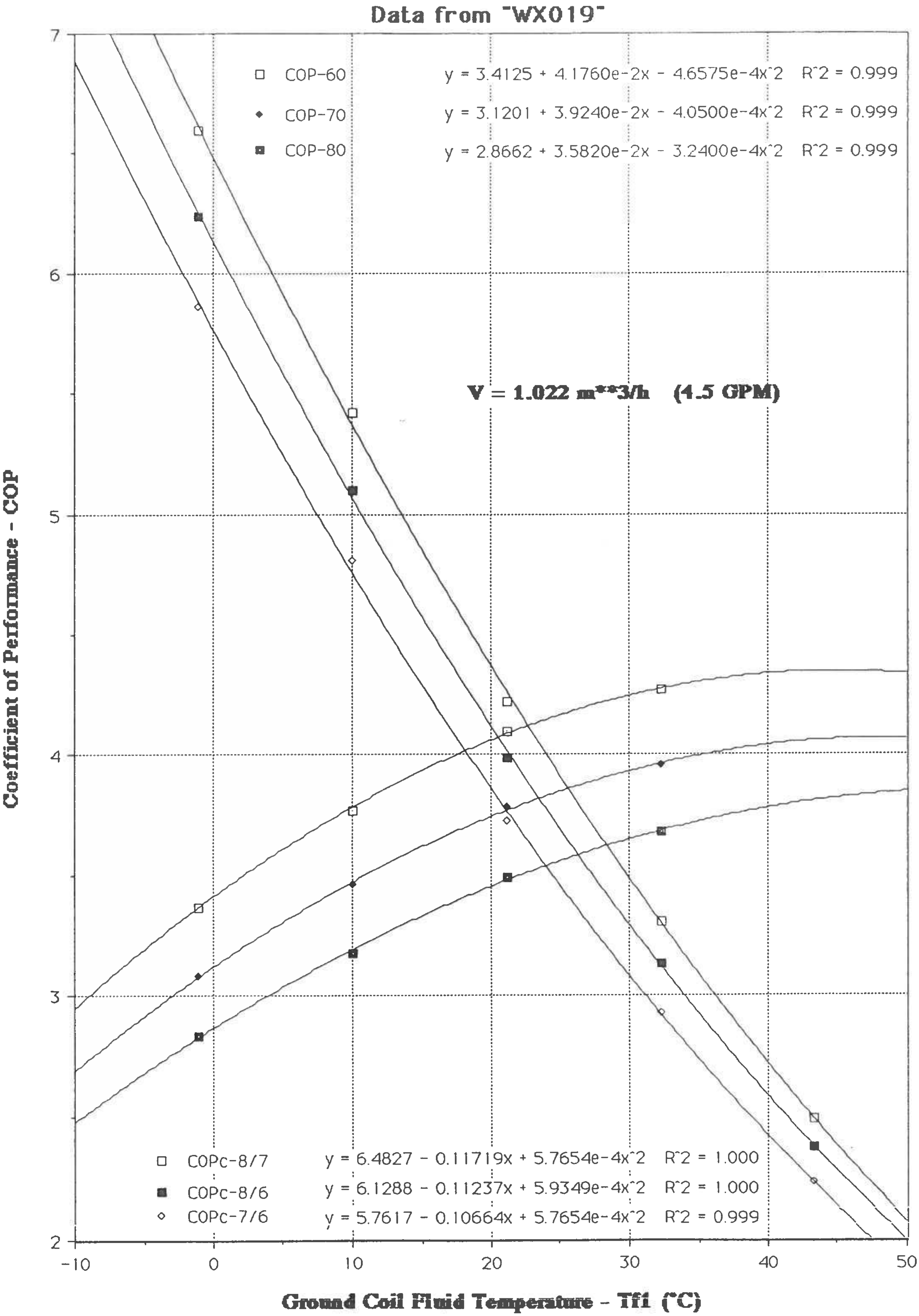

Data from "WX019"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 7.2901 - 7.3857e-3x - 4.7479e-4x^2 R^2 = 0.997
y = 7.8537 - 9.6466e-3x - 5.0871e-4x^2 R^2 = 0.998
y = 8.4047 - 1.0476e-2x - 5.7654e-4x^2 R^2 = 0.998
V = 0.795 m**3/h (3.5 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 2.6065 + 0.11501x - 5.3414e-4x^2 R^2 = 0.999
y = 2.8170 + 0.12239x - 6.5284e-4x^2 R^2 = 0.999
y = 3.0604 + 0.12767x - 7.7154e-4x^2 R^2 = 0.999
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
9
8
7
6
5
4
3
2
-10
0
10
20
30
40
50

Data from "WX019"

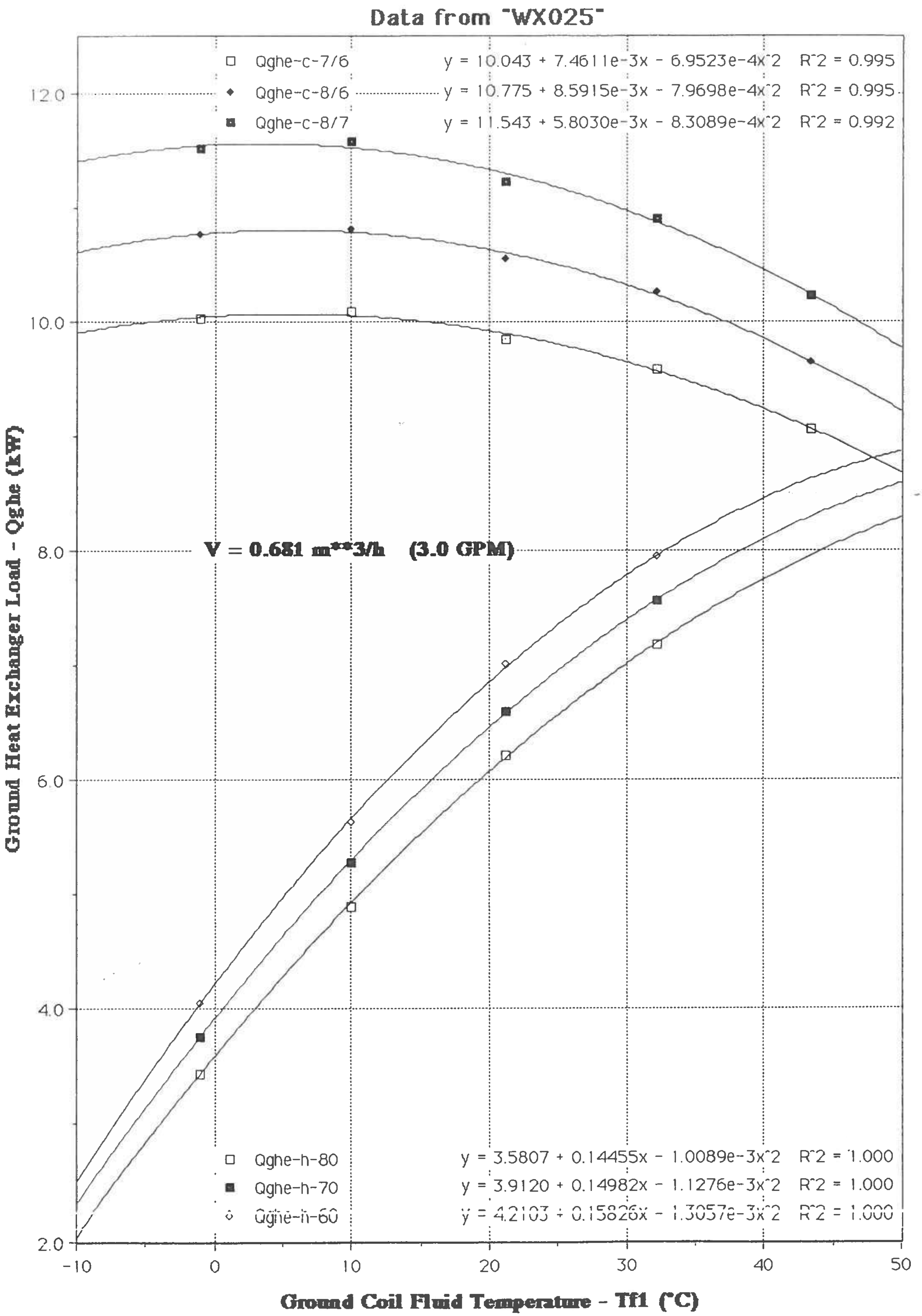



Data from "WX019"
V = 0.568 m**3/h (2.5 GPM)
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
1
-10
0
10
20
30
40
50
COPc-8/7
COPc-8/6
COPc-7/6
y = 5.7617 - 0.10664x + 5.7654e-4x^2 R^2 = 0.999
y = 5.4423 - 9.9556e-2x + 5.0871e-4x^2 R^2 = 0.999
y = 5.0955 - 9.2849e-2x + 4.7479e-4x^2 R^2 = 1.000
COP-80
COP-70
COP-60
y = 2.7670 + 3.7440e-2x - 3.6450e-4x^2 R^2 = 0.999
y = 3.0195 + 3.9600e-2x - 4.0500e-4x^2 R^2 = 0.999
y = 3.2913 + 4.2480e-2x - 4.6575e-4x^2 R^2 = 0.998

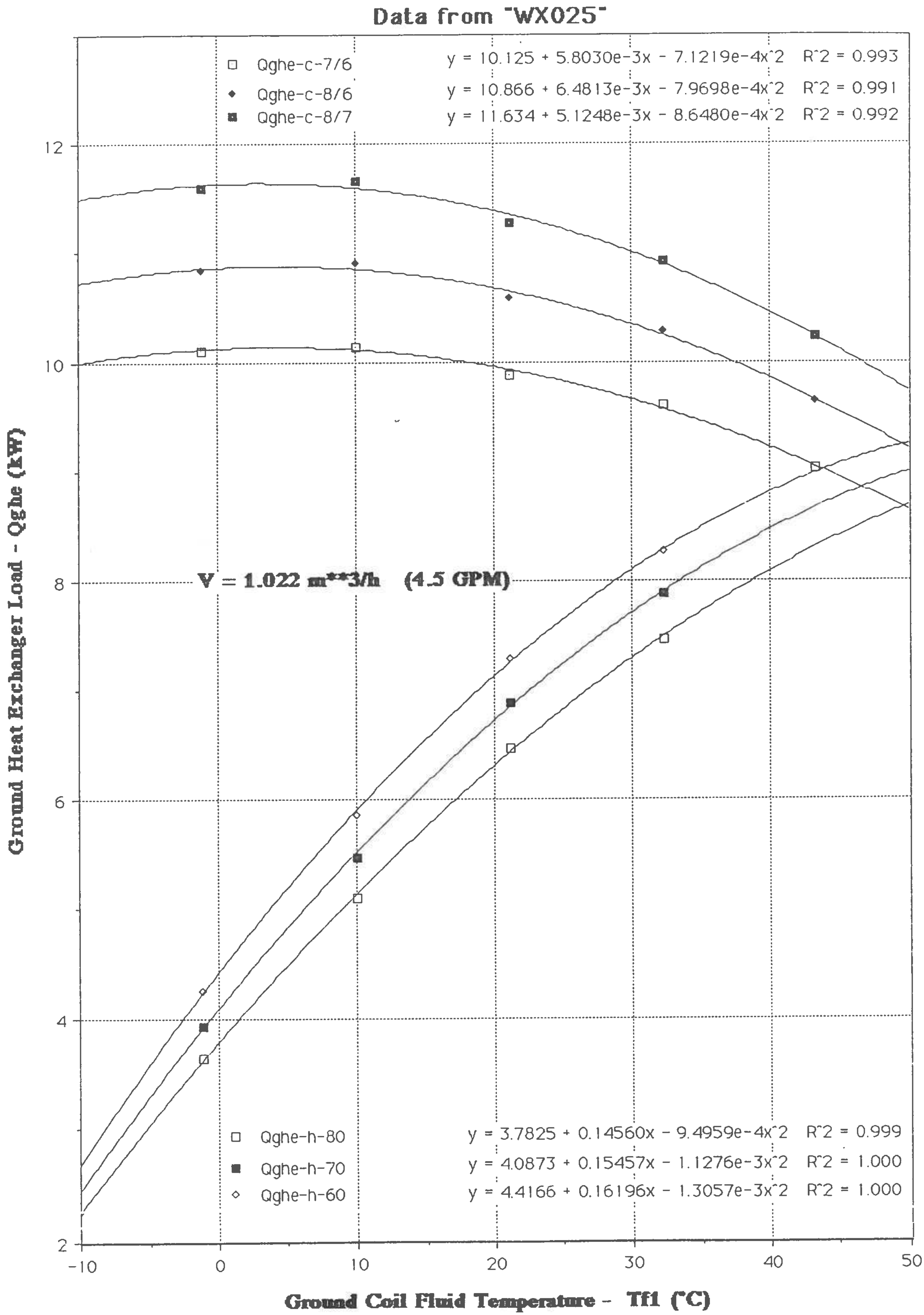

Data from "WX019"
COPc-7/6
COPc-8/6
COPc-8/7
y = 5.4105 - 9.8049e-2x + 4.9175e-4x^2 R^2 = 1.000
y = 5.7578 - 0.10423x + 5.2567e-4x^2 R^2 = 1.000
y = 6.1045 - 0.11094x + 5.5958e-4x^2 R^2 = 0.999
V = 0.795m**3/h (3.5 GPM)
COP-80
COP-70
COP-60
y = 2.8235 + 3.5640e-2x - 3.0375e-4x^2 R^2 = 0.998
y = 3.0774 + 3.9060e-2x - 3.8475e-4x^2 R^2 = 0.998
y = 3.3591 + 4.1940e-2x - 4.4550e-4x^2 R^2 = 0.997
Coefficient of Performance - COP
Ground Coil Fluid Temperature Tf1 (°C)
7
6
5
4
3
2
-10
0
10
20
30
40
50



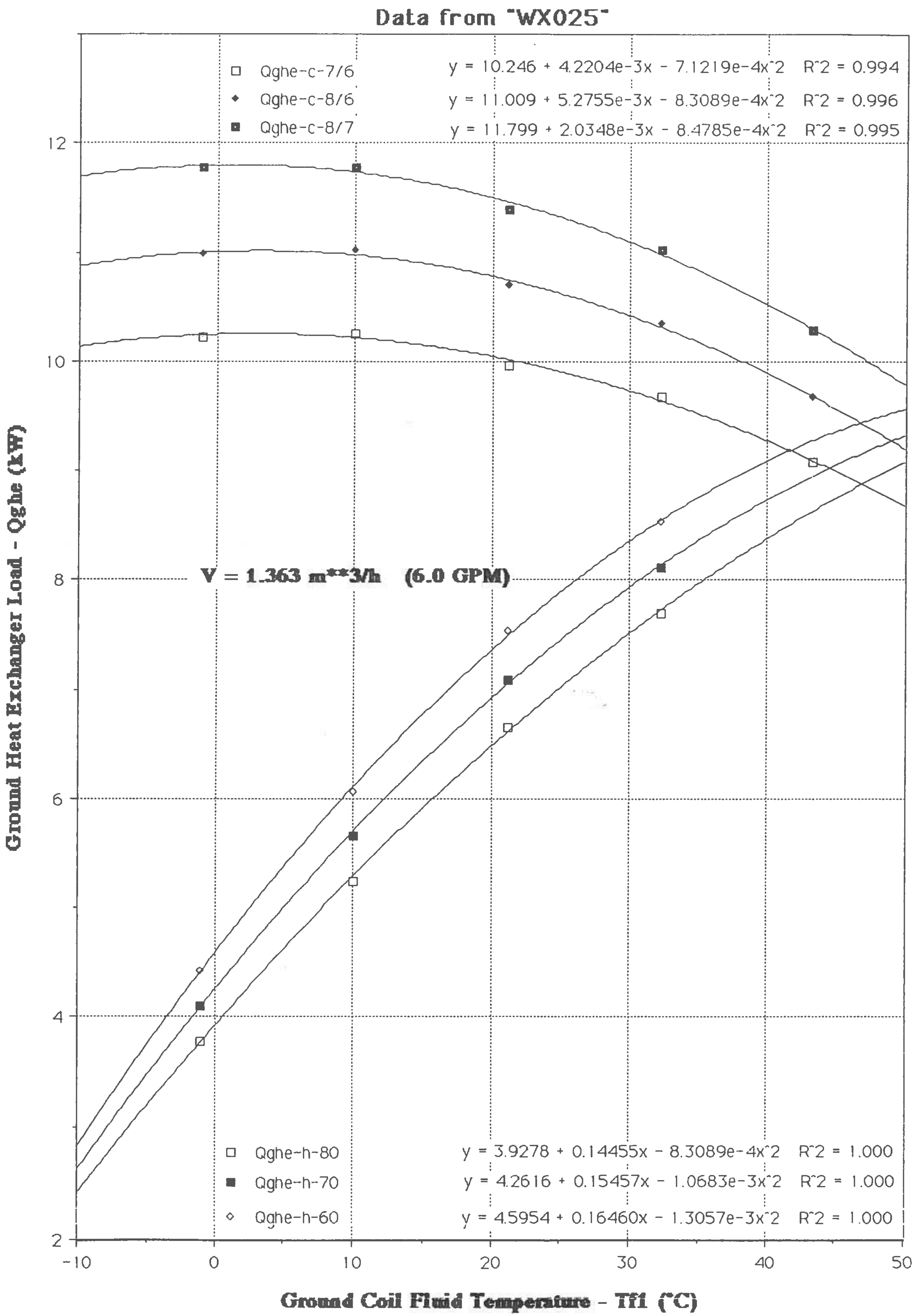
Data from "WX019"
COP-60 y = 3.4125 + 4.1760e-2x - 4.6575e-4x^2 R^2 = 0.999
COP-70 y = 3.1201 + 3.9240e-2x - 4.0500e-4x^2 R^2 = 0.999
COP-80 y = 2.8662 + 3.5820e-2x - 3.2400e-4x^2 R^2 = 0.999
V = 1.022 m**3/h (4.5 GPM)
COPc-8/7 y = 6.4827 - 0.11719x + 5.7654e-4x^2 R^2 = 1.000
COPc-8/6 y = 6.1288 - 0.11237x + 5.9349e-4x^2 R^2 = 1.000
COPc-7/6 y = 5.7617 - 0.10664x + 5.7654e-4x^2 R^2 = 0.999
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)



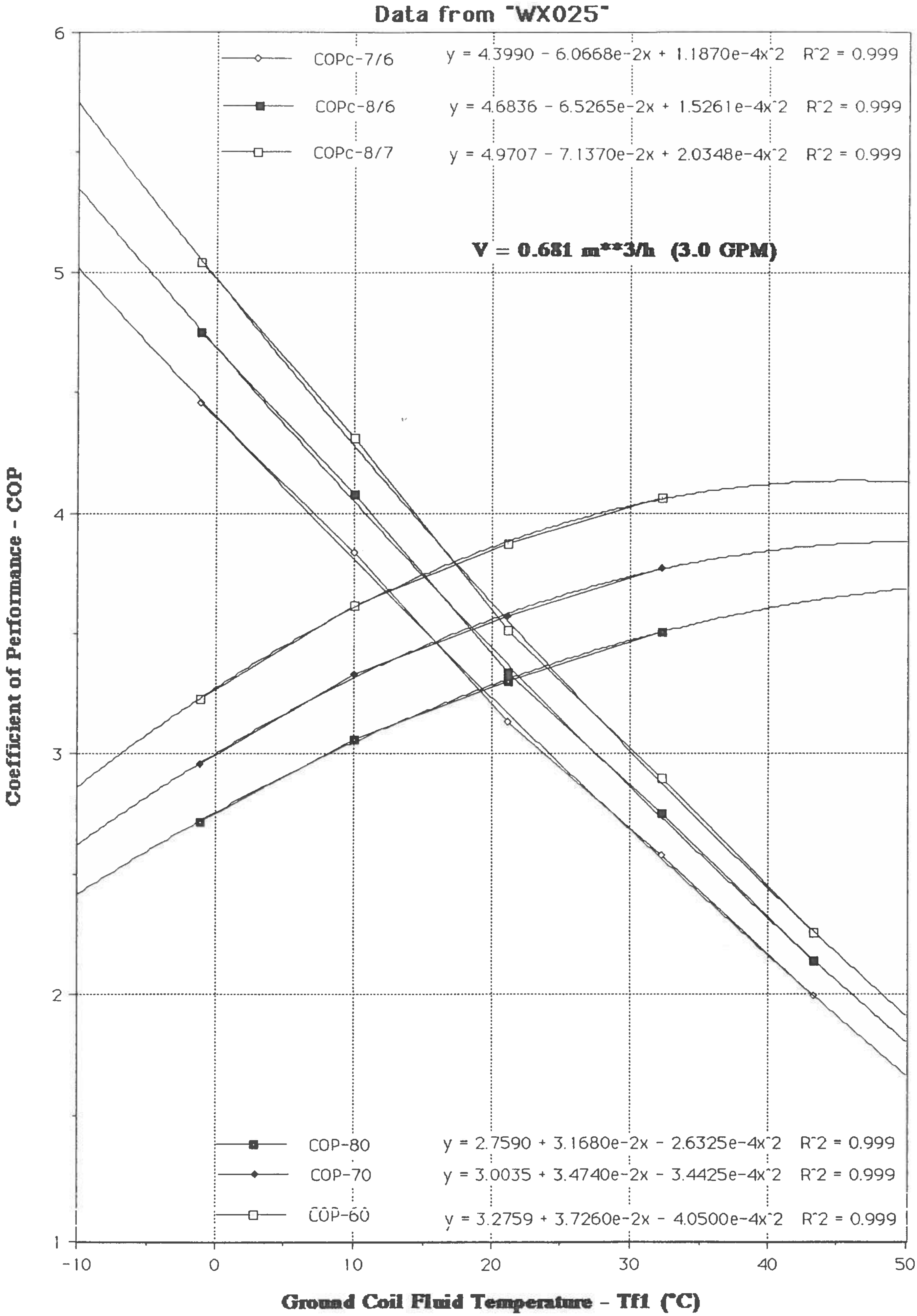
Data from "WX025"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 10.043 + 7.4611e-3x - 6.9523e-4x^2 R^2 = 0.995
y = 10.775 + 8.5915e-3x - 7.9698e-4x^2 R^2 = 0.995
y = 11.543 + 5.8030e-3x - 8.3089e-4x^2 R^2 = 0.992
V = 0.681 m**3/h (3.0 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 3.5807 + 0.14455x - 1.0089e-3x^2 R^2 = 1.000
y = 3.9120 + 0.14982x - 1.1276e-3x^2 R^2 = 1.000
y = 4.2103 + 0.15826x - 1.3057e-3x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
2.0
4.0
6.0
8.0
10.0
12.0
-10
0
10
20
30
40
50

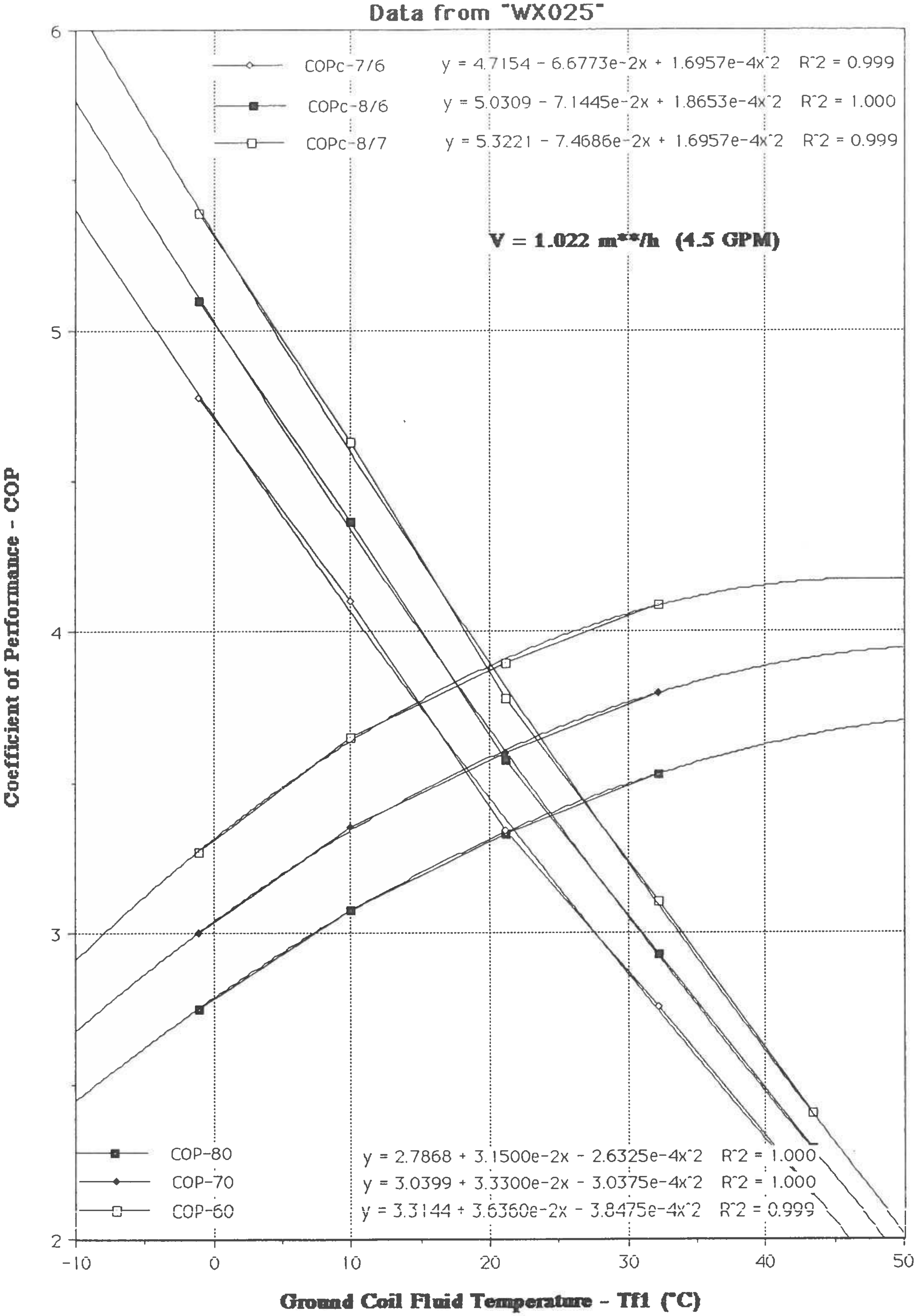


Data from "WX025"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 10.125 + 5.8030e-3x - 7.1219e-4x^2 R^2 = 0.993
y = 10.866 + 6.4813e-3x - 7.9698e-4x^2 R^2 = 0.991
y = 11.634 + 5.1248e-3x - 8.6480e-4x^2 R^2 = 0.992
V = 1.022 m**3/h (4.5 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 3.7825 + 0.14560x - 9.4959e-4x^2 R^2 = 0.999
y = 4.0873 + 0.15457x - 1.1276e-3x^2 R^2 = 1.000
y = 4.4166 + 0.16196x - 1.3057e-3x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
2
4
6
8
10
12
-10
0
10
20
30
40
50

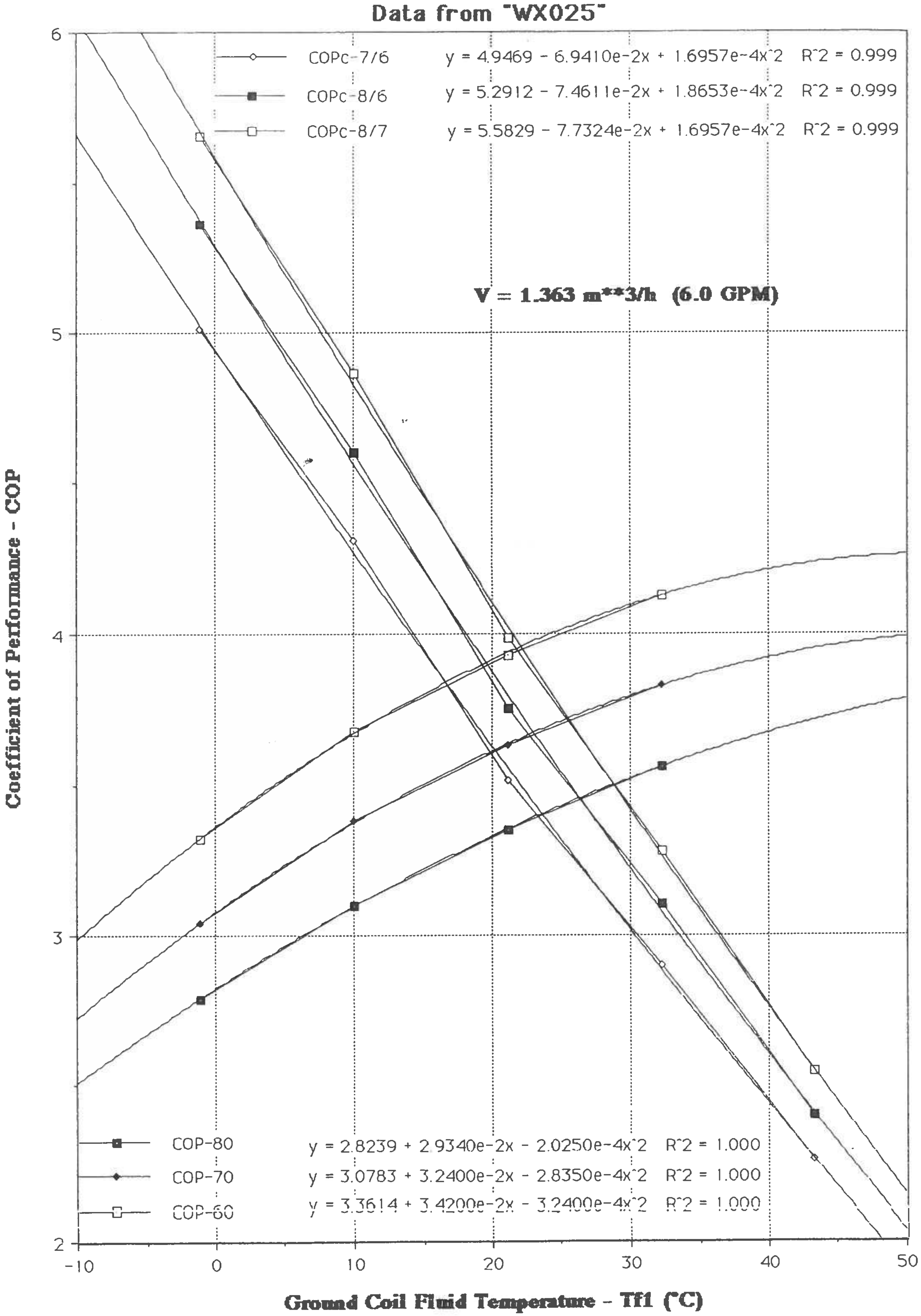


Data from "WX025"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 10.246 + 4.2204e-3x - 7.1219e-4x^2 R^2 = 0.994
y = 11.009 + 5.2755e-3x - 8.3089e-4x^2 R^2 = 0.996
y = 11.799 + 2.0348e-3x - 8.4785e-4x^2 R^2 = 0.995
V = 1.363 m**3/h (6.0 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 3.9278 + 0.14455x - 8.3089e-4x^2 R^2 = 1.000
y = 4.2616 + 0.15457x - 1.0683e-3x^2 R^2 = 1.000
y = 4.5954 + 0.16460x - 1.3057e-3x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
2
4
6
8
10
12
-10
0
10
20
30
40
50

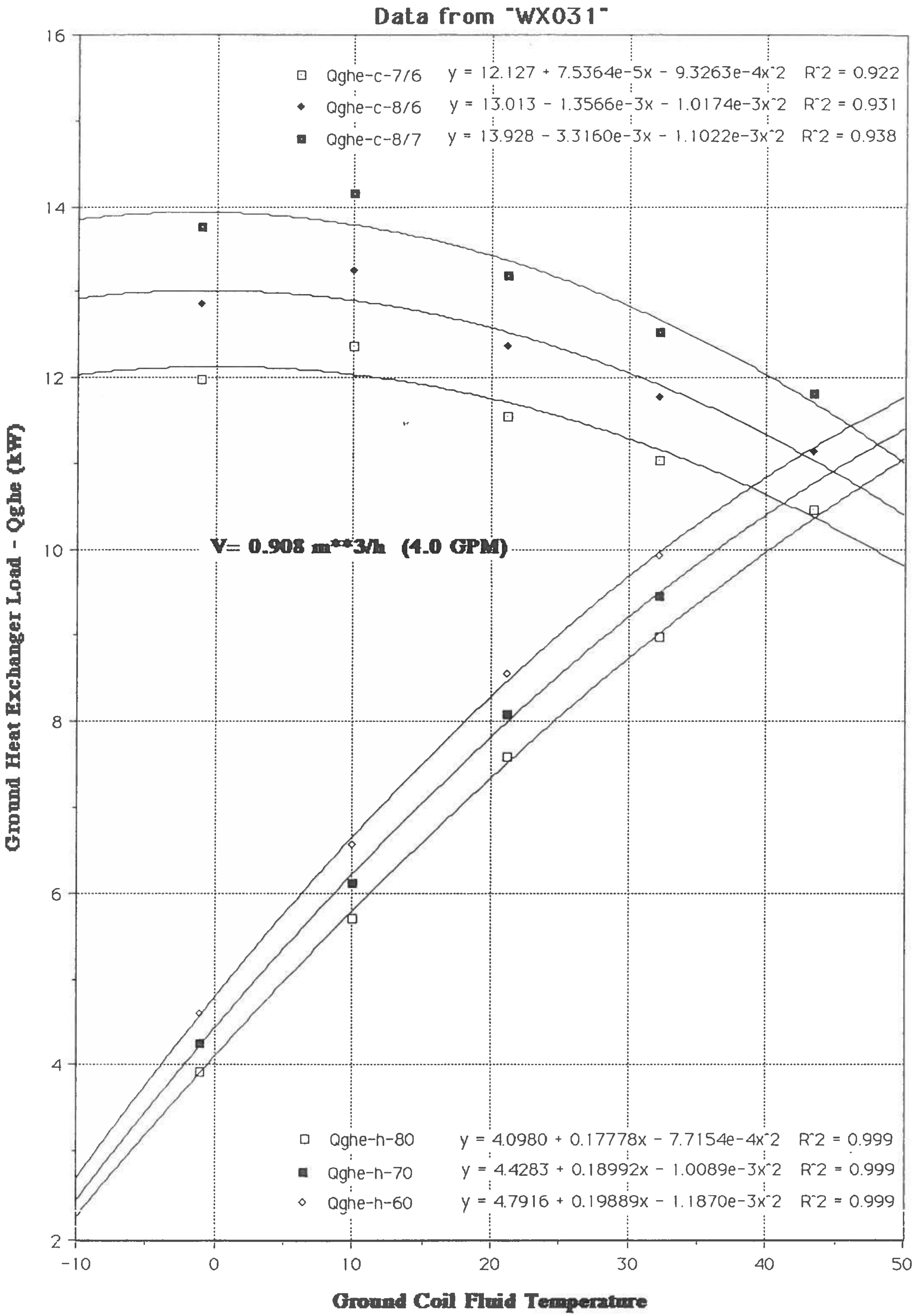

Data from "WX025"
COPc-7/6
y = 4.3990 - 6.0668e-2x + 1.1870e-4x^2 R^2 = 0.999
COPc-8/6
y = 4.6836 - 6.5265e-2x + 1.5261e-4x^2 R^2 = 0.999
COPc-8/7
y = 4.9707 - 7.1370e-2x + 2.0348e-4x^2 R^2 = 0.999
V = 0.681 m**3/h (3.0 GPM)
COP-80
y = 2.7590 + 3.1680e-2x - 2.6325e-4x^2 R^2 = 0.999
COP-70
y = 3.0035 + 3.4740e-2x - 3.4425e-4x^2 R^2 = 0.999
COP-60
y = 3.2759 + 3.7260e-2x - 4.0500e-4x^2 R^2 = 0.999
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
1
-10
0
10
20
30
40
50



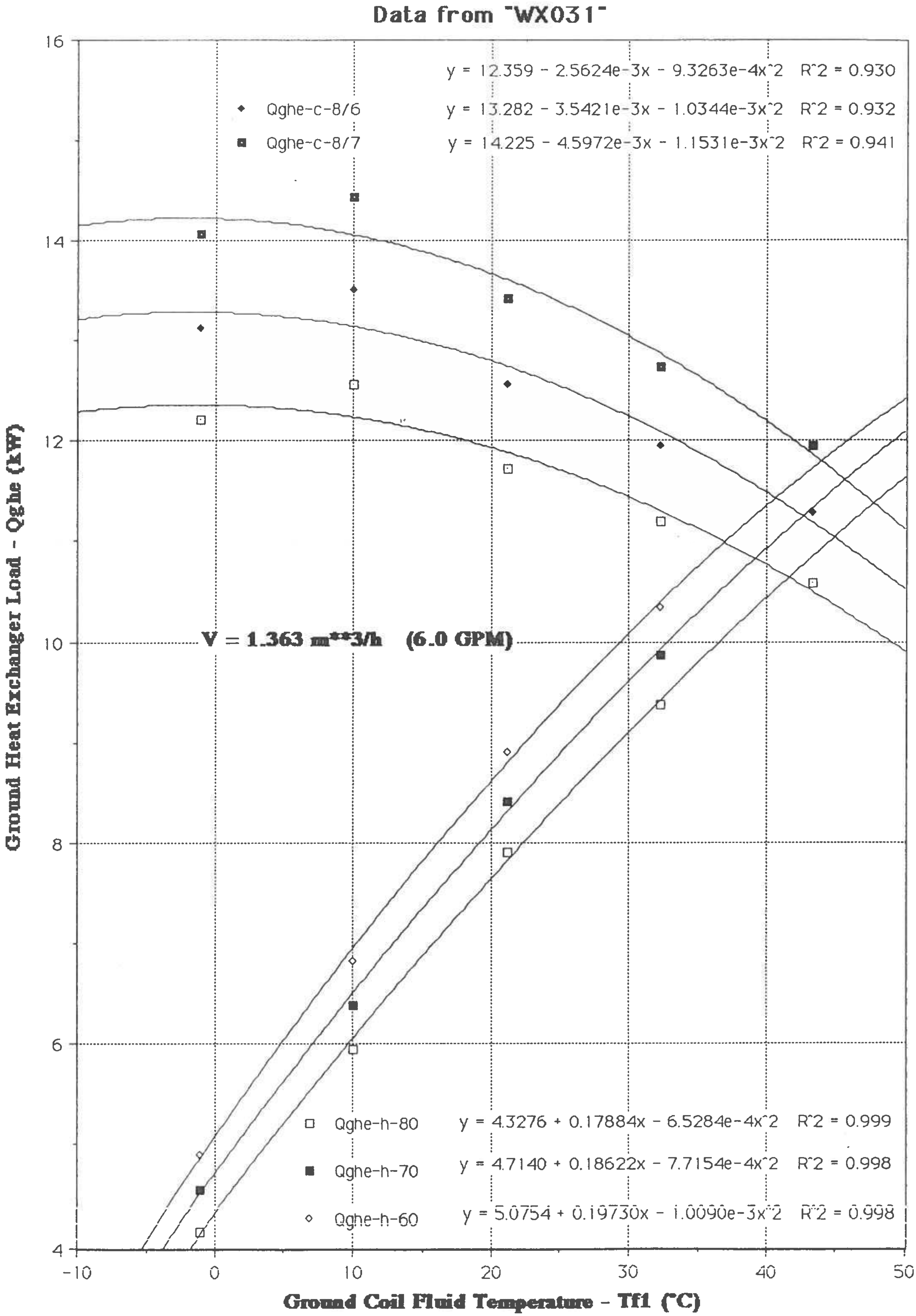
Data from "WX025"
COPc-7/6
y = 4.7154 - 6.6773e-2x + 1.6957e-4x^2 R^2 = 0.999
COPc-8/6
y = 5.0309 - 7.1445e-2x + 1.8653e-4x^2 R^2 = 1.000
COPc-8/7
y = 5.3221 - 7.4686e-2x + 1.6957e-4x^2 R^2 = 0.999
V = 1.022 m**/h (4.5 GPM)
COP-80
y = 2.7868 + 3.1500e-2x - 2.6325e-4x^2 R^2 = 1.000
COP-70
y = 3.0399 + 3.3300e-2x - 3.0375e-4x^2 R^2 = 1.000
COP-60
y = 3.3144 + 3.6360e-2x - 3.8475e-4x^2 R^2 = 0.999
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)



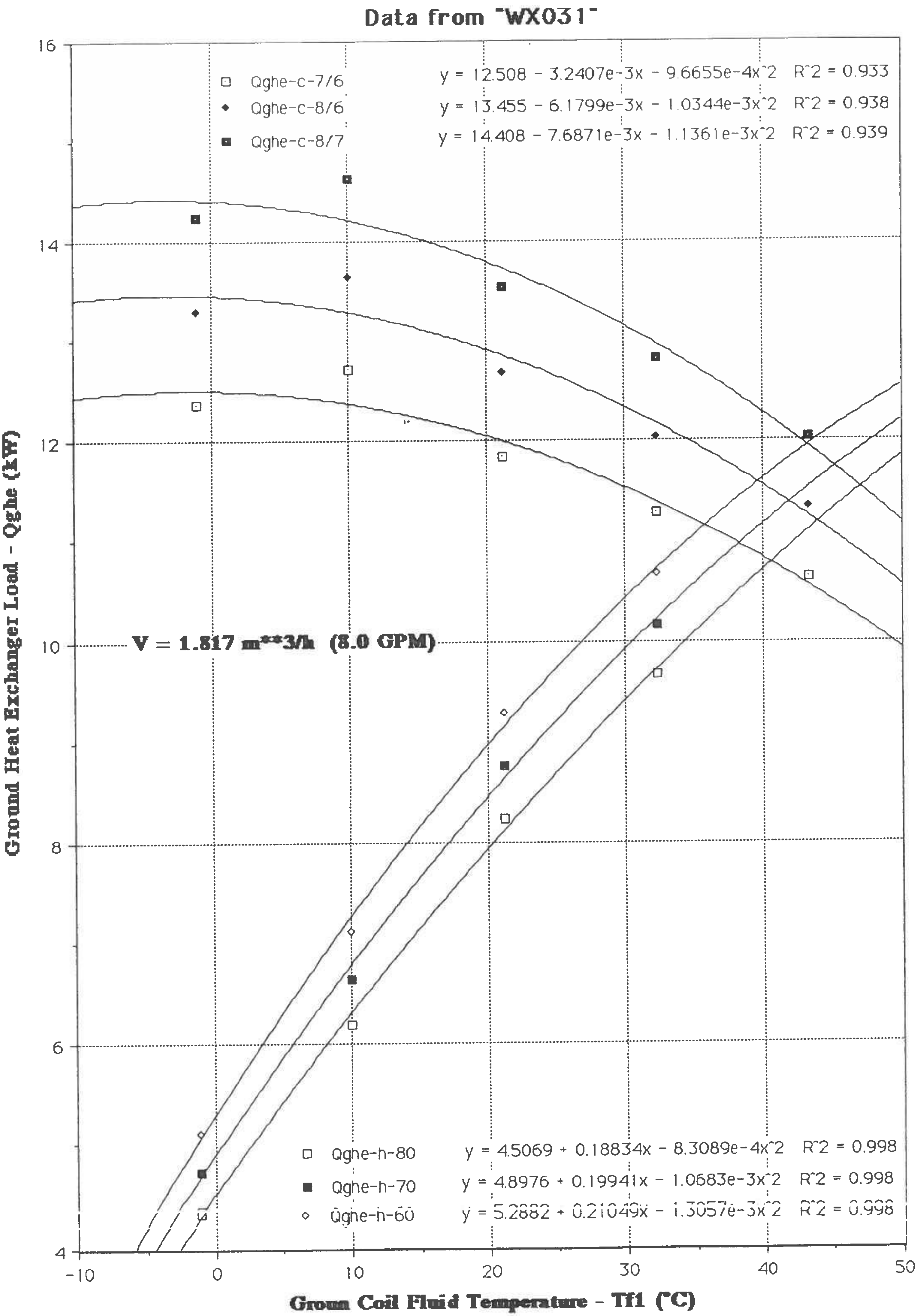
Data from "WX025"
COPc-7/6
y = 4.9469 - 6.9410e-2x + 1.6957e-4x^2 R^2 = 0.999
COPc-8/6
y = 5.2912 - 7.4611e-2x + 1.8653e-4x^2 R^2 = 0.999
COPc-8/7
y = 5.5829 - 7.7324e-2x + 1.6957e-4x^2 R^2 = 0.999
V = 1.363 m**3/h (6.0 GPM)
COP-80
y = 2.8239 + 2.9340e-2x - 2.0250e-4x^2 R^2 = 1.000
COP-70
y = 3.0783 + 3.2400e-2x - 2.8350e-4x^2 R^2 = 1.000
COP-60
y = 3.3614 + 3.4200e-2x - 3.2400e-4x^2 R^2 = 1.000
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50



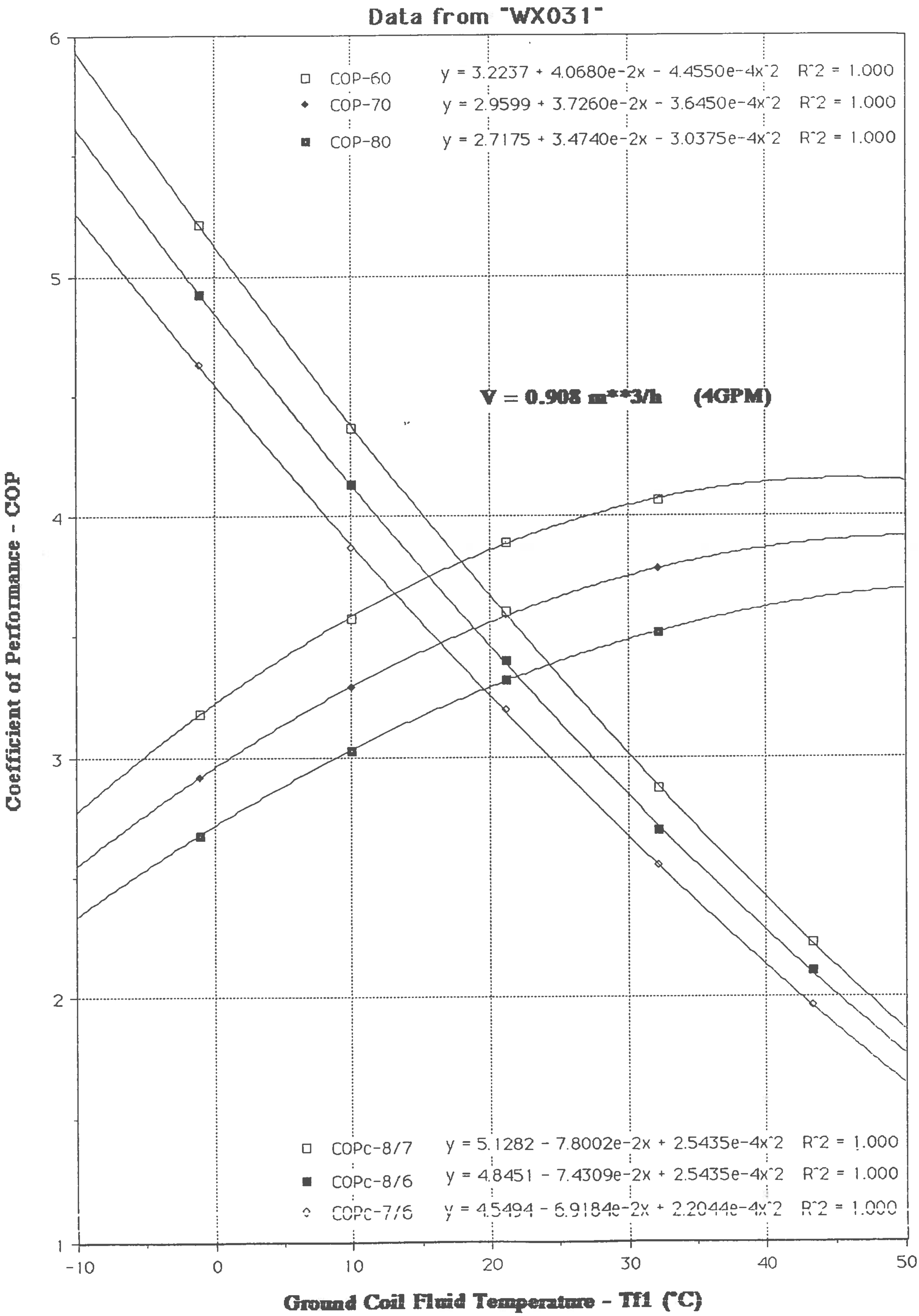
Data from "WX031"
Qghe-c-7/6 y = 12.127 + 7.5364e-5x - 9.3263e-4x^2 R^2 = 0.922
Qghe-c-8/6 y = 13.013 - 1.3566e-3x - 1.0174e-3x^2 R^2 = 0.931
Qghe-c-8/7 y = 13.928 - 3.3160e-3x - 1.1022e-3x^2 R^2 = 0.938
V= 0.908 m**3/h (4.0 GPM)
Qghe-h-80 y = 4.0980 + 0.17778x - 7.7154e-4x^2 R^2 = 0.999
Qghe-h-70 y = 4.4283 + 0.18992x - 1.0089e-3x^2 R^2 = 0.999
Qghe-h-60 y = 4.7916 + 0.19889x - 1.1870e-3x^2 R^2 = 0.999
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature
16
14
12
10
8
6
4
2
-10
0
10
20
30
40
50

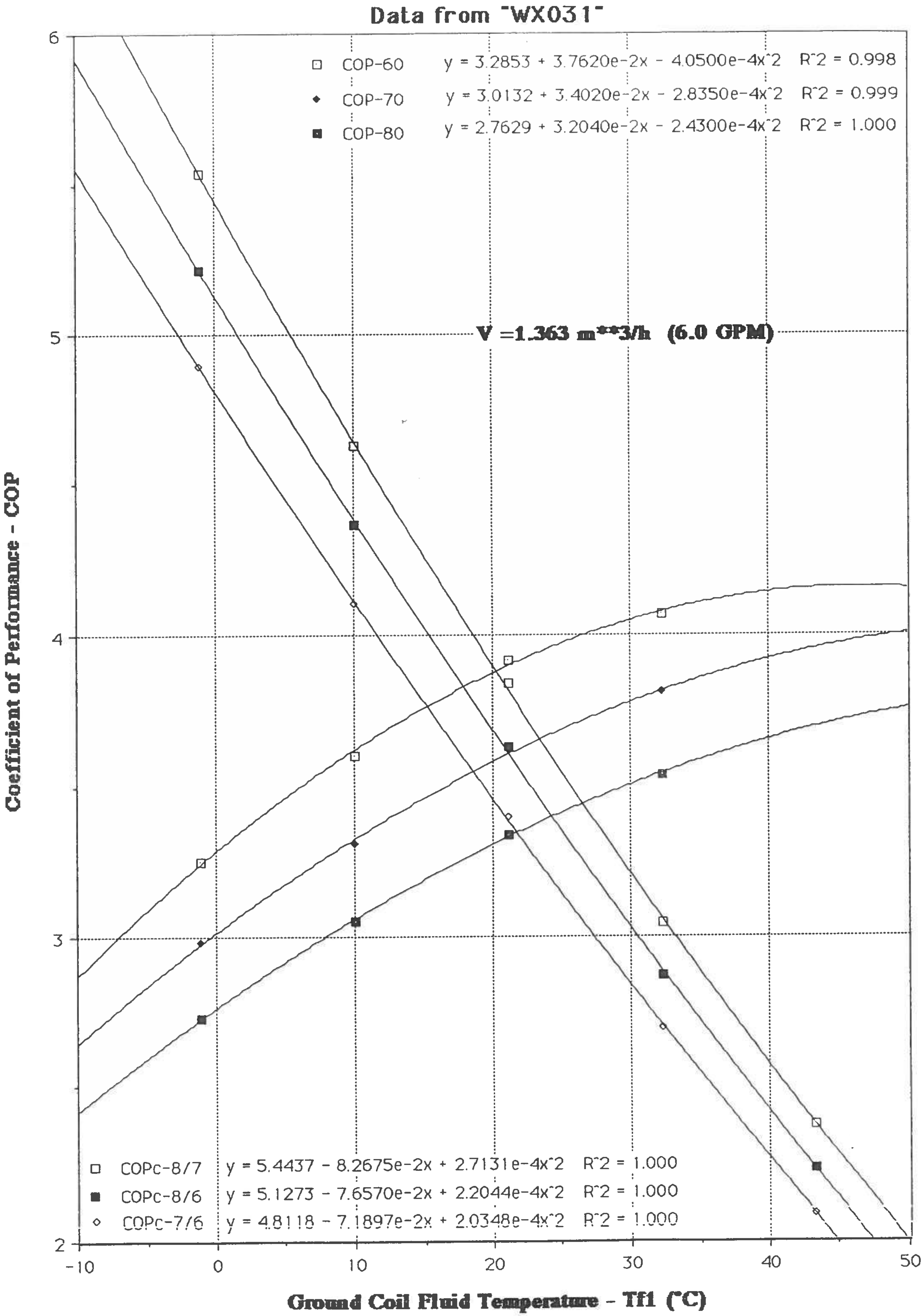


Data from "WX031"
y = 12.359 - 2.5624e-3x - 9.3263e-4x^2 R^2 = 0.930
Qghe-c-8/6
y = 13.282 - 3.5421e-3x - 1.0344e-3x^2 R^2 = 0.932
Qghe-c-8/7
y = 14.225 - 4.5972e-3x - 1.1531e-3x^2 R^2 = 0.941
V = 1.363 m**3/h (6.0 GPM)
Qghe-h-80
y = 4.3276 + 0.17884x - 6.5284e-4x^2 R^2 = 0.999
Qghe-h-70
y = 4.7140 + 0.18622x - 7.7154e-4x^2 R^2 = 0.998
Qghe-h-60
y = 5.0754 + 0.19730x - 1.0090e-3x^2 R^2 = 0.998
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
16
14
12
10
8
6
4
-10
0
10
20
30
40
50

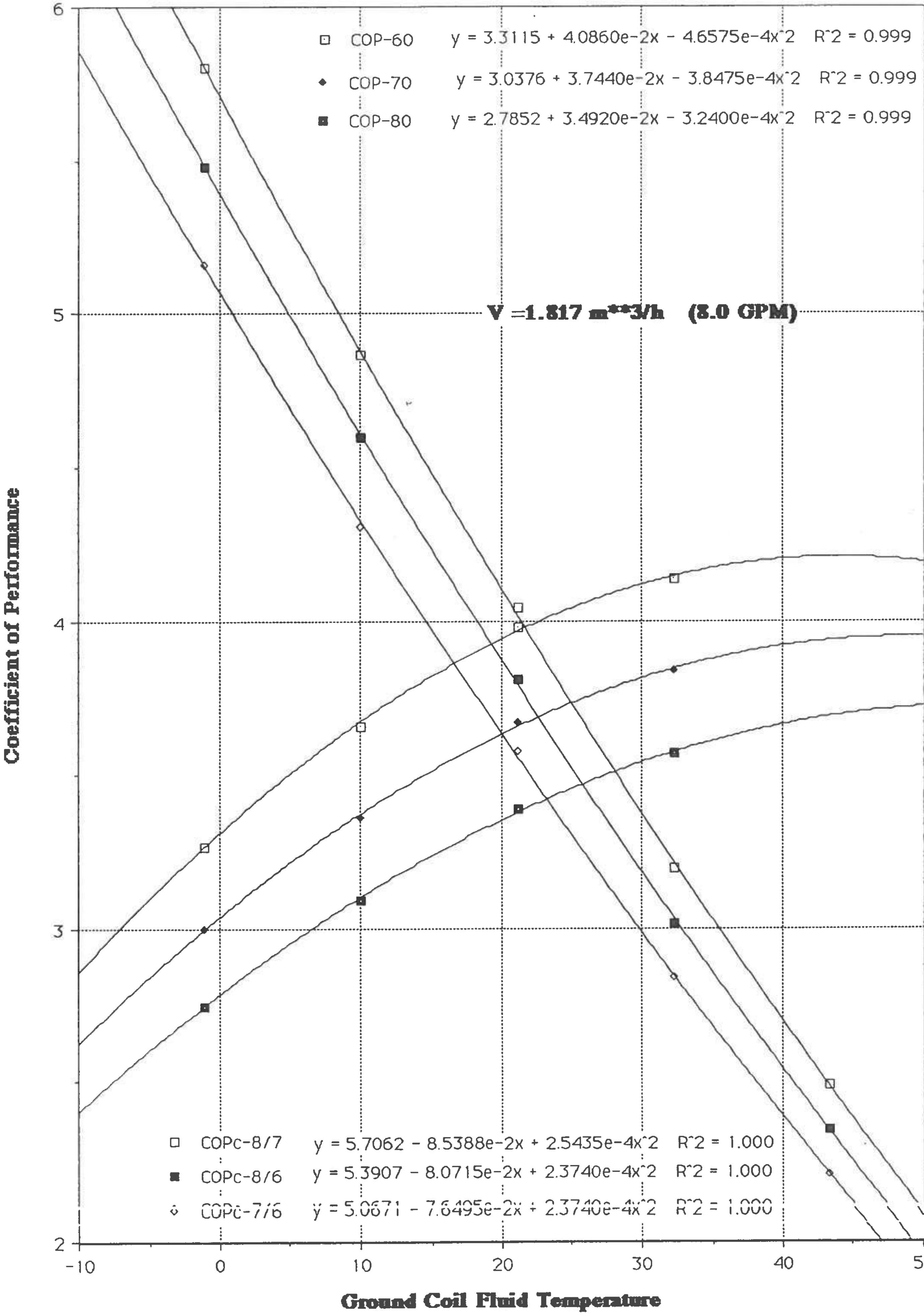


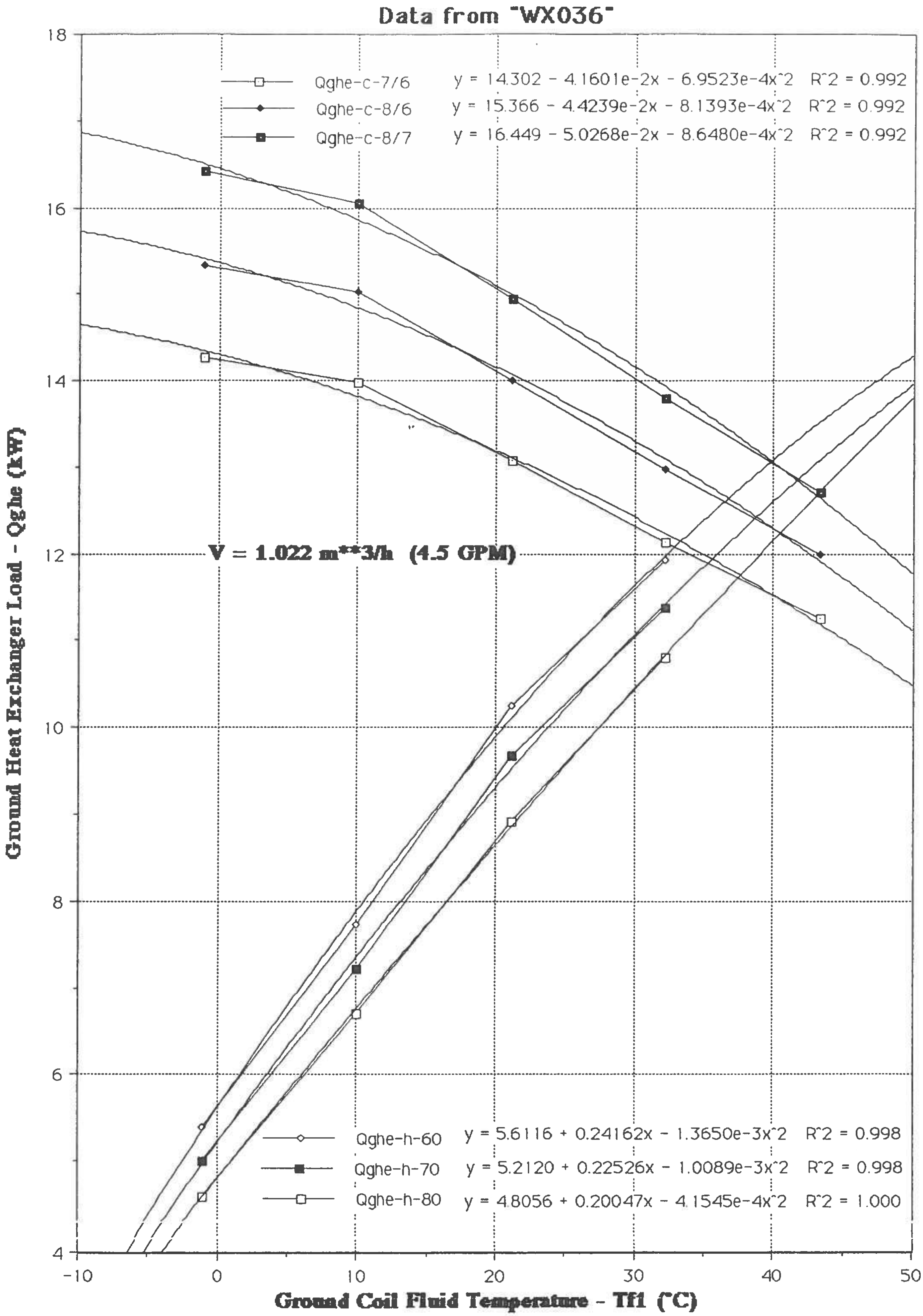
Data from "WX031"
Qghe-c-7/6
Qghe-c-8/6
Qghe-c-8/7
y = 12.508 - 3.2407e-3x - 9.6655e-4x^2 R^2 = 0.933
y = 13.455 - 6.1799e-3x - 1.0344e-3x^2 R^2 = 0.938
y = 14.408 - 7.6871e-3x - 1.1361e-3x^2 R^2 = 0.939
V = 1.817 m**3/h (8.0 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 4.5069 + 0.18834x - 8.3089e-4x^2 R^2 = 0.998
y = 4.8976 + 0.19941x - 1.0683e-3x^2 R^2 = 0.998
y = 5.2882 + 0.21049x - 1.3057e-3x^2 R^2 = 0.998
Ground Heat Exchanger Load - Qghe (kW)
Groun Coil Fluid Temperature - Tf1 (°C)
16
14
12
10
8
6
4
-10
0
10
20
30
40
50

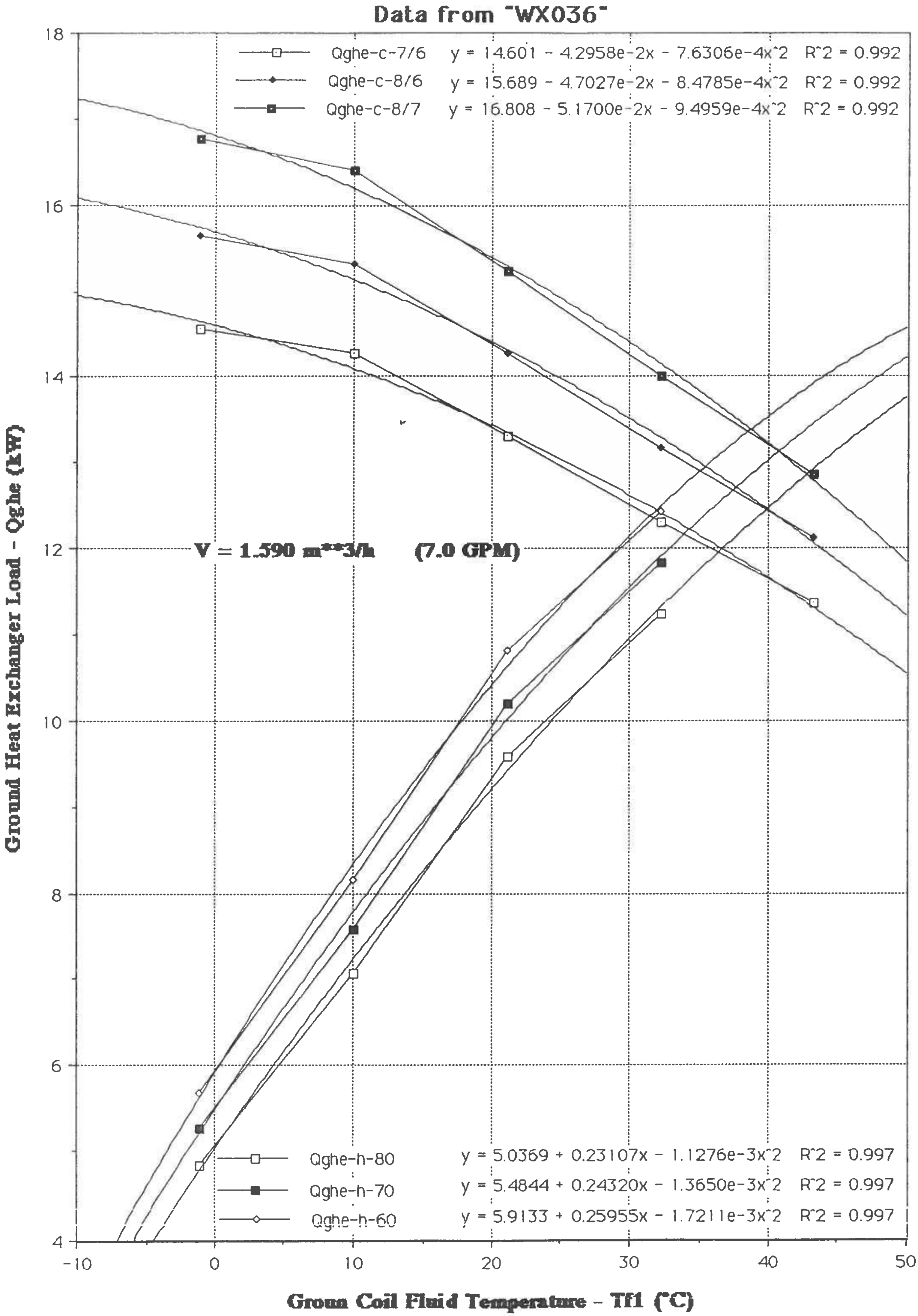

Data from "WX031"
COP-60 y = 3.2237 + 4.0680e-2x - 4.4550e-4x^2 R^2 = 1.000
COP-70 y = 2.9599 + 3.7260e-2x - 3.6450e-4x^2 R^2 = 1.000
COP-80 y = 2.7175 + 3.4740e-2x - 3.0375e-4x^2 R^2 = 1.000
V = 0.908 m**3/h (4GPM)
COPc-8/7 y = 5.1282 - 7.8002e-2x + 2.5435e-4x^2 R^2 = 1.000
COPc-8/6 y = 4.8451 - 7.4309e-2x + 2.5435e-4x^2 R^2 = 1.000
COPc-7/6 y = 4.5494 - 6.9184e-2x + 2.2044e-4x^2 R^2 = 1.000
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
1
2
3
4
5
6
-10
0
10
20
30
40
50


Data from "WX031"
COP-60 y = 3.2853 + 3.7620e-2x - 4.0500e-4x^2 R^2 = 0.998
COP-70 y = 3.0132 + 3.4020e-2x - 2.8350e-4x^2 R^2 = 0.999
COP-80 y = 2.7629 + 3.2040e-2x - 2.4300e-4x^2 R^2 = 1.000
V =1.363 m**3/h (6.0 GPM)
COPc-8/7 y = 5.4437 - 8.2675e-2x + 2.7131e-4x^2 R^2 = 1.000
COPc-8/6 y = 5.1273 - 7.6570e-2x + 2.2044e-4x^2 R^2 = 1.000
COPc-7/6 y = 4.8118 - 7.1897e-2x + 2.0348e-4x^2 R^2 = 1.000
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50

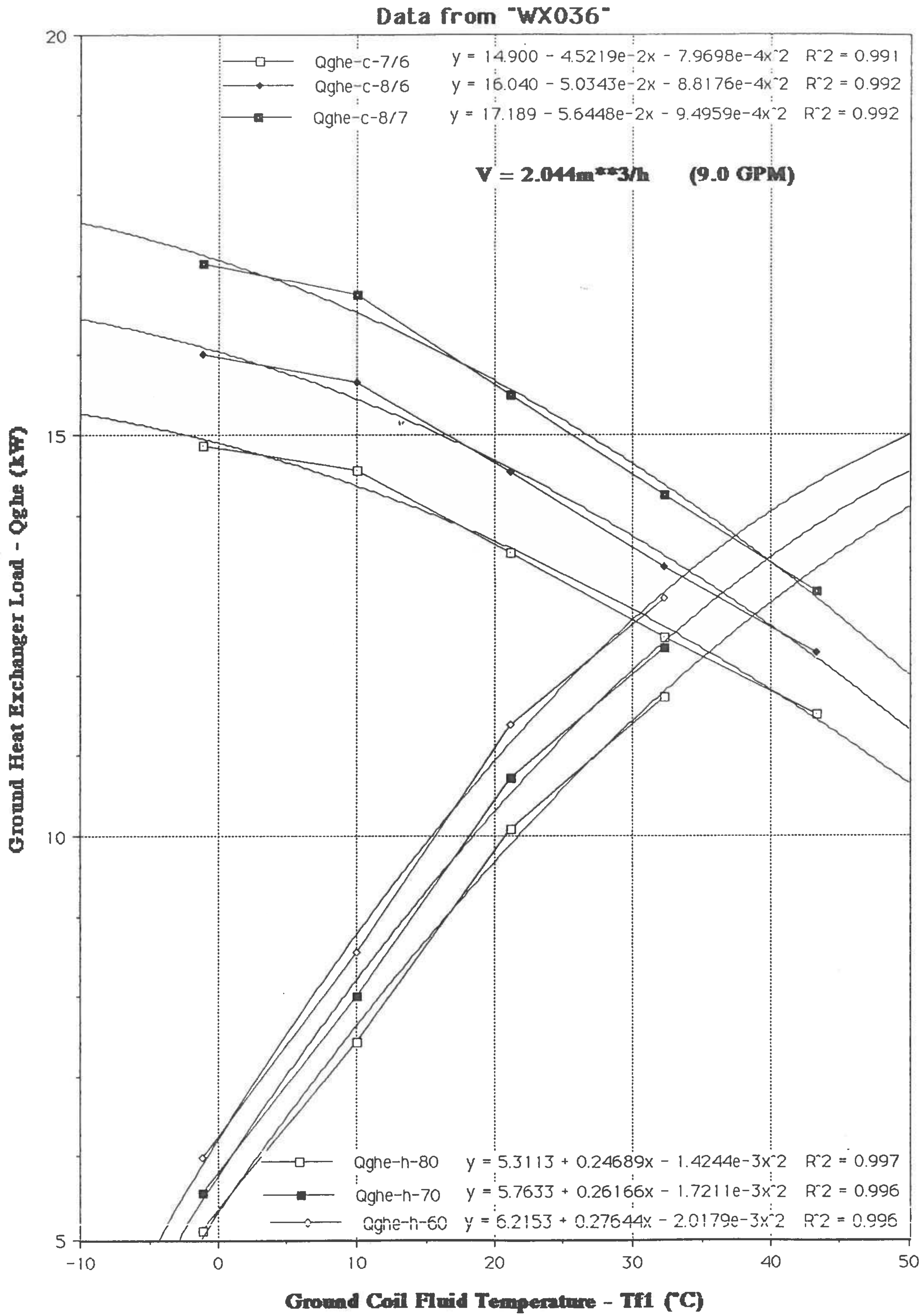
Data from "WX031"



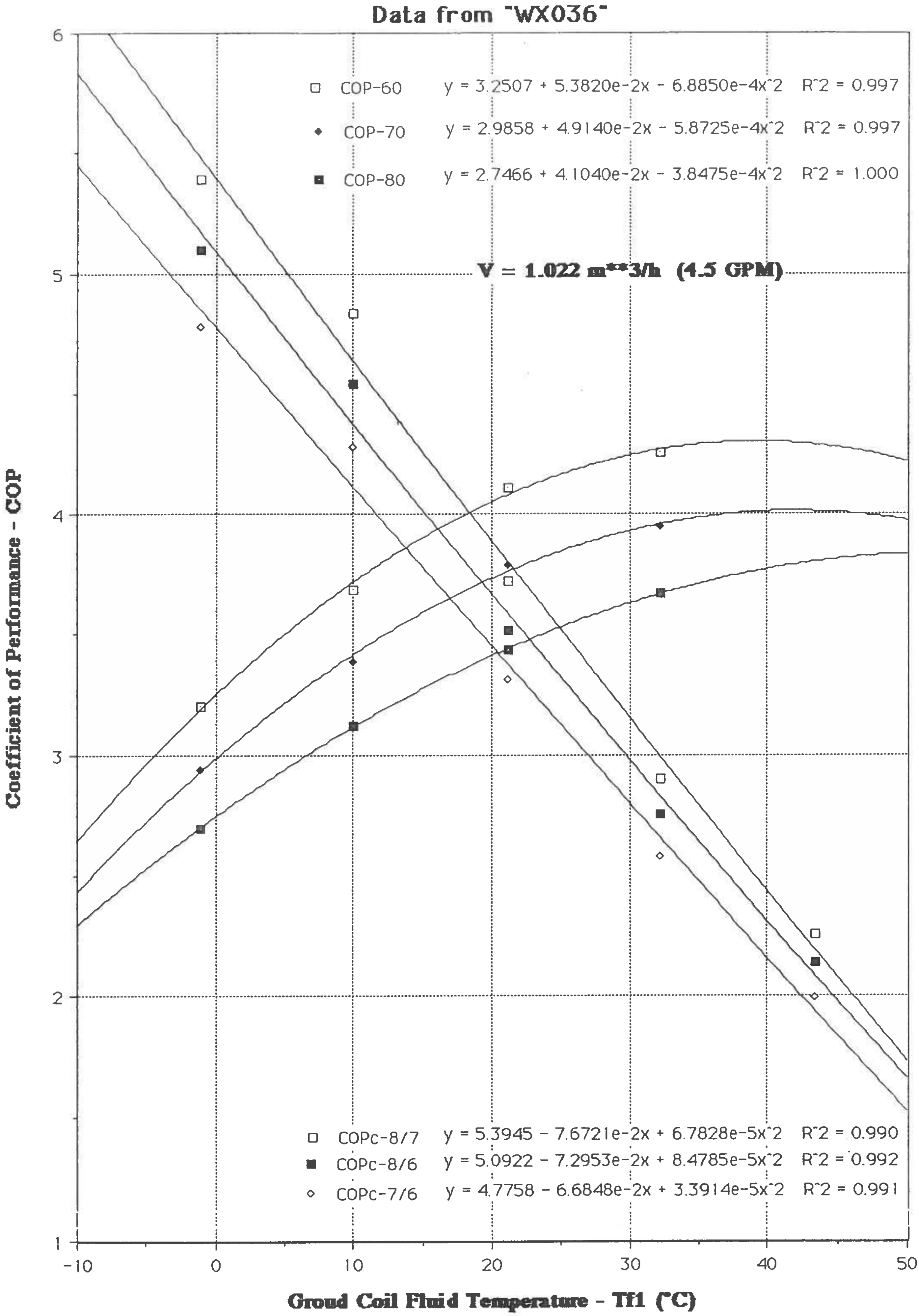

Data from "WX036"
Qghe-c-7/6 y = 14.302 - 4.1601e-2x - 6.9523e-4x^2 R^2 = 0.992
Qghe-c-8/6 y = 15.366 - 4.4239e-2x - 8.1393e-4x^2 R^2 = 0.992
Qghe-c-8/7 y = 16.449 - 5.0268e-2x - 8.6480e-4x^2 R^2 = 0.992
V = 1.022 m**3/h (4.5 GPM)
Qghe-h-60 y = 5.6116 + 0.24162x - 1.3650e-3x^2 R^2 = 0.998
Qghe-h-70 y = 5.2120 + 0.22526x - 1.0089e-3x^2 R^2 = 0.998
Qghe-h-80 y = 4.8056 + 0.20047x - 4.1545e-4x^2 R^2 = 1.000
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
18
16
14
12
10
8
6
4
-10
0
10
20
30
40
50



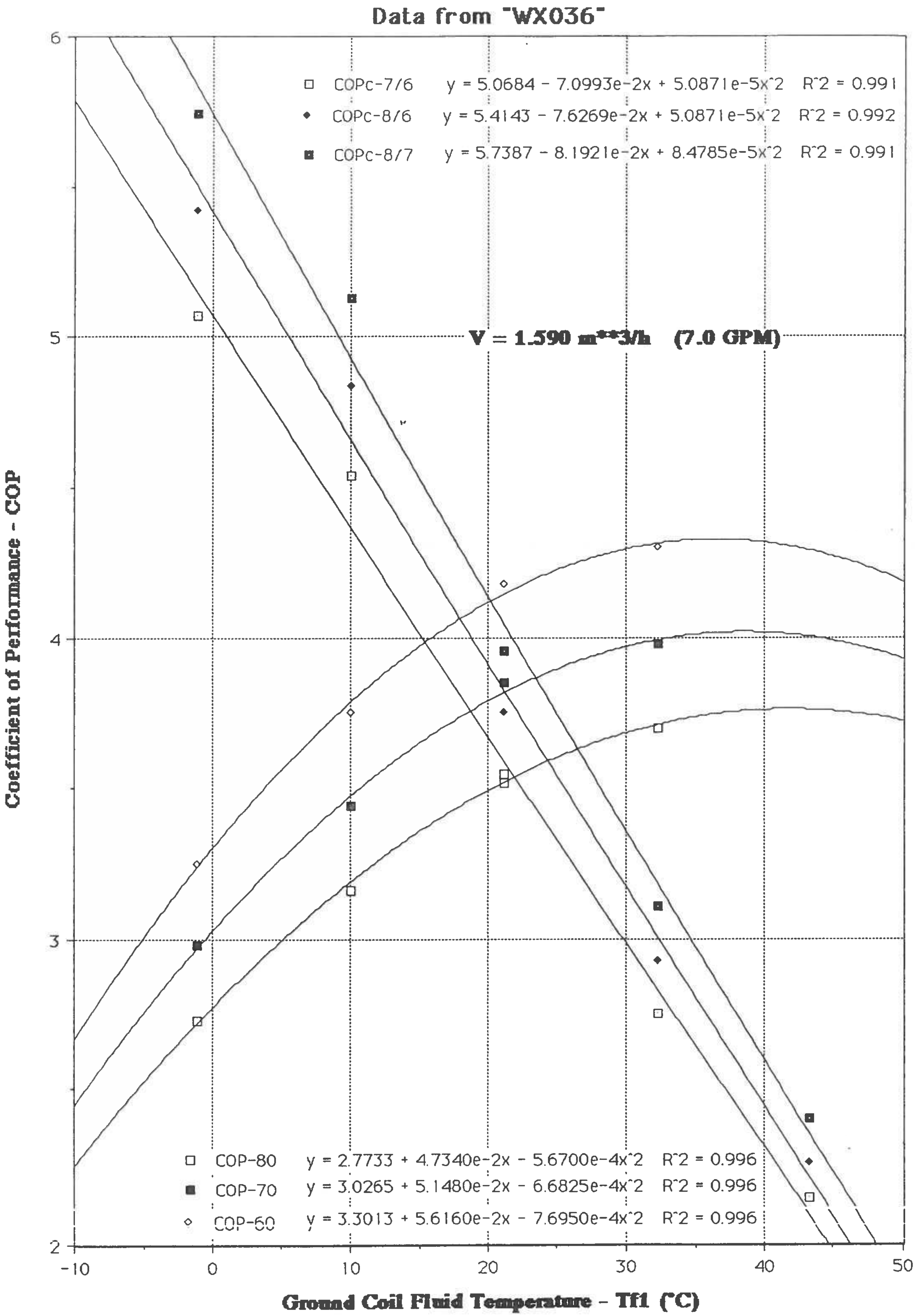
Data from "WX036"
Qghe-c-7/6 y = 14.601 - 4.2958e-2x - 7.6306e-4x^2 R^2 = 0.992
Qghe-c-8/6 y = 15.689 - 4.7027e-2x - 8.4785e-4x^2 R^2 = 0.992
Qghe-c-8/7 y = 16.808 - 5.1700e-2x - 9.4959e-4x^2 R^2 = 0.992
V = 1.590 m**3/h (7.0 GPM)
Qghe-h-80 y = 5.0369 + 0.23107x - 1.1276e-3x^2 R^2 = 0.997
Qghe-h-70 y = 5.4844 + 0.24320x - 1.3650e-3x^2 R^2 = 0.997
Qghe-h-60 y = 5.9133 + 0.25955x - 1.7211e-3x^2 R^2 = 0.997
Ground Heat Exchanger Load - Qghe (kW)
Groun Coil Fluid Temperature - Tf1 (°C)
18
16
14
12
10
8
6
4
-10
0
10
20
30
40
50

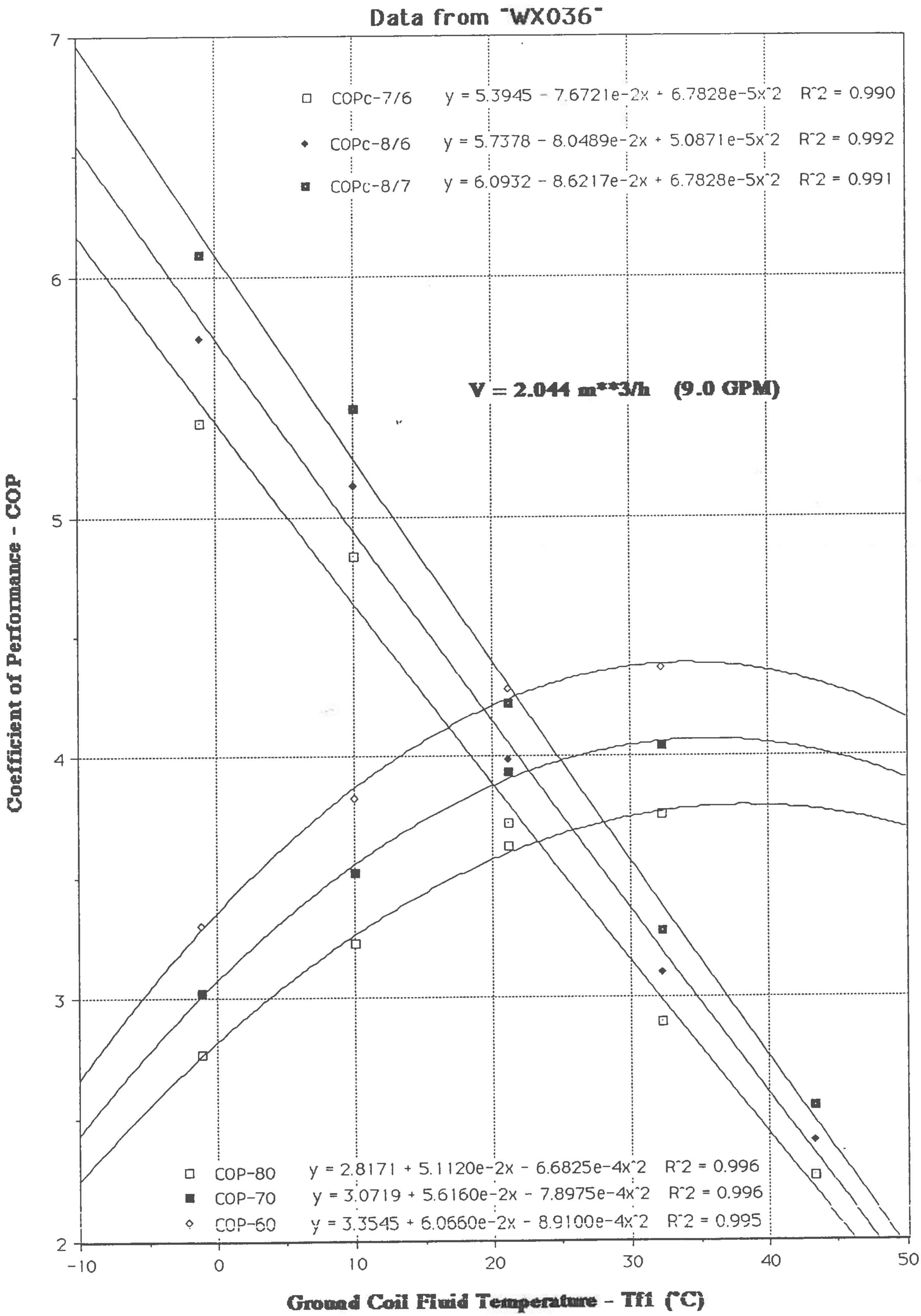


Data from "WX036"
Qghe-c-7/6 y = 14.900 - 4.5219e-2x - 7.9698e-4x^2 R^2 = 0.991
Qghe-c-8/6 y = 16.040 - 5.0343e-2x - 8.8176e-4x^2 R^2 = 0.992
Qghe-c-8/7 y = 17.189 - 5.6448e-2x - 9.4959e-4x^2 R^2 = 0.992
V = 2.044m**3/h (9.0 GPM)
Qghe-h-80 y = 5.3113 + 0.24689x - 1.4244e-3x^2 R^2 = 0.997
Qghe-h-70 y = 5.7633 + 0.26166x - 1.7211e-3x^2 R^2 = 0.996
Qghe-h-60 y = 6.2153 + 0.27644x - 2.0179e-3x^2 R^2 = 0.996
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
20
15
10
5
-10
0
10
20
30
40
50

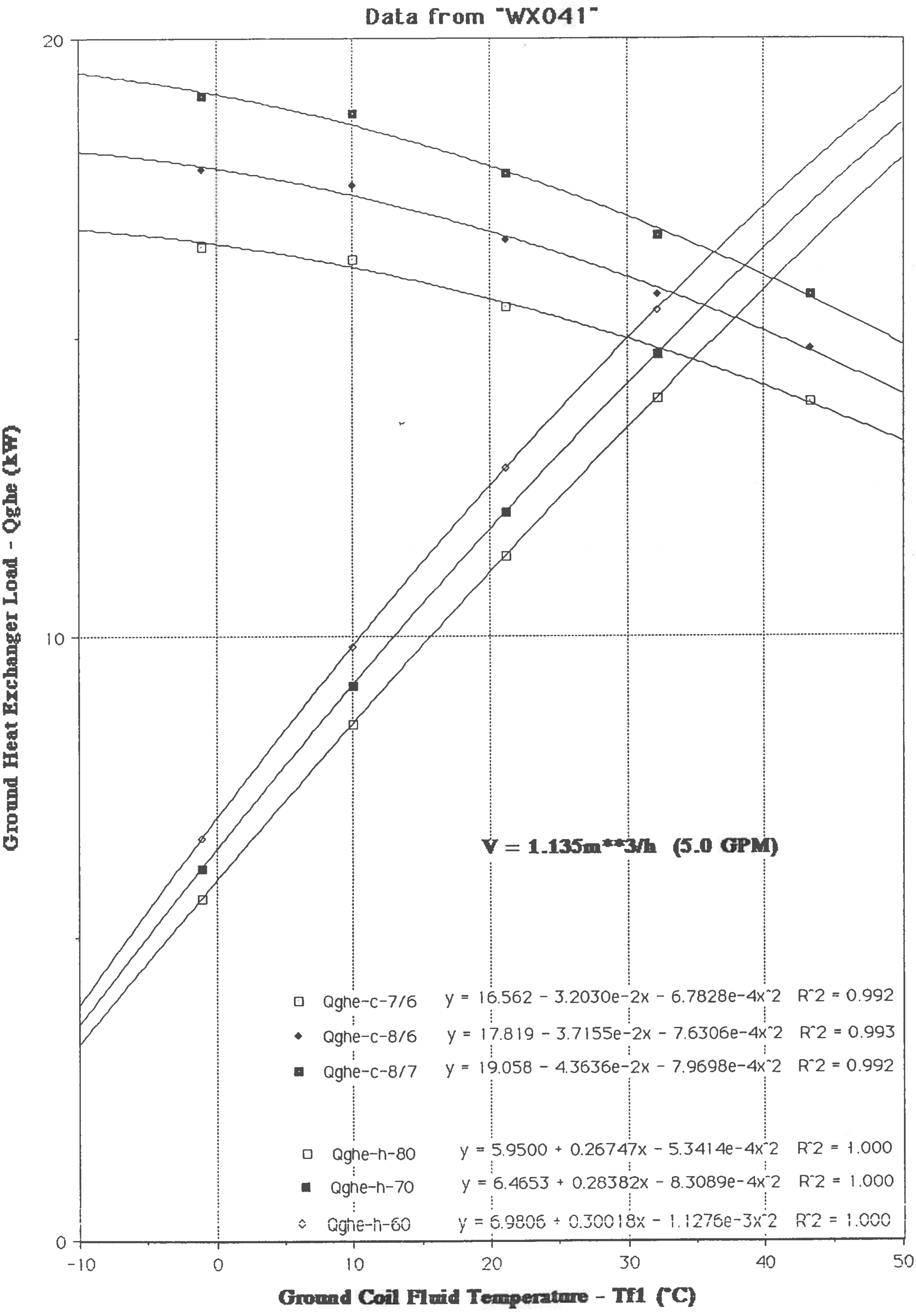


Data from "WX036"
COP-60 y = 3.2507 + 5.3820e-2x - 6.8850e-4x^2 R^2 = 0.997
COP-70 y = 2.9858 + 4.9140e-2x - 5.8725e-4x^2 R^2 = 0.997
COP-80 y = 2.7466 + 4.1040e-2x - 3.8475e-4x^2 R^2 = 1.000
V = 1.022 m**3/h (4.5 GPM)
COPc-8/7 y = 5.3945 - 7.6721e-2x + 6.7828e-5x^2 R^2 = 0.990
COPc-8/6 y = 5.0922 - 7.2953e-2x + 8.4785e-5x^2 R^2 = 0.992
COPc-7/6 y = 4.7758 - 6.6848e-2x + 3.3914e-5x^2 R^2 = 0.991
Coefficient of Performance - COP
Groud Coil Fluid Temperature - Tf1 (°C)
1
2
3
4
5
6
-10
0
10
20
30
40
50

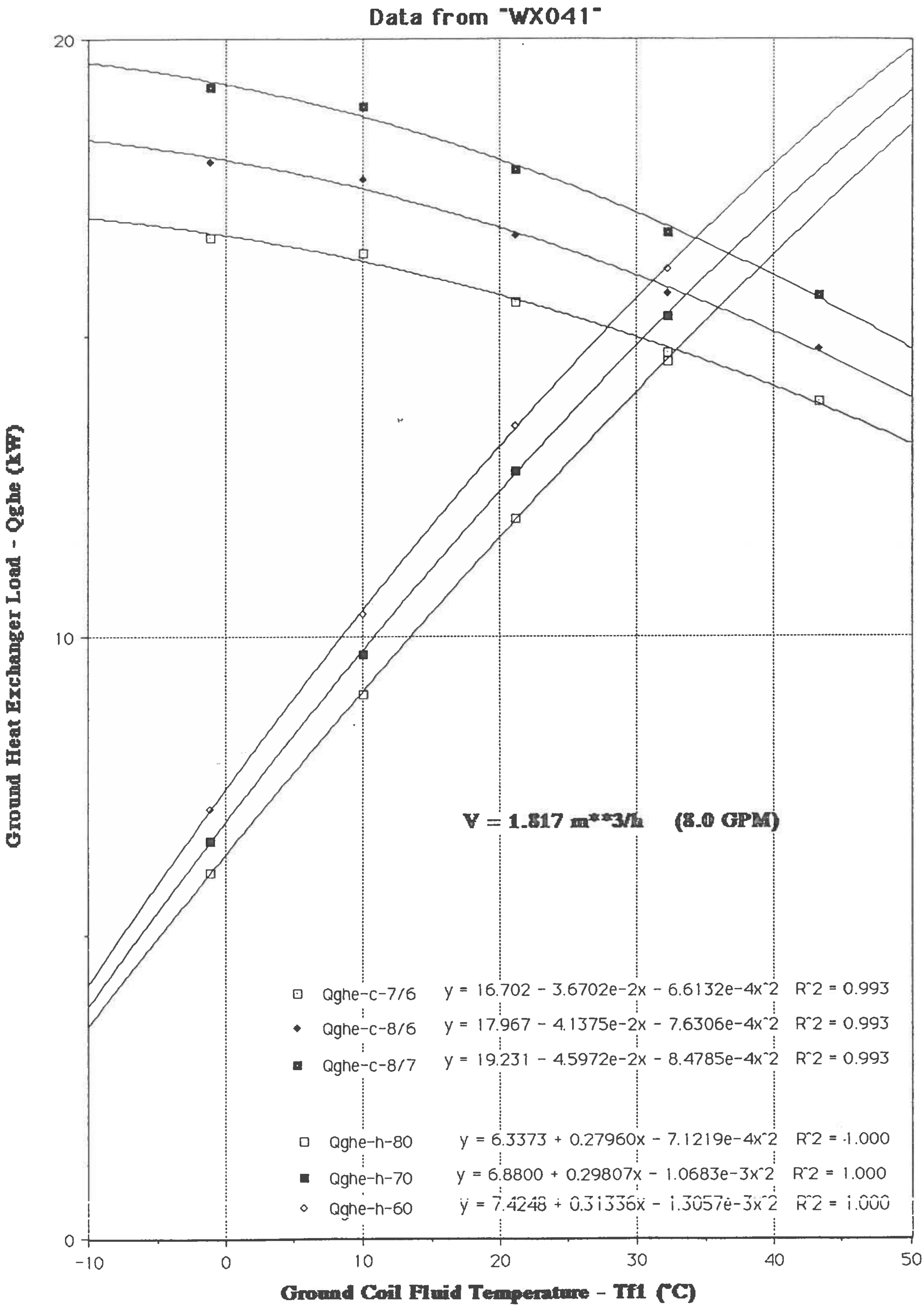

Data from "WX036"
COPc-7/6 y = 5.0684 - 7.0993e-2x + 5.0871e-5x^2 R^2 = 0.991
COPc-8/6 y = 5.4143 - 7.6269e-2x + 5.0871e-5x^2 R^2 = 0.992
COPc-8/7 y = 5.7387 - 8.1921e-2x + 8.4785e-5x^2 R^2 = 0.991
V = 1.590 m**3/h (7.0 GPM)
COP-80 y = 2.7733 + 4.7340e-2x - 5.6700e-4x^2 R^2 = 0.996
COP-70 y = 3.0265 + 5.1480e-2x - 6.6825e-4x^2 R^2 = 0.996
COP-60 y = 3.3013 + 5.6160e-2x - 7.6950e-4x^2 R^2 = 0.996
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50



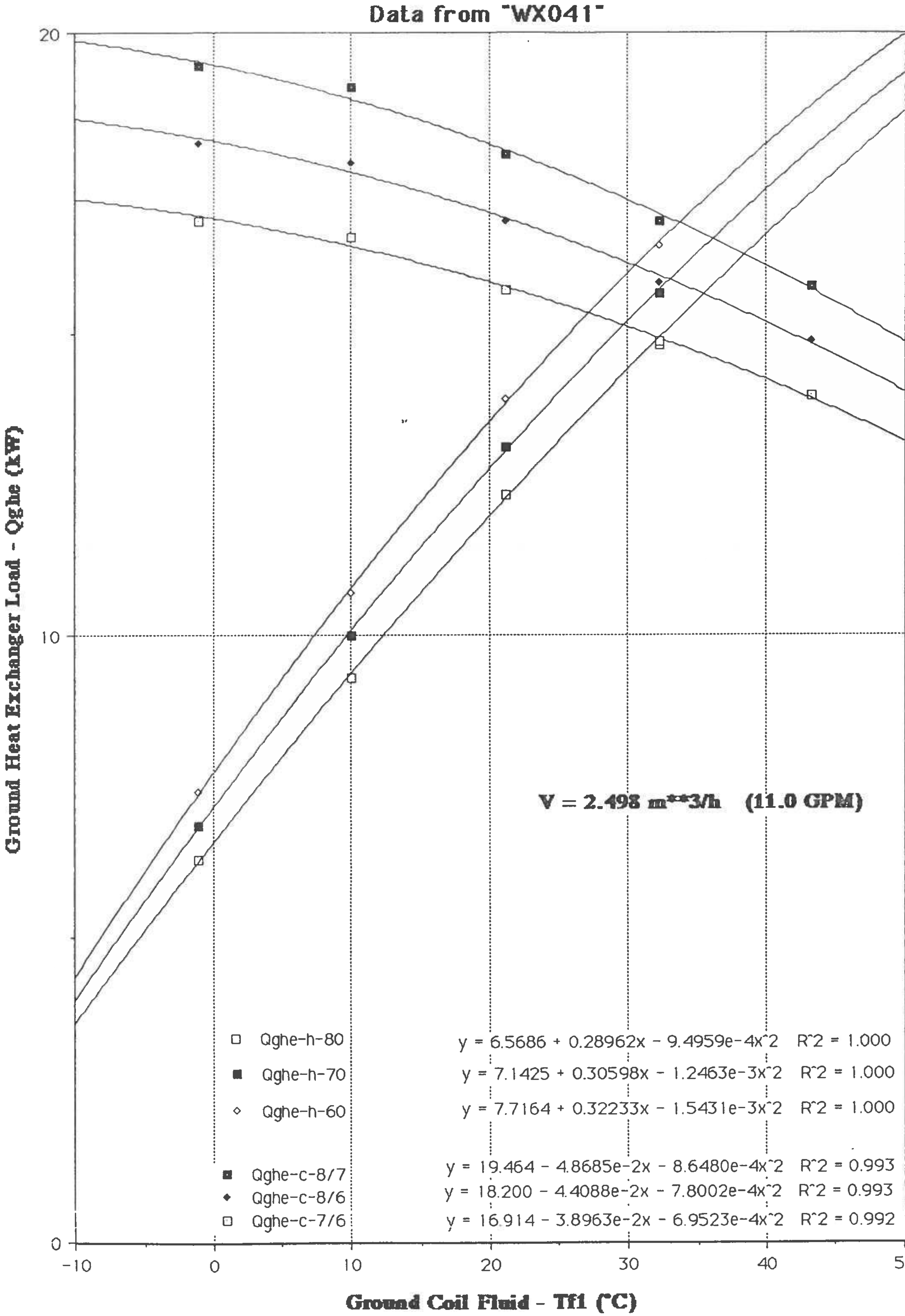
Data from "WX036"
COPc-7/6 y = 5.3945 - 7.6721e-2x + 6.7828e-5x^2 R^2 = 0.990
COPc-8/6 y = 5.7378 - 8.0489e-2x + 5.0871e-5x^2 R^2 = 0.992
COPc-8/7 y = 6.0932 - 8.6217e-2x + 6.7828e-5x^2 R^2 = 0.991
V = 2.044 m**3/h (9.0 GPM)
COP-80 y = 2.8171 + 5.1120e-2x - 6.6825e-4x^2 R^2 = 0.996
COP-70 y = 3.0719 + 5.6160e-2x - 7.8975e-4x^2 R^2 = 0.996
COP-60 y = 3.3545 + 6.0660e-2x - 8.9100e-4x^2 R^2 = 0.995
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
7
6
5
4
3
2
-10
0
10
20
30
40
50

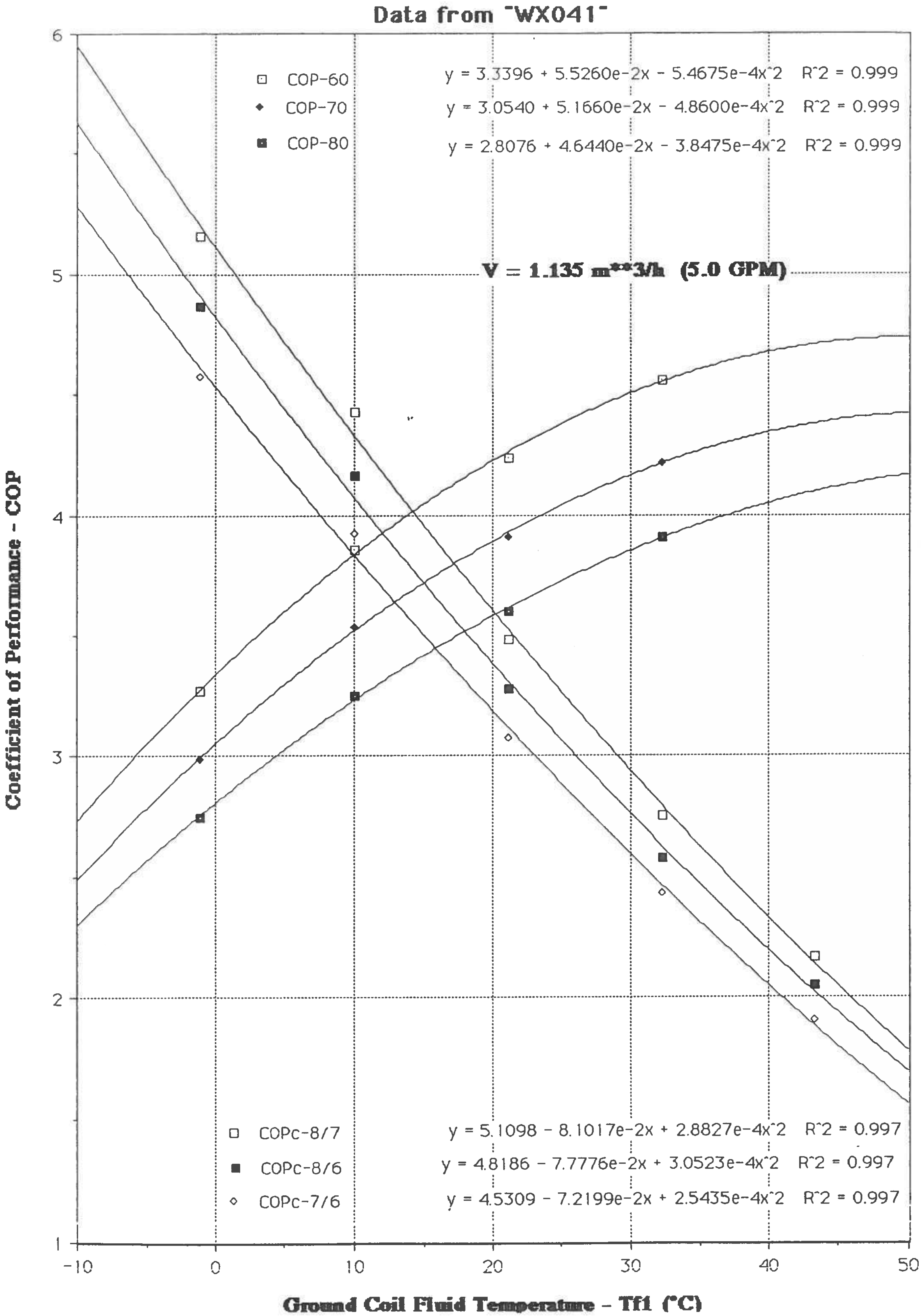


Data from "WX041"
20
10
0
-10
0
10
20
30
40
50
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
V = 1.135m**3/h (5.0 GPM)
Qghe-c-7/6 y = 16.562 - 3.2030e-2x - 6.7828e-4x^2 R^2 = 0.992
Qghe-c-8/6 y = 17.819 - 3.7155e-2x - 7.6306e-4x^2 R^2 = 0.993
Qghe-c-8/7 y = 19.058 - 4.3636e-2x - 7.9698e-4x^2 R^2 = 0.992
Qghe-h-80 y = 5.9500 + 0.26747x - 5.3414e-4x^2 R^2 = 1.000
Qghe-h-70 y = 6.4653 + 0.28382x - 8.3089e-4x^2 R^2 = 1.000
Qghe-h-60 y = 6.9806 + 0.30018x - 1.1276e-3x^2 R^2 = 1.000

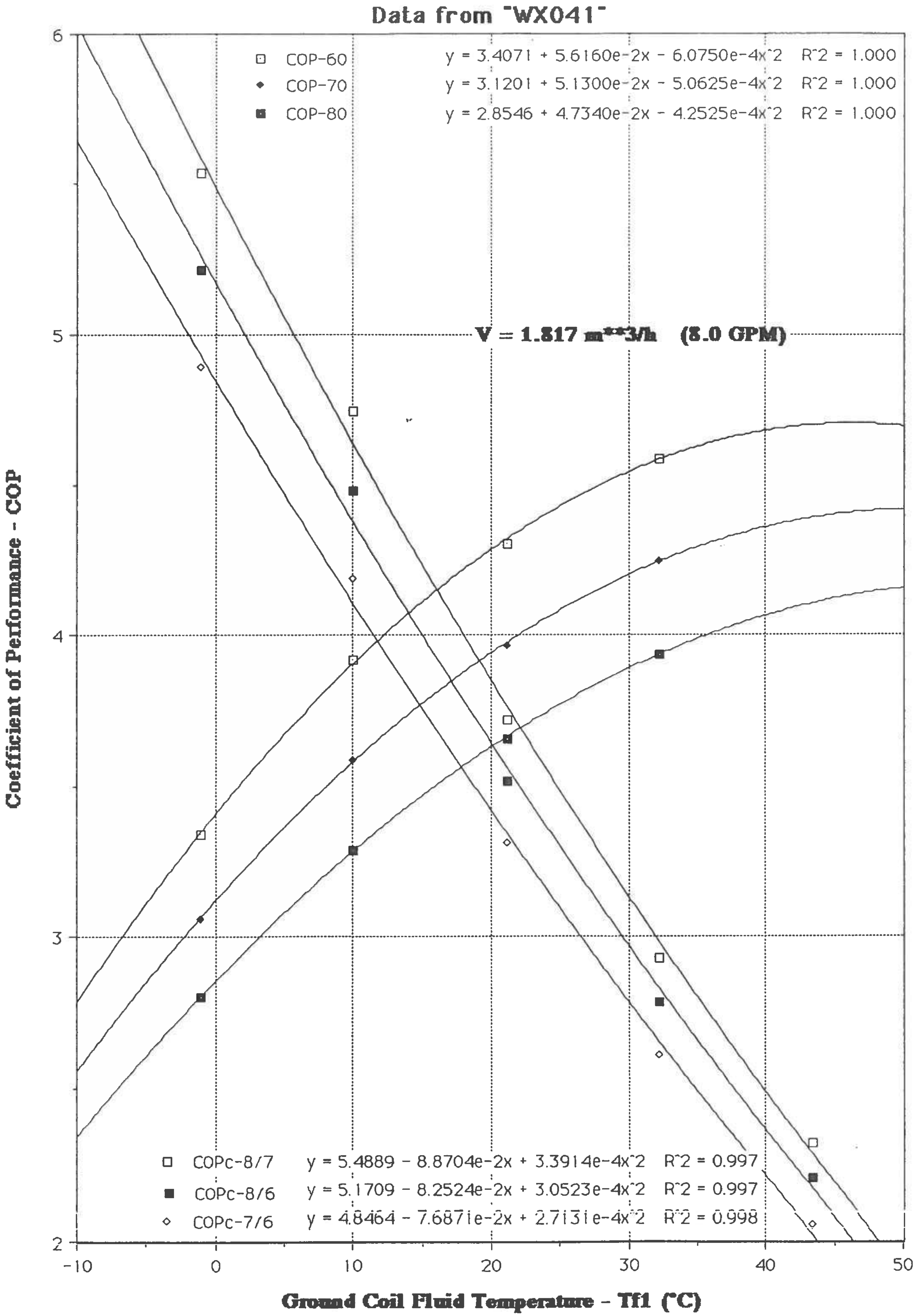


Data from "WX041"
20
10
0
-10
0
10
20
30
40
50
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid Temperature - Tf1 (°C)
V = 1.817 m**3/h (8.0 GPM)
Qghe-c-7/6 y = 16.702 - 3.6702e-2x - 6.6132e-4x^2 R^2 = 0.993
Qghe-c-8/6 y = 17.967 - 4.1375e-2x - 7.6306e-4x^2 R^2 = 0.993
Qghe-c-8/7 y = 19.231 - 4.5972e-2x - 8.4785e-4x^2 R^2 = 0.993
Qghe-h-80 y = 6.3373 + 0.27960x - 7.1219e-4x^2 R^2 = 1.000
Qghe-h-70 y = 6.8800 + 0.29807x - 1.0683e-3x^2 R^2 = 1.000
Qghe-h-60 y = 7.4248 + 0.31336x - 1.3057e-3x^2 R^2 = 1.000

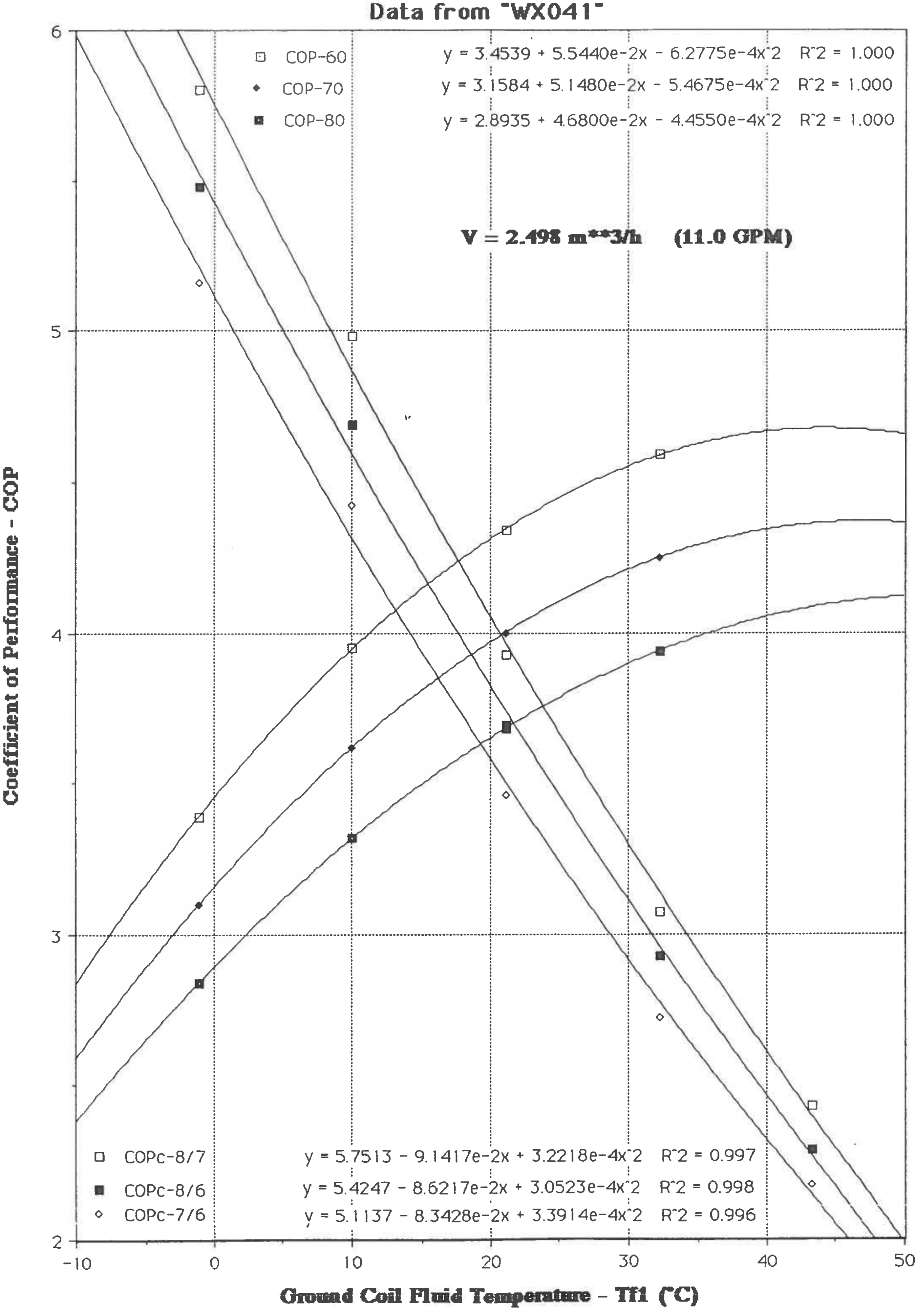

Data from "WX041"
Ground Heat Exchanger Load - Qghe (kW)
Ground Coil Fluid - Tf1 (°C)
20
10
0
-10
0
10
20
30
40
50
V = 2.498 m**3/h (11.0 GPM)
Qghe-h-80
Qghe-h-70
Qghe-h-60
y = 6.5686 + 0.28962x - 9.4959e-4x^2 R^2 = 1.000
y = 7.1425 + 0.30598x - 1.2463e-3x^2 R^2 = 1.000
y = 7.7164 + 0.32233x - 1.5431e-3x^2 R^2 = 1.000
Qghe-c-8/7
Qghe-c-8/6
Qghe-c-7/6
y = 19.464 - 4.8685e-2x - 8.6480e-4x^2 R^2 = 0.993
y = 18.200 - 4.4088e-2x - 7.8002e-4x^2 R^2 = 0.993
y = 16.914 - 3.8963e-2x - 6.9523e-4x^2 R^2 = 0.992



Data from "WX041"
COP-60
COP-70
COP-80
y = 3.3396 + 5.5260e-2x - 5.4675e-4x^2 R^2 = 0.999
y = 3.0540 + 5.1660e-2x - 4.8600e-4x^2 R^2 = 0.999
y = 2.8076 + 4.6440e-2x - 3.8475e-4x^2 R^2 = 0.999
V = 1.135 m**3/h (5.0 GPM)
COPc-8/7
COPc-8/6
COPc-7/6
y = 5.1098 - 8.1017e-2x + 2.8827e-4x^2 R^2 = 0.997
y = 4.8186 - 7.7776e-2x + 3.0523e-4x^2 R^2 = 0.997
y = 4.5309 - 7.2199e-2x + 2.5435e-4x^2 R^2 = 0.997
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
1
2
3
4
5
6
-10
0
10
20
30
40
50



Data from "WX041"
COP-60 y = 3.4071 + 5.6160e-2x - 6.0750e-4x^2 R^2 = 1.000
COP-70 y = 3.1201 + 5.1300e-2x - 5.0625e-4x^2 R^2 = 1.000
COP-80 y = 2.8546 + 4.7340e-2x - 4.2525e-4x^2 R^2 = 1.000
V = 1.817 m**3/h (8.0 GPM)
COPc-8/7 y = 5.4889 - 8.8704e-2x + 3.3914e-4x^2 R^2 = 0.997
COPc-8/6 y = 5.1709 - 8.2524e-2x + 3.0523e-4x^2 R^2 = 0.997
COPc-7/6 y = 4.8464 - 7.6871e-2x + 2.7131e-4x^2 R^2 = 0.998
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50



Data from "WX041"
COP-60
COP-70
COP-80
y = 3.4539 + 5.5440e-2x - 6.2775e-4x^2 R^2 = 1.000
y = 3.1584 + 5.1480e-2x - 5.4675e-4x^2 R^2 = 1.000
y = 2.8935 + 4.6800e-2x - 4.4550e-4x^2 R^2 = 1.000
V = 2.498 m**3/h (11.0 GPM)
COPc-8/7
COPc-8/6
COPc-7/6
y = 5.7513 - 9.1417e-2x + 3.2218e-4x^2 R^2 = 0.997
y = 5.4247 - 8.6217e-2x + 3.0523e-4x^2 R^2 = 0.998
y = 5.1137 - 8.3428e-2x + 3.3914e-4x^2 R^2 = 0.996
Coefficient of Performance - COP
Ground Coil Fluid Temperature - Tf1 (°C)
6
5
4
3
2
-10
0
10
20
30
40
50