



# **The design, fabrication, testing, and deployment of a temperature probe for determining fluid flow rates at Chemosynthetic Biological Communities**

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## **ABSTRACT**

Long-term monitoring of flow rates at Chemosynthetic Biological Communities (CBCs) is necessary to investigate the dynamics of cold seep processes. A new stand-alone 1.5 meter long temperature probe was built to resolve flow rates from 1 m/yr to 1 km/yr at 1 minute resolution by logging measurements of ambient temperature at 15 depths below the seafloor at 0.01°C resolution. Upon instrument recovery, flow rates can be calculated from the curvature of the temperature-depth profile. A description of the electrical, software, and mechanical engineering phase of instrumentation; instrument assembly, testing and deployment at a Monterey Bay CBC Extrovert Cliffs is presented. Instrument tests in the lab, cold room and test tank show the precision of the temperature measurements meet the design requirements. An equilibration time of fifteen minutes is observed for the thermistors which are encased by a 1/8" wall polycarbonate tubing, however temporal resolution of relative flow rate changes is significantly shorter as a temperature transient causes an immediately observable change in thermistor circuit output. The recovery of the temperature probe from Extrovert cliffs is scheduled for September 20, 2006. Calibration of the thermistors can be preformed after instrument recovery.

## **INTRODUCTION**

The many CBCs active in Monterey Bay today are thought to be driven by lateral flow of hydrocarbons/gases, meteoric waters, and/or vertical flow of overpressured fluids at depth due to tectonic compression (Greene et. al. 1999). By measuring flow rates at CBCs scientists can obtain insight into the dynamic processes occurring beneath the seafloor, for example, the mechanisms driving fluid flow and water-rock chemical interactions. Also, the support of resident biological and even microbial organisms depends on rates of nutrient rich fluids that change through time. Furthermore, measurements in input fluxes into the ocean are important for chemical mass balance calculations.

Existing techniques for measuring flow rates include producing an artificial chemical or heat tracer and measuring concentration-dilution, or time of flight measurement of the tracer, directly measuring volume flux, or inferring flow rate from profile measurements of temperature or concentration of a naturally occurring conservative chemical with depth (Fisher, 2005, Tryon et. al., 2005 and references therein). I have chosen to make the desired long-term measurements of flow rate at CBCs using the temperature-depth profiling technique. Advantages of this technique are: 1) the instrument doesn't obstruct flow pathway causing fluid deflection, allowing for absolute flow rate determination at high flow rates, km/year, 2) its simple design makes it quick and cost efficient to build, and 3) with no limited reserve for tracer or sample collection, it can be hooked up to observatory networks providing power and communication and requires no additional support.

The conversion of temperature-depth profile data into vertical advective flow rates is straightforward as the following analytical temperature-depth relationship exists for vertical flow through a saturated, isotropic, and homogeneous semiconfined layer (Bredehoeft and Papadopulos, 1965):

$$f(\beta, z/L) = (T_z - T_0) / (T_L - T_0) = [\exp(\beta z/L) - 1] / [\exp(\beta) - 1] \quad (1)$$

$T_z$  is the temperature at any depth  $z$ ,  $T_0$  and  $T_L$  are the uppermost and lowermost temperature measurements respectively,  $L$  is the length of the vertical section over which the temperature measurements are made and

$$\beta = v_z c_0 \rho_0 L / \kappa, \quad (2)$$

where  $v_z$  is the vertical fluid velocity,  $\kappa$  is the thermal conductivity of the solid-fluid complex,  $c_0$  is the specific heat of the fluid, and  $\rho_0$  is the density of the fluid. A sediment layer with no vertical flow has a geothermal gradient, a linear increase in temperature with depth, figure 1 ( $\beta \rightarrow 0$ ). As advection is faster than conduction any vertical flow distorts the temperature profile, e.g. when hotter fluids are pushed upward temperature-depth curve bows upward ( $\beta < 0$ ) and when colder fluids are pulled downward the profile bows downward ( $\beta > 0$ ). A type-curve method can then be used to determine the dimensionless parameter  $\beta$  from which an absolute flow rate determination can be made using equation 2. Even without knowing the material parameters, the temperature-depth profile can be used for making relative flow rate measurements at seeps in a simple and non-obstructive way.

While scientists have been using temperature probes for decades (Hyndman et.al., 1979, Fisher and Hounslow, 1990, Davis and Villinger, 1992) making successful measurements of heat flux at a single point in time by dropping probes from a surface ship, a temperature probe for long-term monitoring of flow rates is desired for controlled penetration into an active seep using an ROV or manned submersible. In order to resolve flow rates of meters to kilometers per year at CBCs the temperature probe built needed to have a temperature resolution of  $0.01^\circ\text{C}$ . A 1 minute temporal resolution is required for detection of transient flow events. Although a 10% accuracy of flow rate determination is desirable, the detection of relative changes in flow rates is of primary importance. Other functional requirements for the temperature probe are that it: 1) be a stand-alone instrument that will operate and log data for 16 months, 2) be strong enough to withstand insertion into clays and silty-sands via ROV/ submersible manipulation, 3) be pressure rated to 4000 meters, 4) measure a temperature range of at least  $0\text{-}12^\circ\text{C}$ , 5) record a bottom water temperature record with temporal resolution of at least 1440 samples per

day to capture changes in bottom water, and 6) measure sediment temperatures at a temporal resolution adequate for the particular environment, i.e. a minimum sampling rate of 1440 samples per day at high flow rate seeps (100 m/yr or greater) and 24 samples per day at a lower flow rate seeps (10 m/yr or less). Additional desires including the capability to remove the temperature sensors in order to make changes after assembly, and a mechanism for determination of the quality of readings from temperature sensors in the probe after penetration into the sediment were addressed as well. Other potential enhancements that have been noted as possible future modifications, but were not attempted in this summer project, are listed in the recommendations section.

## **MATERIALS AND METHODS**

The stand-alone temperature probe built to meet these specified functional requirements consists of several physical components: 1) hardware for encasing electronics to protect them from the saltwater, 2) the electronics: temperature sensors, circuitry, data logger and batteries, and 3) cabling. With the time constraints of the internship project, leverage of available existing components was essential. The pressure housing for the circuitry, data logger and battery pack was provided by Hans Jannasch. Cabling between the pressure housing and a temperature probe to house the temperature sensors was provided by Hans Jannasch and the ROV Ventana group. The tasks for the summer then included: 1) select a temperature sensor, 2) design and fabricate a temperature probe, 3) select a data logger, 4) design and wire necessary circuitry to take digital readings of the analog sensor, 3) program the data logger to perform sampling and recording tasks and interface with the user, 4) assemble the temperature probe and mount electronics in pressure housing, 5) test the instrument's performance, 6) deploy the package, 7) recover and download temperature-depth profile data, and 8) calibrate the temperature sensors in order to convert logged temperature sensor measurements into absolute temperatures.

## **SENSOR SELECTION**

Criteria for sensor selection are listed in order of importance for this particular application: 1) *Stability* over time of resistance readings needs to be excellent. 2) *Resistance to temperature ratio* ( $\%/^{\circ}\text{C}$ ), a measure of change of resistance for a unit change of temperature, should be as high as possible to achieve the greatest resolution in temperature measurements. Material constant  $\beta$ , or temperature coefficient  $\alpha$ , are also proxies of the sensor sensitivity. 3) *Nominal resistance value* - the lower the better (as long as resistance is at least 10 k $\Omega$  so lead wire length resistances are insignificant) since the ADC requires an input current on the order of tens of micro-amps to accurately convert the analog signal. 4) *Size and ease of handling* needs to be appropriate for necessary spacing of thermistors, diameter of probe desired for thermal propagation from surrounding sediments into probe, but at the same time be reasonably easy to handle. 5) *Dissipation constant* should be as high as possible to minimize the self heat error. This is lower on the priority list because most NTC thermistors out there have a dissipation constant that results in an insignificant amount of error for the amount of power that will be applied to the circuit. 6) *Interchangeability and tolerances* don't matter so much since calibration of each sensor is to be performed in order to achieve desired accuracy.

I chose a glass encapsulated negative temperature coefficient (NTC) type thermistor for the best stability and resistance to temperature ratio. It is in an easy to handle package, but still sufficiently small. For a given material a thermistor with a higher nominal resistance value has a higher resistance to temperature ratio. There is a trade off between the resulting improvement in resolution due the steeper resistance to temperature curve and the reduction of resolution due to reduction of input current. Ultimately, the selection of values for many of the above criteria were predetermined by which glass encapsulated beads the manufacture had available in a sufficient quantity, i.e. at least twenty. The thermistor used in this temperature probe, YSI part #51A76, is 0.5" long x 0.1" diameter with 28AWG radial leads. It has a nominal resistance of 100 k $\Omega \pm 6\%$ , a temperature coefficient of  $-4.6 \%/^{\circ}\text{C}$ , and a dissipation constant of 3.5mW/ $^{\circ}\text{C}$  in still oil.

## TEMPERATURE PROBE

Having purchased the optimal temperature sensor that was immediately available, meeting the functional requirements had to be ensured through the physical design of the probe. This involved analytical analysis to: 1) determine the temperature resolution necessary to sense the 1 m/yr lower limit of flow rate, and 2) determine the thermistor spacing required to distinguish the 1 km/yr upper limit of flow rate. The time constant of the material encasing the thermistors was determined by using both an analytical one-term approximation to the series solution for transient one-dimensional conduction, and a finite element numerical approximation. I also performed a finite element numerical analysis to determine the effect of longitudinal propagation of changes in bottom water temperatures along a metallic probe outer casing.

To distinguish a 1m/yr flow rate from no flow, the curvature of the temperature depth profile must be measurable. Recall equation 1. For a given flow rate the beta value is higher, and hence the curvature is more distinct, for longer probe lengths. Through a consensus of opinions of ROV Ventana pilots, MBARI scientists, and engineers with experience inserting elongate objects into the cold seeps, a 1.5 meter length probe was chosen as a maximum length for feasible insertion into the seep site. By plugging an expected 9.5°C minimum temperature at a 110 meter minimum depth of the fluid source for the extrovert cliff seep (LaBonte et.al., in review) and a minimum  $\beta$  magnitude of -0.2 ( $\rho = 1000\text{kg/m}^3$ ,  $c = 4200\text{ J/kg}^\circ\text{C}$ ,  $v = -1\text{m/yr} = -3.2\text{e-}8\text{m/s}$ , maximum  $\kappa = 1\text{W/m}^\circ\text{C}$ ) into equation 1 and solving for temperature  $T_z$  at each potential thermistor location along the 1.5 meter probe, it is easy to see the maximum difference from linearity,  $>0.02^\circ\text{C}$ , occurs mid-length along the probe, Figure 2. This calculation demonstrates that a  $0.01^\circ\text{C} \pm 0.005^\circ\text{C}$  temperature resolution would be adequate to distinguish a 1m/yr flow rate from a geothermal gradient.

While the limit for detecting low flow rates depends on the temperature resolution, the limit for absolute determination of high flow rates depends on the spacing of uppermost thermistors in the case of upward advecting fluids. The maximum distance between the seafloor where the first thermistor is ideally aligned and the second thermistor, and consecutive several thermistors was chosen by again calculating  $T_z$  values for a 1 km/yr upward flow rate, a maximum  $\beta$  magnitude of -200, and finding the spacing at which at least two temperature measurements are made over the sharp increase in

temperature at the seawater interface. Figure 3 illustrates the final selection of thermistor spacing of 0.00889m (0.35") between the uppermost thermistor located at the seafloor and the next consecutive 5 thermistors. The 4<sup>th</sup> 5<sup>th</sup> and 6<sup>th</sup> thermistors in the thermistor string are at the same small spacing as the 1<sup>st</sup> 2<sup>nd</sup> and 3<sup>rd</sup> in order to design for difficulty in perfectly aligning the 1<sup>st</sup> thermistor with the seawater interface.

Next, the thickness and type of the material between the thermistor and sediments were chosen. Traditionally probes are made with a metallic outer casing for rapid conduction of heat from the surrounding sediments through to encased temperature sensors that are touching the inner wall. However, a concern of changes in bottom water temperatures conducting longitudinally and skewing thermistor readings at depth led me to consider alternatives. The suggestion of an epoxy filled length of heat shrink encasing an inner steel or plastic rod backbone to which the thermistors could be mounted was considered. However, I opted for a serviceable thermistor string assembly inside a polycarbonate outer casing, which is strong enough to withstand ROV manipulation, clear, and available in a variety of sizes.

I chose to use polycarbonate tubing with 1" outer diameter (OD), and a 0.125" wall thickness. The time constant for the polycarbonate cylinder to reach 90% equilibration when subject to an external heat transient was calculated using analytical one-term approximation to the series solution for transient one-dimensional conduction (Incropera and DeWitt), and a finite element numerical approximation resulted in values of 1600 seconds and 400 seconds respectively. The cause for the discrepancy between the two approximations has yet to be worked out. Results from a preliminary finite element numerical analysis later showed the effects of longitudinal propagation along a 0.5" OD length of stainless steel tubing with 0.035" wall is negligible as the high specific heat of surrounding saturated sediments dissipates any heat anomaly propagating down the probe. Upon completion of these thermal analyses three weeks into the internship, a decision at the critical design review was made to move forward with fabrication of the probe using the polycarbonate outer casing already in hand while noting a metal housing with a lower time constant is a possible future upgrade. A more immediate upgrade would be to reduce the time constant by pitting the outside of the polycarbonate probe housing at thermistor locations. This would not induce any local failure as the probe is oil

filled since the buckling stress of the polycarbonate housing is exceeded when subjected to the pressure of 4000 meter depth.

## DESIGN and FABRICATION OF TEMPERATURE PROBE

The microprocessor is stacked with two 8-channel analog-to-digital converters (ADC). The system is capable of monitoring 16 channels. One channel will be recording the bottom water temperature from a thermistor mounted within the electronic pressure housing, and the remaining 15 channels will read signals from thermistors mounted in the temperature probe. Design specifications emerging from the theoretical analyses in the previous section include the spacing of the thermistors at 0, 0.35, 0.7, 1.05, 1.4, 1.75, 3.5, 5.5, 7.5, 10.5, 16, 26, 36.5, 47, 58 inches depth, figure 2 and figure 3, and a polycarbonate 1" OD, 0.125" wall tubing as the outer casing for the probe. The remaining design requirements for the physical construction of the temperature probe are: 1) the majority of volume inside probe be filled with mounting material to reduce the potential of convection of the void filling oil and disturbing the thermal gradient, internal structure also helps with rigidity of probe length upon insertion and resistance to being crushed by ROV manipulator grip 2) the 15 thermistors in the probe be stabilized at their chosen locations, 3) the thermistors be pressed up against the inner diameter (ID) of the polycarbonate housing, 4) there is adequate space for thermistor circuit wiring 5) the components are sealed from the external environment, 6) there is a bulkhead connector passing circuit wiring to submersible cabling 7) there is a port for oil filling the probe, 8) there is an attached oil compensation volume, 9) there are locations for ROV manipulator to grip, push and pull, 10) there is a visible and potentially physical marker of insertion stop point, and 11) removal of thermistor string from polycarbonate housing be possible.

A solid Delrin rod that fits snugly in inside the polycarbonate tubing was used to mount the 15 thermistors, figure 4. The Delrin rod is not permanently mounted, rather a 5/8" compression spring ensures the distal end of Delrin rod rests against the probe tip, a pointed acrylic plug welded into the distal end of the polycarbonate tubing. A 1/8" through hole across the diameter of the proximal end of the Delrin rod allows for

insertion of a cross pin to assist in removal of this thermistor mount. I drilled holes in the rod through which thermistors and their leads are sleeved. Behind each thermistor sits a compressed spring forcing the thermistor to push against the inner wall of the polycarbonate outer casing, figure 5. A groove runs along the length of the probe where the leads of the thermistor exit the Delrin rod, opposite the head of the thermistor, and wire connections are made. To ensure a water tight probe, joints at the probe tip, and probe head were machined to fit snugly, and weld-on #16 was used to seal the joints. O-ring groove bore and plug diameters were modified from Parker o-ring catalogue specifications, and all o-ring surfaces have at least a 32 finish, figures 6,7&8. Because it is an oil filled system there is no external pressure holding probe head together. Four external tie rods hold the probe head plug to ensure the o-ring is in contact with the bore hole. The wall thickness of acrylic junction head cylinder is adequate for threading the bulkhead connector and NPT port for oil filling the probe and probe head, figure 8. The port for oil filling is 1/4" NPT and is located in the upper corner of the probe head to allow for air escape. This port also acts as port for attaching a length of tubing for oil compensation volume. For ROV handling during deployment, sections of the probe between thermistors can be gripped, figure 9a. The top cap of the probe head has no ports and pressure can be applied to force the probe down into the sediments. A monkey's fist attached to two eyebolts on two of the tie rods allows for the ROV to pull up the probe for recovery, figure 9b. The base of probe head is flush with the 0" depth thermistor. All fabrication of the probe and probe head was completed in the model shop at MBARI using the mill, lathe, wet saw, do-all saw.

## DATA LOGGING UNIT SELECTION

The functional requirements considered while selecting the microprocessor/data logger are that the instrument is to operate independently for 16 months and log data to solid state memory. Additional considerations include the size of the board, and user friendly operation. I purchased the Persistor CF2, a small, low power, data logging system with a built-in PicoDOS® operating system for this application. The Persistor CF2 is a 16Mhz Motorola 68332 based Single Board Computer, with 1MB SRAM and a CompactFlash

card drive. It operates at 3.3 volts but has a built in power regulator that accepts 3.6 to 20 volt input. In suspend mode it runs at a low current of <10uA and has a real time clock that allows wake from suspend mode. The Persistor CF2 is accessed via the RS232 port. To program the CF2, code is written in C and compiled with Metroworks Code Warrior linking with the provided Persistor CF2 libraries.

In addition to the microprocessor, a device for sampling the 16 temperature sensor outputs is required. Two narrow micro recipe cards (MRCP) were purchased from Persistor. The MRCP boards stack together under the CF2. Each MRCP has an analog-to-digital converter (ADC) that can convert signals on 8 channels at 16bit resolution, figure 10. To sample from the two ADCs on the two MRCP boards in the stack a few minor wiring modifications are necessary. The chip select 3, “C” connector pin 17, will be used to sample the ADC on the upper MRCP board, and the unused chip select 2, “C” connector pin 15, is wired to sample the ADC on the second MRCP board. These wiring modifications are made only on the lower MRCP board and include cutting the trace from chip select 3, “C” connector pin 17, that runs to the /CS on ADS8344, and adding a jumper from the chip select 2 trace from “C” connector pin 15 to trace running out to /CS that is no longer connected to chip select 3, figure 11.

## THERMISTOR CIRCUITRY

Thermistors are simply temperature sensitive resistors. In the previous section I introduced the ADC as the device that would take sample readings of the temperature sensors. However, the ADCs that convert the signal from the temperature sensor are converting an analog voltage signal to a digital voltage reading. Therefore, the signal the ADC converts is actually a voltage that is dependent on the resistance of the thermistor. This thermistor circuitry is simply a voltage divider circuit, with the negative temperature coefficient thermistor (NTC) in the place of R1, figure 12. The input voltage to the thermistor circuit is Vref. The output voltage from the circuit is a function of the resistance of the thermistor:

$$V_{out} = V_{in} * R2/(R1+R2).$$

An increase in temperature results in an increase in  $V_{out}$  as the resistance of the NTC thermistor decreases. To optimize the temperature resolution of the sensor circuitry, a value of 200K-Ohm is chosen for R2. Go to the YSI Excel spreadsheet that uses the third order polynomial equation to approximate the resistance-temperature curve and find that the resistance of 200K would result in the maximum change in resistance per degree C over the instrument operating temperature range specified in the functional requirements, 0-12 °C.

For best accuracy and precision, all 16 thermistor circuits are powered with  $V_{ref}$  supplied from voltage regulator LT1461 on the upper MRCP board.  $V_{ref}$  is the reference voltage that is supplied to the ADCs on both the upper and lower MRCP boards, see modifications in figure 11. The equivalent resistance of this thermistor circuitry at 4 °C is 33.75 K-Ohm, therefore, when powered at 2.5 volts, 0.074mA of current is drawn from the LT1461, an insignificant amount when compared to the 50mA current that the device can supply.

The current supplied to each ADC channel for sampling the signal from each thermistor is then a mere 4.5  $\mu$ A. This is only four times the leakage current of the ADC device, and likely will result in erroneous readings. To design out this possible problem, an external capacitor was put in parallel with R2 and acts to build up charge between the sample burst that occurs every minute. Also note that a 0.1 microfarad cap for filtering out high frequency 60 kHz noise in the lab was added to the circuit, again in parallel to R2. A 0.01 °C resolution was measured during the testing of ADC readings of the sensor circuitry. Having met the resolution necessary to distinguish flow rates specified in the functional requirements, no operational amplifiers, or further modifications to the circuitry were necessary to amplify the signal. This is fortunate as any amplification would likely amplify the noise as well.

## POWER SOURCE

The power supply is a twenty C cell battery pack arranged in four parallel circuits of five cells each. The most cost efficient arrangements for this 7.5V source were five, or four,

stacks of four, or five, C cells, respectively. Five stacks of four C cells was the arrangement that would fit inside of the pressure housing and leave enough room for the microprocessor/data logging unit, and thermistor circuitry. The battery pack was ordered from Energy Sales (Part number ES3205).

## SOFTWARE - DATA LOGGING and INTERFACING

By writing the software program that the microprocessor/data logging unit will run, the user is able to specify the tasks that need to be performed such as 1) sample all 16 ADC channels and remember them, 2) go to sleep, 3) periodically wake up to see if any tasks are waiting completion, 4) when memory is full, record accumulated data on CompactFlash.

In the final software programmed to run on the CF2 for temperature probe deployments, "JULY31.RUN", the first task to sample all 16 ADC channels is implemented at a specified time period of once per minute by calling a sample procedure. With the accompanying time stamp, each temperature-depth profile record is 36 bytes and the data acquisition rate is less than 1 MB per year. Within the sample procedure an average of 100 samples on each ADC channel is calculated to reduce noise by a factor of 10. The average for each of the 16 channels is stored in a sample buffer. After 512 calls to the sample procedure, the sample buffer is full and the data from the buffer is written to the CompactFlash card. At a 1 minute sample interval, this data dump occurs every 9 hours after which the buffer begins to fill again. This is done to minimize the number of writes to the CompactFlash card as the writes consume a relatively large amount of power.

The program also listens for commands to transmit data over the serial port, and exit the program. As long as the RS232 transmit, receive, and ground lines are passed from the Persistor CF2 in the pressure housing through a bulkhead connector in the end cap, in this case a SeaCon pie connector, on deck pre-deployment checks are practical, and making a connection to an observatory network would require only a minor modification.

While not sampling, saving to the flash card, or responding to commands sent over the serial port, the microprocessor is in a low power suspend mode to keep power consumption to a minimum.

## LED INDICATOR

After insertion of the probe into the sediment, a mechanism for immediate determination of flow rate is ideal. This would ensure that the probe is positioned in a seep recording a measurable flow rate before it is left deployed for months to years. As a reduced attempt to observe the performance of the probe right off, a decision to add a simple LED to the circuit was made. The LED wouldn't indicate the flow rate, or even the temperature deviation at the site, but rather ensure the user of the functionality of the individual thermistor circuits during deployment. The LED is mounted for maximum visibility inside the seat for the compression spring in the top cap of the probe head with RTV sealant.

The software modifications for the LED circuit included a check on all 16 channels for 2.5 volt reading, indicating a short in the thermistor circuitry, or a 0 volt reading, indicating an open circuit, or broken connection. This check occurs each time the sample procedure is called, every minute, and the counts of shorts and opens are updated accordingly. The software then controls a blinking pattern of the green LED to indicate to the user if all 16 thermistors check out okay, and if not, how many thermistors are shorted, and how many are open, by setting connector "C" pin 27 to high to turn the LED on, and conversely, switching the pin to low to turn it back off. Timing of the blinks is as follows: 1) if all thermistors circuits are functioning properly: [LEDOn (2 seconds) LEDoff (2 seconds)], 2) if any shorts or opens are detected: [LEDoff (5s)]; repeat [LEDOn (0.5s) LEDoff(0.5s)] #shorts+1 times; [LEDoff(2s)]; repeat[LEDOn (0.5s) LEDoff(0.5s)] #opens+1 times. The LED indicator sequence is repeated, changing pattern according to changes in thermistor state if need be, until a preset time limit in the software ceases calls to the LED function. The preset time limit should be around three hours, ample time for the probe to descend with the ROV and be pushed into the seep sediments.

Circuitry for the LED should be implemented carefully. Clues from the tank test results, see TESTING section, I found out the hard way not to drive the LED without a constant current resistor in series, and even after adding this resistor, found that the 20mA still being drawn from the Persistor CF2 I/O pin was still significantly exceeding the current of 1-2mA that the microprocessor can supply. I finally added a NPN transistor to switch the primary current being provided to the LED from the I/O pin on the Persistor CF2 itself, to the 3.3 volt system power supply, but it was too late, and even the transistor's sub-milliamp current draw to the I/O pin caused problems in the readings of the ADC channels. A decision to scrap the LED indicator for this deployment was made.

#### ELECTRONIC ASSEMBLY and CABLING

Additional manufacturing, assembly and wiring besides that of the thermistor mount in the temperature probe itself include wiring the internal circuitry through the bulkhead connectors mounting the electronics within the pressure housing, and linking the probe and pressure housing with an underwater cable, etc.

Fabrication of the mounting board for the electronics, i.e. batteries, microprocessor/data logger, and circuitry, figure 13, from a 0.063" sheet of aluminum was completed on the mill. The microprocessor and circuitry were mounted to the board with 1/4" and 3/8" stand-offs. The battery pack was secured with tie-wraps.

Wire terminal connectors were added to the probe and pressure housing internal circuitry and mating terminal connectors were added to wires passing through the SEACON MINK-19 BCR bulkhead in the probe head, and the SEACON pie connector bulkhead in the pressure housing. Terminal connector genders were chosen so the probe and pressure housing internal circuitry could be connected directly, bypassing the bulkhead and cable connection.

All o-rings for both bulkhead connectors were cleaned and lubricated before the bulkhead connectors were screwed in. The junction between the three 6 circuit SEACON pie piece cables, D, E & F, and the 19 circuit MINK-19-CCP cable was potted. The resulting length of the underwater cable is two meters, allowing for ROV to maneuver the probe without tugging on the attached pressure housing.

A final cabling job was to junction a DB-9 connector cable to the SEACON pie piece cable for communication with the microprocessor while it is sealed inside the pressure housing via pie connector port C. In accordance, the transmit receive and ground circuit connections had to be made to the internal SEACON bulkhead connector wiring as well using mating plug and housing wire terminal receptacles.

## TESTING

The testing phase included an overnight test in the lab, a 24 hour cold room test, and a tank test. These tests were completed in last four days before deployment, so any failures discovered had to be dealt with quickly or not at all.

The overnight test was set up by directly connecting the electronics circuitry internal to the probe to circuitry in the pressure housing, bypassing the underwater cable. The LED indicator was not connected. A jumpy signal was observed on ad\_2 channel 7, corresponding to the bottom water thermistor measurement. After changing out the thermistor potted in the pressure housing, I realized the thermistor itself was not the problem, but rather this particular thermistor circuit was not properly grounded.

After fixing the grounding error, all 16 thermistor circuits were confirmed to be functional. The LED indicator circuit was connected so the condition of the thermistors could be monitored during the wet test. To prepare for the tank test, the probe and its oil compensation volume were filled with less than a pint of Tellus 22 oil, desiccant packs were placed in the pressure housing, probe and pressure housings were sealed and connected via the two meter joining underwater cable, and the securing jacket for pie connector connections was tightened down. Lines were tied to both the pressure housing and probe, and the two instrument pieces were simultaneously lowered to the bottom of the tank. The LED repeated the two second on, two second off sequence, indicating no thermistor circuit failures had occurred for the entire tank test of about an hour and a half. With this LED indicator, I could be largely confident there were no water leaks.

After recovering the temperature probe instrument, I transferred the data to a desktop computer via the RS232 DB-9 to pie connector cable. Unfortunately, readings on channels ad\_1 channels 1 and 2, corresponding to thermistors at depths 0.35” and 0.7”, strongly oscillate with LED blinks and oscillation is detectable on all other

channels. Paul McGill helped me to pinpoint the problem, that the driving circuitry for the LED was drawing too much current from the microprocessor I/O pin. His suggestion to add a transistor to the circuit was attempted, however, readings still oscillate, and it is possible I already damaged the I/O pin. Out of time, the decision to leave the LED unconnected for the deployment was made.

A final test was completed before the upcoming deployment in the cold room which is kept at approximately 4°C. Results showed that with the LED unplugged, the oscillation in the signal is gone, although channels 1 and 2 on ad\_1 still look a bit suspicious in their magnitude and rate of change as compared to the rest of the thermistors. Otherwise, the system performed as expected during this simulation of seafloor temperature conditions.

## DEPLOYMENT

After bringing the temperature probe from the cold room back to the lab, the final software program to be used for the deployment, 'JULY31.RUN', ran on the microprocessor for the remainder of the weekend. On the morning of July 31<sup>st</sup>, 2006, the data was transferred for final confirmation of thermistor functionality. Channels 1 and 2 on ad\_1 still looked unreliable, and a short on ad\_2 channel 4, corresponding to the thermistor at a 36.5" depth, had materialized. Through resistance checks I found the short to be within the oil filled temperature probe itself. I decided to go ahead and deploy the prototype probe despite the one short and the unreliable readings on two channels. Instead of using the base of the probe head as the seafloor boundary indicator, I added yellow labeling tape to the tie rods to mark a new seafloor boundary so the probe would only be inserted up to the thermistor being recorded on ad\_1 channel 2 and the properly functioning thermistors being recorded on ad\_1 channels 3, 4, and 5 would be correctly positioned to capture the sharp temperature gradient near the seafloor.

At 13:22 GMT I started the software program 'JULY31.RUN', providing an output filename of 'JULY31DAT' in the command line. After loading the instrument onto the boat, and taping off the thermistor locations to mark where probe should not be gripped with the ROV manipulator, I transferred the data acquired during the morning for

final confirmation that the program is currently running and sampling the 16 ADC channels every minute.

With the program still running, the pie connector C dummy plug properly replaced after the data transfer through the pie C port, and all other connections, o-ring seats secured, the temperature probe was secured onto the porch of the ROV Ventana. At 17:30 GMT the probe was inserted to the base of the new yellow label tape in the Extrovert Cliffs seep at the southwest end of the lineament of seeps, 36° 46.5705N 122° 05.1425W.

## CALIBRATION

Calibration of the thermistors in order to convert thermistor readings into absolute temperatures will be completed during the recovery dive on September 20, 2006. With the CTD turned on for accurate temperature measurements, the ROV will stop for 10-15 minutes at the seafloor, and make an additional one or two stops along the ascent of the instrument.

## RESULTS

As the temperature probe instrument has yet to be recovered from Extrovert Cliffs, results of instrument performance pertaining to the overall design of the instrument as deduced from the testing phase are reported here. Circuitry errors discovered in the testing phase were previously discussed in the TESTING section.

The temperature resolution requirement of 0.01°C for the thermistor measurements was met. Theoretically, the range of flow rates that can be determined using this temperature probe will be the desired 1 m/yr to 1 km/yr. The instrument is capable of long-term monitoring of the 15 thermistor measurements recording the temperature depth profile, and one bottom water thermistor measurement at 1 minute sample resolution. Probe held up to insertion into the CBC via ROV manipulation, and although not tested, I am confident the instrument will withstand pressures at 4000m.

## POWER CONSUMPTION CALCULATION

Measurements of current draw during low power suspend mode, sample, and write to CompactFlash were 3mA, 45mA and 53mA, respectively. The sample procedure duration is on the order of tens of milliseconds every minute, and the write to flash procedure duration is on the order of seconds every nine hours. From these measurements a conservative estimate of 3.022 mA average current consumption is calculated. The alkaline C cell 7.5 volt DC source has a 33.3 Amp hours capacity. A quick approximation implies the temperature probe can run for just under 460 days.

## TIME CONSTANT FOR THERMAL EQUILIBRATION

A fifteen minute time constant, or the time by which the thermistor reading is 90% of the way to equilibrium, is very close to the analytical approximation for an infinite cylinder. Larger delays in response time for both the bottom water thermistor measurement and the thermistor at the end of probe, 60.5” are observed.

## DISCUSSION

As a prototype instrument, the temperature probe shows promising results. The “musts” of the functional requirements have all been met. It is important to understand that the fifteen minute equilibration time does not impede the one minute temporal resolution specified in the functional requirements if the primary goal is to measure relative flow rates. For example, a transient heat event occurs and although the time to reach equilibrium is longer than one minute, these transient temperature changes are still detectable immediately since heat transfer throughout the probe section begins the moment the transient occurs.

## CONCLUSIONS/RECOMMENDATIONS

The problems that I encountered during the testing phase were all instructive. The short failure in the probe thermistor wiring circuit emphasizes the benefit of a removable and serviceable probe design. With a prototype-testing phase cut short, I ran into problems that the engineering review process would have helped to avoid, such as the incorrectly wired LED circuit.

Before any future deployments, a quick test of ADC readings with the LED indicator transistor circuit driven from a different I/O pin on the CF2 microprocessor, or from a new CF2 and MRCPs stack, needs to be done before the LED indicator circuit is connected back up for future deployments. Further modifications to this prototype would be adding a more intelligent mechanism for determination of flow rate and adequate probe positioning at the time of deployment. Possibilities include 1) make an RS232 connection for communication using an Inductive Coupled Link (ICL), and 2) have the LED indicate temperature at the deepest thermistor.

Recommendations for a second prototype temperature probe that may not be optimal at Extrovert Cliffs, but would be capable of making measurements at more extreme environments include 1) be pressure rated to 6500 meters for measurements at Marianas Mud Volcanoes, 2) measure a temperature range of 0-50° C using a titanium sheath for protection in corrosive hydrothermal fluids.

I am sure more recommendations for improvement will form after the scheduled recovery of the temperature probe on September 20<sup>th</sup>, 2006, calibration of the sensors, and analysis of the data.

## **ACKNOWLEDGEMENTS**

I'd like to acknowledge my primary mentors Bill Kirkwood and Paul McGill, as well as science advisors Hans Jannasch and Geoff Wheat. The technical I received from engineers and technicians throughout MBARI was a lifesaver. The ROV Ventana crew, and Ken Johnson deserve thanks for ensuring the instrument got deployed during my internship. Finally, thank you to my design review committee members for their suggestions and encouragement, George Matsumoto for the internship experience, and MBARI as a whole.

## **References:**

Bredehoeft, J.D., and I.S. Papadopoulos, (1965). Rates of vertical groundwater movement estimated from the Earth's thermal profile. *Water Resources Research*, **1**: 325-328.

Davis, E.E., and H. Villinger, (1992). Tectonic and thermal structure of the middle valley sedimented rift, northern Juan de Fuca ridge. In: *Proceedings of the Ocean Drilling Program, Initial Reports*, edited by Davis, E.E., M.J. Mottl, A.T. Fisher, et. al., **139**: 9-40.

Fisher, A.T., (2005). Marine hydrogeology: recent accomplishments and future Opportunities. *Hydrogeology Journal*, **13**: 69-97.

Fisher, A.T., and M.W. Houslow, (1990). Transient fluid flow through the toe of the Barbados accretionary complex: constraints from ocean drilling program leg 110 heat flow studies and simple models. *Journal of Geophysical Research*, **95**: 8845-8858.

Greene, H.G., N. Maher, T.H. Naehr, and D.L. Orange, (1999). Fluid flow in the offshore Monterey Bay region, in *Late Cenozoic Fluid Seeps and Tectonics Along the San Gregorio Fault Zone in the Monterey Bay Region, California*. *American Association of Petroleum Geologists, Pacific Section, Volume and Guidebook*, edited by R.E. Garrison, I.W. Aiello, and J.C. Moore, pp. 1-19.

Hyndman, R.D., E.E. Davis, and J.A. Wright, (1979). The measurement of marine geothermal heat flow by a multipenetration probe with digital acoustic telemetry and insitu thermal conductivity. *Marine Geophysical Researches*, **4**: 181-205.

Incropera, F.P., and D.P. DeWitt (1981). *Fundamentals of Heat and Mass Transfer*, 2<sup>nd</sup> Edition, John Wiley & Sons, Inc., pp. 174-206.

LaBonte, A., K.M. Brown, and M.D. Tryon, (in review). Monitoring periodic and episodic flow events at Monterey Bay seeps using a new optical flow meter, *Journal of Geophysical Research*.

Tryon, M., K. Brown, L.R. Dorman, and A. Sauter, (2001). A new benthic aqueous flux meter for very low to moderate discharge rates. *Deep-Sea Research Part I-Oceanographic Research Papers*, **48**: 2121-2146.

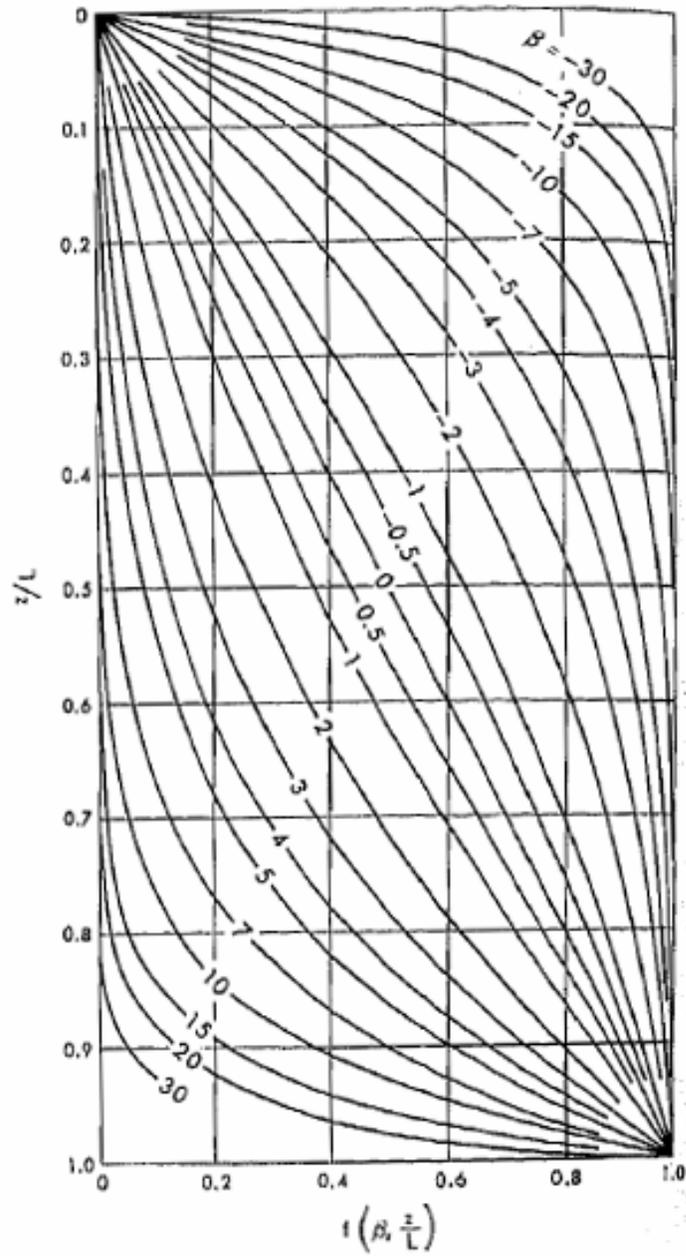


Figure 1: Type curves for function  $f(\beta, z/L)$ . From Bredehoeft and Papadopoulos, 1965.

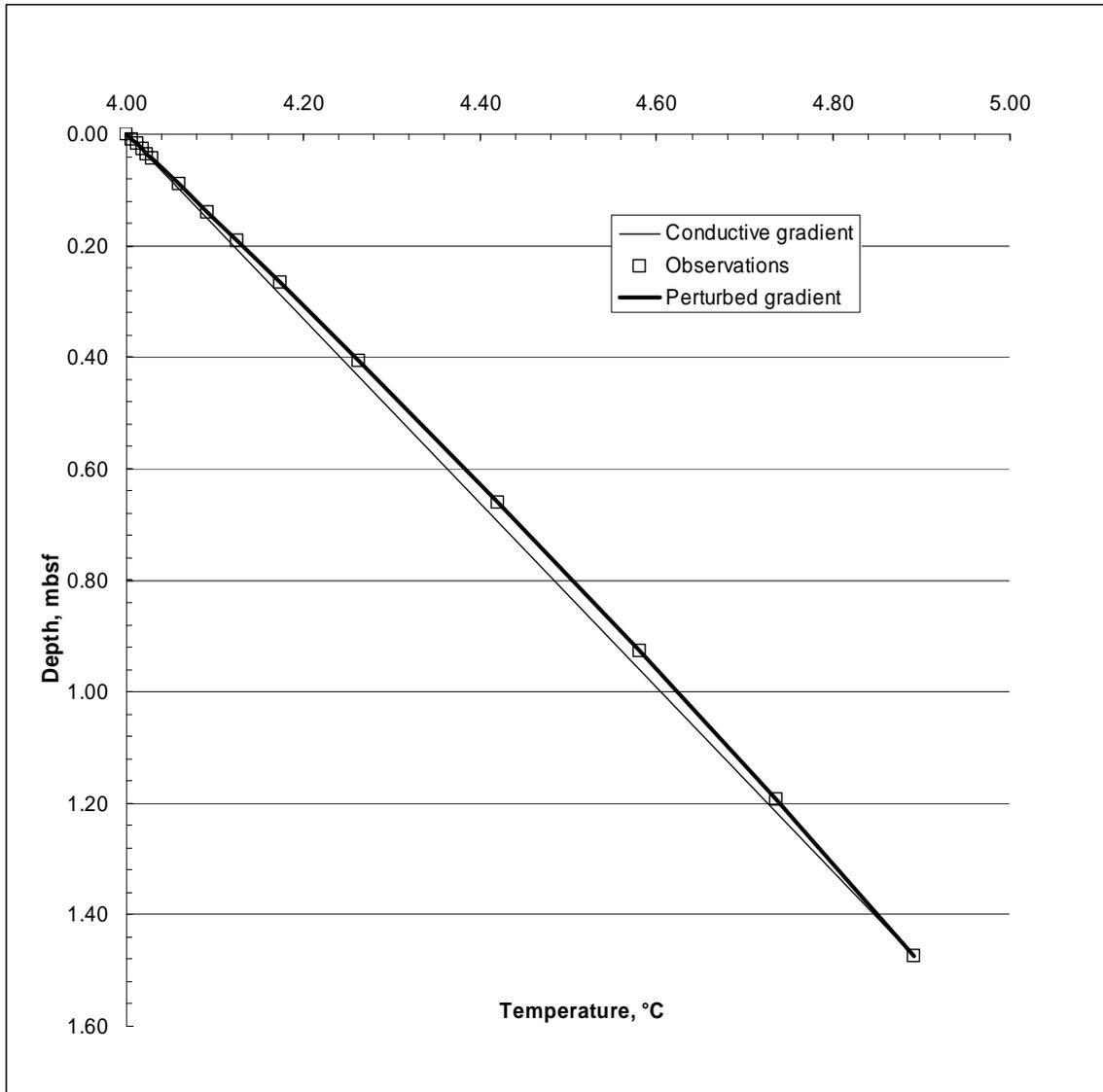


Figure 2: Analytical result of temperature-depth profile for vertical fluid flow of 1m/yr (perturbed gradient) as compared to a profile with no advective flow (conductive gradient). Squares along the curved, or perturbed temperature gradient indicate locations of thermistors along the 1.5 meter temperature probe, and their temperature readings.

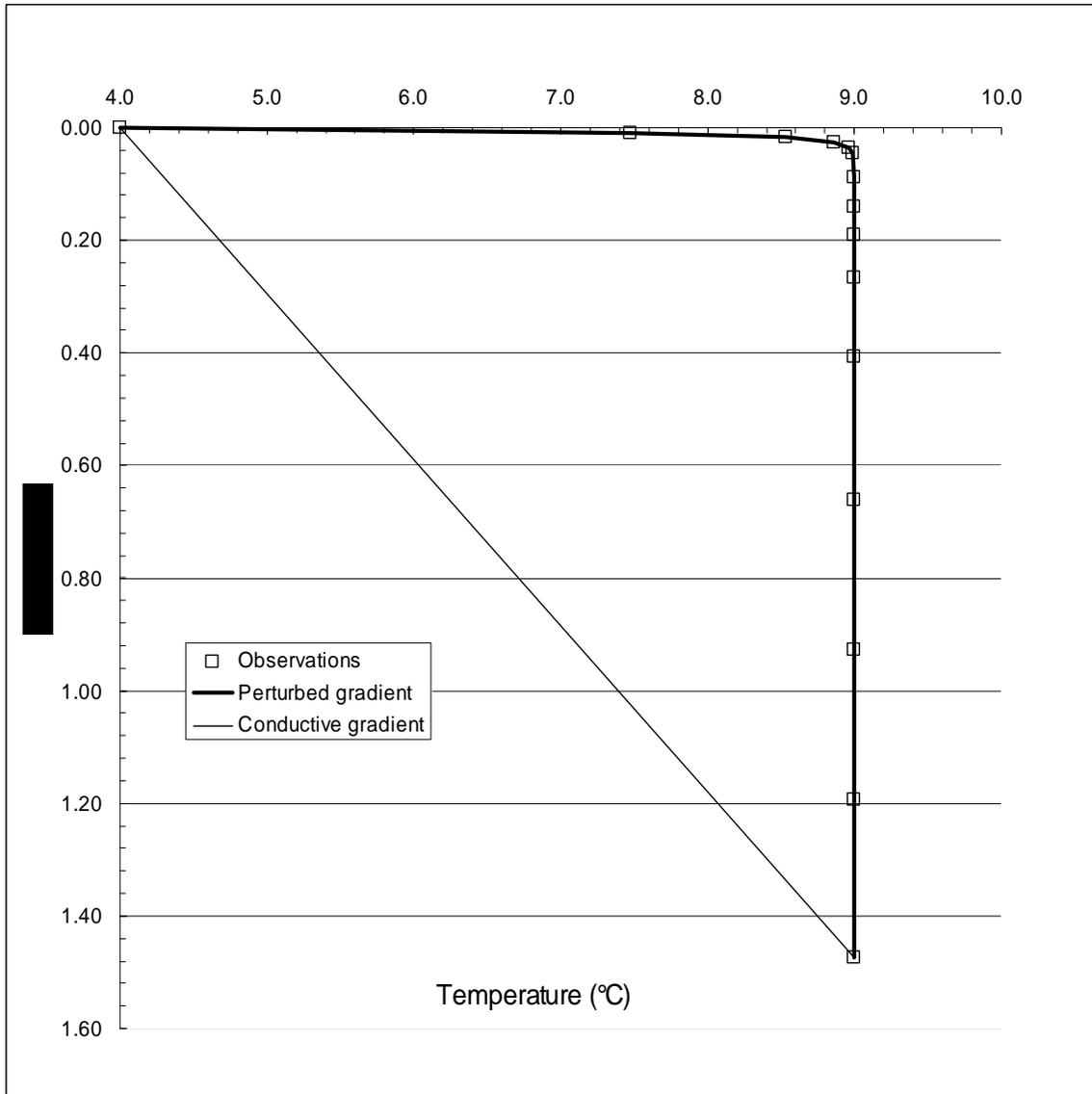


Figure 3: Analytical result of temperature-depth profile for vertical fluid flow of 1km/yr (perturbed gradient) as compared to a profile with no advective flow (conductive gradient). Squares along the curved, or perturbed temperature gradient indicate locations of thermistors along the 1.5 meter temperature probe, and their temperature readings.

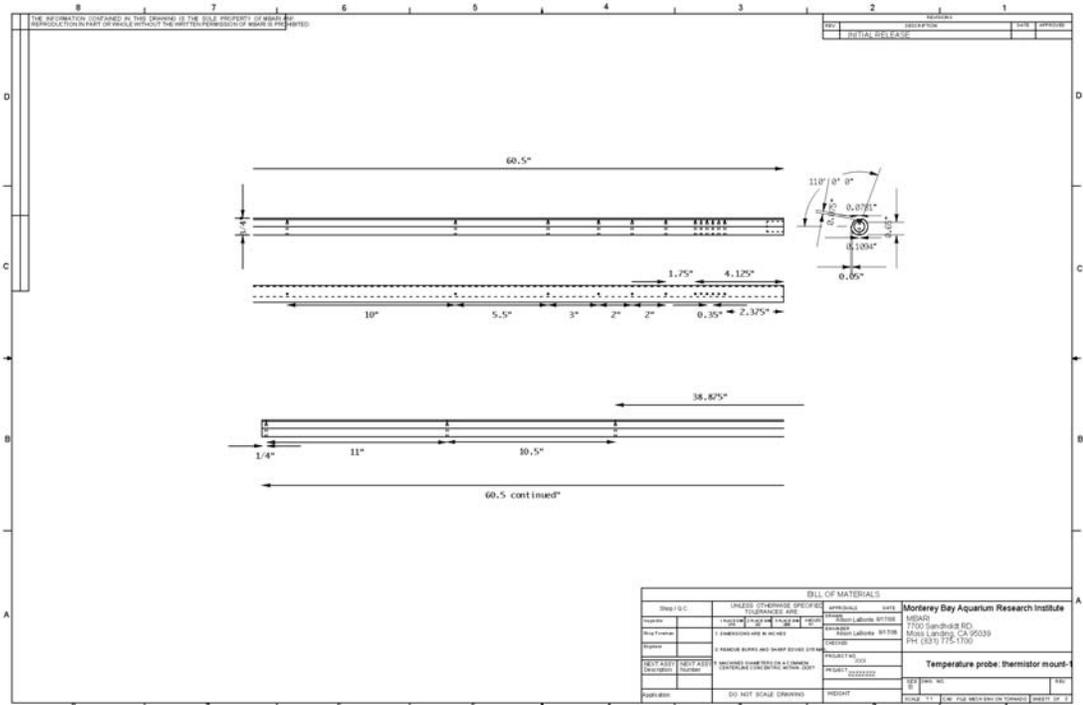


Figure 4: 3/4" Delrin rod thermistor mount design drawing.



Figure 5: Thermistor, compression spring that sits behind thermistor, and Teflon insulation around downstream lead of thermistor (not the Vref lead) shown before being sleeved into mounting hole in Delrin rod.







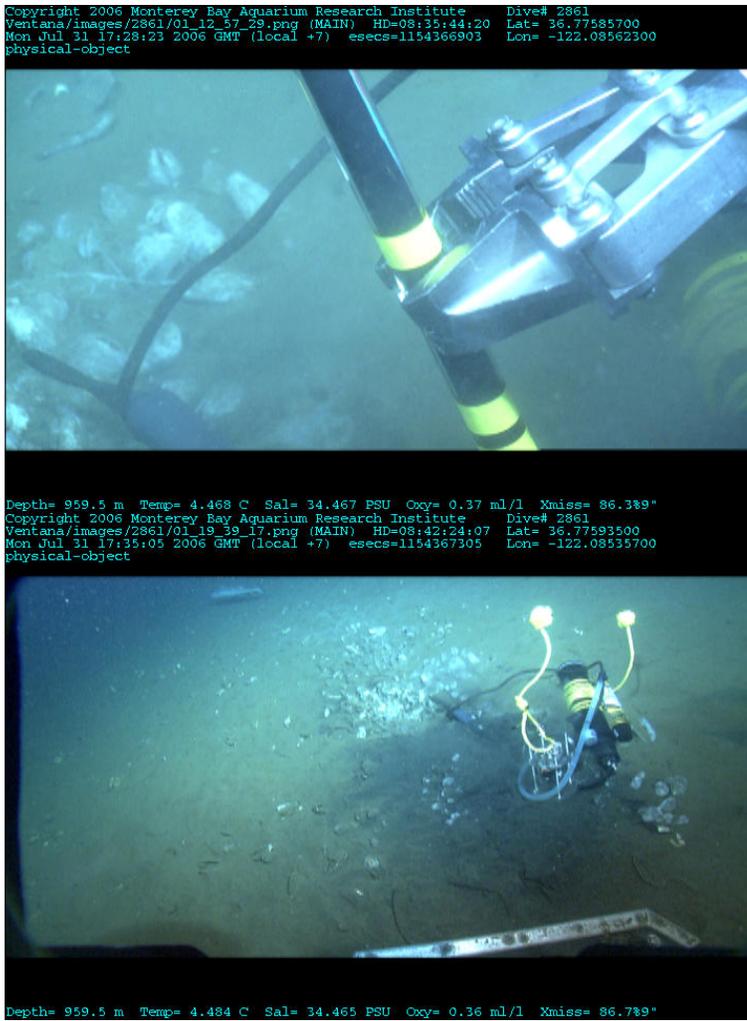


Figure 9a: ROV manipulator gripping between taped thermistor locations.  
9b: Pressure housing and probe head with monkey's fists for easy recovery.

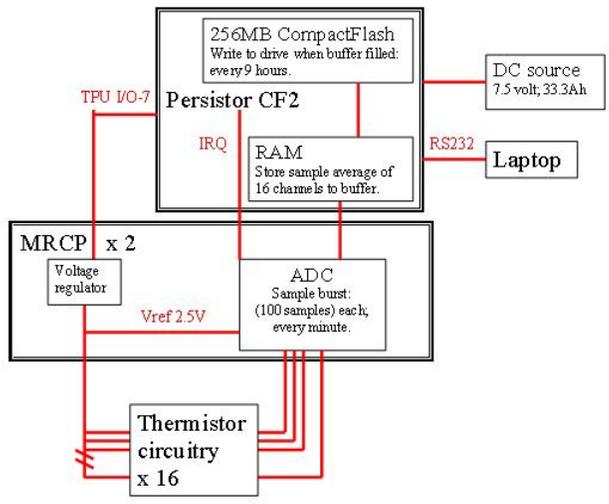


Figure 10: Schematic of electronic components of the temperature probe on a system control level.

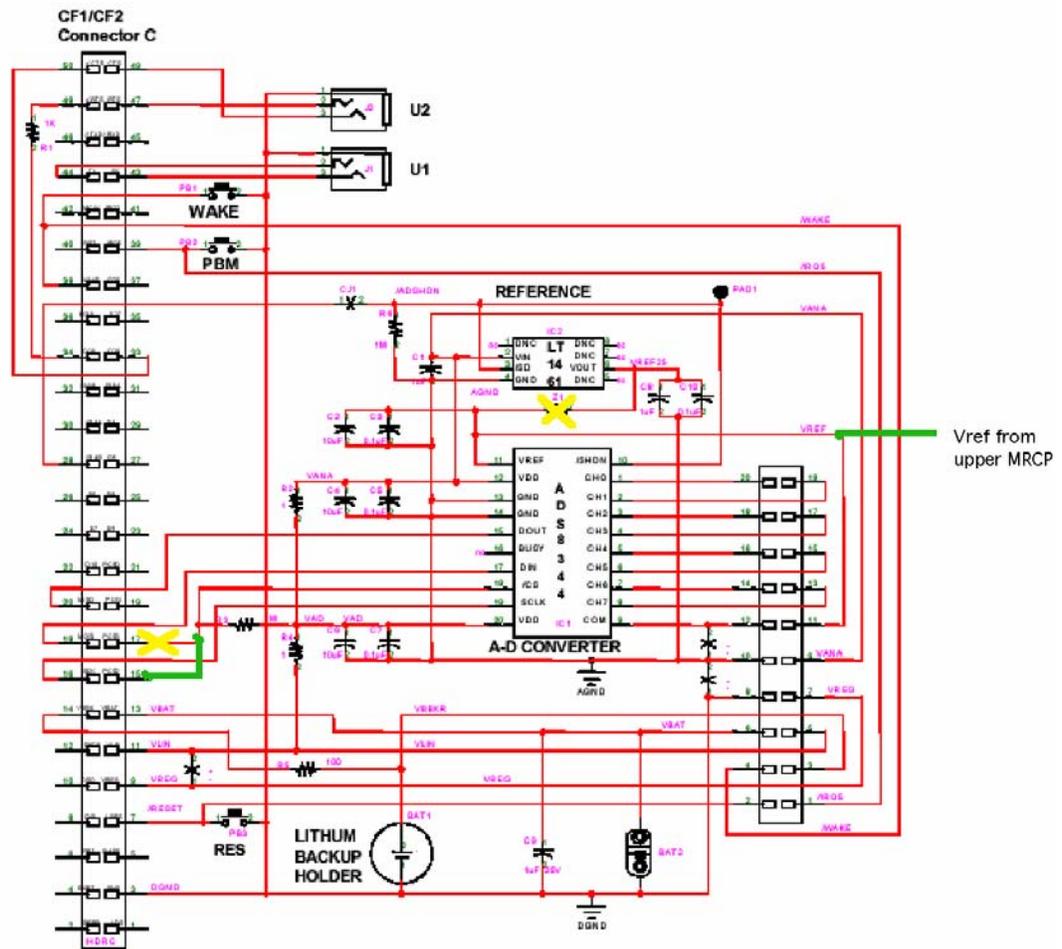


Figure 11: Schematic of lower micro recipe (MRCP) board with necessary modifications when stacked with another MRCP board indicated. Yellow 'X's indicate locations where the circuit has been broken. Green lines indicate new circuit connections.

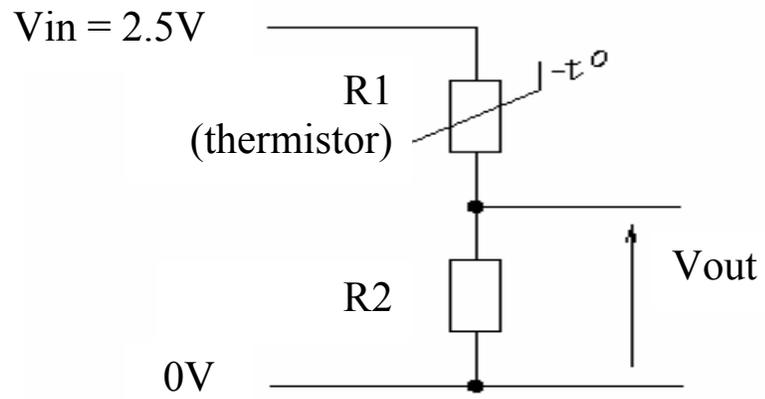


Figure 12: Schematic of voltage divider thermistor circuit before addition of external capacitors.

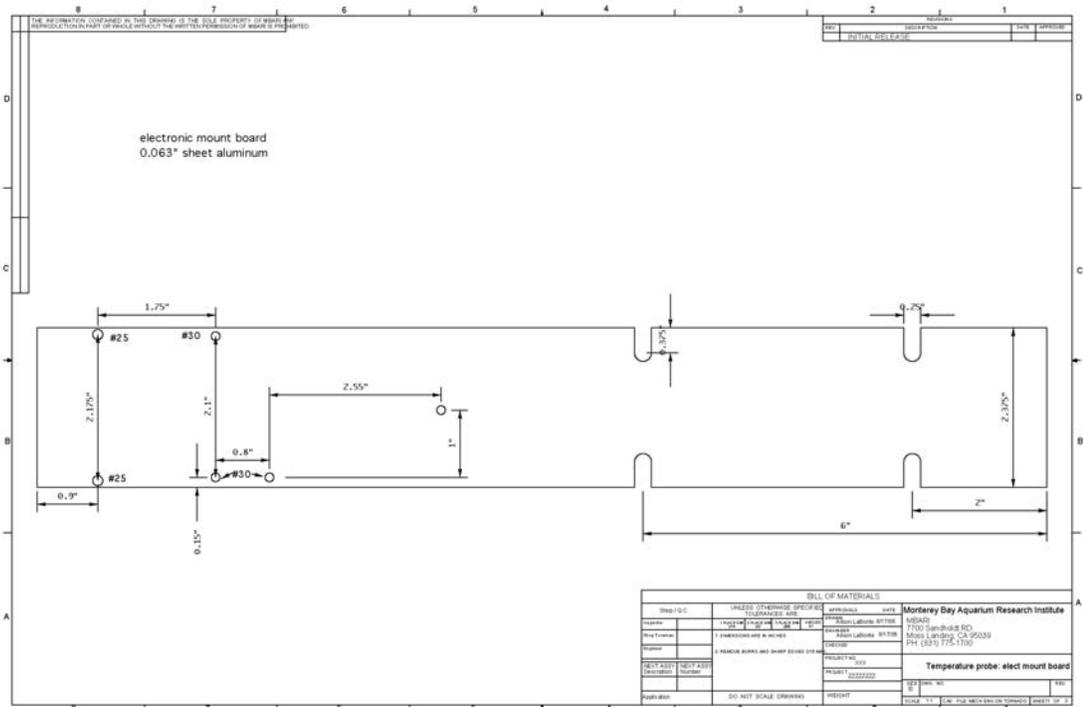


Figure 13: Electronics mounting board design drawing.