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Development and Demonstration of a Bidirectional Advective Flux Meter for Sediment-Water Interface

by

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Notice

The U. S. Environmental Protection Agency through its Office of Research and Development funded the research described here. This report has been subjected to Agency's peer review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Foreword

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Sally Gutierrez , Director
National Risk Management Research Laboratory

Abstract

A bidirectional advective flux meter for measuring water transport across the sediment-water interface has been successfully developed and field tested. The flow sensor employs a heat-pulse technique combine with a flow collection funnel for the flow measurement. Because the direction of flow was initially unknown, the heater was located in the center of the flow tube. Two thermocouples were symmetrically placed to both sides of the heater for temperature monitoring. For each measurement cycle, the heater generates and injects a heat-pulse to the center of the flow tube, the water flow inside the flow tube carries the heat-pulse down gradient, and the temperature is monitored at each thermocouple over time. In theory, the heat-pulse arrival time is inversely proportional to the flow rate. The bidirectional feature of the flux meter is realized through the temperature measuring capability on either side of the flow tube.

The system has automatic data acquisition, real time data display, and signal display/analysis capability. The instrument has undergone several calibrations to establish empirical relations between flow rate and heat-pulse travel time. Flow rate can be derived as a function of peak temperature arrival time, or as a function of first temporal moment of the heat-pulse. In the field operation, the flow across sediment-water interface is funneled through a dome to the flow tube; the rate of water flowing through the flow tube is measured. The advective flux through the sediment-water interface, in term of vertical Darcy velocity, is calculated by dividing the flow rate by the dome area. The dome serves as an amplifier to bring the generally low Darcy flow within a measurable range by the flow sensor. The larger the dome area, the smaller the flow it can detect.

The flux meter has undergone field tests at three very different settings. The first test site was a shallow turbulent stream at Santo Domingo, Nicaragua. The large magnitude and frequency of shifts between base-flow and storm-flow caused by rainfall events during our field deployment prevented us from obtaining reproducible data. Nevertheless, invaluable lessons were learned. The second test site was at Grand Calumet River, Hammond, IN, which is a slow moving river with fine texture organic rich sediment. And the final test site was at a large reservoir with deeper sediment at Lake Hartwell, SC. The last two field deployments were successful in that the flux meter was operational, reasonable characterization of flux were obtained, and bidirectional flow measurement capability was demonstrated.

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Introduction

Understanding chemical inputs into ecosystems and its availability for biological uptake is a key factor in estimating the risk potential that a chemical poses to human and ecological receptors. The technology for assessing risk potential is an ongoing topic of investigation (U.S. EPA 2006). The traditional approach is to characterize a site by estimating the location and concentration of chemicals within a volume of interest and then estimate the ecological risk based on this concentration data. Recently an alternative option for estimating risk includes flux as a key component in the analysis. Flux is primarily reported as either volume flux or mass flux. Volume flux (LT^{-1}) is usually related to the fluid carrying the chemical while mass flux ($\text{mass } L^{-2} T^{-1}$) is used to refer to the transported chemical. The mass flux is the flow weighted concentration times the volume flux. The hypothesis is that ecological systems are in fact impacted by the integrated mass flux of chemical introduced into the system. Research conducted by (Bockelmann, Ptak et al. 2001; Annable, Hatfield et al. 2005; de Jonge and Rothenberg 2005) provide the design of flux measurement approaches and successful field application to quantify contaminant mass fluxes and assess its related ecological risk.

Most efforts to date have been limited to characterizing contaminant transport from one place to another within subsurface soil or ground water environments. Little research has been performed to quantify water (or contaminant) fluxes from ground water or submerged sediments to surface water (U.S. EPA 2000). Impacts from the discharge of contaminated ground water on the ground-water/surface-water (GW/SW) transition zone ecosystem have often been ignored, even though this ecosystem provides important ecological services and is the most exposed to ground-water contaminants. The GW/SW transition zones at the interfaces are extremely biologically active and capable of metabolizing chemicals or excreting chemicals as water passes from one environment into another. This region can dramatically change the risk of chemicals and needs to be understood. Numerous well-known methods exist for parameter estimation and process identification in aquifers and surface waters. The transition zone, however, has only in recent years become a subject of major research interest, and the need has evolved for appropriate methods applicable in this zone (Kalbus, Reinstorf et al. 2006). Providing a tool that can measure both the volumetric flux of water and the mass flux of the chemicals associated with the water would increase our understanding of the active processes. An example is the influence of caps on contaminated sediments. Much of the design of a cap is based on the slow diffusion of chemicals through a cap. When diffusion is the dominant transport mechanism a cap can provide isolation from the contamination for significant periods of time. However, a small amount of advective flux will significantly reduce the life expectancy of this engineering system to reduce risk. Since advective flux is a key component affecting chemical inputs from sediments to impacted ecosystems (Simmons 1992; Harris 1995; Huettel, Ziebis et al. 1998; Shaw, Moore et al. 1998; Li, Barry et al. 1999; Jahnke, Nelson et al. 2000; Uchiyama, Nadaoka et al. 2000; Liu, Jay et al. 2001; Yang, Hwang et al. 2002; Jahnke, Alexander et al. 2003; Slomp and Van Cappellen 2004), it is important to develop such flux measuring capability to aid in better environmental risk assessment and management. The direction of this research is to develop tools that can be utilized to measure volume flux through

the ground-water/surface-water interface, hydraulic properties of the hyporheic zone, and chemical fluxes.

The field effort to measuring water flux in lake was initially conducted by (Lee 1977) using seepage flux measurement with seepage meters coupled with measurement of hydraulic gradient through the sediment. This was performed as a part of a water quality study to evaluate the input of N and P to the lake through groundwater from a nearby septic tank. Recharge to a body of surface water occurs when the hydraulic gradient at any recharge point in a flow system exceeds the downward-directed gravity force. Conventional design for measuring in situ (seepage) water flux cross sediments consists of a submerged chamber (e. g., an inverted dome) connected to a piece of tubing and a thin plastic film collection bag. Water flux released through sediment-water interface is calculated by measuring the change in weight of the bag after some time has elapsed (Lee and Cherry 1978). Water flux measurement made with this method, however, can be highly variable. Concerns have been raised about the accuracy of these devices (Fellows and Brezonik 1980; Shaw and Prepas 1989; Shaw and Prepas 1990; Belanger and Montgomery 1992; Shinn, Reich et al. 2002). The published literature provides examples of the transient effects of meter installation on flows through the lakebed (Shaw and Prepas 1989), head loss related to the ratio of meter diameter to tubing diameter (Fellows and Brezonik 1980; Belanger and Montgomery 1992), and errors associated with bag type and size (Fellows and Brezonik 1980; Shaw and Prepas 1990; Schincariol and McNeil 2002). Nevertheless, numerous field and laboratory studies have demonstrated these devices can yield accurate data provided adequate care is taken in making measurements and proper calibration coefficients are applied.

The original method was modified by (Murdoch and Kelly 2003) by adopting equilibrium pumping out from the submerged chamber. The nearby axial piezometer was also used to determine the vertical hydraulic head gradient through the sediments encompassed by the submerged chamber. The established constant equilibrium pumping rate (L^3/T) without head change divided by cross section (L^2) area of submerged chamber is equal to seepage rate (L/T). However, this flux measuring method has a limited application only to shallow depth with relatively high vertical hydraulic conductivity (~ 108 m/day). Several researches have modified the original approach of Lee (1977) by replacing the sampling bag with a flow meter which permits near continuous measurements. The approaches include heat-pulse methods (Taniguchi and Fukuo 1993), ultrasonic methods (Paulsen, Smith et al. 2001), electromagnetic flow meters (Rosenberry and Morin 2004), and dye dilution approaches (Krupa, Belanger et al. 1998; Sholkovitz, Herbold et al. 2003).

Data from numerous investigations where seepage meters were used indicate flux through the lakebed commonly varies over three orders of magnitude and can vary by as much as five orders of magnitude. Results also have shown that spatial variability in seepage can be considerable, even on a scale of only a few meters (Shaw and Prepas 1990). Seepage measurements have been shown to correlate well with oceanic tides (Lee 1977; Sebestyen and Schneider 2001), typically varying inversely with tidal stage by as much as an order of magnitude in areas where ground water discharges to the ocean or estuaries. Seepage rates also have been related to lake seiche (Taniguchi and Fukuo 1996). Modeling investigations have also been conducted studying the importance of wave and tidal actions showing significant flow reversals ranging in time from diurnal

tidal reversals to a few seconds to tens of seconds for wave action (e.g.(Li and Barry 2000).

Considering the extent of field investigations dealing with seepage processes, relatively little effort has been directed toward examining the temporal variability of seepage flux (Sebestyen and Schneider 2001). Originally this is due primarily to the fundamental limitations of the half-barrel, bag type measurement scheme. If fluxes are very small, it can take from hours to days to accumulate enough volumetric flow to make a single reliable measurement. Moreover, each measurement is time integrated, and no information related to temporal variations within the measurement span is available. Several automated seepage meters have been developed to monitor transient, as well as longer-term, seepage effects through sediments in rivers, lakes, and oceans (Taniguchi, Burnett et al. 2003). Currently, none of these devices is available commercially.

The initial phase of the work has been to develop a robust methodology to quantify the advective volumetric flux through a plane normal to the instrument. In addition methods have been demonstrated to use this information to calculate the hydraulic properties of the formation materials. Methodology to measure the chemical flux remains to be accomplished and was not included.

Objectives

There is a significant amount of interest in the movement of water between surface water bodies and ground water. The interest ranges from ecological studies concerned about turnover rates of chemicals in benthic environments, water resources studies evaluating gain and loss of water from surface water bodies, to contamination studies involved in containment transfer or remediation of contaminated sediments. The original impetus for the research was an interest in determining the long term viability of sediment caps under conditions of advective flux. In a no flow condition caps should provide an effective low cost method of isolating contaminants since diffusion is a very slow process and a cap of as little as a meter in thickness could isolate the contamination potentially for decades. In this project, the objectives are to develop a method of measuring the bidirectional advective flux of water at the sediment-water interface; demonstrate the viability of the flow sensor in a laboratory environment and; combine the flow sensor with a flow collection funnel that can be implemented in a variety of field settings. The flow range of interest was slightly less than 1 cm/day to as much as 20 cm/day. For much of the work, only a single flow collection design was used. However, when a different flow range is expected this could be modified by changing the diameter of the collection funnel. This report covers the design and operation of the instrument, calibration of the flow sensor and measurements made at selected field locations.

Flux Meter Development

The advancement of flux meter involved development of the hardware and software, as well as laboratory testing and calibration.

1) Hardware

With the objectives in mind, a prototype advective flux meter capable of measuring bidirectional water flow across sediment/water interface has been developed (Figure 1). The operational principle of this device is based on the concept of heat-pulse technique, which has been widely utilized as a proven method for a variety of measurements (Campbell, Calissendorff et al. 1991; Choi, Lee et al. 1991; Taniguchi and Fukuo 1993; Paillet, Crowder et al. 1996; Sonnenschmidt and Vanselow 1996; Bilskie, Horton et al. 1998; Ren, Kluitenberg et al. 2000; Basinger, Kluitenberg et al. 2003; Heitman, Basinger et al. 2003; Mortensen, Hopmans et al. 2006). The basic unit consists of a dome (flow collecting funnel), a flow tube, a USB interface box, and a laptop computer. The dome unit consists of a stainless steel dome and a polyethylene cylinder joined and sealed by gasket material and secured with four cables. This two-piece dome design allows intermittent measurements to be made at the same location by leaving the cylinder in the sediment between measurements. The dome and the flow tube are connected, and the water flows in or out of the unit dependent on the direction of the gradient. The electronics of the flow tube are connected through a cable to the USB interface box/circuit board which provides power to the flow tube. A USB cable connects the interface box to a laptop computer which contains the operational software. A vent pipe is extended from the top of the dome to the atmosphere to reduce the interference of sporadic gas flow, which can be a significant problem when the bottom sediment is biologically active.

For field implementation as illustrated in Figure 2, the cylinder portion of the dome unit is pushed into the sediment to isolate the flow path so that only water flow vertically through the isolated section of the sediment should flow through the flow tube. The electrical cable connects the flow tube to the data acquisition unit on the shore or on a boat. In field operation, the unit is powered by 12V batteries and inverters.

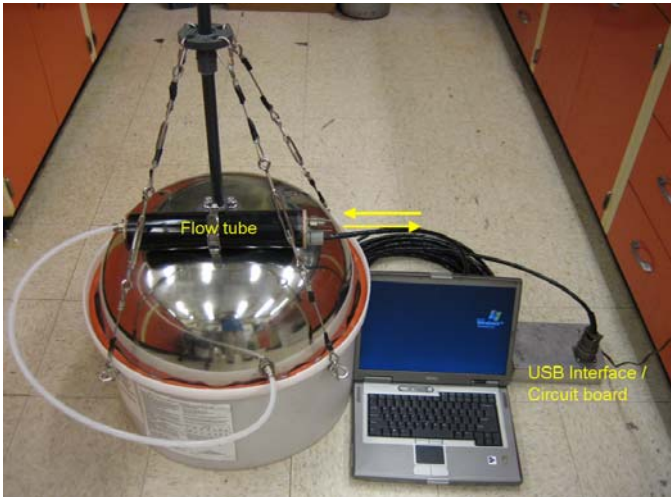


Figure 1. The basic unit of a proto type advective flux meter.

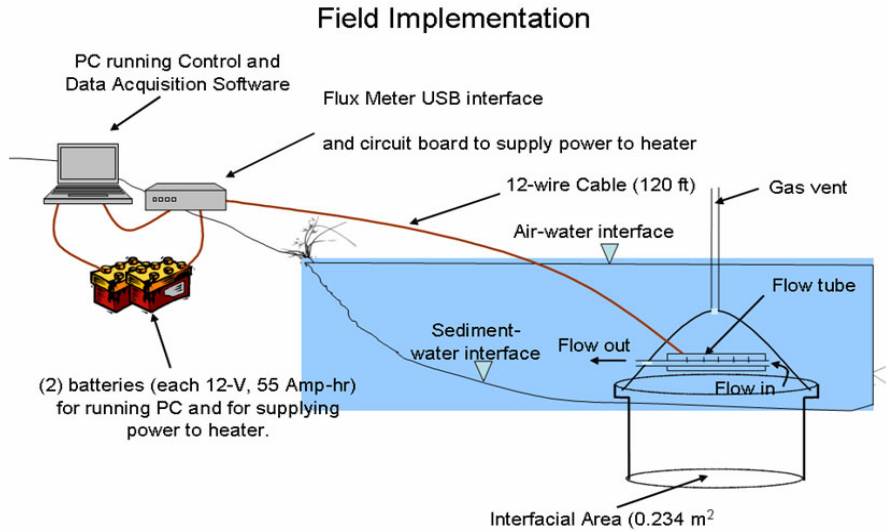


Figure 2. Schematic of field implementation of the flux meter.

The key component of the flux meter is the flow sensor which is schematically illustrated in Figure 3. It consists of a flow pipe, a heater, type T thermocouples, instrumentation amplifiers and reference temperature junction. The entire flow sensor unit was encapsulated inside a plexiglass outer tube with resin for electrical insulation and water seal. Because the direction of flow was initially unknown, the heater was located in the center of the flow pipe. There is one thermocouple at the heater to measure the heat-pulse that's been generated. Two thermocouples were symmetrically placed to both sides of the heater for monitoring temperature. All thermocouples are connected to the same reference temperature. The thermocouple reference junctions are maintained at a common temperature and this temperature is measured using the forward drop across a semiconductor. Microvolt level signals are amplified at the flow sensor using micro powered instrumentation amplifiers capable of producing output indicating differential temperatures with a sensitivity of approximately 100 mV/°C. The absolute temperature of the reference junction is measured as mentioned above using the forward voltage drop across a P-N junction with an output of approximately 10 mv/°C. The reference temperature is calibrated over a range of temperature of 0 – 50 °C with an accuracy of ±2 °C. The thermocouples are used only for relative temperature and are not calibrated. The gain of the instrumentation amplifier was selected to yield approximately 100 mV/°C. The nearest standard resistor was used in the circuit. The flow sensor circuit board layout is shown in Figure 4.

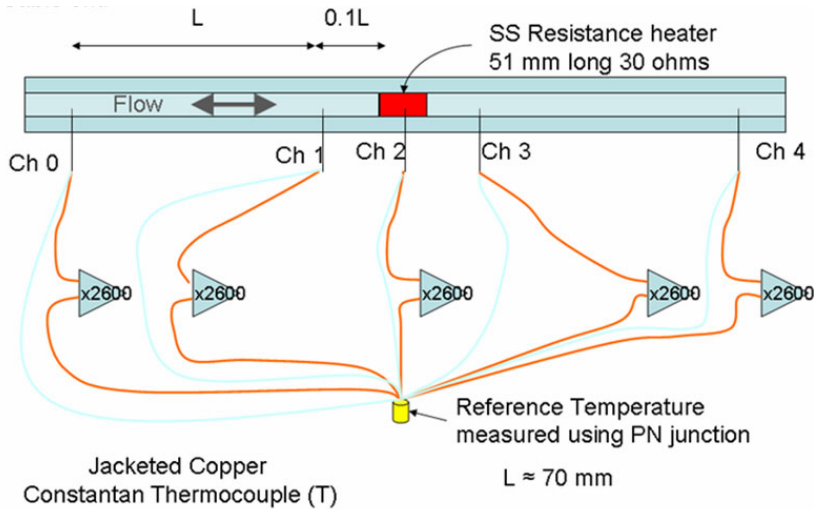


Figure 3. Conceptual Drawing of the flow sensor.

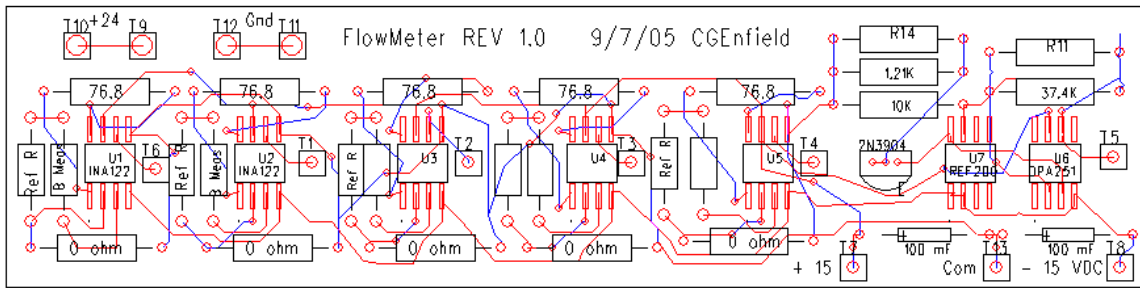


Figure 4. Flow sensor circuit board.

For each flow measuring cycle, the heater generates and injects a heat-pulse to the center of the flow tube, the water flow inside the flow pipe carries the heat-pulse down gradient, and the temperature is monitored at each thermocouple over time. In theory, the heat-pulse arrival time is inversely proportional to the flow rate. Therefore, the higher the flow rate the shorter time it takes for the heat-pulse to arrive. The bidirectional feature of the flux meter is evident by the heat-pulse measuring capability on either side of the flow tube. In the field deployment, the rate of water flowing through the flow tube is measured. The advective flux at the sediment-water interface, in term of vertical Darcy velocity, is calculated by dividing the measured flow rate to the dome area. While Darcy velocity may range several orders of magnitude, the detection range of the flow sensor is limited to a range of 1 to 40 ml/min. Dependent upon the specific study, the size of the dome may require changes to accommodate the Darcy flux range. The dome serves as an amplifier to bring the generally low Darcy flow to a measurable range by the flow sensor. The larger the dome area, the smaller the flow it can detect.

The heat-pulse flow measurement approach has a set of tradeoffs related to heat losses, noise that is reflected in error of temperature measurement and precision in

determining how fast the heat-pulse is traveling. The advective flux is interpreted from an analysis of time and temperature data collected at each of the thermocouples. Each of the temperature data points reported is an average of N observations. The data collection algorithm could be modified to average out the observed noise by increasing the number of observations at the expense of increasing the time between sampling events. A decision was made to use $N = 100$ as a reasonable compromise. Laboratory analysis of the measurement system indicates the noise on any given data channel is approximately ± 0.02 °C. The laboratory data shown in Figure 5 indicate that under near isothermal conditions (variation of approximately 0.03 °C (12.93-12.96 °C)) over a period of 12,000 seconds the time weighted average differential temperature did not change significantly but the noise in the differential temperature measurement is approximately ± 0.02 °C. If the temperature of the measuring thermocouple approaches the temperature of the reference junction, the differential temperature measurement will simply reflect the random noise. Thus, the smaller the magnitude of the thermal peak the greater the potential error in determining the heat-pulse arrival. When flow is low, much of the energy is lost to the surrounding environment. For this reason, one pair of thermocouples is placed close to the heat sensor and is the preferred detector under low flow conditions.

The primary differences between the flux meter developed in this project and the flow sensor developed by (Taniguchi and Fukuo 1993; Taniguchi and Fukuo 1996) are the bidirectional measurement capability of ours, the type of temperature detector (thermocouples vs. thermistors) and methods of data interpretation (using both moment analysis and peak temperature arrival time vs. just peak arrival).

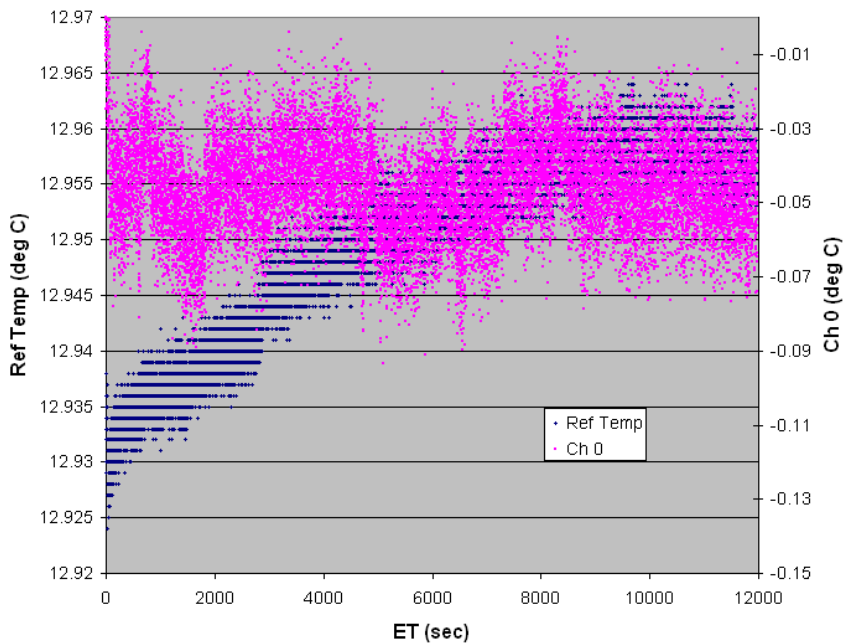


Figure 5. Thermal noise during near isothermal conditions.

2) Software

The key controlling mechanism of the flux meter is the software. The code is written in Visual Basic 6.0 (see Appendix C). The data acquisition module (Figure 6) provides operational control and data acquisition. It allows changes to various operation parameters such as the site description, duration of baseline readings, duration of heating cycle, duration of data collection, number of test cycles, pause-time between cycles, etc. It displays raw data of each channel in real-time during each test cycle. For each round of test cycle, a raw data file is automatically generated and named after the beginning date & time of the cycle. Data is stored in ASCII format (see Appendix D) on the computer's hard drive with the extension (.dat). The data is kept in its raw form and only evaluated within the analysis algorithm. The first line of the data file contains information about how the test was performed, the flow sensor that was used, the diameter of the dome and the sampling location. From the second line on, the accumulative time and thermocouple responses from all 5 channels are recorded until end of the test cycle.

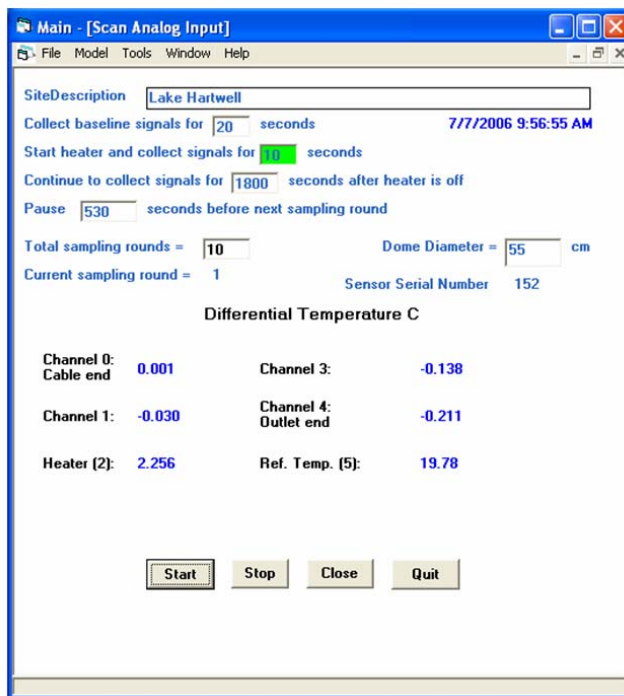


Figure 6. Software: Data Acquisition Module.

The signal display module (Figure 7) allows one to choose which data file to display and process. It automatically finds the calibration for the flow sensor used. It then analyzes the data and displays the thermographs and the results. The data display shows relative temperature of the individual thermocouples on the “y1” axis and absolute temperature of the reference junction on the “y2” axis and elapsed time on the x axis where $t = 0$ is the beginning of the heating cycle. The relative temperature is the difference in temperature between the reference junction and the temperature in the flow

tube at the measuring thermocouple. The analyzed results are stored in a separate file with the same name as the raw data file except with the extension (.csv) which is directly readable by Excel. Two primary approaches are used for data analysis. The first is related to the arrival time of the peak temperature detected at each thermocouple and the other is the normalized first moment of the thermal breakthrough curve.

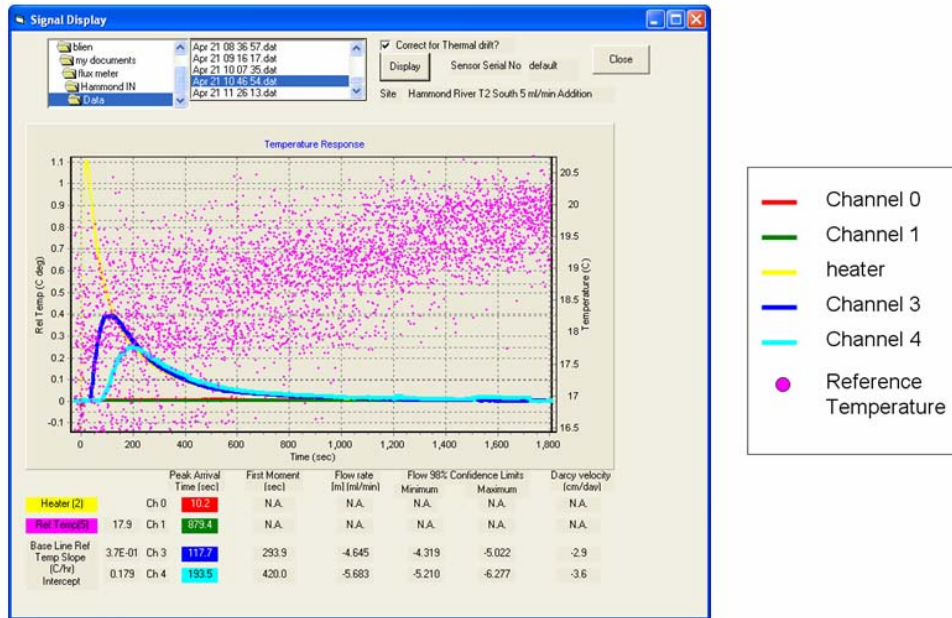


Figure 7. Software: Signal Display Module.

3) Calibration

The calibration process involves passing water through the flow sensor at known flow rates using a precision metering pump. Temperature response is monitored at each thermocouple and the reference temperature junction as a function of time. Prior to the injection of heat-pulse a baseline temperature is recorded for a known period of time (adjustable under program control). Heat-pulse is then injected to the center of the flow tube. A 10 second heating cycle has been experimentally determined as a desirable heating time and used as a default value. Although the duration of heating cycle is adjustable under program control, this value should not be changed unless calibration is available for that particular heating cycle duration. It is of importance to recognize calibration curves are dependent on the duration of the heating cycle. Once the duration is determined it should be maintained throughout the calibration process. Finally, temperature is recorded during the heating cycle and continued for a period of time after heating. There are 6N discrete temperature measurements for each test cycle. N is the number of time steps in a complete cycle. The number of time steps is dependent on the speed of the computer used to collect the data as well as the speed of the interface card's

analog to digital converter. The system is operated at the maximum speed possible to minimize magnitude of the time step. The error in time measurement is then dependent on the sampling frequency which is computer dependent. The data analysis package displays all of the data graphically. Occasionally random noise is observed in the response. These noisy data points are obvious to a casual observer because they do not follow the expected temporal decay pattern in the data and can be eliminated without statistical analysis. The analysis algorithm currently does not reject abnormal data. This must be performed manually by the user.

Initially a base line analysis is performed. Both the mean value and slope of the baselines are determined. The drift in reference temperature is displayed on screen. If the user has selected to correct for baseline drift, all of the raw data may be adjusted for the drift in the base line prior to determining peak arrival time or moment analysis. The duration of the data series should be at least two times the time reported for the first moment. The baseline is assumed to be a linear function based on the temperatures measured before the heat-pulse and the last 30 data points from the data set. Baseline offset is adjusted prior to data display for either approach. Peak arrival time and amplitude is determined by sequentially searching each data record for the maximum observed voltage. Note that if there was a spike in the data an incorrect value may be determined. The user must look at the selected value to make sure that it is reasonable. Moment analysis is performed on the same data to determine the time of travel for the center of the heat mass. To include a significant portion of the response curve, the experimental data collected after 80% of the peak arrival time is fit to an exponential curve. This removes the potential for negative values and is the approach commonly used in other tracer experimental analysis. This minimizes the difficulty in handling values as they approach zero. Standard algorithms are used for calculating the normalized first moment (Shook and Forsmann 2005; Wu 2006). Computer code for the first moment calculation is included in Appendix C.

An empirical function which describes the flow of heat through the flow sensor is fit to the calibration data. Heat flow is controlled by two primary components. At low flow rates the predominant component is heat conduction through the media. At high flow rates the primary component is advective flow of the water. The equation describing heat flow through the transducer based on normalized first temporal moments is:

$$Q = \frac{c_1 - Mc_3}{M + c_2} \quad 1.1$$

Where

Q is the volumetric flow rate (L^3T^{-1})

M is the normalized first temporal moment (T)

c_1 , c_2 and c_3 are constants

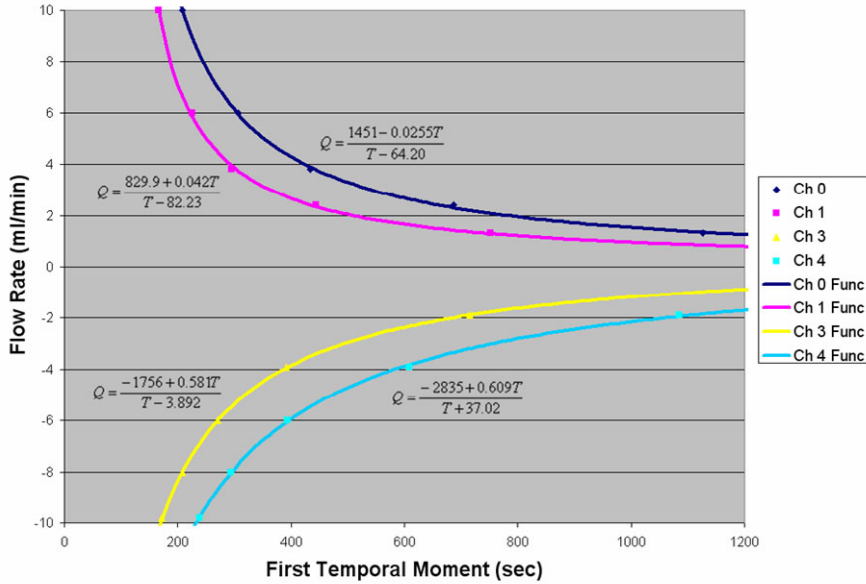


Figure 8. Calibration curves for flow sensor SN151 based on the method of moment.

An example calibration curve is shown in Figure 8. Data points in the figure represent the average of N replicate measurements at the same flow rate with N typically equal to ten. For the purpose of distinguishing flow direction in the flow tube, flow vector is assigned. Positive flow is considered as flow toward the cable end of the flow sensor and negative flow is flow away from the cable end of the flow sensor. Moment analysis is performed on experimental data after initially measuring the differential temperature for a period of time to establish a baseline. This takes into consideration both the differential temperature at time zero as well as instrumentation amplifier offset voltages. At the end of the baseline measurements the data are averaged and subtracted from the remaining measurements prior to moment analysis. The starting time for the moment analysis begins with the first sample after baseline measurements. Data analysis begins with the first observation after the end of the heat-pulse. To minimize errors in moment analyses, the thermograph is divided into two parts (Figure 9). The first portion of data, beginning at the end of the heating cycle and continuing to the time when the temperature has dropped to 80% of the peak temperature, is analyzed directly without interpolation and extrapolation. From 80% of peak temperature until the signal is less than or equal to 30% of the maximum temperature measured, the data is fit to a logarithmic function. This function is used to interpolate and extrapolate anticipated temperatures in the moment calculations. It is necessary to fit the tail portion of the breakthrough curve to a function which permits extrapolating the data to very small values. The noise in the temperature measurements that occurs during heat-pulse switching is illustrated in Figure 10. We were not able to remove this noise using analog techniques on the circuit board.

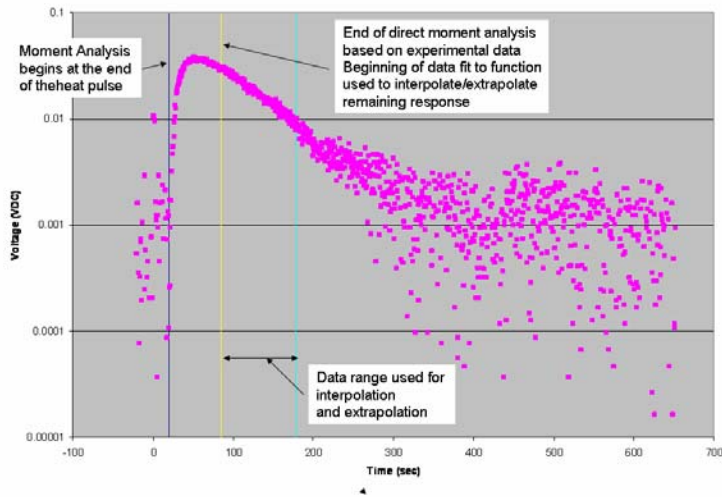


Figure 9. Experimental thermograph plotted on log scale. Time zero is the beginning of heating.

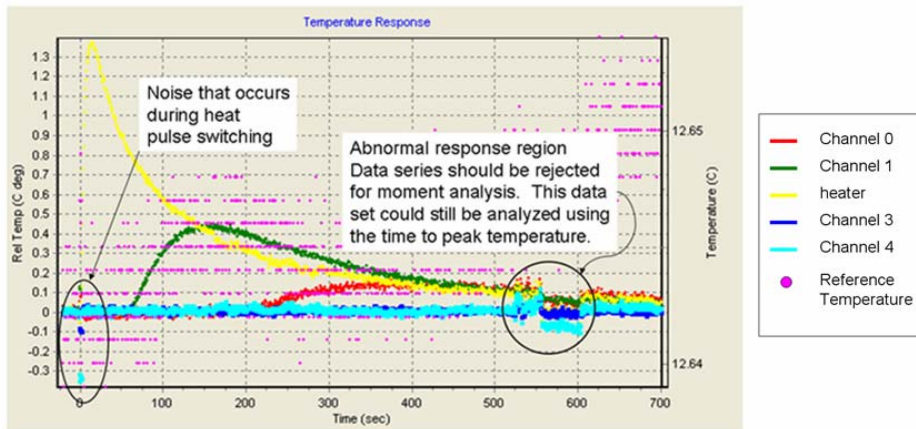


Figure 10. Illustration of abnormalities in thermographs.

Since relatively long travel times are encountered at low flow, the error associated with discrete sampling times is small. When flow is high the pair of thermocouples placed at a greater distance provides a more reliable result. Selecting the appropriate thermocouple is determined by the magnitude of the measured heat-pulse compared to noise in the temperature measurement. It is possible to increase the magnitude of the heat-pulse by increasing the duration of heating cycle or the voltage applied to the heater. However, increasing the magnitude of the heat-pulse increases the potential buoyancy of the water and may induce thermal flow. Keeping the heat-pulse small is essential to minimize the bias that may be introduced if the flow sensor is not horizontal.

The time for the temperature to reach a peak value is less complicated to analyze. It does not have the “noise” problems associated with values approaching zero. However, the actual peak arrival time does have errors associated with the “noise” in the measurement and the discrete sampling interval used in the data collection. As discussed

later the coefficient of variation in repeated measurements of the same flow rate is greater for the peak arrival time than it is for the time for the normalized first moment. This suggests that using moment analysis may be a preferred approach for data interpretation.

The empirical equation describing heat flow through the flow sensor based on the peak temperature arrival time follows:

$$Q = ct^b$$

Where

Q is the volumetric flow rate (L^3T^{-1})

t is the time when the peak temperature is observed (T)

c and b are constants

An example of calibration curves based on peak temperature arrival is shown in Figure 11.

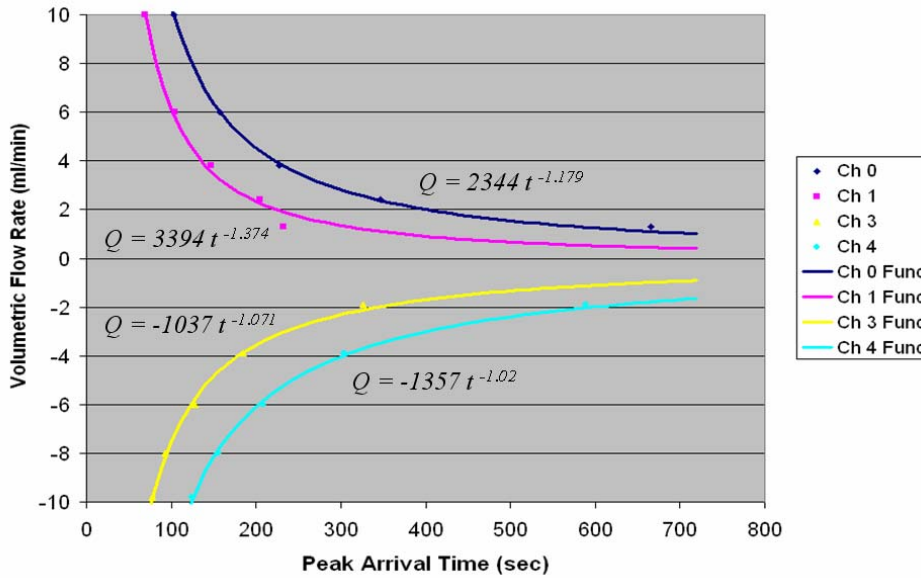


Figure 11. Calibration curves for flow sensor SN151 based on peak temperature arrival time.

Both peak temperature arrival and method of moment techniques provide good calibration results as demonstrated in Figure 8 & Figure 11. The coefficient of variation for repeat measurements under laboratory conditions of near constant temperature and constant flow using a peristaltic pump are typically 2% based on the method of moments and 4% based on peak temperature arrival. The R^2 values are also consistently better when the method of moments is used, but both methods typically give R^2 of 0.99 or better. Just because laboratory measurements suggest moment analysis will provide a better result does not mean the results under field conditions are better using moment analysis. Variability in flow during the measurement may cause greater errors in the moment analyzed response curves than in the peak temperature arrival time analysis.

Potential Sources of Error

- flow bypassing
- Bernoulli Effect
- dome geometry
- gas flow
- wave action
- thermal drift

The primary sources of environmental measurement error are related to flow bypassing and unstable flow. If the flow that enters or exits the dome through the sediment interface and respectively exits or enters at a location other than the sensor, there will be an error in the measurement. There is potential for leaks at the interface between the dome and the sediment as well as joints and fittings in the dome. For rocky formations where it is difficult to obtain a seal, a flange can be installed on the cylinder to reduce the probability of flow bypassing between the dome and the sediment (as shown in Figure 12). Sandbags could be placed on the inner tube to help create a seal. To evaluate these potential errors in the field either a standard addition or standard subtraction is used. The standard addition method is performed by measuring the flow rate and then immediately repeating the measurement while adding a known flow rate to a port on the dome. The resulting measurement should be the sum of the two flows. Flows may change diurnally but the error associated with measurements closely spaced in time should be minimal after an initial stabilization period. The flow meter is calibrated over a finite range of flows. If the existing flow is close to the upper limits of calibration, it may be preferred to perform a flow subtraction rather than a flow addition. Conversely, flow addition is the preferred method when flow is near zero. Flow additions when the flow is near zero may be used to refine the measurement such that a more sensitive region of the calibration curve is used.



Figure 12. Tire inner tube placed around dome cylinder to improve seal to formation. Photo by Göran Bengtsson, Santo Domingo, Nicaragua.

A second source of potential error is related to the Bernoulli Effect that may cause the head in the dome to be different than the head outside the dome (Libelo and MacIntyre 1994; Shinn, Reich et al. 2002). This is possible in rapidly moving streams but not considered to be a significant source of error in slow moving bodies of water such as lakes or estuaries. If there is a potential for significant Bernoulli-induced flow, the pressure difference is measured manually by measuring the head difference using tubing as a water manometer. When a gradient exists the discharge point of the flux meter is rotated to find the direction where the gradient is no longer significant. Figure 13 shows a testing of head differential between inside the dome and the stream at the flow meter's discharge point. The potentiomanometer used for the direct measurement of differences in hydraulic head is similar to the design of (Winter, LaBaugh et al. 1988). One of the tubes is inserted through the vent pipe to inside the dome and the other is placed in the stream near the discharge point of the flux meter. Hand vacuum pump (far left of photo) was used to create a common vacuum allowing the measurement of the differential pressure. The discharge point on the flux meter is adjusted to zero the pressure differential between inside the dome and outside the dome.



Figure 13. Bernoulli Effect is anticipated under the turbulent flow conditions in the rapid stream. The schematic illustration shows installation of potentiomanometer for head differential measurement. Photo by Göran Bengtsson, Santo Domingo, Nicaragua.

Dome geometry can have a significant impact on errors. Three geometries have been considered each having potential issues. An open cylinder, as shown in Figure 14, that has one end penetrating the sediment-water interface has desirable characteristics of ease of placement, not influenced by gas production in the sediment and low cost. The potential shortcoming of this method of measurement is when the water table is changing as would be the case in tidal environments. For example if the water table were to

increase 1 mm during a 10 min measurement time and the dome diameter were 50 cm, the change in water volume within the dome would be almost 200 ml or 20 ml/min. With this much change during the measurement, it would not be possible to obtain any relevant data. To correct for this error a pressure transducer would be needed to monitor the head within the dome during measurements.



Figure 14. Open cylinder used for advective flow measurement. Photo by Göran Bengtsson, Santo Domingo, Nicaragua.

An alternative approach would be to place a sealed dome over the sediment-water interface where there would be no change in volume. This would eliminate the problem of changing hydraulic heads in the water body. However, if there is gas accumulation inside the dome it would potentially dampen the water flow because of its compressible nature until sufficient gas accumulates in the dome to cause gas flow through the sensor. Gas flow would create other problems in flow measurement due the different thermal properties of the two fluids. The effect of gas bubbles can be illustrated by Figure 15, which shows abnormal thermographs observed in laboratory when a stream of gas bubbles was introduced through the flow tube and significant ambient temperature drift was present during the measurement cycle. Drifting in the reference temperature was most likely also the cause of the thermal drift in the thermographs.

A third alternative is a compromise between the two approaches. A small diameter pipe ($\frac{1}{2}$ " NPT) has been selected to provide a vent for escaping gas as shown in Figure 1. This will minimize the gas problem which will show up as noise in the data rather than having a consistent pattern. The error in flow will be relatively small under slowly changing conditions similar to what was seen at Hammond Indiana. The nominal inside diameter of a Schedule 80 $\frac{1}{2}$ " NPT is 1.4 cm. Thus, the volume change within the dome for a 1 mm change in head would be 0.16 ml which results in a 0.016 ml/min using the conditions described above. With a target detection limit for flow-rate of 1 ml/min this would not be a quantifiable error. A pressure transducer would still be necessary when fluctuations are expected to be rapid or large but may not be necessary under quiescent

environmental conditions. In large lakes and estuaries, wave action is likely to be 300 mm or more within a period of less than a minute (Li and Barry 2000). If one assumes the period is one minute and the change in head is 300 mm, this would be equivalent to 46 ml/min (for the ½” NPT pipe on a 50 cm dome) flow reversal every minute as illustrated in Figure 16. Note that the green and red curves are the thermocouples on one side of the heater and the blue and cyan curves are on the other side of the heater. When the red and green curves show an increase in temperature, the blue and cyan curves coincide with a decrease in temperature, suggesting water flow periodically reversing in direction. The period appears to be approximately every two minutes. The phenomena caused by the apparently wave-driven advective flow (Precht and Huettel 2004) makes it difficult to correctly determine the peak temperature arrival time and an accurate moment analysis would also be nearly impossible. Even in locations where the water surface is relative quiescent, boat traffic may create a significant water surge and sudden flow reversal as shown in Figure 17. A possible solution to this problem is used of a closed dome that is only vented periodically to remove gas accumulation in between test cycles. An approach utilizing a spring loaded port door (Menheer 2004) may be applicable for this purpose. Note that even such a modified dome may still not be ideal in all circumstances.

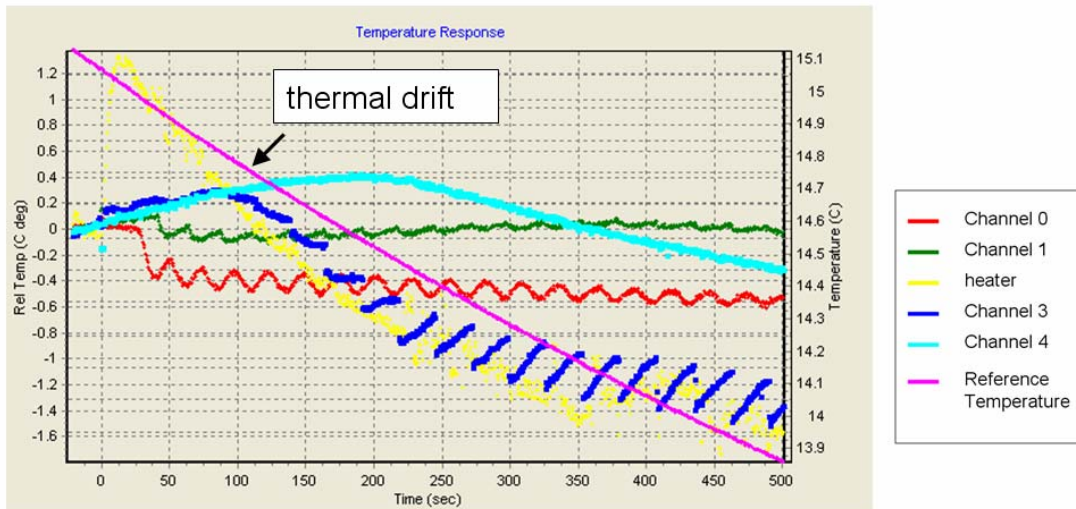


Figure 15. Abnormal thermographs observed in laboratory when a stream of gas bubbles was introduced through the flow tube and significant ambient temperature drift was present.

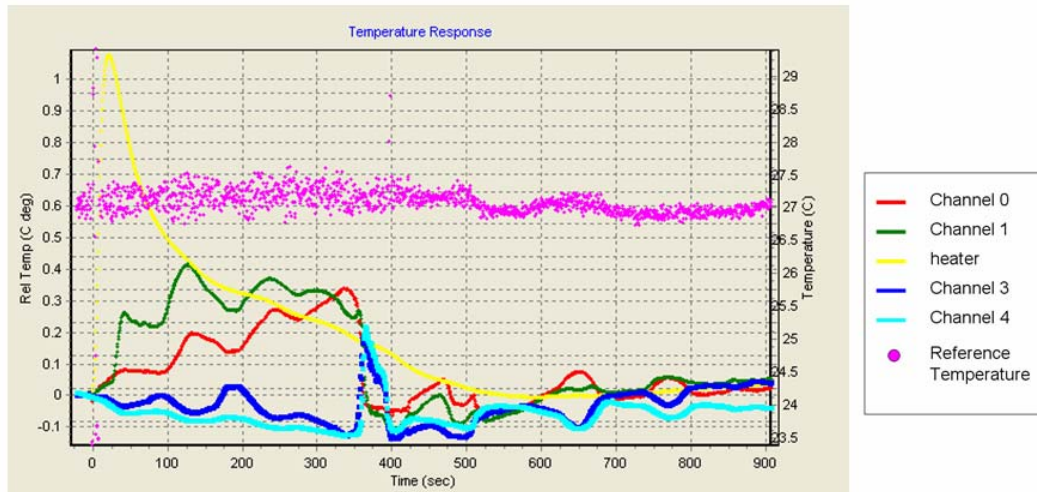


Figure 16. Apparent wave action causing water flow periodically reversing in direction (observed at Lake Hartwell, SC), such that rise and fall of the thermographs are coincidentally reversed on opposite side of the heater.

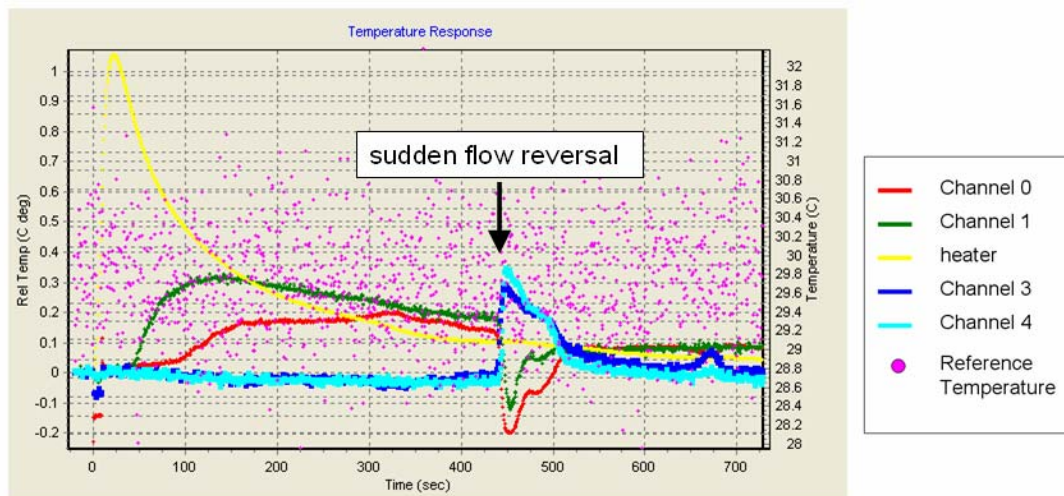


Figure 17. Illustration of a sudden flow reversal observed in otherwise normal thermographs. Flow reversal is believed to be due to wave-induced flow caused by boat activities (observed at Lake Hartwell, SC).

A final potential source of error can occur when the flux meter is initially placed into a new location where the temperature of the water body is different than the reference temperature of the flow sensor. When this happens, a drift in baseline temperature is observed. This creates errors in determining when the maximum temperature is observed or in the moment analysis. Corrections can be made in the data analysis by adjusting the measurements based on the slope of the baseline temperature. This correction should not be made when the drift is very small; small enough such the

reference temperature is capable of tracking the temperature of surrounding media. An analysis as to when a correction should be made and when it shouldn't be made has not yet been developed. The rule of thumb is when the drift on the baseline is smaller than or equal to the noise ($0.02\text{ }^{\circ}\text{C}$), then correction should not be necessary. The data analysis software permits either considering baseline drift or ignoring baseline drift at user discretion. Raw data as displayed in Figure 18 can be adjusted under program control (signal display module) to correct for baseline drift. The assumption that is made is that the drift is linear. Data collected prior to starting the heater is averaged and the last 30 data points are employed. These two averaged values are used to determine the slope of the baseline and the thermograph is adjusted to remove baseline drift. The raw data file is not modified, only the file containing the interpreted data is modified.

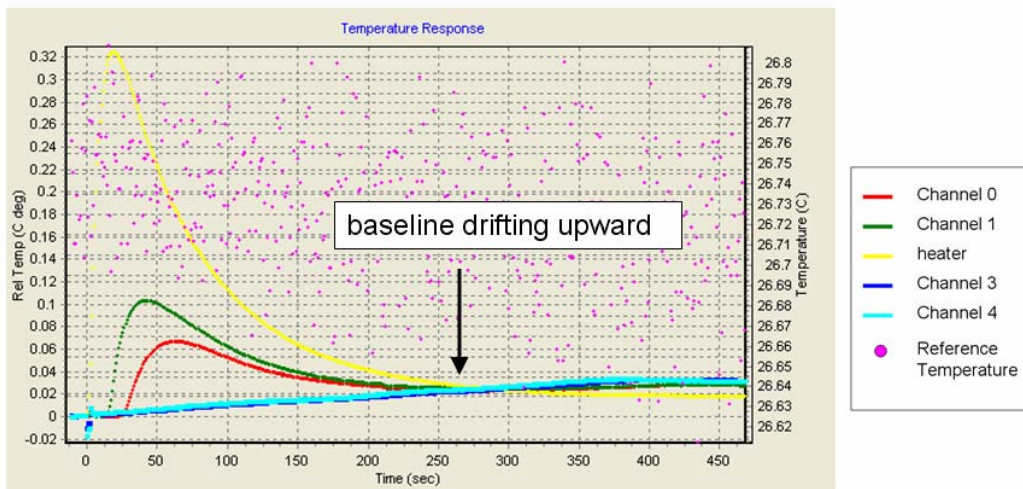


Figure 18. Thermographs illustrating upward baseline drift during measurement. Note that the reference temperature (magenta colored points) is not showing trend of drifting and is not considered as the cause of the baseline drift.

Field Applications

Field demonstrations of the advective flux meter were conducted at three very different environmental settings: (1) a fast moving and turbulent shallow stream with cobbly stream bed where Bernoulli Effect is expected; (2) a slow moving river with fine sediments where flux is expected to be low; and (3) a large reservoir with deeper sediments where lake seiche and wave action are expected.

1) Santo Domingo, Nicaragua

This field demonstration was a joint effort with Dr. Göran Bengtsson, University of Lund Sweden to investigate the magnitude of groundwater discharge in a mercury-contaminated stream near Santo Domingo, Nicaragua. Santo Domingo is a gold mining town in the mountains of Nicaragua. There are frequent intense rainfall events with large

amounts of runoff causing large swings in the hydrograph. Surface water is relatively fast moving and turbulent. When water flows over and/or around the flux meter, the sudden increase in water speed creates a pressure difference between the inside and the outside of the dome, and thus creates a Bernoulli-induced flow through the flux meter. Based on our observations, the Bernoulli Effect could cause more than ± 10 cm water differential pressure depending on how the dome is oriented in the stream. Just a few degrees of dome rotation could create a significant difference in gradient.

As shown in Figure 13, the flux meter was not fully submerged because of the shallow water depth. Therefore, an open cylinder was used (Figure 14) instead of the closed dome. The flow sensor was installed below water and through the wall of the cylinder. Flow sensor SN152 was used at this site (see Appendix A for the calibration). The stream's bottom sediment was rocky. The flexible flange made from an inner tube appeared to provide an adequate seal to the formation. However, due to the large swings in hydrograph caused by the frequent rainfall events during our field deployment, we were not able to obtain reproducible data for analysis.

2) Hammond, Indiana

This field deployment is part of a joint study with Dr. Chad Jafvert, Purdue University to investigate capping as a potential remedy for the polycyclic aromatic hydrocarbon (PAH) contaminated sediments in Hammond, IN. The Grand Calumet River is a slow moving river with its source primarily originating at the discharge from a sewage treatment plant. The river sediment is composed generally of silt-sized particles with a very high percentage of organic matter, consisting of both natural organic matter and coal tar as previously reported (Jafvert, Lane et al. 2006). Below this 8-12 ft organic-rich sediment layer was 1-2 ft of fine to medium grain sand layer over a continuous impermeable clay layer. The sand layer was extensive enough to be connected, but not always present.

Purdue University conducted a preliminary testing of the advective flux meter (flow sensor SN151) from mid July to late October, 2005. Because the hydraulic conductivity within the sediment of the Grand Calumet River was expected to be low due to its silty-organic texture, the seepage meter was calibrated for low flows (the calibration is shown in Appendix B). Note that the flow vector was not designated in this calibration; flow direction was determined by the orientation of the flow tube and the channels showing heat-pulse response. In this particular case, discernible response on channel 3 & 4 indicates groundwater discharge to surface water; response on Channel 0 & 1 points to groundwater recharge. In order to allow for the calculation of sediment hydraulic conductivity, the piezometric head gradients at each measurement location was measured. The piezometers and stream gauges were installed manually by pushing to the target depth. In the river, six piezometer clusters were installed, with each cluster consisting of two piezometers pushed to depths of 4 and 8 ft below the sediment-water interface, and one stream gauge, each located approximately 6" apart. The location of each cluster is shown on Figure 19. River clusters 1 to 4 (RC1 to RC4) were installed in the center of the river at an interval of approximately 80 ft from upstream (RC1) to downstream (RC4). River clusters RC2S and RC2N were installed at the same downstream location as RC2, approximately 3-4 ft from the south and north banks of the

river, respectively. Two additional stream gauges, SG1 and SG2, were installed approximately 250 ft upstream of RC1 and 100 ft downstream of RC4 to measure the total horizontal hydraulic head gradient of the river. Over this period, the average horizontal hydraulic gradient was 3.1×10^{-4} ($\pm 0.4 \times 10^{-4}$). The river elevation steadily decreased over time from an average depth at each of the river clusters of approximately 3.5 ft in August to approximately 2.5 ft in October.

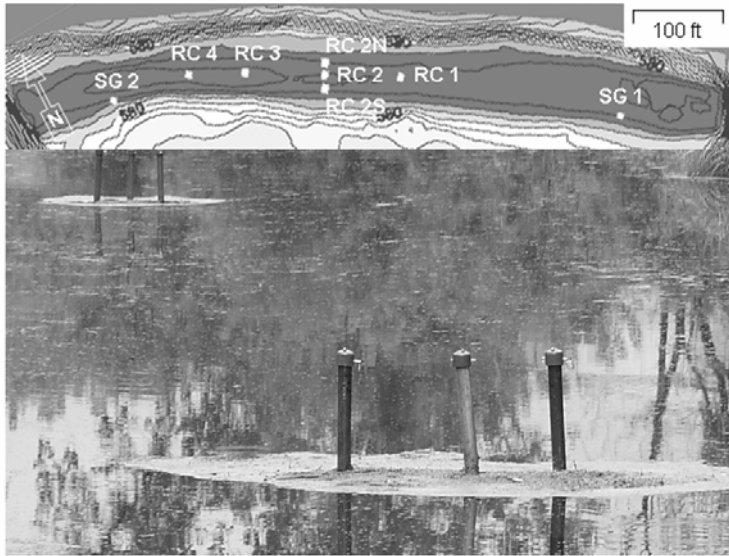


Figure 19. Grand Calumet River section monitored. Photo by Dr. Jafvert, Purdue University.

At each river cluster, the vertical hydraulic head gradient was calculated by dividing the hydraulic head differences between the piezometers and stream gauge by the depth difference. The water levels within the 4 and 8 ft piezometers were generally higher than the river elevation, with all 3 levels generally decreasing over the 3 months of continuous measurement from mid July to late October, 2005. The vertical gradients indicate upward vertical water flow with a gradient of 0.1 to 0.2. The temporal changes in the gradients were minimal over the measurement period, except after high rainfall events when the change in elevation of the river was much more significant than the changes in water levels within the piezometers. This probably results from the difference in the characteristic response times of the piezometers compared to the stream gauges.

The flow of water across the sediment-water interface was measured with the flux meter within 1-2 ft of each piezometer cluster on at least two different days at each location. At each location, the cylinder was pushed into the sediment and the dome was secured with the four cables. After all flow measurements, the dome was removed leaving the cylinder in the sediment, which allows for returning later to make measurements at the same location by re-attaching the dome to the cylinder already in the sediment. After placing the dome on the cylinder, measurements were delayed for about 1 hr until the thermocouples approached thermal equilibrium with the surrounding water. During each series of field measurements, water levels in the associated stream gauge and piezometers were measured manually. When flux is low, signal response in the

thermograph is feeble and less apparent as shown in Figure 20 as an example. Nonetheless, the uprisings of both blue and cyan curves do suggest flow in the direction of groundwater to surface water. The ascending of the green curve but not the red curve reveals dispersion of heat up-gradient against flow direction, because at very low flows dispersion of heat may occur in either direction. When this occurred, the active method (addition or subtraction of known flow rate to the existing flow) could be employed to improve the signal response for better data quality and also minimize the dispersion of heat against flow direction, as shown in Figure 21.

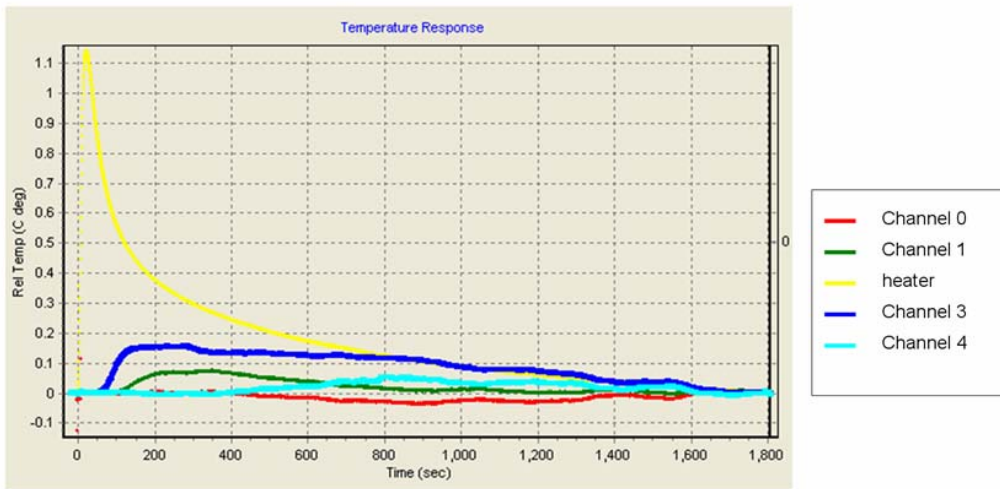


Figure 20. Example of passive method signal response from RC2S. The green curve indicates dispersion of heat up-gradient in low flow condition.

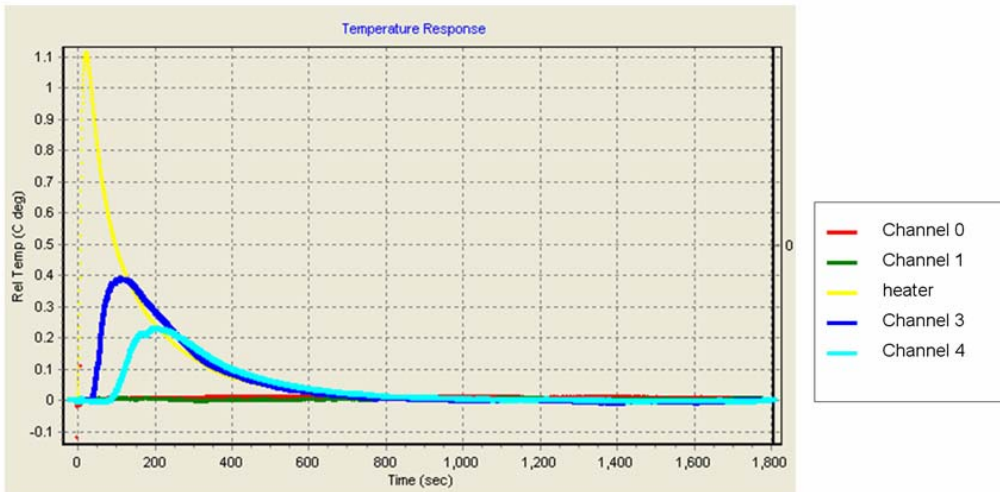


Figure 21. Example of active method (5 ml/min addition) signal response from RC2S showing much distinguishable thermograph. It provides better data quality and also minimizes heat dispersion up-gradient.

The advective flux, in term of vertical Darcy velocity q in cm/day, measured at each river cluster positions are reported in Table 1. Note that the analyses are based strictly on peak temperature arrival and not moment analysis. Also reported in Table 1 are the vertical hydraulic head gradients (i , ft/ft) at each respective river cluster measured manually on the same day when flux was measured. All measurements were made between August 10 and September 20, 2005. Over all measurements, the range in the flux was 0.3 - 2.63 cm/day. Table 1 shows values of flux measured with the passive method were within 50% of each other, with 9 of 12 measurements occurring between 1.14 and 2.0 cm/day. This same variation in the measurements over spatial and temporal scales also occurred using the active flow addition method; however the reproducibility of the results at each location and time were greatly improved as indicated by the much smaller standard deviations on these values.

The vertical hydraulic conductivity, K (cm/d), within the top 4 ft sediment layer is calculated by dividing the value of flux by the corresponding vertical hydraulic head gradient. The calculated values of K also are reported in Table 1 with the values measured by the active method ranging from 1.55×10^{-5} to 1.99×10^{-4} cm/sec, and the values measured by the passive method ranging from 2.31×10^{-5} to 2.39×10^{-4} cm/sec. These values are within the range expected for the silty sedimentary material found at the site.

Table 1. Advective flux (q), hydraulic conductivities (K), and vertical gradients (i) at each location. Data from Dr. Jafvert, Purdue University.

ID	Date	Passive Method			Active Method			i (ft/ft)	
		q (cm/day)	K at 0-4 ft (cm/sec)	n^b	q (cm/day)	K at 0-4 ft (cm/sec)	n	0-4 ft	4-8 ft
RC1	9/6/05	1.90 (0.85) ^a	1.31×10^{-4}	3	1.49 (0.07) ^a	1.03×10^{-4}	3	0.168	0.095
RC2N	8/23/05	1.89 (0.30)	1.44×10^{-4}	11	0.78	5.90×10^{-5}	1	0.153	ND ^c
	8/29/05	0.31 (0.038)	2.31×10^{-5}	3	0.36 (0.05)	2.70×10^{-5}	3	0.155	0.070
RC2	8/15/05	1.14 (0.49)	8.52×10^{-5}	3				0.155	0.033
	8/23/05	1.66 (0.38)	1.45×10^{-4}	6				0.133	0.048
	10/3/05	1.27 (0.16)	1.16×10^{-4}	3	0.793 (0.02)	7.20×10^{-5}	3	0.128	0.063
RC2S	8/10/05	2.63 (0.38)	2.39×10^{-4}	9				0.128	ND ^c
	8/15/05	2.00 (0.13)	1.03×10^{-4}	3	0.30 (0.26)	1.55×10^{-5}	2	0.225	0.045
	9/26/05	1.29 (0.49)	5.89×10^{-5}	3	1.13 (0.04)	5.21×10^{-5}	3	0.253	0.085
RC3	9/12/05	1.46 (0.42)	2.12×10^{-4}	3				0.080	0.245
	9/20/05	0.93 (0.40)	1.24×10^{-4}	3	1.50 (0.20)	1.99×10^{-4}	3	0.088	0.240
RC4	9/12/05	1.15 (0.55)	1.33×10^{-4}	3	1.09 (0.04)	1.26×10^{-4}	3	0.100	0.047

^a Numbers in parenthesis are standard deviation of replicates.

^b n = Number of measurements.

^c ND = Not determined, because the piezometric head in 8 ft piezometer did not reach at steady-state.

A final set of measurements at location RC2S were taken April 20-21, 2006. The purpose of this data set was to compare data analysis methods between the method of moment and peak temperature arrival. It was already known from previous measurements that flow was likely from ground water to surface water and the flow would be very small. RC2S location was chosen because the cylinder was previously installed and left in the sediment. On April 20, the dome was re-attached to the cylinder, and one set of data was taken to insure the unit was functional. Six data sets were collected on the next day, three with passive method and three with active method where 5 ml/min were added.

Like the previous tests, flow sensor SN151 was also used; calibration curves shown on Figure 8 & 11 were used instead to include moment analysis. Negative flow implies groundwater discharge whereas positive flow indicates recharge. Figure 22 shows the flux at RC2S estimated using both moment analysis and peak temperature arrival methods. All data show groundwater discharge to the Grand Calumet River. The first 3 data sets in the earlier time scale were collected with the passive method, and the later 3 were collected with the active method. When the active method was employed, the estimates based on the moment analysis yield smaller variation between the two channels than the estimates based on the peak temperature arrival. However, there was insufficient signal for meaningful moment analysis from the first and third set of data when the passive method was used. Therefore, it is inconclusive to categorically say which data analysis method is better.

Both passive and active methods produced similar results which gave confidence that the flow bypassing was negligible at most; the loss of water from the aquifer was consistently greater than zero, with 80% of the overall data showing upward groundwater discharge between 0.37 to 1.21 cm/day. The overall moment analysis showed groundwater discharge of 0.67 ± 0.37 cm/day, while the peak arrival yielded 1.03 ± 0.57 cm/day. Since one of the reasons for selecting this location for study was the consideration of using a cap to isolate the contamination in the formation, the potential for this low flow to dramatically reduce the life expectancy of a cap needs to be investigated before implementation.

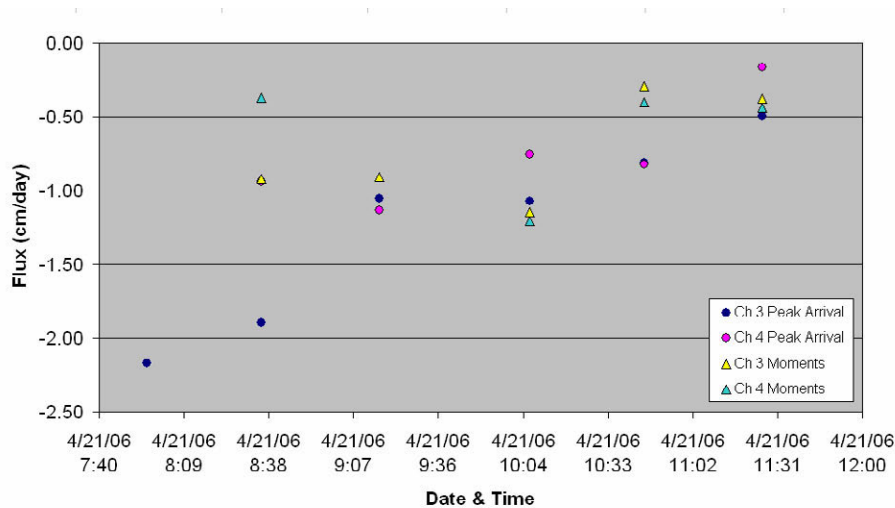


Figure 22. Temporal flux at location RC2S estimated using both methods of analysis. Note: negative flux value indicates groundwater discharge to surface water.

3) Lake Hartwell, South Carolina

Monitored natural recovery (MNR) has been studied by the USEPA as a potential remedy for the polychlorinated biphenyl (PCB) contaminated sediments at Lake Hartwell. Advective flux through sediment could have potential negative impact on the successful implementation of MNR. In May 2006, flux measurements were conducted at Transect O and Transect N illustrated in Figure 23. Lake Hartwell provided an opportunity to test the flux meter in deeper sediments in a large reservoir.

Measurements were made at two different locations. They are designated OB (transect O location B) and NB (transect N location B). Locations OB and NB were about 30 feet and 20 feet off the east shore, and the water depth was 14 feet and 10 feet, respectively. The units tested at Lake Hartwell employed a two-piece dome with a nominal ½" schedule 80 PVC pipe extended above water that functioned as a vent, but also served as a mechanism to push the unit into sediment for installation. The cylinder was polyethylene and the dome was constructed of stainless steel. Difficulties were encountered in attempting to install the dome at depths of 10 feet+ in the turbid water. The original thought was that the dome unit would be installed by a diver that would have visual confirmation as to how the dome was contacting the sediment. However, a diver was not available at the time. There was sufficient flex in the vent pipe as well as movement in the boat leaving doubt as to whether the cylinder was properly sealed to the bed sediment. Although a suction pull was felt when attempting retrieval, which could serve as an indication that the dome was probably sealed to the bed sediment. There was also flex in the dome itself because the stainless steel is thin and not very rigid. Where this wasn't a problem in the shallow installations it proved to be problematic in the deeper sediments especially when relying on pushing down the vent pipe for installation. There was also potential for leaks at the seal between the cylinder and the dome, and the connections between the dome and vent pipes.

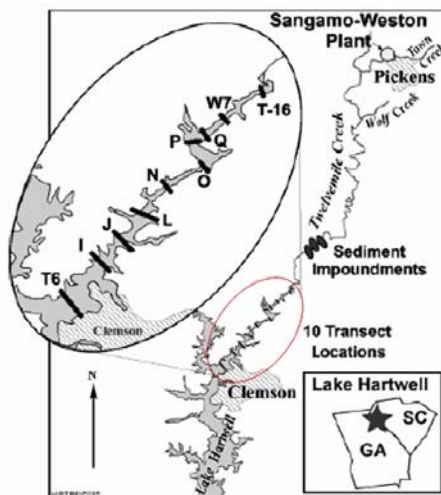


Figure 23. Lake Hartwell Transect locations.

The flux meter was first deployed at OB on May 3 in the early afternoon. Flow sensor SN151 was used; calibration curves shown on Figure 8 & 11 were applied to the data analysis. A few measurements were made to insure the unit was functional; the data suggested groundwater recharge and the flux value ranged from 5.73 – 8.93 (median = 7.09) cm/day based on peak temperature arrival and 0.97 – 9.39 (median = 7.68) cm/day based on the method of moment. Measurements were continued at the same location in the morning of May 4. The temporal flux values averaged from the two channels are presented in Figure 24 and Figure 25; results were based on the peak temperature arrival and the method of moment, respectively. The flux meter was then re-deployed at NB in the afternoon of May 4. During the deployments, there were boat activities near both locations, especially quite frequent at NB, which were causing a lot of wave action and disturbance to the water body during measurements. The unit as deployed only performs adequately when the surface water is reasonably still. Some of the data appears to have evidence of periodic flow in both directions (see Appendix F). It is believed that this is likely due to wave action. It was possible that when the vent pipe remained open during the measurements, hydraulic head could be fluctuated by sufficient lake seiche and/or wave action, and alternated the flow direction making it impossible to interpret some of the data.

Reasonable results were obtained at OB (see Figure 24 and 25), suggesting groundwater recharge from surface water at the time of the measurements. Figure 24 and 25 were plotted on the same scale so the results can be visually compared. The temporal variation of flux based on the peak temperature arrival appears to be smaller. The variations between the two channels were also smaller based on the peak temperature arrival. While the peak arrival analysis relies on one single peak temperature value, the method of moment requires the entire longer period of data. Therefore, it is reasonable that in an environment with noticeable wave action the method of moment could yield higher uncertainty. Figure 24 shows the range in temporal groundwater recharge was 2.68-9.48 cm/day with an average of 5.53 ± 2.44 cm/day. Figure 25 shows 11 out of 14 flux values were below 9 cm/day ranging 2.53-8.75 cm/day, with an average of 5.22 ± 1.68 cm/day when discounting the three high values. Although sensible interpretation of the data was impractical for NB due to poor data quality caused by the frequent boat activities, the thermographs did confirm that the reservoir was losing water. Note that calibrations shown on Figure 8 & 11 were employed for the data analysis. Positive flow, in this case, indicates groundwater recharge.

When the dome is first installed the flow system is disturbed. Measurements may not correctly reflect the near steady state flow in the system. This has been observed at each field location where measurements were made. Figure 24 & 25 both show higher temporal variation in the early measurements than the later ones. The data illustrates the concern expressed by (Shaw and Prepas 1989) regarding the impact of the installation of the flow meter on the actual flow through the sediment. The data suggests that the system required additional time to fully reach equilibrium. This demonstrates the importance of having either semi-permanent deployment or the ability of returning to the exact same spot as was done at Grand Calumet River in Hammond, Indiana. To reinstall for deeper depths a diver must be used.

The original design of the unit with the vent pipe open to the atmosphere is based on the assumption that the changes in head during the measurement will be small. But the data from Lake Hartwell suggested that much of the “noise” that was seen in the data is likely head fluctuation as a result of wave action. In future measurement this can likely be eliminated by using a closed dome that is periodically vented prior to measurement sequence to remove gas accumulation, but is closed during the measurement. Some of the standard addition or standard subtraction did not give the results anticipated. This would suggest a leak in the system, or it could simply be owing to the inherent nature of flow variation in a dynamic environment. There was no evidence that the flow meter was not functional once it was returned to the laboratory.

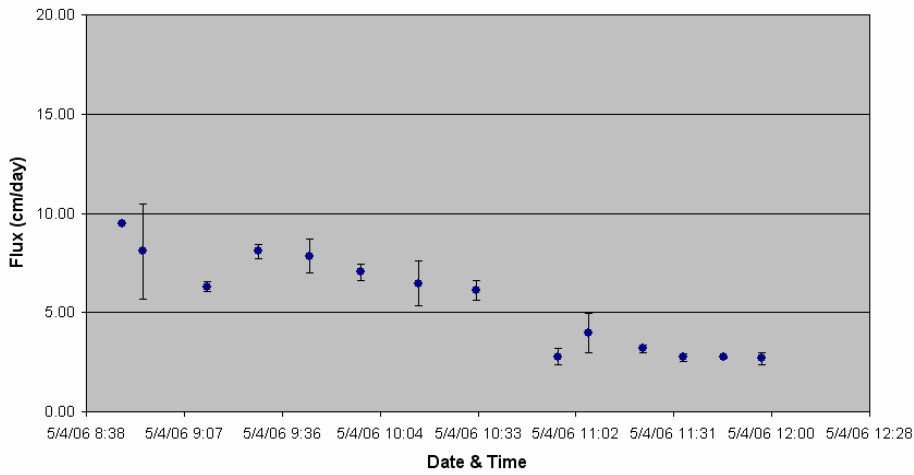


Figure 24. Temporal flux at location OB estimated based on peak temperature arrival. Note: positive flux value indicates groundwater recharge from surface water.

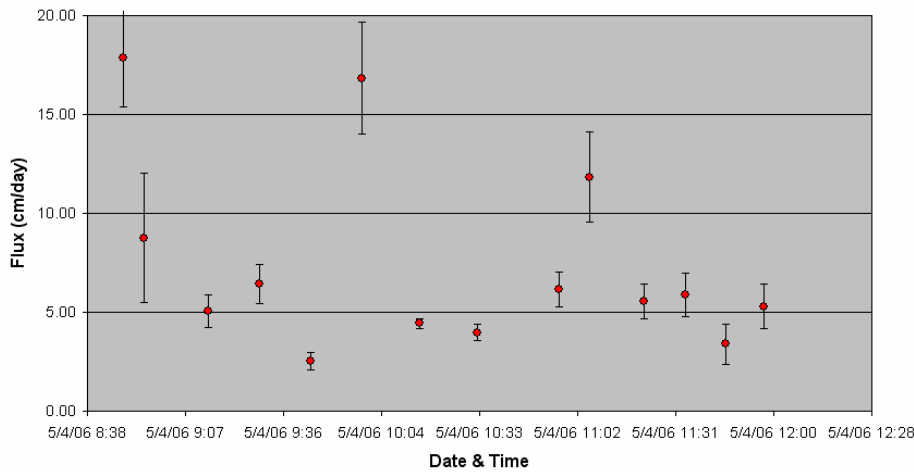


Figure 25. Temporal flux at location OB estimated based on normalized first moments. Note: positive flux value indicates groundwater recharge from surface water.

Lessons Learned and Ideas for Improvement

1. From the field deployment in Nicaragua we learned that it would be desirable to have a differential pressure transducer measuring the difference in pressure heads in order to correct for the Bernoulli Effects. This will be most important when installing the device where horizontal currents are significant.
2. It would be desirable to have a gauge pressure measurement that could monitor the hydraulic head at the site. This will be important where the river/stream stage is changing or there is wave action that could potentially change the flow.
3. We need to install a vent valve that can be opened or closed under program control. This should minimize some of the problems that were observed where the surface water was turbulent. This will be important whenever the head changes significantly during the measurement period.
4. When installing the dome at deeper locations it would be preferable to utilize a diver. If this is not practical then an underwater video camera should be used to monitor the installation process. The vent pipe needs to be made out of a heavy gauge metal to reduce flex during installation. This is particularly important if the installation is going to be from the surface rather than by a diver. Currently there is also too much flex in the dome. It is recommended that the dome be constructed out of a more robust material.
5. The location of the flow sensor also needs to be considered as well as its orientation. If the dome is installed from the surface, there is concern that suspended sediment might be pushed up and accumulated in the flow sensor creating errors in the measurements or creating a potential pressure drop across the device leading to measurement errors. It should be considered to first install the dome and flush the dome before installing the flow sensor.
6. Multi-elevation piezometer data will be needed if calculating the hydraulic conductivity of the bed sediment is advantageous. For evaluating the impacts of capping this will be beneficial. It would also be desirable to measure the vector of the potential gradient. The flow meter only measures the flow normal to the plane of the collection cylinder.
7. There is electronic noise that is being picked up due to the very low level signals being transmitted. It is believed that these signals should be converted to a frequency output at the signal source so that attenuation and cross talk is minimized.
8. Temporal data either returning to the same location or leaving the unit at the same location will permit learning about more long term changes. The data at the Hammond Indiana site illustrate a near continuous record. It is believed continuous monitoring will be required to identify and avoid unsound readings due to perturbations caused by the initial installation. Short term measurements should only be considered as qualitative rather than quantitative.

9. For long term monitoring, it would be desirable to transmit the signal from a buoy located at the water surface back to land where it could be re-transmitted to an office environment for continuous monitoring. This would require converting the system to one that could be operated from solar cell recharged batteries and a wireless network installation.
10. At the present time the unit does not allow for the collection of water samples. When studying water quality issues, it would be desirable to be able to collect representable samples discharging from the sediment. It would have problems properly sampling where the flow direction reverses frequently.

Conclusions

Significant advancements have been achieved in the development and demonstration of a bidirectional advective flux meter. We have successfully developed the device based on a heat-pulse technique and derived empirical relations between flow rate and heat-pulse travel time. Operational control and data analysis software were developed in Visual Basic 6.0. Both peak temperature arrival method and the method of first temporal moment were made available to provide multiple data analysis options. Each analysis approach has advantages depending on the environmental conditions when the measurements were made. Laboratory calibrations of both methods yield quality results with R^2 of 0.99 or better. The flux meter has undergone field tests at three different sites. The first test site was a shallow turbulent stream at Santo Domingo, Nicaragua; the large swings in hydrograph caused by the frequent rainfall events during the field deployment prevented us from obtaining reproducible data. The second test site was at Grand Calumet River, Hammond, IN, which is a slow moving river with fine sediments. And the final test site was at a large reservoir with deeper sediments at Lake Hartwell, SC. The last two field deployments were successful in that the flux meter was operational, reasonable characterization of flux were obtained, and bidirectional flow measurement capability was demonstrated. The field demonstration has provided insights on how improvements can be made. Nevertheless, under appropriate conditions the units, as currently configured, should provide continued long term data and analysis capabilities.

Acknowledgement

This work couldn't have been completed without the goodwill and efforts of Dr. Göran Bengtsson, University of Lund Sweden, Dr. Chad Jafvert, Purdue University and Dr. Marc Mills, U.S. EPA. They have been instrumental in providing the sites where the unit was tested and offering continued encouragement to the development and testing of the device. The author also likes to express his gratitude to the University of Cincinnati contract support for providing invaluable contribution and innovation to this project.

References

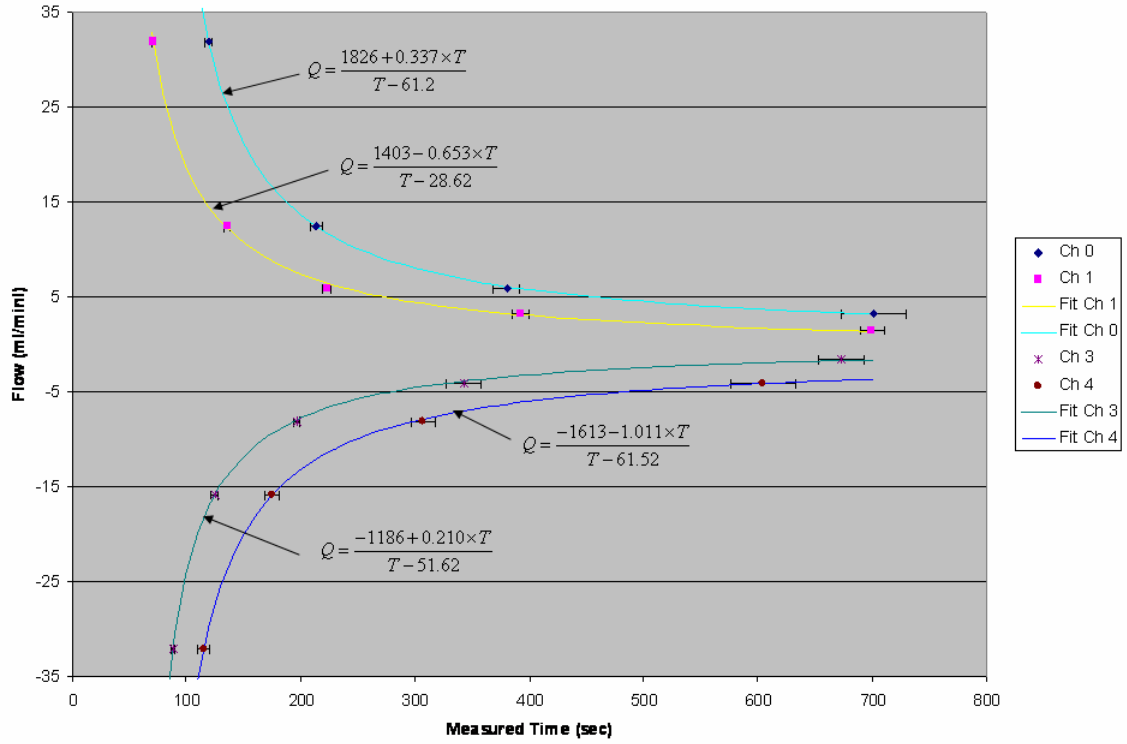
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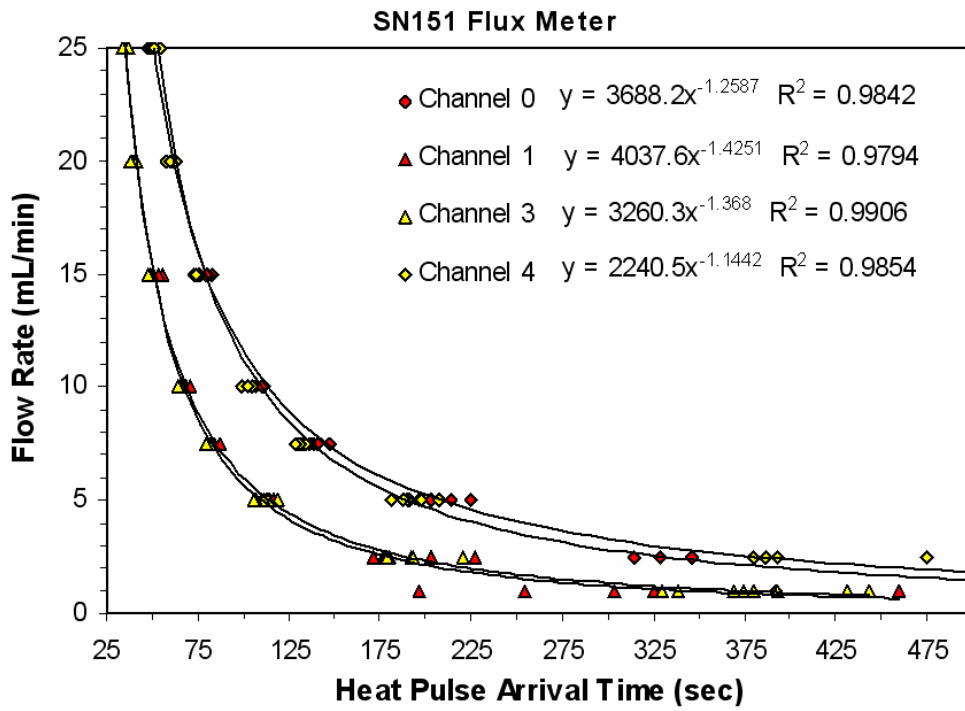
Appendix A Calibration Curve for SN152

Calibration for sensor # 152



Appendix B Calibration Curve for SN151

Heating cycle = 3 seconds



Appendix C Computer Code

Option Explicit

' Scans a range of A/D Input Channels, stores the data in an array
' and output the data to Ascii files.

'Averages signals collected to minimize noise by scanning the data _
before output to file

'send digital output to switch heater ON/OFF

'channel 0-1: flow temperature

'channel 2: heater temperature

'channel 3-4: flow temperature

'channel 5: reference junction temperature

'channel 6: Unique resistor used to determine serial number.

'channel 7: Internal Reserved for future use most likely a pressure transducer

' last revised 02/1/06 by Carl Enfield

Const BoardNum% = 1 ' Board number

Const PortNum% = AUXPORT ' use digital auxiliary port

Const Direction% = DIGITALOUT ' program digital auxiliary port for output

Const FirstPoint& = 0 ' set first element in buffer to transfer to array

Dim ADDData%() ' dimension an array to hold the input values

Dim addata1(5) ' array to hold initial thermocouple offset data

Dim addata2() 'dimension an array to transfer ADDData% to double precision numbers

Dim addata3(8)

Public baseline 'time used to collect temperature data prior to injecting heat

Public heater 'time in seconds heater is turned on

Public tail ' time in seconds experimental data is collected

Public pause ' time in seconds before next cycle of data collection allows heat to
dissipate

Dim counter%, rounds, RateCount

Dim DataValue% ' digital value to write to Auxport

Dim fname As String * 50

Dim fname2 As String * 50

Dim site As String * 64

Public LowChan% 'First channel to read

Dim MemHandle& ' define a variable to contain the handle for
' memory allocated by Windows through cbWinBufAlloc%()

Public HighChan% ' Last channel to be read

Dim i, k, j, N ' counter

Dim Options ' used as variable in the scan function call

Dim SampleTime, startpause

```

Dim PCCDAS1616AO, mytime
Dim finish, timepast, t, timezero
Dim sum(8)
Dim ULStat As Long          'universal library styatic return
Dim volrange
Dim SumAdata As Double
Dim SRate As Long          'Scan rate universal library function
Dim Data()
Dim A_Data As Double
Dim DomeDia
Dim SerialNo
Dim textline
Dim Resistor(), c10(), c20(), c30(), cv0(), c11(), c21(), _
    c31(), cv1(), c13(), c23(), c33(), cv3(), c14(), c24(), _
    c34(), cv4(), SerNo(), Tslope(), Tint()
Private Sub CmdClose_Click()
    Unload Me
End Sub

Private Sub cmdStart_Click()
    *****
    ' Turn off heater
    *****
    SRate = 10000
    DataValue% = 1
    'config. digital output port
    ULStat = cbDConfigPort(BoardNum%, PortNum%, Direction%)
    If ULStat <> 0 Then Stop

    'digital out
    ULStat = cbDOut(BoardNum%, PortNum%, DataValue%)
    If ULStat <> 0 Then Stop

    *****
    ' Determine serial number of flow sensor by measuring voltage on channel 6.
    ' Look up flow meter in data base and make sure it exists then display serial
    ' number on display
    *****
    ReDim ADData%(100)
    ReDim Data(100)
    MemHandle& = cbWinBufAlloc(100)
    If MemHandle& = 0 Then Stop

    Date = Now
    Time = Now

```

```

baseline = CDBl(txtBaseline.Text) ' time to collect baseline data (sec)
heater = CDBl(txtHeater.Text)     ' time for heater to be turned on (sec)
DomeDia = CDBl(txtDDia.Text)     ' Diameter of the Dome
voltrange = BIP10VOLTS           ' voltage range +- 10 VDC
site = CStr(txtSite.Text)        ' site description

ULStat = cbAInScan(BoardNum%, 6, 6, 100, SRate, voltrange, MemHandle&,
    Options)
If ULStat = 91 Then
    ULStat = cbErrHandling(DONTPRINT, DONTSTOP)
ElseIf ULStat <> 0 Then
    Stop
End If
' transfer values from Windows buffer to data array used by VBA
ULStat = cbWinBufToArray(MemHandle&, ADDData%(1), FirstPoint&, 100)
ULStat = cbWinBufFree(MemHandle&) ' Free up memory for use by
If ULStat <> 0 Then Stop          ' other programs

SumAdata = 0
For j = 1 To 100
    ULStat = cbToEngUnits(BoardNum%, voltrange, ADDData%(j), Data(j))
    SumAdata = SumAdata + Data(j)
Next j
A_Data = SumAdata / (100# * 0.0001) 'assumes a current source of 100 uA is used to
    evaluate resistor
'write baseline, heat-pulse duration, Resistance, and Site description
fname = "c:\temp\" + Format$(Date, "mmm dd ") + Format$(Time, "hh mm ss") +
    ".dat"
Open fname For Output As #1
Write #1, Format(Now), Format(baseline, "#0.0"), _
    Format(heater, "#0.0"), Format(A_Data, "#0.0000"), _
    Format(DomeDia, "#0.0000"), Format(site)

Close
*****
' Look up calibration data and display sensor serial number
*****
ChDir ("C:\Program Files\Flux_Meter_CGE")
Open "Calibration_Data.csv" For Input As #4
N = 0
Do While Not EOF(4)
Line Input #4, textline
N = N + 1 ' n is the number of records or values
Loop
Close #4

```

'MsgBox (n)

'Allocate space to hold arrays place calibration data into arrays

ReDim Resistor(N), c10(N), c20(N), c30(N), cv0(N), c11(N), c21(N), _
c31(N), cv1(N), c13(N), c23(N), c33(N), cv3(N), c14(N), c24(N), _
c34(N), cv4(N), SerNo(N), Tslope(N), Tint(N)

ReDim Resistor(N), con0(N), exp0(N), con1(N), exp1(N), con3(N), exp3(N), con4(N),
exp4(N), SerNo(N)

Open "Calibration_Data.csv" For Input As #5

N = 0

Do While Not EOF(5)

Input #5, Resistor(N), c10(N), c20(N), c30(N), cv0(N), c11(N), c21(N), _
c31(N), cv1(N), c13(N), c23(N), c33(N), cv3(N), c14(N), c24(N), _
c34(N), cv4(N), SerNo(N), Tslope(N), Tint(N)

N = N + 1

Loop

Close #5

' Find serial Number assumption value can be detected +-2% +-3 ohms

For j = 2 To N - 1

If A_Data > (Resistor(j) * 0.98 - 3) And _
A_Data < (Resistor(j) * 1.02 + 3) Then GoTo 100

Next j

If j = N Then SerNo(j - 1) = "default" ' Serial number not detected

j = j - 1

100 lblSerNo.Caption = SerNo(j)

MemHandle& = cbWinBufAlloc(100) ' begin scan for cahnnel 0

For i = 1 To 5

ULStat = cbAInScan(BoardNum%, i - 1, i - 1, 100, SRate, volrange, MemHandle&,
Options)

If ULStat = 91 Then

ULStat = cbErrHandling(DONTPRINT, DONTSTOP)

ElseIf ULStat <> 0 Then

Stop

End If

' transfer values from Windows buffer to data array used by VBA

ULStat = cbWinBufToArray(MemHandle&, ADDData%(1), FirstPoint&, 100)

SumAdata = 0

For j = 1 To 100

ULStat = cbToEngUnits(BoardNum%, volrange, ADDData%(j), Data(j))

```

    SumAdata = SumAdata + Data(j)
  Next j
  adddata1(i) = SumAdata / (100#)
Next i

ULStat = cbWinBufFree(MemHandle&) ' Free up memory for use by
If ULStat <> 0 Then Stop          ' other programs

*****
' Initialize settings required to scan thermocouples
' Channels 0 through 5 are scanned. All range settings are set the same. Each channel
' is measured 100 times using the cbAInScan function.
*****

MemHandle& = cbWinBufAlloc(100)
  If MemHandle& = 0 Then Stop

ReDim ADDData%(100)

  tail = Cdbl(txtTail.Text)      ' time to collect data avter heater is turned off (sec)
  pause = Cdbl(txtPause.Text)    ' wait time before next sampling round (sec)
  S_rate = Cdbl(txtRate.Text)    ' sampling rate (samples/sec)
  rounds = Cdbl(txtRounds.Text)  ' Number of data sets to collect
  counter% = 0                    'sampling round counter
  SampleTime = baseline + heater + tail 'total sampling time
  volrange = BIP1VOLTS           ' voltage range +- 1 VDC
  Do While PCCDAS1616AO <> -1     'main loop

    Date = Now
    Time = Now
    counter% = counter% + 1
    Label12.Caption = counter%

    timezero = Timer

    t = 0
    k = 0

11  Do While t < SampleTime - 1
    'calculate accmulated time
    If Timer < timezero Then 'if cross midnight
      t = 86400 - timezero + Timer
    Else
      t = Timer - timezero
    End If

```

```

'control when to activate analog output
  If t <= baseline Then DataValue% = 1: txtBaseline.BackColor = &HFF00&
  If t > baseline Then txtBaseline.BackColor = &HFFFFFF
  If (t > baseline And t <= (baseline + heater)) Then DataValue% = 0:
    txtBaseline.BackColor = &HFFFFFF: txtHeater.BackColor = &HFF00&
  If t > (baseline + heater) Then DataValue% = 1: txtHeater.BackColor = &HFFFFFF:
    txtTail.BackColor = &HFF00&
'digital out
ULStat = cbDOut(BoardNum%, PortNum%, DataValue%)
If ULStat <> 0 Then Stop
MemHandle& = cbWinBufAlloc(100) ' begin scan for cahnnel 0
For i = 1 To 6
  ULStat = cbAInScan(BoardNum%, i - 1, i - 1, 100, SRate, voltrange, MemHandle&,
    Options)
  If ULStat = 91 Then
    ULStat = cbErrHandling(DONTPRINT, DONTSTOP)
  ElseIf ULStat <> 0 Then
    Stop
  End If
' transfer values from Windows buffer to data array used by VBA
  ULStat = cbWinBufToArray(MemHandle&, ADDData%(1), FirstPoint&, 100)
  SumAdata = 0
  For j = 1 To 100
    ULStat = cbToEngUnits(BoardNum%, voltrange, ADDData%(j), Data(j))
    SumAdata = SumAdata + Data(j)
  Next j
  adddata3(i) = SumAdata / (100#)
Next i

  ULStat = cbWinBufFree(MemHandle&) ' Free up memory for use by
  If ULStat <> 0 Then Stop ' other programs
,

Open fname For Append As #1
'write data in voltage
  Write #1, Format(Now), Format(t, "#0.00000"), _
    Format(adata3(1), "#0.00000"), Format(adata3(2), "#0.00000"), _
    Format(adata3(3), "#0.00000"), Format(adata3(4), "#0.00000"), _
    Format(adata3(5), "#0.00000"), Format(adata3(6), "#0.00000"), _
    Format(adata3(7), "#0.00000"), Format(adata3(8), "#0.00000")
Close

'display data in voltage
For i = 1 To 5
  lblADDData(i).Caption = Format((adata3(i) - adata1(i)) * 10, "#0.000")
Next i
  lblADDData(6).Caption = Format(adata3(6) * 100, "#0.00")

```

```

lblADData(9).Caption = Now 'display time

Refresh

DoEvents
If PCCDAS1616AO = -1 Then GoTo 44
Loop '11

48 Close #1

txtTail.BackColor = &HFFFFFF
startpause = Timer ' Set start time.
t = 0
txtPause.BackColor = &HFF00&

14 Do While t < pause

    If Timer < startpause Then 'if cross midnight
        t = 86400 - startpause + Timer
    Else
        t = Timer - startpause
    End If
    DoEvents ' Yield to other processes
    If PCCDAS1616AO = -1 Then GoTo 44
    Loop '14

txtPause.BackColor = &HFFFFFF
' lblADData(8).BackColor = &HFFFFFF

If counter% = rounds Then PCCDAS1616AO = -1
If (counter% < rounds) Then

    fname = "c:\temp\" + Format$(Date, "mmm dd ") + Format$(Time, "hh mm ss") +
        ".dat"
    Open fname For Output As #1
        Write #1, Format(Now), Format(baseline, "#0.0"), _
            Format(heater, "#0.0"), Format(A_Data, "#0.0000"), _
            Format(DomeDia, "#0.0000"), Format(site)

    Close
End If
Loop 'main

'PCCDAS1616AO = 0 'continue
44 txtBaseline.BackColor = &HFFFFFF
txtHeater.BackColor = &HFFFFFF

```



```

txtTail.BackColor = &HFFFFFF
txtPause.BackColor = &HFFFFFF
cmdStart.Enabled = -1
PCCDAS1616AO = 0
GoTo 45

45 End Sub

Private Sub CmdStop_Click()
    PCCDAS1616AO = -1
End Sub

Private Sub cmdStopConvert_Click()

    ULStat = cbWinBufFree(MemHandle&) ' Free up memory for use by
                                ' other programs
' If ULStat <> 0 Then Stop

    End

End Sub

Private Sub Form_Load()

' declare revision level of Universal Library

    ULStat = cbDeclareRevision(CURRENTREVNUM)

' Initiate error handling
' activating error handling will trap errors like
' bad channel numbers and non-configured conditions.

' Parameters:
' PRINTALL :all warnings and errors encountered will be printed
' DONTSTOP :if an error is encountered, the program will not stop,
'           errors must be handled locally

    ULStat = cbErrHandling(PRINTALL, DONTSTOP)
    If ULStat <> 0 Then Stop

' If cbErrHandling% is set for STOPALL or STOPFATAL during the program
' design stage, Visual Basic will be unloaded when an error is encountered.
' We suggest trapping errors locally until the program is ready for compiling
' to avoid losing unsaved data during program design. This can be done by
' setting cbErrHandling options as above and checking the value of ULStat%

```

' after a call to the library. If it is not equal to 0, an error has occurred.

End Sub

Private Sub Initialize_Click()

DataValue% = 0

'config. digital output port

ULStat = cbDConfigPort(BoardNum%, PortNum%, Direction%)

If ULStat <> 0 Then Stop

'digital out

ULStat = cbDOut(BoardNum%, PortNum%, DataValue%)

If ULStat <> 0 Then Stop

End Sub

```

'last revised 02/1/06 by Carl Enfield
Option Explicit
Private Sub CmdClose_Click()
    Unload Me
End Sub

Private Sub Dir1_Change()
    File1.Path = Dir1
End Sub

Private Sub Form_Load()
    Dir1.Path = "c:\temp"
    File1.Path = Dir1
End Sub

Private Sub Command1_Click() ' List1

    Screen.MousePointer = 11
    Dim textline
    Dim time0() As String
    Dim time1 As String 'used to store time file created needed to determine age of file and
        be compatible with older data

    Dim ch() 'dynamic array to hold analog data stored on .dat file
    Dim t() 'dynamic array to hold elapsed time data
    Dim ct As Integer ' , pt_odd, pt_half As Integer
    Dim tmax(6) As Double
    Dim tempmax(6)
    Dim bline
    Dim heater
    Dim N, j, i, l, m, g, k, z, ii, N1 As Integer
    Dim CalResistor
    Dim Resistor()
    Dim DomeDia
    Dim site As String * 64
    Dim Q0, Q1, Q3, Q4, Q0min, Q1min, Q3min, Q4min, Q0max, Q1max, Q3max,
        Q4max
    Dim V0, V1, V3, V4
    Dim dat_type As Boolean
    ChDir Dir1
    *****
' Initialize all of the calculated outputs other than peak arrival time to "N.A."
' to make sure only recomputed values are displayed if this isn't done
' it is possible to display a value from a previous data set
    *****
    lblMom1.Caption = Format("N.A.")

```

```

    lblMom2.Caption = Format("N.A.")
    lblMom4.Caption = Format("N.A.")
    lblMom5.Caption = Format("N.A.")
Q0 = "N.A."
Q0min = "N.A."
Q0max = "N.A."
lblQ0.Caption = Format(Q0)
lblQ0min.Caption = Format(Q0min)
lblQ0max.Caption = Format(Q0max)
Q1 = "N.A."
Q1min = "N.A."
Q1max = "N.A."
lblQ1.Caption = Format(Q1)
lblQ1min.Caption = Format(Q1min)
lblQ1max.Caption = Format(Q1max)
Q3 = "N.A."
Q3min = "N.A."
Q3max = "N.A."
lblQ3.Caption = Format(Q3)
lblQ3min.Caption = Format(Q3min)
lblQ3max.Caption = Format(Q3max)
Q4 = "N.A."
Q4min = "N.A."
Q4max = "N.A."
lblQ4.Caption = Format(Q4)
lblQ4min.Caption = Format(Q4min)
lblQ4max.Caption = Format(Q4max)
V0 = "N.A."
V1 = "N.A."
V3 = "N.A."
V4 = "N.A."
lblV0.Caption = Format(V0)
lblV1.Caption = Format(V1)
lblV3.Caption = Format(V3)
lblV4.Caption = Format(V4)

*****
' Import calibration data
*****

ChDir ("C:\Program Files\Flux_Meter_CGE\")

Open "Calibration_Data.csv" For Input As #6
*****
' determine the number of calibration curves in the data table
*****

```

```

l = 0
Do While Not EOF(6)
Line Input #6, textline
l = l + 1 'l is the number of calibration curves
Loop
Close #6

'*****
'Allocate space to hold arrays place calibration data into arrays
'*****

ReDim Resistor(l), c10(l), c20(l), c30(l), cv0(l), c11(l), c21(l), _
    c31(l), cv1(l), c13(l), c23(l), c33(l), cv3(l), c14(l), c24(l), _
    c34(l), cv4(l), SerNo(l), Tslope(l), Tint(l)
Open "Calibration_Data.csv" For Input As #7
'*****
' Import calibration data
'*****
l = 1
Do While Not EOF(7)
Input #7, Resistor(l), c10(l), c20(l), c30(l), cv0(l), c11(l), c21(l), _
    c31(l), cv1(l), c13(l), c23(l), c33(l), cv3(l), c14(l), c24(l), _
    c34(l), cv4(l), SerNo(l), Tslope(l), Tint(l)
l = l + 1
Loop
' MsgBox (l)
Close #7
ChDir Dir1

'*****
'Determine the number of records in the data file
'*****

Open File1 For Input As #1
N1 = 0
N = 0
Do While Not EOF(1)
Line Input #1, textline
N = N + 1 'n is the number of records or values
N1 = N1 + 1 'N1 is the number of records or values do not reset this counter
Loop

Close #1
If (N1 - 20 < 0) Then
MsgBox "Not enough data points. Please check file."
' MsgBox (t(j))

```

```

'   MsgBox (bline)
      GoTo 44
End If
*****
'Allocate space to hold arrays
*****
j = 8

ReDim time0(N + 1) As String '+1?
ReDim t(N)
ReDim ch(j, N)
*****
' find data collection date older data did not have a header file with information
' on time of the base line or time heater was on
*****

Open File1 For Input As #3
Input #3, time1, bline, heater, CalResistor, DomeDia, site
Close #3

' before 4/26/04 there was no header line on the data file. From4/26/04 to 8/4/05
' there was a header with three values the time the measurement was initiated,
' the time the base line data was collected, and the time the heater was turned on.
' After 8/4/05 three additional parameters were added the estimate of the resistor
' included in the to select the calibration curve, the diameter of the dome, and
' a field to identify the purpose of the data collection.
If (Year(time1) < 2004) Then GoTo 3
  If (Year(time1) = 2004 And Month(time1) < 4) Then GoTo 3
  If (Year(time1) = 2004 And Month(time1) = 4 And Day(time1) <= 25) Then GoTo
    3 'pre header file
'   If (Year(time1) < 2005) Then GoTo 4
'   If Year(time1) = 2005 And Month(time1) < 8 Then GoTo 4
' If (Year(time1) = 2005 And Month(time1) = 8 And Day(time1) <= 4) Then GoTo 4
'   If (Year(time1) = 2005 And Month(time1) = 8 And Day(time1) <= 4) Then GoTo 4
  If (IsDate(CalResistor) = True) Then GoTo 4
GoTo 5
3 Open File1 For Input As #2 ' place data in arrays
  j = 0
  N = 0
  bline = 0
  heater = 0
  Do While Not EOF(2)
  j = j + 1
  N = N + 1
  Input #2, time0(j), t(j), ch(1, j), ch(2, j), ch(3, j), ch(4, j), ch(5, j), ch(6, j), ch(7, j), ch(8,
    j)

```

```

Loop
  Close #2
  lblSiteD.Caption = "No Data" 'No Data available
  lblSerNo.Caption = "Not Assigned" 'Before Serial numbers
  GoTo 14
4 Open File1 For Input As #4
  ' MsgBox ("branch 4")
  j = 0
  N = 0
  Do While Not EOF(4)
    If j = 0 Then
      Input #4, time0(j), bline, heater
    End If
    j = j + 1
    N = N + 1
    Input #4, time0(j), t(j), ch(1, j), ch(2, j), ch(3, j), ch(4, j), ch(5, j), ch(6, j), ch(7, j), ch(8,
      j)
  Loop
  Close #4
  lblSiteD.Caption = "No Data" 'No Data available
  lblSerNo.Caption = "Default" 'Serial Number data not stored in file default used
  GoTo 14
5 Open File1 For Input As #5
  j = 0
  N = 0
  Do While Not EOF(5)
    If j = 0 Then
      Input #5, time0(j), bline, heater, CalResistor, DomeDia, site
      'MsgBox (bline)
      'MsgBox (heater)
      'MsgBox (CalResistor)
    End If
    j = j + 1
    N = N + 1
    Input #5, time0(j), t(j), ch(1, j), ch(2, j), ch(3, j), ch(4, j), ch(5, j), ch(6, j), ch(7, j), ch(8,
      j)
  Loop
  Close #5
  lblSiteD.Caption = site

13 j = j - 1
  '*****
  ' Find serial Number assumption value can be detected +-2% +-3 ohms
  '*****
  For i = 2 To 1 - 1
    If CalResistor - (Resistor(i) * 0.98 - 3) > 0 And _

```

```

        CalResistor - (Resistor(i) * 1.02 + 3) < 0 Then GoTo 100
    Next i
    If i = 1 Then SerNo(i - 1) = "default" ' Serial number not detected
    i = i - 1
100    lblSerNo.Caption = SerNo(i)
    ii = i ' ii is used as the record number of the for the calibration data
    MsgBox (ii)
*****
' Determine if sufficient data for possible analysis
*****
14  If (t(j) - bline < 0) Then
    MsgBox "Not enough data points. Please check file."
'    MsgBox (t(j))
'    MsgBox (bline)
    GoTo 44

    End If

*****
' Analyze base line data and determine slope and intercept analysis based on baseline
' data and last 30 observations. These values are averaged to calculate the slope and
' intercept assuming a streight line is appropriate. There should probably be a data
' string length of at least 3 times the peak arival point.
*****
    Dim sumx(6)
    Dim sumy(6)
    Dim sumx1(6)
    Dim sumy1(6)
    Dim avgx(6)
    Dim avgy(6)
    Dim Slope(6)
    Dim sInt(6)
    Dim avgx1(6)
    Dim avgy1(6)

    'calculate sums used to calculate baseline averages, slopes, and intercepts
    For j = 1 To 6
    sumx(j) = 0
    sumy(j) = 0
    sumx1(j) = 0
    sumy1(j) = 0
    Next j
'    MsgBox (bline)
    ct = 1 'counter
    Do 'While t(ct) < bline

```



```

' MsgBox ((t(ct) - bline))
  For j = 1 To 6
    sumx(j) = sumx(j) + t(ct)
    sumy(j) = sumy(j) + ch(j, ct)
  Next j
  ct = ct + 1
  Loop Until (t(ct) - bline) > 0

  For j = 1 To 6
    avgx(j) = sumx(j) / (ct - 1)
    avgy(j) = sumy(j) / (ct - 1)
  Next j

*****
' Determine average voltage for end of curve
*****

  ct = N1 - 30
  Do ' last 30 values
    For j = 1 To 6
      sumx1(j) = sumx1(j) + t(ct)
      sumy1(j) = sumy1(j) + ch(j, ct)
    Next j
    ct = ct + 1
    Loop Until (ct - N1) = 0
    For j = 1 To 6
      avgx1(j) = sumx1(j) / 30
      avgy1(j) = sumy1(j) / 30
    Next j
    ct = 1 'counter
  *****

' Calculate Slopes and Intercepts
*****

  For j = 1 To 6
    Slope(j) = (avgy(j) - avgy1(j)) / (avgx(j) - avgx1(j))
    sInt(j) = avgy(j) - (Slope(j) * avgx(j))
  Next j
' MsgBox (Slope(6))
' MsgBox (sInt(6))
  lblTemp.Caption = Format(avgy(6) * 100, "#0.0")
  LblBLSlope.Caption = Format(Slope(6) * 36000, "0.0E-00")
  LblBLInt.Caption = Format(sInt(6), "#0.000")
' MsgBox (Check1)
If Check1 = 0 Then 'For drift correction
*****

```

```

'subtract baseline and keep variable name This routine is to compensate for drift in the
      base
' line. To be used the sampling time should be atleast two times the first monemt of the
      effluent
' transducer. Change the fort color is insufficient data to use.
*****
  For i = 0 To N
  For j = 1 To 5
  ch(j, i) = ch(j, i) - avgy(j)
' If i = 1 And j = 1 Then
'   MsgBox (ch(j, i))
' End If
  Next j
  Next i
Else
'   MsgBox ("Temp Cor")
'   MsgBox (ch(6, 1))
  For i = 1 To N
  For j = 1 To 5
  ch(j, i) = ch(j, i) - (Slope(j) * t(i) + sInt(j))
  Next j
  Next i
'   MsgBox (ch(6, 1))
'   MsgBox (sInt(6))
End If

*****
' find time at maximum signal
' the time is calculated as max time - base line time - (pulse time/2)
' This will be one of the metrics evaluated to determine travel time
*****
Dim jmax(6) As Integer 'sample number at max temperature

  For i = 1 To 6
    tempmax(i) = ch(i, 1)
    tmax(i) = t(1)
  Next i
  For i = 1 To 6
  For j = 2 To N
  If (ch(i, j) - tempmax(i) > 0) Then
    tempmax(i) = ch(i, j)
    tmax(i) = t(j)
    jmax(i) = j
  End If
  Next j
  Next i

```

```

    lbltmax1.Caption = Format(tmax(1) - bline, "#0.0")
    lbltmax2.Caption = Format(tmax(2) - bline, "#0.0")
    lbltmax4.Caption = Format(tmax(4) - bline, "#0.0")
    lbltmax5.Caption = Format(tmax(5) - bline, "#0.0")
*****
'Begin Moment analysis - Data will be extrapolated based on a lograthmetic
' function based on a sum of squares fit to the data between 80% of tempmax
' and next occurance of <= 0.002 VDC or the end of file which ever comes first
' first determine sample number correlated to 80%of tempmax to perform moment
  analysis
' there should be only one peak and it should occure in the first 40% of the data set
' if peak temperature occures after the 40% of the data points do not make moment
  analysis
*****
Dim jbegin(5) As Integer 'jbegin is the sample number for the first sample to use in
  generating fit
Dim jend(5) As Integer 'jend is the last sample to use
  If ((0.4 * N1) - jmax(1) < 0) And ((0.4 * N1) - jmax(2) < 0) And ((0.4 * N1) -
    jmax(3) < 0) _
    And ((0.4 * N1) - jmax(4) < 0) And ((0.4 * N1) - jmax(5) < 0) Then
'   MsgBox (j)
'   MsgBox (N1)
'   MsgBox ((0.4 * N1) - j)
    lblMom1.Caption = Format("N.A.")
    lblMom2.Caption = Format("N.A.")
    lblMom4.Caption = Format("N.A.")
    lblMom5.Caption = Format("N.A.")
    GoTo 200
  End If
For i = 1 To 5
  j = jmax(i)

  Do Until ((tempmax(i) * 0.8) - ch(i, j) > 0) 'determine sample number for first sample
    ' to use in enterpolating and extrapolating
    ' moments 80% of peak was qualitatively
    ' estimated as being sufficient to be away
    ' from the curvature at the peek

    j = j + 1
    If (j - N = 0) Then
      jbegin(i) = j
      jend(i) = j
      GoTo 90
    End If
'   jend(i) = jend(i) + 1
Loop

```

```

    jbegin(i) = j
    j = j + 1
    If j >= N1 Then GoTo 89
Do Until (0.002 - ch(i, j) > 0) 'determine last sample number considered valid for
    'interpolating or extrapolating moments noise was measured
    'at +- 2 mv. data has already been adjusted for baseline
    'offset

    j = j + 1
    If j >= N1 Then GoTo 89
Loop
89  jend(i) = j
90  Next i
'MsgBox (t(jmax(1)))
'MsgBox (jbegin(1))
'MsgBox (jend(1))
*****
' Fit log transformed data to a streight line first determine if there is enough data
' there should be a minimum of minobs observations to calculate the extrapolation
  function
*****
Dim sumxx(5)
Dim sumyy(5)
Dim sumxy(5)
Dim avgxx(5)
Dim avgyy(5)
Dim Mslope(5) As Double
Dim Mint(5) As Double
Dim minobs As Integer 'minimum number of observations between jbegin(i) and jend(i)
                        'to permit moment analysis 20 is considered minimm
Dim minsignal As Single 'minimum peak signal in volts for analysis
minobs = 20
minsignal = 0.001

For i = 1 To 5 'initialize values
    sumxx(i) = 0
    sumyy(i) = 0
    sumxy(i) = 0
    avgxx(i) = 0
    avgyy(i) = 0
    Mslope(i) = 0
    Mint(i) = 0
Next i
For i = 1 To 5
    If ((jend(i) - jbegin(i) - minobs) > 0) And (tempmax(i) - minsignal > 0) Then
        For j = jbegin(i) To jend(i) - 1

```

```

    avgxx(i) = avgxx(i) + t(j)
    If ch(i, j) < 0 Then ch(i, j) = 1E-50
    avgyy(i) = avgyy(i) + Log(ch(i, j))
Next j
avgxx(i) = avgxx(i) / (jend(i) - jbegin(i))
avgyy(i) = avgyy(i) / (jend(i) - jbegin(i))
Else
End If
Next i
For i = 1 To 5
    If ((jend(i) - jbegin(i) - minobs) > 0) And (tempmax(i) - minsignal > 0) Then
        For j = jbegin(i) To jend(i) - 1
            If ch(i, j) < 0 Then ch(i, j) = 1E-50
            sumxx(i) = sumxx(i) + (t(j) - avgxx(i)) ^ 2
            sumyy(i) = sumyy(i) + (Log(ch(i, j)) - avgyy(i)) ^ 2
            sumxy(i) = sumxy(i) + (t(j) - avgxx(i)) * (Log(ch(i, j)) - avgyy(i))
        Next j
        Mslope(i) = sumxy(i) / sumxx(i)
        Mint(i) = avgyy(i) - (Mslope(i) * avgxx(i))
    Else
    End If
Next i
*****
'Calculate zero and first moments
*****
Dim Momzero(5)
Dim Mom1(5)
Dim c1, c2
Dim T1, T2
Dim timecor 'time correction such that zero time is at the end of base line measurements
Dim jstart 'sample number to begin moment calculations this is to remove switching
           noise
timecor = bline
For i = 1 To 5
    If ((jend(i) - jbegin(i) - minobs) < 0) Or (tempmax(i) - minsignal < 0 Or Mslope(i) > 0)
        Then
            Mom1(i) = "N.A."
        ' GoTo 300
    Else
        Momzero(i) = 0
        Mom1(i) = 0
        ch(i, 0) = 0
        t(0) = 0
    *****
    ' Start moment analysis beginning with sample after heat-pulse
    ' Correct time scale to begin half way through the heat-pulse in moment calculations

```

```

' First step is to determine sample number after end of heat-pulse
'*****
  j = 1
Do Until (t(j) - bline - heater) > 0
  j = j + 1
Loop
  jstart = j - 1
  For j = jstart To jbegin(i)      'first part of curve
    Momzero(i) = Momzero(i) + ((t(j) - t(j - 1)) * (ch(i, j) + ch(i, j - 1))) / 2
    Mom1(i) = Mom1(i) + (1 / 6) * ((ch(i, j - 1) * (t(j - 1) - timecor) + ch(i, j) * _
      (t(j) - timecor)) * (t(j) - t(j - 1)) + (ch(i, j - 1) _
      + ch(i, j)) * ((t(j) - timecor) * (t(j) - timecor) - (t(j - 1) - timecor) * _
      (t(j - 1) - timecor)))
  Next j
' MsgBox (i)
' MsgBox (Momzero(i))
' MsgBox (Mom1(i))
' MsgBox (ch(i, j))
' MsgBox (Mslope(i))
' MsgBox (Mint(i))
  'end of first part of curve begin analysis for the curve fit portion of the curve
  c1 = ch(i, j)
  T1 = t(j)
  j = 1
Do Until (c1 - 0.001 * tempmax(i) < 0)
  T2 = T1 + 1
  c2 = Exp(Mslope(i) * (T2) + Mint(i))
  Momzero(i) = Momzero(i) + (c1 + c2) / 2
  Mom1(i) = Mom1(i) + (1 / 6) * ((c1 * (T1 - timecor) + c2 * (T2 - timecor)) * _
    (T2 - T1) + _
    (c1 + c2) * ((T2 - timecor) * (T2 - timecor) - (T1 - timecor) * (T1 - timecor)))
  T1 = T2
  c1 = c2
Loop
End If

300 Next i

'MsgBox (Mom1(1))

If ((jend(1) - jbegin(1)) > minobs) And (tempmax(1) - minsignal > 0 And
  IsNumeric(Mom1(1))) Then
  lblMom1.Caption = Format(Mom1(1) / Momzero(1), "#0.0")
Else
  lblMom1.Caption = Format("N.A.")
End If

```

```

If ((jend(2) - jbegin(2)) > minobs) And (Not Not tempmax(2) - minsignal > 0 And
    IsNumeric(Mom1(2))) Then
    lblMom2.Caption = Format(Mom1(2) / Momzero(2), "#0.0")
Else
    lblMom2.Caption = Format("N.A.")
End If
If ((jend(4) - jbegin(4)) > minobs) And (tempmax(4) - minsignal > 0 And
    IsNumeric(Mom1(4))) Then
    lblMom4.Caption = Format(Mom1(4) / Momzero(4), "#0.0")
Else
    lblMom4.Caption = Format("N.A.")
End If
If ((jend(5) - jbegin(5)) > minobs) And (tempmax(5) - minsignal > 0 And
    IsNumeric(Mom1(5))) Then
    lblMom5.Caption = Format(Mom1(5) / Momzero(5), "#0.0")
Else
    lblMom5.Caption = Format("N.A.")
End If

*****
' generate labels for flow
*****

Dim CL
CL = 2.326
' Channel 0 Captions
If ((jend(1) - jbegin(1)) > minobs) And (tempmax(1) - minsignal > 0) And _
    (tmax(1) - bline - 1.5 * heater > 0) And IsNumeric(Mom1(1))) Then
    Mom1(1) = (Mom1(1) / Momzero(1))
    Q0 = (c10(ii) - (c30(ii) * Mom1(1))) / (Mom1(1) + c20(ii))
    Q0min = (c10(ii) - (c30(ii) * Mom1(1) * (1 + CL * cv0(ii)))) / (Mom1(1) * (1 + CL
        * cv0(ii)) + c20(ii))
    Q0max = (c10(ii) - (c30(ii) * Mom1(1) * (1 - CL * cv0(ii)))) / (Mom1(1) * (1 - CL *
        cv0(ii)) + c20(ii))
'MsgBox (Mom1(1))
'MsgBox (c10(ii))
    lblQ0.Caption = Format(Q0, "#0.00")
    lblQ0max.Caption = Format(Q0max, "#0.00")
    lblQ0min.Caption = Format(Q0min, "#0.00")
Else
    Q0 = "N.A."
    Q0min = "N.A."
    Q0max = "N.A."
    lblQ0.Caption = Format(Q0)
    lblQ0min.Caption = Format(Q0min)
    lblQ0max.Caption = Format(Q0max)
End If

```

```

' Channel 1 Captions
If (jend(2) - jbegin(2) > minobs) And (tempmax(2) - minsignal > 0) And (tmax(2) -
    bline - 1.5 * heater > 0 _
    And IsNumeric(Mom1(2))) Then
    Mom1(2) = (Mom1(2) / Momzero(2))
    Q1 = (c11(ii) - c31(ii) * Mom1(2)) / (Mom1(2) + c21(ii))
    Q1min = (c11(ii) - c31(ii) * Mom1(2) * (1 + CL * cv1(ii))) / (Mom1(2) * (1 + CL *
        cv1(ii)) + c21(ii))
    Q1max = (c11(ii) - c31(ii) * Mom1(2) * (1 - CL * cv1(ii))) / (Mom1(2) * (1 -
        cv1(ii)) + CL * c21(ii))
    lblQ1.Caption = Format(Q1, "#0.000")
    lblQ1max.Caption = Format(Q1max, "#0.000")
    lblQ1min.Caption = Format(Q1min, "#0.0")
Else
    Q1 = "N.A."
    Q1min = "N.A."
    Q1max = "N.A."
    lblQ1.Caption = Format(Q1)
    lblQ1min.Caption = Format(Q1min)
    lblQ1max.Caption = Format(Q1max)
End If
' Channel 3 Captions
If (jend(4) - jbegin(4) > minobs) And (tempmax(4) - minsignal > 0) And _
    (tmax(4) - bline - 2 * heater > 0 And IsNumeric(Mom1(4))) Then
    Mom1(4) = (Mom1(4) / Momzero(4))
    Q3 = (c13(ii) - c33(ii) * Mom1(4)) / (Mom1(4) + c23(ii))
    Q3min = (c13(ii) - c33(ii) * Mom1(4) * (1 + CL * cv3(ii))) / (Mom1(4) * (1 + CL *
        cv3(ii)) + c23(ii))
    Q3max = (c13(ii) - c33(ii) * Mom1(4) * (1 - CL * cv3(ii))) / (Mom1(4) * (1 - CL *
        cv3(ii)) + c23(ii))
    MsgBox (c13(ii))
    MsgBox (c33(ii))
    MsgBox (c23(ii))
    lblQ3.Caption = Format(Q3, "#0.000")
    lblQ3max.Caption = Format(Q3max, "#0.000")
    lblQ3min.Caption = Format(Q3min, "#0.000")
Else
    Q3 = "N.A."
    Q3min = "N.A."
    Q3max = "N.A."
    lblQ3.Caption = Format(Q3)
    lblQ3min.Caption = Format(Q3min)
    lblQ3max.Caption = Format(Q3max)
End If
' Channel 4 Captions
If (jend(5) - jbegin(5) > minobs) And (tempmax(5) - minsignal > 0) And _

```



```

    (tmax(5) - bline - 1.5 * heater > 0 And IsNumeric(Mom1(5))) Then
Mom1(5) = (Mom1(5) / Momzero(5))
Q4 = (c14(ii) - c34(ii) * Mom1(5)) / (Mom1(5) + c24(ii))
Q4min = (c14(ii) - c34(ii) * Mom1(5) * (1 + CL * cv4(ii))) / (Mom1(5) * (1 + CL *
    cv4(ii)) + c24(ii))
Q4max = (c14(ii) - c34(ii) * Mom1(5) * (1 - CL * cv4(ii))) / (Mom1(5) * (1 - CL *
    cv4(ii)) + c24(ii))
'MsgBox (Q4)
lblQ4.Caption = Format(Q4, "#0.000")
lblQ4max.Caption = Format(Q4max, "#0.000")
lblQ4min.Caption = Format(Q4min, "#0.000")
Else
    Q4 = "N.A."
    Q4min = "N.A."
    Q4max = "N.A."
    lblQ4.Caption = Format(Q4)
    lblQ4min.Caption = Format(Q4min)
    lblQ4max.Caption = Format(Q4max)
End If
*****
' Generate Darcy velocity lables
*****
If DomeDia > 0.1 Then 'Data exists to calculate flux
    If Q0 <> "N.A." Then
        V0 = Q0 * 60 * 24 / (3.1415 * DomeDia * DomeDia / 4)
        lblV0.Caption = Format(V0, "#0.0")
    Else
        V0 = "N.A."
        lblV0.Caption = Format(V0)
    End If
    If Q1 <> "N.A." Then
        V1 = Q1 * 60 * 24 / (3.1415 * DomeDia * DomeDia / 4)
        lblV1.Caption = Format(V1, "#0.0")
    Else
        V1 = "N.A."
        lblV1.Caption = Format(V1)
    End If
    If Q3 <> "N.A." Then
        V3 = Q3 * 60 * 24 / (3.1415 * DomeDia * DomeDia / 4)
        lblV3.Caption = Format(V3, "#0.0")
    Else
        V3 = "N.A."
        lblV3.Caption = Format(V3)
    End If
    If Q4 <> "N.A." Then
        V4 = Q4 * 60 * 24 / (3.1415 * DomeDia * DomeDia / 4)

```

```

        lblV4.Caption = Format(V4, "#0.0")
    Else
        V4 = "N.A."
        lblV4.Caption = Format(V4)
    End If
Else
    V0 = "N.A."
    V1 = "N.A."
    V3 = "N.A."
    V4 = "N.A."
    lblV0.Caption = Format(V0)
    lblV1.Caption = Format(V1)
    lblV3.Caption = Format(V3)
    lblV4.Caption = Format(V4)
End If

```

```

*****

```

```

' set up arrays for plotting

```

```

*****

```

```

200 Dim Graph() As Single
    Dim x As Integer
    Dim myXarray() As Double
    Dim myYArray0() As Double
    Dim myYArray1() As Double
    Dim myYArray2() As Double
    Dim myYArray3() As Double
    Dim myYArray4() As Double
    Dim myYArray5() As Double
' Dim myXarray5(1) As Double
' Dim myYArray5(1) As Double
ReDim myXarray(N)
ReDim myYArray0(N)
ReDim myYArray1(N)
ReDim myYArray2(N)
ReDim myYArray3(N)
ReDim myYArray4(N)
ReDim myYArray5(N)

```

```

*****

```

```

'Generate some x y data.

```

```

*****

```

```

myXarray(0) = t(1) - bline
myYArray0(0) = ch(1, 1) * 10
myYArray1(0) = ch(2, 1) * 10

```

```

myYArray2(0) = ch(3, 1) * 10
myYArray3(0) = ch(4, 1) * 10
myYArray4(0) = ch(5, 1) * 10
myYArray5(0) = ch(6, 1) * 100
' myYArray5(0) = 0
' myYArray5(1) = 0.03
' myXarray5(0) = 0
' myXarray5(1) = heater

' MsgBox n
For x = 1 To N - 1

    myXarray(x) = t(x) - bline 'value for X-axis
    myYArray0(x) = ch(1, x) * 10 'value for Y-axis
    myYArray1(x) = ch(2, x) * 10
    myYArray2(x) = ch(3, x) * 10
    myYArray3(x) = ch(4, x) * 10
    myYArray4(x) = ch(5, x) * 10
    myYArray5(x) = ch(6, x) * 100

Next x

With TChart1
.AddSeries scPoint
.Series(0).AddArray UBound(myYArray0), myYArray0(), myXarray()
.Series(0).XValues.TempValue = True
.Series(1).AddArray UBound(myYArray1), myYArray1(), myXarray()
.Series(2).AddArray UBound(myYArray2), myYArray2(), myXarray()
.Series(3).AddArray UBound(myYArray3), myYArray3(), myXarray()
.Series(4).AddArray UBound(myYArray4), myYArray4(), myXarray()
.Series(5).AddArray UBound(myYArray5), myYArray5(), myXarray()
End With

Screen.MousePointer = 1
*****
' write output file with processed data
*****
ChDir Dir1
Dim fname2 ' file name for output data
fname2 = Format$(time1, "mmm dd hh nn ss") + ".a.CSV"
Open fname2 For Output As #8
Write #8, Format("baseline"), Format("heater"), Format("Ref Resistor"),
Format("Dome D"), Format("site")
Write #8, Format(bline, "#0.0"), _
Format(heater, "#0.0"), Format(CalResistor, "#0.0000"), _
Format(DomeDia, "#0.0000"), Format(site)

```

```

Write #8, Format("Peak arrival time in seconds")
Write #8, Format(tmax(1), "#0.0"), Format(tmax(2), "#0.0"), Format(tmax(3),
"#0.0"), _
Format(tmax(4), "#0.0"), Format(tmax(5), "#0.0")
Write #8, Format("Maximum differential temperature or reference temperature c")
Write #8, Format("Ch 0"), Format("Ch 1"), Format("Ch 2"), Format("Ch 3"),
Format("Ch 4"), _
Format("Ref Temp")
Write #8, Format(tempmax(1) * 10, "#0.0"), Format(tempmax(2) * 10, "#0.0"),
Format(tempmax(3) * 10, _
"#0.0"), Format(tempmax(4) * 10, "#0.0"), Format(tempmax(5) * 10, "#0.0"),
Format(avgy(6) * 100, "#0.0")
Write #8, Format("Normalized First Moments Calculated beginning at the end of the
base line samples")
If ((jend(1) - jbegin(1)) > minobs) And (tempmax(1) - minsignal > 0 And _
Mom1(1) <> 0 And IsNumeric(Mom1(1))) Then
Write #8, Format("Ch 0"), Format(Mom1(1), "#0.0")
Else
Write #8, Format("Ch 0"), Format("N.A.")
End If
If ((jend(2) - jbegin(2)) > minobs) And (tempmax(2) - minsignal > 0 And _
Mom1(2) <> 0 And IsNumeric(Mom1(2))) Then
Write #8, Format("Ch 1"), Format(Mom1(2), "#0.0")
Else
Write #8, Format("Ch 1"), Format("N.A.")
End If
If ((jend(3) - jbegin(3)) > minobs) And (tempmax(3) - minsignal > 0 And _
Mom1(3) <> 0 And IsNumeric(Mom1(2))) Then
Write #8, Format("Ch 2"), Format(Mom1(3), "#0.0")
Else
Write #8, Format("Ch 2"), Format("N.A.")
End If
If ((jend(4) - jbegin(4)) > minobs) And (tempmax(4) - minsignal > 0 And _
Mom1(4) <> 0 And IsNumeric(Mom1(4))) Then
Write #8, Format("Ch 3"), Format(Mom1(4), "#0.0")
Else
Write #8, Format("Ch 3"), Format("N.A.")
End If
If ((jend(5) - jbegin(5)) > minobs) And (tempmax(5) - minsignal > 0 And _
Mom1(5) <> 0 And IsNumeric(Mom1(5))) Then
Write #8, Format("Ch 4"), Format(Mom1(5), "#0.0")
Else
Write #8, Format("Ch 4"), Format("N.A.")
End If
Close
Refresh

```

```
DoEvents
GoTo 45
44 Unload Me
    Screen.MousePointer = 1
```

```
45 End Sub
```

```
Private Sub TeeCommander2_OnEditedChart()
```

```
End Sub
```

```
Private Sub Mom4_Click()
```

```
End Sub
```

Appendix D Sample raw data file

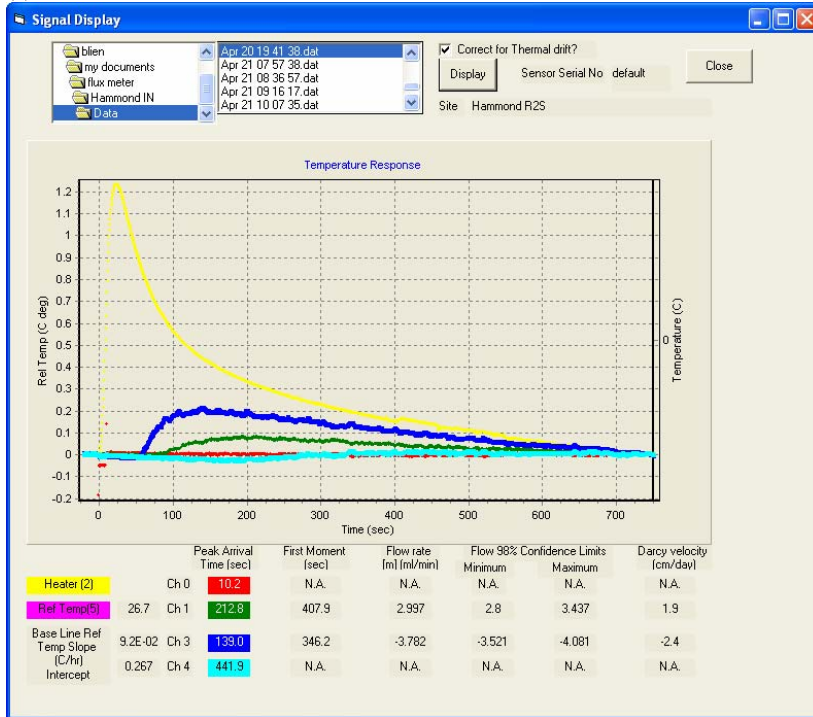
This raw data is one sample run from the calibration data set for the flow meter used at Lake Hartwell. After the first row that describes the data being collected the first column is the date time the sample was collected, the second column it elapsed time, the next 5 columns are differential temperature and the last column with data is the absolute temperature.

```
"5/26/2006 5:15:55 AM","20.0","10.0","99996.9482","0.1969","Purdue Calibration pump 15 6 ml/min"
"5/26/2006 5:15:55 AM","0.00000","-0.13058","-0.13232","-0.09803","-0.12581","-0.13805","0.24682",""
"5/26/2006 5:15:56 AM","0.55078","-0.13067","-0.13236","-0.09801","-0.12579","-0.13803","0.24698",""
"5/26/2006 5:15:56 AM","1.11133","-0.13054","-0.13229","-0.09806","-0.12578","-0.13804","0.24772",""
"5/26/2006 5:15:57 AM","1.66211","-0.13053","-0.13229","-0.09799","-0.12590","-0.13794","0.24880",""
"5/26/2006 5:15:57 AM","2.21289","-0.13052","-0.13237","-0.09803","-0.12582","-0.13806","0.24664",""
"5/26/2006 5:15:58 AM","2.76367","-0.13059","-0.13239","-0.09799","-0.12574","-0.13806","0.24853",""
"5/26/2006 5:15:58 AM","3.31445","-0.13053","-0.13224","-0.09799","-0.12572","-0.13805","0.24754",""
"5/26/2006 5:15:59 AM","3.86523","-0.13056","-0.13227","-0.09803","-0.12578","-0.13808","0.24922",""
"5/26/2006 5:15:59 AM","4.41602","-0.13058","-0.13231","-0.09798","-0.12575","-0.13805","0.24859",""
"5/26/2006 5:16:00 AM","4.96680","-0.13057","-0.13232","-0.09802","-0.12578","-0.13811","0.24807",""
"5/26/2006 5:16:01 AM","5.51758","-0.13050","-0.13232","-0.09797","-0.12575","-0.13801","0.24752",""
"5/26/2006 5:16:01 AM","6.06836","-0.13062","-0.13236","-0.09801","-0.12578","-0.13814","0.24856",""
"5/26/2006 5:16:02 AM","6.61914","-0.13055","-0.13229","-0.09803","-0.12570","-0.13816","0.24842",""
"5/26/2006 5:16:02 AM","7.16992","-0.13057","-0.13234","-0.09801","-0.12583","-0.13802","0.24701",""
"5/26/2006 5:16:03 AM","7.72070","-0.13049","-0.13238","-0.09792","-0.12579","-0.13805","0.24820",""
"5/26/2006 5:16:03 AM","8.27148","-0.13060","-0.13229","-0.09808","-0.12587","-0.13801","0.24844",""
"5/26/2006 5:16:04 AM","8.82227","-0.13061","-0.13242","-0.09800","-0.12575","-0.13804","0.24648",""
"5/26/2006 5:16:04 AM","9.37305","-0.13066","-0.13222","-0.09797","-0.12567","-0.13812","0.24821",""
"5/26/2006 5:16:05 AM","9.92383","-0.13061","-0.13224","-0.09802","-0.12577","-0.13809","0.24707",""
"5/26/2006 5:16:06 AM","10.47461","-0.13054","-0.13239","-0.09798","-0.12579","-0.13799","0.24881",""
"5/26/2006 5:16:06 AM","11.02539","-0.13053","-0.13227","-0.09799","-0.12576","-0.13804","0.24713",""
"5/26/2006 5:16:07 AM","11.57617","-0.13054","-0.13229","-0.09802","-0.12578","-0.13803","0.24707",""
"5/26/2006 5:16:07 AM","12.12695","-0.13051","-0.13231","-0.09804","-0.12578","-0.13798","0.24700",""
"5/26/2006 5:16:08 AM","12.68750","-0.13059","-0.13230","-0.09799","-0.12573","-0.13807","0.24856",""
"5/26/2006 5:16:08 AM","13.23828","-0.13051","-0.13241","-0.09802","-0.12583","-0.13800","0.24851",""
"5/26/2006 5:16:09 AM","13.78906","-0.13064","-0.13230","-0.09800","-0.12580","-0.13804","0.24681",""
"5/26/2006 5:16:09 AM","14.33984","-0.13053","-0.13231","-0.09804","-0.12570","-0.13802","0.24713",""
"5/26/2006 5:16:10 AM","14.89063","-0.13058","-0.13235","-0.09804","-0.12576","-0.13805","0.24748",""
"5/26/2006 5:16:10 AM","15.44141","-0.13058","-0.13242","-0.09801","-0.12574","-0.13804","0.24700",""
"5/26/2006 5:16:11 AM","15.99219","-0.13052","-0.13228","-0.09798","-0.12575","-0.13803","0.24683",""
"5/26/2006 5:16:12 AM","16.54297","-0.13050","-0.13229","-0.09804","-0.12575","-0.13803","0.24926",""
"5/26/2006 5:16:12 AM","17.09375","-0.13055","-0.13229","-0.09802","-0.12591","-0.13798","0.24861",""
"5/26/2006 5:16:13 AM","17.64453","-0.13058","-0.13243","-0.09794","-0.12574","-0.13812","0.24767",""
"5/26/2006 5:16:13 AM","18.19531","-0.13060","-0.13221","-0.09800","-0.12580","-0.13795","0.24823",""
"5/26/2006 5:16:14 AM","18.74609","-0.13051","-0.13233","-0.09799","-0.12572","-0.13809","0.24745",""
"5/26/2006 5:16:14 AM","19.29688","-0.13059","-0.13239","-0.09798","-0.12565","-0.13810","0.24944",""
"5/26/2006 5:16:15 AM","19.84766","-0.13059","-0.13231","-0.09796","-0.12580","-0.13809","0.24720",""
.
.
. (truncated)
.
"5/26/2006 5:46:17 AM","1821.87900","-0.13064","-0.13226","-0.09814","-0.12604","-0.13821","0.24751",""
"5/26/2006 5:46:17 AM","1822.43000","-0.13068","-0.13232","-0.09811","-0.12606","-0.13823","0.24944",""
"5/26/2006 5:46:18 AM","1822.98000","-0.13073","-0.13239","-0.09812","-0.12609","-0.13826","0.24939",""
"5/26/2006 5:46:19 AM","1823.53100","-0.13067","-0.13246","-0.09816","-0.12616","-0.13828","0.24951",""
"5/26/2006 5:46:19 AM","1824.08200","-0.13074","-0.13245","-0.09815","-0.12611","-0.13816","0.24583",""
"5/26/2006 5:46:20 AM","1824.63300","-0.13070","-0.13248","-0.09815","-0.12607","-0.13822","0.24917",""
"5/26/2006 5:46:20 AM","1825.18400","-0.13070","-0.13232","-0.09816","-0.12600","-0.13827","0.24893",""
"5/26/2006 5:46:21 AM","1825.73400","-0.13072","-0.13236","-0.09813","-0.12600","-0.13816","0.24669",""
"5/26/2006 5:46:21 AM","1826.28500","-0.13067","-0.13244","-0.09812","-0.12618","-0.13814","0.24928",""
"5/26/2006 5:46:22 AM","1826.83600","-0.13067","-0.13232","-0.09814","-0.12608","-0.13816","0.24819",""
"5/26/2006 5:46:22 AM","1827.38700","-0.13068","-0.13242","-0.09816","-0.12611","-0.13817","0.24698",""
"5/26/2006 5:46:23 AM","1827.93800","-0.13070","-0.13238","-0.09815","-0.12617","-0.13807","0.24694",""
"5/26/2006 5:46:24 AM","1828.48800","-0.13066","-0.13235","-0.09812","-0.12604","-0.13818","0.24982",""
```

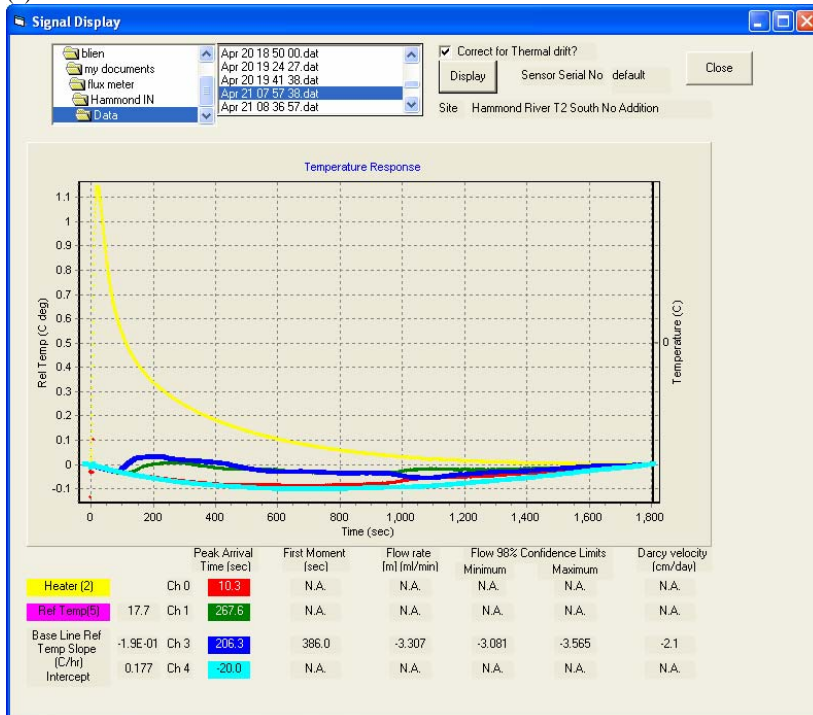
"5/26/2006 5:46:24 AM","1829.03900","-0.13071","-0.13236","-0.09814","-0.12618","-0.13809","0.24636","",,""

Appendix E Results from Hammond, IN

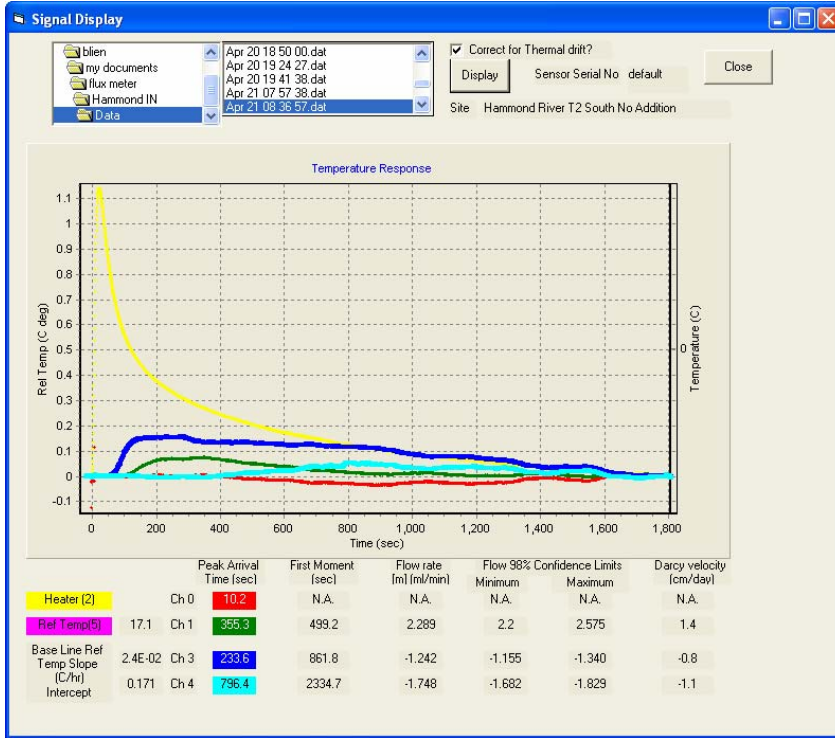
(1)



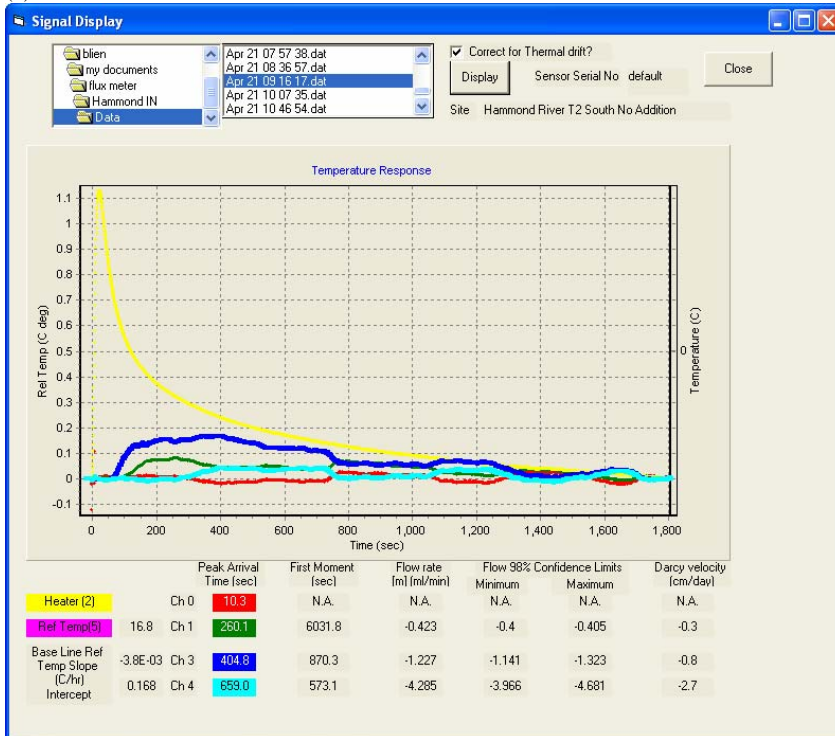
(2)



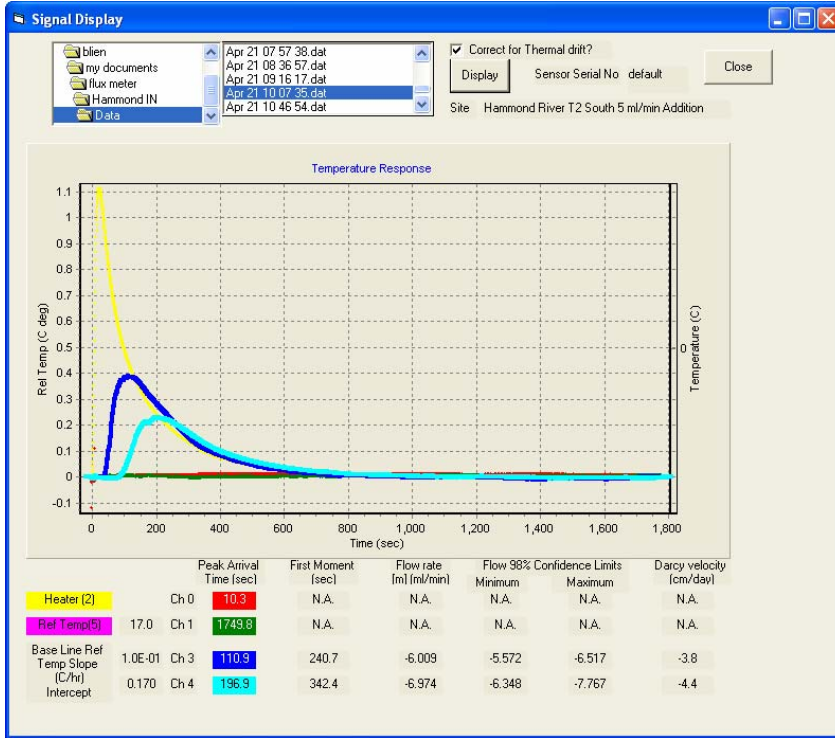
(3)



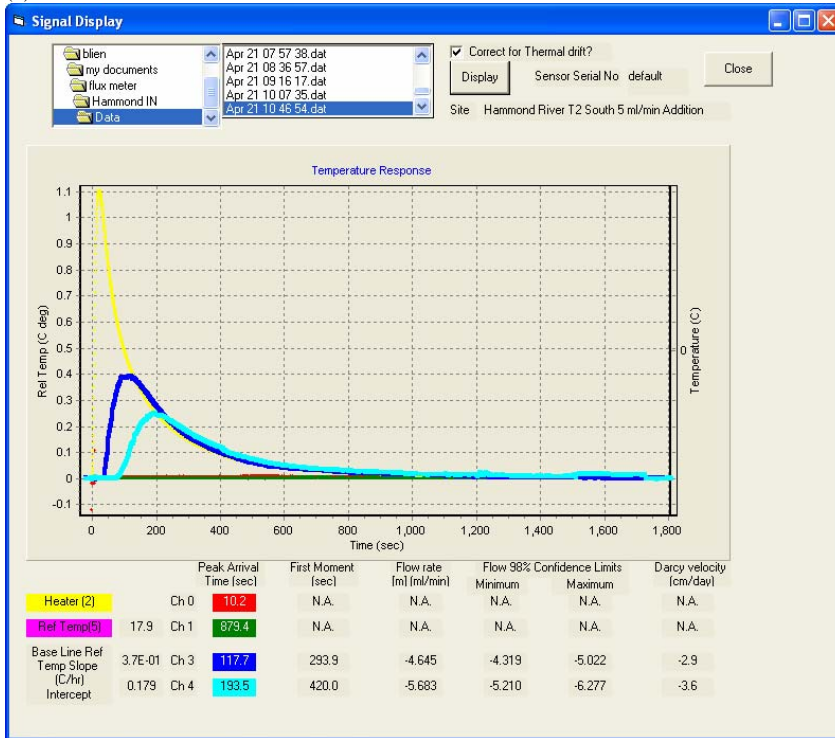
(4)



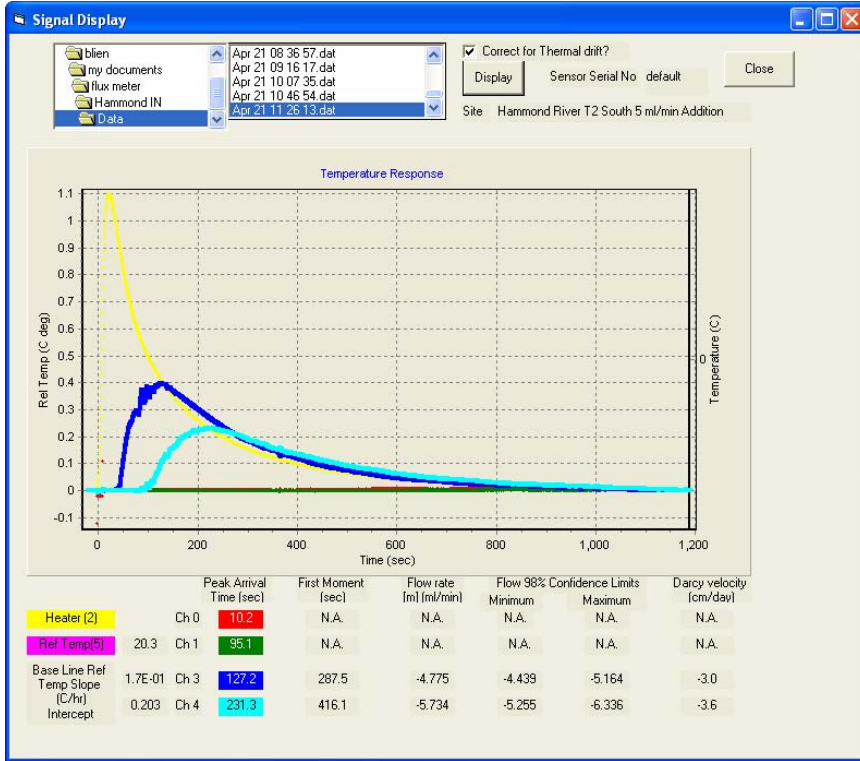
(5)



(6)

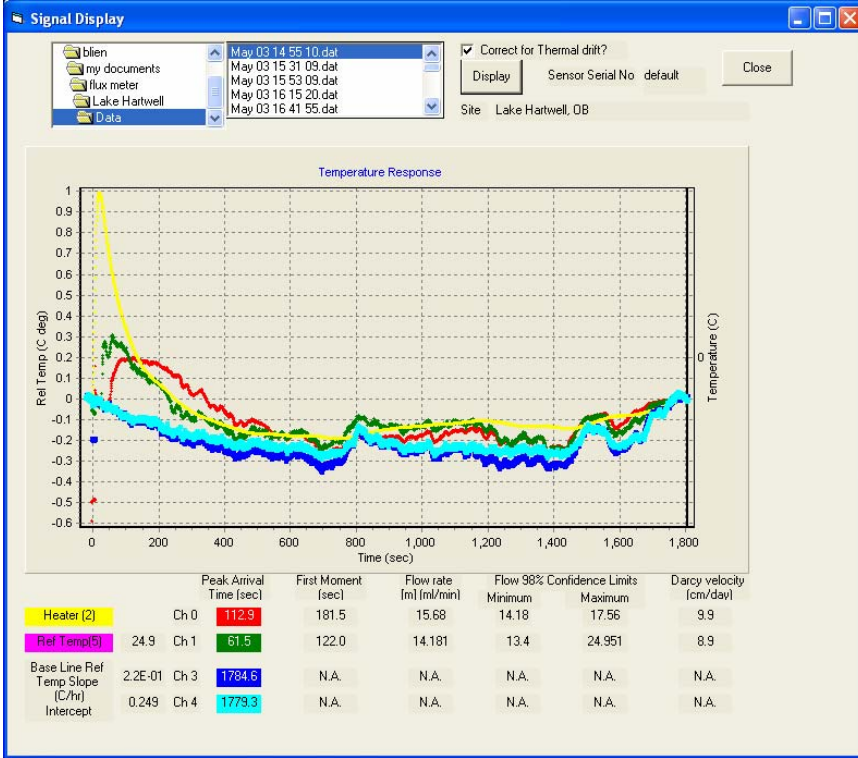


(7)

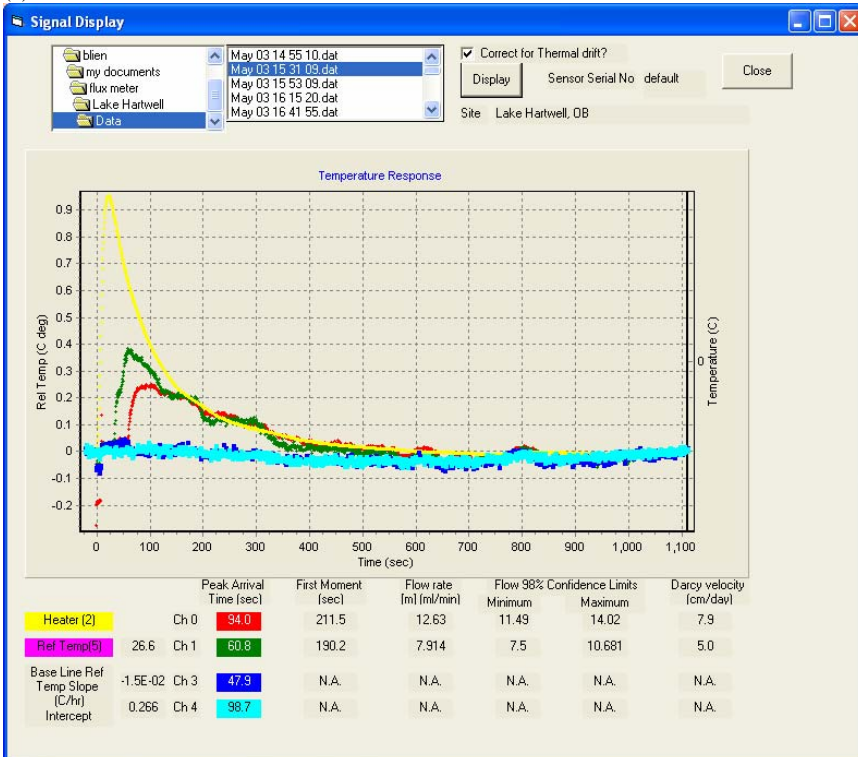


Appendix F Results from Lake Hartwell, SC

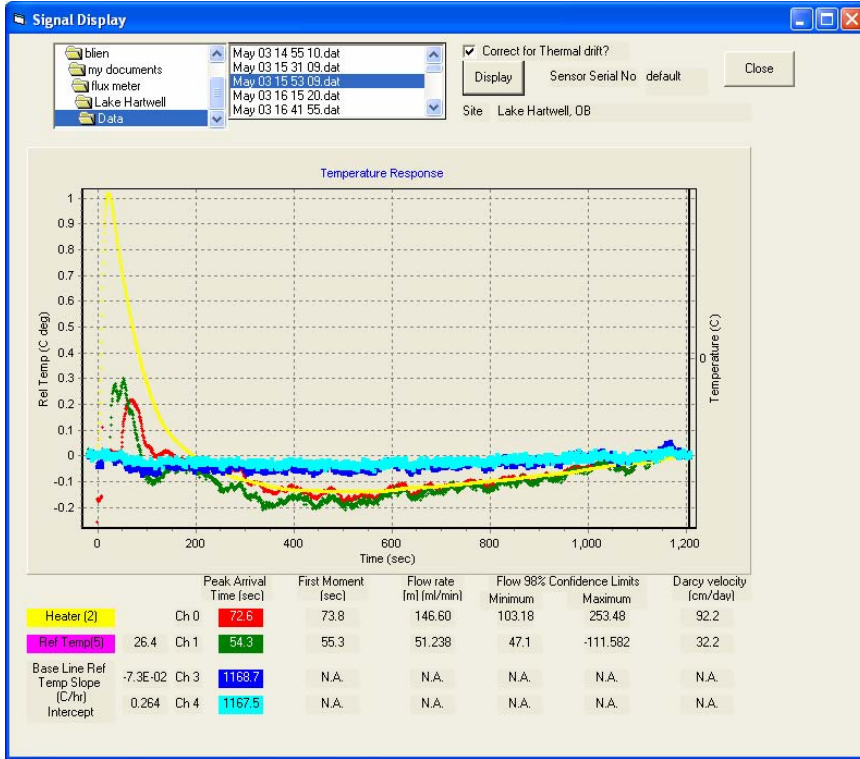
(1)



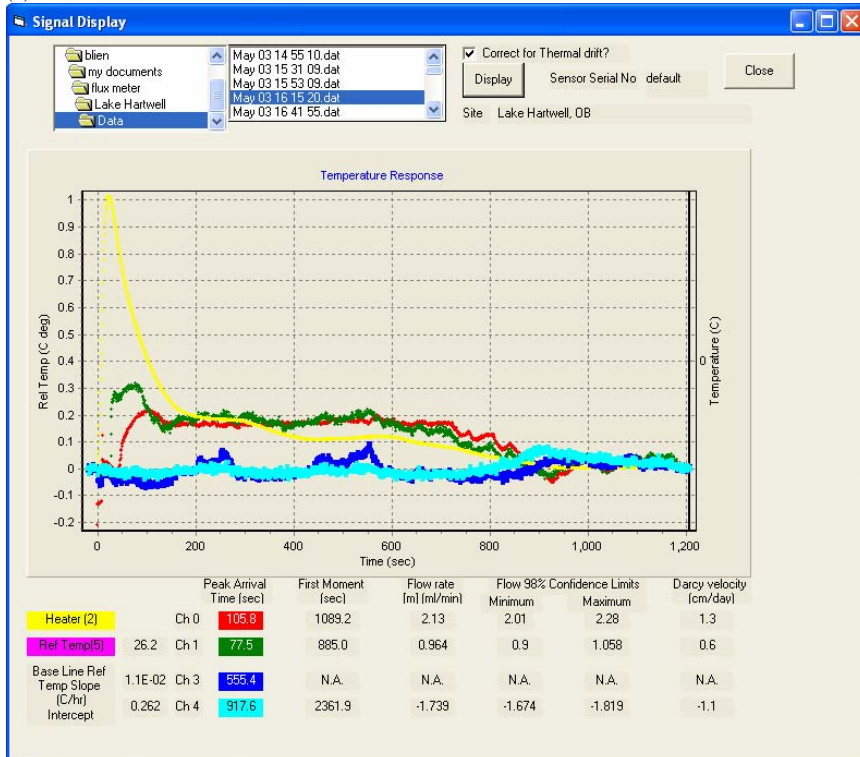
(2)



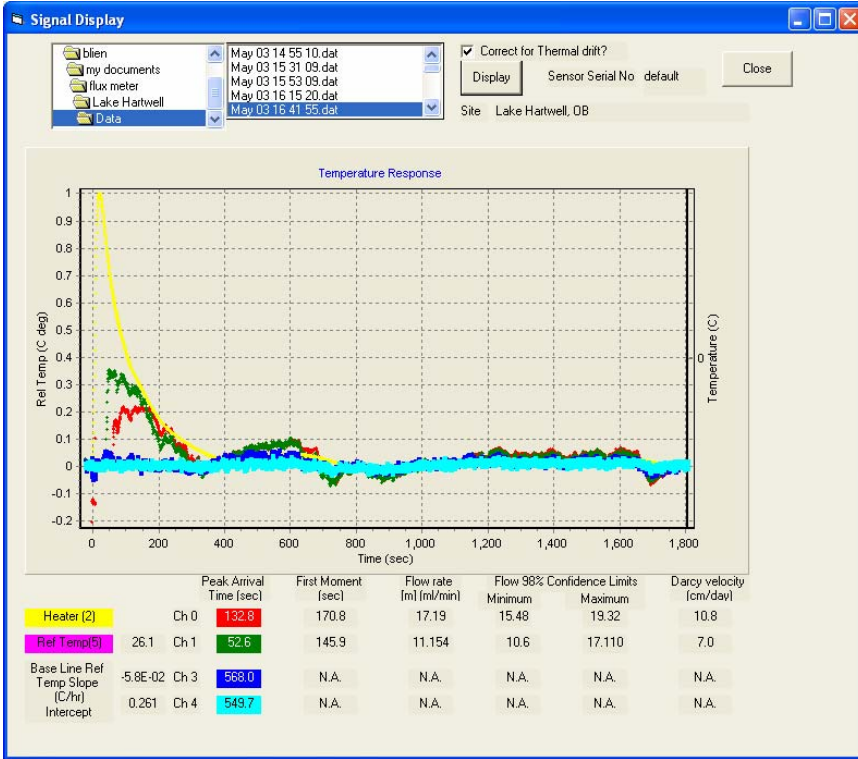
(3)



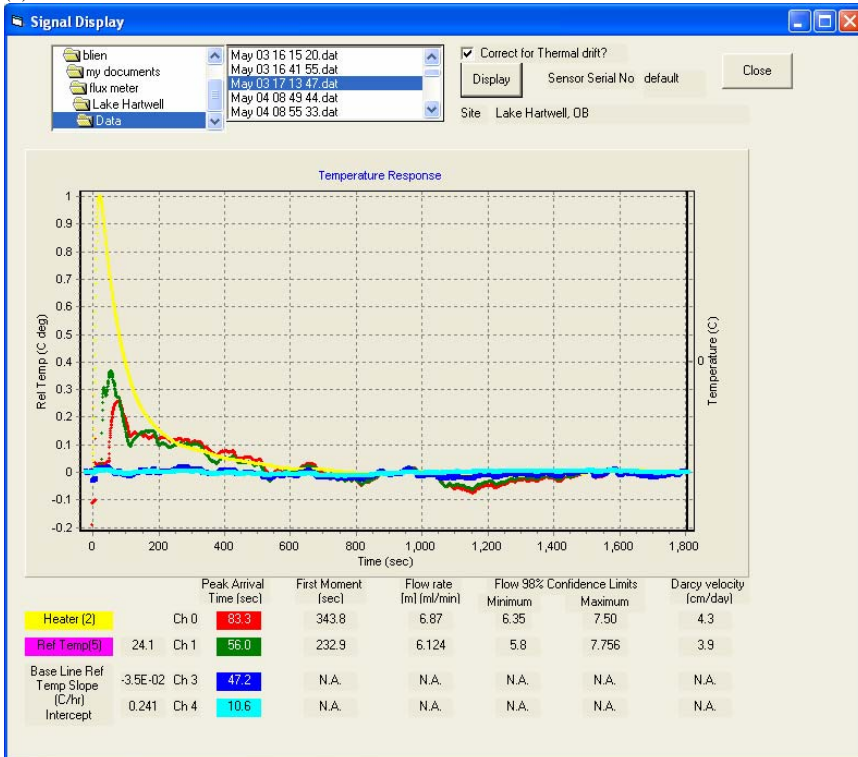
(4)



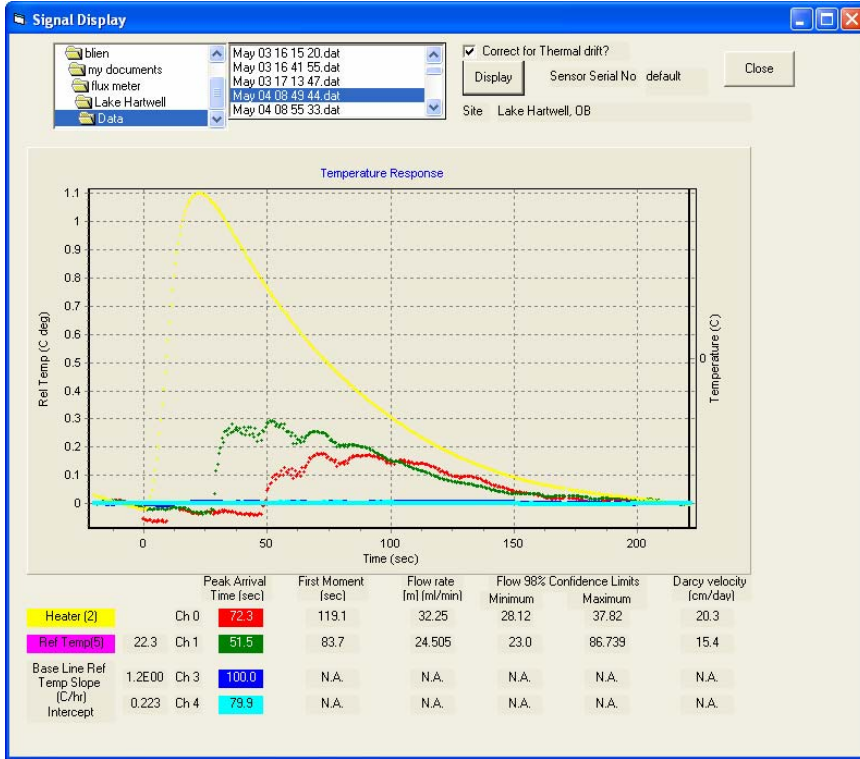
(5)



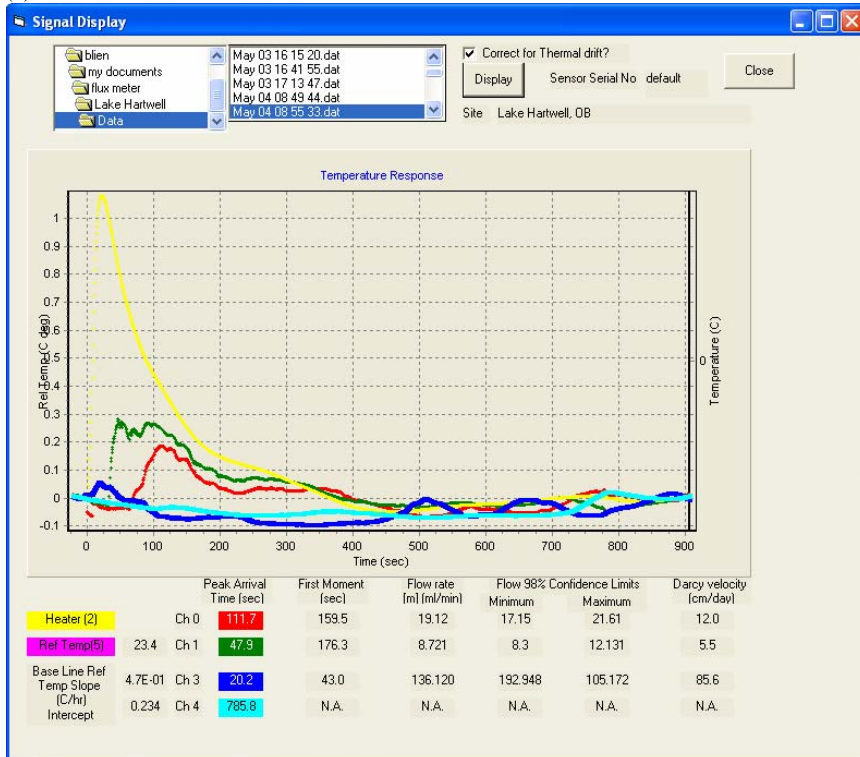
(6)



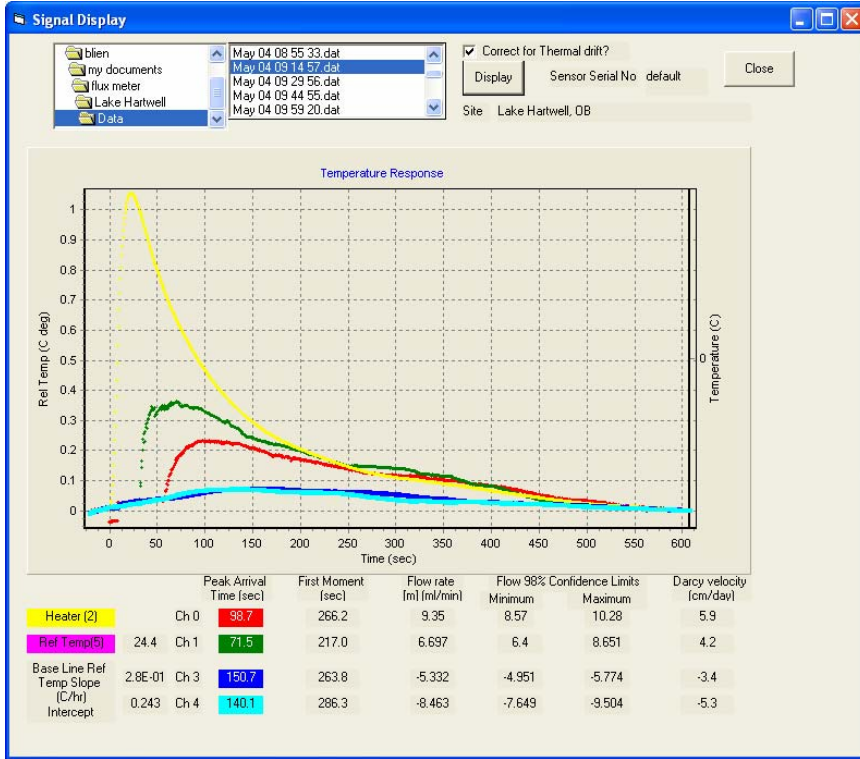
(7)



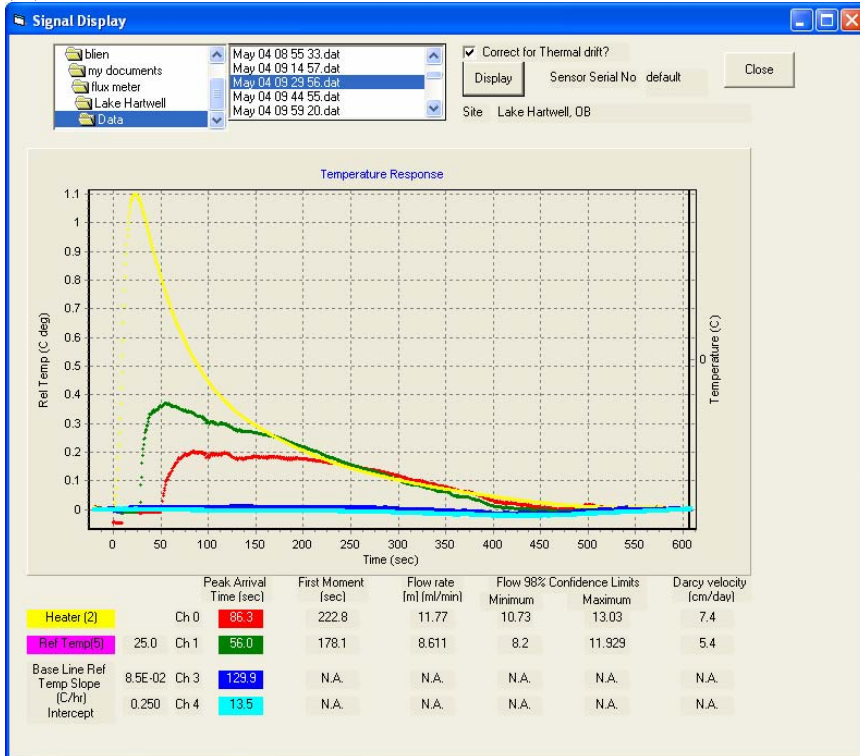
(8)



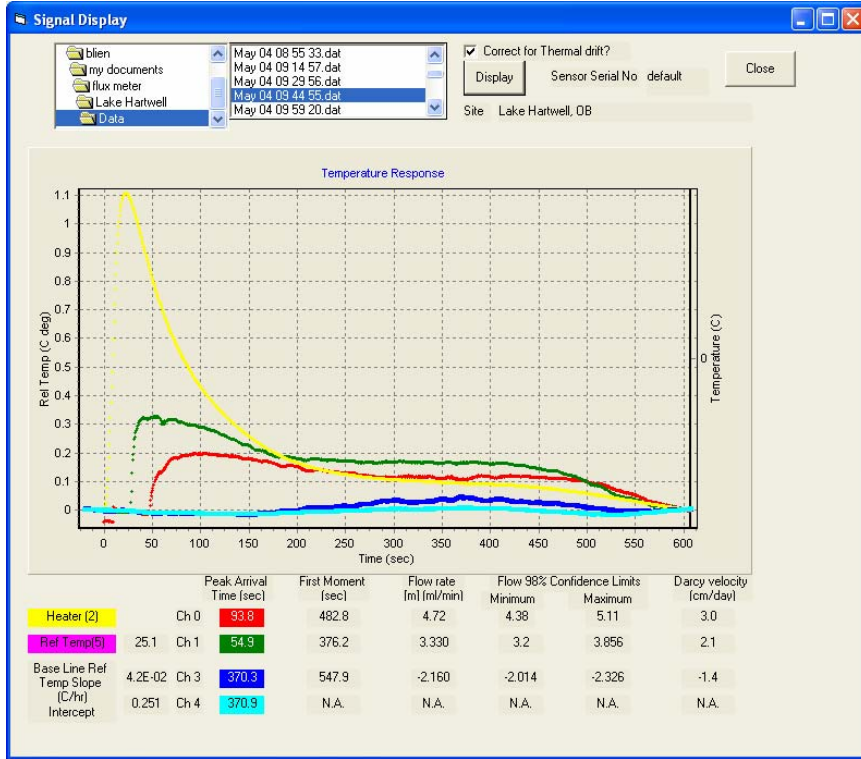
(9)



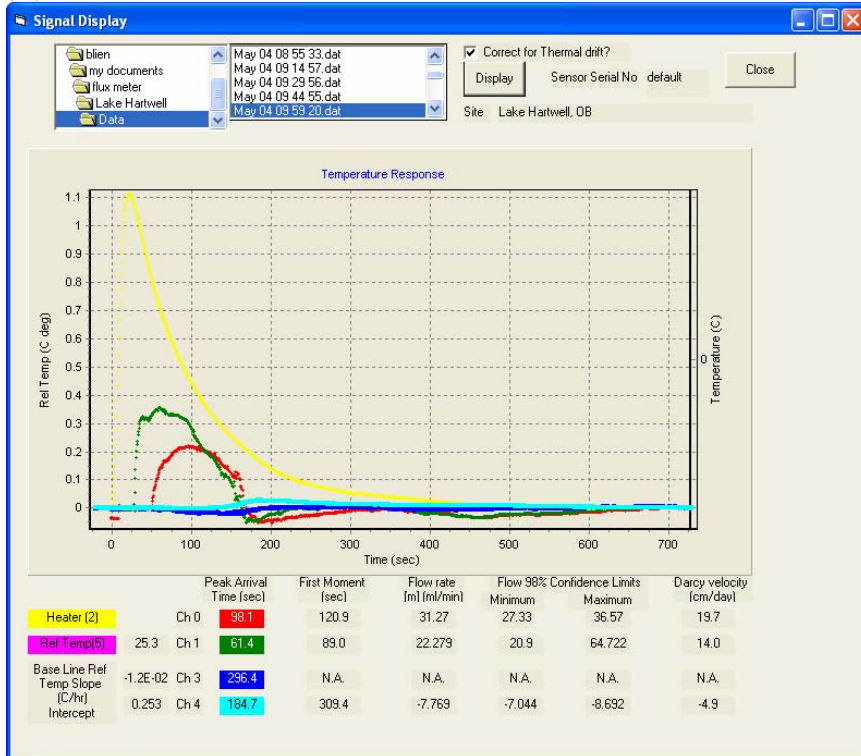
(10)



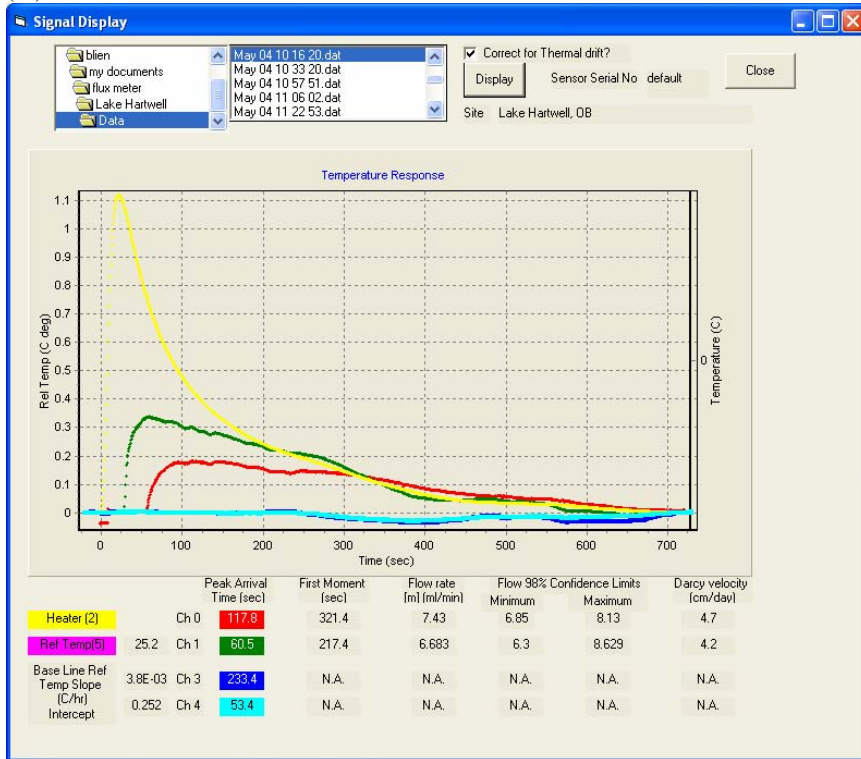
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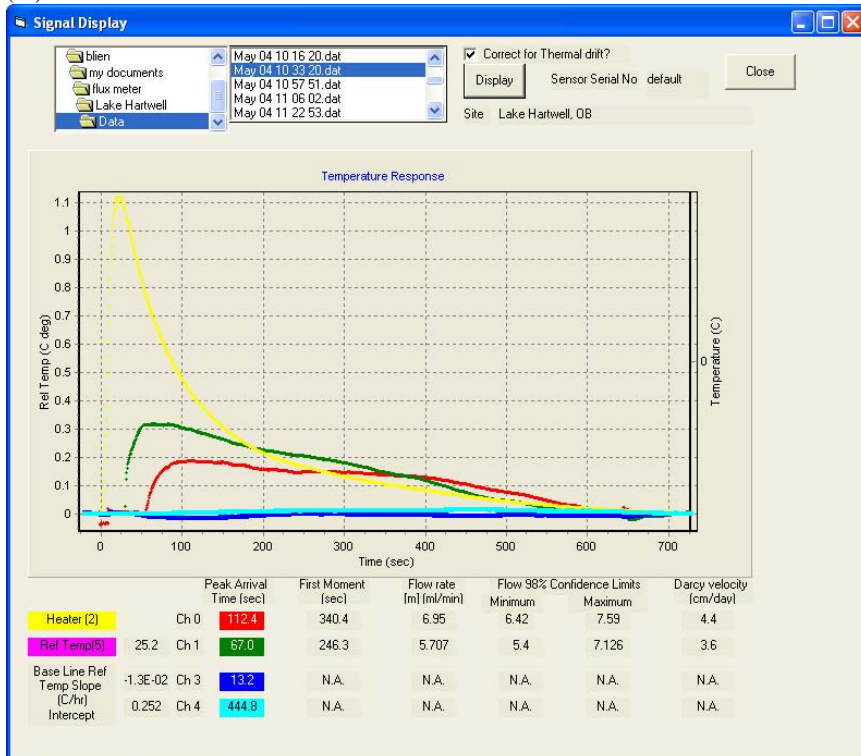
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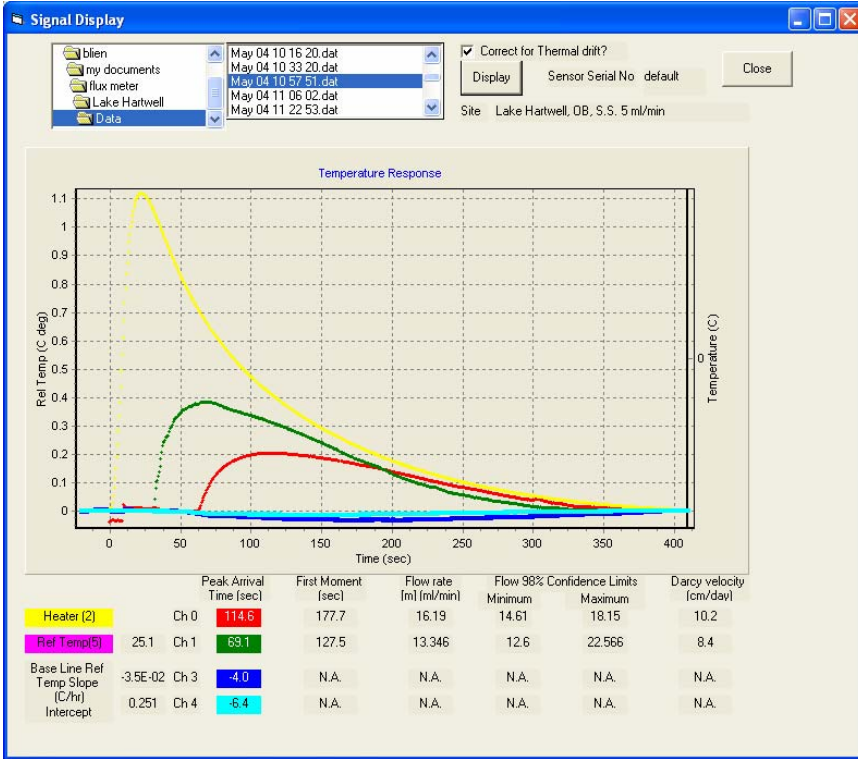
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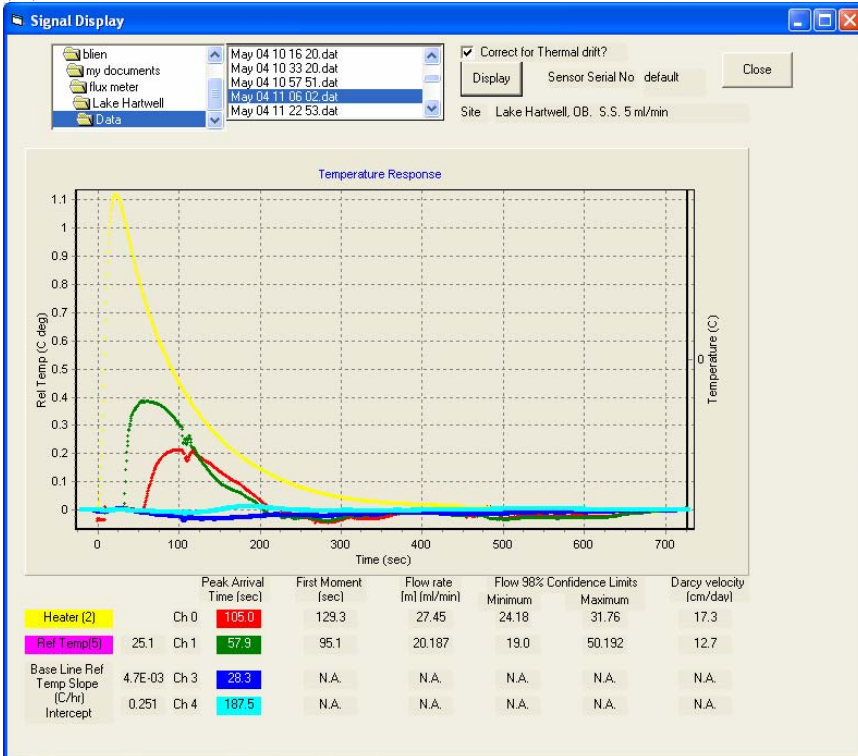
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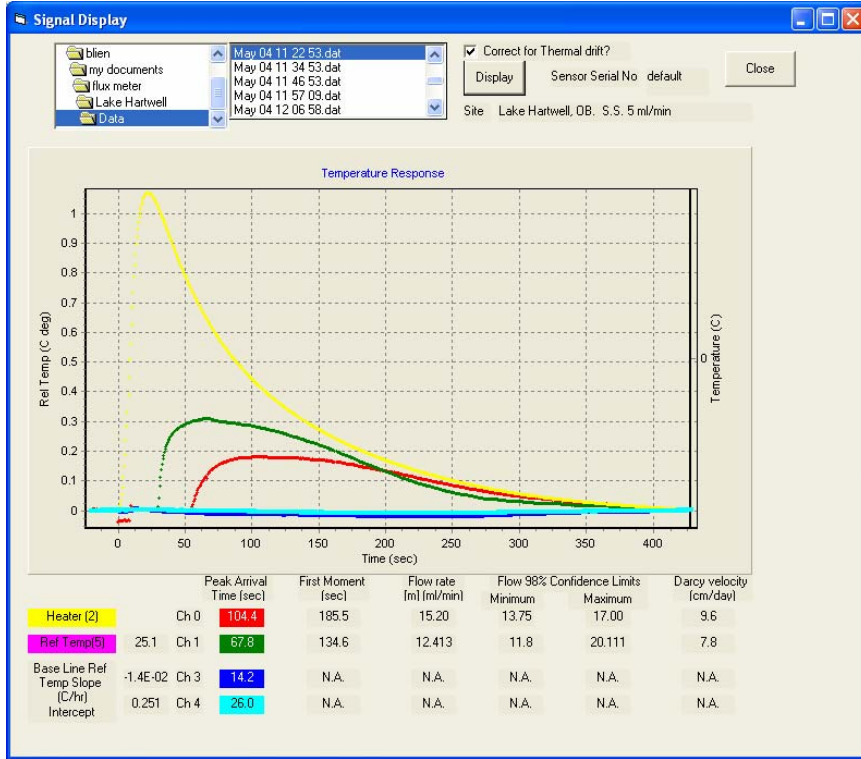
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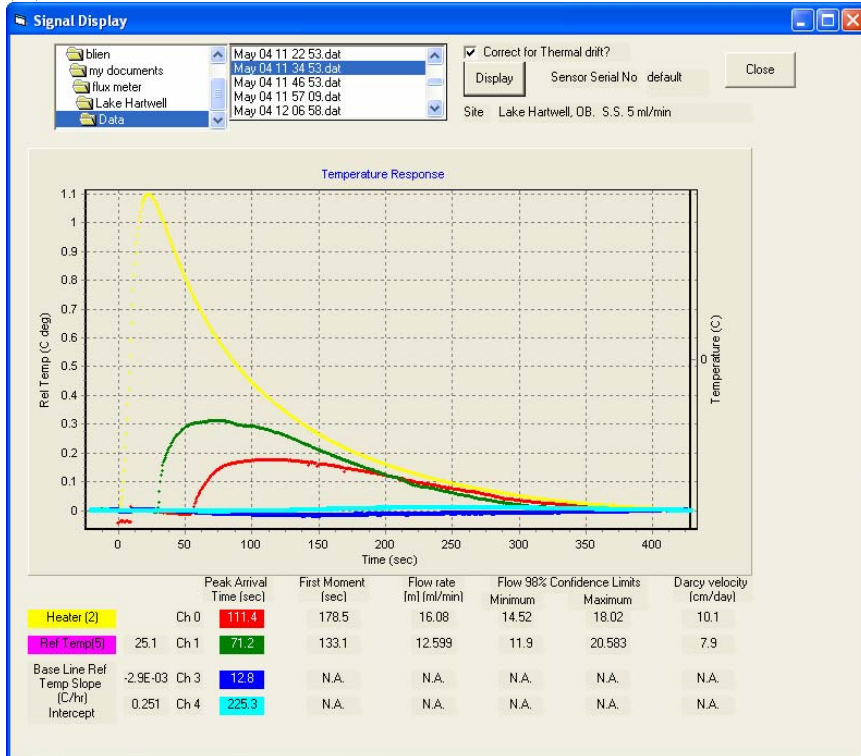
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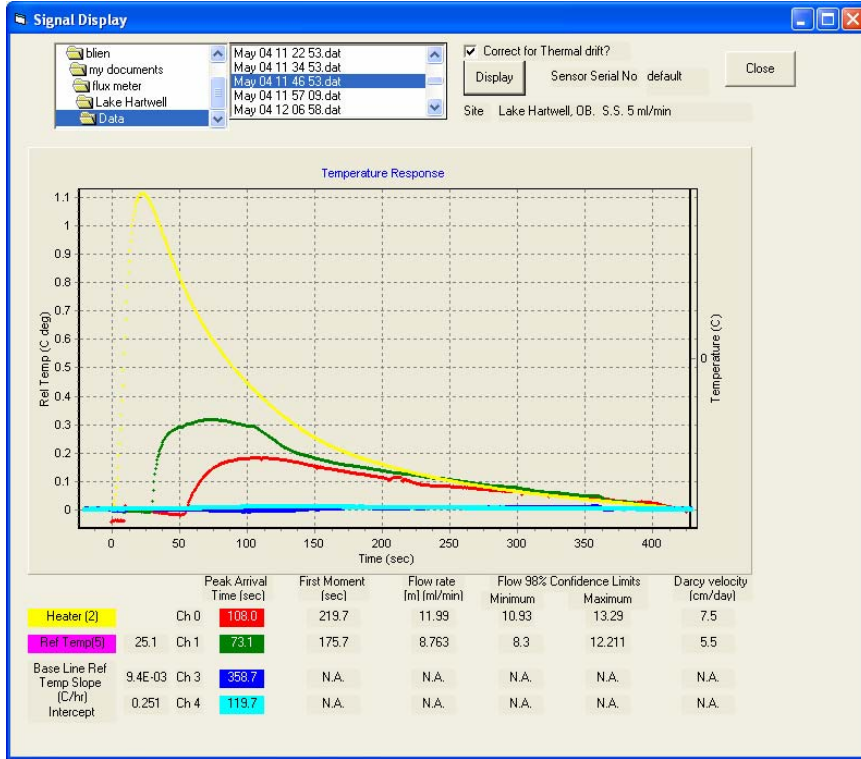
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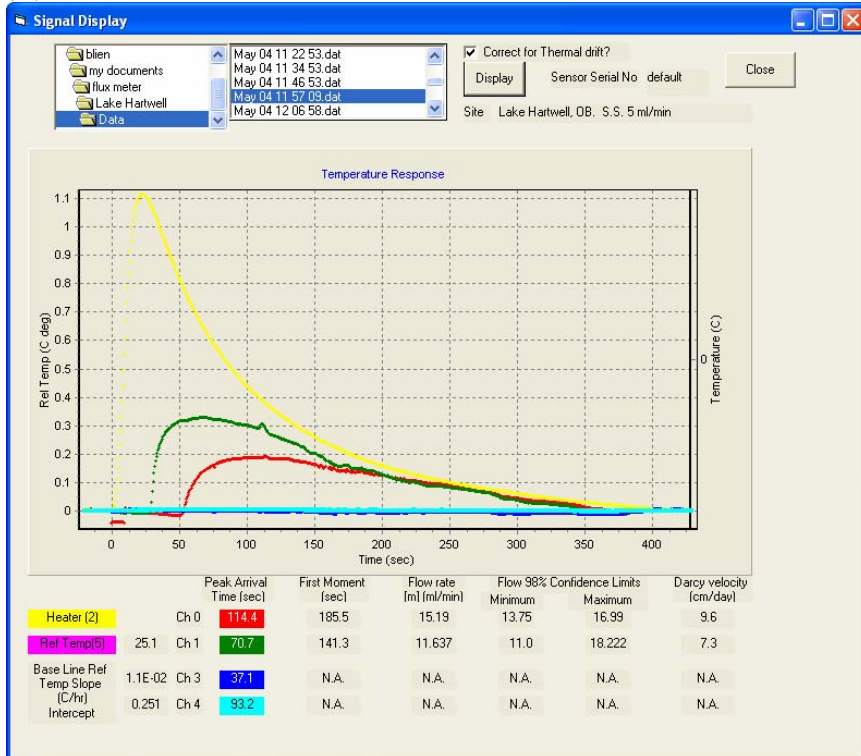
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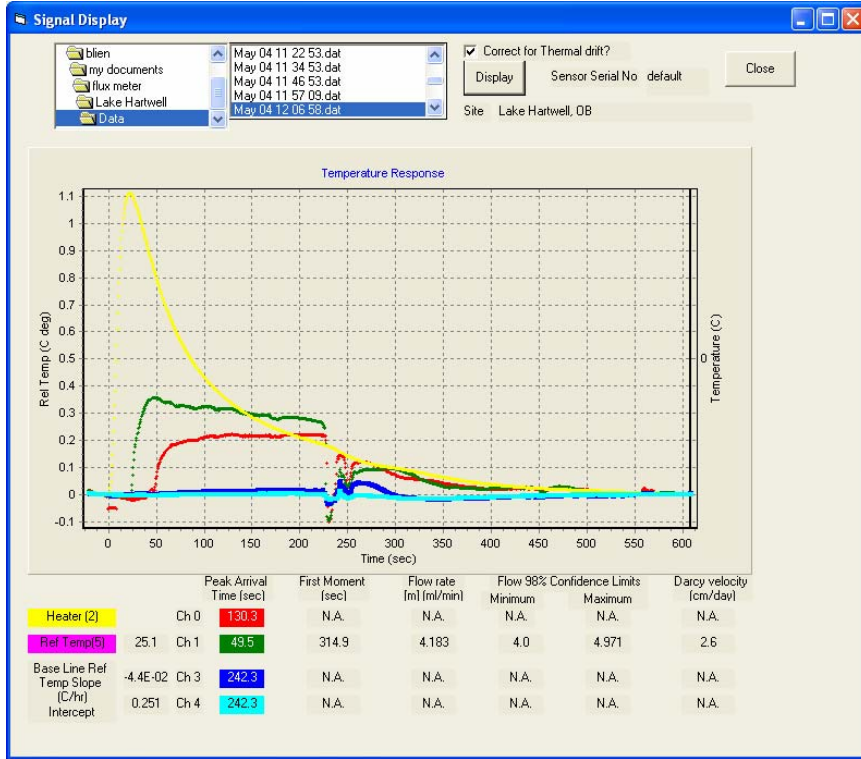
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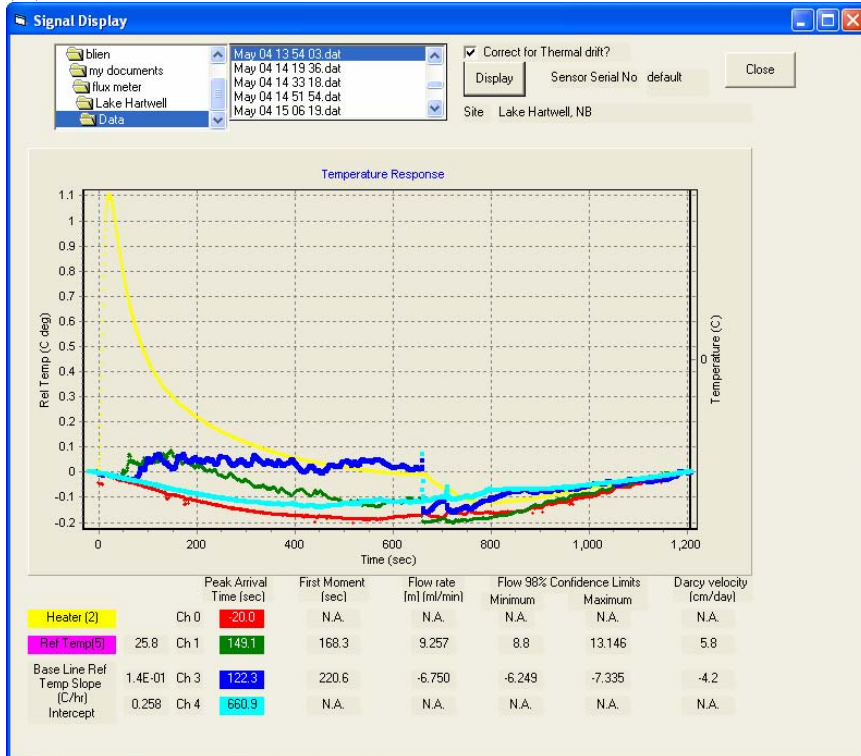
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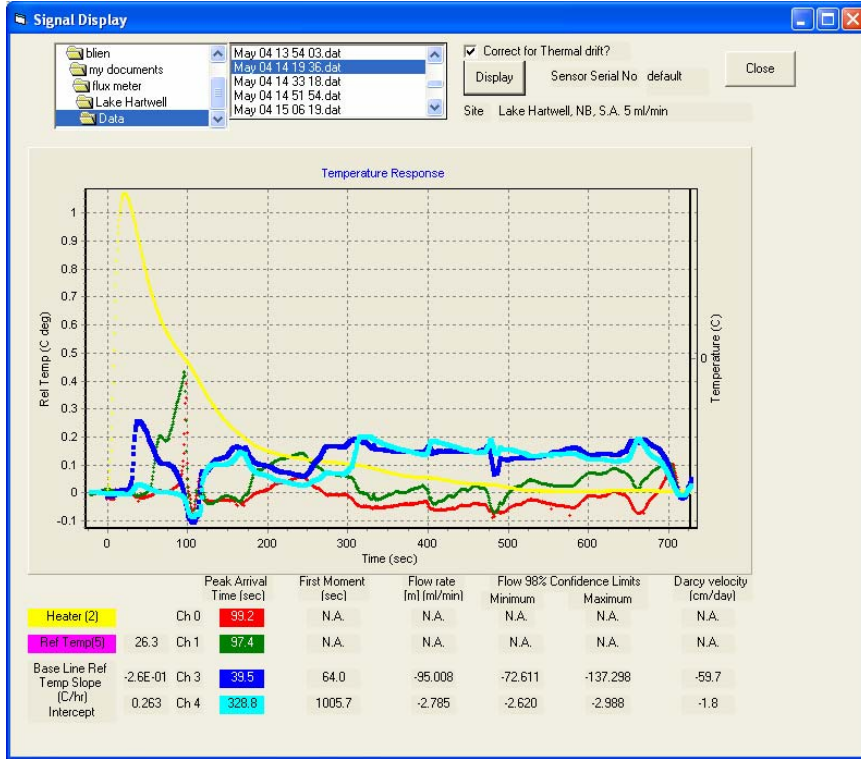
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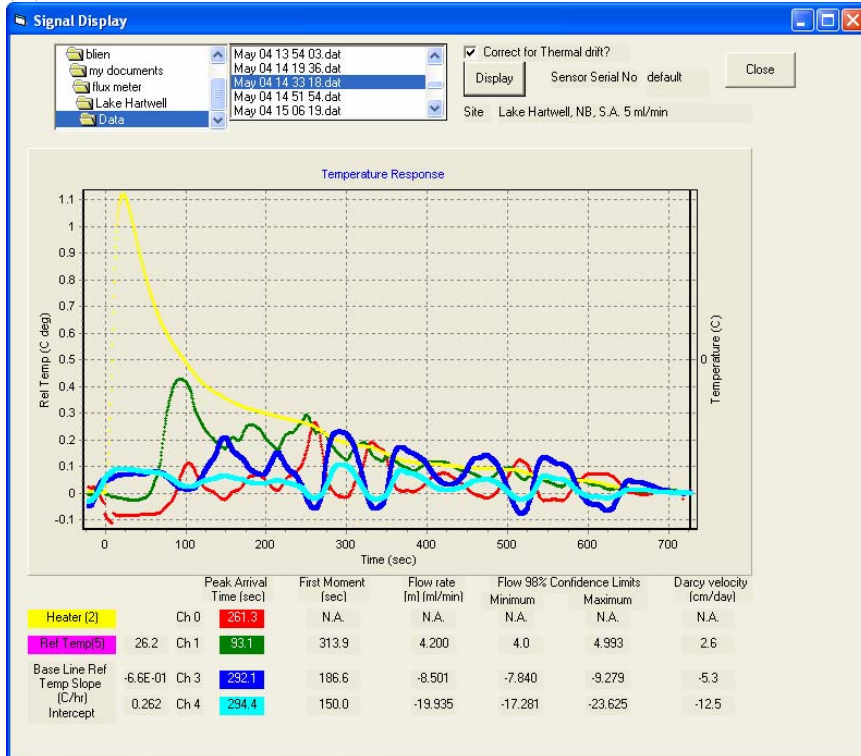
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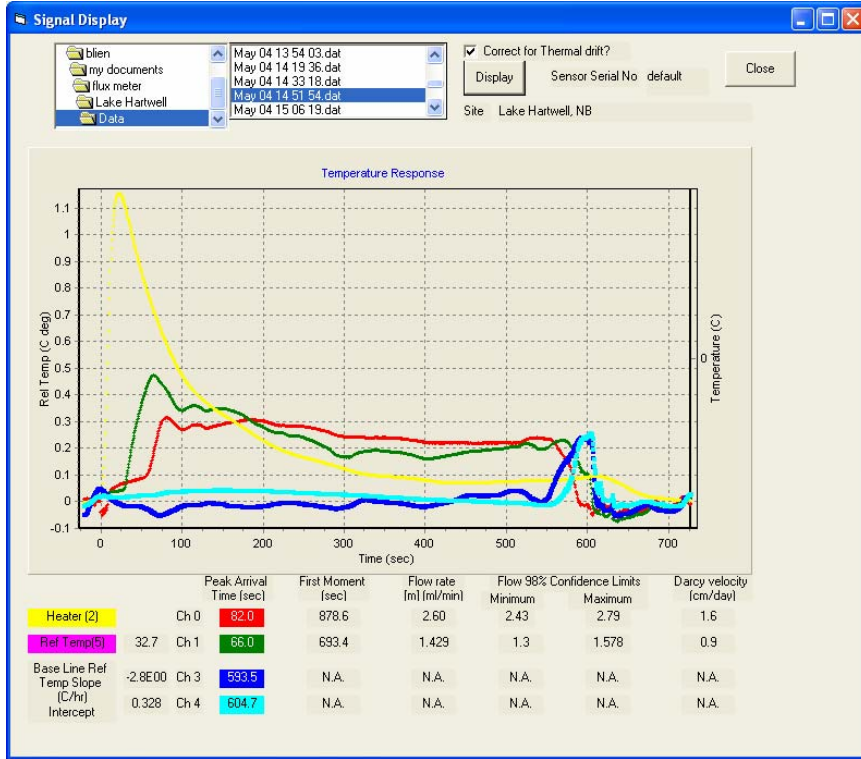
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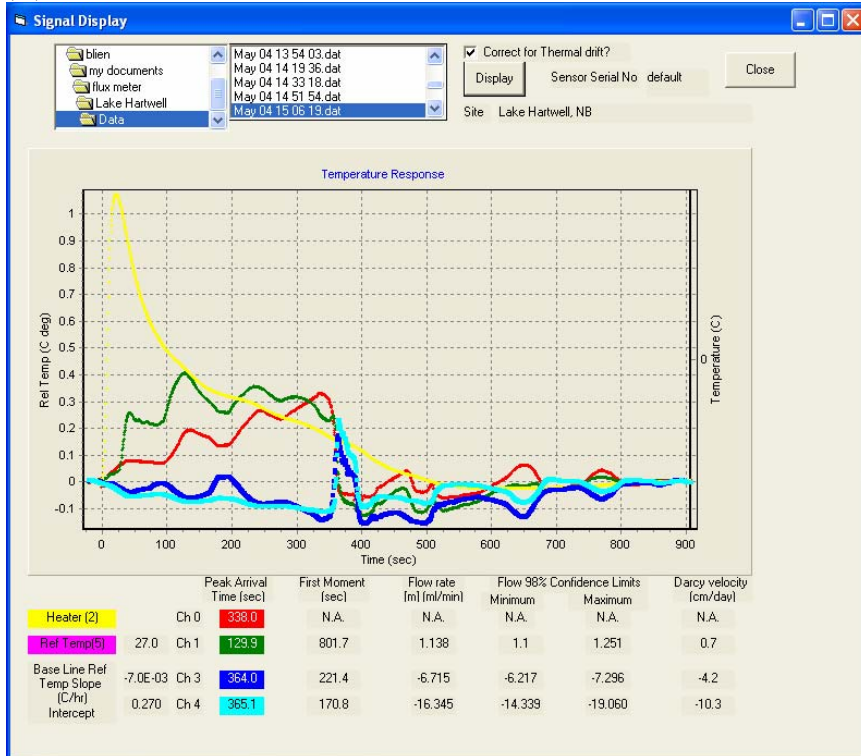
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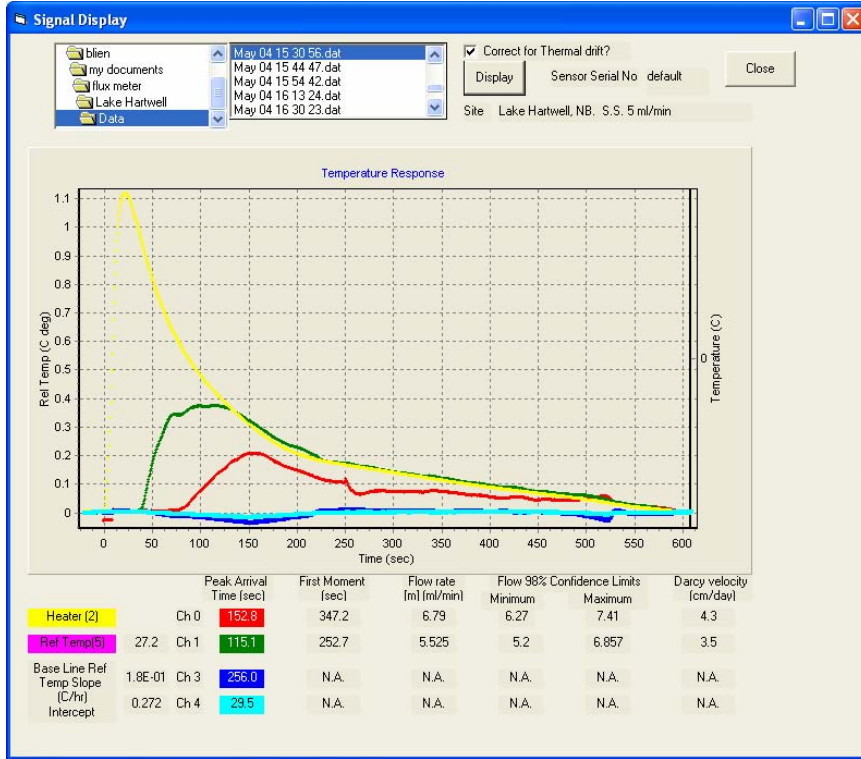
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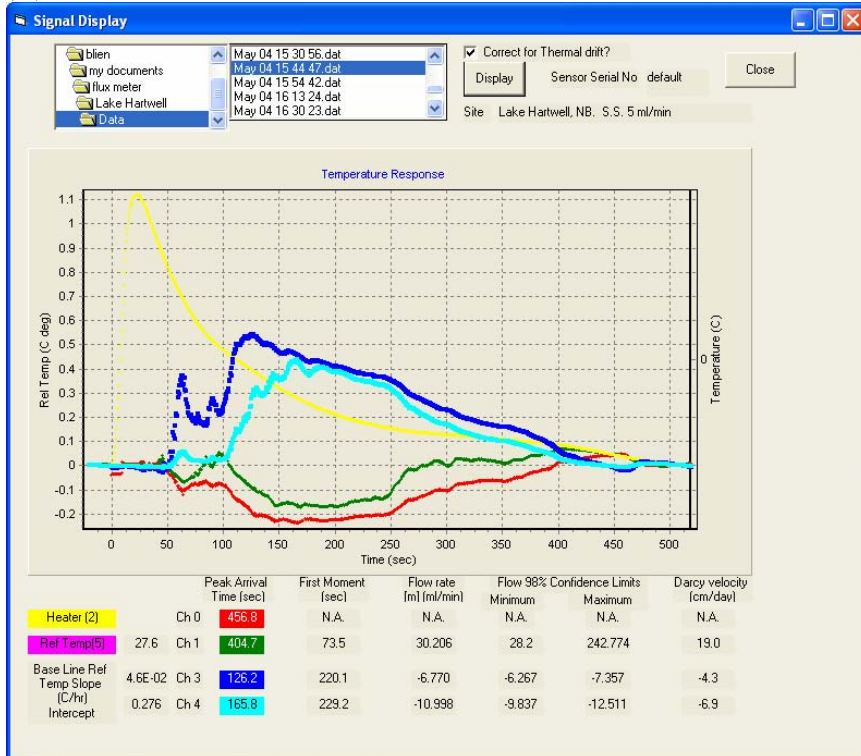
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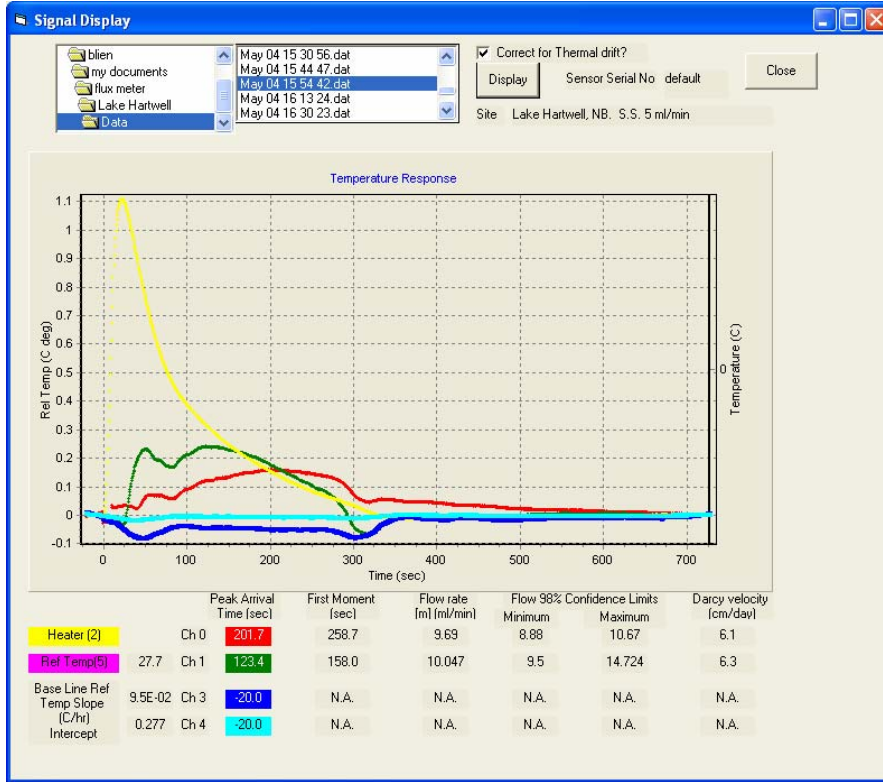
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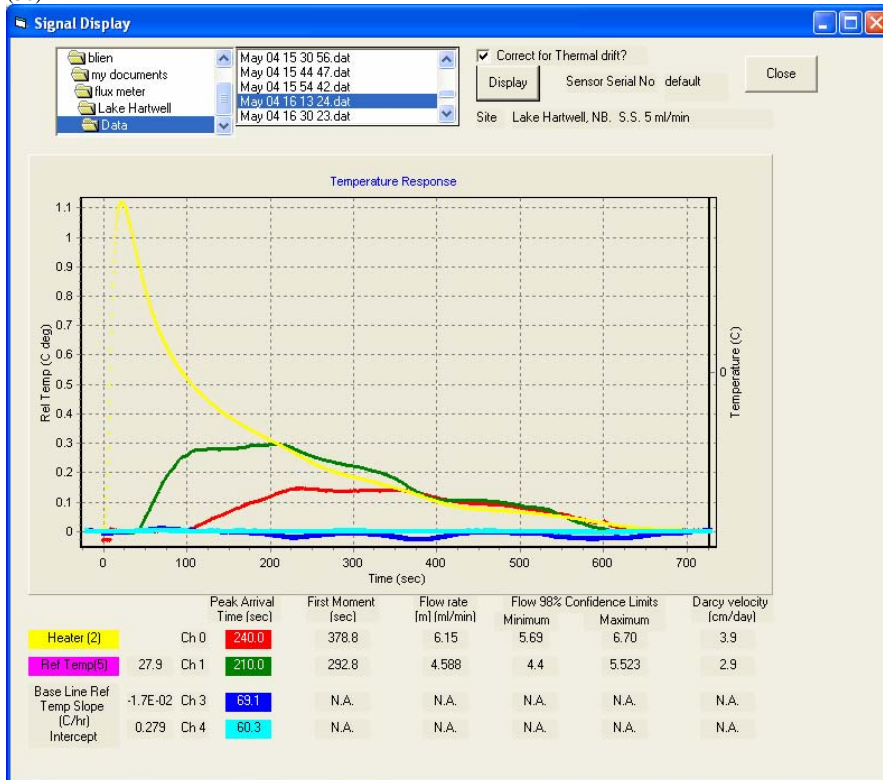
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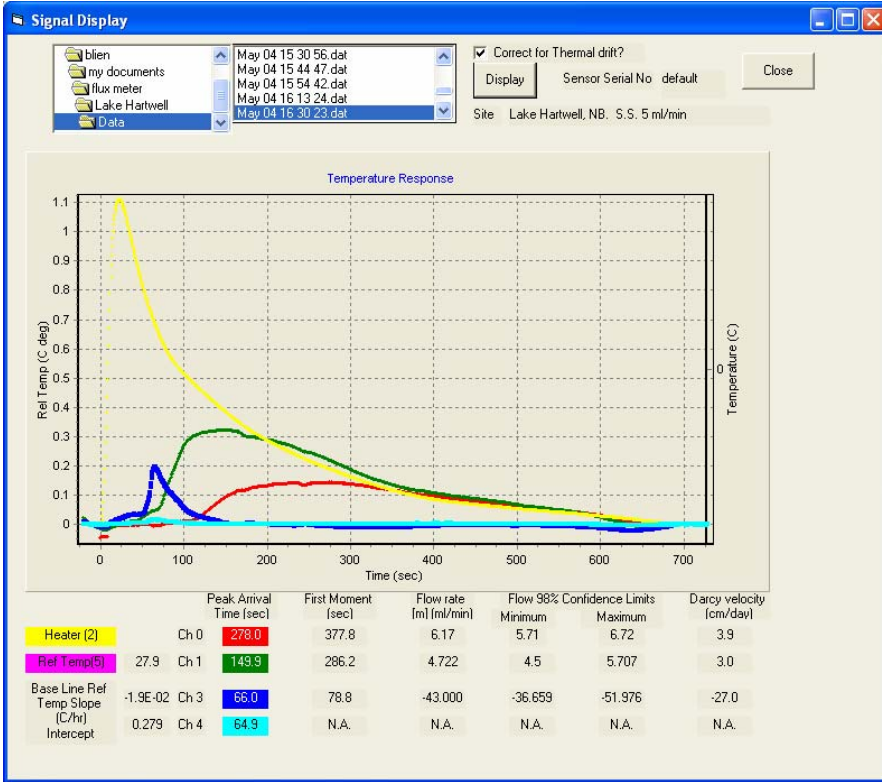
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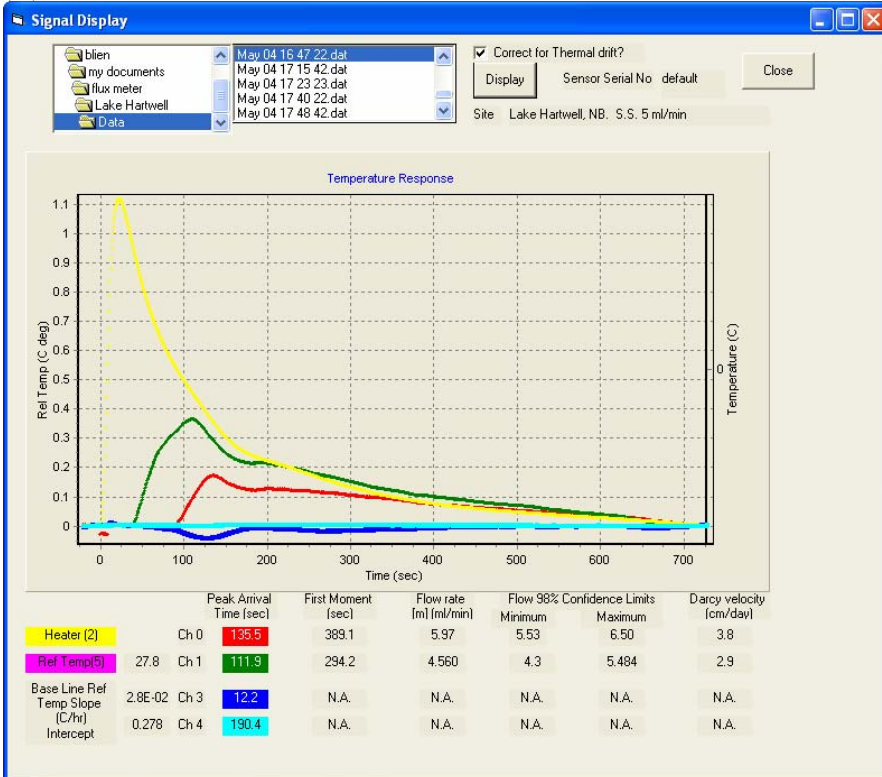
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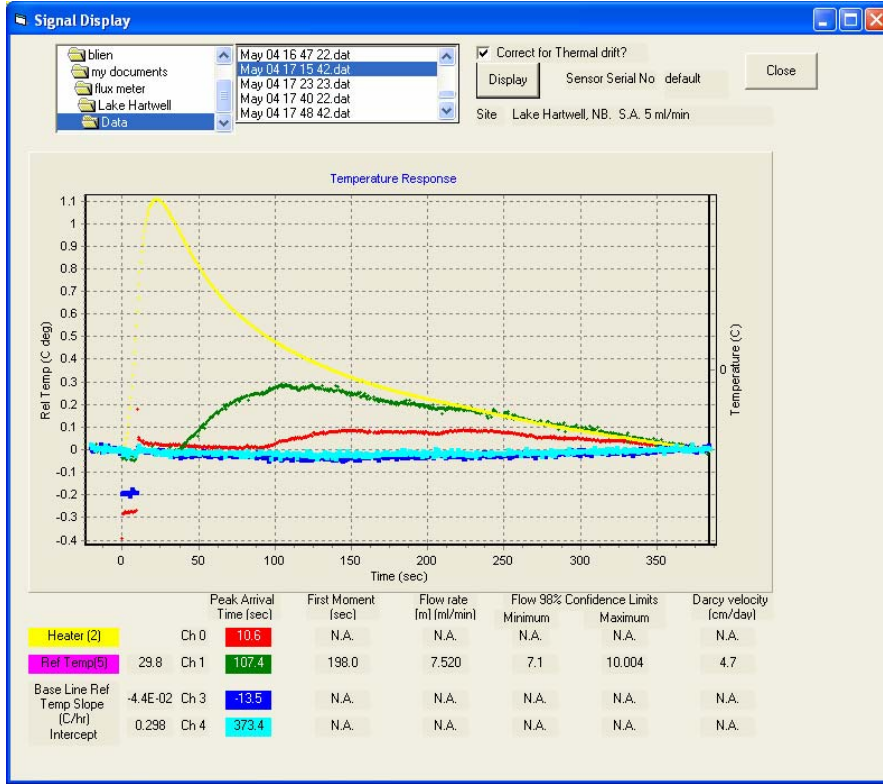
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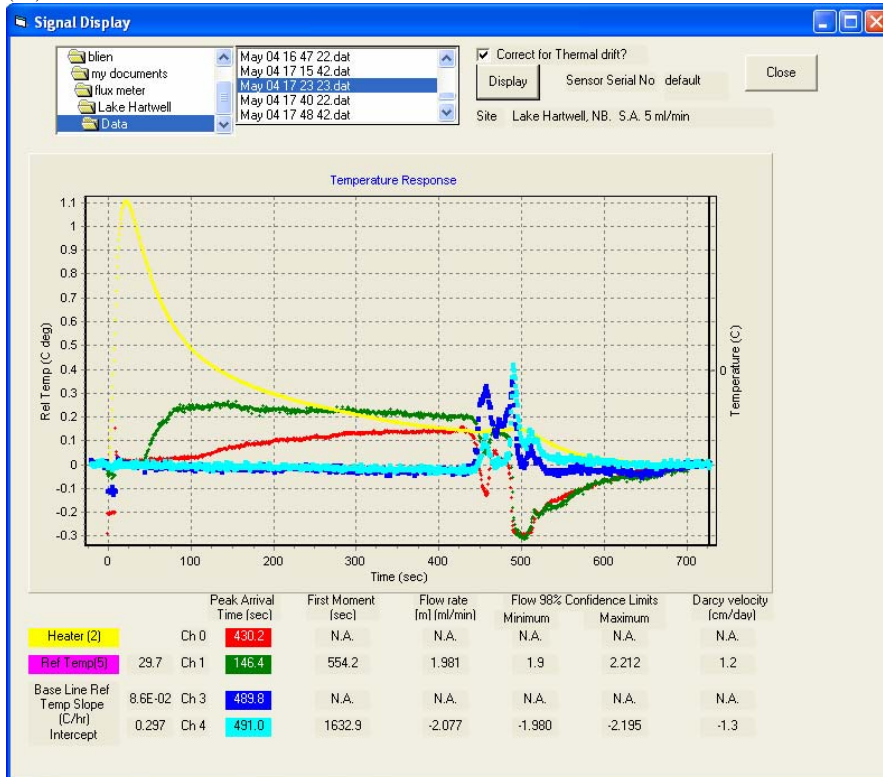
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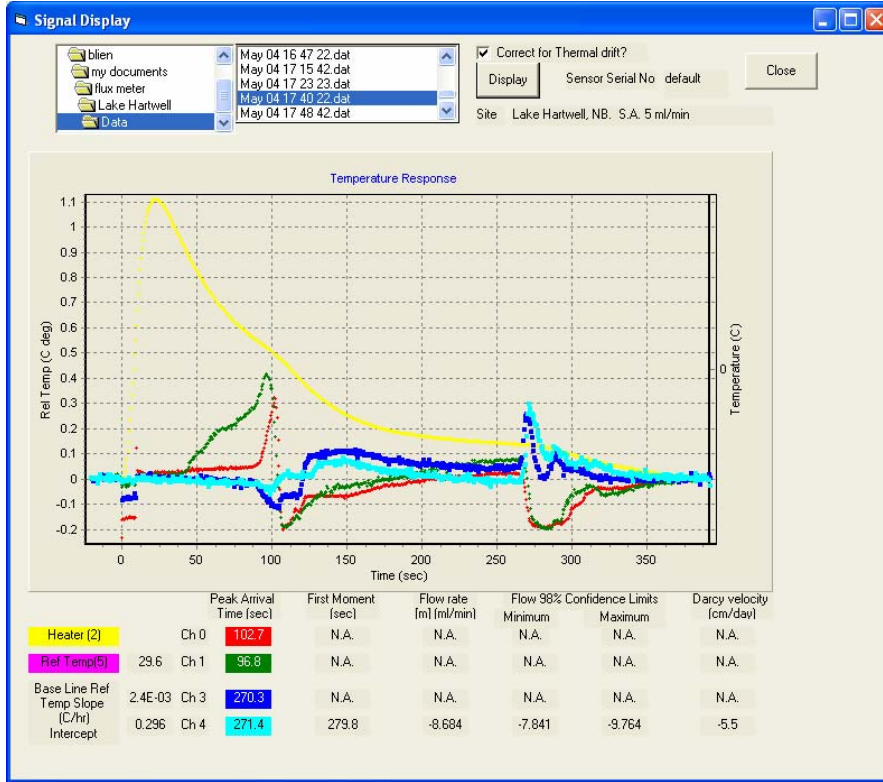
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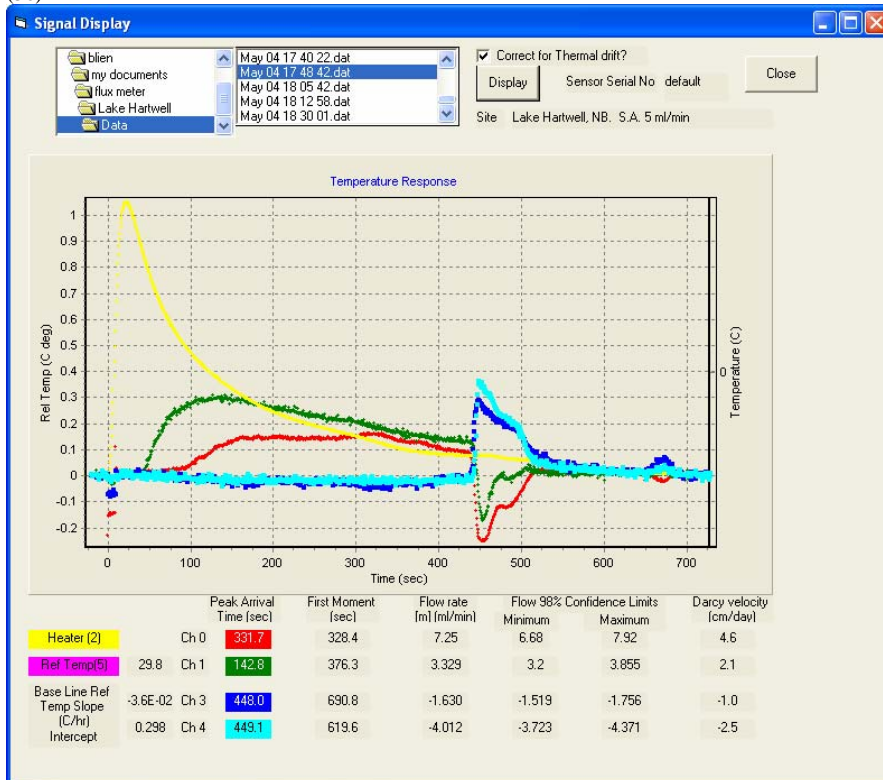
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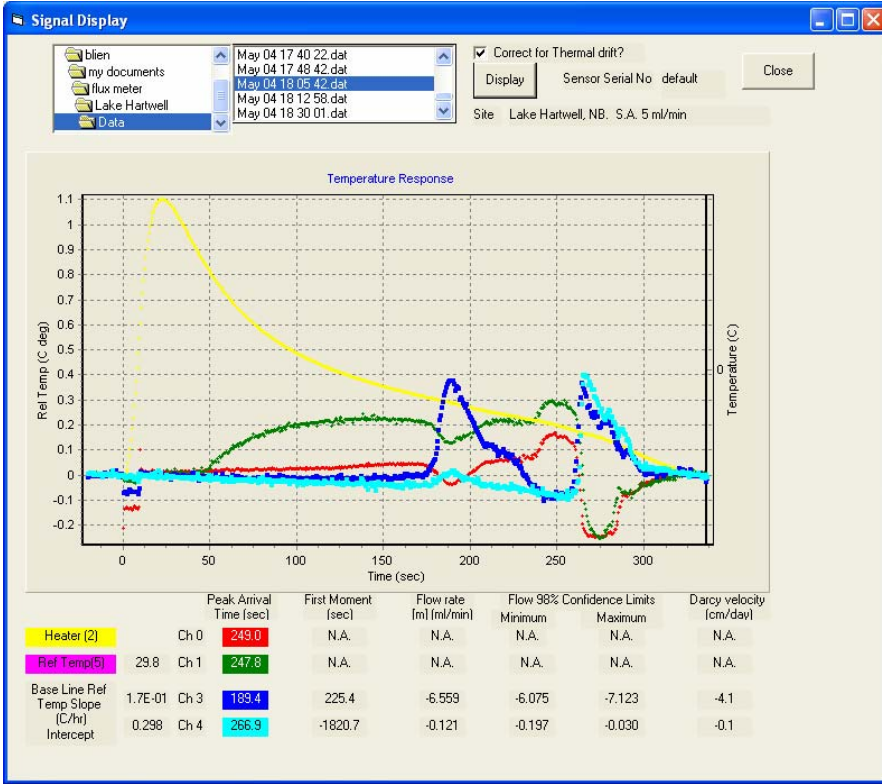
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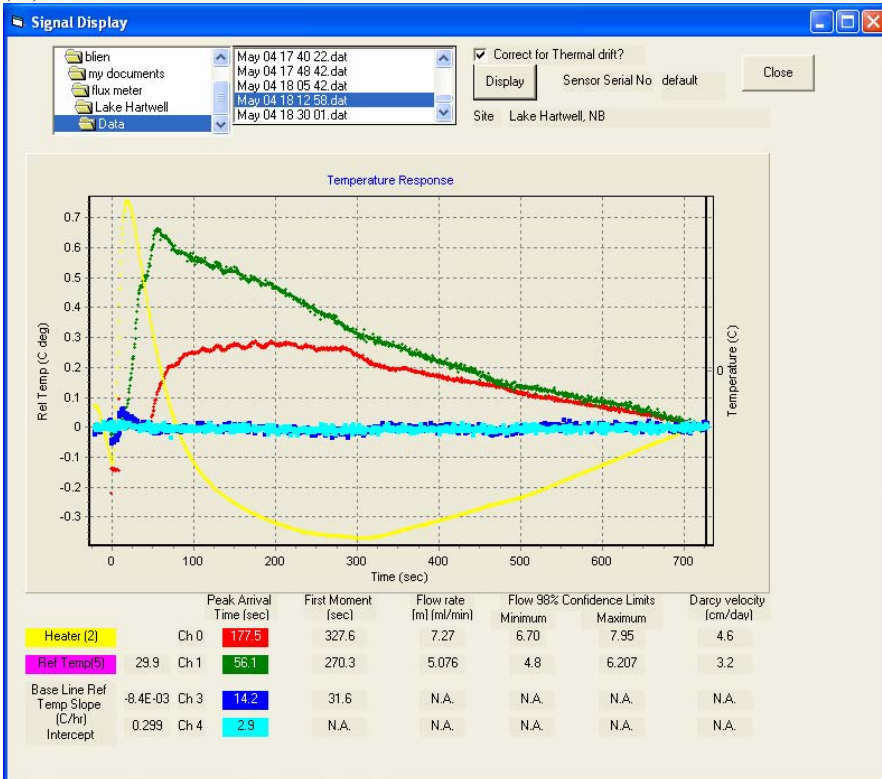
(36)



(37)



(38)



(39)

