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A Preliminary Evaluation of the DOE-2.1E Ground Vertical Well Model Using Maxey School Measured Data

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INTRODUCTION

Interest in geothermal (ground-source) heat pumps (GHPs) is high because of their potential of providing benefits, such as providing a relatively constant temperature heat sink-source for the heat pump, quiet operation, low maintenance costs, and reduced peak electric demand. GHP systems generally use closed-loop ground-coupled tubes for heat exchange, which are frequently plastic U-tubes in vertical wells. Vertical wells have the advantage of requiring less ground surface and being sufficiently deep to minimize the influence of the daily and annual ground surface temperature conditions.

A constraint in the employment of GHPs has been the lack of confidence in simulation programs predicting performance and energy consumption of GHP systems. DOE-2 is an hourly simulation tool used widely in the building industry for evaluating energy use and costs in alternative building construction and associated HVAC systems (Winkelmann et al. 1993). But only recently (1995) were GHP simulation routines introduced into the later versions of DOE-2.1E (Gates and Hirsch 1996). They are also incorporated in DOE-2.2, the simulation engine for PowerDOE (Gates and Hirsch 1997).

The DOE-2 ground heat exchange routines were developed by R. Merriam. They represent a compromise between slow detailed numerical models and fast simple analytical models to perform calculations in a short time. The DOE-2 vertical well heat exchange routine calculates the return circulating fluid temperatures from the fluid flow rates and heat loads using well configuration and soil parameter data. Testing of this routine with measured data has been limited thus far. Rainer et al. (1998) used these models in DOE-2.1E simulations of single-family residences. For each residence, they estimated the undisturbed deep soil temperature and the soil thermal conductivity and diffusivity using the vertical well heat exchange routine as a stand alone program to find the best fit to the field data for each residence.

In August 1995, the Lincoln, NE school district started operation of four new elementary schools using GHPs for space conditioning. These buildings have extensive energy management system (EMS) data collected on the operation of the HVAC systems. These data provide an opportunity to test the DOE-2 representation of the GHP systems.

The focus of this paper is to compare GHP vertical well field performance predicted by the DOE-2 subroutine with the measured field data. The goal of this effort is to validate (and correct if needed) the subroutines and develop a calibrated program to compare the GHP performance with alternative systems. A parallel effort is being done using the TRNSYS program that uses the ground heat storage model developed at the University of Lund, Sweden (Pahud and Hellstrom 1996).

VWELL SUBROUTINE

In DOE-2.1E, heat exchange between the GHP circulating fluid and the ground is calculated in a subroutine called VWELL. (DOE-2.2 uses a modified version of this subroutine called GLHX_Vertical.) Here, the temperature of the fluid leaving the well field and entering the building's heat pump water loop (EFT) is calculated hourly from the liquid flow rate and the imposed heat load on the well field.

The calculation is done in three steps: 1.) heat transfer from the circulating fluid to the well boundary, 2.) dissipation of the heat from the well boundary into the ground, and 3.) transfer of the heat from the ground to the atmosphere. The temperature of the ground undisturbed by the construction and operation of the well field, T_g, is specified in the input data. For deep wells, greater than 150 ft. (46m), T_g changes little with the ground surface conditions.

Relations developed by Kavanaugh (1985) are used to calculate heat exchange between the circulating fluid and the well boundary. The well boundary is assumed in the program as being at the well equivalent diameter, defined as

$$D_{eqv} = \sqrt{2} D_o \qquad (1)$$

where D_o is the outside tube diameter.

The algorithm accounts for temperature drop through the fluid boundary layer and the pipe wall. An additional term is added to account for heat exchange between the adjacent legs of the U-tube. In DOE-2, heat exchange between the well boundary and the adjacent soil is assumed to be in the radial direction only and the average boundary temperature, T_{wb}, is used for the entire length of the well. For a fluid leaving the building and entering the well at a temperature of T_i higher than T_{wb} and adding heat to the ground, a simple balance predicts the outlet temperature T_o (relative to T_{wb}) to be

$$T_o = T_i \exp\left(\frac{-L}{mc_pR_{eqv}}\right) \tag{2}$$

where L is the depth of the well, m and c_p are the mass flow rate and specific heat of the circulating fluid, and R_{eqv} is the equivalent thermal resistance from the fluid to the well boundary. For a given heat load, Q, the fluid outlet temperature is

$$T_o = \frac{Q}{mc_p}\left[\frac{\exp\left(\frac{-L}{mc_pR_{eqv}}\right)}{1-\exp\left(\frac{-L}{mc_pR_{eqv}}\right)}\right] \tag{3}$$

R_{eqv} is defined as

$$R_{eqv} = \frac{1}{CN}\left[R_f + R_p\right] + \frac{L^2}{2(mc_p)^2 R_{sc}} \tag{4}$$

where R_f is the fluid film thermal resistance

$$R_f = \frac{1}{\pi D_i h_f} \tag{4a}$$

and R_p is the pipe wall thermal resistance

$$R_p = \frac{\ln\left(D_o/D_i\right)}{2\pi k_p} \tag{4b}$$

The term C is a correction factor for nonuniform heat exchange at the pipe perimeters, and it has a value of 0.85 for a single U-tube as recommended by Kavanaugh (1987). N is the number of pipes in each well, and is 2 for a single U-tube.

R_{sc} is the resistance for the thermal short between the two U-tube pipes, which is defined as

$$R_{sc} = \frac{2}{(3/8)}\left[R_f + R_p\right] + R_{qc} \tag{4c}$$

The 3/8 terms for the film and pipe wall resistances reflect that only this part of the pipe outer surfaces face each other in order to match the experimental data (Kavanaugh 1987). From potential theory, the resistance through the soil between the pipes is

$$R_{qc} = \frac{\cosh^{-1}\left[1 + \frac{X_s}{D_o}\right]}{\pi\, k_s L} \tag{4d}$$

where k_s is the soil thermal conductivity and X_s is the distance between the pipes. As presently written this subroutine does not consider the use of grout that has a conductivity different from that of the adjacent soil in the well. This omission can be very important because of the relatively high heat flux rates in the areas close to the U-tubes (Kavanaugh and Rafferty 1997).

The film coefficient is calculated using the Dittus-Boelter relation for cooling using transport properties for 60 °F (15.6°C) water.

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.3} \tag{5}$$

This relation is a good approximation of the heat transfer data for Re greater than 10,000 (Rohsenow et al. 1985). The subroutine assumes that the fluid circulation pump operates intermittently when the heat pump is on, and that the flow through the U-tube is constant at these times.

For dissipation of heat into the ground or the extraction of heat from the ground, the program treats the well boundary as a line source or sink having an uniform temperature along its length. The soil temperature difference at a distance r from a line source having the strength of Q/L is (Carslaw and Jaeger 1959)

$$\Delta T = \frac{Q}{4\pi\, k_s L}\, E1\left[\frac{-\left(D_{eqv}/2\right)^2}{4\alpha\tau}\right] \tag{6}$$

where α is the soil thermal diffusivity, and E1 is the exponential integral defined as

$$E1(x) = \int_{-x}^{\infty} \frac{-e^{-u}}{u}\, du \tag{6a}$$

Values of E1(x) are tabulated in Abramowitz and Stegun (1964) and they have been correlated as a function in DOE-2.

In VWELL, a line source function G(i), derived from Equation 6, is used to calculate the soil temperature increase at the well equivalent diameter.

$$G(i) = \frac{\Delta T}{Q} = \frac{1}{4\pi\, k_s L} E1\left[\frac{-\left(D_{eqv}/2\right)^2}{4\alpha\tau}\right] \qquad (7)$$

Sixteen values of this function are calculated at times, τ, varying from 1, 2, 3, 6 hours to 1536, 2184, 4368, 8760, and 8760×N_{year} hours, (N_{year} is the number of years of prior operation). Then by superposition, the soil temperature difference is

$$\Delta T = Q(1)G(1) + \sum_{i=2}^{16} Q(i)\left[G(i) - G(i-1)\right] \qquad (8)$$

where Q(i) is the average heat load for the period between τ(i) and τ(i-1).

ΔT, calculated from Equation (8) is added to the undisturbed ground temperature, T_g, to obtained the average well surface temperature T_{wb}. T_o, calculated by Equation (3), is then added to T_{wb} to predict the temperature of the circulating fluid leaving the well field and entering the building (EFT).

For hours when there is no flow through the wells, EFT drifts towards T_{wb}. This effect is estimated in the program using the relation

$$EFT = f_r \cdot T_{wb} + (1 - f_r) \cdot EFT_p \qquad (9)$$

The parameter, f_r, is a recovery factor, presently specified in the program to have a value of 0.2. EFT_p is the EFT value for the previous hour.

After a year or two of operation, ground temperature interactions between wells in a multiple well field can appear (Eskilson 1987, Kavanaugh and Rafferty 1997). This is accommodated in the subroutine by modifying Equation (7) to be

$$G(i) = G(i,1) + \sum_{k=2}^{n} g(k)\, G(i,k) \qquad (10)$$

where G(i,1) is the value of G(i) calculated by Equation (7), and for k greater than 1

$$G(i,k) = \frac{1}{4\pi\, k_s L} E1\left[\frac{\left(p(k) \cdot P_{well}\right)^2}{4\alpha\tau}\right] \qquad (10a)$$

P_{well} is the distance between adjacent wells in the well field. The constants g(k) and p(k) for 18 different well field configurations are incorporated in the source code DATA statements. These configurations vary from fields having 2 wells fields to fields having 32 wells in a 4 x 8 rectangular configuration.

The above relations do not consider the long term three dimensional effects of heat exchange in the ground. Eskilson (1987) developed a dimensionless temperature-response function curve in terms of a dimensionless time scale, defined as τ/τ_s, where

$$\tau_S = \frac{L^2}{9\alpha} \tag{11}$$

He used a numerical model to calculate this curve for wells having a diameter-to-depth ratio of 0.001. Correlations were developed from this information and used in VWELL to correct the G(i) values.

MAXEY SCHOOL VERTICAL WELL SYSTEM DATA

Maxey Elementary School is located in Lincoln, NE, and is one of the four schools built recently (1995) that uses GHP for space conditioning. The school has about 70,000 $ft.^2$ (6,503 m^2) of floor area and has a staff of about 50 people serving about 500 students. It has 54 heat pumps distributed in the classroom and activity areas. Heat is added to or rejected from the heat pumps to a common loop that uses a 22% aqueous propylene glycol solution as the working fluid. The loop pumps, having 575 gpm (36.27 L/s) rated capacity, circulate the solution through a vertical well field, where heat is exchanged between the solution and the ground. The pumps are variable speed pumps and the flow through the loop is dependent on the number of individual heat pumps operating each hour.

The well field, located outside of the school building, is made up of 120 vertical wells located on a 12 by 10 rectangular pattern. Centerline distance between adjacent wells is 20 ft. (6.1 m). Each well is 4.5 in. (114 mm) in diameter and 240 ft. (73.1 m) deep. The liquid is circulated through a polyethylene U-tube in each well that has a nominal diameter of 1 in. (25.4 mm). The wells are backfilled with a mixture of sand and fine gravel up to 10 ft. (3.1 m) below the ground surface. A bentonite plug seals the top 10 ft. (3.1 m) of the well.

Liquid flow to and from the well field is through buried horizontal pipes connected to the circulation pump and the HVAC liquid distribution loop in the building mechanical room. EMS differential pressure and temperature sensors for measuring the circulating liquid flow rate and inlet and outlet temperatures are located in this room. The sensor for measuring the temperature of the solution leaving the building is downstream of the pump. These parameters can be recorded by the EMS every 10 minutes.

Building operation started in August 1995, and 10 minute operating data were obtained by Carlson (1998) for the period beginning November 1995 and ending October 1997. Carlson reviewed the data, made adjustments and filled in the missing data, where necessary, for this period. He then averaged the data on an hourly basis and calculated the heat load on the well field from the flow rate and the difference in the temperature between the fluid entering and leaving the well field. The convention was used that heat added to the well field has a positive value and heat extracted from the well field has a negative value. The 1996 data were the most complete and they were used for comparison in his analysis. A limitation using these data is that well field was new and the time to observe interactions between adjacent wells and ground surface effects is probably insufficient.

The parameter of interest for comparison is EFT, the temperature of the solution leaving the well field and entering the building. Figure 1 are plots of the hourly measured EFT and flow rates for a week in January and another week in May.

During the winter months, a minimum flow is maintained, even when the heat demand is minimal or zero. This is reflected in the plot for January, when flow rates low as 25 gpm (1.58 L/s) have been observed. At these times EWT tended to drift. to about 52°F (11.1°C). During the summer, the circulation pumps are turned off when there are no demands on the well field. At these times, the observed EFT tended to drift, above 70°F (21.1°C) during the week and above 80°F (26.7°C) during the weekend, as shown in the plot for May. Because of this, EFTs measured only when the liquid flow was equal or greater than 25 gpm (1.58 L/s) were considered for comparison.

APPLICATION OF VWELL ROUTINE TO MAXEY SCHOOL

A stand alone Fortran program was written using information extracted from the source code for the DOE-2.1E VWELL subroutine. Hourly solution flow and heat load data in the files obtained from Carlson (1998) were used as inputs to the program the hourly values of EFT were calculated. These calculated results were then compared with the measured EFT data.

The program was applied for the time from August, 1995 through December, 1996. A new thermally undisturbed well field was assumed for the analysis. Since the measured data file did not have information for August 1995 through October 1995, input data for August 1996 through October 1996 were substituted for this period in the input file. This was done to approximate the ground temperature change for the operation of the well field during that time. The calculated EFT values were then compared with the measured EFT values at times when the overall well field flow rate is equal to or greater than 25 gpm (1.58 L/s).

Soil and U-tube parameters selected for the calculations are listed in Table 1. The soil parameters were derived by Shonder from data collected at a test well at the school (1998). The grout used to backfill the well probably has thermal conductivity lower than the surrounding soil, but we have not yet included it in the simulations.

Table 1. Assumed soil and U-tube parameters for the calculation

Undisturbed soil temperature, T_g, °F, (°C)	54.34	(12.42)
Soil thermal conductivity, k_g, Btu/hr-ft.-°F, (W/m-K)	1.36	(0.196)
Soil thermal diffusivity, α, ft.^{2}/hr, (m^2/s)	0.0417	(1.08×10^{-6})
Pipe thermal conductivity, k_p, Btu/hr-ft.-°F, (W/m-K)	0.226	(0.0325)
Pipe outside diameter. D_o, in., (mm)	1.315	(33.40)
Pipe inside diameter, D_i, in., (mm)	1.080	(27.43)

For the simulations, we selected an arrangement consisting of four well fields, each having a 4 x 8 rectangular configuration. This results in the simulated field having 128 wells, which is greater than the actual 120 installed wells. To correct for this, the 240 ft. (73.1 m) well depth was multiplied by a factor of 120/128 to yield an effective depth of 225 ft. (68.6 m). The total flow to each well is assumed to be total flow to the well field divided by the number of wells.

The *first* test was to use the existing VWELL algorithms to calculate the EFTs. The distance between two legs of the U-tube, X_s, was assumed to be 0.3 in. (7.62 mm). Results for a week in January and a week in May are plotted in Figure 2. Comparison with the measured values for flows 25 gpm (1.58 L/s) or greater shows that the match between the calculated and measured data leaves something to be desired.

This initial calculation was checked assuming 120 well fields, each consisting of a single 240 ft. (73.1 m) deep well. The results were nearly identical to those generated in the initial calculation. This is not surprising, since the well field is new and has not been operated sufficiently long to show significant interaction between the adjacent wells.

The *second* test was to modify the program allow variable flow through the well field each hour and to use film heat transfer correlations dependent on the fluid properties and the flow rate. Correlations of the transport properties for the 22 % propylene glycol solution were developed from the published data in the ASHRAE handbook (ASHRAE 1997) and added to the program. The transport data showed that the flow through the wells could easily be laminar when the total solution flow rate is below 300 gpm (18.9 L/s). This makes the use of the Dittus-Boelter equation (Equation 5) for the film coefficient questionable. We replaced this relation with the following relations. For Re <= 2300, the Hausen relation for laminar flow in tubes having constant wall temperature (Eckert and Drake 1987)

$$Nu = 3.65 + \frac{0.0668\left(\frac{Di}{L}\right)RePr}{1 + 0.04\left[\left(\frac{Di}{L}\right)RePr\right]^{2/3}} \qquad (12)$$

For Re > 2300, the Gnielinski relation for transition-turbulent flow in smooth tubes (Rohsenow et al. 1985)

$$Nu = \frac{(Re - 1000) Pr \frac{f}{2}}{1 + 12.7\left(Pr^{2/3} - 1\right)\sqrt{\frac{f}{2}}} \qquad (13)$$

where f is the Fanning friction factor calculated as

$$f = \frac{1}{(1.58 \ln(Re) - 3.28)^2} \qquad (13a)$$

Results of this calculation using the replaced heat transfer film correlations are also plotted in Figure 2 for the selected weeks in January and May. They show significant improvement in the calculated results, but more refinements in the model are needed. Although the plot for May shows reasonable agreement, the results for the year show a bias for the calculated EFTs being about 2 to 2.5 °F (1 to 1.4 °C) lower for much of the year.

The *third* test reflects two small changes made in the calculation of the source functions. These are 1.) substitution of cylindrical source functions for the line source functions when the argument in Equation (7) is less than -0.0333, and 2.) modifying the calculation of the line source function, G(16), when the well field had been operating for more than one year.

For short times, less than a few hours, the argument in Equation (7) can be small. If it drops below -1/30, the line source approximation for the calculation of G(i) becomes questionable and a cylindrical source function is a better way to calculate this parameter (Kavanaugh 1985). The cylindrical source function relation and its values as a function of Equation (7) argument are published by Carslaw and Jaeger (1959) and by Kavanaugh (1985). These values were correlated as a power series and incorporated into the program.

The VWELL subroutine is now set up to calculate the G(i) values only during the first hour of simulation. These values remain invariant for the rest of the year, and the routine uses a moving aggregation routine to calculate the historical time average heat loads when the difference between times at the index i is greater than 1. The time at the i = 16 is $8760 \times N_{year}$ hours, where N_{year} is the number of years of previous operation. For new wells, such as at the Maxey School, N_{year} is 0 and the value of G(16) is 0. For system operation greater than one year, we included a routine to calculate G(16) each hour using the time, τ, equal to the total hours since the wells were placed in operation.

The impact of these changes on the calculated EFT values was found to be very small. At the end of 1996, the wells had been in operation only 17 months. Moreover, the accumulated heat extracted from the ground was partially balanced by heat added to the ground during that time.

In the *fourth* test, we added the distance between the two U-tube legs, X_s, to the value of the equivalent diameter calculated by Equation (1). This was suggested to obtain a better fit to the data (Kavanaugh 1985, Kavanaugh and Rafferty 1997). This effectively reduces the value of the source function at the well perimeter.

In the simulations, we varied the value of X_s in the modified equivalent diameter definition from 0.3 in. to 1.0 in. (7.6 to 25.4 mm). Results of these simulations for the weeks in January and May, as discussed in the previous tests, are plotted in Figure 3. (The reference case, X_s = 0.0 included X_s=0.3 in. (7.6 mm) for the calculation of the thermal short, Equation (4d), but not in the definition of the well equivalent diameter.) These plots show improvement in the predicted EFT values, the agreement with the measured data for May is good. But for much of the year, particularly when heat is extracted from the ground, the calculated values tend to be about 2°F (1°C) below the measured values. This difference is greater when there is a high heat demand, as shown in Figure 3.

In the *fifth* test, we varied the reference ground temperature, T_g, and X_s in the modified definition of the well equivalent diameter. We adjusted these parameters, watching the average square of the difference between the predicted and the measured EFT values for the hours having at least 25 gpm (1.58 L/s) flow through the well field during 1996. At the minimum average square of the differences, T_g is 57.14 °F (13.97°C) and X_s is 1.87 in. (47.5 mm) The reference ground temperature here is 2.8°F (1.55°C) higher than 54.36°F (12.42°C) reported by Shonder (1998). The sum of the diameters of the two legs of the U-tube plus the X_s value here is 4.5 in. (114.3 mm), which is the actual well diameter.

We also calculated the arithmetic average of these EFT value differences for 1996 and found that it is about zero for the chosen parameters.

The EFT values from this test are displayed for selected months in Figure 4. Overall, there is reasonable agreement with the measured values. The plots show that the swings in the calculated EFTs are greater than the measured values. For January, comparison of Figures 1 and 4 indicates that adjusting T_g allowed the predicted values to generally agree with the measured data, but caused the low flow predictions to be high.

For May, the data match well, overall, but did not agree with the outliers. We elected to leave these data in the plots for completeness, but recognize that they can be misleading. As stated earlier for the initial calculations, these are hourly averages for data recorded every ten minutes. This first ten minute datum point is high because of the temperature sensor drift when the pumps are off.

During the cooling season, the predicted temperatures are low, particularly at times of low flow rates through the wells, as illustrated in the plot for August. But the agreement becomes better for the rest of the year. The plot for November shows good agreement between the predicted and measured data.

DISCUSSION

We made a number of improvements to the vertical well performance program, but still had to make empirical adjustments to the undisturbed ground temperature and the well equivalent diameter in order to get reasonable agreement with the measured data. We have yet to consider the difference in the thermal conductivity of the backfill material in the well and the soil. As for Maxey School, the backfill material often has a lower thermal conductivity (Kavanaugh and Rafferty 1997). This is important because of the higher heat fluxes near the U-tube.

The data comparisons suggest that the thermal mass effects in the ground near the well and in the well, itself, should be treated in more detail. Inspection of the source functions, G(i), calculated for Maxey School, also suggest that the greatest impacts are due to the short time functions. These are the functions that are most affected by the choice of the equivalent diameter of the well. There has been considerable activity about the near field behavior of GHP vertical wells. Among the recent papers are those by Gu and O'Neil (1998) and by Rottmayer et al. (1997). These include both analytical and numerical simulation of the well temperatures. These works should be reviewed for their applicability to the DOE-2 simulations.

Since the Maxey School data are for a new well field, they do not support long term comparison of the predicted data. An indirect procedure comparing the VWELL model predictions with the University of Lund ground heat storage model (Pahad and Hellstrom 1996) predictions is recommended. Experience with the University of Lund model is much more extensive. If the temperature predictions for long term well operation agree using the two models, this would provide more confidence in the VWELL subroutine.

CONCLUSIONS

The DOE-2.1E VWELL subroutine was evaluated using a stand alone program derived from the subroutine. We made a number of improvements in the routine, but still had to resort to adjusting the spacing between the legs of the U-tube and the undisturbed ground temperature to obtain a reasonable fit to the measured data. Detailed inspection of the results and the intermediate numbers in the calculations suggests that the source of difficulty is the short time source functions used in the program. Work by a number of people is being done in this area, and it should be reviewed for it applicability in the DOE-2 program.

For the long term operation of the vertical wells, comparison of the VWELL model predictions with the University of Lund model is recommended. Although this method is indirect, it should give greater confidence to the VWELL model if the predictions agree.

Finally, the entire DOE-2.1E model should be run to determine the effect of the differences in the predicted EFT values to evaluate the impact of the well model differences with the measured data on the school's HVAC system hourly energy consumption. The EFT differences are of interest, but the parameter of major significance is the impact on the building's energy consumption.

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NOMENCLATURE

C = correction factor for nonuniform heat exchange at the pipe perimeter
c_p = fluid specific heat
D_{eqv} = equivalent diameter
D_i = inside tube diameter
D_o = outside tube diameter
E1 = exponential integral
EFT = temperature of fluid discharging from well field and entering building
EFT_p = previous hour EFT value
f = Fanning friction factor
fr = heat recovery factor
G(i) = line or cylindrical source fucntion
G(i,k) = contribution of adjacent well k in a multiwell field to G(i)
g(k) = weighting factor for G(i,k)
h_f = fluid film coefficient
k_p = pipe wall thermal conductivity
k_s = soil thermal conductivity
L = well depth
m = mass flow rate
N = number of pipe legs in well (2 for a single U-tube)
Nu = Nusselt number
p(k) = weighting factor for distance to well k in a multiwell field
Pr = Prandtl number
P_{well} = distance between adjacent wells in a multiwell field
R_{eqv} = equivalent overall thermal resistance from fluid to well boundary
R_f = fluid film thermal resistance
R_p = pipe wall thermal resistance
R_{qc} = soil resistance to thermal short circuiting
R_{sc} = total resistance to thermal short circuiting
Re = Reynolds number
Q = thermal load
T_i = temperature of fluid entering U-tube relative to T_{wb}
T_o = temperature of fluid leaving U-tube relative to T_{wb}
T_{wb} = average well wall temperature at D_{eqv}

X_s = fill thickness between U-tube legs
α = soil thermal diffusivity
τ = time
τs = time scale defined as $L^2/9\alpha$

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Figure 1. Measured flow rates and building entering temperatures (EFT) for fluid circulating through Maxey School well field.

Figure 2. Comparison of measured and predicted entering fluid temperatures using the original VWELL algorithm and the modified algorithm incorporating variable flow rates and improved fluid heat transfer coefficient correlations.

Figure 3. Influence of adding the distance between the U-tube legs, X_s, to the original equivalent diameter definition, $\sqrt{2}\,D_o$, where D_o the outside tube diameter.

Figure 4. Final entering fluid temperature (EFT) calculations incorporating $X_s = 1.87$ in. (47.5 mm) in the equivalent diameter definitions and adjusting the reference ground temperature, T_g, to be 57.14°F (13.97°C).

Measured Flow Rates and EFT (1/7/96 - 1/13/96)

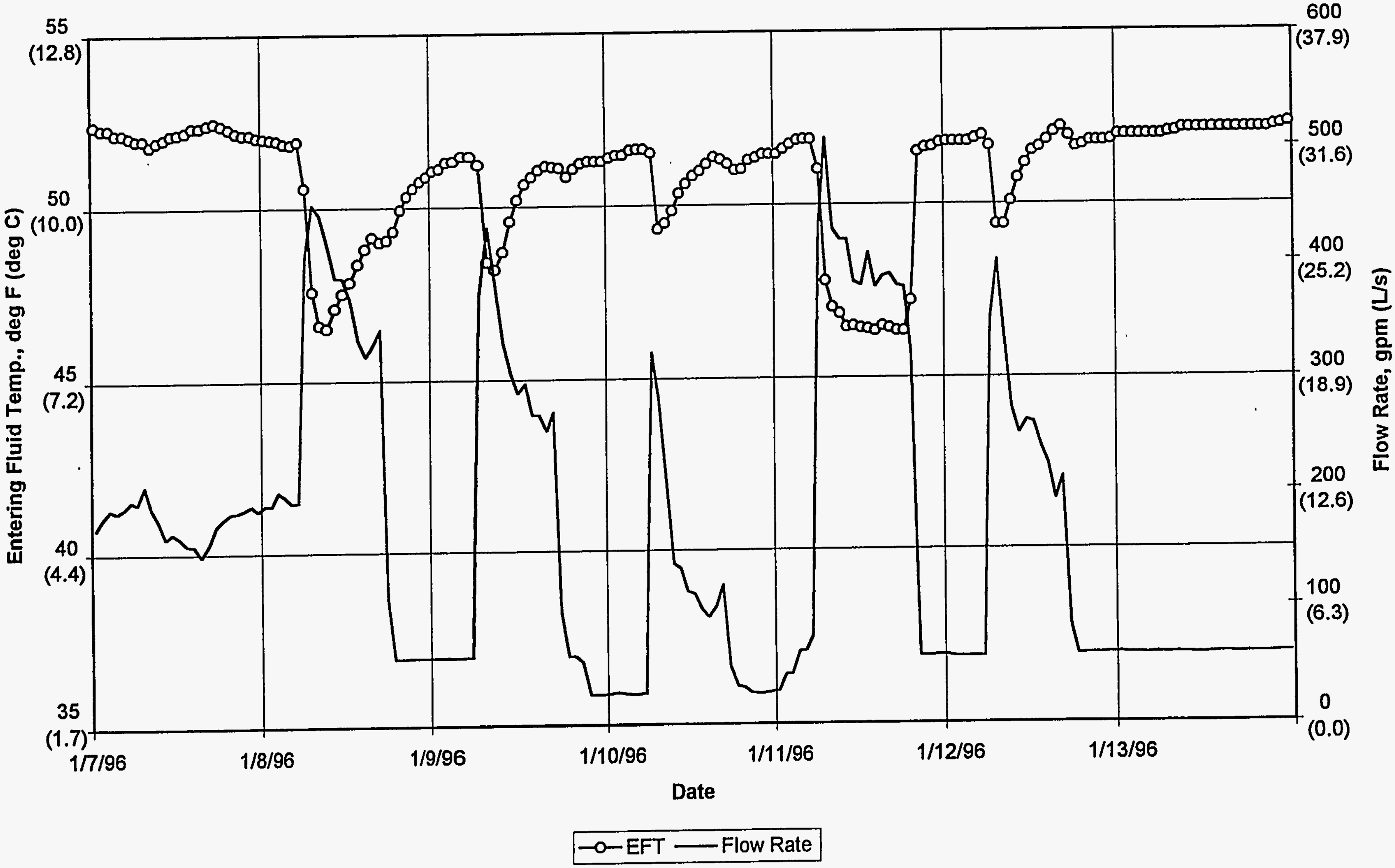
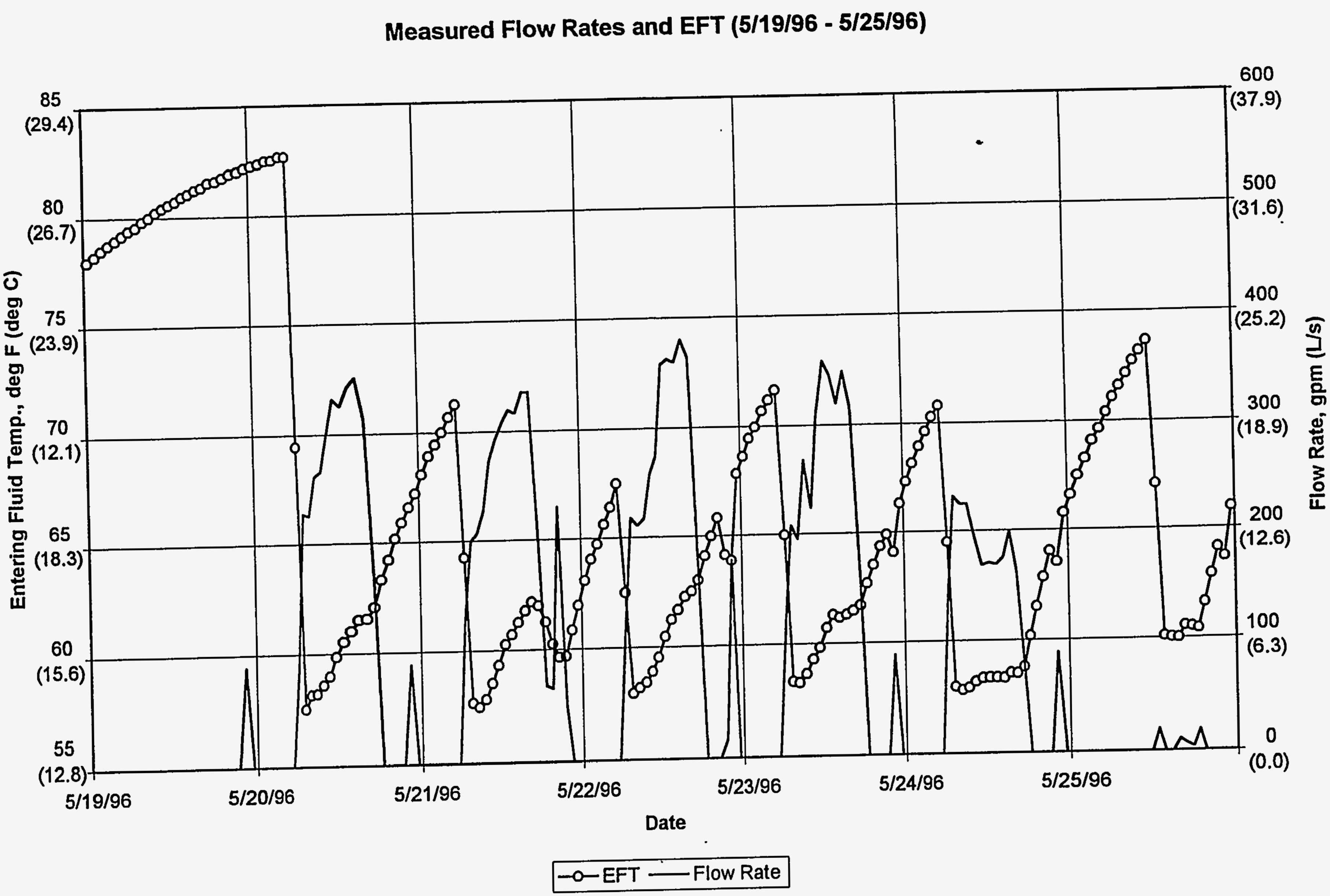


Fig 1a

Fig 1b



Measured Flow Rates and EFT (5/19/96 - 5/25/96)
85 (29.4)
80 (26.7)
75 (23.9)
70 (12.1)
65 (18.3)
60 (15.6)
55 (12.8)
Entering Fluid Temp., deg F (deg C)
600 (37.9)
500 (31.6)
400 (25.2)
300 (18.9)
200 (12.6)
100 (6.3)
0 (0.0)
Flow Rate, gpm (L/s)
5/19/96
5/20/96
5/21/96
5/22/96
5/23/96
5/24/96
5/25/96
Date
EFT
Flow Rate

Measured and VWELL Predicted EFT (1/7/96 - 1/13/96)

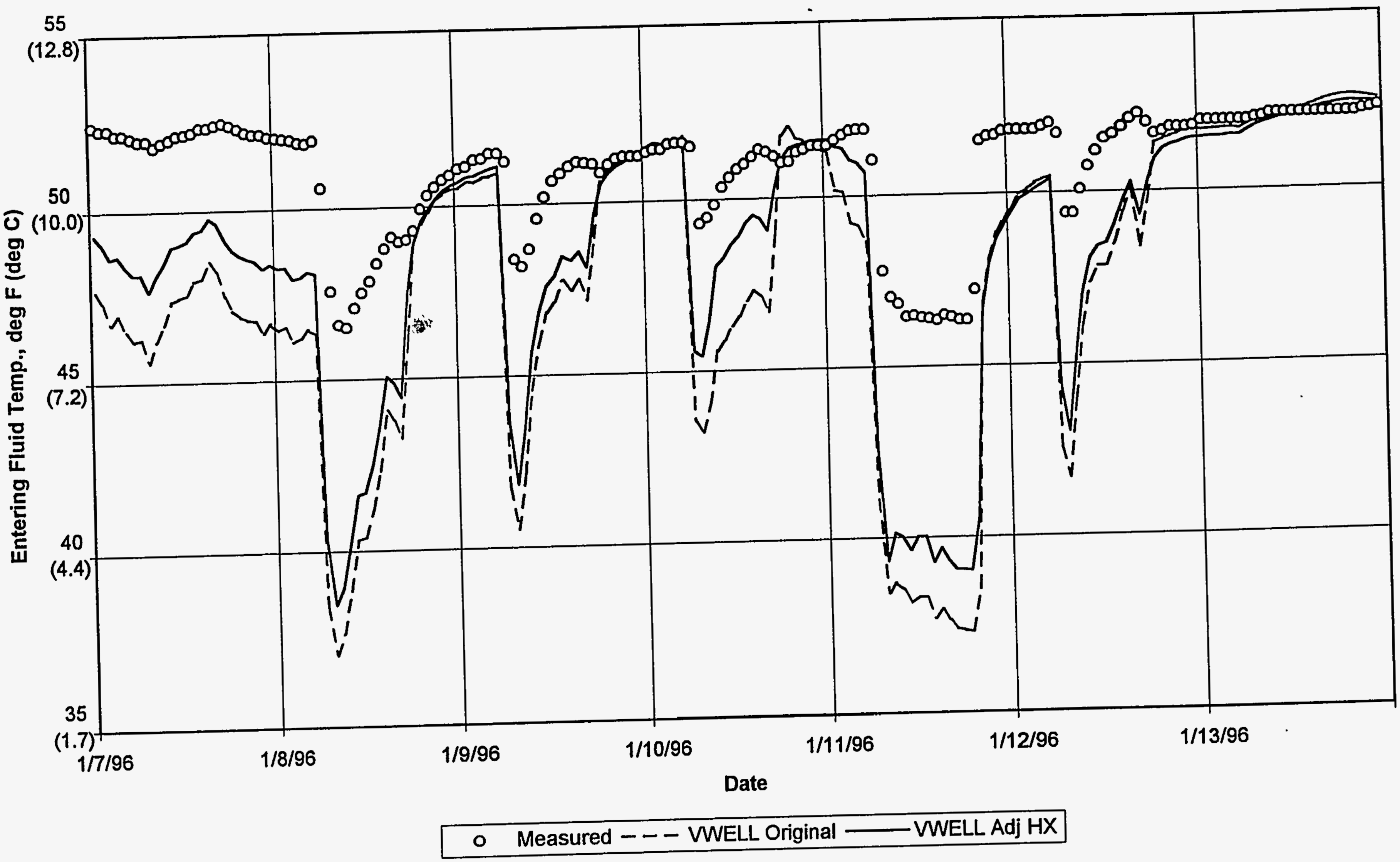
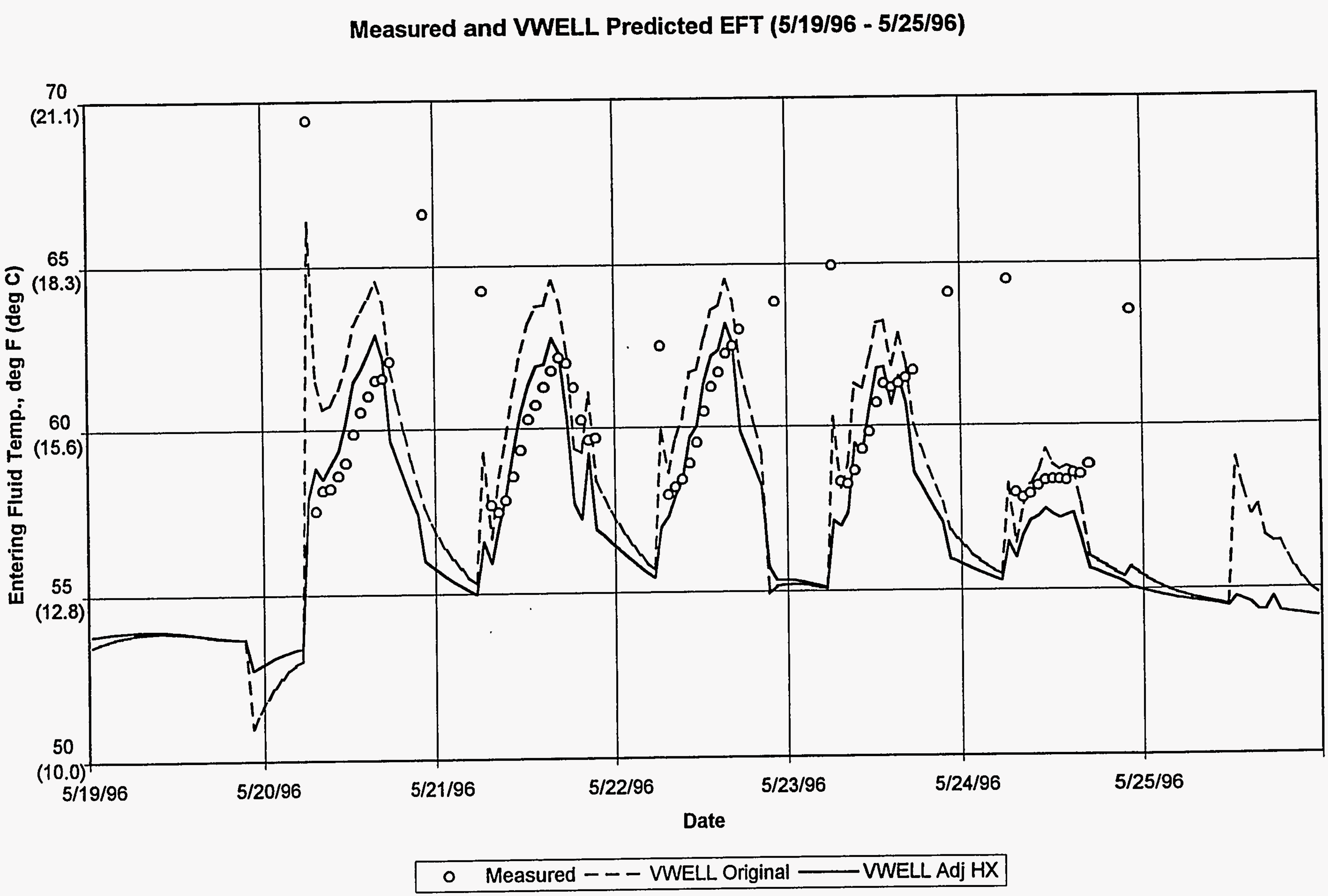


Fig 2a

Fig 2b



Measured and VWELL Predicted EFT (5/19/96 - 5/25/96)
70 (21.1)
65 (18.3)
60 (15.6)
55 (12.8)
50 (10.0)
Entering Fluid Temp., deg F (deg C)
5/19/96
5/20/96
5/21/96
5/22/96
5/23/96
5/24/96
5/25/96
Date
Measured
VWELL Original
VWELL Adj HX

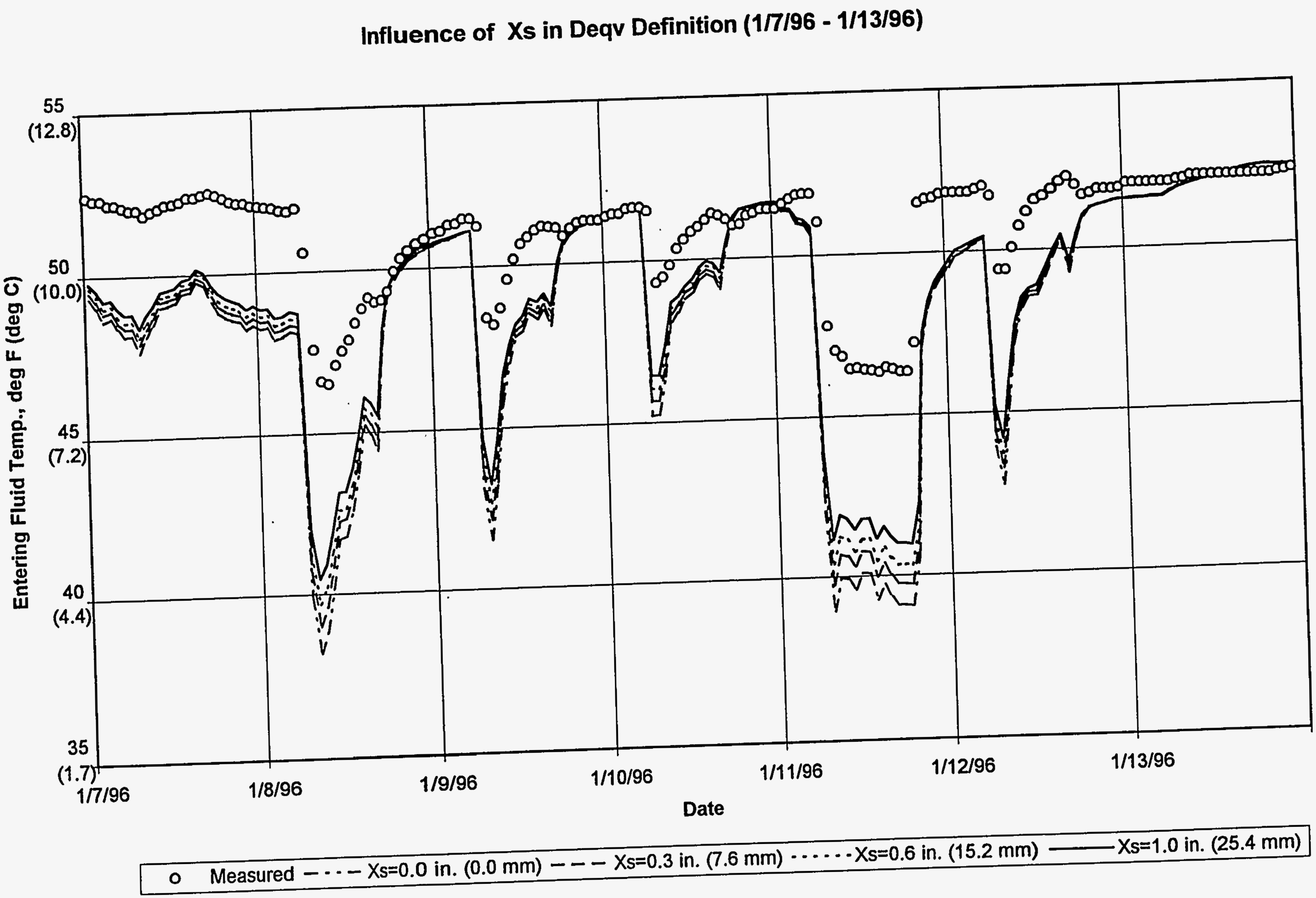

Influence of Xs in Deqv Definition (1/7/96 - 1/13/96)
Entering Fluid Temp., deg F (deg C)
55 (12.8)
50 (10.0)
45 (7.2)
40 (4.4)
35 (1.7)
1/7/96
1/8/96
1/9/96
1/10/96
1/11/96
1/12/96
1/13/96
Date
Measured
Xs=0.0 in. (0.0 mm)
Xs=0.3 in. (7.6 mm)
Xs=0.6 in. (15.2 mm)
Xs=1.0 in. (25.4 mm)

Fig 3a.

Influence of Xs in Deqv Definition (5/19/96 - 5/25/96)

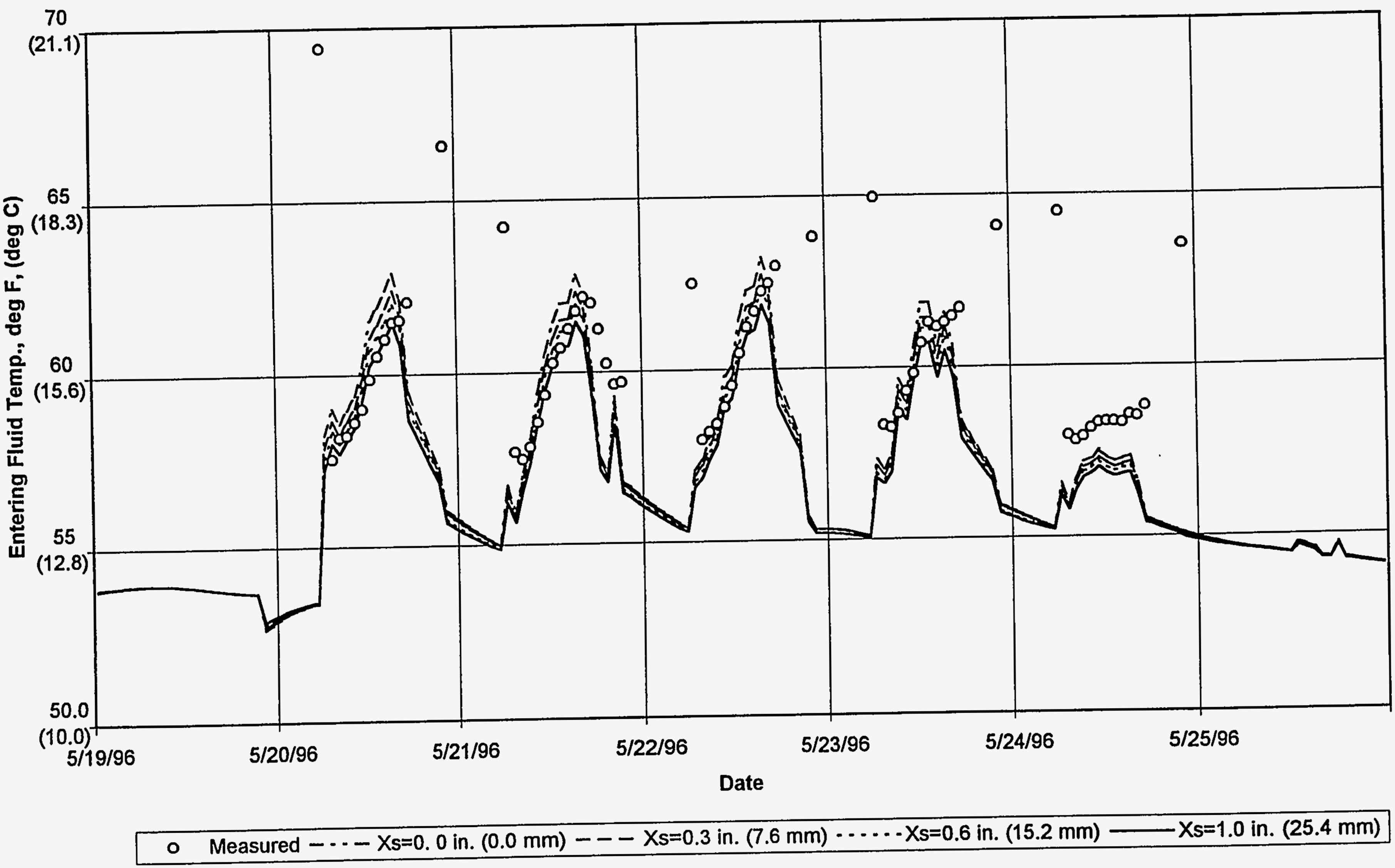
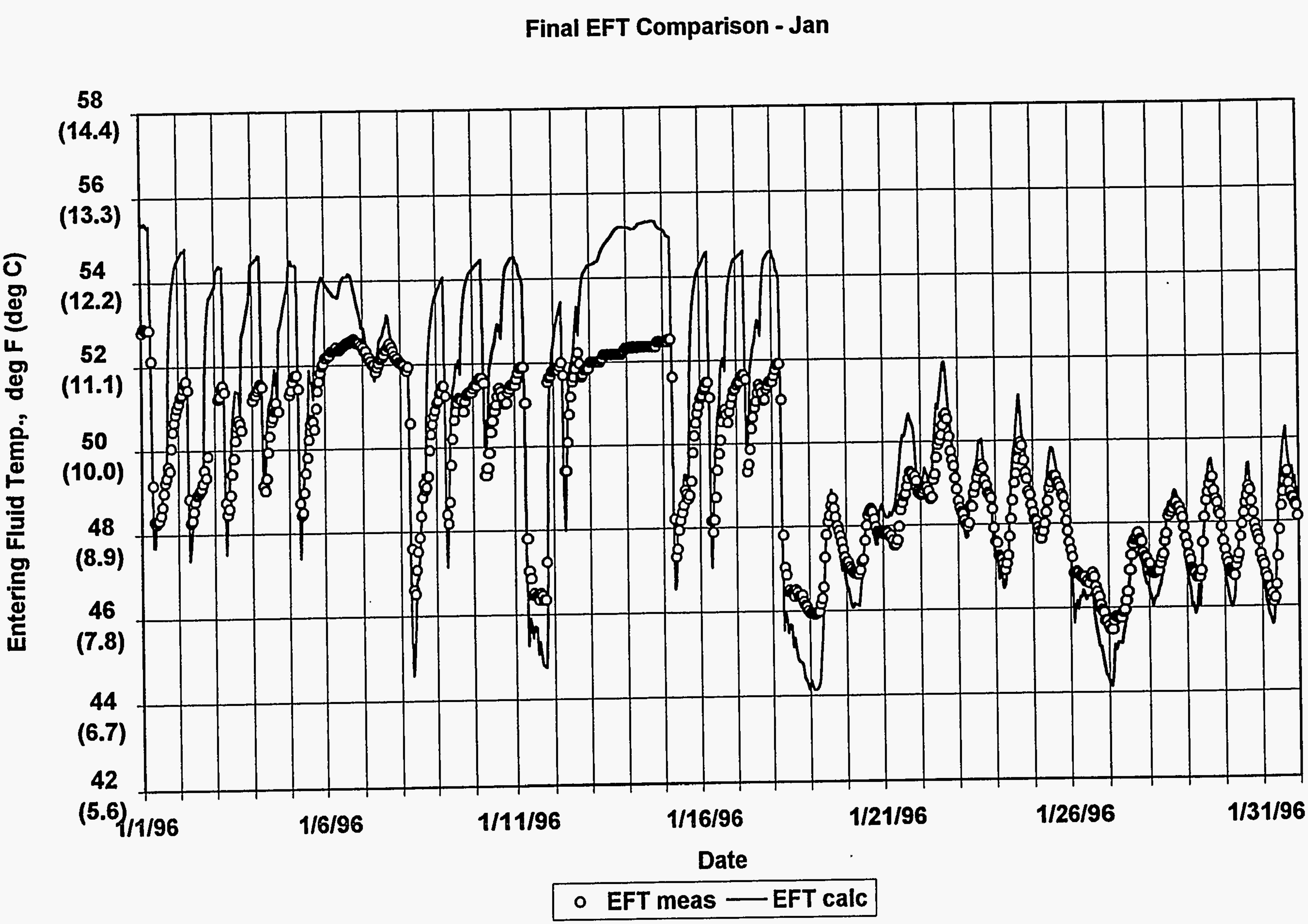


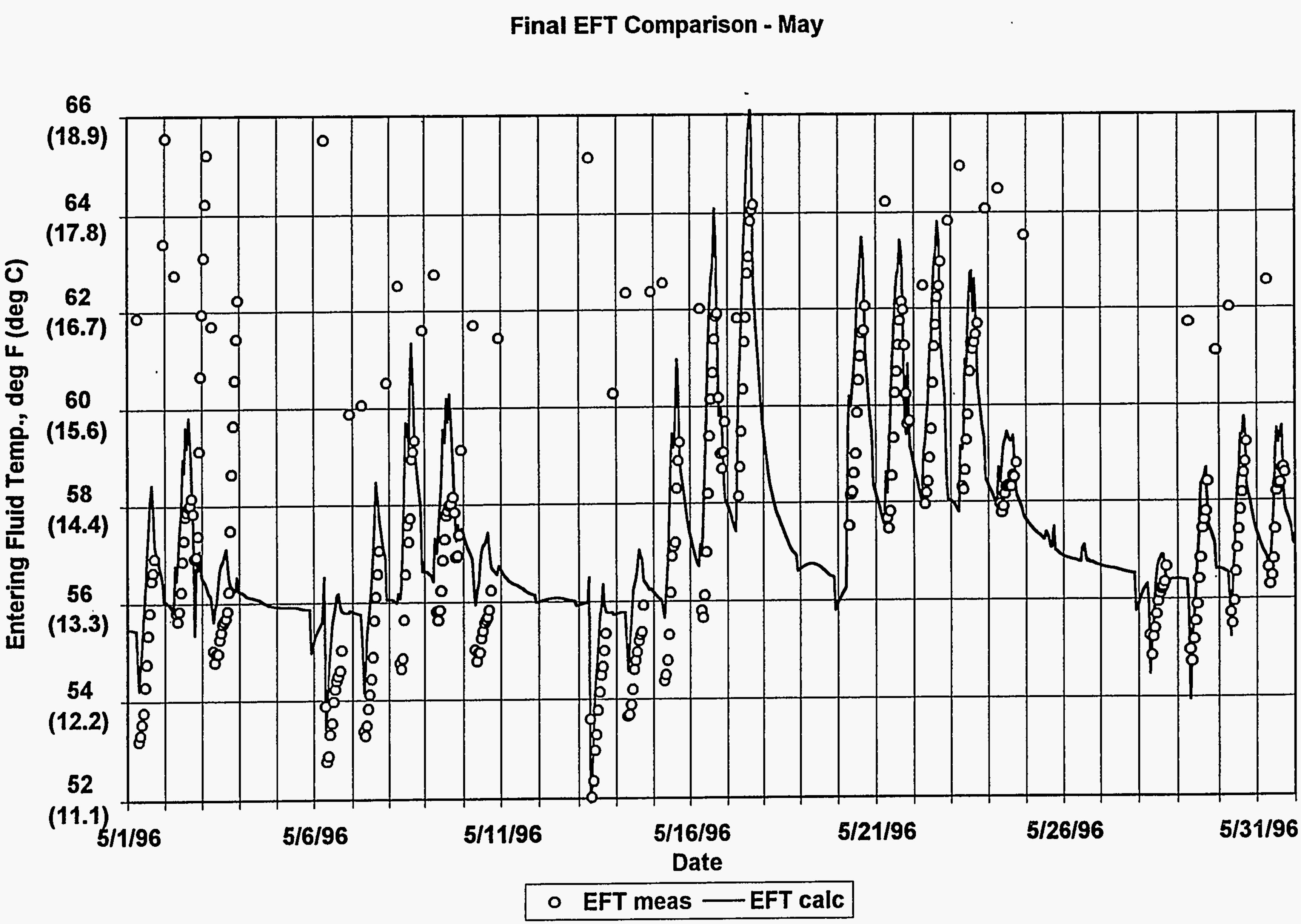
Fig 3b



Final EFT Comparison - Jan
Entering Fluid Temp., deg F (deg C)
58 (14.4)
56 (13.3)
54 (12.2)
52 (11.1)
50 (10.0)
48 (8.9)
46 (7.8)
44 (6.7)
42 (5.6)
1/1/96
1/6/96
1/11/96
1/16/96
1/21/96
1/26/96
1/31/96
Date
EFT meas
EFT calc

Fig 4a

Fig 4b



Final EFT Comparison - May
Entering Fluid Temp., deg F (deg C)
66
(18.9)
64
(17.8)
62
(16.7)
60
(15.6)
58
(14.4)
56
(13.3)
54
(12.2)
52
(11.1)
5/1/96
5/6/96
5/11/96
5/16/96
5/21/96
5/26/96
5/31/96
Date
EFT meas
EFT calc

Final EFT Comparison - Aug

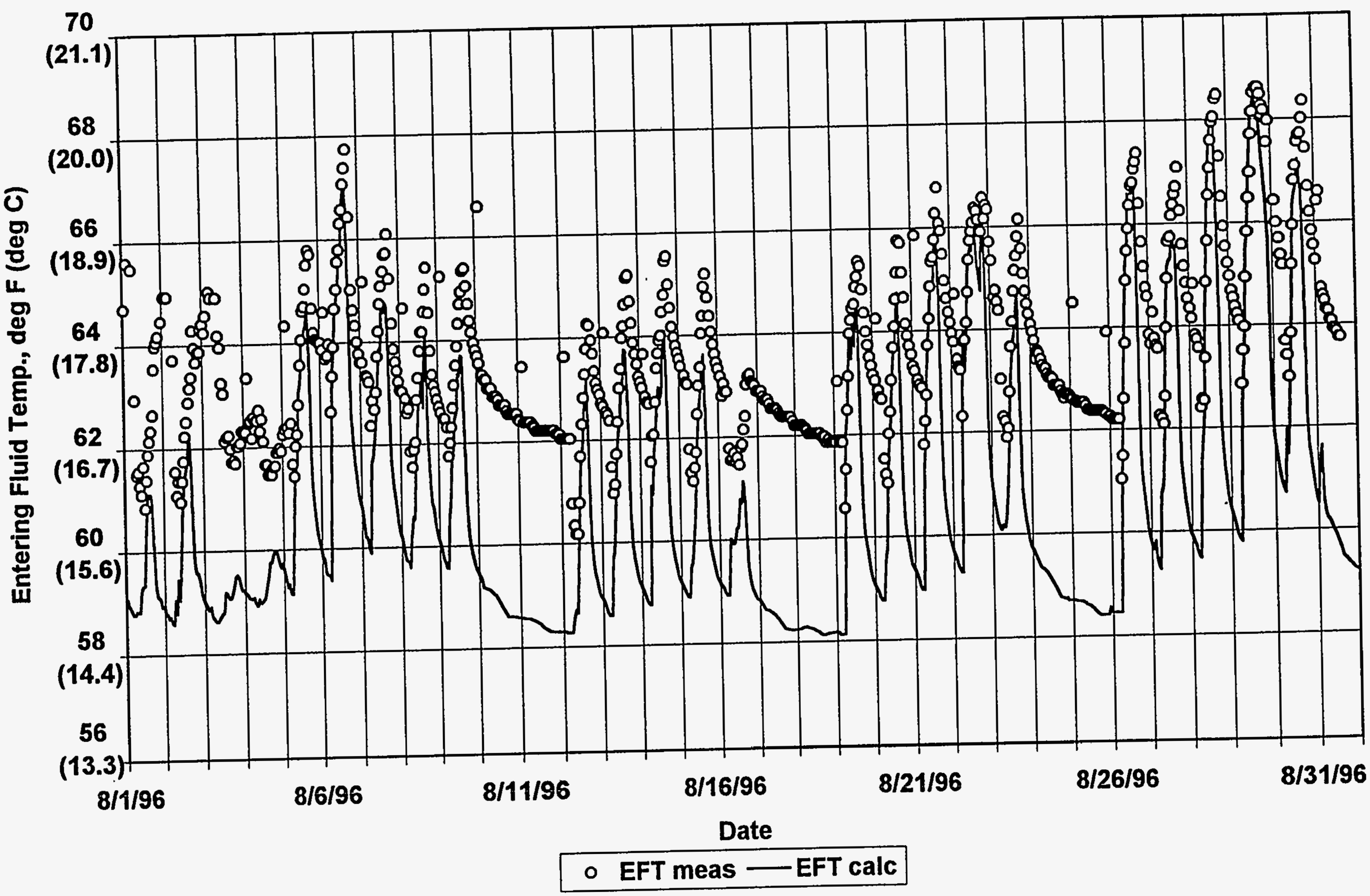


Fig 4c

Fig 4d

Final EFT Commparison - Nov