PRECISE MEASUREMENT OF THE HEAT FLUX FROM A HYDROTHERMAL VENT SYSTEM

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Introduction

The very essence of a hydrothermal system is transfer of heat by a convecting fluid. Despite this central role played by heat transfer, we have a woefully poor knowledge of the flux of heat from seafloor hydrothermal systems and its variation through time. This lack of knowledge is not from a lack of trying. Many different investigators have made estimates of the flux of heat from seafloor hydrothermal systems. The Endeavour Segment of the Juan de Fuca Ridge is perhaps the best-studied example [*Baker and Massoth,* 1987; *Rosenberg et al.*, 1988; *Thomson et al.*, 1992; *Schultz et al.*, 1992; *Bemis et al.*, 1993; *Ginster et al.*, 1994]. We will return to the details of these studies, but for now there are issues of what style(s) of venting are included in the estimates, the errors inherent in the measurements, sampling statistics, and the spatial and temporal averaging that is associated with each of the individual approaches. Thus, while the reported values are of a reasonable order of magnitude, the resulting estimates vary widely (from ~100 to ~10000 MW), have large uncertainties (often spanning an order of magnitude), and do not allow us to address very fundamental questions, for example, is the flux of heat steady or varying through time? We propose to take advantage of technological advances in deep sea autonomous vehicles to make precise measurements, achieving uncertainty better than 20%, of the heat flux from the Main Endeavour Field (MEF) [*Delaney et al.*, 1992], and as time permits a series of nearby vent fields.

RIDGE Relevance and Relationships to Other Programs

A central theme of RIDGE is defining the temporal variability of ridge processes, a theme that is the foundation of the RIDGE Observatory Experiment (ROBE). An essential component of an observatory program directed at improving our understanding of hydrothermal processes is the measurement of the flux of heat through time. These measurements link the volcanic and tectonic processes important in controlling the evolution of heat transfer and chemical exchange deep in the crust with the seafloor manifestations of hydrothermal activity including sulfide mineralization, biological productivity, and the dynamics of the near-vent deep ocean environment.

The Endeavour Segment of the Juan de Fuca Ridge has emerged as the locus of activity within ROBE for examining the behavior of hydrothermal systems. Of the nine central questions posed within ROBE [*Spiess et al.*, 1995], this proposal is most directly related to two:

- “What are the nature and origins of spatial/temporal variability in submarine hydrothermal systems? What are the dominant physical processes involved?”
- “What is the space/time extent of exchange of heat, fluid volume and chemical mass between hydrothermal systems and the overlying ocean?”

This proposal contributes to addressing these questions through measurement of the integrated hydrothermal flux from the Main Endeavour Field (MEF). The data to be collected will provide the first precise measure of the flux of heat from the field and would underpin following programs to assess the stability of the flux of heat and chemical components. This proposal is part of a coordinated, multiple program effort to examine the temporal character of hydrothermal processes at MEF involving a focussed field component in Summer 1999, see <http://ridge.unh.edu/observatory/>. Among these programs, our proposal has been developed in parallel with a proposal being submitted by Johnson, Tivey and Fisher in which they propose to examine the conductive and diffuse heat flow in the area around the MEF and make related measurements of gravity and magnetic fields. The combined data sets would provide an unprecedented view of the overall heat budget of a vent system. While each of these two proposals represents individual experiments with intrinsic merit, the program is strengthened by the combination of the complementary scientific elements and by the efficiencies of conducting a joint field program. In the following discussion, common to both proposals, we develop the shared scientific rationale.

Hydrothermal Activity on the Endeavour Segment

The Endeavour Segment of the Juan de Fuca Ridge

The locus of spreading on the Endeavour Segment consists of a 500 to 800 meter wide axial valley flanked by two linear volcanic ridges with inward-facing faults and outward-facing constructional volcanic surfaces. These are interpreted as the splitting of a once-intact volcanic ridge [*Kappel and Ryan*, 1986; *Tivey and Johnson*, 1987]. Closely-spaced water column surveys and detailed seafloor mapping indicate that the shoalest third of the segment has (at least) four hydrothermally active and several inactive sites of past sulfide deposition distributed over an along-axis distance of 15 km [*Delaney et al.*, 1991, 1996]. The large Main Endeavour Vent Field (MEF) is one of these 4 large hydrothermal fields on the segment, and has been sampled and mapped through a number of ALVIN and ROPOS programs [*Delaney et al.*, 1992]. Another active, but less well-studied field, the High Rise Vent field, is located 1.8 km north of the Main Endeavour field [*Robigou et al.*, 1993]. Salty Dawg was first visited in 1995, about 3.5 km north of MEF [*Delaney et al.*, 1995] and Mothra Field in 1996 about 2.8 km south of MEF [*Delaney et al.*, 1996]. These hydrothermal systems and their geological context have been described extensively in the literature [*Delaney et al.*, 1992; *Karsten et al.*, 1986; *Johnson and Holmes*, 1989; *Tivey and Delaney*, 1986; *Baker and Massoth*, 1987; *Kappel and Ryan*, 1986; *Stakes and Moore*, 1991; *Bemis et al.*, 1993; *Butterfield et al.*, 1994; *Schultz et al.*, 1992; *Thomson et al.*, 1992; 1995; *Robigou et al.*, 1993, *Fornari and Embley*, 1995; *Hannington et al.*, 1995].

Scientific Problems

Although high temperature, smoker-style venting is the most visually spectacular phenomena on the floor of the ocean, its contribution to the total thermal budget of crustal formation is not clear, and present interpretations are based on limited data and poorly constrained assumptions. The Endeavour Segment, particularly the well-studied Main Endeavour Field, offers an environment well-suited to making progress in evaluating issues related to the thermal budget of young oceanic crust. Critical questions addressed in this pair of proposals include:

<u>Sub-Surface Fluid Circulation Paths:</u> The sites of discharge and recharge of a hydrothermal system, the depth of this circulation, and the processes that control these parameters are largely unknown. A striking feature of the mapped vent field locations on Endeavour Segment is the apparent regularity of their occurrence along axis, with spacing of order 2 km [*Delaney et al.*, 1991]. Early studies attributed the size, geometry and long-lived nature of these systems to 1) the presence of cross-cutting faults that obliquely intersect the ridge-parallel (020° N) normal faults [*Delaney et al.*, 1992; *Robigou et al.*, 1993]. Other hypotheses regarding the regular spacing of hydrothermal vent fields include: 2) progressive deepening of the cracking front that penetrates the warm lower crustal rocks [*Lister*, 1983], 3) characteristic size for circulation cells within the diffuse porosity of the upper crustal rocks [*Delaney et al.*, 1991], 4) fluid circulation cell size within a narrow fissure zone [*Caine et al.*, 1996; *Karson and Rona*, 1990], and 5) periodic dilation zones in the overlapping normal faults that define the axial valley [*Willemse*, 1997]. These models are poorly constrained by existing data sets although they imply: 1) different physical properties of the upper crust, 2) different recharge zones for the high temperature vent fluids, and 3) distinct distributions of diffuse/conductive heat flow.

<u>Total Thermal Budget of Crustal Formation</u>*:* The total flux of heat from any portion of the mid-ocean ridge, at both the scale of a convection-cell or of a ridge segment is also a fundamental but completely unknown parameter. A variety of approaches have been used to estimate heat flux from vent systems. One very basic approach is to measure all known sites of high temperature discharge within an area and then attempt to integrate these measurements. A modification to this approach (for diffuse and conductive flux) is to make measurements over a regular-spaced grid, where the grid is large enough to encompass the relevant area, but with grid-spacing small enough to resolve (detect) all of the major heat sources. A third, fundamentally different, approach is to employ the integrating effect of plume generation, particularly as represented in the neutrally buoyant layer [*Baker et al.*, 1995]. In the plume method, it is necessary to couple the inventory of excess heat contained within that layer to some measurement of time (e.g., either measurements of tidal currents to establish the net transport from a control volume, or the use of a vent-derived radiotracer to establish a time scale). The disadvantage of the discrete-measurement approach is the large number of measurements and instruments required for an accurate estimate, particularly for fields of the size characteristic of the region. The disadvantages of the plume method are the limits imposed on the possible resolution in both time and space. Despite the obvious limitations, the best estimates of the high temperature flux presently rely on measurements within the overlying plume. Conductive and diffuse flux, presumed to be non-uniformly distributed over a wide area, require the use of a systematic grid of discrete measurements. Our integrated program to measure all three of these components will necessarily use both approaches.

<u>Partitioning of the Energy of Discharge:</u> The total heat output at the ridge axis is distributed between high-temperature focused flow, low temperature diffuse flow, and conductive heat transfer, but the relative importance of these different modes is not understood. Although previous studies of diffuse heat flux are few, there is

general agreement that the energy transported by this mode is substantial, since it occurs over a much larger area than focused high-temperature flow [*Little et al.*, 1988; *Schultz et al.*, 1992; *Rona and Trivett*, 1992; *McDuff* 1995]. Diffuse effluent has been observed over much of the axial zone on many spreading centers at a variety of spreading rates, may be a major distribution process of crustal heat in the off-axis flank regions, and provides the primary energy supply for biological growth in virtually all known vent systems.

Estimates of Heat Flux

A variety of approaches have been applied to estimating the heat flux from vent systems. Six different estimates have been made of the thermal output of the MEF: 1) two using plume measurements of thermal content and time-series of currents to estimate the net export of heat [*Baker and Massoth*, 1987; *Thomson et al.*, 1992], 2) one similar measurement of thermal content using ^{222}Rn as a radioactive clock [*Rosenberg et al.*, 1988], and 3) three made by integrating estimates made at individual vents [*Bemis et al.*, 1993; *Ginster et al.*, 1994; *Schultz et al.*, 1992]. These estimates range from ~100 to ~10000 MW. An unlikely explanation is that this range represents temporal variability. One cause of the wide range is that there are uncertainties inherent to each of these approaches. Long time-series are necessary to estimate the net transport of fluid from a control volume limiting the temporal resolution of the technique and resulting in large formal uncertainties in derived values [*Thomson et al.*, 1992]. The interpretation of the radon measurements is made difficult by the contribution of diffuse flow very enriched in radon and by the need for discrete samples, limiting spatial resolution. Instrumenting all individual sources within a vent field is simply not feasible and there are important questions as to the reliability of extrapolating data from a limited number of instruments. A second cause for the wide range is that there are distinct differences in each of the approaches as to what exactly is being measured. Table 1 summarizes the results from these measurements in more detail. From the information in this table we can form several general conclusions:

- Tidally induced variability in deep currents makes it very difficult to provide a well-constrained estimate of the heat flux from measurements in the neutrally buoyant, laterally spreading portion of a plume. The error analysis in *Thomson et al*. [1992] indicates that a six-month record is only sufficient to constrain the net transport within an order of magnitude. A much longer record would provide a better estimate, but the resolution temporally would be quite poor.
- There is reasonable agreement of the estimates made from data from the neutrally buoyant plume. The radon-based value is somewhat higher than the other two and may reflect a significant component of radon entrained from diffusely venting fluids (Rn/heat ratios are much higher in low temperature discharge). While the location of the maximum anomalies suggest a strong source at MEF, the continuity of anomalies at this level leave open the possibility that a portion of the flux is advected from elsewhere.
- The second estimate in *Thomson et al*. [1992], the “instantaneous” value, depends on a mechanistic interpretation of the intersected plume cross section as being a horizontally deflected upflow. If this is not the case then it represents a significant overestimate.

Table 1. Previous Estimates of Heat Flux from MEF

Reference	Heat Flux (MW)	Method
Baker and Massoth [1987]	1700 ± 1100	Integrated anomaly in a section scaled by net transport as determined from current meters
Thomson et al. [1992]	1000 ± 620	Temperature anomaly in control volume scaled by net transport from current meters
Thomson et al. [1992]	12000 ± 6000	“instantaneous flux” for plume core
Rosenberg et al. [1988]	3000 ± 2000	Temperature anomaly scaled by Rn inventory
Bemis et al. [1993]	70-239	Analysis of velocity and temperature structure of 18 plumes interpreted with MTT plume theory
Ginster et al. [1994]	364	Extrapolation of temperature and velocity measurements at 11 smoker orifices
Schultz et al. [1992]	9400	Extrapolation of single point measurement of heat flux of ~10°C fluid from flange surface

- The two estimates based on measurements at discrete smoker-style vents fall at the bottom of the range of values. The *Bemis et al.* [1993] estimate excludes plumes that have coalesced and so is an underestimate by some unknown quantity. The methodology applied may or may not include entrained diffuse flow; we are unaware of any model that would let us answer that question. The *Ginster et al.* [1994] data extrapolate measurements made on 31 smokers. The range of strengths of individual sources shows enough variability that the uncertainty in the integrated estimate is about a factor of three. Both of these studies are limited by the lack of knowledge of the substantial number of vents in the SW portion of the field; at the time only vent 8E was known.
- The only direct estimate of diffuse flow is the point measurement reported by *Schultz et al.* [1992]. The contrast between the estimates from discrete smoker sources and in the neutrally-buoyant layer support of strong component of entrainment of diffuse flow, but about a factor of ten smaller than inferred by extrapolating this single point measurement to the entire vent field. There are significant questions as to the strength of diffuse sources and the fate of this fluid (e.g., contrast *Schultz et al.* [1992] with *Rona and Trivett* [1992]).

An Approach to Precise Measurement of Fluxes

The discussion above illustrates the limitations of existing approaches for measuring the flux of heat from a hydrothermal system. With advances in AUV technology it is feasible to employ an intermediate approach in which surveys are conducted to characterize the flux of heat in the ***rising*** portion of the plumes emanating from a vent field. While tidal currents will cause the cross section of a rising plume to move about and vary in area, the transport will remain predominantly vertical. The requirements for conducting such a survey are precise navigation, good facility at maneuvering the vehicle on a series of tracklines within this navigation network and suitable instruments mounted on the vehicle to determine the temperature, salinity, and velocity fields. With the ABE vehicle, a series of grid lines at ~10 meter spacing could be completed in of order 6 hours in an area several hundred meters on a side. Navigation within a network of conventional long-baseline acoustic transponders should be sufficient for the purposes of this survey. While precision would be limited to ~1 m, the tight spacing of lines is meant to provide a statistical averaging of plume conditions; multiple lines will intersect the cross section of plumes emanating from a single vent complex. The central assumption is that above the vent field the flux is predominantly vertical. Previous work in the vicinity of the vent field suggest that there are not significant thermal anomalies on vertical planes that would totally enclose the vent field and thus a flux could not be supported. However one of the key activities during the field work would be to verify that this assumption is true (and if not true to appropriately modify the survey strategy). We emphasize that the nature of the approach is to measure the flux across the walls of a control volume enclosing the vent field. In doing so we integrate all heat emanating from the field, be it of focused, diffuse or conductive origin.

Related and important measurements are the fluxes of chemical constituents. A unique characteristic of the MEF is co-variation of salinity and volatile contents and inverse correlation of temperature and salinity in fluids within a relatively narrow geographical area. Salinities decrease from NE to SW from ~90% of seawater levels to ~10% and temperatures increase from ~345°C to ~380°C [*Butterfield et al.*, 1994]. These data have allowed us to hypothesize that spatial and temporal variability in vent fluid properties may result from changes in the relative proportions of mixing of the fluids from two adjacent convection cells [*McDuff et al.*, 1994]. The simplest approach to establishing chemical fluxes of *unreactive* constituents is to use the observed systematic relationship of chemistry and heat in vent fluids to calculate the chemical fluxes from the heat flux [*Jenkins et al.*, 1978; *Edmond et al.*, 1979a]. While the gradient of $\Delta c/\Delta T$ relationships in the Endeavour field will make this approach uncertain, the salinity data taken on ABE will provide an independent estimate, allowing us to assess the validity of the approach. If estimates from these two methods agree, then strategies to measure fluxes of reactive constituents, which have different $\Delta c/\Delta T$ relationships as compared to the high temperature fluids from which they are derived (e.g. *Edmond et al.* [1979b]; *Baker et al.* [1993]), could be developed.

Synthetic Sampling of a Model Plume

The crucial question is the quality of the measurement of the heat flux that can be obtained by such a survey technique. If we could measure at all points enclosing a volume and had perfect sensors then the technique would yield a highly precise result. However a survey vehicle will only provide data at a finite set of points and so we must ask what density of sampling will be required to yield precise estimates of the true value? In addition sensors for temperature, salinity and velocity will each have errors associated with them. At low heights of rise above the seafloor the signals will be high and the instrumental noise is relatively small while much further above the seafloor the signals to be detected become comparable to the uncertainty introduced by the sensors. Because the horizontal cross section of a plume increases with height above the seafloor there is a tradeoff between these two determinants of uncertainty.

We have analyzed this question through synthetic sampling of a set of model plumes. A model plume will not contain all the complexity of a real one, for example it will not mimic the largely unknown nature of plumes once they begin to coalesce; it will not include the effects of entrainment of nearby diffuse discharge. Nonetheless, this modeling approach does capture sufficient reality to ascertain whether a discrete set of field measurements will provide a useful result. We emphasize that the observational approach we propose is not dependent in any way on this choice of model. Rather we are relying on the general correspondence between the estimates of parameters coming from the plume models and observations made to date in rising plumes [*Lupton*, 1995].

The time-averaged theoretical description of a plume has its roots in the classic work of *Morton, Taylor and Turner* [1956]. While considerable subsequent work has refined their model, it still represents a useful framework to parameterize plume behavior. The MTT model is a "top hat" model, that is outside a plume the fluid has the properties of the ambient environment while inside the plume the properties are averaged and so are only a function of distance above the plume source. The MTT model involves conservation of mass, momentum, and as many additional parameters as are necessary to describe the density contrast between the plume and the surrounding environment. When applied to hydrothermal plumes, the four conservation equations usually considered are those for mass, momentum, heat, and salinity. (Other components present in the vent fluid may also have a significant effect on the density, especially silica [*McDuff*, 1995]). The essence of the MTT formulation is that closure of the model is made through an entrainment assumption which establishes a proportionality between the horizontal velocity of fluid entrained at the edge of the plume to the vertical velocity of the plume at that level: $E = \alpha(2\pi r)W$, where α is the entrainment coefficient (empirically about 0.07), r is the plume radius, W is the vertical velocity and E is entrainment rate. With this assumption, the conservation equations for mass, salt, heat and momentum can be written:

mass $\quad \dfrac{d}{dz}(AW) = EA^{1/2}W \qquad$ salt $\quad \dfrac{d}{dz}(SAW) = \bar{S}EA^{1/2}W$

heat $\quad \dfrac{d}{dz}(\theta AW) = \bar{\theta}EA^{1/2}W \qquad$ momentum $\quad \dfrac{d}{dz}(AW^2) = g\dfrac{(\rho-\bar{\rho})}{\rho_0}$

In these equations z is the vertical coordinate, S is salinity, θ is potential temperature, and the notation $\bar{X}$ denotes the vertical variation of property X in the ambient water column. This set of equations can be integrated numerically once the properties of the venting source (A, W, θ, and S), an equation of state ($\rho(T,S)$) and the local stratification ($\bar{\theta},\bar{S}$) are specified.

This set of equations was solved for conditions representative of a fluid venting from a smoker-style vent into an environment with the stratification typical of the northeast Pacific. The buoyancy force acting on the fluid brings about changes in momentum. Near to the source both the momentum flux and buoyancy flux are positive. As the plume rises momentum increases at the expense of buoyancy. At the point of buoyancy reversal, the momentum reaches a maximum. Because of the remaining momentum at this level the plume overshoots. When the level of zero momentum is reached, the plume overturns, sinks back to its level of neutral buoyancy, and spreads laterally. Temperature contrast with the surrounding ambient fluid decays rapidly with height as does vertical velocity (though not quite as steeply). The radius of the plume grows linearly with height above the vent.

Using this single plume as representative we assembled a composite model with characteristics of the Main Endeavour Field. Laboratory studies demonstrate that Gaussian profiles across the plume reasonably approximate the time-averaged behavior [*Papanicolaou and List*, 1988] and so although we use the top-hat model to calculate plume properties, we distributed these spatially in a Gaussian fashion to provide a more realistic representation of *in situ* conditions. The field spans a 200 x 400 meter area. The ten km range of the survey vehicle would thus allow twenty-five 400 meter long tracks spaced 8 meters apart. Within the field about 150 discrete smoker vents have been mapped. The radius of the plumes emanating from these sources grows about 10 cm per meter of rise, so the total area grows with height by the relationship $A = 150 \times \pi(0.1h)^2$ (for scale this relationship says that at 50 meters of rise the plume cross sectional area is about 12% of the survey area). Previous studies evaluating the hydrographic structure of plumes show that the temperature anomaly *q* (as defined by *McDougall* [1990]) can be determined to about ±10 mdeg. With ensemble-averaging of ADCP data, the vertical component of the fluid velocity can be evaluated to ±1 cm/s (the ensemble-averages apply on a horizontal scale of ~5 meters). Similar performance is achievable with the V-D-V sensor. Uncertainties of this magnitude were randomly added to the modeled spatial distribution.

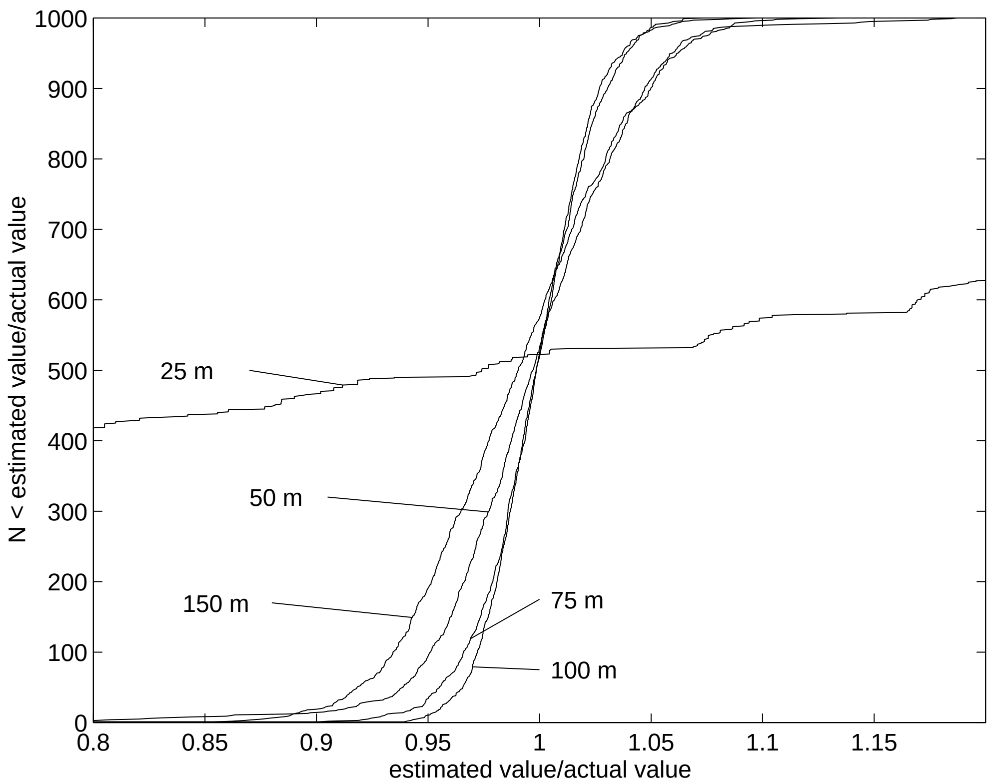
We have considered synthetic surveys flown at heights of 25, 50, 75, 100 and 150 meters. Table 2 summarizes the plume characteristics used in the analysis.

Table 2. Parameters Used in Synthetic Survey Analysis

Altitude (m)	temperature anomaly, *q* (°C)	vertical velocity (m/s)	plume cross sectional area/total survey area	Uncertainty in estimated value (as fraction of true value) based on range containing 95% of values	Uncertainty (estimated/true) due to propagation of sensors errors into integrated heat flux
25	1.9	.145	.028	0.64	.015
50	0.3	.105	.115	.076	.025
75	0.18	.092	.264	.049	.030
100	0.10	.075	.468	.044	.045
150	0.044	.052	1.068	.083	.085

Figure 1 shows the cumulative number distribution of computed heat flux from 1000 replicate surveys at each height; each survey follows a new set of regularly spaced survey lines through a static temperature and velocity field. The positions of the track lines are changed as a proxy for variability in plume position resulting from varying tidal currents. At 25 meters height, the distribution of results is extremely broad and less than a quarter of the estimates fall within 20% of the true value. This is because many of the replicate surveys have few tracks intersecting the plume (as the area in which plume is present is small) while at other times plume-influenced fluid is over-represented and the estimated value is high. As the survey height increases, the distribution narrows considerably indicating that the sampling becomes more representative. But also contributing to the uncertainties is the resolution of the sensors themselves. The right hand column of Table 2 indicates the formal error in the computed integrated flux due this source of uncertainty. At 25 meters this is a small number and most of the error is due to the problem of representative sampling. At greater survey heights the contribution from uncertainties related to the sensor precision increases so that at 150 meters most of the range seen in Figure 1 is due to the sensors. The distribution is most narrow at 75 and 100 meters and indicates that there is an optimal level at which to conduct a survey to estimate the heat flux. At this level one could compute estimates from a single survey that would be reliable to of order ±20%. An important element of the first year of work for this project would be to collect data at different heights off the seafloor as a basis for refining this error analysis and to optimize the strategy applied for the remaining surveys.

Figure 1. Cumulative Number Distribution of Estimated Heat Flux as a Fraction of True Heat Flux for 1000 Replicate Synthetic Surveys.

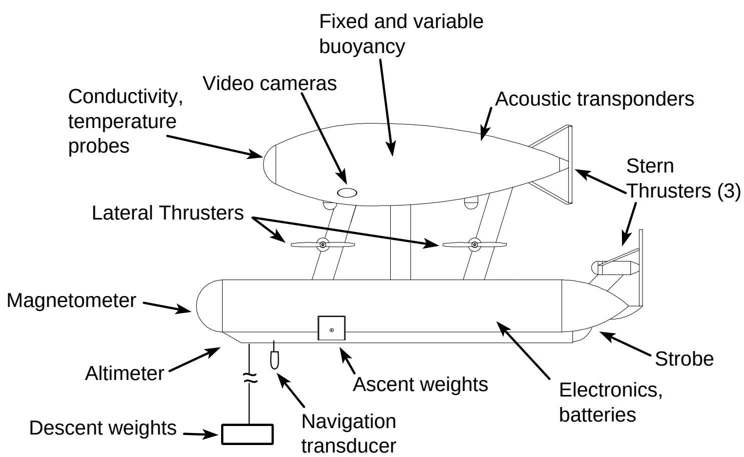


Field Program

By subcontract, Dana Yoerger and Al Bradley of Woods Hole Oceanographic Institution would participate in this program and provide the services of the Autonomous Benthic Explorer (ABE). The approach proposed takes advantage of the unique, proven capabilities of ABE. Past programs conducted in 1995 and 1996 have shown that ABE can fly carefully controlled tracklines either at constant depth or while following rugged terrain. These capabilities have been demonstrated both in the context of seafloor magnetics and plume mapping. ABE's stability and controllability make it an excellent platform for making the needed CTD and vertical velocity measurements required to implement the approach described above. ABE has made 21 deep dives over the past two years. More information on ABE and past field programs can be found at <http://www.dsl.whoi.edu/~dana/abe_serious.html>.

Capabilities of ABE

ABE performs deep ocean surveys carrying a variety of sensors including a magnetometer, CTD, optical backscatter sensor, bathymetric sonar, and snapshot stereo video. ABE navigates itself using long baseline acoustic transponders both in-hull with a backup at the surface. ABE uses knowledge of its position to follow preprogrammed tracklines. It can either fly at preprogrammed depths or it can follow the bottom at a programmed separation. ABE is extremely stable and can hold its heading quite steady (better than 1 degree) and it can hold its depth to better than 0.15 meters. Its normal transit speed is 0.7 meters/second. The current batteries allow for 10 km of trackline for constant-depth operation. Figure 2 shows the major features of ABE:



With present battery capacity, dives can be conducted on a 50% duty cycle (12 hour dive followed by 12 hour turnaround). UW personnel will provide a list of trackline endpoints, depth control options, and desired sensor and sampler control sequences. From these specifications, WHOI personnel will develop the mission program. They will check the tracklines and also analyze the resulting transponder coverage graphically against background bathymetry. The mission program will then be tested in simulation on the vehicle computer system, with the results displayed graphically in real-time. This simulation takes about 2 hours. At the same time batteries are charging and the vehicle undergoes its final checks. The drop weights are rigged and the releases tested. The long baseline navigation is tested, as are all thrusters. Likewise, the cameras and strobes are checked, as are the recovery aids (strobes, RF beacon). Before launch, the ship is maneuvered to a point within a few hundred meters of the starting point of the first trackline. Ship positioning is not critical, as ABE will actively guide itself to the correct point on the seafloor. Long baseline navigation is initiated on the ship (used to passively monitor ABE's progress), and then ABE is launched with the ship's crane. After launch, ABE descends to the seafloor under the pull of its descent weight. ABE descends the first few hundred meters passively. Next it executes a few slow spins to enable the magnetometer to be calibrated. It then starts actively homing on the desired starting spot. It controls its position by using its natural forward motion during descent and making occasional changes in its heading. This allows ABE to reach the starting point while using little energy. In 2500 meters water depth, the descent takes about 2 hours. During the entire mission, ABE's movement is tracked from the surface using long baseline tracking. The surface tracking is almost entirely passive, as both ABE and the ship have precision timebases; the ship pings only every few hours to keep the clocks in synchronization. During critical points in the mission (arrived on-bottom, end of trackline, etc.), ABE signals with a series of pings that can be detected through the surface LBL system. When ABE reaches the seafloor, it releases its descent weight and starts its first trackline. If needed to synchronize the mission with other cruise activities, ABE can delay the start of the trackline as long as desired. ABE then executes the list of tracklines, following the bottom or holding specified depths as appropriate. The operations team can monitor all vehicle movements via the long baseline navigation. The resolution is sufficient to follow ABE climb and descend over the terrain. If ABE terminates the dive early for any reason, it will signal with a series of pings. After the last trackline is complete, ABE signals with a series of pings and drops its ascent weights. In 2500 meters depth, the ascent takes about 2 hours. After recovery, WHOI personnel extract the data and make preliminary plots. In about one hour the basic data set is ready for analysis by the UW group. Recomputation of the in-hull navigation takes several more hours. Data from the dives will include:

- Vehicle position determined at the long baseline (LBL) transponder cycle interval, typically every 10 seconds (water depth dependent). This data is obtained by ABE directly, so errors caused by uncertainties in the sound velocity profile of the water column are minimal.
- Data from vehicle science sensors, sampled at 1 Hz. These include a 3-axis magnetometer (Develco 9200C-01), SeaBird conductivity and temperature sensors, and an optical backscatter sensor (Seapoint Turbidity Meter).
- Fluid velocity. The ABE group has recently acquired a 1.2 MHz RDI Doppler and will have it operating both as a bottom lock navigator and to determine the profile of three-component velocity vectors in bins beneath the vehicle. An UW-acquired flow-density-velocity (Focal Technologies VDV-1) will also be installed on the vehicle to provide point measurements of current. This sensor, based on BASS technology [*Williams et al.*, 1987], includes multiple redundant acoustic paths as a means of correcting for deflection of the flow by the sensor. We have verified from depth records of past dives that the vertical acceleration of the vehicle will not create significant uncertainty in the velocity records.

- Vehicle attitude (pitch, roll, heading), depth, and altitude at the LBL cycle interval or at higher rates up to 2 samples/second. Pitch and roll are measured with inclinometers. Heading is a composite estimate obtained from a flux gate compass and a rate gyro. Depth is measured with a Paroscientific pressure sensor. Altitude is obtained from the acoustic altimeter, which points forward 30 degrees and has a beam width of approximately 15 degrees. These data will be used to place velocity measurements in a x-y-z coordinate system.
- Engineering data from the vehicle. These data include commanded thrust levels, measured propeller speeds, battery voltage, power consumption. These data will be checked for changes in operating conditions that may introduce artifacts into the primary data.
- Magnetic data collected during our surveys would be provided to Tivey and would complement their proposed near-bottom data collection.
- Imagenix 675 kHz scanning sonar for cross-track bathymetry out to ranges of approximately 30 meters may soon be available. We will consider whether data from this system might be useful in evaluating plume shape, as has been done with similar acoustic techniques by *Rona et al.* [1991].

Field Work

The proposed field program is joint with the Johnson/Tivey/Fisher program and consists of 29 days at sea on the *RV Atlantis*. Making the two distinct sets of measurements on the same ship, with their use of ALVIN and JASON for detailed bottom work as the daytime program and ours with ABE during the night, is an unusually efficient use of limited and expensive resources. More important however is the integration of scientific results of these two projects. Our complementary observations, made in the same area and at the same time, will make the composite program much more valuable than the simple sum of the individual experiments. We would plan to complete a minimum of 15 ABE dives. An initial four dives would be conducted at 50, 60, 80 and 100 meters above typical vent depth to refine the synthetic error analysis described earlier and to identify the optimal level to conduct survey from the standpoint of achieving the best precision. Comparison of the heat flux at each of these levels provides one way of verifying the absence of significant horizontal fluxes; in the absence of horizontal fluxes there must be conservation of heat between levels. The next three dives would be made on vertical sections at the edge of the survey area to examine the magnitude of horizontal fluxes into or out of the vent field. These dives would be complemented by hydrographic data collected by using the dynamic positioning capability of the ship and long-baseline navigation to position a CTD rosette on the vertical walls of the control volume. These data provide a second test of whether a survey strategy focussing solely on vertical fluxes will be adequate or whether the strategy must include both the sides and top of the control volume. The remainder of the dives would be used to characterize the heat fluxes from MEF and to establish the variability that might exist on the scale of days to weeks. Analysis of any variability found would include comparison with observations from discrete vents made at the same time by a proposed Delaney et al. program examining tide-induced variability in venting. The possibility exists that we will find no significant variation of heat flux in the initial dives and first several optimized dives. In this case we would plan to make exploratory surveys of the three adjacent vent fields (High Rise and Salty Dawg to the north, Mothra to the south) both to set a regional context for MEF and to help in interpreting existing data for laterally spreading, neutrally buoyant plumes.

Personnel

Russell McDuff will serve as principal investigator for this program. He will be responsible for coordination of field work with Johnson, reduction of data, and interpretation and publication of the results including integration with the studies of other ROBE investigators. Fritz Stahr, who is completing his Ph.D. in physical oceanography working with Tom Sanford, will be a postdoctoral researcher on the program. He will work with McDuff on integrating sensors with ABE, sensor calibrations, and survey design. A graduate research assistant will work with McDuff on processing and analyzing the data. A team of four people operates ABE: Dana Yoerger, Al Bradley, Rod Catanach and Al Duester. Yoerger and Bradley are responsible for planing and programming each ABE dive in collaboration with McDuff. Catanach and Duester assist with vehicle operations and turnaround. Yoerger and McDuff will conduct the transponder deployment and transponder surveys for the long-baseline navigation system.

A Temporal Perspective

The collective advice from two earlier submissions of this proposal was to collapse its scope to a single field season, focussing on heat alone and without making related chemical measurements. The outcome of the complementary field programs will be to have mapped hydrothermal circulation and measured heat output that represents, geologically, a single point in time. Though the field program covers a period of almost a month, we will not have determined if the heat flux of this system is steady, oscillatory, or evolving with time. We view this initial program as a critical demonstration that hydrothermal fluxes can be measured with sufficient precision so that conducting time-series measurements would be of value.